UNIVERSIDAD DE EXTREMADURA

TESIS DOCTORAL

DISEÑO DE MATERIALES SOSTENIBLES DENTRO DE UNA ECONOMÍA CIRCULAR

Blas Cantero Chaparro

PROGRAMA DE DOCTORADO EN DESARROLLO TERRITORIAL SOSTENIBLE

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TESIS DOCTORAL

TÍTULO:

DISEÑO DE MATERIALES SOSTENIBLES DENTRO DE UNA ECONOMÍA CIRCULAR

DESIGN OF SUSTAINABLE MATERIALS WITHIN A CIRCULAR ECONOMY

AUTOR:

BLAS CANTERO CHAPARRO

PROGRAMA DE DOCTORADO EN:

DESARROLLO TERRITORIAL SOSTENIBLE

CONFORMIDAD DE LOS DIRECTOES:

Fdo: Dr. César Medina Martínez
Profesor Titular de Universidad
Universidad de Extremadura

Fdo. Dr. Carlos Thomas García
Profesor Contratado Doctor
Universidad de Cantabria

”La conformidad de los directores de la tesis consta en el original en papel de esta Tesis Doctoral”

2021

A mi familia, en especial a

Nieves y Camila

Incluso las acciones más pequeñas
deben ir alineadas con un fin
Marco Aurelio

Preámbulo

Informe razonado de los Directores de la Tesis Doctoral

Los Doctores César Medina Martínez, Profesor Titular de Universidad de la Escuela Politécnica de la Universidad de Extremadura y Carlos Thomas García Profesor Contratado doctor en la Escuela Técnica Superior de Ingenieros de Caminos Canales y Puertos de la Universidad de Cantabria, en calidad de directores, informan:

Que esta Tesis Doctoral se ha realizado bajo nuestra dirección en el Área de Ingeniería de la Construcción del Departamento de Construcción, de la Escuela Politécnica de la Universidad de Extremadura y en el Programa de Doctorado en Desarrollo Territorial Sostenible de la Universidad de Extremadura, siendo realizada por el doctorando Blas Cantero Chaparro. Dicho trabajo de investigación se desarrolla en el campo de nuevos hormigones reciclados sostenibles en el ámbito de la ingeniería civil y la edificación, tratando por primera vez en el ámbito nacional e internacional establecer las bases científico – técnicas que permitan introducir simultáneamente residuos de la construcción y demolición (RCD) desde una doble vertiente; bien como parte del esqueleto granular y/o adición sustituyendo parcialmente a los áridos naturales y al cemento, respectivamente. Adicionalmente, esta investigación contribuirá a implementar el concepto de economía circular en el sector de la construcción y aumentar la tasa de reciclado de estos RCD. Los resultados y conclusiones mostrados han sido publicados en revistas científicas indexadas en Journal Citation Reports (JCR) acorde a los requisitos necesarios para el programa de Doctorado en Desarrollo Territorial Sostenible de la Universidad de Extremadura en la modalidad de Tesis por compendio de artículos. Por tanto, consideramos que se reúnen los requisitos necesarios para ser presentada a la comisión de esta Universidad para su exposición y defensa.

Y para que así conste, y en cumplimiento de la legislación vigente, se firma la presente en Cáceres y Santander, el día 25 de octubre de 2021

Fdo: Dr. César Medina Martínez
Profesor Titular de Universidad
Universidad de Extremadura

Fdo. Dr. Carlos Thomas García
Profesor Contratado Doctor
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"La conformidad de los directores de la tesis consta en el original en papel de esta Tesis Doctoral"

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Fecha fin / *End date*: 08/12/2019

Firma del Investigador/a responsable:
Signature of the researcher in charge:

Jorge de Brito

CΞRIS : Civil Engineering Research and Innovation for Sustainability

RESEARCH STAY CERTIFICATE

The undersigned, **Professor Dr. Jorge de Brito**, Full Professor at the Department of Civil Engineering, Architecture and Georesources of Instituto Superior Técnico (IST), University of Lisbon, Portugal, on behalf the Institution:

CETIFICATE that **Blas Cantero Chaparro** PhD student of the School of Technology at University of Extremadura, has acted since **1st March 2021 until 2nd July 2021** a research stay framed in the development of his doctoral thesis in the **Instituto Superior Técnico (University of Lisbon)**.

During the stay, he has collaborated in numerous training activities and research works, some of which are: development and characterization of concretes with alkali-activated binders from construction and demolition waste from different sources (concrete, ceramics and glass). These works ara included in the Research Project "Recycled Inorganic Polymer Concrete: Towards a cement-free and fully recycled concrete" (PTDC/ECI-COM/29196/2020).

In witness whereof, and for such purposes that may arise, the following certification is issued in Lisboa, Portugal, on 2nd July, 2021.

Signature:

DECIVIL
DEPARTAMENTO DE ENGENHARIA CIVIL, ARQUITETURA E GEORRECURSOS
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Jorge de Brito

Full Professor of the Instituto Superior Técnico, University of Lisbon

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Publicaciones Científicas

Informe sobre las aportaciones derivadas de la Tesis Doctoral y factor de impacto de las revistas científicas (Journal Citation Reports):

Publicaciones en revistas científicas (Capitulos de la Tesis Doctoral)

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1. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, C. Medina. Effect of Recycled Aggregate on Performance of Granular Skeleton. *ACI Materials. Journal.* (2020), 117, 113–124. https://doi.org/10.14359/51720299 [Category: Construction & Building Technology, Q3 (38/63)].

2. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, C. Medina. Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes. *Construction and Building Materials* (2018), 185, 93–101. https://doi.org/10.1016/j.conbuildmat.2018.07.060 [Category: Engineering Civil, Q1 (11/134)]

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5. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, C. Medina. Water transport mechanisms in concretes bearing mixed recycled aggregates. *Cement and Concrete Composites* (2020), 107, 103486. https://doi.org/10.1016/j.cemconcomp.2019.103486 [Category: Construction & Building Technology, Q1 (3/63)].

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8. B. Cantero, M. Bravo, J. de Brito, I.F. Sáez del Bosque, C. Medina. Thermal Performance of Concrete with Recycled Concrete Powder as Partial Cement Replacement and Recycled CDW Aggregate. *Applied Sciences* (2020) 10 (13), 4540. https://doi.org/10.3390/app10134540 [Category: Engineering, Multidisciplinary, Q2 (32/91)].

9. B. Cantero, J. Sainz-Aja, A. Yoris, C. Medina, C. Thomas. Resonance Fatigue Behaviour of Concretes with Recycled Cement and Aggregate. *Applied Sciences* (2021), 11 (11), 5045. https://doi.org/10.3390/app11115045 [Category: Engineering, Multidisciplinary, Q2 (32/91)].

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José Saínz-Aja; Blas Cantero Chaparro; Carlos Thomas García; Isidro Carrascal; Jesús Seitén; Juan Antonio Polanco; Ana Cimentada; José A. Casado. Fatigue in recycled aggregate concrete for railway superstructure applications. Waste and Byproducts in Cement-Based Materials. Innovative Sustainable Materials for a Circular Economy. *Woodhead Publishing Series in Civil and Structural Engineering*. 1 - 1, pp. 715 - 733. Elsevier, ISBN 978-0-12-820549-5.

Comunicaciones presentadas a congresos nacionales e internaciones

1. C. Medina, I.F. Sáez del Bosque, B. Cantero, P. Plaza, P. Velardo, M. Frías, M.I. Sánchez de Rojas. Los Áridos Reciclados en la Industria del Hormigón. International Congress of Construction and Demolition Waste Recycling (C&D Waste). Edited by Fueyo Editores pp. 64-67 (2019). Madrid (España). ISBN: 978-84-942420-9-0. (Digital Book of Articles).

2. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, C. Medina. Recovery and Use of C&DW Recycled Plant Materials in Construction. 15th International Congress on the Chemistry of Cement. Edited by Research Institute of Building Materials Prague Ltd. (2019). Prague (Czech Republic). ISBN: 978-80-906541-4-3. (Digital Book of Articles).

3. B. Cantero, I.F. Sáez del Bosque, M.I. Sánchez de Rojas, M. Frías, C. Medina. Efectos de los Residuos de la Construcción y Demolición en la Durabilidad de los Hormigones Reciclados. II Congreso Nacional PRE-COMPAT " Avances en Control de Calidad Patología y Recuperación de la Construcción". (2019) Alicante. (España). ISBN 978-84-09-03646-2. (Digital Book of Abstract)

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6. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, M. Frías, C. Medina. Mixed Recycled Aggregate in the Design of Sustainable Recycled Concrete. 10th ACI/RILEM International Conference on Cementitious Materials and Alternative Binders for Sustainable Concrete. Edited by Arezki Tagnit-Hamou, American Concrete Institute (ACI) pp. 656 (2017). Montreal (Canadá). ISBN: 9978-1-945487-77-4. (Digital Book of Articles).

7. C. Medina. I.F. Sáez del Bosque, A. Matías, B. Cantero, P. Plaza, P. Velardo, E. Asensio, M. Frías, M.I. Sánchez de Rojas. Recycled Aggregate in Civil Works and Building Construction. International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste. Edited by TU Delft Library pp. 193-197 (2017) Delf (Holanda) ISBN: 978-94-6186-826-8. (Digital Book of Articles).

8. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, M. Frías, C. Medina. Effect of Recycled Aggregate on Concrete Permeability to Water. 14th International Conference on Durability of Building Material and Components. Edited by RILEM Publications S.A.R.L. pp.117-118. Ghent (Belgium), ISBN: 978-2-35158-159-9.

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10. E. Asensio, C. Medina. I.F. Sáez del Bosque, B. Cantero, M. Frías, M.I. Sánchez de Rojas. Sulfate resistence in blended cements with fired clay-based additions. Procedings of the Workshop External Sulfate Attack. Edited by LNEC. (Laboratório Nacional de Engenharia Civil) pp.107-115. (2017) Lisboa, (Portugal) ISBN 978-972-49-2297-3. (Digital Book of Abstract)

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12. B. Cantero, I.F. Sáez del Bosque, A. Matías, M.I. Sánchez de Rojas, M. Frías, C. Medina. Valorización de los áridos reciclados en el ámbito de la Ingeniería Civil. XIV Congreso Nacional de Materiales. (2016) Gijón (España). Material-ES 2017:1 (1); 1-23. ISSN: 2530-6405

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JUNTA DE EXTREMADURA
Consejería de Economía e Infraestructuras

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MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

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Resumen

Durante las últimas décadas nuestra sociedad viene proponiendo e impulsando cada vez con mayor compromiso y celeridad, políticas medioambientales que traten de reducir el consumo de recursos naturales y la producción de residuos. El sector de la construcción es el mayor consumidor de recursos naturales no renovables, además de encontrarse entre los que más residuos producen en todo el mundo. La valorización y reciclado de estos residuos se presenta como una oportunidad para transformar el sector y hacerlo más sostenible, al incorporarlos nuevamente al sistema productivo como nuevas materias secundarias, en el marco de la economía circular.

El objetivo principal que se plantea en la presente Tesis Doctoral es investigar y valorizar los residuos de construcción y demolición (RCD) procedentes de diferentes plantas de reciclaje situadas en España y Portugal, así como explorar nuevas fuentes alternativas en el diseño y fabricación de hormigones que incorporen esta tipología de materiales desde una doble vertiente, bien como parte parcial de su esqueleto granular o como sustituto parcial del cemento.

Para alcanzar este objetivo, se ha llevado a cabo un plan de trabajo basado en cinco fases experimentales.

En una primera fase, se caracterizaron los áridos naturales y reciclados mixtos desde un punto de vista físico, químico, mineralógico y mecánico mediante ensayos normalizados y técnicas instrumentales con el fin de verificar el cumplimiento de los requisitos establecidos por la Instrucción Española de Hormigón Estructural – EHE-08 para los áridos destinados a la fabricación de hormigones estructurales e interpretar el efecto de las nuevas materias primas recicladas en las prestaciones de los hormigones en estado fresco y endurecido. Estos resultados indican que los áridos reciclados mixtos tenían un bajo porcentaje en impurezas (madera, yeso y asfalto, entre otros) que en ningún caso superan el 1 % en peso. De forma general, estos nuevos áridos presentan una menor densidad seca y mayor porosidad respecto a sus homólogos naturales debido a la presencia de mortero adherido y partículas cerámicas. Asimismo, estos áridos reciclados cumplieron con los requisitos físicos, químicos y mecánicos recogidos en la normativa vigente.

En una segunda fase, se caracterizó el cemento convencional y tres cementos que incorporaban en su composición como adición ultra finos procedentes de los RCD: i) cemento portland tipo I de clase resistente 42,5 MPa y endurecimiento rápido (CEM I 42,5 R); ii) cemento con un 25 % de ultra finos de base cerámica procedente de los RCD (cemento patentado (Nº:ES2512065) por

el Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC)); y iii) cementos con un 10 % y un 25 % de ultra finos de hormigón reciclado procedentes de RCD. Resultado de esta caracterización física, química y mecánica, se constató el cumplimiento de los requisitos establecidos por la norma europea EN 197-1 para cementos de clase resistente 42,5 R.

En una tercera fase, se investigaron las propiedades físicas en estado fresco (trabajabilidad, densidad y contenido de aire), endurecido (densidad y conductividad térmica) y prestaciones mecánicas (resistencia a compresión, resistencia a tracción, resistencia a flexión, módulo de elasticidad y límite de fatiga) de los hormigones que incorporaban de forma simultánea e independiente áridos reciclados mixtos y/o cemento con adiciones de distinta naturaleza procedentes de los RCD. Los resultados obtenidos ponen de relieve que la sustitución de un 50 % de árido reciclado mixto de forma simultánea con cementos que incorporan un 25 % de ultra finos de base cerámica o un 10 % de ultra finos de hormigón reciclado cumplen con las prestaciones mecánicas para ser utilizados en hormigones para fines estructurales.

En la cuarta fase, se abordaron los diferentes aspectos de durabilidad tales como: absorción total de agua, porosidad abierta, absorción de agua por capilaridad, resistividad eléctrica, retracción, permeabilidad al agua, permeabilidad al oxígeno, permeabilidad al CO_2 y permeabilidad a los cloruros. En cuanto a los resultados de esta fase, se observa que los hormigones que incorporaban de forma simultánea y/o independiente árido reciclado mixto y adiciones recicladas de base cerámica (25 %) y de hormigón (10 %) mostraron una estructura porosa suficientemente impermeable. Según los valores registrados en los coeficientes de permeabilidad al oxígeno y permeabilidad al agua, estos hormigones reciclados se encuentran dentro del rango normal del hormigón convencional. Adicionalmente indicar que son aptos para su exposición en ambientes agresivos asociados a la corrosión de armaduras y exposiciones ambientales específicas (ataque químico, hielo-deshielo, sales fundentes, abrasión y cavitación) según la EHE-08 y el nuevo Código Estructural Español.

Finalmente, en una quinta fase, se fabricaron piezas a escala industrial de elementos prefabricados sin armadura (bajantes de talud) y con armadura (pretiles tipo New Jersey) en la empresa de prefabricados ROCACERO S.A. situada en Polanco (Cantabria). Estas piezas se sometieron a ensayos mecánicos, diseñados específicamente, de flexión (bajante de talud) y prueba de impacto en laboratorio (pretiles tipo New Jersey). Los resultados obtenidos en esta fase, permiten concluir que las piezas fabricadas que incorporan simultáneamente la fracción gruesa del árido reciclado mixto y un 25 % de ultra finos de base cerámica como adición al cemento cumplen con las prestaciones mecánicas requeridas para estas aplicaciones.

Abstract

Over the last few decades society has been proposing and with ever more conviction and urgency driving, environmental policies aimed at lowering natural resource consumption and waste generation. Construction consumes more non-renewable natural resources than any other industry and is among the sectors that generate most waste, worldwide. Valorising and recycling that waste in keeping with circular economy premises affords the opportunity to render the industry more sustainable by redirecting the refuse to production as new secondary materials.

Two primary aims were pursued in the research giving rise to this dissertation: to study and valorise construction and demolition waste (CDW) from a number of recycling plants in Spain and Portugal; and to explore alternative approaches to concrete design and manufacturing that include such materials either as part of their granular skeleton or as a partial cement replacement.

The five-stage working plan designed to that end included the following tasks.

In the first stage natural and mixed recycled aggregate were physically, chemically, mineralogically and mechanically characterised using standardised tests and instrumental techniques. The purpose was to verify compliance with the requirements laid down in Spanish Structural Concrete Code (EHE-08) for aggregate used in structural concrete manufacture and to analyse the effect of the new recycled raw materials on fresh and hardened concrete performance. The findings showed that the impurity (wood, gypsum and asphalt, among others) content in mixed recycled aggregate was consistently <1 wt %. Generally speaking, the new aggregates had lower dry density and higher porosity than the natural product due to the presence of bound mortar and masonry particles. They nonetheless met the physical, chemical and mechanical requirements stipulated in the existing legislation.

The second stage involved characterising conventional cement and three cements additioned with CDW ultrafines: i) a type I 42.5 MPa rapid-setting portland cement (CEM I 42.5 R); ii) a cement bearing 25 % CDW masonry fines patented by the Eduardo Torroja Institute for Construction Science (a National Research Council body) (patent No. ES2512065); and iii) cements bearing 10 % or 25 % recycled concrete ultrafines sourced from CDW. Physical, chemical and mechanical characterisation showed that all three binders met the requirements laid down in European standard EN 197-1 for 42.5 R strength class cements.

In the third stage fresh concrete physical (workability, density and entrained air content) and hardened (density and thermal conductivity) concrete properties as well as mechanical performance (compressive, tensile and flexural strength, modulus of elasticity and fatigue limit) were studied in concretes bearing mixed recycled aggregate and/or cement additioned with different types of CDW materials, either separately or jointly. According to the findings, concretes containing 50 % mixed recycled aggregate used in conjunction with cements containing 25 % masonry waste ultrafines or a cement 10 % additioned with recycled concrete ultrafines were standard-compliant for structural use.

The fourth stage addressed durability characteristics such as total water absorption, effective porosity, capillary water absorption, electrical resistivity, shrinkage and permeability to water, oxygen, CO_2 and chlorides. The concretes bearing mixed recycled concrete aggregate and cement containing recycled masonry (25 %) or concrete (10 %) additions, jointly or separately, exhibited sufficiently impermeable pore structures. On the grounds of the values recorded for the oxygen and water permeability coefficients, these recycled concretes lay within the normal range for conventional concrete. The recycled materials were also found apt for exposure to aggressive environments associated with reinforcement corrosion and other specific conditions (chemical attack, freeze-thaw, salt fluxes, abrasion and cavitation) further to the provisions of EHE.08 and Spain's recently instituted building code.

In the fifth and last stage, precast bulk (embankment runoff pipes) and reinforced (New Jersey guard rails) concrete elements were manufactured on an industrial scale at the ROCACERO S.A. precast concrete plant sited in the Spanish province of Cantabria. These elements were tested mechanically to specifically designed trials (runoff pipes) and standard laboratory impact procedures (New Jersey guard rails). The findings for this final stage confirmed that the precast elements bearing both coarse mixed recycled aggregate and 25 % masonry waste as a cement addition were compliant with the performance requirements for the respective applications.

Capítulo 1

Organización de la Tesis

Capítulo 1

Organización de la Tesis

La presente Tesis Doctoral ha sido redactada cumpliendo los requisitos del programa de doctorado "Desarrollo Territorial Sostenible" de la Universidad de Extremadura y de acuerdo con la normativa académica vigente para la Mención de Doctorado Internacional.

Este trabajo se presenta como una colección de artículos de investigación, que han sido publicados en revistas internacionales incluidas en el **Journal Citation Report** (JCR ISI).

Para una mejor compresión, esta tesis se ha organizado en diez capítulos que se presentan de la siguiente forma:

- CAPÍTULO 2: introducción general del estado del arte y antecedentes del tema abordado en la presente tesis doctoral destacando la valorización de los residuos de construcción y demolición (RCD) como árido reciclado grueso y como nuevas adiciones al cemento en la fabricación de hormigones sostenibles.

- CAPÍTULO 3: descripción del objetivo principal y objetivos parciales planteados en la presente tesis doctoral.

- CAPÍTULO 4: aborda la caracterización física, mecánica, química y mineralógica de todas las fracciones gruesas de hormigón y mixtas resultantes del proceso de gestión llevado a cabo en la planta de reciclaje de RCD de ARAPLASA situada en Plasencia, Cáceres, España. Asimismo, se estudian las nuevas prestaciones físicas y mecánicas del esqueleto granular de mezclas granulares constituidas por diferentes proporciones de áridos convencionales y áridos reciclados. Posteriormente, estos resultados se compararon con los requisitos exigidos en la normativa nacional e internacional para su uso como material granular en la fabricación de hormigón y capas de firme en la construcción de carreteras. Este trabajo ha sido publicado en la revista *ACI Materials Journal* con el título "Effect of Recycled Aggregate on Performance of Granular Skeleton".

- CAPÍTULO 5: evalúa las prestaciones de los hormigones reciclados con fines estructurales que incorporan distintos porcentajes de sustitución (20 %, 25 %, 50 %, 75 % y 100 %) de áridos gruesos reciclados mixtos analizando las propiedades físicas en estado fresco (trabajabilidad, densidad y contenido de aire), así como las propiedades físicas (densidad) y mecánicas (resistencia a compresión, resistencia a flexión y resistencia a tracción) en estado endurecido. Asimismo, todos los resultados fueron tratados estadísticamente con el fin de encontrar un porcentaje óptimo de remplazo. Esta investigación fue publicada en la revista *Construction and Building Materials* con el título "Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes".

- CAPÍTULO 6: centra su objetivo en evaluar el efecto simultáneo de incorporar parcialmente la fracción ultra fina de base cerámica procedentes de RCD como adición en un 25 % en peso como sustituto del cemento Portland, cemento con menor contenido en clínker patentado (Nº:ES2512065), y/o áridos reciclados mixtos gruesos de RCD como sustitución parcial (25 % y 50 %) del árido grueso natural. Con este fin, se estudió las propiedades mecánicas (resistencia a compresión) del cemento, así como trabajabilidad, densidad y contenido de aire en estado fresco y la densidad, resistencia a compresión, flexión y tracción en estado endurecido de los hormigones reciclados. Asimismo, todos los resultados se trataron estadísticamente evaluando la influencia de los factores (porcentaje de árido reciclado y tipo de cemento). Este trabajo fue publicado en la revista *Archives of Civil and Mechanical Engineering* con el título "Inclusion of construction and demolition waste as a coarse aggregate and a cement addition in structural concrete design".

- CAPÍTULO 7: estudia el comportamiento mecánico de hormigones reciclados que incorporan conjuntamente ultra finos de hormigón como sustituto parcial (10 % y 25 % en peso) del cemento y/o áridos reciclados mixtos (0 % y 50 %) procedentes de los RCD. Con este objetivo, se evaluó las propiedades físicas (demanda de agua, estabilidad de volumen y tiempo inicial de fraguado) y mecánicas de los nuevos cementos que incorporan un 10 % y 25 % en peso de ultra finos de hormigón. Posteriormente, se analizó la variabilidad estadística en las propiedades de resistencia a compresión, resistencia tracción, módulos de elasticidad y densidad en estado endurecido de los nuevos hormigones reciclados sostenibles. Asimismo, se realizaron ensayos no destructivos mediante pruebas de velocidad de pulso ultrasónico y resistividad eléctrica. Este trabajo fue llevado a cabo parcialmente en el Instituto Superior Técnico de Lisboa durante una estancia de investigación. Este trabajo, fue publicado en la revista *Journal of Cleaner of Production* con el título "Mechanical behaviour of structural concrete with ground recycled concrete cement and mixed recycled aggregate".

- CAPÍTULO 8: evalúa las principales propiedades relacionadas con el transporte de fluidos en hormigones reciclados que incorporan entre un 20 % - 100 % de áridos gruesos reciclados mixtos. Las propiedades analizadas fueron la resistividad eléctrica, permeabilidad de agua bajo presión, absorción de agua total, porosidad accesible al agua y absorción de agua por capilaridad. Mediante el estudio de estas propiedades se pudo evaluar directa e indirectamente la penetración de agua, y consecuentemente predecir el comportamiento a lo largo de la vida útil de estos nuevos hormigones. Esta investigación ha sido publicada en la revista *Cement and Concrete Composites* bajo el título "Water transport mechanisms in concretes bearing mixed".

- CAPÍTULO 9: explora las propiedades de transporte de agua en hormigones que incorporan entre un 10 % y un 25 % de residuos ultra finos de hormigón procedentes de RCD como remplazo parcial del cemento Portland de manera individual y conjunta, con un 50 % de áridos reciclados gruesos mixtos. Para ello se estudiaron los principales indicadores de durabilidad relacionados con la movilidad de fluidos, tales como porosidad abierta, penetración de agua bajo presión, coeficiente de permeabilidad al agua, y absorción de agua capilar y movilidad iónica como la resistividad eléctrica. Además, se realizó un seguimiento de la contracción en todos los hormigones diseñados. Finalmente se evaluó la influencia de cada uno de los factores que intervienen en el comportamiento durable y la contracción por secado mediante análisis ANOVA de tres vías. Este trabajo fue realizado parcialmente en el Instituto Superior Técnico de Lisboa en una estancia de investigación y fue publicado en la revista *Cement and Concrete Composites* con el título "Water transport and shrinkage in concrete made with ground recycled concrete-additioned cement and mixed recycled aggregate".

- CAPÍTULO 10: evalúa los mecanismos de transporte asociados a la entrada de iones cloruros, oxígeno y dióxido de carbono en hormigones que incorporan individual y conjuntamente un 50 % de áridos reciclados mixtos y entre un 10 % y un 25 % de residuos ultra finos de hormigón como sustitución parcial del cemento. Para ello se determina el coeficiente de permeabilidad al oxígeno, el coeficiente de difusión de cloruros y de carbonatación. La estimación de la vida útil, según el método propuesto por el EHE-08, se realiza con el fin de conocer el comportamiento de estos hormigones respecto a la despasivación de sus armaduras en las futuras estructuras diseñadas con estos nuevos materiales reciclados. Este trabajo fue realizado parcialmente en el Instituto Superior Técnico de Lisboa durante una estancia de investigación y fue publicado en la revista *Applied Sciences* con el título "Assessment of the Permeability to Aggressive Agents of Concrete with Recycled Cement and Mixed Recycled Cement and Mixed Recycled Aggregate".

- CAPÍTULO 11: estudia el comportamiento térmico de hormigones fabricados con un 10 % y un 25 % de cemento reciclado de hormigón individual y conjuntamente con un 50 % de áridos reciclados mixtos. Para este fin, se estudiaron las propiedades físicas (densidad seca, porosidad accesible y resistividad eléctrica) y propiedades térmicas (conductividad térmica y calor específico). Posteriormente, mediante un estudio inter propiedades es evaluada las relaciones entre las propiedades físicas y térmicas de estos hormigones. Este trabajo fue realizado parcialmente en el Instituto Superior Técnico de Lisboa durante una estancia de investigación y fue publicado en la revista *Applied Sciences* con el título "Thermal Performance of Concrete with Recycled Concrete as Partial Cement Replacement and Recycled CDW Aggregate".

- CAPÍTULO 12: estudia el comportamiento dinámico de hormigones estructurales fabricados con el cemento patentado (Nº:ES2512065) que contiene un 25 % de ultra finos de base cerámica procedente de RCD como sustitución parcial del clínker y/o conjuntamente con un 25 % y un 50 % de áridos reciclados mixtos procedentes de los RCD. Todos los hormigones diseñados se sometieron a pruebas de aceleradas de fatiga en compresión utilizando el método Locati. Los resultados de esta investigación fueron publicados en la revista *Applied Sciences* con el título "Resonance Fatigue Behaviour of Concretes with Recycled Cement and Aggregate".
- CAPÍTULO 13: se estudio el comportamiento de elementos prefabricados de hormigón diseñados con el cemento patentado (Nº:ES2512065) que contiene un 25 % de ultra finos de base cerámica procedente de RCD como sustitución parcial del clínker y conjuntamente con un 25 % y un 50 % de áridos reciclados mixtos procedentes de los RCD. Se fabricaron piezas sin armadura (bajantes de talud) y con armadura (pretiles New Jersey) y se sometieron a los ensayos según la normativa específica de cada elemento comprobando su viabilidad técnica. Los resultados de esta investigación fueron publicados en la revista *Applied Sciences* con el título "Industrial Low-Clinker Precast Elements Using Recycled Aggregates".
- CAPÍTULO 14: presenta las conclusiones generales de la investigación llevada a cabo en la presente Tesis Doctoral.

Finalmente, indicar que los resultados y la discusión de los mismos se dan entre los capítulos 4 y 13, organizados como artículos de investigación publicados. De este modo, cada uno de ellos contiene las siguientes secciones: Resumen, Introducción, Materiales y Métodos, Resultados, Discusión, Conclusiones y Referencias.

Capítulo 2

Introducción

Capítulo 2

Introducción

A lo largo de la historia el hombre ha utilizado de forma masiva los recursos naturales para su propio beneficio colaborando de forma inconsciente a la degradación paulatina del entorno y a un progresivo deterioro del medio ambiente. En la actualidad, los seres humanos consumen 1,7 veces la cantidad de recursos que la tierra puede producir y se estima que para el 2050 el consumo mundial será el equivalente a tres planetas como la Tierra [1]. En 2018, cada europeo consumió 14 t de materias primas generando 5 t de residuos [2]. Los residuos pueden reutilizarse, repararse o reciclarse. Esta es la base que promueve la economía circular dejar atrás el modelo lineal que ha imperado en el mundo desde la revolución industrial, un cambio del paradigma lineal (extraer-producir-usar-tirar) a un modelo de economía circular (EC) inevitable para preservar los recursos naturales para generaciones futuras, ampliar la vida de los productos, promover un uso más eficiente de las materias primas y minimizar la generación de residuos.

2.1 Hacia un modelo de economía circular

Según una reciente metadefinición basada en un análisis de 114 definiciones del término, la EC se define como un "sistema económico basado en modelos de negocios que reemplazan el concepto de "fin de vida" por reducir, reutilizar, [y] reciclar [...] materiales en los procesos de producción, distribución y consumo, [...], con el objetivo de lograr un desarrollo sostenible, lo que implica generar calidad ambiental, prosperidad económica y equidad social, en beneficio de las generaciones actuales y futuras" [3]. Del mismo modo, la Organización Mundial de la Naciones Unidas para el Desarrollo Internacional [4], define la EC como "una nueva forma de crear valor y, en última instancia, prosperidad". La EC "funciona extendiendo la vida útil del producto a través de un diseño y servicios mejorados, y reubicando los desechos desde el final de la cadena de suministro hasta el principio, utilizando los recursos de una manera más eficiente usándolos una y otra vez".

En un modelo de EC, cada fase (Figura 1) representa oportunidades en términos de reducción de costes y dependencia de los recursos naturales como única fuente de insumo material. El objetivo principal de la EC es maximizar el uso de materiales a través de la recogida y reutilización (etapa 6) y el reciclaje (etapa 7). Esto es reducir la cantidad de desechos (etapa 8) que se generan, lo que conduce a una solución óptima en las que todas las parte involucradas se benefician [5,6].

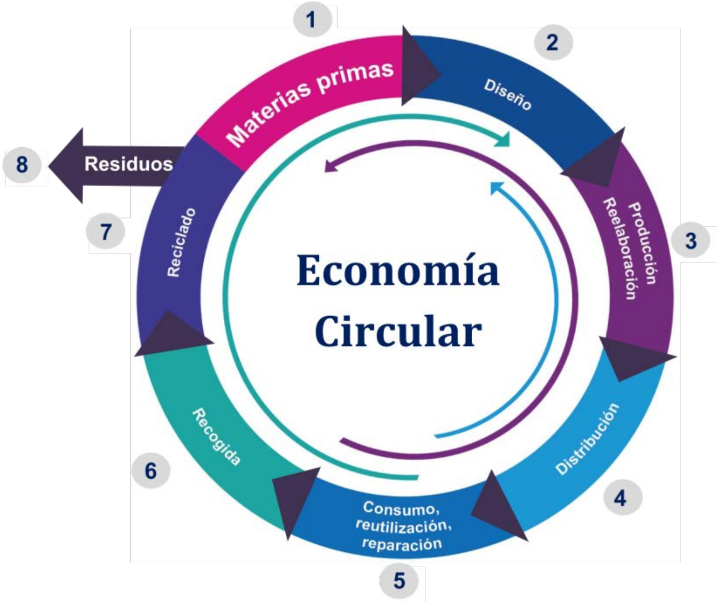


Figura 1. Ciclo cerrado de fases del modelo de economía circular.

El 2 de diciembre de 2015, la Comisión Europea aprobó el llamado "Paquete de economía circular". Este documento establece algunas pautas para garantizar un crecimiento sostenible en la Unión Europea (UE) mediante la utilización de los recursos de una manera más inteligente y sostenible. Es evidente que el modelo lineal de crecimiento económico en el que confiábamos en el pasado no se ajusta ya a las necesidades de las modernas sociedades actuales en un mundo globalizado. Las propuestas sobre residuos necesitan una visión a largo plazo, clara y ambiciosa, respecto al aumento del reciclado y la reducción de los vertidos, proponiendo al mismo tiempo medidas concretas para abordar los obstáculos sobre el terreno en términos de mejora de la gestión de residuos y tomando en consideración la diversidad de las diferentes situaciones de los Estados miembros.

2.1.1 Marco integral de la ecomonía circular

La transición exitosa de un modelo lineal hacia una EC pasa por establecer un marco integral común en el cual se integren beneficios económicos, sociales y ambientales. La Figura 2 muestra un ejemplo de marco integral de la EC basado en estas tres perspectivas interrelacionadas:

- Beneficios económicos: contribuye a un alto nivel de competitividad a través de un aumento en la eficiencia de asignación de recursos, su utilización y productividad. Esto conduce a una mayor estabilidad económica como resultado de generar seguridad en los recursos.

- Beneficios ambientales: reduce los impactos negativos sobre el medio ambiente rediseñando la estructura industrial de manera ecológica.

- Beneficios sociales: facilita la creación de oportunidades de empleo adicionales, una distribución equitativa del crecimiento económico y mejora del bienestar de las personas

Figura 2. Marco integral de la EC.

La escasez de recursos, el impacto medioambiental y los beneficios económicos cubren objetivos tanto a corto como a largo plazo y están perfectamente vinculados en este marco integral de la EC. Cada una de las tres perspectivas tiene una visión sistémica con límites específicos, por ello, es necesario describir las relaciones entre estas. De esta forma, para obtener beneficios económicos, la actividad industrial depende fundamentalmente de los recursos necesarios para realizar los trabajos de fabricación y transformación de materias primas en productos y bienes. A cambio, la volatilidad en los precios de los recursos y los riesgos de suministro tienen una influencia directa en la ventaja competitiva de las empresas y su capacidad para realizar su actividad industrial de manera sostenible y rentable. Al mismo tiempo, mientras las empresas persiguen beneficios económicos, la actividad industrial de éstas influye en el medio ambiente natural que deberán ser restringidas por la legislación a través de, por ejemplo, directivas que impongan limitaciones y mejoren la competitividad.

En una EC se reduce la velocidad de agotamiento de los recursos, generación y desaprovechamiento de residuos. Suponiendo una población en rápido crecimiento, la velocidad del agotamiento de los recursos será mayor en una economía lineal que en una economía circular. Del mismo modo, la velocidad de generación de residuos será mayor en una economía lineal que en una economía circular.

2.1.2 Estrategias de implementación práctica de la economía circular

La implementación del concepto de EC es una tarea desafiante dada la mentalidad y las estructuras lineales predominantes en el tejido industrial y social. Si bien los beneficios para el medio ambiente son claros, los beneficios económicos son más complejos de prever. Lieder y Rashid [7] han propuesto una forma práctica de avanzar hacia la implementación de la EC a gran escala. La Figura 3 muestra este enfoque concurrente que opera a través de las instituciones públicas y la sociedad de forma descendente y a través de tejido industrial y empresarial de forma ascendente. Proponer un enfoque simultáneo descendente y ascendente viene del supuesto de que existen intereses inversos entre las partes interesadas que deben alinearse y converger. De este modo, los órganos de gobierno y los responsables políticos abogan por una conciencia colectiva sobre los problemas ambientales, así como el beneficio social de las actividades industriales. Por lo tanto, existe la noción de maximizar los beneficios ambientales mediante un control estricto del sector industrial. Por el contrario, las empresas tienen una alta presión competitiva, su enfoque principal estará centrado en los beneficios económicos y crecimiento, dejando atrás la conciencia sobre los impactos ambientales de sus actividades. En este escenario, puede darse el caso en el que las empresas no vean las ventajas (económicas) de la EC rechazando iniciativas circulares. Este escenario obliga a un proceso concurrente para converger y comprometer los intereses de las instituciones públicas (arriba) y múltiples factores empresariales (abajo) con el objetivo de evitar priorizar en los beneficios económicos, a expensas de los beneficios ambientales y viceversa. Como objetivo último la EC, debe conseguir una economía que sea ambiental y económicamente regenerativa. Finalmente, la Figura 3 ilustra conceptualmente el nexo colectivo que representa la convergencia de todas las partes interesadas.

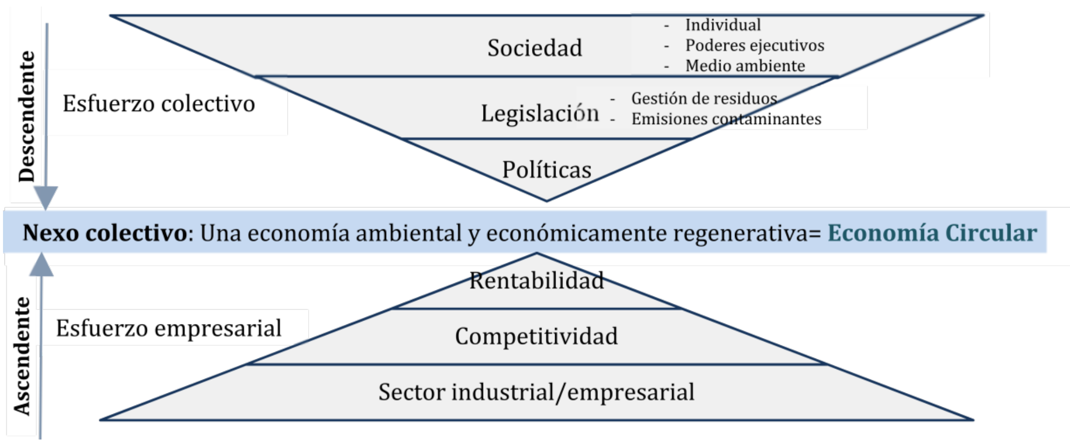


Figura 3. Modelo estratégico de implementación de la EC aplicando un enfoque de descendente y ascendente.

2.1.3 Barreras para la implementación práctica de la economía circular

La Comisión Europea (CE) estima que la implementación de la EC podría llegar a reducir las emisiones de CO_2 a la atmosfera en un 48 %, generar un beneficio económico neto de 1800 millones de euros y más de un millón de puestos de trabajo adicionales para 2030 en la UE [8].

A nivel mundial, Alemania, Japón, China y Europa son reconocidas por haber desarrollado legislaciones sobre la implementación de los principios de EC. En la UE, la EC se ha convertido en un aspecto central en el desarrollo de las políticas y estrategias como parte del nuevo Plan de Acción de la Economía Circular publicado recientemente [1]. Si bien muchos círculos empresariales y políticos han proclamado su apoyo a la EC [9,10], su implementación práctica parece estar todavía en sus primeras etapas [11]. A pesar de las medidas políticas de la CE, adoptando una gran variedad de ambiciosas políticas, por ejemplo “Paquete de Economía Circular” (lanzado en 2015 y actualizado en 2018) con un enfoque en cerrar el ciclo de vida de los productos mediante una mayor reutilización y reciclaje. La adopción de estas medidas políticas, en la mayoría de los Estados miembros de la UE, se ha visto limitada debido fundamentalmente a barreras políticas, sociales, económicas y técnicas (Figura 4).

Barreras Políticas	• Falta de control de los planes de gestión de residuos • Legislación independiente y muy dispersa • Falta de supervisión
Barreras Sociales	• Falta de conciencia • Falta de colaboración entre agentes implicados • Falta de compromiso • Negativa de la reutilización de materiales reciclados
Barreras Económicas	• Finaciamiento inadecuado • Bajos costes de envío de materiales a vertedero o tratamiento • Altos costes de tratamiento y transporte de residuos • Bajos precios de los materiales vírgenes
Barreras Técnicas	• Procesos de gestión ineficaces • Falta de diseño ecológico "ecodiseño" • Falta de recursos humanos con experiencia técnica en la gestión de residuos

Figura 4. Barreras de implementación de la EC.

Estudios recientes destacan con frecuencia las barreras de mercado que obstaculizan la transición hacia una EC debido a costes bajos de materiales vírgenes evitan que los productos de la EC superen a sus equivalentes lineales. Por ello, el acceso a fuentes de financiación adecuadas es clave para que las empresas busquen una transición hacia una EC.

2.1.4 Implicaciones del sector de la construcción en la economía circular

Las actividades propias y/o asociadas del sector de la construcción generan una fuerte influencia en los aspectos sociales, ambientales y económicos de los países [12] formando una parte importante del Producto Interior Bruto (PIB). En 2019, representó el 6,3 % y el 6,5 del PIB mundial, europeo y español, respectivamente [2]. Este hecho, además de generar grandes beneficios económicos y sociales, también supone serios problemas medioambientales. Europa es responsable de consumir el 50 % de todos los materiales extraídos, el 50 % de la energía utilizada, el 25 % del agua consumida y de generar el 25 % de todos los residuos generados [11]. En el ámbito nacional, indicar que el sector de la construcción es el responsable de consumir el 40% de los materiales extraídos, generar el 40 % de todos los residuos, -varios puntos por encima de la UE-, y el 35 % de los gases efecto invernadero [13]. Este contexto pone de manifiesto la necesidad que tiene el sector de la construcción en dedicar esfuerzos en aras de minimizar su impacto en materia de sostenibilidad, y garantizar su progresiva introducción tecnológica y práctica hacia la EC.

Los RCD suponen el mayor volumen de residuos sólidos generados representando en la actualidad entre un 25 % y un 30 % de todos los residuos de la UE. Es por ello que Europa considera esta tipología de residuos como uno de los residuos prioritarios en todas las estrategias políticas relacionadas con la EC [1,14]. Los RCD poseen un alto grado valorización que puede llegar hasta el 100 %. Si bien no existe un sistema de indicadores que permitan valorar la circularidad de estos materiales. A modo de ejemplo, en España se puede observar cómo actualmente solo el 41 % de los RCD declarados son valorizados de alguna forma, quedando lejos del objetivo del 70% establecido a nivel comunitario para 2020. En este sentido, se estima que el 24 % de los RCD se deposita en vertederos y un 30 % aún supone un vertido incontrolado [2]. Teniendo en cuenta esta situación, la Comisión Europea ha previsto que el sector de la construcción sea uno de los sectores prioritarios en el nuevo Plan de Acción de la Economía Circular y, en la misma línea, España también lo contempla como sector prioritario en la Estrategia Española de Economía Circular 2030 [13] definida por el Ministerio para la Transición Ecológica y Reto Demográfico.

La transición del sector de la construcción hacia una economía circular no sólo implicará una importante reducción de los recursos naturales y del impacto ambiental, sino que significará una oportunidad económica derivada de la ventaja competitiva. Además, también significará una mejor restitución y regeneración del capital natural, si se desarrollan los procesos de restauración necesarios.

2.2 Los residuos de construcción y demolición

Los RCD son los residuos generados por la construcción, rehabilitación, renovación y demolición de edificios y de infraestructuras de ingeniería civil y de la edificación; puentes, carreteras, canales, conducciones, ferrocarriles, etc. Estos residuos pueden incorporar materiales como hormigón, ladrillos, materiales cerámicos, yeso, asfalto, vidrio, metales, plásticos y materiales pétreos. La Directiva (UE) 2018/851 del Parlamento y del Consejo europeo por la que se modifica la Directiva 2008/98 /CE sobre los residuos [15] define a los RCD como aquellos "residuos generados por las actividades de construcción y demolición[1]". En el marco legal español, este término se define por primera vez en el Real Decreto 105/2008, del 1 de febrero por el que se regula la producción y gestión de los RCD, como "cualquier sustancia u objeto que", cumpliendo la definición de Residuo incluida en el artículo 3.a de la Ley 22/2011, de 28 de julio, de residuos y suelos contaminados "se genere en una obra de construcción y demolición", considerándose esta como la actividad consistente en:

- La construcción, reparación, reforma o demolición de un bien inmueble, tal como un edificio, carretera, puerto, aeropuerto, ferrocarril, canal, presa, instalación deportiva o de ocio, u otro análogo de ingeniería civil.

- La realización de trabajos que modifiquen la forma o sustancia del terreno o del subsuelo, tales como excavaciones, inyecciones, urbanizaciones u otros análogos, con exclusión de aquellas actividades a las que sea de aplicación la Directiva 2006/21/CE del Parlamento Europeo y del Consejo, de 15 de marzo, sobre la gestión de los residuos de industrias extractivas. Se considerará parte integrante de la obra toda instalación que dé servicio exclusivo a la misma, y en la medida en que su montaje y desmontaje tenga lugar durante la ejecución de la obra o al final de la misma, tales como: plantas de machaqueo, plantas de fabricación de hormigón, grava-cemento o suelo-cemento, plantas de prefabricados de hormigón, plantas de fabricación de mezclas bituminosas, talleres de fabricación de encofrados, talleres de elaboración de ferralla, almacenes de materiales y almacenes de residuos de la propia obra y plantas de tratamiento de los RCD de la obra.

Del mismo modo, los RCD aparecen en el capítulo 17 de la "Lista Europea de Residuos", (códigos LER), aprobada por Orden MAM/304/2002 [16], con exclusión de los residuos peligrosos y del material en estado natural clasificado en la categoría 17 05 04 (tierras y piedras distintas de las especificadas en el código 17 05 03) como se muestran en la Tabla 1.

[1] El sector que origina estos residuos coincide básicamente con las actividades agrupadas en la Sección F de la clasificación europea a actividades económicas, NACE rev. 2 (Parlamento Europeo y Consejo de la Unión Europea, 2006) así como en la nacional, CNAE-2009 (Ministerio de Economía y Hacienda, 2007) bajo el epígrafe de "Construcción"

No obstante, el protocolo de gestión de RCD en la UE [17], considera que estos residuos son los generados en las actividades de las empresas pertenecientes al sector de la construcción e incluidos en la categoría 17 de la citada lista de residuos; es decir, a todos los procedentes de trabajos de construcción, reforma y demolición (peligrosos y no peligrosos, inertes, orgánicos e inorgánicos), aunque excluye de su ámbito de aplicación a la tierra excavada (17 05).

Tabla 1. Capítulo 17 de la "Lista Europea de Residuos" sobre RCD.

17 01	**Hormigón, ladrillos, tejas y materiales cerámicos.**
17 01 01	Hormigón.
17 01 02	Ladrillos.
17 01 03	Tejas y materiales cerámicos.
17 01 06*	Mezclas, o fracciones separadas, de hormigón, ladrillos, tejas y materiales cerámicos, que contienen sustancias peligrosas.
17 01 07	Mezclas de hormigón, ladrillos, tejas y materiales cerámicos distintas de las especificadas en el código 17 01 06.
17 02	**Madera, vidrio y plástico.**
17 02 01	Madera.
17 02 02	Vidrio.
17 02 03	Plástico.
17 02 04*	Vidrio, plástico y madera que contienen sustancias peligrosas o están contaminados por ellas
17 03	**Mezclas bituminosas, alquitrán de hulla y otros productos alquitranados.**
17 03 01*	Mezclas bituminosas que contienen alquitrán de hulla.
17 03 02	Mezclas bituminosas distintas de las especificadas en el código 17 03 01.
17 03 03*	Alquitrán de hulla y productos alquitranados.
17 04	**Metales (incluidas sus aleaciones).**
17 04 01	Cobre, bronce, latón.
17 04 02	Aluminio.
17 04 03	Plomo.
17 04 04	Zinc.
17 04 05	Hierro y acero.
17 04 06	Estaño.
17 04 07	Metales mezclados.
17 04 09*	Residuos metálicos contaminados con sustancias peligrosas.
17 04 10*	Cables que contienen hidrocarburos, alquitrán de hulla y otras sustancias peligrosas.
17 04 11	Cables distintos de los especificados en el código 17 04 10.
17 05	**Tierra (incluida la excavada de zonas contaminadas), piedras y lodos de drenaje.**
17 05 03*	Tierra y piedras que contienen sustancias peligrosas.
17 05 04	Tierra y piedras distintas de las especificadas en el código 17 05 03.
17 05 05*	Lodos de drenaje que contienen sustancias peligrosas.
17 05 06	Lodos de drenaje distintos de los especificados en el código 17 05 05.
17 05 07*	Balasto de vías férreas que contienen sustancias peligrosas.
17 05 08	Balasto de vías férreas distinto del especificado en el código 17 05 07.
17 06	**Materiales de aislamiento y materiales de construcción que contienen amianto.**
17 06 01*	Materiales de aislamiento que contienen amianto.
17 06 03*	Otros materiales de aislamiento que consisten en, o contienen, sustancias peligrosas.
17 06 04	Materiales de aislamiento distintos de los especificados en los códigos 17 06 01 y 17 06 03.
17 06 05*	Materiales de construcción que contienen amianto
17 08	**Materiales de construcción a partir de yeso.**
17 08 01*	Materiales de construcción a partir de yeso contaminados con sustancias peligrosas
17 08 02	Materiales de construcción a partir de yeso distintos de los especificados en el código 17 081
17 09	**Otros RCD.**
17 09 01*	Residuos de construcción y demolición que contienen mercurio.

17 09 02*	Residuos de construcción y demolición que contienen PCB (por ejemplo, sellantes que contiene n PCB, revestimientos de suelo a partir de resinas que contienen PCB, acristalamientos dobles que contienen PCB, condensadores que contienen PCB).
17 09 03*	Otros residuos de construcción y demolición (incluidos los residuos mezclados) que con tienen sustancias peligrosas
17 09 04*	Residuos mezclados de construcción y demolición distintos de los especificados en los códigos 17 09 01, 17 09 02 y 17 09 03.

**Residuos peligrosos*

2.2.1 Composición de los residuos de construcción y demolición

La composición de los RCD puede variar ampliamente entre diferentes regiones y países. Por ejemplo, a nivel europeo podemos observar que existen diferencias significativas (Figura 5). En general, el mayor porcentaje de residuos producidos corresponde a los categorizados como no peligrosos, principalmente materias minerales y tierras excavadas. Entre países existen diferencias en la composición de estos residuos que pueden atribuirse a factores como las diferencias climatológicas, disponibilidad local de materiales, tendencias constructivas, aspectos económicos, culturales, etc. [18]. No obstante, también se explica por las grandes variaciones en la calidad de los datos y los años de referencia, la falta de control y criterios específicos que permitan obtener un registro uniforme de los RCD generados en cada país [19].

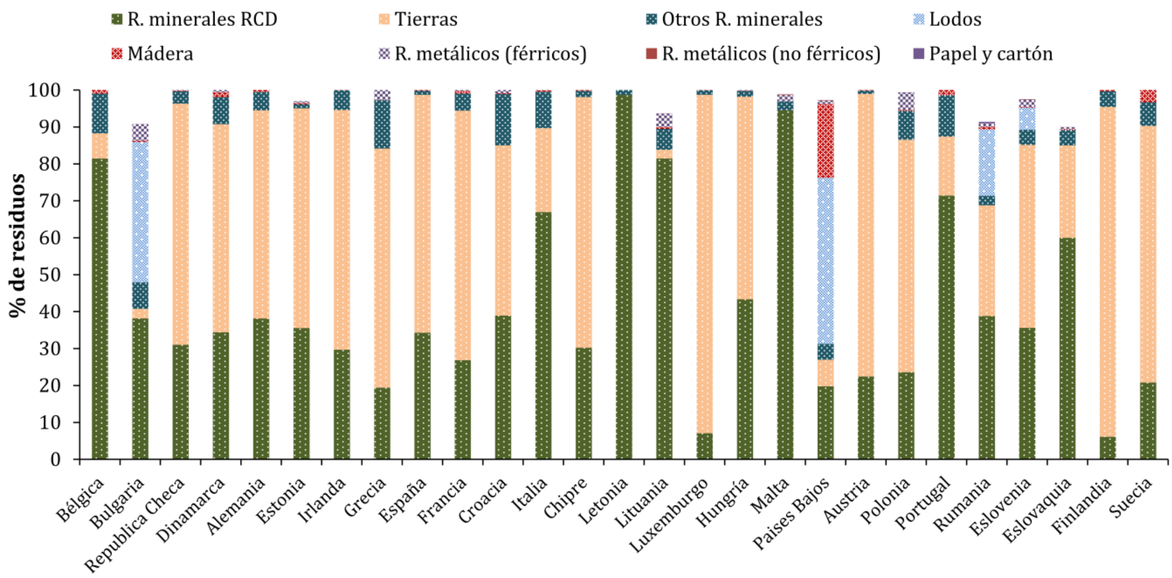


Figura 5. Composición de los residuos generados en el sector de la construcción en la UE-28 (2018). Fuente: Eurostat [20]

En 2018 en España, los residuos generados en las actividades de construcción y demolición estaban compuestos en un 64 % de material natural excavado, un 34 % de residuos minerales (hormigón, ladrillos, cerámicos o áridos no ligados) y un porcentaje minoritario de otros materiales (2 %) (Figura 5). En la Figura 6 se muestran los datos recogidos en el Plan Estatal Marco de Gestión de Residuos 2016-2022 [21] donde la mayor parte de los RCD producidos son residuos inertes (75 %), estando integrada la principal facción por ladrillos, tejas y otros tipos de materiales cerámicos (54 %), escombros de hormigón (12 %), áridos no tratados y piedra natural (9 %) y otros materiales en cantidades variables de residuos de madera, metal, yesos, vidrio, entre otros.

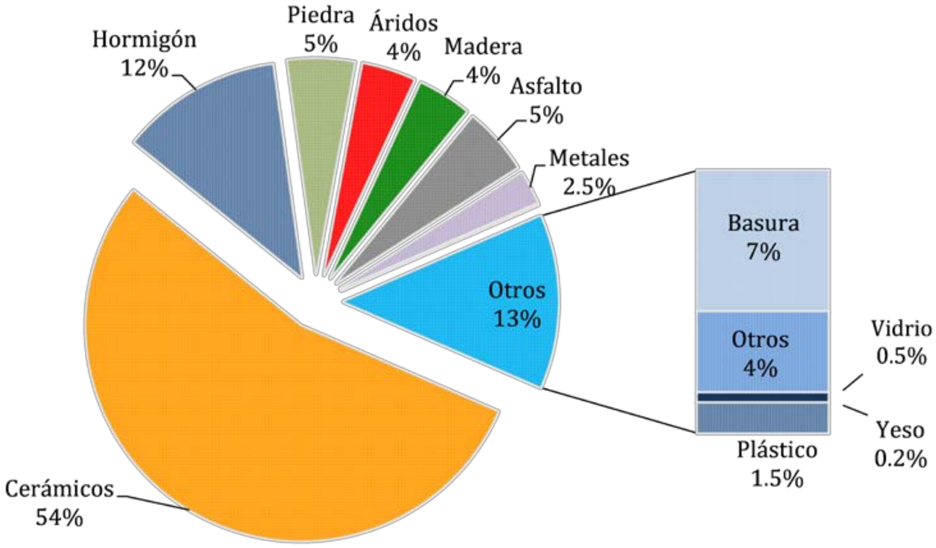


Figura 6. Composición de los RCD en España. Fuente: PEMAR 2016-2022. (Ministerio del Medio Ambiente, 2015)

2.2.2 Generación de residuos de construcción y demolición

Según las últimas cifras actualizadas, en 2018 se generaron unas 6.5 mil millones de toneladas de RCD en todo el mundo, de las cuales Estados Unidos produjo alrededor de 600 Mt, China unas 2360 Mt y Europa (EU-28) alrededor de unas 1000 Mt [22]. La Tabla 8 recoge la cantidad de RCD en los países UE en el periodo de 2010-2018 y la

Figura 7 muestra los países más productores de RCD (>10 Mt en 2018). En la misma, se puede observar la evolución en este periodo, lo cual sugiere algunas diferencias en las tendencias observadas. Por ejemplo, algunos países (Alemania, Países Bajos o Austria) notificaron en términos generales un crecimiento en los RCD generados, debido al bajo grado de implementación de las políticas preventivas, mientras que otros (Francia, Italia o Finlandia), tendieron a generar cada vez menos residuos [23].

Tabla 2. Producción de RCD en los Estados miembros durante el periodo 2010-2018 (datos en toneladas). Fuente: Eurostat [20]

	2010	**2012**	**2014**	**2016**	**2018**
EU-28	875.370.000	843.940.000	870.250.000	924.160.000	976.700.000
Bélgica	16.852.673	17.132.768	18.347.257	19.573.150	22.658.151
Bulgaria	78.880	1.032.651	1.340.467	2.089.131	193.186
Republica Checa	9.353.673	8.592.900	9.409.944	10.141.985	15.800.434
Dinamarca	3.142.215	7.454.350	11.263.066	12.224.799	11.999.177
Alemania	190.990.217	197.527.868	206.466.169	220.499.432	225.260.606
Estonia	436.289	657.089	671.347	1.173.517	2.192.957
Irlanda	1.609.762	1.132.275	1.884.390	1.521.590	1.903.058
Grecia	2.086.080	812.519	479.999	610.636	2.286.467
España	**37.946.523**	**26.129.151**	**20.418.071**	**35.827.923**	**38.075.987**
Francia	260.699.131	246.702.428	227.607.180	224.355.217	240.207.094
Croacia	7.656	674.661	618.158	1.380.861	1.259.569
Italia	59.340.134	52.965.743	51.670.600	54.576.762	60.829.199
Chipre	461.227	965.177	634.801	876.525	1.053.325
Letonia	21.551	7.509	454.281	111.136	310.772
Lituania	356.772	419.136	434.737	505.757	620.285
Luxemburgo	8.866.757	7.079.473	5.979.235	8.035.668	7.320.296
Hungría	4.072.214	4.038.081	3.439.941	3.591.723	6.103.907
Malta	988.070	1.044.088	1.241.079	1.334.053	1.974.801
Países Bajos	78.063.887	79.166.644	90.734.851	98.551.957	101.661.367
Austria	20.927.070	33.468.558	40.265.570	44.914.816	48.883.069
Polonia	20.818.234	15.367.995	17.010.251	18.890.577	16.950.306
Portugal	1.287.140	1.087.141	1.185.489	1.710.703	1.397.749
Rumania	734.946	1.325.341	1.048.011	320.811	647.151
Eslovenia	1.509.476	535.154	815.010	543.690	669.341
Eslovaquia	1.786.430	806.184	1.386.685	967.275	541.876
Finlandia	24.645.393	16.033.874	16.296.811	13.825.168	15.715.231
Suecia	9.381.226	7.655.935	8.866.720	9.810.987	12.383.239
Reino unido	118.910.602	114.120.793	130.284.145	136.196.492	137.798.233

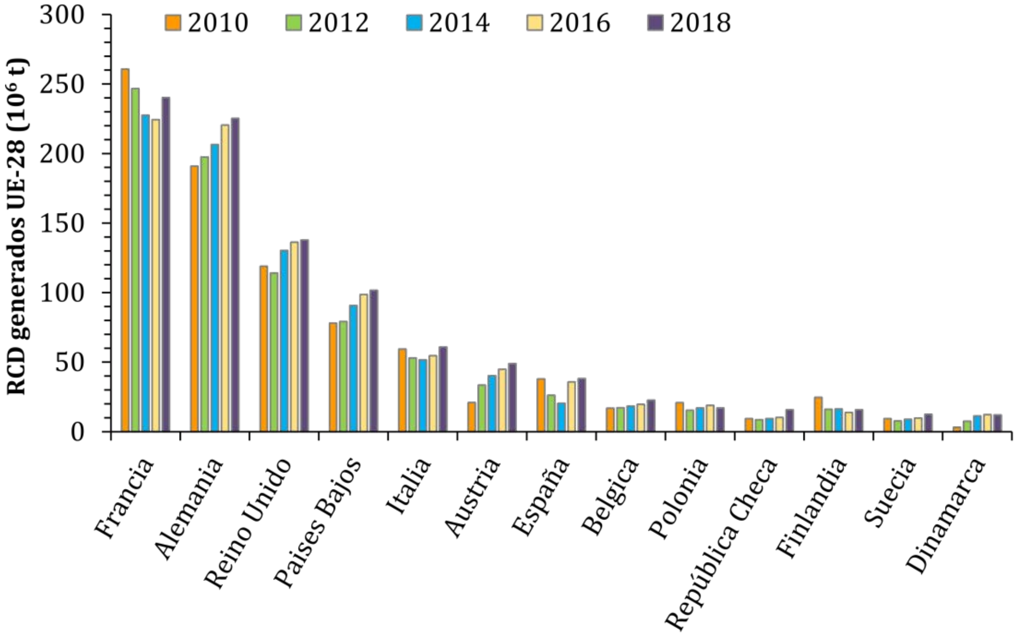


Figura 7. Países de la UE-28 que superan los 10.000 millones de toneladas de RCD (periodo 2010-2018). Fuente: Eurostat [20]

En España, en el año 2018 se generaron en torno a 138 Mt de residuos; de los cuales 40 Mt corresponden a RCD (Eurostat, 2018a). La evolución observada en el tiempo siguió un patrón totalmente diferente al observado en toda la UE, con una disminución considerable del 46 % entre el año 2010 y el 2014, relacionada con la inestabilidad económica de España que se inició en el año 2007, además del avance en el grado de aplicación y de cumplimiento de la normativa vigente. A pesar de ello, la evolución correspondiente a la totalidad del periodo evaluado, desde 2010 a 2018 (Figura 7), muestra tan solo un descenso del 5,6 %.

Respecto a los de producción por comunidades autónomas, la Figura 8 muestra los datos proporcionados por la Asociación Española de Reciclaje de RCD en 2017. En la misma, se observa que las comunidades con mayor generación de residuos son aquellas que han presentado una mayor actividad constructiva, como es el caso de Madrid, Andalucía y Cataluña, así como una disminución en la cantidad de residuos generados de forma generalizada con el paso del tiempo. En el caso concreto de Extremadura (Figura 9) se generaron en 2018 cerca de 315.000 t de RCD, excluidas las tierras y materiales pétreos de excavación. Según datos del Plan Integral de Residuos de Extremadura 2016-2022 el porcentaje de recuperación fue de 27 % de árido reciclado destinado a su comercialización, un 45 % en operaciones de relleno y restauración ambiental, un 2 % se depositó en vertederos de residuos no peligros y el 26 % restante se almacenó en las propias instalaciones en espera del destino final. El elevado porcentaje de RCD almacenado en instalaciones autorizadas refleja algunos de los principales problemas del sistema: dificultades de comercialización, ausencia de lugares próximos a las plantas de tratamiento donde depositar los residuos inertes obtenidos del proceso, como vertederos, o preferiblemente, zonas a restaurar que se encuentren degradadas por otras actividades.

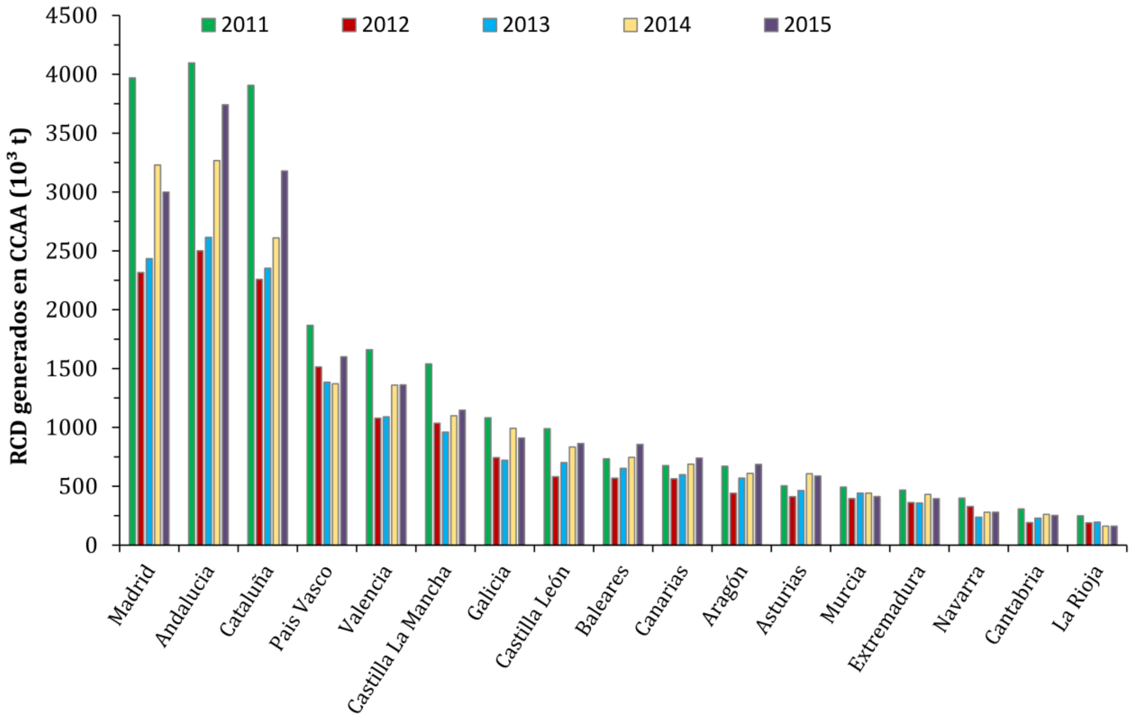


Figura 8. RCD generados por CCAA en el periodo 2010-2015. Fuente: Asociación Española de reciclaje de RCD.

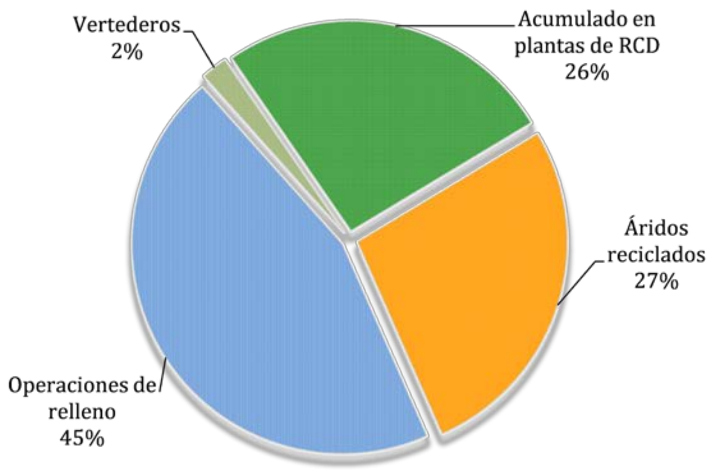


Figura 9. Situación de los RCD en Extremadura. Fuente: Plan Integral de Residuos de Extremadura 2016-2022.

2.2.3 Problemática ambiental de los residuos de construcción y demolición

Los impactos negativos sobre el medio ambiente y altas tasas de residuos generados han convertido a los RCD en una prioridad para los programas de desarrollo de todo el mundo [24]. Entre los impactos ambientales asociados se incluyen la degradación de la tierra, el agotamiento de los vertederos, la contaminación del agua, el alto consumo de energía y el agotamiento de los recursos. A nivel mundial, se estima que alrededor del 35 % de los RCD aún se depositan en lugares no autorizados, mientras que el 24 % de los que se acceden a instalaciones de gestores autorizados, terminan acumulados en las mismas plantas[21]. Estos aspectos causan efectos negativos relacionados con la ocupación de suelo, impacto visual en el medio, contaminación de suelos, acuíferos, y la eliminación de estos residuos sin aprovechamiento de sus recursos valorizables.

Con el objetivo de reducir el impacto derivado de la gestión de los residuos en el medio ambiente, la Directiva Marco de residuos [9] considera no solo la fase de residuo sino todo el ciclo de vida de los productos y materiales, desde su fabricación hasta la destrucción, reforzando así el valor económico de los residuos. En este contexto, la aplicación del análisis de ciclo de vida se utiliza como uno de los principios rectores de la gestión de los residuos, donde los impactos medioambientales generados por los productos y por su proceso de producción se consideran dentro del ciclo de vida de los mismos, al objeto de minimizar, en la medida de lo posible, la carga ambiental que producen [25,26]. Asimismo, los impactos negativos asociados directa o indirectamente al sector de la construcción se podrían reducir gestionando de forma eficiente los residuos generados y utilizándolos como materiales secundarios que puedan ser reincorporados a la actividad constructiva [27,28].

2.2.4 Gestión de los residuos de construcción y demolición

Se entiende por gestión de residuos al camino definido por el residuo, desde su generación hasta su disposición final de forma controlada y segura para el medio ambiente. De acuerdo a las definiciones incluidas en la normativa de residuos, la "gestión de residuos" engloba "la recogida, el transporte, la valorización (incluida la clasificación), y la eliminación de los residuos, incluida la vigilancia de estas operaciones, así como el mantenimiento posterior al cierre de los vertederos, incluidas las actuaciones realizadas en calidad de negociante o agente". El proceso de gestión de residuos constituye el eje principal de cualquier procedimiento que intente reduir el impacto que los mismos producen sobre el medio ambiente y, particularmente, los procedentes de los RCD. Por ello, gestionar de manera efectiva los RCD es un aspecto clave para su posterior reutilización. Cualquier procesamiento y tratamiento requiere la plena aplicación del principio de jerarquía de residuos (Figura 10), el cual ofrece beneficios de amplio alcance en cuanto a eficiencia de los recursos, sostenibilidad y ahorro de costes. Este principio esta consolidado en la normativa comunitaria de residuos desde el año 2008, y es incorporado en la legislación española a través de la Ley 22/2011, de residuos y suelos contaminados manteniendo el siguiente orden de prioridad [29]:

1. **Prevención**: disminución de los residuos que se generan, así como de su peligrosidad y estableciendo medidas de eco-diseño para los nuevos productos. Conlleva el conjunto de medidas adoptadas antes de que el material se haya convertido en residuo. La

prevención en la generación de residuos es la apuesta a la política de residuos que más beneficios ambientales proporciona, por ello ocupa la primera posición en la jerarquía de residuos. En el caso de los RCD, las medidas prácticas de prevención deben incorporarse en las fases del proyecto de construcción, fabricación de materiales, desarrollo de la obra, pasando por las fases en las que se planifican y proyectan las obras.

2. **Preparación y reutilización:** consiste en las operaciones de preparación para la reutilización en la operaciones previas de comprobación, limpieza o recuperación de los residuos originados en la obra, en las cuales estos se prepara para que pueden reutilizarse sin apenas procesamiento.

3. **Reciclado:** incluye toda operación de valorización mediante la cual los residuos generados son transformados en nuevos productos secundarios tanto si es con la finalidad original como con cualquier otra finalidad.

4. **Otras formas de valorización de residuos:** En los casos en los que se producen residuos que no pueden ser reutilizables, no reciclables, en cuyo caso lo que se aprovecha no son los materiales que componen los residuos si no la energía contenida en ellos, a través del tratramiento térmico del residuo (madera, plástico papel y carton). En el caso de los RCD apenas poseen componentes valorizables energéticamente. La Directiva 851 de 2018 (Parlamento Europeo y Consejo de la Unión Europea, 2018b), que modifica a la Directiva Marco, introduce la definición de **valorización de materiales**, como toda operación de valorización distinta de la valorización energética y de la transformación en materiales que se vayan a usar como combustibles u otros medios de generación de energía. Incluye la preparación para la reutilización, el reciclado y el relleno y otras formas de valorización de materiales, tales como la transformación de residuos en materias primas secundarias con fines de ingeniería en la construcción de carreteras u otras infraestructuras.

5. **Eliminación de residuos:** último escalón y menos ecológico en la gestión de residuos, la eliminación queda definida en la Directiva Marco como cualquier operación que no sea la valorización, incluso cuando la operación tenga como consecuencia secundaria el aprovechamiento de sustancias o energía (depósito en vertederos y la incineración sin recuperación de energía).

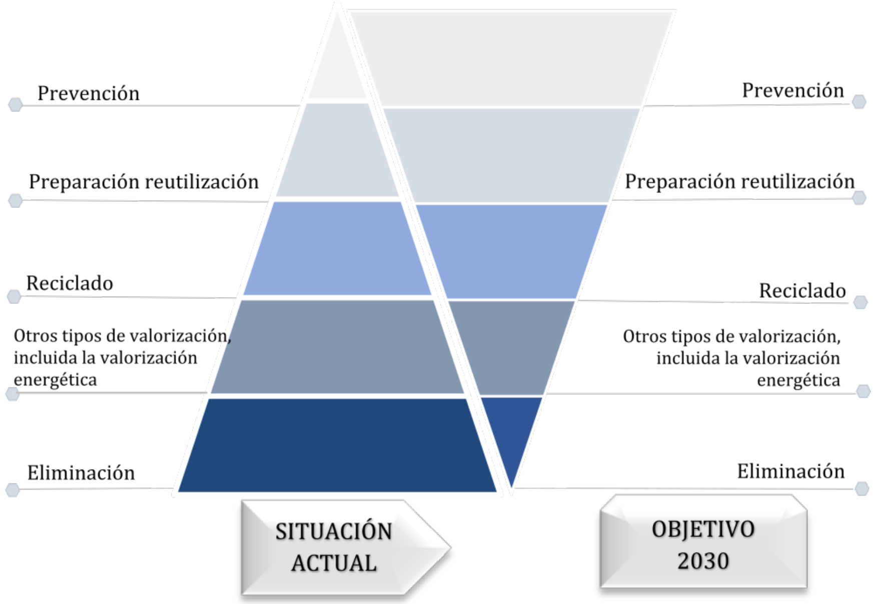


Figura 10. Principio de jerarquía de residuos.

El proceso de gestión RCD incluye un conjunto de acciones operativas a las que se somenten los RCD, manejo en el interior de la obra, recolección, acopio, transporte, pretratamiento y finalizando en el tratamiento de los mismos. Con el objeto de aumentar la confianza en dicho proceso, así como en la calidad de los materiales resultantes del tratamiento de estos residuos, se publicó el protocolo de gestión de RCD de la UE [17]. A nivel nacional, los instrumentos fundamentales de planificación de la estrategia de gestión de residuos son el Real Decreto 105/2008 [29], el Programa Estatal de Prevención de Residuos 2014-2020 y el PEMAR [21].

2.3 Regulación de residuos de la construcción y demolición

Durante las últimas décadas se ha producido un volumen creciente de los residuos procedentes del sector de la construcción. Ante esta problemática, se ha venido desarrollando un proceso tanto de legislación como de normalización técnica, que ha conformado el actual panorama reglamentario relativo a esta tipología de residuos. En los siguientes subapartados se presenta los aspectos legislativos y/o normativos, en el ámbito europeo nacional y autonómico que afectan a los RCD.

2.3.1 Ámbito europeo

En los primeros años de construcción de la CE, los asuntos medioambientales no constituían una prioridad para los poderes públicos y los agentes económicos. No fue hasta la década de los 70 cuando surgió la preocupación por el medio ambiente, que está en la raíz de las primeras iniciativas comunitarias en este ámbito. En la cumbre de París de julio de 1972, los jefes de Estado y de Gobierno reconocieron que, en el contexto de la expansión económica y la mejora de la calidad de vida, debía prestarse una atención especial al medio ambiente. En la actualidad, la UE considera a los RCD como un flujo prioritario de residuos, con la puesta en marcha de los diferentes Programas de Acción Comunitarios, la estrategia de la UE para controlar estos residuos se ha centrado en el uso sostenible de los recursos existentes, destacando en la prevención de los residuos, la utilización del material reciclado y la reconversión energética, con el fin de minimizar los efectos negativos sobre el medio ambiente. En esta línea, se ha publicado sucesivos Programas de Acción en materia de Medio Ambiente (PAMA) que han proporcionado el marco de actuación medioambiental de la UE desde 1973 hasta la actualidad. En la Tabla 3 se muestra las disposiciones que establecen el marco regulador en materia de residuos de la UE. Además, en la Tabla 4 se enumera la regulación existente en materia de sostenibilidad, economía circular y medio ambiente. Entre todas destaca la directiva Marco (Directiva 2008/98/CE) [9] que tiene como objetivo transformar a la UE en una "sociedad de reciclado, la protección del medio ambiente y la salud humana mediante la prevención de los efectos que suponen la producción y la gestión de residuos". Asimismo, introduce un enfoque destinado a tener en cuenta no solo la fase de residuos, sino también todo el ciclo de vida de los productos y materiales. Además, da respuesta a la necesidad de aclarar aspectos relacionados con la gestión de residuos, almacenamiento temporal, distinción entre residuos y subproductos o la diferenciación de operaciones de reciclado, valorización y eliminación.

Tabla 3. Disposiciones reguladoras en materia de residuos en Europa.

Residuos
Directiva 2008/98/CE del Parlamento Europeo y del Consejo, de 19 de noviembre de 2008, sobre los residuos
Decisión 2011/753/UE de la Comisión, de 18 de noviembre de 2011, por la que se establecen normas y métodos de cálculo para la verificación del cumplimiento de los objetivos previstos en el artículo 11, apartado 2, de la Directiva 2008/98/CE.
Decisión de ejecución 2013/727/UE de la Comisión, de 6 de diciembre de 2013, por la que se establece el formato para la notificación de la información sobre la adopción y las revisiones sustanciales de los planes de gestión de residuos y de los programas de prevención de residuos, dictada de conformidad con el art. 33.2 de la Directiva 2008/98/CE.
Reglamento (UE) 1357/2014 de la Comisión, de 18 de diciembre de 2014, por el que se sustituye el anexo III de la Directiva 2008/98/CE del Parlamento Europeo y del Consejo, sobre los residuos y por la que se derogan determinadas Directivas, y en particular, su artículo 38, apartado 2, con relación a las características de los residuos que permiten calificarlos de peligrosos.
Directiva (UE) 2015/1127 de la Comisión de 10 de julio de 2015 por la que se modifica el anexo II de la Directiva 2008/98/CE del Parlamento Europeo y del Consejo, sobre los residuos y por la que se derogan determinadas Directivas.
COM (2015) 595, propuesta de Directiva del Parlamento Europeo y del Consejo 2015/0275 (COD), de 2 de diciembre de 2015, por la que se modifica la Directiva 2008/98/CE, sobre los residuos.
DOUE (L) 42 de 18/02/2017. Corrección de errores del Reglamento (UE) 1357/2014 de la Comisión, de 18 de diciembre de 2014, por el que se sustituye el anexo III de la Directiva 2008/98/CE del Parlamento Europeo y del Consejo, sobre los residuos y por la que se derogan determinadas Directivas.
DOUE 2018/C 124/01. Comunicación de la Comisión — Orientaciones técnicas sobre la clasificación de los residuos.

Directiva (UE) 2018/851 del Parlamento europeo y del Consejo de 30 de mayo de 2018 por la que se modifica la Directiva 2008/98/CE sobre los residuos.

Tabla 4. Documentos informativos en materia de sostenibilidad, economía circular y medio ambiente en Europa.

Sostenibilidad, economía circular y medio ambiente
COM (2010) 2020. Comunicación de la Comisión de 3 de marzo de 2010. Europa 2020. Una estrategia para un crecimiento inteligente, sostenible e integrador.
COM (2011) 21. Comunicación de la Comisión de 26 de enero de 2011. Una Europa que utilice eficazmente los recursos - Iniciativa emblemática con arreglo a la Estrategia Europa 2020.
COM (2011) 571. Comunicación de la Comisión de 20 de septiembre de 2011. Hoja de ruta hacia una Europa eficiente en el uso de los recursos.
COM (2012) 433. Comunicación de la Comisión de 31 de julio de 2012. Estrategia para una competitividad sostenible del sector de la construcción y de sus empresas.
COM (2014) 397. Propuesta de Directiva del Parlamento Europeo y del Consejo 2014/0201 (COD), del 2 de julio de 2014, por la que se modifican varias Directivas, entre ella la Directiva 2008/98/CE.
COM (2014) 445. Comunicación de la Comisión de 1 de julio de 2014. Oportunidades para un uso más eficiente de los recursos en el sector de la construcción.
COM (2014) 398. Comunicación de la Comisión de 25 de septiembre de 2014. Hacia una economía circular: un programa de cero residuos para Europa.
DOUE 2017/C 265/08. Resolución del Parlamento Europeo, de 9 de julio de 2015, sobre el uso eficiente de los recursos: avanzar hacia una economía circular (2014/2208(INI)).
COM (2015) 614. Comunicación de la Comisión de 2 de diciembre de 2015. Cerrar el círculo: Un plan de acción de la UE para la economía circular.
COM (2016) 739. Comunicación de la Comisión de 22 de noviembre de 2016. Próximas etapas para un futuro europeo sostenible. Acción europea para la sostenibilidad.
COM (2016) 773. Comunicación de la Comisión de 30 de noviembre de 2016. Plan de trabajo sobre diseño ecológico 2016-2019.
COM (2017) 33. Informe de la comisión de 26 de enero de 2017, sobre la aplicación del plan de acción para la economía circular.
COM (2018) 29. Comunicación de la Comisión de 16 de enero de 2018, sobre un marco de seguimiento para la economía circular.
Decisión 1386/2013/UE del Parlamento Europeo y del Consejo, de 20 de noviembre de 2013, relativa al Programa General de Acción de la Unión en materia de Medio Ambiente hasta 2020 «Vivir bien, respetando los límites de nuestro planeta» (2013-2020).
COM (2017) 63. Comunicación de la Comisión al Parlamento Europeo, al Consejo, al Comité económico y social europeo y al Comité de las regiones, de 3 de febrero de 2017. Revisión de la aplicación de la normativa medioambiental de la UE: problemas comunes y cómo combinar esfuerzos para obtener mejores resultados.

2.3.2 Marco legal estatal

En España la normativa se fundamenta en la legislación europea. En general estas políticas deben ser incorporadas a las legislaciones nacionales de cada país y los países miembros deber ser responsables de llevar a cabo la gestión de los residuos. Adicionalmente se han promulgado regulaciones específicas, plasmadas en los diferentes planes de prevención y gestión de residuos. En la Tabla 5 y Tabla 6 se muestra el marco regulador actual en materia de residuos y las regulaciones específicas para los RCD respectivamente.

Tabla 5. Marco normativo de los residuos en España.

Residuos
Ley 22/2011, de 28 de julio, de residuos y suelos contaminados, por la que se deroga la Ley 10/1998, de 21 de abril, de residuos y se transpone a la legislación española la Directiva 2008/98/CE, de 19 de noviembre, sobre residuos.
Orden AAA/699/2016, de 9 de mayo, por la que se modifica la operación R1 del anexo II de la Ley 22/2011, de 28 de julio, de residuos y suelos contaminados, y se transpone al marco español la Directiva (UE) 2015/1127, de 10 de julio, por la que se modifica el anexo II de la Directiva 2008/98/CE que establece una lista no exhaustiva de operaciones de valorización.
Vertido de residuos
Real Decreto 1481/2001, de 27 de diciembre, por el que se regula la eliminación de residuos mediante depósito en vertedero, resultante de la transposición de la Directiva 1999/31/CE del Consejo, del 26 de abril, relativa al vertido de residuos.
Real Decreto 1304/2009, de 31 de julio, por el que se modifica el Real Decreto 1481/2001, de 27 de diciembre, por el que se regula la eliminación de residuos mediante el depósito en vertedero.
Lista de residuos
Orden MAM/304/2002, de 8 de febrero, por la que se publican las operaciones de valorización y eliminación de residuos y la lista europea de residuos. Corrección de errores en BOE núm. 61, de 12de marzo de 2002.
Prevención de residuos
Resolución de 20 de diciembre de 2013, de la Dirección general de calidad y Evaluación Ambiental y Medio Natural, por la que se publica el Acuerdo del Consejo de Ministros de 13 de diciembre de 2013, por el que se aprueba el Programa Estatal de Prevención de Residuos 2014-2020.
Gestión de residuos
Resolución de 16 de noviembre de 2015, de la Dirección General de Calidad y Evaluación Ambiental y Medio Natural, por la que se publica el Acuerdo del Consejo de Ministros de 6 de noviembre de2015, que aprueba el Plan Estatal Marco de Gestión de Residuos (PEMAR 2016-2022).

Tabla 6. Regulaciones específicas para RCD en España.

Residuos de construcción y demolición
Real Decreto 105/2008, de 1 de febrero, por el que se regula la producción y gestión de los residuos de construcción y demolición.
Orden APM/1007/2017, de 10 de octubre, sobre normas generales de valorización de materiales naturales excavados para su utilización en operaciones de relleno y obras distintas a aquéllas en las que se generaron.

En España la preocupación por la gestión de residuos no surgió hasta 2001 con el primer Plan Nacional de Residuos de Construcción y Demolición I PNRCD [30], que además de describir la situación de los RCD en España, fijaba principios de gestión y los objetivos específicos de reducción, reutilización, reciclado y eliminación, a cumplir para este tipo de residuos. También incorporaba la obligación de implantar planes de gestión de residuos, estudio previo para la obtención de la licencia de obra y aspectos de control como cantidad de residuos y coste de tratamiento.

Por otro lado, la entrada en vigor la Ley 22/2011 de Residuos y Suelos Contaminados, introduce nuevos objetivos cuantitativos que no estaban incluidos en las leyes anteriores. Específicamente, la cantidad de RCD no peligrosos acumulados por su reutilización, el reciclaje y otra recuperación de materiales debe constituir al menos el 70 % de la producción de desechos para 2020 y establece medidas específicas en materia de regulación para lograr tres objetivos principales: recuperación de residuos inertes, erradicación de vertederos ilegales y promoción de la demanda de reciclaje de RCD, especialmente de áridos reciclados.

2.3.3 Ámbito autonómico extremeño

Según el Artículo 148 de la Constitución Española, las comunidades autónomas podrán asumir competencias en diferentes materias, entre las que destaca la gestión en materia de protección del medio ambiente. En el caso concreto de los RCD, la Ley 22/2011, de 28 de julio, de residuos y suelos contaminados, la cual transpone a nuestro ordenamiento jurídico interno la Directiva 2008/98/CE del Parlamento Europeo y del Consejo, de 19 de noviembre de 2008, sobre los residuos y por la que se derogan determinadas Directivas, conocida habitualmente como "Directiva Marco de Residuos", obliga a las Comunidades Autónomas a elaborar, como instrumento esencial para desarrollar las políticas de residuos. En consecuencia, el marco legislativo en materia de RCD dependerá del desarrollo realizado por cada comunidad autónoma en cuestión, siendo estos diferentes en cada comunidad autónoma [31].

El estatuto de autonomía de Extremadura (Ley Orgánica 1/2011, de 28 de enero) incluye en su artículo 10, en materia de medioambiente, sobre "[…] la regulación, protección y corrección de la generación de residuos y vertidos […] y de la contaminación del suelo y del subsuelo". En el caso específico de la gestión de residuos, el marco normativo queda establecido por las disposiciones recogidas en la Tabla 7.

Tabla 7. Legislación específica en materia de residuos producción y gestión de RCD en Extremadura.

Residuos de construcción y demolición
Real Decreto 105/2008, de 1 de febrero, por el que se regula la producción y gestión de los residuos de construcción y demolición
Decreto 20/2011, de 25 de febrero, por el que se establece el régimen jurídico de la producción, posesión y gestión de los residuos de construcción y demolición en la Comunidad Autónoma de Extremadura
Acuerdo del Consejo de Gobierno de 22 de Julio de 2020, por el que se aprueba la Modificación nº1 del Plan Integrado de Residuos de Extremadura (PIREX). 2016/2022.

El Plan Integrado de Residuos de Extremadura (PIREX) 2016-2022 constituye el marco político en materia de residuos no peligrosos en el que se definen los objetivos y propuestas de actuación para integrar el desarrollo socioeconómico con la conservación del medio ambiente y la correcta gestión de los residuos e incrementar la valorización de los mismos.

2.4 Los áridos reciclados procedentes de los RCD

2.4.1 Definición y tipología

De acuerdo con la definición dada por el Comité Técnico Nacional de Normalización AEN/CTN 146 de "Áridos" (o CEN/TC 154, Comité Europeo de Normalización), el "árido reciclado es el material granular resultante del procesamiento de material inorgánico utilizado previamente en la construcción". Esta definición, hace referencia a la parte pétrea de los residuos generados en obras de construcción demolición o rehabilitación.

Teniendo en cuenta la gran heterogeneidad de este material granular, existen diversos criterios de clasificación de los áridos reciclados: composición, granulometría, grado de limpieza del material, calidad (en función de sus propiedades técnicas) y, finalmente, atendiendo a su uso. La Tabla 8 muestra la clasificación de la "Guía Española de Áridos Reciclados procedentes de Residuos de Construcción y Demolición"[32] en relación a la composición de componentes del árido reciclado y la Figura 11 los componentes individuales de los mismos, según nomenclatura utilizada en la norma UNE EN-12620 [33].

Tabla 8. Clasificación de los áridos reciclados en relación a su composición.

<table>
<tr><td>Áridos reciclados de Hormigón (ARH)</td><td colspan="2">A partir de residuos de hormigón tras un proceso de machaqueo, cribado y procesado.
*Rc+Ru > 90 % en peso</td></tr>
<tr><td>Áridos reciclados cerámicos (ARC)</td><td colspan="2">A partir de residuos cerámicos (ladrillos, tejas o baldosas cerámicas).
*Rb > 70 % en peso</td></tr>
<tr><td rowspan="2">Áridos reciclados mixtos (ARM)</td><td rowspan="2">Tratamiento de RCD con mezclas de ARH y ARC</td><td>Mixtos de hormigón
Rc+Ru < 90 % en peso
Rb < 30 % en peso</td></tr>
<tr><td>Mixtos Cerámicos
Rb > 30 % en peso</td></tr>
<tr><td>Áridos reciclados con asfalto (ARA)</td><td colspan="2">Residuos que proceden del fresado de capas de firmes.
5% >*Ra> 30 % en peso</td></tr>
</table>

***Nota:** Según la norma UNE EN-12620, 2009; **Rc**: hormigón, productos de hormigón, mortero elementos de albañilería de hormigón, **Ru**: áridos no ligados, piedra natural, árido ligado hidráulicamente, **Rb**: elementos de albañilería de arcilla, **Ra**: materiales bituminosos.

Esta clasificación permite un sistema general adecuado en el mercado español, que pueda servir de referencia y seguridad en el mismo. Sin embargo, la composición es un criterio insuficiente para determinar por sí misma la calidad del árido reciclado y será el cumplimiento de los requisitos técnicos exigidos para un uso determinado el que establecerá finalmente la viabilidad del material a ese uso.

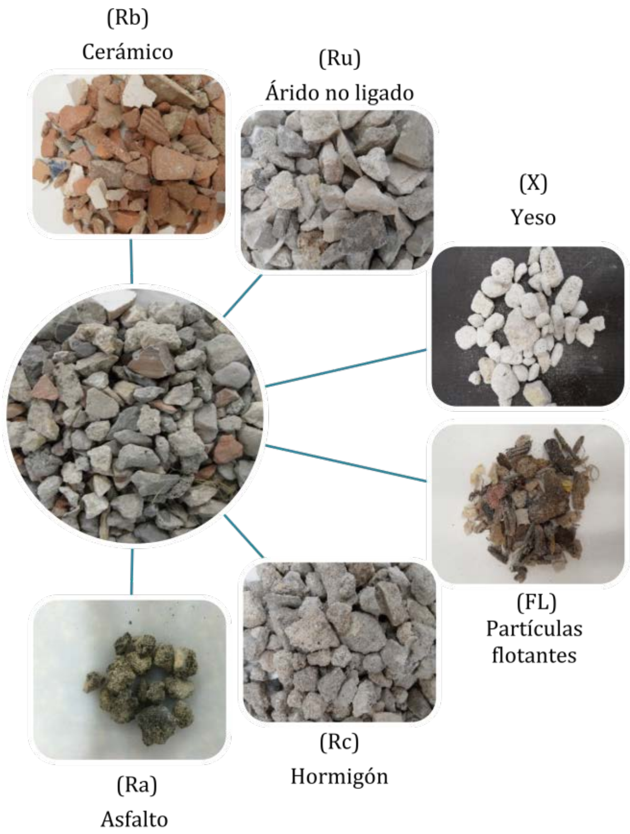


Figura 11. Componentes de los áridos reciclados.

2.4.2 Producción de árido reciclado

La producción de los áridos reciclados se realiza en plantas de tratamiento que, en líneas generales, son similares a las empleadas para los áridos naturales, aunque incorporan de manera específica elementos para la separación de impurezas y otros contaminantes. De acuerdo con el informe Symonds [34], la Tabla 9 muestra la clasificación de las plantas de gestión de RCD según las operaciones de procesamiento realizadas.

Tabla 9. Clasificación de los áridos reciclados en relación a la composición de origen.

Clasificación	Procesamiento
Plantas de Nivel I	Operaciones de trituración y cribado en una unidad móvil, el procesamiento se realiza en la propia obra.
Plantas de Nivel II	Plantas fijas que incluyen separación de magnéticos y operaciones de trituración y cribado en una única línea de producción
Plantas de Nivel III	Incorporan operaciones de trituración cribado y técnicas de separación más sofisticadas para las diferentes impurezas, metal, papel, plástico o incluso yeso, disponiendo de múltiples líneas de procesamiento.

La Figura 12 esquematiza las etapas de procesamiento realizadas en una planta de reciclaje de nivel 3, desde la llegada del RCD hasta la producción del árido reciclado. Además, la Tabla 10 permite identificar los equipos normalmente utilizados en cada fase.

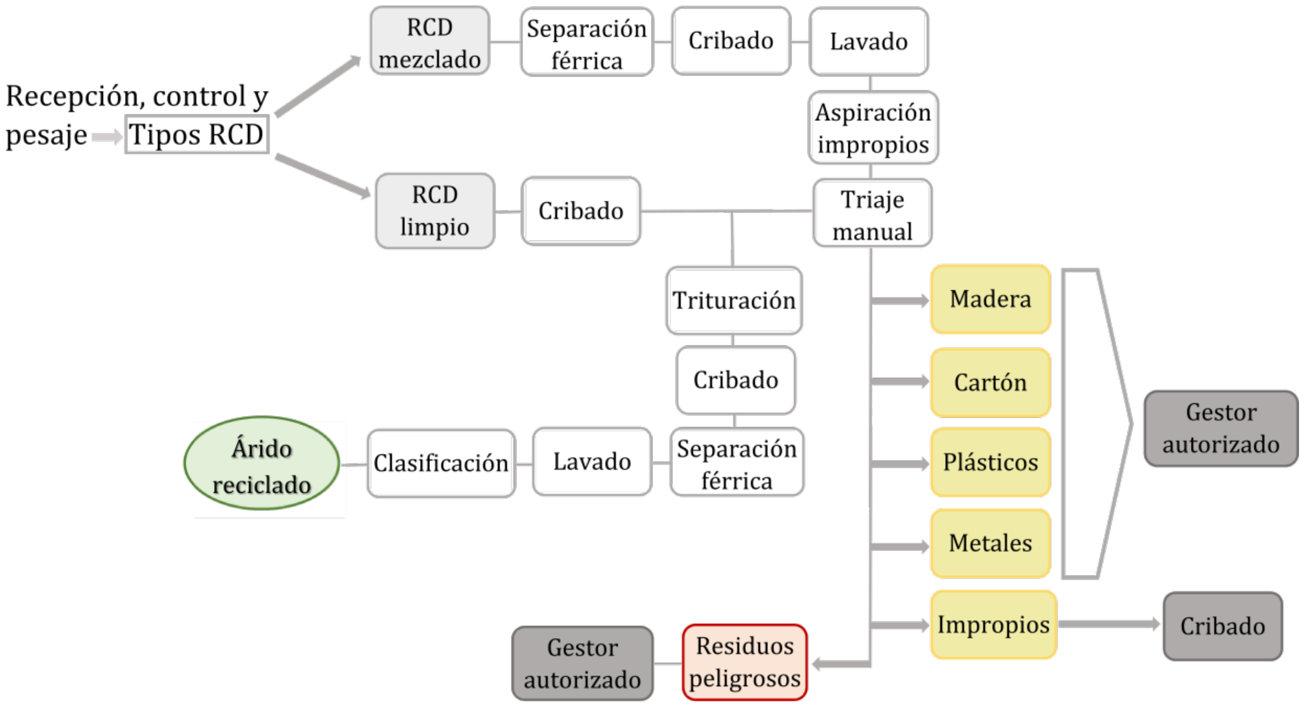
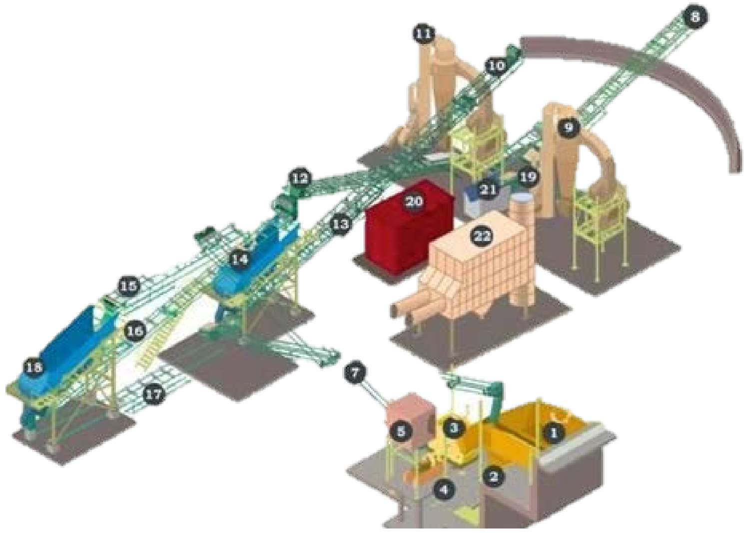


Figura 12. Esquema de funcionamiento de una planta de tratamiento de RCD.

Tabla 10. Esquema de una planta fija de valorización de RCD. Fuente: Asociación de Plantas Fijas de Reciclaje de RCD de Euskadi.

Planta de Valorización RCD. Nivel III



Elementos generales

1.	Tolva de alimentación	**12.**	Cinta de Rechazo
2.	Tolva de pre-molienda	**13.**	Cinta 10/40
3.	Molino triturador de impacto	**14.**	Cribas con mallas
4.	Bandeja Vibrante de Alimentación	**15.**	Cinta Reversible
5.	Puesto de Control	**16.**	Cinta material 0/60
6.	Electroimán	**17.**	Material >60
7.	Cinta de Retorno	**18.**	Criba 2
8.	Cinta giratoria	**19.**	Chimenea filtro de Mangas
9.	Ciclón 1	**20.**	Sistema de Infrarrojos para separación de impurezas
10.	Cinta 0/10	**21.**	Bañera de lavado
11.	Ciclón 2	**22.**	Filtro de Mangas

La clasificación y/o separación de los RCD es quizás la etapa más importante en el reciclaje de estos residuos. Esta etapa permite la división entre residuos pétreos (hormigón, ladrillo, materiales cerámicos y piedra natural) y no pétreos (metales, plásticos, cartón, madera, yeso, etc). Si esta separación no se realiza en origen, debe ser realizada en la planta de reciclaje, con el fin de obtener un material con la menor dispersión posible, consiguiendo por tanto una gestión más eficente de los materiales reciclados.

Generalmente, los áridos reciclados obtenidos en la plantas de tratamiento se adaptan a la demanda de su entorno, siendo estos áridos de diferentes granulometrías y composicón. Las impurezas (metales, madera, papel y cartón) que acompañan a la fracción pétrea del residuo son a su vez valorizables en otros centros de tratamiento. En la Tabla 11 se muestra los tipos de materiales reciclados producidos en la mayoría de las plantas de reciclaje nacionales y su aplicación final.

Tabla 11. Materiales reciclados producidos en las plantas de reciclaje. Fuente: GEAR [32].

Material	Aplicaciones
Suelo de granulometría continua	Suelos reciclados seleccionados o tolerable en terraplenes
Zahorras (0/25 mm) o todo -uno	Reparación de caminos, pistas forestales, mejora de terrenos, rellenos, etc.
Arena (~0/6 mm)	Canalizaciones, saneamiento, rellenos, jardinería
Gravilla (~6/12 mm)	Prefabricados de hormigón, hormigón no estructural, estabilización de terrenos, rellenos y bases.
Grava (~12/32 mm)	Hormigones no estructurales, material de filtro en zanjas de drenaje, cubiertas invertidas, drenaje de muros, nivelación y rellenos

Finalmente, los áridos reciclados obtenidos serán analizados conforme a la normativa técnica armonizada adecuada al uso previsto y, posteriormente, el fabricante emitirá una declaración de prestaciones con el fin de incorporar el nuevo producto al mercado. Del mismo modo, la calidad de los materiales reciclados puede validarse mediante la certificación y acreditación de su marcado CE [17], certificación que garantiza que el producto que se ofrece tiene unas características establecidadas y declaradas por el productor que serán comprobadas periodicamente.

2.4.3 Contexto legal internacional y nacional aplicable a los áridos reciclados

Según el Real Decreto que regula la producción y gestión de RCD [29] "los áridos reciclados obtenidos como producto de una operación de valorización de RCD deberán cumplir los requisitos técnicos legales para el uso al que se destinen". En esta línea, la actual normativa en esta materia se encuentra en un proceso de revisión de las actuales normas con el fin de abordar aspectos técnicos de los áridos reciclados para que estos puedan ser incorporados en las condiciones adecuadas de garantía y calidad.

Hasta el momento las normas europeas relativas a las propiedades de esta tipología de áridos son: determinación del contenido de cloruro soluble en ácido (UNE-EN 1744-5, 2007a); influencia del extracto de áridos reciclados en el tiempo de principio de fraguado del cemento (UNE-EN 1744-6, 2007b); clasificación de los componentes de los áridos gruesos reciclados (UNE-EN 933-11, 2009b); ensayo de los Ángeles en áridos reciclados para fracciones granulométricas alternativas, 16/32 mm, según el anexo G informativo (UNE-EN 1097-2, 2010b); y determinación de los sulfatos solubles en agua en áridos reciclados, apartado 10.2 (UNE-EN 1744-1, 2013).

En la norma europea **"Áridos para Hormigón norma EN 12620"** [33], se especifican las propiedades que deben cumplir los áridos reciclados para ser utilizados en la elaboración de hormigón. Esta norma cubre todos los materiales granulares que vayan a ser utilizados en la elaboración de hormigón estructural, además de otras aplicaciones como carreteras, pavimentos o elementos prefabricados de procedencia natural, reciclada o mezcla de ambos, de densidad superior a 2000 kg/m^3. Asimismo, ofrece la posibilidad de utilizar arenas recicladas siempre y cuando cumplan con las condiciones establecidas para el árido natural o cuya evidencia de comportamiento haya sido comprobado en la práctica. Además, obliga al fabricante a declarar la conformidad del árido mediante el valor obtenido en cada uno de los ensayos, según su uso final y el origen del mismo siempre que sea requerido.

En el ámbito nacional, los áridos empleados para la fabricación de hormigón tienen que cumplir las prescripciones establecidas en la nuevo **"Código Estructural"** [35] que sustituyen a las prescripciones establecidas en la "**Instrucción de Hormigón Estructural (EHE-08)"** [36]. Este nuevo Código, de obligado cumplimiento, establece en su artículo 30.8 "Áridos reciclados" los requisitos físicos, mecánicos, químicos y de composición de los áridos reciclados que anteriormente estaban definidos en el Artículo 28 del Anejo 15 "Recomendaciones para la utilización de hormigones reciclados" de la EHE-08. Igualmente, mantiene las recomendaciones específicas sobre el uso de áridos reciclados en la producción de hormigones. El Artículo 30.8.1 "Generalidades" de esta nueva normativa indica que está permitido el uso de la fracción gruesa del árido reciclado de hormigón hasta un límite máximo de 20 % de sustitución del árido grueso convencional, para la producción de hormigón, tanto en masa como hormigón armado, de resistencia característica no superior a 40 N/mm^2, quedando excluido su empleo en hormigón pretensado. Además de quedar fuera de los objetivos de este artículo los hormigones fabricados con árido fino reciclado, así como los confeccionados con áridos de naturaleza distinta al hormigón (áridos mixtos, cerámicos o asfálticos), entre otras excepciones.". Finalmente, indicar que se mantiene el "Índice de contribución de la estructura a la sostenibilidad", que valora la contribución medioambiental asociada al empleo de áridos reciclados en hormigón.

Por otro lado, a pesar de no tener carácter normativo, la "**Guía Española de Áridos reciclados procedentes de los residuos de construcción y demolición (GERD)"** tiene como objeto caracterizar técnicamente a los áridos reciclados, en la búsqueda de las mejores aplicaciones y usos en obra pública y privada garantizando su comportamiento mecánico y medioambiental, además de servir como instrumento de comercialización y verificación de la calidad de los áridos reciclados en España. Esta guía incluye recomendaciones técnicas y fichas de las diferentes aplicaciones realizadas con áridos reciclados en usos no ligados y a los ligados entre la que destaca las recomendaciones técnicas para áridos procedentes de los RCD a utilizar como materiales tratados con ligante hidráulicos.

2.5 Estrategias de reciclaje de los RCD dentro de una economía circular

De forma general, el campo de aplicación de los áridos reciclados depende de su naturaleza o composición (hormigón, cerámicos, mixtos, y asfalto), aunque será el cumplimiento de los requisitos técnicos exigidos para cada aplicación el que finalmente determinará su uso [32]. Aunque los áridos reciclados entrañan una ventaja medioambiental significativa aún existe una gran deficiencia en el uso de estos materiales tanto en obra pública como privada. El coste añadido que necesitan estos materiales en comparación con sus homólogos naturales son una barrera más para su empleo [37].

A continuación, se hace un recorrido de forma resumida sobre el uso de estos materiales granulares en sus diferentes aplicaciones. Destacar que, entre las posibles aplicaciones de estos áridos, solo se han considerado en la presente Tesis Doctoral, por ser objeto de la misma, las siguientes aplicaciones: i) como áridos reciclados en el hormigón, ii) como adiciones al cemento; y iii) conjuntamente como árido reciclado y adición al cemento en el hormigón.

2.5.1 Hormigón reciclado

En la actualidad, el hormigón sigue siendo el material de construcción más consumido en todo el mundo, y es universalmente aceptado como uno de los materiales más versátiles en la construcción [38]. La producción global de hormigón fue alrededor de 27 Gt en 2017 [39] y teniendo en cuenta los materiales típicos necesarios en su fabricación, se consumieron 19 Gt de áridos y alrededor de 4 Gt de cemento Portland [40]. Con las grandes cantidades de recursos naturales consumidos, es lógico pensar que el aprovechamiento fundamental de los áridos reciclados este dirigido a la fabricación de este material de construcción tan específico y la vez tan variado [41]. Bajo este contexto, existe una importante actividad investigadora sobre el uso de áridos reciclados en la fabricación de hormigón, cuyos resultados indican que los hormigones fabricados con estos materiales muestran un comportamiento físico, mecánico [42] y de durabilidad [43] marcado por la composición del árido reciclado, así como por el diseño de la mezcla [44].

Desde hace más de 50 años, en la literatura existen trabajos de investigación dedicados a evaluar principalmente las propiedades de los áridos reciclados de hormigón y su incorporación parcial en el hormigón [45]. La mayor parte de estos estudios se encuentran limitados a hormigones reciclados de uso no estructural debido a las inferiores propiedades físicas de los áridos reciclados, menor densidad, mayor absorción de agua y menor resistencia a la fragmentación [46] respecto a sus homólogos naturales. Sin embargo, estudios como el de Hendriks y Pietersen [47] informaron que los áridos reciclados podían utilizarse para fabricar hormigones duraderos y sostenibles, aportando considerables beneficios medioambientales, mediante la reducción de los residuos enviados a vertederos, la conservación de los recursos no renovables y la disminución de emisiones de gases de efecto invernadero, entre otros [23].

2.5.1.1 Microestructura del hormigón reciclado

A nivel microestructural, el hormigón reciclado presenta una estructura más compleja que la del hormigón convencional, debido a que este presenta varias zonas de transición: i) una nueva entre los diferentes componentes del árido reciclado y la pasta de cemento, ii) otra vieja entre el árido reciclado y el mortero adherido y iii) la que une a las partículas del árido natural con la pasta de cemento.

Teniendo en cuenta la complejidad y heterogeneidad de la estructura interna del hormigón reciclado, su caracterización lleva consigo la determinación de los tipos, cantidades y distribución de todos sus constituyentes [39,48,49], tanto desde un punto de vista macroscópico (partículas de árido grueso y fino, dispersas en una matriz de pasta de cemento) como a nivel microscópico (zonas de transición, estructuras moleculares y cristalinas, poros capilares y de gel).

Las características de cada fase o componentes del hormigón de forma independiente y la interacción entre ellos ayudan a comprender las propiedades mecánicas y de durabilidad del material, ya que la calidad de la zona de transición entre las fases influye considerablemente en el comportamiento del hormigón [50,51]. La Figura 13 muestra los elementos microestructurales de cada una estas fases que se describen a continuación:

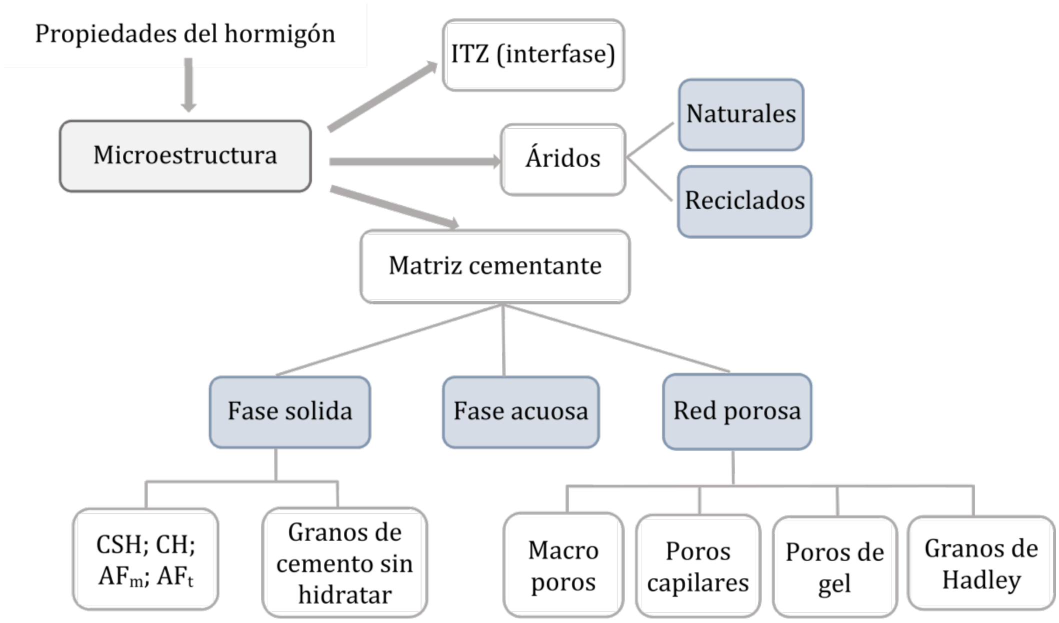


Figura 13. Esquema de fases de la microestructura del hormigón.

- **Matriz cementante**: resultado directo de la reacción química entre los componentes del cemento Portland y una cantidad de agua determinada (20-35 % del peso del cemento). La microestructura de la pasta de cemento hidratada está compuesta por una fase sólida, poros y/o fisuras y agua. Los productos de hidratación de la fase sólida contienen, de modo general, silicato cálcico hidratado (gel C-S-H), portlandita (CH), ettringita (fase AFt), monosulfoaluminatos hidratados (fase AFm) y granos de clínker sin hidratar. La pasta de cemento contiene varios tipos de poros, que juegan un papel importante en las propiedades del hormigón, los cuales se clasifican en: poros interlaminares en el C-S-H (0,01-0,03 μm); poros capilares (0,01-0,05 μm) para una baja relación a/c y (3-5 μm) para una alta relación a/c; granos de Hadley (1-20 μm); y poros de aire atrapado (50 μm a 1 mm). Finalmente, la fase acuosa, que se encuentra en la pasta de cemento, puede encontrarse en varias formas: agua capilar (poros >0,05 μm), agua absorbida, agua interlaminar, y agua combinada químicamente.

- **Áridos naturales o reciclados:** ocupan entre un 60 % y un 80 % del volumen del hormigón confiriendo al hormigón, en gran medida, el peso, módulo de elasticidad y estabilidad volumétrica del material, además ejerce una gran influencia en la resistencias mecánicas y durabilidad del hormigón [52].

- **Zona de transición:** zona más próxima a la superficie de contacto entre los áridos y la pasta de cemento hidratado o entre el mortero de cemento viejo. Se considera la zona más débil del hormigón, debido al mayor volumen y tamaño de poros, contenido y orientación de los cristales CH y presencia de microfisuras. Estas uniones se consideran los puntos de mayor fragilidad dentro de la macroestructura del hormigón, ya que puede afectar a la calidad de la interfase y, consecuentemente, a las propiedades y características del hormigón [51,53,54].

- **Sistema de poros:** formado por los espacios vacíos que se caracterizan por una serie de parámetros que puede ser cuantificados como: i) dimensiones geométricas: poros esféricos, cilíndricos, planares, etc. ii) dimensiones características: macroporos, mesoporos o microporos, iii) grado de conexión entre poros: porosidad total, cerrada, accesible o intercomunicada, iv) comunicación entre poros: de distinto tamaño y/o morfología, como fisuras, conductos, capilares, etc.

La clasificación del tamaño de poro depende generalmente del tipo de técnica o campo de estudio en la Tabla 12 se muestra, por ejemplo, dos clasificaciones del sistema poros y su papel en las propiedades del hormigón

Tabla 12. Clasificación de la red porosa en la pasta de cemento

Metha, P.K., (1986)		**Mindess et al., (2002)**		
Nombre	**Diámetro**	**Nombre**	**Diámetro**	**Propiedad afectada**
Microporos	<2 nm	Microporos "intercapa"	< 0.5 nm	Retracción y fluencia
		Microporos	0.5 nm-2.5 nm	
		Capilares pequeños (gel)	2.5 nm -10 nm	Retracción
Mesoporos	2nm-50 nm	Capilares medianos	10 nm-50 nm	Resistencia, permeabilidad y retracción
Macroporos	>50 nm	Capilares grandes	50nm-10μm	Resistencia y permeabilidad
		Aire ocluido	0.1mm-1mm	Resistencia

> Cada hormigón presenta un volumen de poros o de espacios vacíos respecto al volumen total de la muestra (porosidad), los cuales pueden comunicarse entre sí y con el exterior (porosidad comunicada), reflejando de forma inmediata la capacidad de retener o almacenar un fluido (líquido o gas) en su interior, con lo cual se vería afectada la durabilidad del hormigón. Por el contrario, en el caso de que existan poros pero sin conductos que los comuniquen entre sí y a su vez con el exterior (porosidad cerrada o no comunicada), éstos sólo tendrán incidencia en el comportamiento elástico o mecánico del material [55]

En relación a este aspecto, es posible encontrar en la bibliografía trabajos que han considerado la interfase del mortero como la zona de mayor debilidad, debido a la presencia de poros y grietas que pueden disminuir las propiedades del hormigón reciclado [56,57]. Otros, incluso han indicado que cuando los áridos reciclados proceden de hormigones de alta calidad, se verá reflejado en la calidad del mortero adherido y posteriormente en la del material endurecido, por lo que éste no siempre tiene un efecto negativo en la zona de transición [58,59].

Las condiciones de humedad de los áridos reciclados también es un punto de gran importancia, ya que según el diseño de mezcla utilizado (principalmente, en la relación agua cemento efectiva) la interfase puede presentar diferentes características, que a su vez repercutirán en la propiedades finales del hormigón [60]. En el caso de utilizar estos áridos en estado seco, se ha comprobado que los hormigones obtenidos tienen una microestructura mejorada y unos excelentes valores de resistencia a compresión, en comparación a cuando los áridos se utilizaban en estado saturado con superficie seca [61,62]. Este hecho se ha justificado por la presencia de partículas anhidras de cemento, presentes en el mortero adherido, que puedan aún reaccionar, lo que permitió una mayor adherencia en la interfase mortero-pasta de cemento; además de que la baja relación agua/cemento (a/c) alrededor del árido reciclado, utilizando el árido reciclado seco, dio lugar a la formación de nuevos hidratos que rellenaron rápidamente esta zona de transición. Sin embargo, cuando los áridos reciclados se usan saturados, se forma una película de agua alrededor de éstos, haciendo que la interfase pueda tener una relación a/c casi dos veces mayor que la de la pasta y, por consiguiente más porosa y débil [63], empeorando las propiedades mecánicas del hormigón reciclado [64]. Finalmente, respecto al tratamiento de premojado o mezclado en dos etapas, se ha indicado que algunos poros y grietas se pueden rellenar de una cierta cantidad de cemento, dando lugar a un hormigón con una zona transición relativamente densa y compacta alrededor de los áridos reciclados. A pesar de ello, hormigones fabricados con esta técnica también se ha observado una disminución de la prestaciones mecánicas [54,61,63].

2.5.1.2 Aplicaciones

En los siguientes apartados, se hace un repaso a los aspectos más significativos de las investigaciones realizadas hasta el momento sobre el uso de áridos reciclados en la fabricación de hormigón.

2.5.1.2.1 Hormigón estructural

El ámbito de aplicación del hormigón estructural cubre a todos los elementos de hormigón (en masa, armado o pretensado), tuberías de hormigón, presas, entre otros [35]. Nixon [45] publicó la primera revisión bibliográfica sobre la viabilidad del uso de áridos reciclados en el hormigón estructural. A partir de entonces se ha llevado a cabo numerosas investigaciones que han demostrado que el hormigón reciclado tiene propiedades mecánicas y de durabilidad algo inferiores que el hormigón convencional, cuya diferencia depende principalmente de la calidad de los áridos reciclados utilizados, composición, además de por el porcentaje y la fracción del utilizada [60,65,66]. A pesar de ello, a nivel práctico la utilización de estos materiales reciclados en el hormigón estructural sigue siendo limitado debido a la desconfianza de los consumidores en la calidad del árido [27], así como en la durabilidad del hormigón resultante a largo plazo [67].

En esta línea, los áridos reciclados de hormigón procedentes de piezas rechazadas de la industria del hormigón prefabricado, han demostrado tener un gran potencial de reciclaje, su uso da lugar a hormigones reciclados con características semejantes a la del producto original fabricado con áridos naturales [68]. Es por ello que la gran mayoría de las investigaciones relacionadas en esta aplicación han utilizado áridos procedentes de este tipo de residuos. En estos trabajos se ha indicado que la clase resistente del hormigón de origen influye considerablemente en los resultados obtenidos al usar la fracción gruesa (>4 mm) de los áridos reciclados [69,70], así como la combinación de ésta con la fracción fina (<4 mm), sin que se vean afectadas las prestaciones mecánicas del hormigón [71], ni las de durabilidad [66].

Los residuos generados en la demolición de estructuras de hormigón, también se han estudiado para su uso en hormigón estructural debido a su mayor homogeneidad y baja presencia de impurezas [27,60,72]. En esta línea, los áridos reciclados cerámicos sanitarios procedentes de piezas rechazadas también se han utilizado con éxito en la fabricación de hormigones estructurales, los cuales son una solución alternativa al árido natural [73] para ser utilizados para hormigones estructurales en edificación (<25 MPa) siempre y cuando el porcentaje sea inferior al 50 % en peso [28]. Además Nepomuceno et al. [74] estudiaron el comportamiento de vigas de hormigón pretensado utilizando áridos reciclados cerámicos, procedentes de ladrillos triturados, los cuales pueden ser una solución alternativa al uso de árido natural, siempre que el porcentaje de reemplazo, sea inferior al 30 % - 35 % en peso.

La composición de los áridos reciclados mixtos, es más heterogénea que la de los áridos reciclados de hormigón o cerámicos, entre sus componentes principales destaca la presencia significativa, entre un 5 % y 30 % de materiales base arcilla (tejas, ladrillos, azulejos, entre otros), pero además de otros materiales en forma de impurezas (asfalto, madera, yeso, plástico, vidrio, etc.) [42,75]. La presencia de algunas impurezas en estos áridos podrían dar lugar a resistencias mecánicas inferiores debido a una peor unión y mayor espesor de la ITZ entre estos compuestos (plásticos, yeso, madera, vidrio, entre otros) y la pasta de cemento [51,76].

A pesar de que el empleo de los áridos reciclados mixtos puede disminuir las prestaciones mecánicas y la durabilidad de los hormigones en mayor proporción que los áridos reciclados de hormigón, de acuerdo con la bibliográfica consultada, algunos autores han obtenido buenos resultados en hormigones estructurales. En esta línea, se encuentran los trabajos publicados por Medina et al. [28] que utilizaba áridos reciclados mixtos con altos contenidos de impurezas (asfalto y partículas flotantes) en la fabricación de hormigones estructurales. Estos autores observaron que los hormigones con hasta un 50 % en peso de árido reciclado y, dependiendo del contenido en asfalto y partículas flotantes mostraron resistencias de compresión a los 28 días inferior entre un 15 % y un 20 % respecto al hormigón de convencional, pero estos podrían utilizarse como hormigones estructurales en edificación. El efecto de la incorporación de estos áridos se puede minimizar utilizando relaciones a/c bajas [77] e incorporando árido reciclado seco [28]. Además, el empleo de adiciones al cemento como cenizas volantes o humo de sílice en esta tipología de hormigones ha demostrado tener un beneficioso resultado en las propiedades mecánicas y durables a largo plazo [78].

2.5.1.2.2 Hormigón no estructural

Según la anterior EHE-08 [36] el hormigón no estructural se definía como aquel material que “no aporta responsabilidad estructural a la construcción, pero colabora en mejorar las condiciones durables del hormigón estructural o que aporta el volumen necesario de un material resistente para conformar la geometría requerida para un fin determinado, como es el caso de los hormigones de relleno, aceras, bordillos y productos prefabricados. Esta normativa permitía sustituir hasta el 100 % de la fracción gruesa del árido natural por el reciclado [36].

La tipología de áridos reciclados utilizada en la fabricación de hormigón para uso no estructural es más variada. En este línea, se han utilizado áridos cerámicos de baldosas rechazadas en losas de hormigón [79], donde estos autores resolvieron la alta absorción de las partículas cerámicas presaturando los áridos antes de su uso, obteniendo con ello resistencias superiores a 15 MPa con sustituciones de árido cerámico del 70 %. Mas et al. [80] emplearon hasta un 40 % de áridos reciclados mixtos para fabricación de hormigones en masa con diferentes clases de resistencia (15 MPa, 25 MPa y 65 MPa). López Uceda et al. [81] usaron esta tipología de áridos reciclados mixtos en la fabricación de hormigones de bajas resistencia (15 MPa) y bajo contenido de cemento (200 kg/m^3), cuyos resultados confirman la viabilidad de su uso en carriles bici, cunetas, y hormigón de nivelación entre otros. Martínez-Lage et al. [82] también fabricaron hormigones en masa con esta con esta tipología de áridos, estos autores observaron un descenso lineal de las prestaciones mecánicas entre un 20 % y un 30 % cuando las tasas de remplazo se encontraban entre un 50 % y un 100 % del material natural. Estos autores fabricaron hormigones con una resistencia a la compresión de 25 MPa con 100 % de áridos reciclados mixtos gruesos y 250 kg/m^3 de cemento.

2.5.1.2.3 Elementos prefabricados de hormigón

Un elemento prefabricado de hormigón es el resultado de un proceso industrial realizado bajo un sistema de control de producción definido, que emplea hormigón como material fundamental. Las soluciones constructivas obtenidas con estos productos se pueden utilizar en cualquier tipo de proyecto (edificación e infraestructura, entre otros) y en un momento indeterminado del proceso de construcción. Según la Asociación Nacional de la industria del Prefabricado de Hormigón (ANDECE) caben destacar las siguientes soluciones prefabricadas de uso estructural: cimentaciones, elementos lineales (vigas, pilares, pórticos), elementos para forjados (placas alveolares, viguetas y prelosas), elementos para obra civil (puentes, dovelas, marcos, muros de contención y traviesas) elementos complementarios (impostas, sistemas de contención de vehículos) y no estructural: tuberías, canalizaciones, cunetas, pavimentación (adoquines, bordillos, baldosas, etc.) [83]. Por lo general los elementos prefabricados de hormigón de uso no estructural deben cumplir con el criterio normativo de resistencia mínima de 15 MPa, además de con los requisitos específicos en la normativa vigente para cada producto.

En la actualidad, las nuevas técnicas de producción han permitido que estos elementos consigan propiedades mecánicas totalmente garantizadas. Además, la fabricación con una baja relación agua/cemento y la optimización de los métodos de compactación y curado confieren a estos elementos unas excelentes propiedades en acabado, resistencia y durabilidad, en comparación con otras formas de construcción más tradicionales [84].

En cuanto al tipo de material reciclado utilizado, en los trabajos publicados se ha usado una composición muy variable de áridos reciclados, cerámicos [85,86] mixtos [87,88], de hormigón [89]. La alta capacidad de absorción de los áridos reciclados, principalmente los de naturaleza cerámica y mixta, ha sido un aspecto muy estudiado en la literatura [74,79,86]. Esta propiedad intrínseca de estos áridos reciclados debe contemplarse en la dosificación o en el procedimiento de mezclado para asegurar que exista el agua libre necesaria y suficiente para las reacciones de hidratación del cemento y, consecuentemente, un hormigón con unas adecuadas características, tanto en su estado fresco como endurecido.

La importancia del porcentaje de sustitución también ha sido un tema bastante investigado. Los estudios consultados han demostrado que es factible incorporar hasta el 100 % del árido reciclado (fracción fina y gruesa) para la producción de piezas de hormigón no estructurales, aunque para ello sea necesario usar mayores cantidades de cemento a fin de mantener los requisitos mecánicos [76,90]. En cambio, otros autores han optado por añadir adiciones minerales a la mezcla, bien como sustituto del cemento o adición a este, con el objeto de mejorar el comportamiento de los hormigones reciclados con árido reciclado. Entre las adiciones más utilizadas se encuentran las cenizas volantes [86,91] las escorias granuladas de alto horno [92], o el humo de sílice [88]. En esta línea, también se ha utilizado con éxito adiciones procedentes de residuos cerámicos como reemplazo de la arena natural (<30 %) o del cemento (< 20 %) [85]. El-Dieb y Kanaan [93] estudiaron el comportamiento de hormigones con diferentes clases de resistencia (25 MPa, 50 MPa, 75 MPa) en los que se sustituía un entre un 10 % y un 40 % el contenido de cemento por residuos cerámicos pulverizados procedente de residuos de la industria cerámica. Resultado de sus investigaciones, observaron que los hormigones que incorporaban este residuo presentaban, en general, una menor resistencia a compresión a cortas edades (<28 días), pero sin embargo mostraron un mejor comportamiento frente a los agentes agresivos, concluyendo que estos residuos cerámicos eran viables para ser utilizados como adición en elementos prefabricados de hormigón.

2.5.2 Adiciones al cemento

El cemento es el material básico para la elaboración de hormigón. Su principal propiedad es la de formar masas pétreas resistentes y duraderas cuando se mezcla con áridos y agua. El endurecimiento de la mezcla ocurre transcurrido un cierto tiempo desde el momento en que se realiza la mezcla, lo que permite dar forma (moldear) a la pieza o elemento resultante del proceso de endurecimiento. Estas tres cualidades (moldeable, resistente, duradera) hacen que los materiales de base cemento tengan una gran aplicación en la construcción de infraestructuras y otros elementos constructivos. Sus compuestos principales son silicatos de calcio y, en menor proporción, por aluminatos de calcio que, mezclado con agua se combina, fragua y endurece a temperatura ambiente, tanto al aire como bajo el agua. Los romanos ya utilizaban un cemento natural para unir las piedras. Éstos empleaban una mezcla de cal y materiales procedentes de las cercanías de Pozzuoli, junto al Vesubio, de ahí la denominación de puzolana que damos actualmente a los materiales que se comportan de forma similar.

Según la norma europea UNE-EN 197-1 [94] "son conglomerantes hidráulicos, esto es, materiales artificiales de naturaleza inorgánica y mineral, que finamente molidos y convenientemente amasados con agua forman pastas que fraguan y endurecen a causa de las reacciones de hidrólisis e hidratación de sus constituyentes, dando lugar a productos hidratados mecánicamente resistentes y estables, tanto al aire como al agua". Este endurecimiento hidráulico se debe principalmente a la formación de silicatos cálcicos hidratados y de aluminatos hidratados como resultado de la reacción entre el agua y los constituyentes del cemento. Esta propiedad de conglomerante hidráulico le ha convertido en un material básico en la construcción, imprescindible para la edificación y la realización de infraestructuras.

2.5.2.1 Problemática actual del cemento

La fabricación de cemento requiere el uso de enormes hornos, que consumen grandes cantidades de energía [95]. Durante el proceso de fabricación del clínker, componente que se forma tras calcinar la caliza y la arcilla a unos 1450 ºC, se emiten grandes cantidades de CO_2 que son liberados a la atmosfera [52]. Se estima que por cada tonelada de clínker utilizada en la producción de cemento, se emite a la atmosfera hasta una tonelada de CO_2. Según algunas investigaciones citan a la industria del cemento como la responsable del 5 %-7 % de todas emisiones globales de CO_2 [96,97]. Una alternativa para reducir estas emisiones asociadas a la producción de cemento es incorporar materiales alternativos en sustitución parcial o adición al cemento haciendo su uso más eficiente [98].

En la actualidad, se encuentran numerosas investigaciones que buscan la sostenibilidad de la industria del cemento a través de la estrategia de reducción del clínker empleando diferentes residuos como adiciones al cemento. En esta línea, se encuentran aquellos trabajos que versan sobre la valorización de residuos industriales procedentes de biomasa [99–101], lodos de la industria ornamental [102–104] y arcillas calcinadas [105] entre otros. Estos trabajos refuerzan la importancia de la valorización de residuos de diferentes sectores industriales brindando la oportunidad de reducir las emisiones asociadas al cemento y el consuno de recursos naturales a través de una producción más ecológica que concuerde con los objetivos de desarrollo circular.

2.5.2.2 Tipos de adiciones al cemento

Las adicciones son materiales inorgánicos puzolánicos, y/o hidráulicos o inertes que pueden añadirse al cemento, mortero u hormigón con la finalidad de mejorar algunas de las características físicas-químicas de los mismos o de conferirles algunas especiales. La mezcla puede realizarse antes del molido (Figura 14) o bien como sustitución parcial del cemento antes de ser mezclado con agua. Su principal campo de aplicación son las obras marítimas, bases y sub-bases de carreteras, obras de hormigón en masa en grandes volúmenes (presas, cimentaciones masivas, muros de contención, etc.), y morteros en general, donde la agresividad química del entorno pueda ser muy importante.

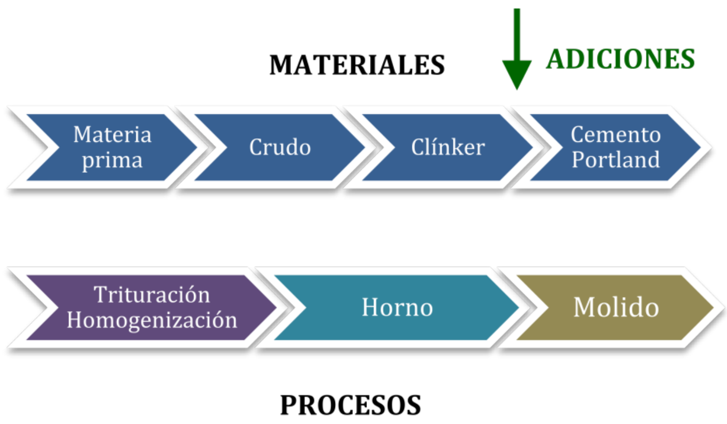


Figura 14. Esquema de fases de producción del cemento.

Según la norma UNE-EN 197-1 [94] las puzolanas son adiciones que pueden incorporarse al cemento para mejorar algunas de sus características, como una mayor durabilidad química frente a los ataques por aguas puras, carbónicas, agresivas o con débil acidez. Las adiciones puzolánicas están compuestas esencialmente por dióxido de silicio reactivo (SiO_2) y óxido de aluminio (Al_2O_3), además de pequeñas cantidades de óxido de hierro (Fe_2O_3) entre otros óxidos minoritaritos. El contenido en SiO_2 reactivo debe ser mayor del 25 % en masa. Los materiales puzolánicos, finamente molidos, a temperatura ambiente y en presencia de agua reaccionan con el hidróxido cálcico [$Ca(OH)_2$] para formar compuestos de silicato cálcico y de aluminato cálcico hidratados capaces de desarrollar resistencia. La reacción entre los materiales puzolánicos, el hidróxido de calcio y el agua se le denomina reacción puzolánica (Ecuación 1) y los productos resultantes generalmente son del mismo tipo que los productos de hidratación del cemento Portland. Los materiales puzolánicos deben prepararse correctamente, es decir, deben ser seleccionados, homogeneizados, secados o tratados térmicamente y pulverizados, dependiendo de su estado de producción o de suministro.

$$Puzolana + H_2O + Ca(OH)_2 \rightarrow C-S-H + C-A-H \qquad \text{(Ecuación 1)}$$

Dependiendo de su origen, las puzolanas pueden se naturales o artificiales:

- **Puzolanas naturales:** son mayoritariamente de origen volcánico o rocas sedimentarias de naturaleza silícea o sílico-aluminosa, capaz de combinarse con la cal procedente de la hidratación de los cementos, en presencia de agua, para formar compuestos similares a los originados en la hidratación de los componentes principales del cemento Portland.

- **Puzolanas artificiales:** se definen como residuos o subproductos industriales de diversos orígenes y características, que tienen como carácter principal y común la actividad puzolánica. Las más utilizadas en la actualidad son las cenizas volantes y el humo de sílice.

El termino actividad puzolánica se refiere a la cantidad máxima de hidróxido cálcico con la que la puzolana se puede combinar. La cantidad de fijación depende de la naturaleza de las fases activas presente en la puzolana (composición mineralógica), de la reacción cal-puzolana de la mezcla, y de la edad de curado; mientras que la velocidad de combinación depende de la finura (o superficie específica) de la puzolana, de la relación agua/sólido y de la temperatura de reacción.

El uso de puzolanas o materiales cementantes en la industria del cemento y del hormigón ha ido cobrando cada vez mayor importancia en las últimas décadas. Entre los beneficios conseguidos con el uso de puzolanas destacan la mejora de las resistencias mecánicas y de durabilidad (19-21), además de los beneficios medioambientales, reducción del consumo de cemento y valorización de subproductos o residuos de otros procesos industriales que serían destinados a vertederos. Al mismo tiempo, las políticas medioambientales persiguen la reducción o eliminación de los escombros mediante la valorización de los residuos y subproductos industriales como materias primas, de acuerdo con los principios de la economía circular. La búsqueda de nuevos tipos de residuos y subproductos con propiedades puzolánicas se ha convertido, por tanto, en una línea de investigación prioritaria.

Dentro de las nuevas adiciones que actualmente están siendo investigadas para que en un futuro puedan ser empleadas en la industria del hormigón, se realizará un análisis de aquellas procedentes de los RCD que representan una línea de investigación novedosa y que son abordadas en la presente Tesis Doctoral.

2.5.2.3 Residuos de construcción y demolición como adiciones al cemento

2.5.2.3.1 Adiciones de base cerámica

Los óxidos mayoritarios presentes en los RCD son (CaO, SiO_2, Al_2O_3 y Fe_2O_3) similares al del cemento [106,107] y semejantes a otros materiales empleados como puzolanas [108]. En general, es conocido que los materiales de construcción de base arcilla, alcanzan una gran actividad puzolánica, cuando son térmicamente activados a temperaturas entre los 600-1000 ºC y molidos con una granulométrica suficientemente fina (<63 µm) [109]. Su composición se basa principalmente en SiO_2, Al_2O_3 y Fe_2O_3 y la pérdida del agua combinada durante la calcinación, destruye la red cristalina de las arcillas, dando lugar a materiales amorfos inestables responsable de su actividad puzolánica [110].

De forma general, la reacción puzolánica de los residuos cerámicos es menos intensa, en comparación con otras puzolanas de uso tradicional en la industria del cemento como el humo de sílice debido a su mayor contenido de fase cristalina [108]. Ensayos en pastas de cemento han encontrado una proporción relevante de hidratos de silicato que están comúnmente presentes en el cemento Portland, pero también se encontraron hidratos de aluminato de calcio e hidratos de aluminosilicatos propios de reacciones puzolánicas [112]. La incorporación de estos residuos puede provocar una pérdida de la fluidez para lograr mantener una misma trabajabilidad. Esta disminución puede ser causada por una forma más irregular (menor trabajabilidad), mayor tamaño y porosidad de sus partículas que absorben mayor cantidad de agua [106].

Algunos estudios en morteros han demostrado que la incorporación de polvos cerámicos con un tamaño de partícula inferior a la del cemento puede refinar en gran medida la estructura de poro de los mismos fabricados con este material debido a los efectos de relleno y reacciones puzolánicas que dan lugar a un aumento de la mesoporosidad (≤50 nm) y una disminución del tamaño de poro [113] viéndose reducida la permeabilidad a los gases, la absorción de agua capilar y la retracción hasta en un 60 % en morteros que contenían un 40 % en peso de este material respecto a los morteros convencionales. Asimismo, morteros fabricados con un tamaño de partículas cercano o similar al cemento no mostraron diferencias significativas en términos de resistencia a compresión, resistencia a flexión y módulo de elasticidad incluso llegaron a ser ligeramente superiores a los 90 días de curado [114,115].

Respecto al uso de estos materiales como sustitución parcial del cemento en el diseño de hormigones, algunos autores encuentran un ligero descenso de las prestaciones mecánicas iniciales (<28 días) debido a procesos de curado más prolongados [116]. Sin embargo, estudios como los de Heidari y Tavakoli [117] no observaron diferencias significativas en la resistencia a compresión a los 28 días de curado en hormigones fabricados con un 20 % de polvo de cerámico procedentes de baldosas como sustitución parcial del cemento y el hormigón con cemento convencional. Del mismo modo, Vejmelkova et al. [118] no encontraron diferencias significativas en las propiedades mecánicas y de transporte de agua en hormigones fabricados con hasta un 20 % de polvo cerámico como sustitución parcial del cemento.

Respecto a las prestaciones durables de estos hormigones, Dieb y Kannan [93] fabricaron hormigones utilizando polvos reciclados cerámicos procedentes del pulido final de baldosas cerámicas como sustituto parcial del cemento entre un 10 % y un 40 % en peso. Estos autores observaron un aumento significativo (de 3.7 a 6.2 veces) en los valores de resistividad eléctrica y un descenso (entre un 17 % y un 40 %) en el volumen total de poros permeables en los hormigones que incorporaban este residuo como remplazo parcial del cemento respecto la mezcla con cemento convencional. Cheng et al. [119] evaluaron la permeabilidad de hormigones que contenían entre un 10 % y un 40 % en peso de polvo reciclado procedente de los residuos generados durante la fabricación de baldosas cerámicas. Estos autores obtuvieron profundidades de penetración de agua inferiores en todos los hormigones que incorporaban estos residuos cerámicos respecto el hormigón con cemento convencional, lo que se traducía en hormigones con un sistema de poros menos conectado que contribuía a mejorar las características de durabilidad del hormigón. Según la reciente revisión de la bibliográfica realizada por Tang et al. [120] pone de relieve que la sustitución parcial de hasta un 30 % en peso como sustituto del cemento en la fabricación de hormigón puede mejorar, si la finura del residuo es la adecuada, las propiedades durables de los nuevos hormigones que incorporan estos residuos en el cemento respecto al hormigón convencional. Estos resultados refuerzan aún más la posibilidad de utilizar estos residuos como adiciones puzolánicas en el diseño de fabricación de hormigones sostenibles. Asimismo, investigaciones recientes apuntan que podrían obtenerse una reducción de las emisiones de CO_2 entre un 7 % y un 8 % por tonelada de cemento producida con la incorporación de hasta 20 % de estos materiales en el cemento [121] considerando únicamente la emisión de descarbonización y ofreciendo un beneficio económico de hasta un 10 % respecto al cemento convencional [113], además de reincorporar estos residuos a la cadena productiva ofreciendo así una solución final técnicamente adecuada y sostenible en consonancia con la principios de la economía circular.

2.5.2.3.2 Adiciones de base cemento

La fracción más fina de los residuos de hormigón (<5 mm) representa la fracción más difícil de valorizar [122]. Su contenido en pasta de cemento es superior a la de los áridos reciclados gruesos de hormigón provocando una mayor absorción de agua que podría poner en peligro las propiedades en estado fresco y endurecidas del hormigón que los incorpore [123]. Algunos investigadores han encontrado, en estos residuos finos (<63 µm), composiciones químicas similares a las del cemento Portland hidratado, con SiO_2 y CaO como óxidos principales así como otras partículas de cemento no hidratadas [107,124] y calcita ($CaCO_3$) atribuido a una porción de la pasta de cemento carbonatada [125]. Estos compuestos pueden contribuir de forma favorable a la hidratación del cemento y/o producir un efecto de relleno cuando se alcanzan una determinada finura [126]. Estudios realizados en pastas de cemento que incorporaban residuos de hormigón molido con sustituto del cemento también encontraron una reducción de la fluidez y un retraso en el tiempo inicial de fraguado respecto las pastas fabricadas con cemento convencional, debido a i) una menor finura, ii) un mayor número de partículas de mayor tamaño y iii) al efecto de dilución asociado al menor contenido de cemento respecto al cemento convencional [127]. Según estos resultados, se recomienda que el porcentaje máximo de incorporación sea igual e inferior a un 15 % en peso.

Recientemente esta tipología de residuo se ha utilizado a escala industrial para fabricar cementos con un 5 % en peso de residuos de hormigón molido como adición al cemento. En una planta de cemento se mezclaron los áridos finos de hormigón (<5 mm) con el clínker durante su triturado para asegurar una mezcla uniforme. Se fabricaron dos tipos de cementos (cemento reciclado con un 5 % de finos de hormigón (CPR-5) y un cemento Portland convencional (CP)). Los resultados mostraron que los cementos fabricados con un 5 % de residuos de hormigón cumplieron los requisitos químicos (contenido de sulfatos y cloruros), físicos (tiempo inicial de fraguado) y mecánicos (resistencia a la compresión) según la norma europea EN 197-1 que especifica los criterios de conformidad de los cementos comunes [126]. Además, según estos autores, la incorporación de estos residuos supone un menor consumo de materias primas, energía y reducción de los emisiones de CO_2 que se pueden cuantificar alrededor de 41 kg CO_2

eq./t de cemento, lo que podría traducirse, según el consumo mundial de cemento, en una reducción alrededor 80 Mt CO_2 eq/año en todo el mundo.

Los estudios del efecto de estos materiales como sustituto del cemento en la fabricación de hormigones aún son muy escasos. En esta línea, algunas investigaciones han encontrado que es posible fabricar hormigones con una resistencia media a la compresión de 30 MPa a 28 días de curado incorporando hasta un 15 % de residuos de hormigón como sustituto cemento convencional. Respecto a las propiedades del módulo de elasticidad y resistencia a tracción se han encontrado ligeros descensos de los mismos, entre un 7 % y un 8 %, para el módulo de elasticidad y alrededor de un 12 % para la resistencia a tracción en hormigones con un 15 % y un 25 % de residuos de hormigón molido como sustituto del cemento. A pesar de estos resultados, los investigadores no encontraron diferencias estadísticamente significativas entre los hormigones que contenían entre un 15 % y 25 % de residuos de hormigón y el hormigón convencional [125].

Otros autores, como Xiao et al. [107] también evaluaron el comportamiento mecánico de hormigones fabricados con RCD mixtos, mezcla de materiales cerámicos y hormigón y molidos como sustituto del cemento. Estos autores concluyeron que era posible sustituir hasta un 30% en peso de estos materiales por cemento con una reducción de la resistencia a la compresión, (< 8 % respecto al hormigón convencional) y un efecto positivo sobre la resistencia a tracción como resultado de las propiedades intrínsecas de estos RCD mixtos (presencia de SiO_2, Al_2O_3 y una superficie específica (640 m^2/kg) mayor respecto al cemento de 350 m^2/kg) que presentan una cierta actividad puzolánica y efecto filler. Este comportamiento, en función del porcentaje de incorporación puede compensar los efectos negativos causados por una menor cantidad de geles C-S-H, al disminuir la cantidad clínker en el cemento.

Por último y de acuerdo a lo publicado en la bibliografía consultada es posible indicar que los RCD tienen un gran potencial como adición en la industria cementera y del hormigón, aunque en la actualidad no se encuentran reguladas en la normativa vigente.

2.5.3 Incorporación simultánea de residuos de construcción y demolición como árido reciclado y adición al cemento en el hormigón.

En cuanto a la valorización de los RCD de forma conjunta como árido reciclado y adición al cemento se observa que la investigación es aún incipiente. En algunos estudios encontrados utilizan residuos de ladrillo como árido grueso y adición al cemento en la fabricación de hormigones [128]. Estos autores observaron que la resistencia a compresión disminuía debido a una mayor porosidad de la fracción reciclada gruesa, sin embargo, la incorporación de un 10 % y un 20 % de ladrillo molido como sustituto del cemento mejoró a largas edades (>28 días) la resistencia a compresión entre un 10 % y 5 % respectivamente respecto al hormigón fabricado solo con la fracción gruesa de ladrillo. Este hecho fue confirmado en base a las menores porosidades observadas en estos últimos hormigones y a una presencia de geles de silicato cálcico hidratado (C-S-H) que incorporaba aluminio en su composición (C-(A)-S-H) debido a la buena actividad puzolánica. Letelier et al. [115] también estudiaron el comportamiento mecánico y las propiedades físicas (densidad y módulo de elasticidad) de hormigones con distintos porcentajes de polvo cerámico (5 %, 10 %, 15 %) como sustitución parcial del cemento y un 30 % de árido reciclado grueso de hormigón. Sus observaciones indicaron cambios producidos en las propiedades mecánicas y físicas de los hormigones con un 30 % de árido reciclado debido a una alta porosidad de estos que puede ser compensado por la presencia de polvo cerámico. Esta adición demostró una mejora en las prestaciones mecánicas (resistencia a la compresión y flexión), elásticas (módulo de elasticidad) y físicas (densidad) con la edad de curado de los hormigones a los 90 días de curado. En esta línea, algunos autores han estudiado el comportamiento de hormigones que incorporación de forma conjunta de 50 % de áridos reciclados mixtos y un 25 % residuos cerámicos (ladrillos, tejas, entre otros) como sustitución parcial del cemento. De forma general sus resultados mostraron resistencias a la compresión a 28 días comparables a las del hormigón convencional (>25 MPa) utilizando 312 kg/m^3. Estos buenos resultados fueron justificados por una menor a/c y un claro refinamiento de la estructura de poros de los hormigones reciclados debido a la presencia de los materiales cerámicos. Estos resultados también se encontraron en consonancia con las observaciones previas de Zhao et al. [129] en hormigones fabricados conjuntamente con la fracción fina (<5 mm) y gruesa (<12 mm) de áridos procedentes ladrillos triturados.

De acuerdo a la bibliografía consultada es necesario clarificar la laguna científico –técnica existente en la actualidad sobre la viabilidad técnica de utilizar simultáneamente RCD como árido grueso y sustitución parcial del cemento como una alternativa sostenible ante la creciente necesidad de convertir el hormigón que actualmente conocemos en un material ecoeficiente, utilizando menos recursos naturales y reincorporando a la cadena productiva materias primas secundarias en consonancia con las estrategias de economía circular. Asimismo, la reincorporación de estas nuevas materias primas secundarias procedentes de los RCD, como áridos reciclados en el hormigón y adiciones al cemento como sustitución del clínker, se encuentra enmarcado dentro de las cinco líneas de actuación indicadas en la hoja de ruta para implantar una economía baja en carbono para 2050. [130] cumpliendo con los Objetivos de Desarrollo Sostenible (ODS) para 2030 “12- Producción y consumo responsable” y “13- Acción Climática”. [4]. En particular, y a modo de resumen final, se presentan las posibles ventajas económicas, medioambientales, técnicas y sociales (Figura 15) de la circularidad simultánea de los RCD en la industria del hormigón como árido reciclado y/o adición como sustituto del clínker.

Ventajas Económicas
- Menor dependencia de recursos naturales.
- Menor consumo de energía.
- Mayor circularidad de los residuos acumulados en las plantas de reciclaje.

Ventajas Medioambientales
- Reducción de las emisiones contaminantes.
- Conservación del entorno natural.
- Menor contaminación ambiental.

Ventajas Técnicas
- Mejores prestaciones mecánicas a largas edades.
- Mejores prestaciones durables frente a la entrada de agentes agresivos.
- Materiales energéticamente más eficientes.

Ventajas Sociales
- Mayor capacidad de generar empleo.
- Mejor calidad de vida de las personas.

Figura 15. Ventajas de la circularidad de los RCD en la industria del hormigón.

Capítulo 3

Objetivos

Capítulo 3

Objetivos

El objetivo principal que se plantea en esta tesis es investigar la viabilidad de utilizar simultáneamente la fracción gruesa y ultra fina de los RCD como nuevas fuentes de materias primas alternativas en el diseño de hormigones estructurales reciclados eco-eficientes con un menor contenido en clínker y áridos naturales. Para alcanzar este objetivo se desarrollaron los siguientes objetivos específicos

OBJETIVO 1: Análisis de la situación actual de la gestión de los RCD.

1.1. Analizar la actual situación de los RCD, asi como su gestión y valorización como árido grueso y adición al cemento en la frabricación de hormigones.

OBJETIVO 2: Caracterización química, mineralógica, morfológica, microestructural y composicional de los RCD.

2.1. Análisis de las propiedades físicas, químicas, mineralógicas y composicionales de la fracción gruesa (>4 mm) y ultrafinos (< 90 μm) resultantes del proceso de gestión de los RCD.

2.2. Análisis de las propiedades mecánicas de las fracción gruesa reciclada.

2.3. Estudio de las prestaciones físicas y mecánicas del esqueleto granular de mezclas granulares constituido por la mezcla en diferentes proporciones de áridos naturales y áridos reciclados.

2.4. Verificación de las exigencias nacionales e internacionales para su uso como material granular en distintas aplicaciones en el sector de la construcción (industria del hormigón, industria cementera y el ámbito de las carreteras como capas de firme).

OBJETIVO 3: Evaluar las propiedades físicas y mecánicas de hormigones estructurales reciclados frabricados parcial y totalmente con áridos gruesos procedentes de los RCD:

3.1. Estudio de las propiedades físicas en estado fresco (trabajabilidad, densidad y contenido de aire) y endurecido la densidad.

3.2. Determinación de las prestraciones mecánicas (resistencia a la compresión, flexión y tracción) de los nuevos hormigones reciclados.

3.3. Verificación del cumplimiento de los requisitos físicos y mecánicos recogidos en la actual Instrucción del Hormigón Estructural (EHE-08) y Eurocodigo 2-Proyectos de Estructuras de Hormigón.

3.4. Análisis estadísticos de todos los resultados con el fin de encontrar un porcentaje óptimo de remplazo.

OBJETIVO 4: Diseño y caracterización física y mecánica de nuevos hormigones eco-eficientes que incorporan en su composición cementos con un menor contenido en clínker y/o áridos reciclados mixtos gruesos.

4.1. Determinación de las propiedades físicas (demanda de agua, estabilidad de volumen y tiempo inicial de fraguado) y mecánicas (resistencia a compresión y flexión) de los cementos utilizados: i) cemento convencional; ii) cemento con un 25 % de ultra finos de base cerámica procedentes de los RCD (número de patente: ES2512065); y iii) cemento con un 10 % y 25 % de ultrafinos de hormigón procedentes de RCD.

4.2. Análisis de las propiedades fisicas en estado fresco (trabajabilidad, densidad y conendido de aire) y endurecido (densidad y módulos de elasticidad)

4.3. Evaluación de las propiedades mecánicas (resistencia a la compresión, flexión y tracción) en estado endurecido.

4.4. Cumplimiento de los requisitos físicos y mecánicos recogidos en la actual Instrucción del Hormgión Estructural (EHE-08) y Eurocodigo 2-Proyectos de Estructuras de Hormigón.

4.5. Análisis estadísticos de todos los resultados evaluando la influencia de los factores (porcentaje de árido reciclado y tipo de cemento).

OBJETIVO 5: Estudiar el comportamiento durable y propiedades térmicas de los nuevos hormigones reciclados diseñados mediente la sustitución parcial y/o total de árido grueso y/o cementos que incorporan parcialmente RCD como adición:

5.1 Análisis de las principales propiedades relaciones con el transporte de fluidos en hormigones evaluando la resistividad eléctrica, permeabilidad de agua bajo presión, absorción de agua total, porosidad accesible al agua y absorción de agua por capilaridad.

5.2 Predecir el comportamiento a lo largo de la vida útil de estos nuevos hormigones.

5.3 Análisis estadísticos de todos los resultados evaluando la influencia de los factores (porcentaje de árido reciclado y tipo de cemento) en las propiedades de transporte de agua relacionadas con la durabilidad de los nuevos hormigones.

5.4 Evaluar la conductividad térmica y calor específico de los nuevos hormigones reciclados con un menor contenido en recursos naturales.

OBJETIVO 6: Estudiar el comportamiento a fatiga de los nuevos hormigones reciclados diseñados mediente la sustitución parcial y total de árido grueso y la incorporación parcial de árido grueso mixto y/o un 25 % de ultra finos de base cerámica como adición al cemento.

6.1. Evaluar el comportamiento fatiga resonante en hormigones estructurales fabricados con áridos gruesos reciclados mixtos y/o cemento con un 25 % de ultra finos de base cerámica procedente de los RCD.

6.2. Establecer correlaciones entre el límite de fatiga y la evolución de la frecuencia de fatiga en resonancia durante pruebas Locati.

OBJETIVO 7: Estudiar el comportamiento de piezas prefabricadas de hormigón que incluyen en su formulación áridos reciclados mixtos y cemento con un 25 % de ultrafinos de base cerámica.

7.1 Análisis de las propiedades mecánicas (resistencia a compresión) y elásticas (módulos de elasticidad) y permeables (permeabilidad al oxigeno) de los hormigones fabricados con estos materiales reciclados.

7.2 Evaluar las propiedades mecánicas de las piezas de hormigón fabricadas con los materiales reciclados comprobando su viabilidad técnica.

7.3 Realización de ensayos de acuerdo con lo establecido en las normativas correspondientes a las piezas prefabricadas.

Capítulo 4

Effect of Recycled Aggregate on Performance of Granular Skeleton

Capítulo 4

Effect of Recycled Aggregate on Performance of Granular Skeleton

Resumen

La valorización integral de los residuos de la construcción y demolición (RCD) representa uno de los principales retos de las sociedades modernas, siendo en la actualidad poco frecuente el empleo simultáneo de todas las fracciones granulométricas resultantes del proceso de gestión de los RCD. En aras de aumentar el conocimiento científico-técnico de la aplicabilidad de estos residuos, independientemente de su naturaleza, es necesario conocer las prestaciones del esqueleto granular constituido por los áridos convencionales y áridos reciclados en distinto porcentaje. El presente trabajo de investigación analiza el efecto que tiene la incorporación parcial de áridos reciclados, de hormigón y mixtos, en las prestaciones finales de la mezcla destinada a la fabricación de hormigones y a la ejecución de capas de firme de carreteras. Inicialmente los áridos analizados se caracterizaron desde un punto de vista físico, químico, mineralógico y mecánico evaluando posteriormente las propiedades físicas y mecánicas de las mezclas, y estableciendo correlaciones que permiten predecir el porcentaje óptimo de mezcla. Los resultados indican que independientemente de la naturaleza y tamaño de estos áridos reciclados cumplen mayoritariamente las prescripciones exigidas por la normativa nacional (EHE-08 y PG-3) y otras recomendaciones internacionales. Asimismo, las mezclas mostraron una fuerte correlación lineal entre las propiedades analizadas y el porcentaje de sustitución de los áridos reciclados, fijando como límite superior un 75 % de áridos reciclados de hormigón (ARH) y áridos reciclados mixtos (ARM) para el diseño y fabricación de hormigones y un 75 % de ARH y un 35 % de ARM para la construcción de capas base e intermedia en carreteras con intensidad media/baja de tráfico.

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Effect of Recycled Aggregate on Performance of Granular Skeleton

by B. Cantero, I. F. Sáez del Bosque, A. Matías, M. I. Sánchez de Rojas, and C. Medina

A full understanding of the characteristics of the granular skeleton comprising different percentages of conventional and recycled aggregates is requisite to the reusability of construction and demolition waste. This study analyzed the effect of partially replacing natural aggregate with recycled concrete (RCA) and mixed (RMA) aggregates on the performance of granular mixtures. Each type of aggregate was characterized physically, chemically, mineralogically, and mechanically, and the physical and mechanical properties of the mixtures were assessed. Correlations were established to predict the optimal mixture proportions. The recycled aggregates analyzed met most requirements laid down in the national legislation and complied with international recommendations. The mixtures exhibited a close linear correlation between the properties analyzed and the recycled aggregate replacement ratios. For concrete, the upper limit was 75% for RCA and RMA, and for the base and intermediate layers in medium/low traffic roads, 75% for RCA and 35% for RMA.

Keywords: construction and demolition waste (C&DW); optimal percentage; performance; recycled concrete aggregate (RCA); recycled mixed aggregate (RMA).

INTRODUCTION

The development of new construction materials that are potentially more eco-sustainable, consume fewer natural raw materials, and lower greenhouse gas emissions is attracting growing interest. Construction and demolition waste (C&DW) is one of Europe's heaviest waste flows, at 800 million tonnes/year,[1] while the United States generates approximately 534 million tonnes/year and China around 200 million tonnes/year.[2] This waste could be viably reused to manufacture high-quality construction materials.[3] Raising the recycling rate of these products, a priority across the European Union,[4] is one of the pillars for the sustainable growth of modern societies and crucial to the institution of a circular economy.[5] In this context, the Waste Framework Directive[6] requires all Member States to adopt the necessary measures to recycle a minimum of 70 weight per cent (wt%) of C&DW materials in 2020. New European policies[7-9] have encouraged innovative techniques and practices to improve the viability of producing new high-quality recycled aggregate (RA).

The construction industry is a large consumer of natural resources, of which natural aggregate (NA), with a worldwide production of nearly 40 billion tonnes in 2014,[10] is no exception. The demand for NA can be lowered by totally or partially replacing NA with RA from C&DW to close construction materials' life cycles. Nonetheless, some of the factors that lower the confidence in RA and limit its use are still in place.[11]

Much research has focused on the potential of C&DW as a new construction material for the manufacture, for instance, of new recycled concrete[11-18] and civil engineering applications road bases,[19-23] sub-bases,[24-27] and pavement.[28-33] Most of these studies explore the characteristics of the end product resulting from the partial replacement of NA with RA. Despite those efforts, a scientific and technical knowledge gap currently exists around the end characteristics of the granular skeleton consisting in the mixture of NA and RA prior to its use as a construction material.

The two primary aims of the present study were: 1) to compare the characteristics of RA to those of NA, analyzing their compliance with national and international specifications on concrete manufacture and road pavements; and 2) to determine the effect of different proportions of RA in mixtures with NA on product density, water absorption, resistance to fragmentation, and deterioration. This research will contribute to the full understanding of the effect of RA on the performance of NA+RA granular mixtures, helping to determine the aptness of such new materials for use in the construction industry.

RESEARCH SIGNIFICANCE

This paper makes a significant contribution to the study of the viability of using all the particle size fractions of recycled concrete and mixed aggregate sourced from construction and demolition waste in concrete and road pavement manufacture. It includes a discussion of the comprehensive analyses conducted on each type of aggregate to determine its physical, chemical, mineralogical, and mechanical characteristics. It also includes a description of the correlations subsequently established to predict the physical and mechanical properties of the granular skeleton of a mixture of natural and recycled aggregates based on the individual values of the starting materials.

EXPERIMENTAL INVESTIGATION

Materials

The six RAs used were supplied by a C&DW processing plant in the region of Extremadura (southwestern Spain),

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Table 1—Coarse recycled aggregate constituents (EN 933-11[42] classification)

Class	Type	Amount, wt%					
		RCA-G	RMA-G	RCA-Gv	RMA-Gv	EHE-08[36]	PG-3[37]
Rc	Concrete, concrete products, mortar	42.58	46.98	39.28	43.98	—	—
Ru	Unbound aggregate, natural stone	56.37	44.92	59.90	43.84	—	—
Rc+Ru		98.95	91.90	99.18	87.82	> 95%	—
Rb	Fired clay materials	0.66	7.15	0.73	10.93	< 5%	—
Ra	Asphalt	0.08	0.56	0.00	0.87	≤ 1%	—
FL	Floating particles	0.02	0.17	0.03	0.02	≤ 1%	—
X	Plaster	0.00	0.04	0.00	0.34	—	—
X+Rg	Others and glass	0.30	0.19	0.05	0.02	≤ 1%	—

while the NA was sourced from a quarry in the same region. The six RAs were three recycled concrete aggregate (RCAs) and three recycled mixed aggregates (RMAs).

The particle size fractions were denominated G (12/22 mm [0.472/0.866 in.]), Gv (6/12 mm [0.236/0.866 in.]) and S (0/6 mm [0/0.236 in.]). The nine samples studied were consequently labeled as follows: NA-G, RCA-G, RMA-G, NA-Gv, RCA-Gv, RMA-Gv, NA-S, RCA-S, and RMA-S.

Methodology

The samples were collected as specified in European standards EN 932-1[34] and 932-2.[35] Subsequent laboratory pre-conditioning consisted in drying in an oven at 50°C (122 °F) to a constant mass (for approximately 72 hours).

The chemical composition of the aggregates was determined by X-ray fluorescence (XRF) and its minerology by X-ray diffraction (XRD). XRF scans were performed on a wavelength-dispersive X-ray fluorescence spectrometer using standardless Spectraplus Quant Express software. Mineralogy readings were taken on a X-ray diffractometer fitted with an energy-dispersive one-dimensional detector and an Ni K-beta filter. The X-ray source was a Cu anode X-ray tube (radiation, 1.54 Å CuKα) running at 40 kV and 30 mA.

The following performance parameters were determined in the RA and compared to the reference NA: 1) composition class; 2) geometry (particle size distribution, fineness modulus, sand equivalent, fracture surfaces, and fines content); 3) physical properties (density, water absorption, and flakiness index); 4) mechanical properties (Los Angeles Coefficient and material deterioration); 5) chemical characteristics (water-soluble chloride, acid-soluble sulfate, and total sulfate content); and 6) thermal and weathering behavior (weight loss after five magnesium sulfate cycles). The test findings were compared to the requirements laid down in Section 28 of the Spanish structural concrete code (EHE-08)[36] on aggregate used in concretes and Section 542 of the road construction specifications (PG-3)[37] on aggregate used to manufacture hot mix asphalt (HMA). European recommended methodology was followed.

The effect of the RA replacement ratio (0, 10, 20, 25, 50, 75, and 100 wt%) on the physical (density and water absorption) and mechanical (Los Angeles Coefficient) parameters as well as the compaction behavior (degradation or reduction in particle size) of the granular mixtures was also determined.

A total of 28 samples was prepared by combining the following four mixtures of coarse NA and RA at all seven percentages cited in the preceding paragraph: 1) RCA-G, containing NA-G+RCA-G; 2) RCA-Gv, containing NA-Gv+RCA-Gv; 3) RMA-G, containing NA-G+RMA-G; and 4) RMA-Gv, containing NA-Gv+RMA-Gv.

The effect of RA in the mixtures was studied by calculating the rate of variation (VR = $P_{RA} - P_{NA}$), where P_{RA} is the value for the property in RA and P_{NA} the value for property in NA. Rate of variation was determined as an absolute value, a higher VR meaning that RA had a greater impact on the end mix and vice-versa. The VR value depends on the magnitude of the property studied. For the sake of comparison, the VRs for recycled aggregates prepared by other authors[32,33,38-41] to manufacture structural concrete and pavement layers were also calculated.

EXPERIMENTAL RESULT AND DISCUSSION

Composition of recycled aggregates

Unlike NAs, RAs (and RMAs in particular) are heterogeneous materials, as shown by the data in Table 1 on the composition class of fractions 12/22 mm (0.472/0.866 in.) and 6/12 mm (0.236/0.866 in.). The data also showed that, further to EHE-08[36] criteria, RCA-G and RCA-Gv were concrete aggregates (with the sum of concrete or mortar [Rc] and unbound aggregate/natural stone [Ru] > 95 wt%) and RMA-G and RMA-Gv (with Rc + Ru < 95%) mixed recycled aggregates. Moreover, all the aggregates met the requirements on impurities: asphalt < 1 wt%, floating particles < 1 wt%, and glass < 1 wt%. Spanish legislation only allows the use of coarse RA in structural and non-structural concrete, in which Rc + Ru accounts for 95 wt% and fired clay-based materials (Rb) for less than 5% of the total. More than 5 wt% Rb is allowed, however, in countries such as Germany (DIN 4226-100),[43] Portugal (E471-2006),[44] United Kingdom (Digest 433),[45] and China (DG/TJ07-008),[46] as well as the RILEM recommendations[47] (aggregate type III). Road construction code PG-3[37] specifies no limits for the composition of RAs used in pavement.

Chemical and mineralogical composition of aggregates

The crushed graywacke, a sedimentary rock used as the NA, was sourced from the Schist-Graywacke Complex and

Table 2—Aggregate chemical composition

Aggregate	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	K_2O	TiO_2	P_2O_5	LOI	Others
NA-G	62.36	15.50	6.22	2.77	1.93	3.05	0.15	2.74	0.80	0.19	4.12	0.17
NA-Gv	58.39	17.40	7.32	3.01	1.72	3.05	0.21	3.23	0.85	0.19	3.93	0.70
NA-S	63.30	15.70	5.92	2.66	1.40	3.22	0.10	2.82	0.81	0.22	3.64	0.20
RMA-G	58.21	9.69	2.42	1.93	12.35	1.38	0.42	2.75	0.40	0.10	10.18	0.17
RMA-Gv	57.70	9.84	2.65	1.88	12.62	1.34	0.44	2.72	0.44	0.15	10.03	0.19
RMA-S	48.55	12.30	3.95	2.18	14.25	1.63	1.54	2.49	0.56	0.22	11.93	0.40
RCA-G	64.17	11.30	3.43	1.61	7.15	1.75	0.41	2.75	0.50	0.17	6.58	0.18
RCA-Gv	63.78	11.40	3.38	1.53	7.44	1.70	0.48	2.80	0.53	0.12	6.66	0.18
RCA-S	55.74	15.00	5.95	2.49	6.63	2.53	0.55	2.85	0.68	0.26	7.10	0.21

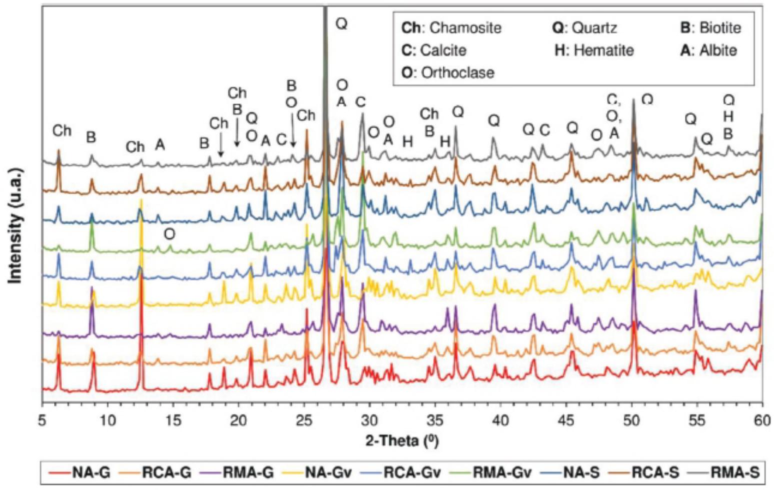

Fig. 1—Aggregate mineralogical composition.

exhibited an uneven morphology with sharp edges. Silica and alumina were the two main chemical composition (>70 wt%) in its composition (Table 2), followed by minority oxides (Fe_2O_3, MgO, Na_2O, and CaO) and trace elements. Quartz, the majority mineral, was found together with feldspars (albite and orthoclase) and phyllosilicates (chamosite and biotite).

The chemical composition of the aggregates in Table 2 shows that the recycled aggregates, irrespective of their nature and particle size distribution, contained primarily silicon oxide (>48.5 wt%), aluminium oxide (>9.7 wt%), calcium oxide (>6.6 wt%), and iron oxide (2.4 wt%), along with minority oxides ((K_2O>MgO>Na_2O>SO_3). The greater loss on ignition (LoI) in RMA than in RCA or NA was attributed to the higher percentage of Rc and Rb fractions present in the former aggregate (Table 1). The small amounts of lime mortar normally present in fired clay material would also raise the LoI in mixed recycled materials.

The values found for SiO_2, Al_2O_3, CaO, and LoI lay within the ranges reported by other authors,[48] who observed mean contents of 66.1% for SiO_2, 11.1% for Al_2O_3, 8.2% for CaO, and an LoI of 9% in these aggregates.

The mineralogical composition of the aggregates analysed is shown in Fig. 1. Irrespective of the nature and size of the recycled aggregates, the majority of their minerals was quartz, followed by feldspars (albite and orthoclase), phyllosilicates (chamosite and biotite), hematites, and a smaller proportion of calcite. These findings were consistent with the mineral phases identified in earlier studies.[49,50]

Geometry and dimensions

Particle size distribution—Further to the curves in Fig. 2 and 3, all the aggregates analyzed had a continuous particle size distribution, a finding directly related to inter-particle interaction, greater compactness, and therefore higher mechanical strength.[53] NA-G, RCA-G, and RMA-G, with a d/D of 10/20 mm (0.393/0.787 in.), were EN 12620[51] category G-85/20 aggregates, whereas NA-Gv, RCA-Gv and RMA-Gv, with a d/D of 5/10 mm (0.196/0.393 in.), were category G_c80/20 materials. Fine aggregates NA-S, RCA-S and RMA-S had a D of 4 mm (0.157 in.) and consequently conformed to category G-85. All the aggregates fell within the range defined by concrete structural code EHE-08[36] for concrete manufacture. The 10/20 mm (0.393/0.787 in.), fractions also complied with the maximum and minimum limits laid down in the Japanese standard (BCSJ 1998)[52] for D = 20. As they were likewise compliant with the D/d > 1.4 requirement recommended in the Spanish structural concrete code,[36] their good fresh and hardened performance was guaranteed. The particle size distribution in all the RAs conformed to road construction code PG-3[37] requirements for use in type AC22 pavements.

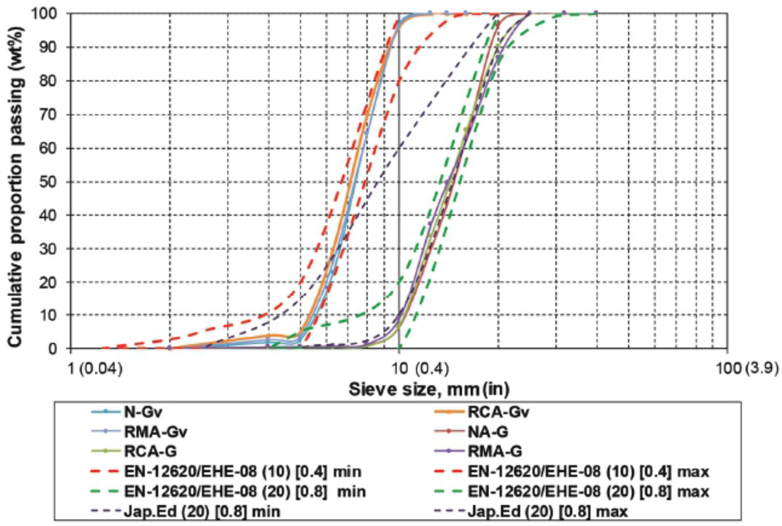

Fig. 2—Coarse NA and RA particle size distribution and recommendations for recycled concrete laid down in EN 12620,[51] EHE-08,[36] and the Japanese standard.[52]

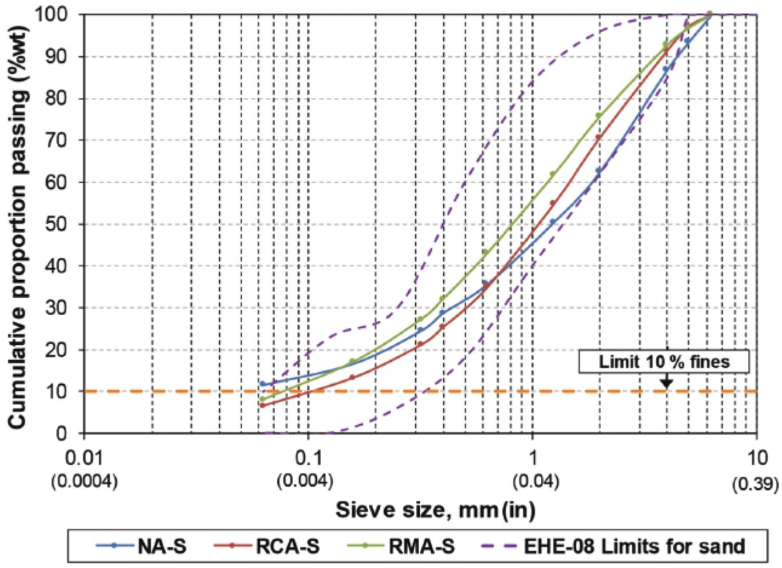

Fig. 3—NA and RA fine particle size distribution (dotted orange line: code EHE-08[36] ceiling [see online version for full-color PDF]).

The fineness modulus ranged from 6.52 to 6.58 in fraction 10/20 mm (0.393/0.787 in.), from 2.94 to 3.17 in fraction 5/10 mm (0.196/0.393 in.), and from 3.53 to 3.81 in fraction 0/6 mm (0/0.236 in.) (Table 3). The values observed were consistent with the findings reported by other authors for maximum sizes of 20 to 25 mm (0.787 to 0.984 in.) (6.2 to 7.6)[54] and 8 to 12 mm (0.315 to 0.472 in.) (3.51 to 3.84).[55] The 0/6 mm (0/0.236 in.) fractions, in turn, lay within the 2.5 to 3.83 range recommended for fine recycled aggregates in a Centre for Public Works Studies and Experimentation (CEDEX) technology transfer report on C&DW valorization.[54]

Fines content—Further to the data in Table 3, the coarse aggregates analyzed were compliant with the EHE-08[36] 1.5% ceiling on fines passing the 0.063 mm (0.002 in.) sieve. The values observed in other studies[54] for coarse C&DW aggregates ranged from 0.27 to 1.14 wt%. The materials studied complied with the 0.5 wt% fines ceiling for coarse aggregate regarded as necessary in code PG-3[37] to guarantee hot mix asphalt layer durability.

Inasmuch as the Spanish structural code[36] does not address the use of recycled sand in the manufacture of structural and non-structural concretes, such sand must meet the same requirements as stipulated for the natural material. The limits set in the standard range from 6 to 16 wt% depending on the type of sand (nature and shape) and exposure class. Natural sand is the product of crushed natural stone, and the recycled sand studied was crushed C&DW with a lower fines content. Having less than 10 wt% (refer to Fig. 2), both RCA-S and RMA-S proved to be apt for the manufacture of exposure class I and II concretes. However, Brazilian standard NBR 15.116[56] does allow the manufacture of non-structural concrete with recycled sand, subject to a 10 wt% limit.

Table 3—Aggregate physical, mechanical, and chemical performance

Property	Standard	Aggregate								
		N-G	RCA-G	RMA-G	N-Gv	RCA-Gv	RMA-Gv	N-S	RCA-S	RMA-S
Maximum size D, mm		20	25	25	10	10	10	6	6	6
Minimum size d, mm		10	10	10	5	5	5	0	0	0
D/d		2.0	2.2	2.2	2.0	2.0	2.0	16.0	16.0	16.0
Particles < 4 mm	EN 933-1[42]	0.36	0.29	0.52	1.88	3.83	2.65	—	—	—
Fines content, wt%		0.00	0.00	0.00	0.00	0.00	0.00	—	—	—
Fineness modulus		6.58	6.55	6.52	3.12	2.94	3.07	11.59	6.50	8.06
Sand equivalent, wt% (0/4 mm fraction)	EN 933-8[57]	—	—	—	—	—	—	66.00	65.00	60.55
Methylene blue (0/2 mm fraction)	EN 933-9[58]	—	—	—	—	—	—	1.30	0.75	0.50
ODD, Mg/m^3	EN 1097-6[59]	2.72	2.48	2.32	2.71	2.37	2.28	2.73	2.73	2.61
SSDD, Mg/m^3		2.74	2.57	2.45	2.75	2.50	2.42	2.76	2.75	2.63
Absorption coefficient, wt%		0.78	3.63	5.27	0.88	5.40	6.28	1.18	4.24	5.39
Los Angeles Coefficient, wt%	EN 1097-2[60]	18	27	36	16	27	32	—	—	—
Flakiness index, wt%	EN-933-3[61]	25	21	10	21	16	10	—	—	—
Degradation particle size, wt %	NLT-370/96[62]	4.21	5.84	6.41	4.88	7.00	8.11	—	—	—
Crushed particles, wt%	EN 933-5[63]	100	97	99	100	100	100	—	—	—
Completely round particles		0.00	0.00	0.00	0.00	0.00	0.00	—	—	—
Resistance to magnesium salts, wt%	EN 1367-2[64]	0.70	0.27	0.53	0.69	0.25	0.52	—	—	—
Water-soluble chloride content	EN 1744-1-7[65]	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Acid-soluble sulfate content, expressed as SO_3	EN 1744-1-12[65]	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	0.011	< 0.002	< 0.002	0.09
Total sulfate content, expressed as S, %	EN 1744-1-11[65]	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.42	< 0.001	0.070	0.36

Note: 1 mm = 0.04 in.; 1 Mg/m^3 = 62.43 lb/ft^3.

Sand equivalent (EA)—Concrete code EHE-08[36] calls for a sand equivalent of over 70 wt% for structures in Class I and II environments and not subject to any specific exposure class, and over 75 wt% for structures exposed to all other types of environments. Road construction code PG-3[37] recommends an EA value greater than 55 wt%.

Table 3 lists the findings for the sand studied. The EA value for sample RCA-S was 65 wt%, for RMA-S 60.55 wt% and for NA-S 66 wt%. Although none of these materials were EHE-08-compliant,[36] they all conformed to the PG-3[37] recommendations for pavements. The values observed were similar to the findings reported (60 to 70%) by other authors.[66,67]

Moreover, where the EA requirement was not met, the fines quality was assessed with the methylene blue (MB) test, which yielded values of 1.30% for NA-S, 0.75% for RCA-S, and 0.50% for RMA-S. Those test results were just barely below the maximum allowed for fine aggregates intended for concrete manufacture.

Proportion of particles < 4 mm (0.157 in.)—As the data in Table 3 show, the percentage of particles under 4 mm in the RA ranged from 0.29 to 3.83 wt%, compared to 0.36 to 1.88 wt% in the NA. All the samples were compliant with the structural concrete code EHE-08[36] 5% ceiling for particles under 4 mm. The Belgian,[68] German,[43] and Japanese[52] standards set ceilings ranging from 10 to 15 wt%.

The proportion of particles passing through a 4 mm screen is usually higher in recycled than in natural aggregate because they may be generated after sieving or even during storage and subsequent transport. Code EHE-08[36] stipulates a disqualified materials content of less than or equal to 10% of the coarse aggregate weight. As the values observed ranged from 0.39 to 5.04%, the aggregates studied were code-compliant in this regard.

Physical performance

Density—As Table 3 shows, density was highest in NA and lowest in RMA (NA>RCA>RMA), a pattern consistent with observations reported by Silva et al.[69] Oven-dried density (ODD) was 2.28 Mg/m^3 (142.3 lb/ft^3) in RMA-Gv and 2.32 Mg/m^3 (144.8 lb/ft^3) in RMA-G, while saturated and surface-dried density (SSDD) was 2.42 Mg/m^3 (151.1 lb/ft^3) in the former and 2.45 Mg/m^3 (152.9 lb/ft^3) in the latter. Those values compare to ODDs of 2.37 Mg/m^3 (147.9 lb/ft^3) in RCA-Gv and 2.48 Mg/m^3 (154.8 lb/ft^3) in RCA-G and SSDD of 2.50 Mg/m^3 (156.1 lb/ft^3)

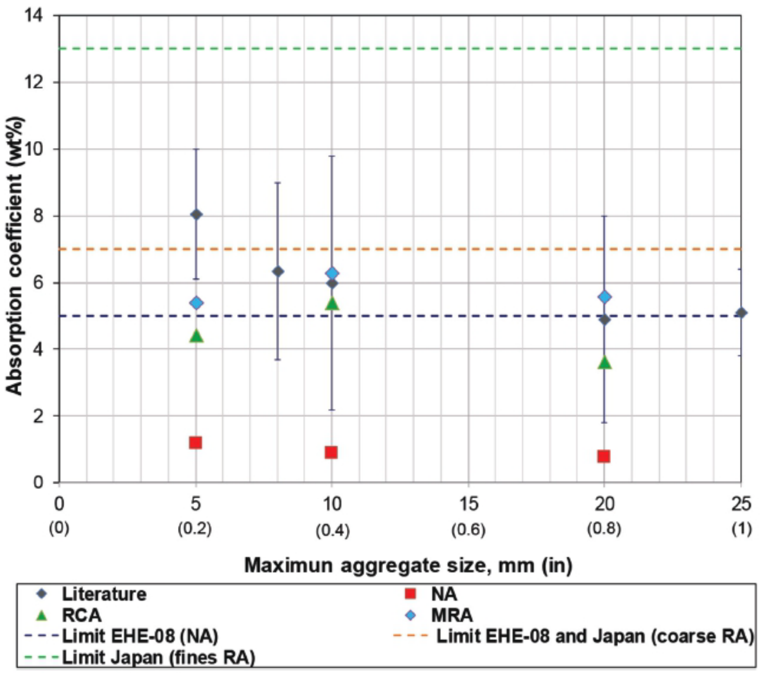

Fig. 4—Absorption coefficient versus maximum aggregate size and recommendations set out in the standards reviewed.

in RCA-Gv and 2.57 Mg/m^3 (160.4 lb/ft^3) in RCA-G. RMA fines, in turn, had an ODD value of 2.61 Mg/m^3 (162.9 lb/ft^3) and an SSDD of 2.63 Mg/m^3 (164.2 lb/ft^3), whereas RCA fines exhibited an ODD of 2.73 Mg/m^3 (170.4 lb/ft^3) and an SSDD of 2.75 Mg/m^3 (171.7 lb/ft^3).

The values recorded for coarse RA were observed to lie in the range reported in the literature of 2.15 to 2.50 Mg/m^3 (134.2 to 156.1 lb/ft^3) for ODD[16,53,69,70] and 2.22 to 2.58 Mg/m^3 (138.6 to 161.1 lb/ft^3) for SSDD.[14,29,69,71] RA fine density, in turn, was slightly higher than reported by earlier authors (2.01 to 2.25 Mg/m^3 [125.5 to 140.5 lb/ft^3] for ODD and 2.27 to 2.43 Mg/m^3 [141.7 to 154.2 lb/ft^3] for SSDD).[69]

German standard DIN 4226-100[43] and RILEM recommendations[47] specify a minimum ODD of ≥2.00 Mg/m^3 (≥124.8 lb/ft^3) for RA containing primarily concrete rubble and ≤10% fired clay materials. Japanese standard JIS A 5022[72] establishes an ODD ≥2.20 Mg/m^3 (≥137.3 lb/ft^3), whereas neither Spain's structural concrete[36] nor its road construction[37] code defines specific limits for RA density.

Water absorption—Sample water absorption is plotted against maximum aggregate size in Fig. 4, which also shows the ceilings laid down in a number of standards. The graph likewise includes the maximum and mean absorption values reported by Gonzalez-Taboada et al.[73] for 152 samples of recycled C&DW aggregate.

Absorption values were lower in NA than in the coarse recycled (RCA and RMA) aggregates due to the intrinsic properties of the mortar attached to and clay constituent in the latter. Other authors[74] reported that RA carrying larger amounts of mortar and clay exhibited higher absorption, due primarily to their greater porosity.

The values observed for recycled sands RCA-S and RMA-S were lower than the 6 to 10% reported earlier.[54]

Spanish structural concrete code EHE-08[36] limits water absorption to ≤4.5 wt% for NA and ≤7.0 wt% for RA. The aggregates studied were EHE-08 compliant, with values of 0.78 to 1.18 wt% for NA and 3.36 to 6.28 wt% for RMA (refer to Table 3). The higher RA water absorption values observed in RMA (Fig. 4) were attributable to its higher fired clay material content (refer to Table 1).

The findings presented herein are similar to the values published in the literature.[71,75] The sands analyzed were also below the 13 wt% water absorption ceiling laid down in the Japanese standard.[52]

Flakiness index—Further to Table 3, the flakiness index for the coarse RAs, irrespective of their nature and maximum particle size, ranged from 9 to 21 wt%—that is, below the 35 wt% maximum stipulated by the existing legislation on coarse aggregates for concrete manufacture[36] and the 25 wt% ceiling laid down in the code[37] for road pavements.

The data showed that under certain conditions natural aggregates NA-G and NA-Gv had flakier shapes than recycled aggregates RCA-G, RMA-G, RCA-Gv, and RMA-Gv, primarily because the mortar attached to the RA tended to round over the sharper edges, a finding also reported by De Juan and Gutiérrez.[76] The RA flakiness indexes found here were consistent with the results reported in the literature.[23,26,41,53]

Crushed and broken surfaces—As a result of C&DW crushing, RA has a large proportion of fracture surfaces.[77] Table 3 shows the fracture surface findings for RA and NA. All the aggregates met the over 90 wt% fracture surface requirement recommended in code PG-3[37] for aggregate used in low traffic load (T3 < 199 heavy vehicles/day) road pavements. As the Gv fractions in the RA and NA had 100 wt% fractures, they could be used for pavements designed to bear heavier traffic. This high totally and partially crushed particle content was closely related to the C&DW crushing process used at the recycling plant.

The recycled aggregates analysed exhibited a higher mean angularity value (85 wt%) than the C&DW and lay within the range observed by other authors.[21,29,31,70,78]

Mechanical performance

Los Angeles Coefficient—The Los Angeles Coefficient provides a measure of coarse aggregate quality: low values denote lower load strain and higher strength. The ceiling for this parameter is set in code EHE-08[36] at 40 wt% and in code PG-3[37] at 25 wt%. The Los Angeles Coefficient abrasion resistance values for the aggregates studied (Table 3) were observed to lie between 16 wt% and 18 wt% for NA and between 27 and 36 wt% for RA, which were therefore EHE-08-compliant (below the 40 wt% ceiling).

In contrast, none of the RAs were road construction code-compliant (<25 wt%). RCA did, however, meet the base layer requirement (<30 wt%). The values observed fell within the range reported in previous literature of 12 to 43 wt% for RMA[11,54,67] and 20 to 50 wt% for RCA.[15,26]

Aggregate degradation—Table 3 gives the aggregate degradation (AD) values for the coarse aggregates analyzed, found as the arithmetic mean of the absolute differences between the percentages retained on pre-defined consecutive sieves before and after compaction. Depending on the particle size fraction, the value found ranged from 4.21 to 4.88 wt% for NA, from 5.84 to 7.00 wt% for RCA, and from 6.41 to 8.1 wt% for RMA. RA underwent greater deterioration than NA during road construction (compaction) and concrete transport and casting. That finding is not detrimental, however, as some authors[30,79] have reported that greater degradation induces a substantial improvement in post-compaction RA resistance to fragmentation, load capacity, modulus of elasticity, and resistance to rutting.

Degradation was greater in RMA than RCA due to the lesser hardness of some of the fired clay-based components (such as brick and block) in the former.

Chemical performance

Water-soluble chloride content—The water-soluble chloride content was under 0.01 wt% in all the aggregates studied, a value below the ceilings established by EHE-08[36] for coarse and fine aggregate, namely 0.05 wt% in reinforced and 0.03 wt% in prestressed concrete. No limitations are stipulated for bulk concrete, although the recommended maximum is 0.15 wt% to prevent possible deterioration in cracking-reduction reinforcement. Code PG-3[37] establishes no limit for this parameter.

Acid-soluble sulfate content—According to the data on acid-soluble sulfates given in Table 3 as a percentage of aggregate weight, RMA-S and RMA-Gv had a higher content (at 0.090 wt% and 0.011 wt%, respectively) than RMA-G, the RCAs and NAs, all of which exhibited values of <0.002 wt%. That finding is directly related to the presence of plaster,[80] which tends to concentrate in the smaller size fractions, in the composition of the mixed recycled aggregate (refer to Table 3).

The values recorded lay below the ceiling specified in code EHE-08[36] (<0.80 wt%) and the Brazilian,[56] German,[43] and Portuguese[44] standards as well as the RILEM[47] recommendations, which set the allowable maximum at 1 wt%.

The values observed were lower than those reported by Bravo et al.,[11] who found SO_3 percentages of 0.1 to 0.8 wt% in RA from construction and demolition waste from different plants.

Total sulfur compound content—The total sulfur compound content (S) given in Table 3 is expressed in weight percent of the dry aggregate. Here also RMA-S (at 0.36 wt%) and RMA-Gv (at 0.42 wt%) had higher values than the rest of the aggregates analyzed (N-G, RCA-G, RMA-G, N-Gv, RCA-Gv and N-S), for which S was under 0.001 wt%.

Those values were below the 1% (by aggregate weight) maximum allowed by code EHE-08.[36] The total sulfur compound values for RCA, in turn, were below the 0.22 to 0.27 wt% observed by other authors[81] for this type of recycled aggregates. The RMA samples, in turn, fell within the 0.15 wt% - 1.70 wt% range reported by Agrela et al.[71] and Bravo et al.[11] for recycled mixed aggregate.

Durability performance

Resistance to magnesium salts—As Table 3 shows, after five magnesium sulfate cycles, the weight loss was 0.70 wt% in NA, 0.27 wt% in RCA, and 0.53 wt% in RMA. Those values are lower than the 18 wt% maximum weight loss allowed by code EHE-08[36] for coarse aggregate in concrete designed to withstand exposure Classes H or F and 15 wt% by code PG-3[37] for wearing courses exposed to winter frost and frequent wintertime viability treatments. The values for RCA lay below and for RMA within the range (0.50 to 21.80 wt%) recommended by CEDEX[54] for recycled aggregates.

Effect of recycled aggregates on mixture properties

Density—SSDD is plotted against the percentage of recycled aggregate in the mixture in Fig. 5, which shows that irrespective of type and fraction, RA density declined linearly with rising replacement ratios. RMA-G and RMA-Gv exhibited a better linear fit than RCA-G and RCA-Gv, although the correlation coefficients for all four was over 0.99. Omary et al.,[82] using experimental data, showed that with R^2 = 0.99, the Voigt model[83] correctly predicted relative density behaviour among granular mixtures. The data observed in this study for SSDD in RMA and RCA supported a perfect fit to the Voigt model, where $SSDD^M$ is defined as follows

$$SSDD^M = SSDD^{RMA\,(or\,RCA)}X_{RA} + (1 - X_{RA})SSDD^{NA}$$

with R^2 values of over 0.99.

The rate of variation (VR) ranged from 0.17 to 0.32 (Table 4) with the RMA mixTURes exhibiting the highest values (RMA-Gv > RMA-G), primarily because that property is closely related to the amount of adhered mortar and fired clay-based materials present in RA (RMA > RCA) (refer to Table 1). These findings are compatible with the range of VR values calculated from data reported in the literature (0.28 to 0.41).[39,71,74]

Absorption coefficient—The water absorption versus replacement ratio graph in Fig. 6 shows that absorption rose

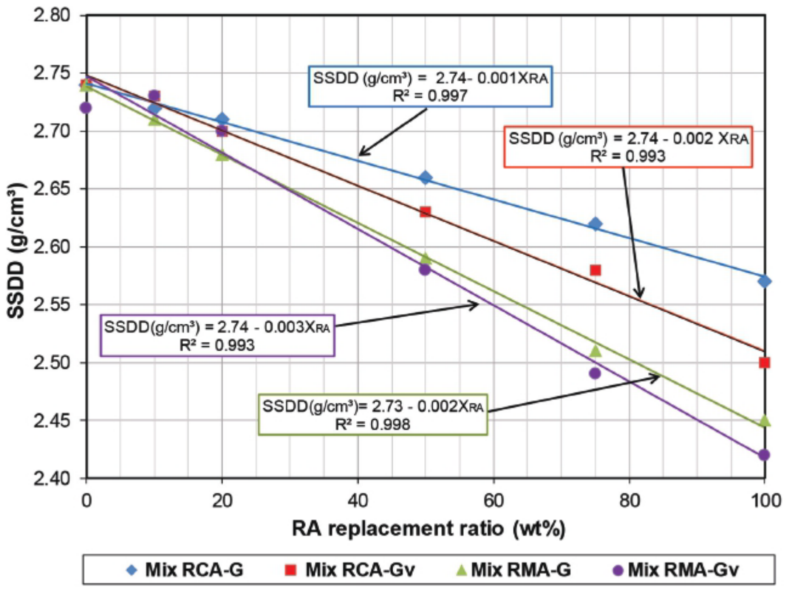

Fig. 5—RA replacement ratio versus SSDD. (Note: 1 Mg/m³ = 62.43 lb/ft³.)

Table 4—Rates of variation for water absorption, density, Los Angeles Coefficient, and aggregate degradation

	Rate of variation (VR)					
	References	Mixture				
Property	VR	RCA-G	RCA-Gv	RMA-G	RMA-Gv	VR_{mixes}
Water absorption, wt%	2.73 to 6.14	2.85	4.62	4.39	5.40	2.85 to 5.40
SSDD, Mg/m³	0.28 to 0.41	0.17	0.24	0.29	0.32	0.17 to 0.32
Los Angeles Coefficient, wt%	6 to 17	9	11	18	16	9 to 18
Aggregate degradation, wt%	—	1.63	2.12	2.2	3.23	1.63 to 3.23

Note: 1 Mg/m³ = 62.43 lb/ft³.

with the ratio, more steeply in the RMA than in the RCA mixtures, due again to the higher mortar and fired clay-based material present in the former.

The closest linear fit was obtained for the RMA mixtures (RMA-G and RMA-Gv), with correlation coefficients of over 0.99, compared to R^2 of 0.96 for the RCA mixtures (RCA-G and RCA-Gv).

The rate of variation ranged from 2.85 to 5.40, depending on the RA and particle size fraction. These values were practically equal to the VR (2.73 - 6.14)[39,71,74] calculated from data in the literature. The VR for the RMA-G experimental findings was 1.5-fold higher than for RCA-G and the RMA-Gv value was 1.2-fold higher than the RCA-Gv rate.

Further to the specification laid down in code EHE-08[36] for concretes with over 20 wt% of RA in the NA/RA mixture, the water absorption coefficient must be ≤5 wt%. Based on code EHE-08[36] criteria and in light of the water absorption values in Fig. 6, 100 wt% RCA-G, 75 wt% RMA-Gv and up to 90 wt% RCA-Gv and RMA-G could be used to replace NA in concrete manufacture.

Table 5 lists the linear regression equations that relate water absorption to SSDD for each mixture type and replacement ratio. The findings revealed a decline in water absorption at higher SSDD values, although the difference was smaller in the RMA mixtures. The linear relationship ($R^2 > 0.94$) between these two physical properties (water absorption and SSDD) was not altered with the inclusion of the new recycled aggregates.

Los Angeles Coefficient—The effect of RA on the Los Angeles Coefficient is shown in Fig. 7. All the mixtures exhibited a good linear fit, with a LA coefficient rising with the RA replacement ratio. The rate of variation (VR) in the mixture ranged from 9 for RCA-G to 18 for RMA-Gv, compared to values of 6 to 17 calculated from data in the literature. The findings in Fig. 7 show that the RMA mixtures were the most sensitive to increases in RA.

Code PG-3[37] recommendations limit the Los Angeles Coefficient to 25 wt% for aggregate to be used in base and intermediate pavement layers in traffic category T2 (>800 vehicles/day) roads or under. According to the graph in Fig. 7, up to 75% RCA-G and RCA-Gv and up to 35% RMA-G and RMA-Gv could be used in base/intermediate pavement layers on roads with medium/low traffic loads.

Aggregate degradation—The aggregate degradation test can be used to compare known to unknown materials. The effect of RA on mixture degradation depicted in Fig. 8 followed a pattern similar to the behavior observed for the Los Angeles test: the higher the replacement ratio, the greater the degradation in the resulting mixture. The rate of variation ranged from 1.63 to 2.12 for RCA mixtures and from 2.20 to 3.23 for the RMA materials. The effect of RA began to be significant at ratios of 50%, when mean degradation

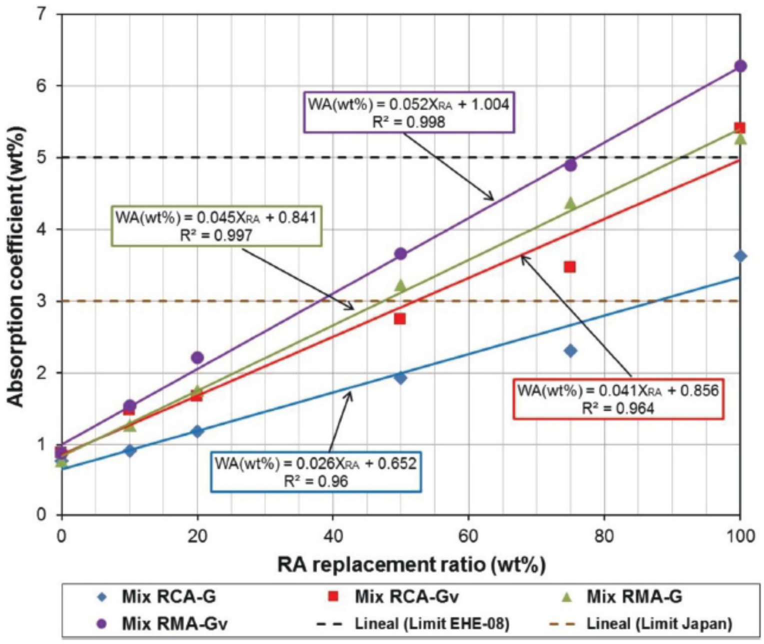

Fig. 6—RA replacement ratio versus water absorption and limits defined in standard EHE-08.[36]

Table 5—Correlation between water absorption and SSDD

Mixture	Linear regression equation	Correlation coefficient
RCA-G	WA (wt%) = 47.35 – 17.04 · SSDD (Mg/m³)	$R^2 = 0.993$
RMA-G	WA (wt%) = 43.28 – 15.50 · SSDD (Mg/m³)	$R^2 = 0.999$
RCA-Gv	WA (wt%) = 50.42 – 17.89 · SSDD (Mg/m³)	$R^2 = 0.937$
MRA-Gv	WA (wt%) = 43.24 – 15.32 · SSDD (Mg/m³)	$R^2 = 0.984$

Note: 1 Mg/m³ = 62.43 lb/ft³.

Table 6—Relationship between Los Angeles Coefficient (LA) and aggregate degradation (DA)

Mixture	Linear regression equation	Correlation coefficient
RCA-G	DA (wt%) = 0.10 + 0.22 · LA (wt%)	$R^2 = 0.938$
RMA-G	DA (wt%) = 1.47 + 0.14 · LA (wt%)	$R^2 = 0.957$
RCA-Gv	DA (wt%) = 1.41 + 0.19 · LA (wt%)	$R^2 = 0.917$
MRA-Gv	DA (wt%) = 2.57 + 0.16 · LA (wt%)	$R^2 = 0.892$

was 22% greater than in NA. At replacement ratios of 25%, mixtures RMA-G, RCA-Gv, and RMA-G exhibited degradation less than 6% higher than in NA. Only the RMA-Gv mixture exhibited degradation 26.5% higher than NA. Table 6 shows the correlation between the Los Angeles Coefficient and the degradation values with increases in RA. The findings exhibited a good linear fit, with R^2 values of 0.89 up to 0.96 (in RMA-G). The findings also revealed a high correlation between aggregate degradation and abrasion resistance.

CONCLUSIONS

The conclusions that can be drawn from the present study are set out as follows:

- The recycled aggregates studied have a low overall impurities content, with asphalt, glass, and plaster each amounting to <1 wt%.
- Recycled mixed aggregates (RMAs) have a higher percentage of fired clay-based material (Rb) and concrete products and mortars (Rc) than the recycled concrete aggregates (RCAs).
- All the aggregates studied have a continuous particle size distribution that lies within the ranges specified by code EHE-08 for concrete manufacture and code PG-3 for road pavements.
- Irrespective of recycled aggregate origin (RCA or RMA), the coarse fractions meet some of the physical (flakiness index and water absorption coefficient), chemical (water- and acid-soluble sulfates and total sulfur compounds), and mechanical (Los Angeles Coefficient) requirements for use in structural concrete manufacture and road pavement construction.
- The fracture surface content and Los Angeles Coefficient test value are the recycled aggregate properties that limit its use in road pavement construction.
- Further to the findings for the recycled and natural aggregate mixtures, RCA and RMA are apt for the design and manufacture of new concretes at replacement ratios of up to 75%. RCA is suitable for base and intermediate layers in roads with medium/low traffic loads also at ratios of up to 75% and RMA can be applied to the latter use at ratios of up to 35%.
- The effects of both recycled concrete and recycled mixed aggregates on recycled+natural aggregate mixture performance parameters are closely and linearly related to the replacement ratio. The experimental findings reveal that saturated surface-dry density, water absorption, Los Angeles Coefficient, and degradation in the end mixtures vary linearly with increasing percentages of recycled aggregate. Those correlations can be used to

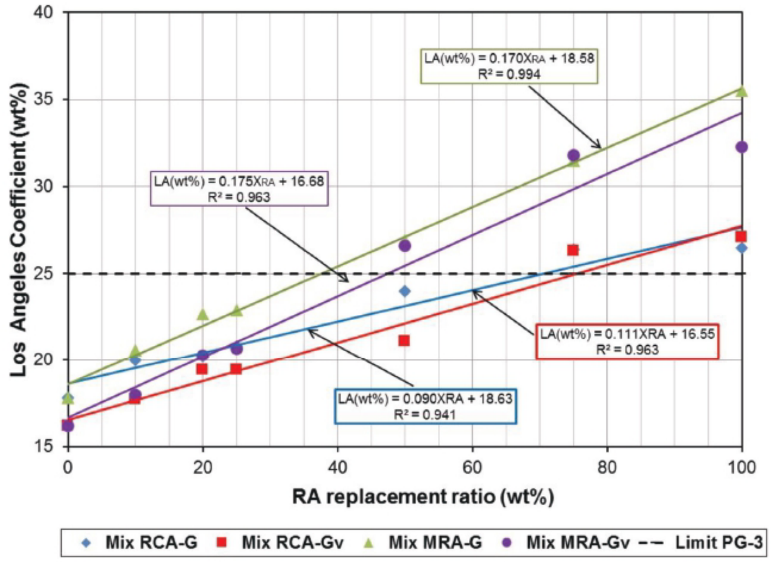

Fig. 7—RA replacement ratio versus Los Angeles Coefficient (LA) and limits defined in standard PG-3.[37]

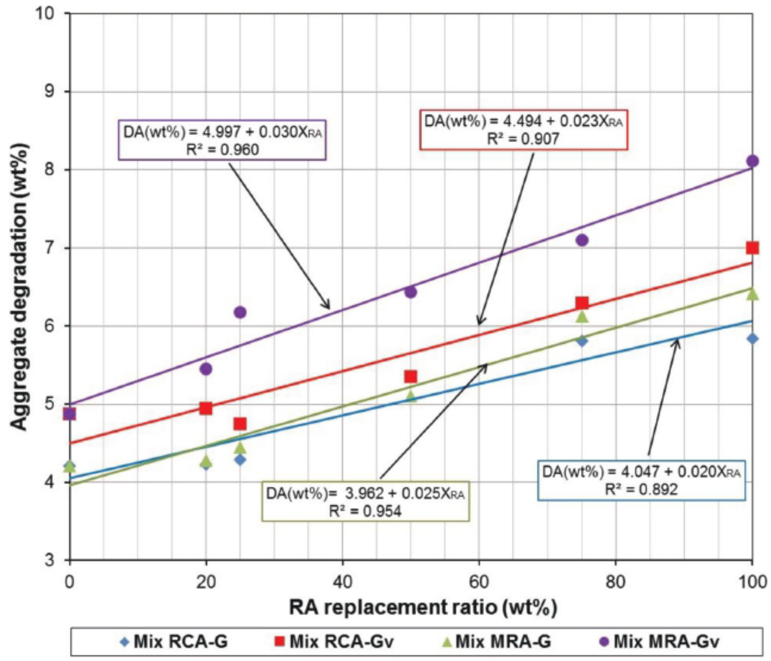

Fig. 8—RA replacement ratio versus aggregate degradation (DA).

estimate the end properties of recycled + natural aggregate mixtures on the grounds of the initial properties of each material taken separately.

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Capítulo 5

Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes

Capítulo 5

Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes

Resumen

Los áridos reciclados mixtos obtenidos del proceso de gestión y reciclaje de los RCD constituyen la mayor fuente de áridos reciclados producidos a nivel mundial. Un uso eficiente y adecuado de estos nuevos recursos ayudará a reducir y hacer frente a los grandes desafíos y problemas medioambientes a los que se enfrentan los actuales modelos de crecimiento económico. Este artículo de investigación tiene como objetivo evaluar las prestaciones de los hormigones estructurales que incorporan distinto porcentaje de sustitución (20 %, 25 %, 50 %, 75 % y 100 %) de árido grueso reciclado mixto. Para ello se estudiaron las propiedades físicas (trabajabilidad, densidad y contenido de aire) en estado fresco y la densidad y las prestaciones mecánicas (resistencia a compresión, resistencia a flexión y resistencia a tracción) en estado endurecido. Posteriormente, los resultados obtenidos se trataron estadísticamente evaluando la influencia de los factores sobre las variables, mediante la realización un análisis de varianza (ANOVA). Resultado de este análisis, se observó que la edad curado y el porcentaje de árido reciclado tiene un efecto estadísticamente significativo. Asimismo, se registró que a medida que aumenta la edad de curado, la reducción de resistencia es menor respecto al hormigón convencional. En hormigones fabricados con hasta un 50 % de árido reciclado se han producido descensos de hasta un 10 % en la mayor parte de las propiedades estudias, incluso a largas edades de curado. Finalmente, indicar que a luz de los resultados obtenidos se puede concluir que los áridos reciclados mixtos empleados en el presente trabajo de investigación pueden ser utilizados en el diseño de hormigones estructurales de una resistencia características igual o superior a 30 MPa.

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Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes

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HIGHLIGHTS

- Structural concretes with mixed recycled aggregate (MRA).
- Fresh concrete properties are not affected by the presence of recycled aggregate.
- The effect of MRA is not statistically significant at replacement ratios ≤50%.
- Compressive strength loss relative to conventional concrete declines with age.
- Replacement of natural with 100% MRA induces losses in mechanical strength of under 19%.

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ABSTRACT

The mixed recycled aggregate obtained from processed construction and demolition waste accounts for the largest share of recycled aggregate produced worldwide. Efficient and appropriate use of these new resources will help reduce and confront the major environmental problems facing today's economic growth model. The research discussed in this paper assessed the performance of structural concretes containing 20%, 25%, 50%, 75% or 100% mixed recycled coarse aggregate, analysing fresh concrete workability, density and air content and hardened concrete compressive, flexural and splitting tensile strength. An analysis of variance (ANOVA) run on the findings to determine the effect of the factors on the variables showed that curing age and percentage of recycled aggregate had a statistically significant impact on concrete performance. The decline in strength relative to conventional concrete was smaller at longer curing ages. Concretes bearing up to 50% recycled aggregate exhibited declines in performance of 10% or under in most of the properties studied, even at late ages. In light of the present findings, the mixed recycled aggregates used in this research may be deemed apt for use in structural concrete with a characteristic strength of up to 30 MPa.

1. Introduction

The construction industry generates large quantities of waste in the erection, demolition, repair and maintenance of buildings and civil works. Theoretically, 80% of construction and demolition waste (C&DW) can be processed to obtain secondary materials usable in new production cycles [1]. The processing and valorisation of new raw materials drives the circular economy model in which products and materials retain their value longer, lengthening their service life [2].

C&DW constitutes an environmental risk, for every year 2 t of such waste is generated per European [2]. The European Commission (EC) deems it a priority waste flow [3], given that it accounts for 34% of the continent's total industrial waste [4], a value only slightly lower than the worldwide figure (~35%) [5]. According to Eurostat, the C&DW recycling and management rate differs substantially across the Union. In Denmark, Germany and the Netherlands nearly 80% of C&DW is reused, whereas the rate in other member countries is closer to 30% [6]. Consequently, the EU's new C&DW management protocol is geared primarily to enhancing confidence in C&DW management processes and product quality [7].

The recycled aggregate resulting from C&DW processing differs in particle size distribution and composition and can be divided into three main categories: recycled concrete aggregate (RCA); recycled masonry aggregate (RMA); and mixed recycled aggregate (MRA). The third accounts for the largest share of aggregate recycled from C&DW [8], constituting around 70% of the total volume in Spain, for instance [9].

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With a view to valorising such waste, in recent years the scientific community has conducted any number of studies on the effect of replacing natural (NA) with recycled C&DW aggregate (RA) on cement-based materials such as concrete [10–19] and mortar [20–22].

Medina et al. [23] observed that concretes bearing coarse aggregate recycled from sanitary ware rejects exhibited 25% higher mechanical strength than the reference and that the use of such waste had no effect on concrete leaching [24]. Pacheco et al. [25] also found compressive strength to be higher in concrete with 30% MRA than in 100% NA concrete. Cachim [26] reported that whilst the use of crushed masonry brick can be used to replace up to 15% of natural aggregate with no strength loss, at 30% replacement concrete performance declined by 20% depending on the type of brick used. Debieb and Kenai [27], in turn, noted that concrete can be made with crushed brick, subject to limiting the replacement of the natural material to 25% in coarse and 50% in fine aggregate.

The use of MRA in the design of structural concrete is not presently addressed in national or international concrete codes and standards, due primarily to the gaps in scientific-technical understanding of performance attributable to a paucity of research. This study aims to contribute to a deeper understanding of the mechanical behaviour of concretes with a granular skeleton comprising 100% mixed recycled aggregate and verify mechanical property inter-relationships, issues not dealt with by the research community to date. Such studies are needed to formulate future standards envisaging the use of this type of recycled aggregate in civil and building construction.

Studies on MRA have been published in the international literature by authors such as: Mas et al. [28,29], who contended that replacement ratios of 20–25% induce declines in strength of <15% in non-structural concrete; Medina et al. [30], who concluded that despite a strength loss of up to 18%, concretes bearing of up to 50% RA are apt for use in housing construction; and Martínez-Lage et al. [9], who noted that compressive strength declined by up to 30% in concrete with 100% MRA.

Mas et al. [28,31] reported that using 75% MRA lowered concrete splitting tensile strength by 21% and flexural strength by 20% relative to concrete with NA, which they attributed primarily to the greater porosity of the masonry in the recycled material. Lovato et al. [31] deemed that the 26% decline in splitting tensile strength observed in concrete with 100% MRA could be ascribed to the brittleness of the recycled relative to the natural aggregate.

Concretes made with MRA are less dense than the conventional materials due to the lower density and higher absorptivity of mortar and masonry [16]. The effect is more intense when the recycled aggregate is used to replace natural sand [6,31,32].

Studies [12,33] conducted on the combined use of RCA and MRA showed that compressive strength was not significantly affected at replacement ratios of up to 75%.

This research explored the feasibility of using 20%, 25%, 50%, 75% or 100% MRA in place of natural coarse aggregate in structural concrete with a characteristic strength of 30 MPa. Consistency and entrained air content were determined in fresh concrete, compressive, splitting tensile and flexural strength in hardened concrete and bulk density in both. The findings were subsequently tested with univariate ANOVA to assess the effect of the factors age and replacement ratio (percentage of MRA) on the response variables.

2. Materials and Methods

2.1. Materials

The natural aggregate used was characterised by an irregular morphology and sharp arris attributable to crushing. Its chemical composition was primarily siliceous, with an SiO_2 content of over 60 wt% and smaller proportions of Al_2O_3, Fe_2O_3, MgO and Na_2O. Quartz, the majority mineral, was found together with feldspars (albite and orthoclase) and phyllosilicates (chamosite and biotite). Three particle size fractions were identified in this aggregate: 22/12 mm (NG-C); 12/6 mm (NG-M); and 6/0 mm (NS).

The recycled aggregate supplied by a C&DW treatment plant in the region of Extremadura (southwestern Spain) had two particle size fractions, 22/12 mm (MRA-C) and 12/6 mm (MRA-M).

The European standard EN 197-1 [34]-compliant CEM I 42.5 R portland cement used was sourced from Lafarge Holcim.

BRYTEN NF, a modified water-base polycarboxylate superplasticiser furnished by FUCHS Lubricantes, was added to the mixes.

2.1.1. Recycled and natural aggregates

In keeping with the composition of the recycled aggregates given in Table 1, and further to Spanish concrete code EHE-08 [35], the MRA-C and MRA-M coarse aggregates were classified as mixed recycled aggregates, for their Rc + Ru was under 95%. They also complied with EHE-08 pollutant ceilings for use in concrete manufacture.

The physical, mechanical and chemical properties of the aggregates are listed in Table 2, which shows that irrespective of their nature they met the requirements laid down in European standard EN 12620 [37] on aggregates for concrete.

Due primarily to their higher porosity, the recycled aggregates had a lower density than the natural materials in all particle sizes. The values were found to lie in the 2.27 Mg/m^3 to 2.53 Mg/m^3 range reported by other authors [12,38]. These aggregates also absorbed more water than the NA, a consequence of the adhered mortar and masonry particles present in the new materials, which exhibited absorption percentages within the range (4.49 –10%) observed by other authors [38–40] for this type of recycled aggregates.

As the adhered mortar tended to smooth its sharpest angles, RA had a lower flakiness index than NA. The recycled materials had a higher Los Angeles coefficient than the NA, likewise due to the adhered mortar and the presence of masonry. Here also the values ranged within the 20–40% reported in the literature for recycled aggregate [38,39,41].

All the RAs studied met the chloride, soluble sulfate and total sulfate content requirements laid down in European standard EN-12620 [37].

2.2. Concrete design

Six types of concrete were prepared for this study: one conventional concrete with natural coarse aggregate (NC) and five concretes bearing 20% (MC-20), 25% (MC-25), 50% (MC-50), 75% (MC-75) or 100% (MC-100) MRA.

Batching was performed as in the British mix approach [46] with the following starting data: concrete 28 d characteristic strength (f_{ck}) = 30 MPa; concrete strength class = 42.5 R; w/c ratio = 0.45; and maximum aggregate size = 20 mm.

The mix proportions resulting from batching are given in Table 3. All the mixes designed complied with the minimum cement and maximum w/c ratio laid down in Spanish structural concrete code EHE-08 [35]. The $(w/c)_{effective}$ ratio was constant across all the mixes to ensure comparability between the performance of the new and the conventional concrete.

Table 1
Coarse recycled aggregate constituents (EN 933-11 [36] classification).

Class	Type	Amount (wt%) MRA-C	MRA-M	EHE-08
Rc	Concrete, concrete products, mortar	46.98	43.98	–
Ru	Unbound aggregate, natural stone	44.92	43.84	–
Rc + Ru		91.90	87.82	>95%
Rb	Fired clay/masonry materials	7.15	10.93	<5%
Ra	Asphalt	0.56	0.87	≤1%
FL	Floating particles	0.17	0.02	≤1%
X	Plaster	0.04	0.34	–
X + Rg	Other and glass	0.19	0.02	≤1%

Table 2
Physical, mechanical and chemical properties of the aggregates.

Property [standard]	Aggregate					
	NS	NG-C	NG-M	MRA-C	MRA-M	EN-12620
SSD density (Mg/m^3) [42]	2.76	2.74	2.74	2.45	2.42	–
Absorption coefficient (wt%) [42]	1.18	0.78	0.88	5.27	6.28	< 5
Los Angeles coefficient (wt%) [43]	–	18	16	36	32	40
Flakiness index (wt%) [44]	–	25	21	10	10	35
Water-soluble chloride content [45]	<0.01	<0.01	<0.01	<0.01	<0.01	0.05
Acid-soluble sulfate content (shown as SO_3) [45]	<0.002	<0.002	<0.002	<0.002	0.011	0.80
Total sulfate content (in % of S) [45]	<0.001	<0.001	<0.001	<0.001	0.42	1

Table 3
Concrete batching.

Concrete	Material (kg/m^3)								
	NS	NG-C	NG-M	MRA-C	MRA-M	Cement	Water	SP	$(w/c)_{ef}$	$(w/c)_{ap}$
NC	732.36	766.69	382.96	0.00	0.00	400.00	193.03	6.20	0.45	0.48
MC-20	720.79	603.66	301.53	146.24	72.60	400.00	200.21	6.20	0.45	0.50
MC-25	720.79	565.94	282.69	182.80	90.75	400.00	202.08	6.20	0.45	0.51
MC-50	705.38	369.22	184.43	357.77	177.62	400.00	210.63	6.20	0.45	0.53
MC-75	693.81	181.58	90.70	527.86	262.06	400.00	219.02	6.20	0.45	0.55
MC-100	678.39	0.00	0.00	688.17	341.65	400.00	226.83	6.20	0.45	0.57

Note. $(w/c)_{ef}$: $(w/c)_{effective}$; $(w/c)_{ap}$: $(w/c)_{apparent}$; SP: superplasticiser.

The process followed to prepared the recycled concretes is summarised in the diagram in Fig. 1.

2.3. Characterisation of fresh and hardened concrete

The physical and mechanical properties analysed in the fresh and hardened concretes are listed in Table 4. The following were prepared per mix and test age: three 150 mm cubic specimens to test for compressive strength, three cylindrical specimens (100 mm ϕ; 200 mm high) to test for splitting tensile strength and three prismatic specimens (100x100x400 mm^3) to test for flexural strength. These specimens were demoulded after 24 h and cured at 100% RH and a constant 20 °C until the test age.

2.4. Statistical analysis

The findings for 28 d bulk density and compressive, splitting tensile and flexural strength were tested for normality with the Shapiro-Wilk [54] procedure. A one-way ANOVA was then run to study the effect of the inclusion of recycled aggregate on those properties. Tukey's honestly significant difference (HSD) test was conducted to establish groups within which the difference in the effect of including recycled aggregate was not statistically significant (equal in-group variance). All the tests were run for a confidence level of 95%, equivalent to a p-value (maximum experiment-wise error) of 5%. The effect of the factors curing time and replacement ratio on concrete compressive strength was also analysed statistically with univariate analysis (ANOVA). IBM SPSS software, version 22, was used for the statistical analyses.

Table 4
Properties studied to characterise concrete.

Property	Standard
Fresh concrete	
Bulk density	EN-12350-6 [47]
Air content	EN-12350-7 [48]
Consistency (slump test)	EN-12350-2 [49]
Hardened concrete	
Bulk density	EN-12390-7 [50]
Compressive strength	EN-12390-3 [51]
Splitting tensile strength	EN-12390-6 [52]
Flexural strength	EN-12390-5 [53]

3. Results and discussion

3.1. Properties of fresh concrete

3.1.1. Workability

Fresh concrete slump, air content and density are given in Table 5. As the data in the table show, the use of recycled aggregate induced no loss in workability, with all five experimental concretes

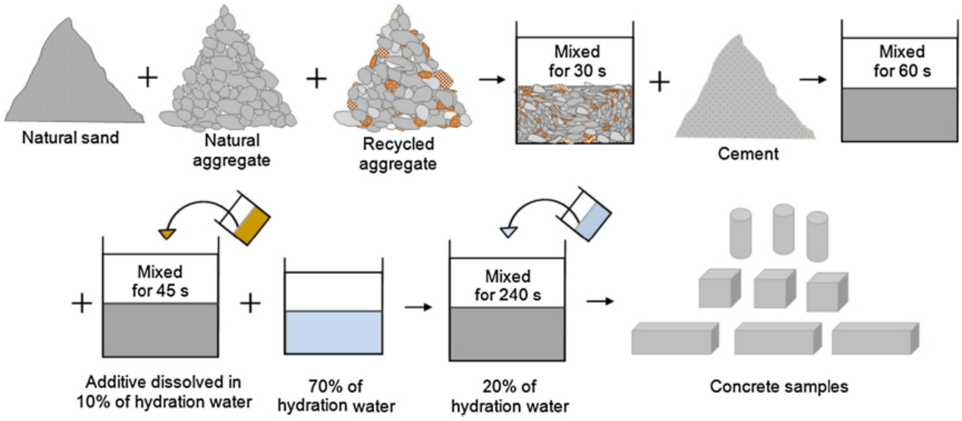

Fig. 1. Concrete preparation.

Table 5
Fresh concrete properties (Std: standard deviation).

Concrete	Property					
	Slump		Air content		Bulk density	
	cm	Std	%	Std.	Mg/m^3	Std
NC	11	1.08	1.9	0.09	2.45	0.01
MC-20	13	1.28	1.9	0.12	2.38	0.01
MC-25	12	1.78	1.8	0.12	2.39	0.00
MC-50	13	2.04	2.2	0.14	2.36	0.01
MC-75	13	2.28	2.5	0.43	2.27	0.02
MC-100	14	2.38	3.0	0.29	2.28	0.02

exhibiting slumps of 12–14 cm. With such values, under Spanish structural concrete code EHE-08 [35] they would be labelled 'fluid' and under Eurocode-2 they would lie in consistency class S3 [55]. Those findings were consistent with results published by Medina et al. [30] and Barbudo et al. [56], who reported that the use of recycled aggregate had no significant impact on concretes with a constant effective w/c ratio.

3.1.2. Bulk density and air content

Further to Table 5, the bulk density for the fresh concretes ranged from 2.45 Mg/m^3 to 2.28 Mg/m^3 and the entrained air content from 1.9% to 3.0%, i.e., a 6.9% decline in density and a 36.7% rise in air content relative to NC.

The graph in Fig. 2 shows that the two properties analysed were directly and linearly related (correlation coefficient, $R^2 > 90\%$) to the percentage of recycled aggregate in the concretes. That was ascribed to the lower dry surface bulk density of the recycled aggregates observed in earlier studies [57] on concretes bearing recycled aggregate. The values observed fell within the range reported by other authors [28,58]: 2.43 Mg/m^3 to 2.30 Mg/m^3 for RCA and 2.43 Mg/m^3 to 2.22 Mg/m^3 for MRA.

3.2. Hardened concrete properties

3.2.1. Statistical analysis

The mean values, standard error and 95% confidence intervals for all the tests conducted on the 28 d concretes are listed in Table 6. The Shapiro-Wilk normality test values for the 28 d hardened concretes are listed in Table 7. All the variables were observed to have skewness- and kurtosis-to-standard error ratios lying within the −2 to +2 range, indicating no significant deviation

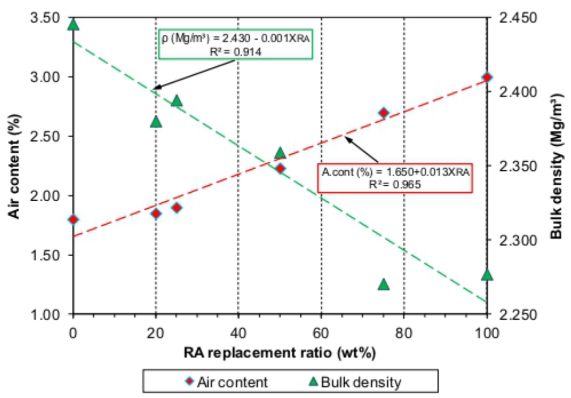

Fig. 2. Fresh concrete air content and density versus percentage of recycled aggregate in concretes.

Table 6
Bulk density and compressive, splitting tensile and flexural strength for the 28 d concretes, with statistical parameters.

Concrete	Mean	Standard error (%)	95% Confidence Interval	
			Lower limit	Upper limit
Bulk density (Mg/m^3)				
RC	2.45	0.36	2.44	2.46
RM-20	2.37	0.03	2.36	2.37
RM-25	2.40	0.61	2.38	2.41
RM-50	2.36	0.92	2.34	2.37
RM-75	2.28	0.19	2.27	2.28
RM-100	2.27	0.55	2.26	2.28
Compressive strength (MPa)				
RC	51.16	12.75	50.91	51.41
RM-20	51.56	81.12	49.97	53.15
RM-25	51.69	45.98	50.79	52.59
RM-50	51.16	41.12	50.35	51.97
RM-75	49.69	69.50	48.33	51.05
RM-100	47.78	35.81	47.08	48.48
Splitting tensile strength (MPa)				
RC	4.08	6.57	3.95	4.21
RM-20	3.51	9.34	3.33	3.69
RM-25	3.41	9.42	3.23	3.59
RM-50	3.51	15.66	3.20	3.82
RM-75	3.38	22.80	2.93	3.83
RM-100	3.59	11.33	3.37	3.81
Flexural strength (MPa)				
RC	6.80	12.44	6.56	7.04
RM-20	6.95	12.96	6.70	7.20
RM-25	6.09	27.04	5.56	6.62
RM-50	6.31	30.17	5.72	6.90
RM-75	5.71	9.62	5.52	5.90
RM-100	5.29	33.98	4.62	5.96

Table 7
Shapiro-Wilk normality test.

Parameter	Property			
	Bulk density (Mg/m^3)	*Compressive strength* (MPa)	*Splitting tensile strength* (MPa)	*Flexural strength* (MPa)
Skewness/standard error	−0.10	−1.23	0.27	−0.74
Kurtosis/standard error	−1.20	−0.11	0.19	−0.78
Shapiro-Wilk p-value	0.088	0.192	0.967	0.241

from a normal distribution [59,60]. Normality for all the properties was further supported by the Shapiro-Wilk p-values, all of which were over 5%.

The findings delivered by the univariate ANOVA conducted on the effect of the factor 'replacement ratio' (percentage of MRA) on the properties studied in the 28 d specimens are listed in Table 8. Further to those findings, this factor explained at least 75% of the variability in the properties studied, except for splitting tensile strength, for which only 11% was explained; and the inclusion of recycled aggregate had a statistically significant (p-value < 5%) effect on most of the variables studied, again with the exception of splitting tensile strength (p-value = 89.4%).

Table 8
Univariate ANOVA results.

Property	Mean squares	F-value	P-value	R^2
Bulk density (Mg/m^3)	14.45	1.72	0.00	98.60
Compressive strength (MPa)	63.87	8.25	0.13	77.50
Splitting tensile strength (MPa)	0.02	0.31	89.40	11.60
Flexural strength (MPa)	1.21	7.55	0.20	75.90

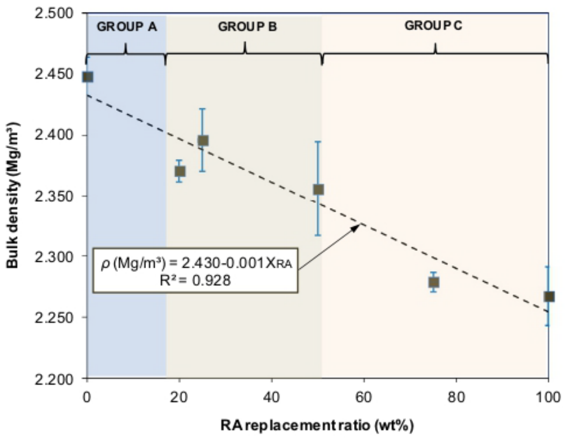

Fig. 3. Bulk density vs replacement ratio and Tukey's HSD groupings.

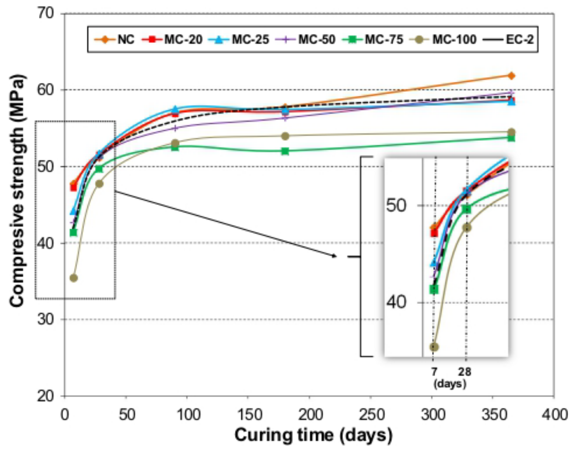

Fig. 4. Concrete compressive strength over time.

3.2.2. Bulk density

Hardened concrete bulk density is plotted against the replacement ratio for the 28 d materials in Fig. 3. The graph shows that this property declined linearly (R^2 = 0.928) with rising percentages of recycled aggregate due to the lower density of these relative to the natural materials (see Table 2). The 7.4% downturn observed for MC-100 relative to NC was slightly higher than the range (5.0–3.3%) recorded by earlier authors [58,28,38] using up to 100% recycled [58] and mixed [28,38] aggregate in concrete. That value was nonetheless consistent with the percentage found by Medina et al. [16,61] (with a correlation coefficient of over 0.91) for concretes containing recycled clay-based and mixed aggregate at replacement ratios of less than or equal to 50%. The values obtained were observed to lie within the range (2.45 Mg/m^3–2.27 Mg/m^3) reported by other authors [9,30,62] working with mixed recycled aggregate.

Fig. 3 also shows the three groups identified by the HSD multiple range tests for hardened concrete bulk density (in which the means were not significantly different, p-value > 5%): group A (p-value = 100%), conventional concrete; group B (p-value = 63.70%), concretes with up to 50% recycled aggregate (MC-20, MC-25 and MC-50); and group C (p-value = 39.40), concretes with a replacement ratio of over 50% (MC-75 and MC-100). Bulk density declined by 3.1% in group B and 4.2% in group B relative to group A.

3.2.3. Compressive strength

The concrete compressive strength - time curve in Fig. 4 shows that irrespective of the type of concrete compressive strength rose with curing age, almost in parallel with the conventional concrete and as specified in standards EHE-08 and EC-2 (see Table 9); and 28 d mean strength was higher than the 30 MPa design characteristic strength, indicating that these concretes are apt for structural use (see Table 6). Cylindrical (15x30 cm^2) specimens would likewise be compliant, although the nominal values would be lower than the 15x15x15 cm^3 cubic specimen experimental values, inasmuch as pursuant to the Spanish structural concrete code [35] conversion consists in applying a correction factor of 0.90. The inference drawn from that finding is that no component in the recycled aggregate interacted adversely during cement hydration. That good behaviour, attributable to the microstructural similarity (microelastic properties and thickness) between the new mixed recycled aggregate constituent/paste interfaces (ITZs) and the natural aggregate/paste interfaces, was consistent with the findings reported by Otsuki et al. [18], Medina et al. [40] and Sáez del Bosque et al. [63].

Table 9
Concrete compressive strength relative to the 28 d value.

Concrete	Curing time (days)				
	7	28	90	180	365
NC	0.93	1.00	1.11	1.13	1.21
MC-20	0.92	1.00	1.10	1.11	1.14
MC-25	0.86	1.00	1.11	1.11	1.13
MC-50	0.83	1.00	1.04	1.10	1.17
MC-75	0.83	1.00	1.06	1.09	1.12
MC-100	0.74	1.00	1.11	1.11	1.14
EC-2	0.82	1.00	1.09	1.13	1.16

Further to the figure, 28 d performance loss relative to NC was practically nil at replacement ratios of under 50% and only 7% for MC-100. These findings were consistent with the 5% decline recorded by Bravo et al. [6] for recycled aggregate with a similar composition. The pattern observed concurred with earlier findings [6,28,64] on compressive strength development in up to 180 d recycled concretes made with C&DW-sourced aggregates of varying compositions.

Table 9 gives the relative compressive strength of the 7 d, 90 d, 180 d and 365 d experimental concretes relative to the 28 d value. The data showed that as a rule, strength gain was very similar in the recycled and conventional concretes. All the concretes except MC-100 exhibited 7 d strengths over 83% higher than at 28 d and therefore higher than the 82% estimated by EHE-08 and EC-2 for rapid hardening concretes and higher than the 70% assumed for unadditioned portland cement concretes with a water/cement ratio of around 0.45 [65].

That pattern was consistent with the range of values (0.65–0.93) observed by Bravo et al. [6] for recycled concretes made with C&DW. Strength was observed to grow more slowly at late (>90 d) than early ages, although after 365 d the values were at least 12% greater than after 28 d.

Further to the multiple range HSD findings for 28 d compressive strength shown in Fig. 5, there were no significant differences in the means for the concretes with recycled aggregate containing up to 50% recycled aggregate. Two groups with equal variances were identified: group D (p-value = 18.80); and group E (p-value = 15.10). These findings concurred with those reported by Poon et al. [10], Gomes et al. [12] and Lofty et al. [66], who observed that replacing small percentages of natural with recycled aggregate had no significant effect on concrete compressive strength.

Further to the graph in Fig. 6 plotting 28 d compressive strength against hardened concrete density, both normalised to the MRA

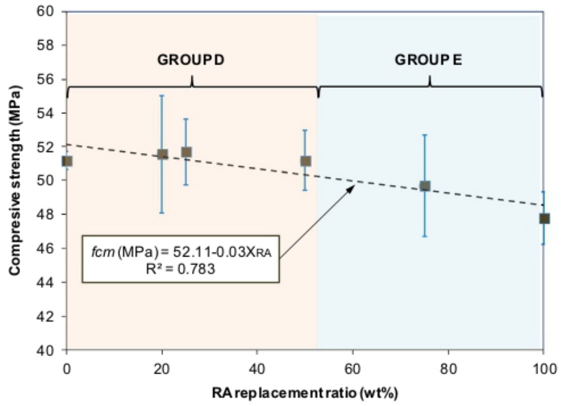

Fig. 5. 28 d compressive strength and Tukey HSD groupings.

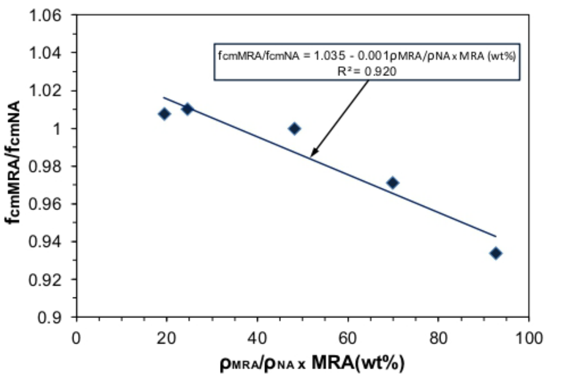

Fig. 6. Concrete compressive strength vs concrete density, both normalised to the MRA replacement ratio.

content (wt%), the two parameters were linearly related (Equation (1). With a value of 0.92, the determination coefficient (R^2) denoted good correlation between the two properties as the MRA content varied. These findings attested to the dependence of concrete compressive strength on bulk density and the percentage of MRA.

$$f_{cm,MRA} = \left(1.035 - 0.001 \times \frac{\rho_{MRA}}{\rho_{NA}} \times MRA(\%)\right) \times f_{cm,NA} \quad (1)$$

Where $f_{cm,MRA}$ is mean MRA-bearing concrete compressive strength; $f_{cm,NA}$ mean NA-bearing concrete compressive strength, both in MPa; ρ_{MRA} bulk density of MRA-bearing concrete; ρ_{NA} bulk density of the NA-bearing concrete, both in Mg/m^3; and MRA (%) the recycled aggregate replacement ratio in %.

The univariate ANOVA findings on the effect of the factors 'replacement ratio' and 'curing time' on concrete compressive strength listed in Table 10 showed statistical significance (p-value = 0% < 5%). That result was consistent with those of earlier studies [38,58,67].

The statistical model explained 98% of the variability observed, 77% attributable to curing time, 16% to replacement ratio and 5% to the interaction between them. These findings further support the greater impact of curing time than of the presence of recycled aggregate on compressive strength.

3.2.4. Splitting tensile strength

The 28 d splitting tensile strength vales for the recycled concretes are shown in Fig. 7, along with the values estimated with the expression $f_{ctm} = 0.30 \cdot \sqrt[3]{f_{ck}^2}$ set out in EHE-08. The Tukey multiple range HSD results are also shown. All the concretes had splitting tensile strengths greater than or equal to the values proposed in Spanish structural code EHE-08 [35]. The highest losses relative to NC ranged from 3% for MC-75 to 4% for MC-100. These values were smaller than the 12% to 14% observed by other authors [11,67–69] for concretes prepared with 100% recycled aggregates containing from 10% to 14% brick masonry.

The Tukey HSD tests detected homogeneity across the entire sample, referred to here as group F (p-value = 100%), affording proof that splitting tensile strength was not significantly affected by the presence of recycled aggregate. These results were consistent with reports [70,71] according to which splitting tensile strength in recycled concretes is comparable to that of conventional concrete.

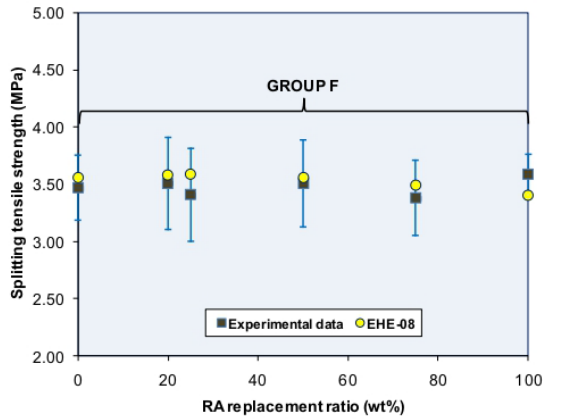

Fig. 7. 28 d concrete splitting tensile strength, code EHE-08 recommended values and Tukey HSD results.

Table 10
Results of two-way univariate ANOVA.

Source of variation	Type III sum of squares	Df	Mean squares	F	p-value
Corrected model	3103.31[a]	29	107.011	129.40	0.00
Intersection	246976.94	1	246976.94	298655.25	0.00
Replacement ratio	504.53	5	100.90	122.02	0.00
Curing time	2427.65	4	606.91	733.91	0.00
Interaction between percentage and curing time	171.13	20	8.556	10.347	0.00
Error	49.61	60	0.827		
Total	250129.87	90			
Corrected total	3152.931	89			

Df: degrees of freedom.
[a] R^2 = 0.984 (corrected R^2 = 0.977)

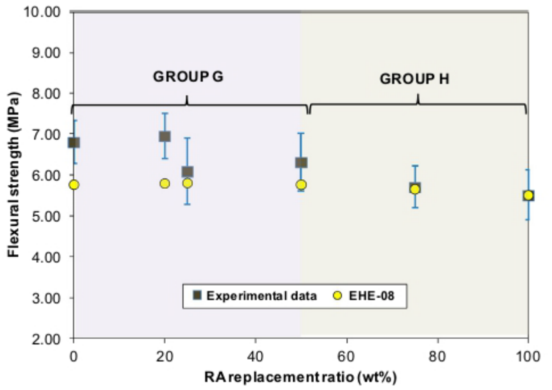

Fig. 8. 28 d concrete flexural strength, code EHE-08 recommended values and Tukey HSD groupings.

3.2.5. Flexural strength

Fig. 8 shows the 28 d flexural strength of recycled concrete and the flexural strength estimated from the expression proposed in EHE-08, $f_{ctm,fl,est} = f_{ctm} \times (1.6 - h/1000)$, where f_{ctm} is as defined in item 3.2.4 and h is specimen height (see Section 2.4). The Tukey multiple range HSD groupings are also shown. All the concretes had flexural strengths greater than or equal to the values proposed in Spanish structural code EHE-08 [35]. Losses in flexural strength were significant only at replacement ratios of over 50%, with declines of 16% in MC-75 and 19% in MC-100. These values were greater than the 14% recorded by other authors [67] for concretes containing up to 100% recycled aggregate consisting in 14% crushed brick. The Tukey HSD test identified two groups with uniform variance: group G (p-value = 16.7%), consisting in concretes with up to 50% recycled aggregate; and group H (p-value = 5.7%) for concretes with replacement percentages of over 50%. As in compressive strength, flexural strength behaviour in recycled concretes with up to 50% recycled aggregate was equivalent to that of conventional concrete. This pattern was observed previously by Senthamari and Manoharan [72] in recycled concrete aggregate and López et al. [73] in recycled masonry aggregate for concretes bearing <50% of the recycled material.

3.2.6. Morphological analysis

Fig. 9 reproduces photographs of thin sections of a conventional concrete (NC, Fig. 9a)) and a concrete with 50% MRA (Fig. 9b)). Both the natural and the recycled aggregate were distributed uniformly across the concrete matrix, an indication that the use of the new materials induced no segregation.

The main constituents of MRA, namely masonry, sanitary ware, unbound aggregate and concrete, can also be seen in Fig. 9b).

The micrograph of the MRA reproduced in Fig. 9c) shows that integration in the concrete matrix was similar in the recycled and natural aggregates (Rn). That good performance was attributable to the tight bond formed between the masonry, concrete and unbound aggregate and the cement matrix, resulting in a consistently compact and continuous interface. These findings corroborated the high mechanical strength observed in recycled concrete as discussed in earlier sections of this paper.

These observations were consistent with the results reported by other authors studying (sanitary ware [74], concrete block [64], concrete [74]) coarse recycled aggregate/paste ITZ properties. None of those studies observed any significant change in the thickness or micro-elastic properties of the new recycled aggregate/paste ITZs.

4. Conclusions

The conclusions that may be drawn from the results of this study are listed below.

- Concrete workability was not adversely affected by the use of 100% mixed recycled aggregate.

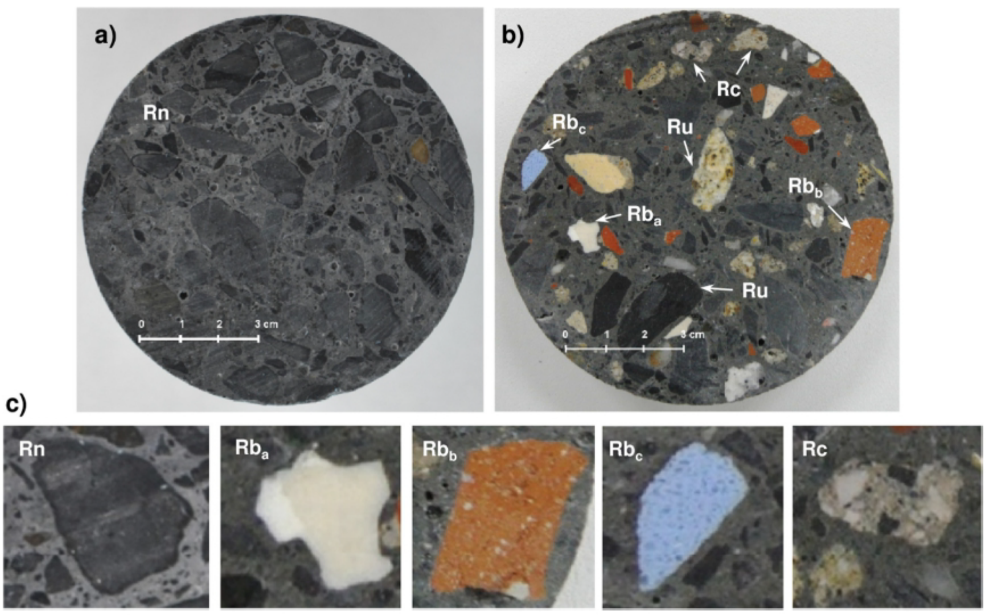

Fig. 9. a) Conventional concrete (NC); b) Concrete with 50% MRA (MC-50); and c) **Rn**: natural aggregate; **Ru**: unbound aggregate; **Rb$_a$**: sanitary ware waste; **Rb$_b$**: crushed brick; **Rb$_c$**: crushed roof tile; and **Rc**: concrete aggregate.

- The higher the replacement ratio, the lower the fresh concrete density and the higher the air content: in MC-100 concrete, density was 7% lower and air content 37% higher than in the reference.
- The statistical study showed density to be the hardened concrete property that varied the most in concretes made with mixed recycled aggregate.
- Neither compressive nor flexural strength varied significantly at replacement ratios of under 50%. At higher percentages, statistically significant differences were observed for both parameters.
- The lower strength (7% compressive, 4% tensile and 19% flexural) in MC-100 than in NC was much smaller than the 100% replacement ratio.
- On the grounds of their mechanical performance, these new recycled concretes would be apt for structural use (f_{ck} > 30 MPa).
- The morphological study revealed close similarity between the recycled aggregate/paste and natural aggregate/paste ITZs.

The present results provide grounds for including this type of aggregate in the existing legislation, a development that would fuel construction and demolition waste recycling. That in turn would help EU Member States comply with their 70% reuse rate target in 2020 and spur introduction of the circular economy in the construction industry.

Conflict of interest

None.

Acknowledgements

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Capítulo 6

Inclusion of construction and demolition waste as a coarse aggregate and a cement addition in structural concrete design

Capítulo 6

Inclusion of construction and demolition waste as a coarse aggregate and a cement addition in structural concrete design

Resumen

Disociar el crecimiento económico del uso de los recursos naturales es imperativo para el desarrollo sostenible de la industria de la construcción. El uso de materias primas secundarias mediante el procesamiento y la gestión de residuos de construcción y demolición (RCD) es uno de los principales desafíos para la transición hacia un modelo de economía circular. Este estudio evaluó el efecto de usar simultáneamente la fracción fina mixta a base de arcilla cocida y el árido reciclado mixto (ARM) ambos procedentes de los RCD en el diseño de hormigones estructurales. Para este fin, se evaluó la trabajabilidad, la densidad y el contenido de aire del concreto fresco y la densidad, resistencia a compresión, flexión y tracción en estado endurecido. Asimismo, se realizaron análisis de regresión y varianza de los todos los resultados para determinar el efecto del ARM, el tipo de cemento y su interacción sobre las variables dependientes. Se observó que el porcentaje de ARM es el determinante más significativo para la densidad del hormigón y el contenido de aire. Los resultados muestran que el porcentaje de ARM es el factor más determinante en la densidad y el contenido de aire de los hormigones. Respecto, a la resistencia a compresión se ve afectada principalmente por el cemento reciclado a edades tempranas, pero si se consideran edades de curado más avanzadas, las resistencias son comprables a las del hormigón fabricado con cemento convencional. El efecto combinado entre el tipo de cemento y el porcentaje de RMA no ha mostrado tener influencia significativa en la resistencia a tracción y flexión. Por el contrario, las diferencias observadas en estas propiedades se debieron al efecto separado de cada factor. Finalmente, los resultados mostraron que el uso de cemento que contiene adiciones de RCD y hasta un 50 % de ARM no comprometió sustancialmente las nuevas prestaciones del hormigón.

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Original Research Article

Inclusion of construction and demolition waste as a coarse aggregate and a cement addition in structural concrete design

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ABSTRACT

Dissociating economic growth from the use of natural resources is imperative to the sustainable development of the construction industry. The use of secondary raw materials by processing and managing construction and demolition waste (C&DW) is one of the major challenges to transition to a circular economy. This study assessed the effect of simultaneously using cement additioned with the ceramic (fired clay-based) fraction of C&DW and recycled mixed aggregate (RMA) in concrete manufacture by analysing fresh concrete workability, density and air content and hardened concrete compressive, flexural and splitting tensile strength. Regression and variance analyses were run on the findings to determine the effect of RMA and cement type and their interaction on the dependent variables. The percentage of RMA was observed to be the most significant determinant for concrete density and air content. Early age compressive strength was impacted by cement type, although strength in the later age materials was comparable to that of concrete manufactured with conventional cement. The combined effect of cement type and percentage of RMA appeared to have no significant effect on tensile or flexural strength. On the contrary, the differences observed in these properties were due to the separate effect of each factor. The findings showed that the use of cement containing C&DW additions and up to 50% RMA did not substantially compromise concrete performance.

1. Introduction

The growing concern over the rise in waste generation, the depletion of non-renewable natural resources and the increasingly severe damage caused by pollution is driving governments the world over to reinforce environmental policies geared to mitigating these problems. One such policy, recycling, reusing and valorising waste as an alternative source of raw materials, is a priority target for sustainable growth in developed societies.

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The construction industry presently consumes 50% of all the natural raw materials extracted, generates up to 40% of anthropogenic waste and emits 30% of all polluting gas (CO_2) [1]. The 859.5 million tonnes of construction and demolition waste (C&DW) generated yearly in the European Union (EU) alone [2] constitute the largest flow of discarded materials Europe-wide. That waste contains around 54% by volume of fired clay-based, also called ceramic, materials [3]. Many EU countries are striving to reach 70% valorisation of such waste by 2020 [4]. According to the latest European Commission report [5], 20 Member States claim to have already met that goal, although their data may include materials used in landfills to regenerate the landscape in excavated areas or for landscape engineering, activities that form part of the objective. Nonetheless, such practices neither maintain the value of those materials in the economy nor contribute to the circular economy, an essential vehicle to meeting the Agenda 2030 Sustainable Development Goals [5]. The industry is nonetheless transitioning to more sustainable development to balance economic growth, the environment and social welfare. For decades, under the leadership of cement and concrete manufacturers, it has mined industrial waste, including C&DW, for alternative raw materials to be used either as additions in cement or aggregate in concrete.

C&DW is presently processed at management plants that produce so-called recycled aggregate. Depending on their content, these materials are classified as recycled concrete aggregate (RCA), recycled ceramic aggregate (CA) or recycled mixed aggregate (RMA). RCA has been widely researched in recent years to determine the viability of its reuse in the construction industry, in particular in connection with concrete manufacture [6]. The consensus opinion in the scientific community, reached on the grounds of the many studies conducted on its potential as a coarse aggregate in structural concrete, is that at replacement ratios of up to 30% it does not compromise the performance of the resulting new material. Thanks to that research, RCA can now be employed as coarse aggregate in structural concretes calling for a compressive strength of under 30 MPa. Many national building codes and standards across Europe, as well as in Australia and China, provide for the use of this new crushed concrete aggregate at replacement ratios ranging from 20% to 60% [7].

Much less is known about CA (fired clay-based materials such as brick, roof tile, block and sanitary ware) and RMA, due to the heterogeneity of these materials, RMA in particular. The number of studies in the international literature on the use of RMA in concrete is small compared to the research on RCA, despite the volume of such waste, which in countries such as Spain amounts to 70% of the total C&DW [8]. Cantero et al. [9] found that neither compressive nor flexural strength varied significantly at replacement ratios of under 50%. Medina et al. [10] concluded that while exhibiting 18% lower strength than conventional concrete, materials with up to 50% RMA are apt for use in building construction. Martínez-Lage et al. [8] likewise observed a decline in compressive strength equal to the RMA replacement ratio (30%). In contrast, Mas et al. [11] reported that in concretes manufactured with up to 25% replacement, compressive and tensile strength were just ≤15% lower than in conventional concrete.

The cement industry, in turn, has spied an opportunity in C&DW valorisation as additions, another innovative line of international research that has been scantly exploited to date. The present authors found that new cements containing 10% or 20% C&DW exhibited optimal calorimetric and rheological performance. In a similar vein, Asensio et al. [12] assessed the durability, strength and calorimetric behaviour of cements containing 10–30% ceramic waste. Their satisfactory results served as a basis for the award of two patents (Sánchez de Rojas et al. [13,14]).

Moreover, in recent years the desire to improve the performance of recycled aggregate concrete has driven interest in the effect of the simultaneous use of supplementary cementitious materials (SCMs) such as fly ash (FA), silica fume (SF) and granulated blast furnace slag (GGBS), and RCA [15,16]. The growing use of SCMs has encouraged some researchers to seek new, more economically sustainable sources of such materials. Some have studied the joint use of thermally activated cement dust [17] or even ground brick [18] with aggregate produced by crushing concrete debris. The findings showed that 20% RCA and 5% thermally activated cement or 30% RCA and 15% ground brick can be used simultaneously with no significant loss in later age concrete mechanical strength.

The originality of the present study lies in the exploration of the simultaneous valorisation in new concretes of C&DW as coarse recycled mixed aggregate and its mixed ceramic fraction as an SCM in low-clinker cement design, an unprecedented approach that would fuel scientific progress and constitute a major advance in the management and valorisation of such waste. Adittionally, the reuse of such waste is not addressed in the legislation on structural concrete manufacture, which restricts recycled aggregate to crushed concrete, envisaging replacement ratios of 20%, 25%, 30% or 60% depending on the country. Specifically, it analyses the effect of the joint use of cement with 25% ceramic C&DW [34] and RMA from C&DW to partially (25% and 50%) replace the natural coarse aggregate in structural concrete. The consistency, entrained air content and bulk density of fresh concrete, along with the colour, bulk density and compressive, tensile and flexural strength of hardened concrete are determined. A univariate analysis of variance (UNIANOVA) is applied to the findings to assess the effect of RMA percentage and cement type and a combination of the two on the response variables analysed.

2. Materials and methods

2.1. *Materials*

2.1.1. *Cement*

The concretes were manufactured with 100% conventional 42.5 R unadditioned portland cement (CEM I 42.5 R) supplied by a Lafarge Holcim group cement plant located in the Spanish province of Toledo or with 75 wt% of that cement and 25 wt% of the ceramic fraction of construction and demolition waste (CEM-25CDW). The latter product, classifiable as 42.5 MPa CEM II/B or CEM/IV cement, is registered under patent No. ES2512065.

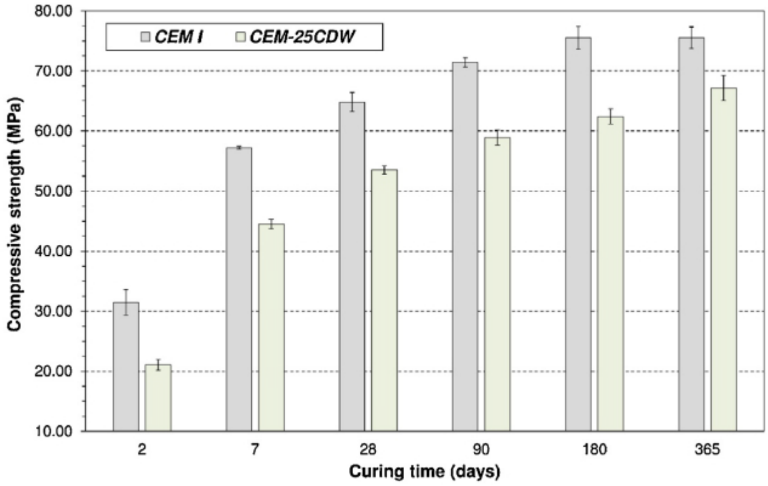

Fig. 1 – Mechanical strength of the cements used in concrete preparation.
Both binders also met the sulfate, chloride and insoluble residue content, loss on ignition, soundness and initial setting time requirements established in EN 197-1 [19].

Further to X-ray fluorescence (XRF) analysis, the oxides present in cement CEM-25CDW included: SiO_2: 31.30%; Al_2O_3: 8.26%; Fe_2O_3: 3.24%; CaO: 48.99%; MgO: 2.86%. SO_3: 2.43%; Na_2O: 0.51%; K_2O: 1.58%; TiO_2: 0.35%; P_2O_5: 0.19%.; and Cl: 0.040%; loss on ignition was 2.66%.

The recycled powder used as an SCM consisted primarily in SiO_2 (59.63%), Fe_2O_3 (5.92%), CaO (4.78%) and <4% each of SO_3, Na_2O and K_2O [3]. At 35.1%, the reactive silica content was higher than the 25% required by Spanish and European standard UNE EN 197-1 for natural pozzolans.

Further to the data on compressive strength of the mortars made with these cements shown in Fig. 1, both binders met the mechanical strength requirements laid down in European standard EN 197-1 [19] for 2 d and 28 d 42.5 R cements. The figure also shows that strength gain was slower in the new than in the conventional cement due to the pozzolanicity of the addition, studied by Asensio et al. [3,12].

2.1.2. *Superplasticiser*

BRYTEN NF, a modified water-base polycarboxylate superplasticiser furnished by FUCHS Lubricantes, was added to the mixes. This brownish, chloride-free admixture has a solids content of 20%, a density of 1.1 g/cm^3 and a pH of 8.0.

2.1.3. *Aggregates*

The recycled aggregate was supplied by a C&DW processing plant in Extremadura (western Spain). The two fractions supplied, 12/22 mm and 6/12 mm, were respectively labelled RMA-1 and RMA-2. The natural crushed siliceous aggregate consisted in three particle size fractions: natural sand (NS, 0/6 mm), natural gravel 1 (NG-1, 12/22 mm) and natural gravel 2 (NG-2, 6/12 mm).

The coarse aggregate particle size distributions and the maximum and minimum ranges set out in EN 12620 [20] for concrete aggregate are shown in Fig. 2 All the materials used

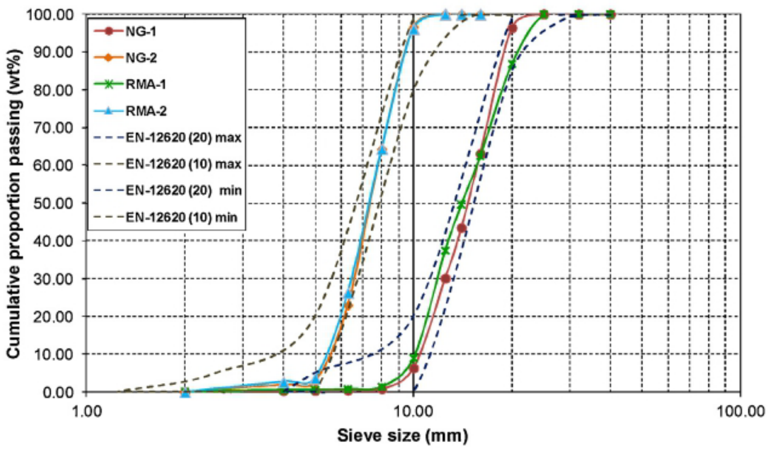

Fig. 2 – Particle size distribution of coarse aggregates and EN 12620 [20] allowable ranges for use in concrete.

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Table 1 – Physical and mechanical properties of the aggregates.

Property [standard]	Aggregate					
	NS	NG-1	NG-2	RMA-1	RMA-2	EN-12620 [42]
SSDD (Mg/m^3) [43]	2.76	2.74	2.74	2.45	2.42	–
Absorption coefficient (wt%) [43]	1.18	0.78	0.88	5.27	6.28	<5%
Los Angeles coefficient (wt%) [44]	–	18	16	36	32	40
Flakiness index (wt%) [45]	–	25	21	10	10	35

were well graded and lay within the particle size ranges recommended in EN 12620 [20] for coarse aggregate with maximum sizes of 20 mm or 10 mm. The practically identical particle size distribution in the natural and recycled aggregates ensured that as the granular skeleton would not be modified, it would have no differential effect on end concrete performance.

Table 1 lists the physical and mechanical properties of the coarse recycled aggregates and the provisions in EN 12620 [20] and Spanish Structural Concrete Code (EHE-08) [21] on aggregate used in concrete manufacture. The recycled aggregates had lower saturated surface dry density (SSDD) and higher absorption values than natural aggregates NG-1 and NG-2, due primarily to the presence of bound mortar and ceramic materials. Absorption was 5.3% for RMA-1 and 6.3% for RMA-2, both higher than the 5% ceiling laid down in EN 12620 [20] and EHE-08 [21] for concrete aggregate. The Los Angeles coefficient values, at 32% for RMA-2 and 36% for RMA-1, were higher than the 16–18% range in the natural aggregate, likewise due to the bound mortar and ceramic fraction comprising the RMA, which rendered them more brittle. These values were nonetheless below the 40% ceiling established in EHE-08 [21] and EN 12620 [20] for use in concrete. The flakiness index was higher, at 21% to 25%, in the natural aggregate (NG-1 and NG-2) than in the RMA (10%), although this property is not a boundary condition for using

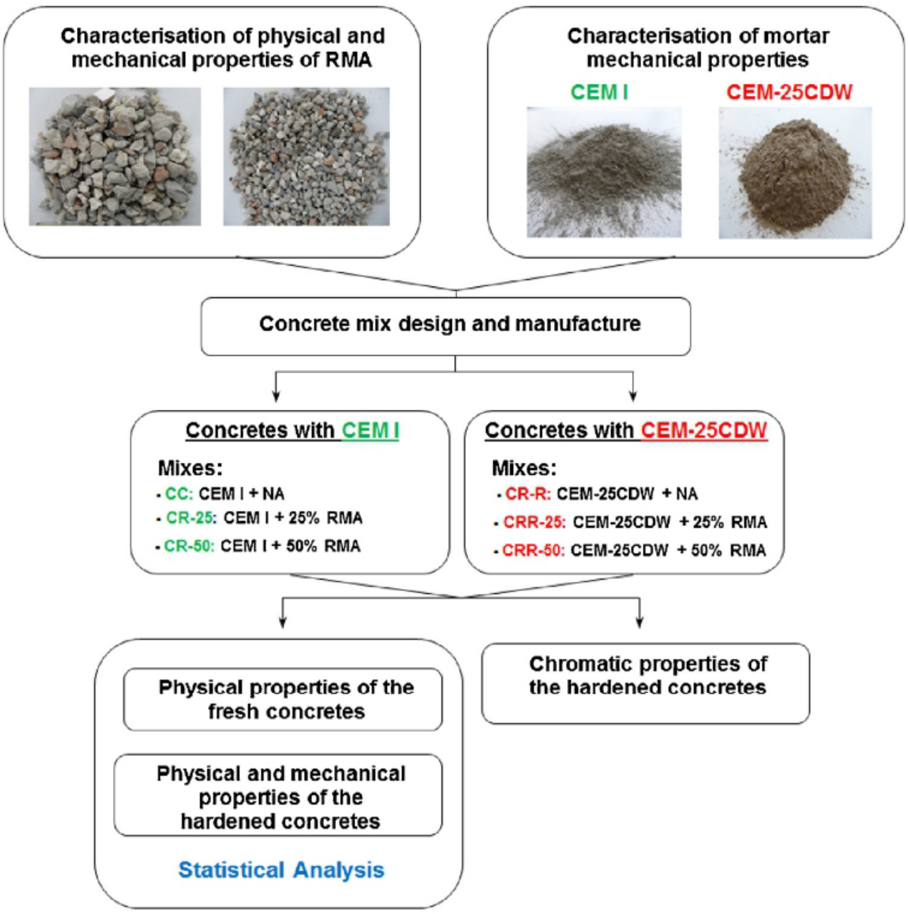

Fig. 3 – Experimental programme.

Table 2 – Concrete mixes.

Mix	Material (kg/m^3)								
	NS	NG-1	NG-2	RMA-1	RMA-2	Cement	Water	SP	$(w/c)_{effective}$
CC	732.36	766.69	382.96	–	–	400.00	193.03	6.20	0.45
CR-25	720.79	565.94	282.69	182.80	90.75	400.00	202.08	6.20	0.45
CR-50	705.38	369.22	184.43	357.77	177.62	400.00	210.63	6.20	0.45
CR-R	732.36	766.69	382.96	–	–	400.0[a]	193.03	6.20	0.45
CRR-25	720.79	565.94	282.69	182.80	90.75	400.0[a]	202.08	6.20	0.45
CRR-50	705.38	369.22	184.43	357.77	177.62	400.0[a]	210.63	6.20	0.45

[a] Mix prepared with CEM-25CDW.

aggregate in concrete manufacture [20,21]. The composition of RMA-1 and RMA-2 consisted in >87% unbound concrete and aggregate, <7% ceramic (Rb) material and <1% minority components such as bituminous matter, gypsum and floating particles. In light of that composition, further to EHE-08 [21] the recycled aggregates would be classified as recycled mixed aggregate with an Rb content of over 5%.

2.2. *Sample preparation*

The concretes were prepared as summarised in the flowchart in Fig. 3. Six mixes were prepared: (i) conventional concrete with portland cement and natural aggregate (CC); (ii) concrete with portland cement and 25% recycled mixed aggregate (CR-25); (iii) concrete with portland cement and 50% recycled mixed aggregate (CR-50); (iv) concrete with recycled cement and natural aggregate (CR-R); (v) concrete with recycled cement and 25% recycled mixed aggregate (CRR-25); and (vi) concrete with recycled cement and 50% recycled mixed aggregate (CRR-50).

The mixes were batched to the British method [22], which defines the starting data as: 28 d concrete characteristic strength (f_{ck}) = 30 MPa; cement strength class = 42.5 R; w/c ratio = 0.45; and maximum aggregate size = 20 mm. As the batching proportions in Table 2 show, all the mixes had a constant $(w/c)_{effective}$ to ensure comparability of concrete properties.

2.3. *Test methodology*

Each fresh concrete was analysed to European standards for density (EN 12350-6 [23]) air content (EN 12350-7 [24]) and workability (EN 12350-2 [25]). The hardened materials were tested for density (EN 12390-7 [26]), compressive strength (EN 12390-3 [27]), tensile strength (EN 12390-6 [28]), bending strength (EN 12390-5 [29]) and colour. The colour parameters were quantified on a Minolta CM-2500d portable spectrophotometer designed to determine the L*a*b* colour space (L* = lightness and a* and b* = colour coordinates), first defined by the International Commission on Illumination (CIE) (Commission Internationale de l'éclairage) in 1976 [30].

Three specimens were prepared per mix and test age for each trial: for compressive strength, 150 mm cubes; for flexural strength, 100 × 100 × 400 mm prisms; and for tensile strength, 150 mm diameter, 300 mm high cylinders. The specimens were cured at 20 °C for the first 24 h and then under water at 20 ± 2 °C until tested. The samples were prepared to European standard EN 12390-1 [31] and EN 12390-2 [32] recommendations.

The morphological study was conducted on 2 cm thick wafers sliced off 28 d, 100 mm diameter x 200 mm high specimens. Three-cm diameter cores were subsequently drawn from the wafers for the optical microscope study.

2.4. *Statistical analysis*

Regression analysis and analysis of variance (UNIANOVA) were performed to determine whether the percentage of RMA and cement type or their interaction had a statistically significant effect on the response variables. Here the response variables at each curing age were: fresh concrete workability, density and air content; and hardened concrete density and compressive, tensile and flexural strength. Compressive strength was determined at 7 d, 28 d, 90 d, 180 d and 365 d and density and splitting tensile and flexural strength at 28 d and 90 d. All the response variables were tested for normal distribution and homoskedacity prior to running the UNIANOVA [33]. All the statistical tests were conducted using IBM SPSS software, version 22, entering the mean values for each mix except in the tests for normality, where each sample was treated separately. A 95% confidence level was adopted throughout.

3. Results and discussion

3.1. *Properties of fresh concrete*

3.1.1. *Workability*

Mix workability was unaffected by the inclusion of RMA, either alone or with recycled cement. The slump data recorded for all the concretes ranged from 11 cm to 13 cm, values compliant with the fluid consistency (10–15 cm) defined by EHE-08 [21] and the S3 requirement laid down in European standard EN 206-1 [34].

The UNIANOVA findings on the effect of %RMA and cement type on concrete workability (Table 3) showed that neither factor separately nor their interaction had a statistically significant effect on that parameter (p-value >0.05). Those results were consistent with the patterns recorded by Medina et al. [10] for <50% recycled mixed aggregate and Barbudo et al. [35] for <100% recycled concrete aggregate, in which the use of recycled aggregate had no significant effect on the workability of concretes prepared with a constant effective w/c ratio.

Table 3 – Results of UNIANOVA for bulk density, air content and workability in fresh concrete.

Factor	Bulk density (ρ_{fresh})		Air content (Ac)		Workability	
	p-value[a]	Contribution (%)	p-value[a]	Contribution (%)	p-value[a]	Contribution (%)
RMA (%)	0.00	67.10	0.05	32.90	0.24	20.20
Cement type	0.00	25.70	0.08	15.10	0.59	1.90
RMA (%) x cement type	0.14	3.70	0.76	2.30	0.94	0.70

[a] Confidence level ≥95%.

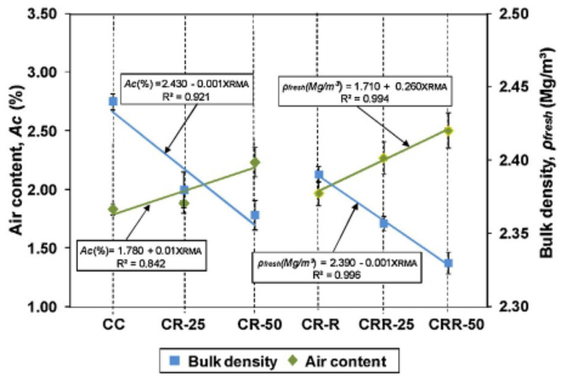

Fig. 4 – Variation in mean air content (Ac) and fresh bulk density (ρ_{fresh}) with recycled aggregate content (X_{RMA}) in conventional and recycled cement concretes (lines = standard deviation).

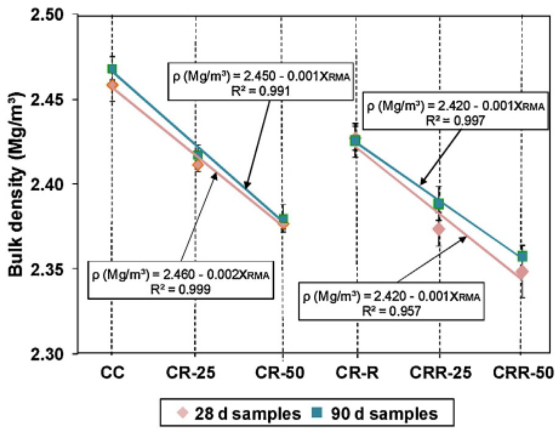

Fig. 5 – Variation in mean bulk density with RMA (X_{RMA}) content in 28 d and 90 d concretes made with conventional and recycled cement (lines = standard deviation).

3.1.2. *Bulk density and air content*

The plots of bulk density and air content against the percentage of recycled mixed aggregate in concretes made with CEM I or CEM-25CDW showed the relationships to be linear (Fig. 4). Both properties were directly related to the RMA content with strong ($0.80 \geq R^2 \leq 0.95$) linear correlation coefficients: $R^2 > 0.92$ for density and $R^2 > 0.84$ for air content [36]. The decline in density and rise in air content were due to the lower density (Table 1) and higher porosity [9,37] of the recycled mixed aggregate.

The UNIANOVA results for the effect of %RMA and cement type on density and air content are given in Table 3. The percentage of RMA accounted for 67% of the variation in density, cement for 26% and their interaction for a marginal 4%. That marginality was consistent with the lack of statistical significance of the effect of the recycled cement-RMA combination on density (p-value >0.05). The findings also showed that cement type had no significant effect on concrete density, in keeping with results reported by Ge et al. [38] for conventional concretes prepared with ≤40% ground brick.

The statistical test for air content exhibited a pattern similar to that observed for density, inasmuch as the two properties are directly related. The RMA accounted for 33% of the variation in this property and cement type for 15%. The combination of the two factors had no statistically significant effect on air content (p-value >0.05), contributing, like density, only marginally to variation.

3.2. *Properties of hardened concrete*

3.2.1. *Bulk density*

Hardened concrete bulk density is plotted against the replacement ratio and cement type for the 28 d and 90 d materials in Fig. 5. Density declined linearly ($R^2 > 0.95$) with rising RMA content, irrespective of the type of cement used to prepare the concretes. That decline was primarily attributable to the lower density of recycled than conventional aggregate (see Table 1). The pattern observed was consistent with the bulk density findings for fresh concrete (item 3.1.2) and the results reported by Matías et al. [39] for RCA and Beltrán et al. for RMA [40] for concretes.

In the 28 d OPC concretes, density was 2% lower in CR-25 and 3% lower in CR-50 than in CC. In the recycled cement concretes, 28 d density was 1% lower in CR-R, 3% lower in CRR-25 and 4% lower in CRR-50 than in CC (see Table 4). Those values lay within the 2% to 4% range observed by Mas et al. [11] and López-Uceda et al. [41] in concretes made with up to 40% RMA. The differences in density between the concretes with CEM I and the respective materials with CEM-25CDW was never in excess of 2%.

The 90 d bulk density values for all the concretes was practically the same as the 28 d values, with variations of ≤1%. The figure nonetheless shows that the difference was greater in the concretes with CEM-25CDW due to the pozzolanicity of the ceramic C&DW comprising the SCM.

Table 4 – 28 d and 90 d concrete density (ρ) and tensile ($f_{,st}$) and flexural ($f_{,fl}$) strength (± = standard deviation).

Concrete	28 d			90 d		
	ρ (Mg/m^3)	$f_{,st}$ (MPa)	$f_{,fl}$ (MPa)	ρ (Mg/m^3)	$f_{,st}$ (MPa)	$f_{,fl}$ (MPa)
CC	2.46 ± 0.01	4.28 ± 0.25	6.78 ± 0.19	2.47 ± 0.01	4.92 ± 0.17	6.88 ± 0.22
CR-25	2.41 ± 0.01	4.14 ± 0.29	6.09 ± 0.38	2.42 ± 0.01	4.55 ± 0.16	6.04 ± 0.16
CR-50	2.38 ± 0.02	3.86 ± 0.16	6.32 ± 0.43	2.39 ± 0.01	4.19 ± 0.10	6.27 ± 0.25
CR-R	2.43 ± 0.01	4.06 ± 0.13	6.03 ± 0.41	2.43 ± 0.02	4.38 ± 0.39	6.62 ± 0.41
CRR-25	2.37 ± 0.01	3.22 ± 0.25	5.81 ± 0.15	2.39 ± 0.01	4.16 ± 0.22	6.68 ± 0.10
CRR-50	2.35 ± 0.01	3.28 ± 0.18	5.64 ± 0.21	2.36 ± 0.02	3.51 ± 0.41	5.71 ± 0.20

Table 5 – UNIANOVA results for bulk density.

Factor	28 d bulk density		90 d bulk density	
	p-value[a]	Contribution (%)	p-value[a]	Contribution (%)
RMA (%)	0.00	78.80	0.00	80.37
Cement type	0.00	19.04	0.00	11.74
RMA (%) x cement type	0.50	0.00	0.04	3.04

[a] Confidence level ≥95%.

The UNIANOVA results for the effect of %RMA and cement type on concrete bulk density (Table 5) showed that here also the factor with the greatest impact was RMA (80% of the variation) at both ages, followed by cement type (<20% of the variation) and the interaction between the two (<5% of the variation). The effect of cement type declined with rising curing time due to the intrinsic properties of cement CEM-25CDW. Each factor separately had a statistically significant effect (p-value <0.05) on density, whereas their interaction did not (p-value >0.05).

The portland cement concrete density/recycled cement concrete density ratio is plotted against the percentage of RMA in Fig. 6. The linear relationship (R^2 = 0.98) attested to the similarity of the behaviour in the two variables with rising RMA content (Eq. 1):

$$\rho_{CEM-25CDW} = \frac{\rho_{CEMI}}{1.1079 + 0.0003X_{RMA}(\%)} \quad (1)$$

where: $\rho_{CEM-25CDW}$ is recycled cement density in Mg/m^3, ρ_{CEMI} conventional cement concrete density in Mg/m^3 and X_{RMA} recycled mixed aggregate content in percentage (%).

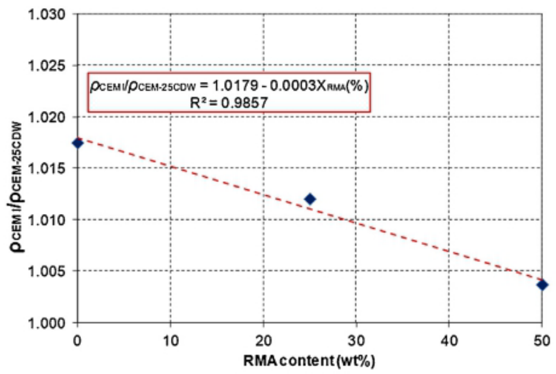

Fig. 6 – Variation in portland cement concrete mean bulk density/recycled cement concrete bulk density with RMA content (X_{RMA}).

3.2.2. *Compressive strength*

The mean 7 d ($f_{cm,7}$), 28 d ($f_{cm,28}$), 90 d ($f_{cm,90}$) and 365 d ($f_{cm,365}$) compressive strength values are given in Table 6. Mean 28 d ($f_{cm,28}$) compressive strength was greater than the 30 MPa characteristic strength, irrespective of cement type and percentage of recycled mixed aggregate.

The inclusion of RMA (CR-25 and CR-50) induced no significant difference in 28 d strength relative to CC. Those findings might be related to interface (ITZ) similarities, i.e., between the paste and the new components in the mixed recycled aggregate (ceramic materials, concrete…) on the one hand and the paste and the natural aggregate on the other. That premise is supported by earlier reports (Medina et al. [42,43] and Sáez del Bosque et al. [44]) based on nanoindentation and scanning electron microscope studies of the various constituents in mixed recycled aggregate.

Table 6 – Compressive strength values by age (± standard deviation).

Concrete	Compressive strength, f_{cm} (MPa)			
	$f_{cm,7}$	$f_{cm,28}$	$f_{cm,90}$	$f_{cm,365}$
CC	47.78 ± 0.02	51.17 ± 0.18	56.96 ± 1.01	60.93 ± 1.16
CR-25	44.24 ± 0.22	51.69 ± 0.65	57.51 ± 0.56	58.53 ± 0.28
CR-50	42.70 ± 0.45	51.17 ± 0.58	53.19 ± 0.33	59.65 ± 0.23
CR-R	38.65 ± 0.65	46.06 ± 0.60	51.83 ± 0.69	57.79 ± 0.62
CRR-25	35.25 ± 0.30	45.71 ± 1.41	47.87 ± 0.49	57.00 ± 0.94
CRR-50	30.38 ± 0.73	41.18 ± 0.10	47.52 ± 1.06	56.41 ± 0.43

In the concrete with CEM-25CDW cement (CR-R), 28 d strength was 10% lower than in concrete with CEM I. That decline was smaller than the 14% reported by Subasi et al. [45],

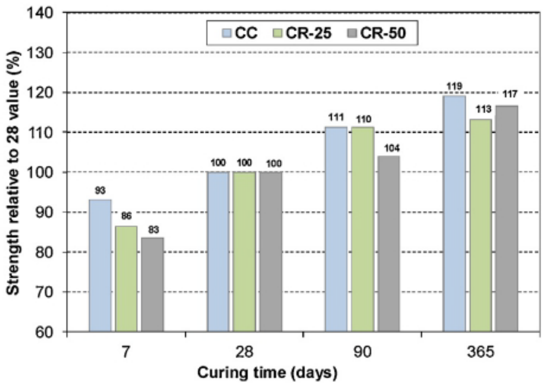

Fig. 7 – Compressive strength in concretes made with CEM I cement relative to their respective 28 d values, by age.

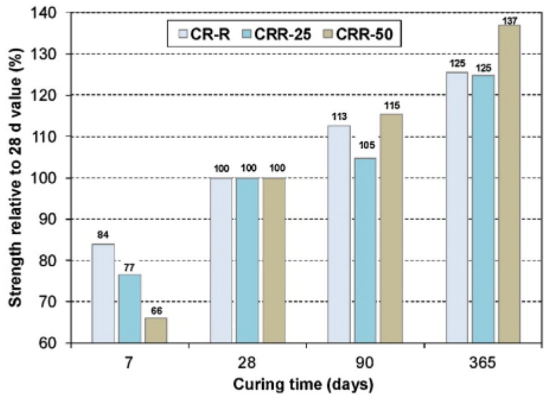

Fig. 8 – Compressive strength in concretes made with CEM-25CDW cement relative to their respective 28 d values, by age.

who added 20% ceramic waste as a filler in self-consolidating concretes.

The simultaneous use of CEM-25CDW and RMA (CRR-25 and CRR-50) induced declines of 11–20% relative to CC. Those values lay within the 11–33% range observed by Letelier et al. [17,18] in concretes to which 5– 15% thermally activated recycled cement and 20–40% RCA or 15% recycled ground brick and 30% RCA were simultaneously added.

Compressive strength by age relative to each concrete's 28 d value is shown in Fig. 7 for the CEM-I family and in Fig. 8 for the CEM-25CDW family. Compressive strength rose with curing time in both the concretes made with recycled cement (CR-R, CRR-25 and CRR-50) and those prepared with conventional cement (CC, CR-25 and CR-50). The inclusion of recycled aggregate consequently had no effect on concrete hardening. The recycled cement concretes exhibited lower relative strength at 7 d and higher values at >90 d than the conventional cement concretes. Those findings were closely related to the intrinsic properties of the new cement, for its 25% ceramic waste component was characterised by high late age pozzolanicity (see item 2.1.1).

The 7 d CEM I concretes with 25% RMA exhibited 86% of the strength of their 28 d value, and those with 50% RMA, 83%. Those values were consistent with the 75–90% reported by Bravo et al. [46] for concretes with up to 50% recycled C&DW aggregate sourced from different recycling plants in Portugal. Strength in the 7 d concrete with recycled cement (and natural aggregate) was 84% of its 28 d value, only slightly lower than the 93% recorded for conventional concrete. Concrete strength in 7 d CRR-25 was 77% of its 28 d value and in CRR-50 66%. Those numbers, also lower than observed in the respective materials with conventional cement, lay within the 66–71% range observed for concretes with 25% and 35% fly ash and 20–50% recycled concrete aggregate [16].

Late age strength followed a different pattern than observed for the 7 day findings. In the 365 d materials, the greatest rises were found in concretes containing both recycled cement and RMA: in mix CRR-25 strength was 25% and in CRR-50 37% higher than their 28 d values. Strength rose less steeply in the CEM-I mixes, with CR-25 13% higher and CR-50 17% higher than their 28 d strength values.

The 365 d mix made with CEM-25CDW and natural aggregate (CR-R) exhibited a 25% rise over its 28 d strength, 6 points higher than observed for the control mix (CC). The greater rise in performance with curing age in the concretes with the new recycled cements (CR-R, CRR-25 and CRR-50) than in the concretes with conventional cement (CC, CR-25 and CR-50) was directly related to the intrinsic properties of the former, as discussed earlier. This behaviour was consistent with the what Kannan et al. [47] and Ge et al. [38] observed in concretes containing 10–40% roof tile or brick waste in the stead of portland cement. Those authors reported that strength rose more with curing time in the new concretes than those made with conventional cement, due to the pore system refinement induced by the late age pozzolanicity exhibited by the waste.

The UNIANOVA results on the effect of %RMA and cement type on concrete compressive strength are listed in Table 7. The factor with the greatest effect on compressive strength was cement type, accounting for over 60% of the variation in all the ages studied, followed by percentage of RMA (22%) and the combination of the two (7%). Nonetheless, although the recycled cement (CEM-25CDW) was the factor that impacted compressive strength the most, the decline in strength was never observed to exceed 29% (value for 7 d concretes with 50% RMA) relative to the respective concretes with conventional cement. The difference narrowed to 5% at 365 d, a value much lower than the SCM replacement ratios involved. The declining percentage of the contribution of the cement to the variation in the dependent variable was a further indicator of that fact (see Fig. 9). At later ages, then, compressive strength in the new concretes with both recycled cement and RMA was comparable to conventional concrete strength.

3.2.3. *Relationship between portland and recycled cement compressive strength*

The ratio between mean 28 d compressive strength of CEM I and CEM-25CDW is plotted against RMA content in Fig. 10 (Eq. 2). At 0.95, the correlation coefficient (R^2) was indicative of a close relationship between the two strengths and their linear correlation to the percentage of RMA.

Table 7 – UNIANOVA results for compressive strength.

Factor	Df	Sum of squares	Variance	F[a]	p-value[a]
7 d compressive strength					
RMA (%)	1	133.81	66.90	204.96	0.00
cement type	2	463.20	463.20	87504.38	0.00
RMA (%) × cement type	2	10.62	5.31	16.27	0.00
28 d compressive strength					
RMA (%)	1	24.71	12.35	15.61	0.00
cement type	2	222.25	222.25	280.93	0.00
RMA (%) × cement type	2	20.27	10.14	12.81	0.00
90 d compressive strength					
RMA (%)	1	49.35	24.67	26.62	0.00
cement type	2	208.83	208.83	250.65	0.00
RMA (%) × cement type	2	18.25	9.13	10.95	0.00
180 d compressive strength					
RMA (%)	1	1.37	0.68	0.76	0.00
cement type	2	87.10	87.10	96.92	0.49
RMA (%) × cement type	2	2.92	1.46	1.62	0.24
365 d compressive strength					
RMA (%)	1	8.74	4.37	5.85	0.02
cement type	2	31.26	31.26	41.82	0.00
RMA (%) × cement type	2	2.77	1.38	1.86	0.20

[a] Confidence level ≥ 95%.

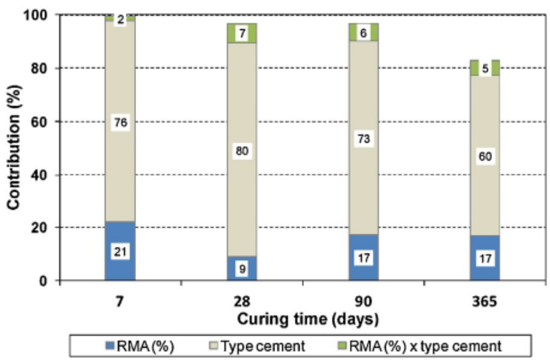

Fig. 9 – Contribution of factors and their interaction to variation in compressive strength.

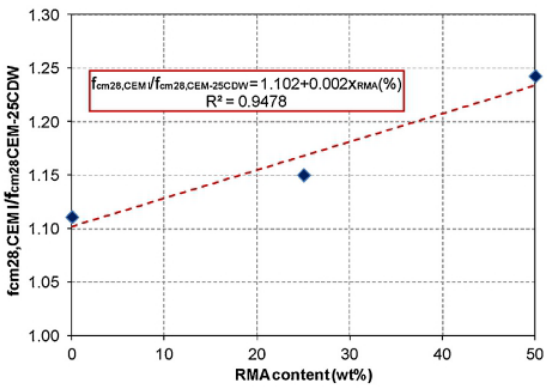

Fig. 10 – Variation in 28 d portland cement compressive strength/28 d recycled cement compressive strength ratio with RMA replacement ratio (%).

$$f_{cm28,CEM-25CDW} = \frac{f_{cm28,CEMI}}{1.102 + 0.002X_{RMA}(\%)} \quad (2)$$

where: $f_{cm28,CEM-25CDW}$ is 28 d recycled cement compressive strength in MPa, $f_{cm28,CEMI}$ 28 d conventional cement compressive strength in MPa and $X_{RMA}(\%)$ (see Eq. 1)

3.2.4. *Splitting tensile strength*

The 28 d and 90 d splitting tensile strength findings (f_{st}) are shown in Fig. 11, along with the linear regression equations for performance and replacement ratio, all of which exhibited strong linear correlations, except the equation for concretes manufactured with 28 d recycled cement, where the R^2 was <0.7. Some authors nonetheless deem R^2 values of ≥0.65 to be acceptable where recycled concretes are concerned [36]. Strength declined with rising RMA content in all the concretes, irrespective of cement type and age. The same pattern was observed by Evangelista and Brito [48] for recycled concrete aggregate and Yang et al. [49] for recycled mixed aggregate concretes. Both reported that the decline in strength was due in particular to the greater porosity in the recycled aggregate.

In the 28 d concretes, tensile strength relative to CC was 3% lower in CR-25, 10% lower in CR-50 and in the concrete with the

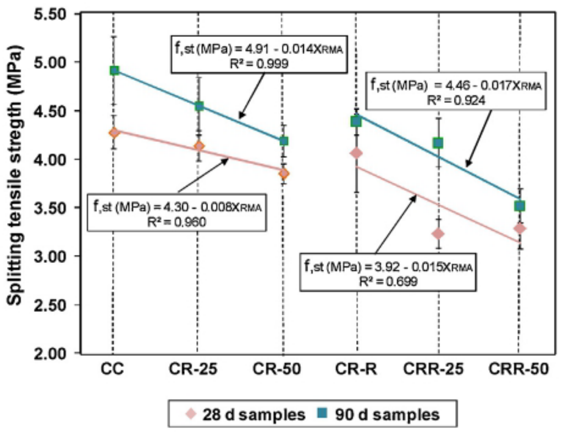

Fig. 11 – Variation in 28 d and 90 d splitting tensile strength with RMA content in concretes made with conventional and recycled cement (lines = standard deviation).

new recycled cement (CR-R), 5% lower. The decline was slightly steeper when both recycled cement and RMA were used: 23% in CRR-25 and 25% in CRR-50. These findings were consistent with the results observed by Kou et al. [16] who, using concretes with the same amount of cement and the same w/c ratio as in this study, found that tensile strength declined by 8–36% in concretes with 20–35% fly ash and 20% to 50% recycled concrete aggregate.

In 90 d CR-25, tensile strength was 9% higher and in CR-50, 10% higher than their respective 28 d values. Combining recycled cement and RMA yielded 7% higher 90 d than 28 d strength in CRR-25 and 29% higher in CRR-50. That rise in tensile strength with curing age in concretes with recycled cement was consistent with earlier observations [15] for concretes with different mineral additions (35% fly ash, 15% metakaolin, 10% silica fume) and 50% RCA relative to conventional cement concretes bearing 50% RCA.

Irrespective of age, the decline recorded relative to the reference concrete was consistently smaller than the RMA replacement ratio (see Eq. 3). That behaviour may be explained by: (i) the similarity in the properties of the RMA/paste and natural aggregate/paste ITZs [42,50]; and (ii) the presence of micro cracks in the recycled aggregate which would partially offset the lower resistance to tensile stress [51].

$$\Delta f_{,st} = \frac{f_{,st(CC)} - f_{,st(CR)}}{f_{,st(CC)}} \times 100 \quad (3)$$

where $\Delta f_{,st}$ is the relative decline in tensile strength; $f_{,st(CC)}$ the tensile strength of the reference concrete; and $f_{,st(CR)}$ the tensile strength of the recycled concrete. The subscript may be adapted to refer to CR-25, CR-50, CR-R, CRR-25 or CRR-50, depending on the relative strength to be calculated. For instance, 28 d $\Delta f_{,st}$ for CRR-50 was 24%, a value lower than the 50% of RMA substituted for NA in the recycled concrete.

The UNIANOVA results for tensile strength in Table 8 show that %RMA and cement type were the factors with the greatest effect on that parameter. The RMA contributed 30% to the 28 d variation and cement type 36%, whilst in the 90 d concretes RMA accounted for 43% and cement type for 28%. Cement type was the primary determinant in 28 d tensile strength, whereas in the 90 d materials the percentage of RMA prevailed, as in compressive strength. That reversal was attributed to the pozzolanicity of the ceramic waste in the C&DW used to manufacture the recycled cement, a finding reported earlier by Asensio et al. [52] and Medina et al. [53].

The interaction between cement type and percentage of RMA showed no statistically significant effect on tensile strength (p-value >0.05), with a p-value of 0.17 at 28 d and of 0.75 at 90 d.

The factor with the heaviest impact in both families, CEM I (CC, CR-25 and CR-50) and CEM-25CDW (CR-R, CRR-25 and CRR-50), was %RMA, although the contribution of this factor was 1.3 times greater in the latter than in the former, as Fig. 11 shows.

3.2.5. *Flexural strength*

The 28 d and 90 d flexural strength ($f_{,fl}$) values for the concretes are charted in Fig. 12. As in the other mechanical properties, a linear correlation was observed between that parameter and the RMA content, except in 90 d recycled concrete, where the R^2 value was <0.7 and smaller than observed for compressive strength. As noted earlier, however, other authors [36] have contended that R^2 values ≥0.65 are

Table 8 – UNIANOVA results for tensile strength.

Factor	Df	Sum of squares	Variance	F[a]	p-value	Contribution (%)
28 d splitting tensile strength						
RMA (%)	1	1.22	0.61	6.98	0.00	29.68
Cement type	2	1.47	1.47	16.90	0.00	35.92
RMA (%) × cement type	2	0.36	0.18	2.09	0.17	8.88
90 d splitting tensile strength						
RMA (%)	1	1.97	0.99	9.03	0.00	42.58
Cement type	2	1.29	1.29	11.77	0.01	27.73
RMA (%) × cement type	2	0.07	0.03	0.30	0.75	1.40

[a] Confidence level ≥95%.

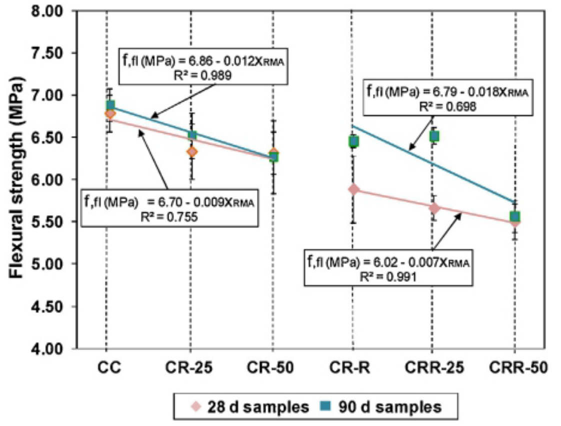

Fig. 12 – Variation in 28 d and 90 d flexural strength with RMA content (X_{RMA}) in concretes made with conventional and recycled cement (lines = standard deviation).

acceptable when dealing with recycled concrete. These findings concurred with the results observed in earlier studies [18,54–56], according to which flexural strength was less affected by the amount of recycled aggregate than compressive and tensile strength.

CR-25 exhibited 6%, CR-50 10% and CR-R 11% lower 28 d strength than CC. Those values lay within the 5–15% found by Bravo et al. [46] for concretes with 25–50% recycled aggregate with a composition similar to that used in this study. Concrete CRR-25 had 14% and CRR-50 17% lower strength than CR-R. Those values compared to the 10–14% observed for concrete made with 20–40% RCA and concrete manufactured with 15% thermally activated cement powder [18]. They were similar to the ≈17% recorded by Letelier et al. [17] for concretes made with 15% recycled ground brick and 30% RCA.

The concretes prepared with conventional cement (CC, CR-25 and CR-50) exhibited 90 d flexural strength values similar to those observed in the 28 d materials (Fig. 12). In the concretes with recycled cement (CR-R, CRR-25 and CRR-50), however, strength rose with age by 2–11%, ultimately reaching values similar to those recorded for concretes made with CEM I. Those findings were consistent with the greater rises in compressive and tensile strength with curing age in the mixes made with recycled cement (CEM-25CDW) than in those with conventional cement (see items 3.2.2 and 3.2.4).

The UNIANOVA values for flexural strength given in Table 9 varied depending on curing age. In the 28 d concretes, the most significant factor was cement type, accounting for 35% of the variation, compared to 19% for percentage of RMA. The interaction between cement type and percentage of RMA had no statistically significant effect (p-value = 0.54) on flexural strength.

In the 90 d materials, the factor carrying the greatest weight was percentage of RMA (38% variation), whilst cement type was not statistically significant (p-value = 0.73). These findings corroborated the significant improvement in 90 d flexural strength in concretes made with recycled cement, with values comparable to those for concretes made with conventional cement.

Analysing the results by families revealed differences between %RMA and curing age depending on the cement used. Curing age was significant for family CEM-25CDW but not for family CEM I (p-value >0.05). Further attesting to a slower strength gain than in the conventional concrete due to the pozzolanicity of the new addition.

3.3. *Compliance*

The 28 d splitting tensile ($f_{,st}$) and flexural ($f_{,fl}$) strength values for the recycled concretes are shown in Fig. 13, along with the values estimated with Eq. 4 for the former and Eq. 5 for the latter, recommended in both EHE-08 [21] and EC-2 [57]:

$$f_{ctm} = 0.30 \cdot \sqrt[3]{f_{ck}^2} \quad (4)$$

$$f_{ctm,fl.est} = f_{ctm} \times (1.6 - h/1000) \quad (5)$$

where: f_{ctm} is the theoretical tensile strength as per EHE-08/EC-2, f_{ck} is mean 28 d compressive strength found by applying a factor of 0.90 to convert cubic to cylindrical specimens further to EHE-08 [21] recommendations, $f_{ctm,fl.est}$ is theoretical flexural strength as per EHE-08/EC-2 and h is the height of the sample tested (see section 2.3).

With the exception of CRR-25, in which it was slightly lower, experimental was greater than theoretical tensile strength in all the concretes. In the CEM I family, strength was 1–7% higher than the theoretical value in the RMA concretes and in the CEM-25CDW family, likewise with RMA,

Table 9 – UNIANOVA results for flexural strength.

Factor	Df	Sum of squares	Variance	F[a]	p-value	Contribution (%)
28 d flexural strength						
RMA (%)	1	0.79	0.40	2.75	0.10	19.01
Cement type	2	1.46	1.46	10.10	0.01	34.94
RMA (%) × cement type	2	0.19	0.94	0.65	0.54	4.51
90 d flexural strength						
RMA (%)	1	1.75	0.87	6.19	0.01	37.72
Cement type	2	0.02	0.02	0.12	0.73	0.37
RMA (%) × cement type	2	1.17	0.59	4.16	0.04	25.33

[a] Confidence level ≥95%.

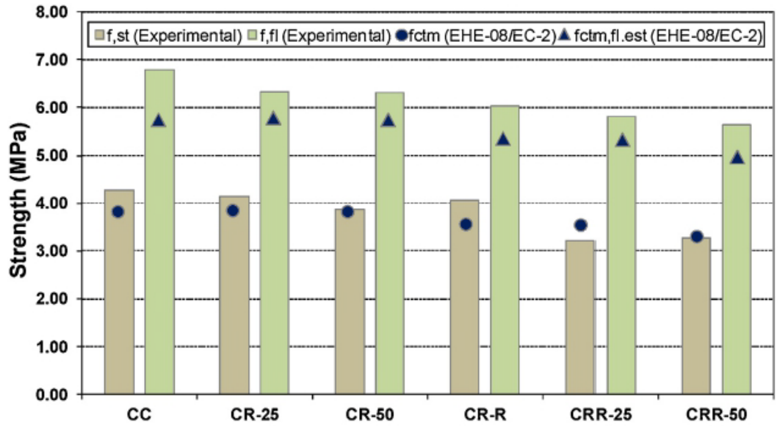

Fig. 13 – Experimental and EHE-08 [21]/EC-2 [57] theoretical tensile and flexural strength of the concretes studied.

from 1% to 11% higher. Mix CR-R exhibited the highest strength relative to the theoretical value, at 11%, higher also than the 10% recorded for its analogue, the reference concrete (CC).

The pattern for flexural strength was similar, with higher experimental than the theoretical values found with the expression for conventional concretes. Specifically, in the CEM I family with RMA, the rise ranged from 8% to 9% and in the CEM-25CDW family with recycled aggregate, from 7% to 12%.

The above findings showed that the equations proposed in EHE-08 and EC-2 are apt for predicting flexural strength in all these concretes. In contrast, in the RMA concretes, with or without recycled cement, the theoretical tensile strength equations did not correctly predict behaviour. Rather, a correction factor of 0.85 had to be applied to the EHE-08/EC-2 equation to accommodate the combined effect of the two new materials.

3.4. *Morphological analysis*

Further to the enlarged photos of the cross-sections (Fig. 14) of concretes CR-50 (Fig. 14a) and CRR-50 (Fig. 14b), the natural aggregate and the components of the recycled mixed aggregate were distributed uniformly in the cementitious matrix,

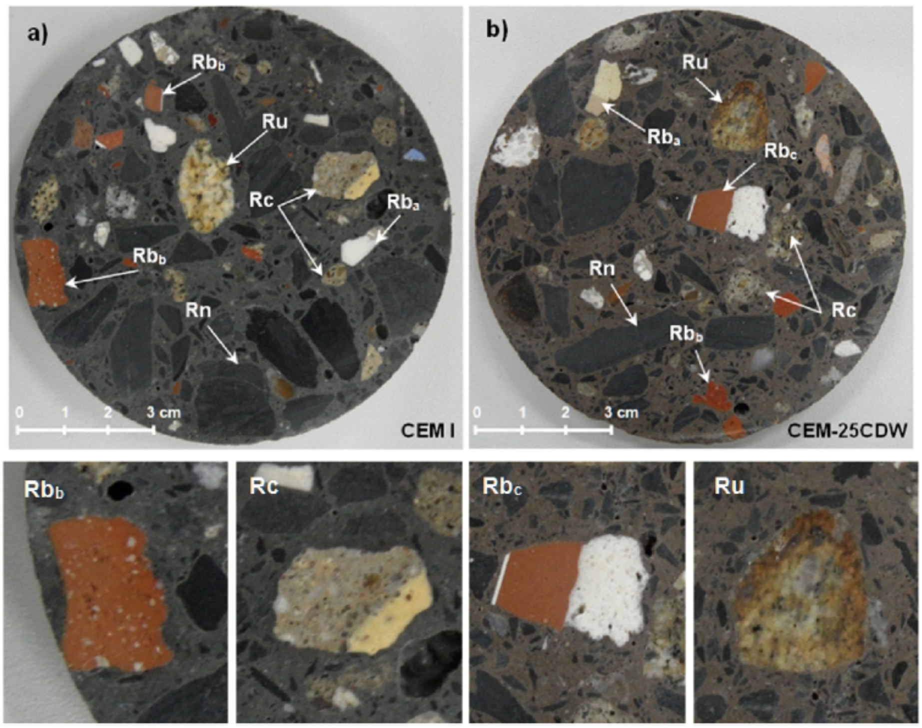

Fig. 14 – a) Concrete with 50% RMA (CR-50); b) concrete with recycled cement and 50% RMA (CRR-50).
(Note: *Rn:* **natural aggregate;** Ru: **unbound aggregate;** Rb$_a$: **sanitary ware waste;** Rb$_b$: **crushed brick;** Rb$_c$: **crushed roof tile; and** Rc: **concrete aggregate).**

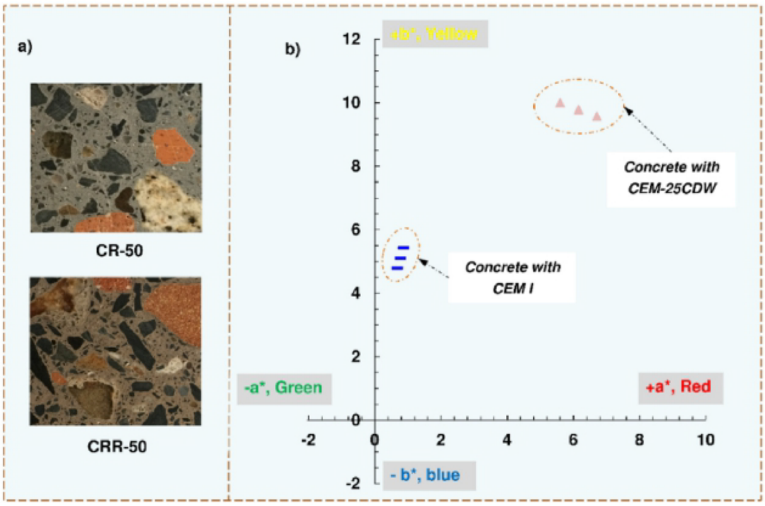

Fig. 15 – Concrete colour: a) micrographs; b) coordinates a* and b*.

whilst the two materials varied in colour (see section 3.5). The figure also shows the RMA/paste ITZ for some of the components, according to which they bonded effectively to the matrix, irrespective of cement type (CEM I or CEM-25CDW). No significant differences were perceptible between natural aggregate/paste and RMA component/paste ITZ thickness. That was consistent with earlier reports by authors deploying nanoindentation to study the micro-elastic properties and thickness of the ITZs between paste and ceramic sanitary ware [42], ceramic block [44] and concrete waste [44]. Their observations were likewise consistent with the macroscopic behaviour recorded here.

3.5. *Colour*

Micrographs showing the colour of CEM I and CEM-25CDW concretes are reproduced in Fig. 15a and their colour coordinates in Fig. 15b. The colour coordinate ranges (a* = 0-0.9 and b* = 4.0–5.6) lay in the grey zone [58]. The inclusion of ceramic waste such as roof tile and block as SCMs in the cement induced a rightward (i.e., redward) shift in the + a*/+b* axis relative to the CEM I concretes. Similar, albeit smaller, shifts were reported by other authors assessing the effect on these properties in mortars made with cements bearing industrial waste such as paper sludge [59] or coal tailings [60].

The use of CEM-25CDW lowered the lightness (L*) value in these concretes to ≈68%, compared to ≈77% in the CEM I materials.

That change in colour added value to this new cement, for the resulting rusticity made it ideal for concrete elements, particularly in building construction where colour or a lower visual impact with natural or rural surrounds may be design requisites.

4. Conclusions

The conclusions to be drawn from the present study are as follows.

- Neither RMA nor cement type had a statistically significant effect on concrete workability.
- The 2–5% decline in density and rise in entrained air in the concretes were primarily accounted for by the percentage of RMA. Cement type made no statistically significant contribution to the variation in those properties.
- Late age mechanical performance was similar in concrete bearing recycled cement and material made with conventional cement.
- Compressive strength was affected primarily by the type of cement used. Concretes with recycled cement and RMA exhibited 10–20% lower 28 d strength than concrete made with conventional cement. That decline narrowed with curing time, to 5–7% in 365 d concretes made with CEM-25CDW and 50% RMA.
- The interaction between recycled cement and RMA had no significant impact on concrete tensile or flexural strength. The declines in strength observed in concretes CR-R, CRR-25 and CRR-50 were attributable to the separate action of the two factors.
- The presence of recycled cement was the determinant in 28 d tensile and flexural strength. In the 90 d materials, however, the percentage of RMA was the prevailing factor.
- The effect of cement type on the properties analysed declined with concrete curing age.
- The equations proposed by EHE-08 and the Eurocode for estimating flexural strength proved to be apt for these new concretes. The expression for estimating tensile strength in those two codes had to be corrected by a factor of 0.85, however, to accommodate the effect of RMA, with or without cement CEM-25CDW.
- The use of CEM-25CDW induced a rightward shift in the colour coordinates (red scale) and a 12% decline in lightness relative to CEM I.

In light of the present findings, construction and demolition waste can be used simultaneously as supplementary cementitious materials (25%) and coarse aggregate (<50%) in structural concrete for both civil and building construction applications requiring a characteristic compressive strength of 30 MPa. Such joint valorisation of C&DW as SCMs and coarse aggregate would help mitigate the worldwide environmental problem generated by such waste and contribute to CO_2 emissions abatement by lowering the construction industry's demand for conventional portland cement and natural aggregate.

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Capítulo 7

Mechanical behavior of structural concrete with ground recycled concrete cement and mixed recycled aggregate

Capítulo 7

Mechanical behavior of structural concrete with ground recycled concrete cement and mixed recycled aggregate

Resumen

Este artículo de investigación analiza los efectos de valorizar conjuntamente polvo reciclado de hormigón (PRH) como sustituto parcial (10 % y 25 % en peso) del cemento y áridos reciclados mixtos (0 % y 50 %) procedentes de los residuos de construcción y demolición (AR-RCD) en el diseño de hormigones estructurales con menor contenido de cemento. Con este objetivo, se diseñó un programa experimental evaluando de este modo la variabilidad en las propiedades de resistencia a compresión, resistencia tracción, módulos de elasticidad y densidad en estado endurecido. Además, se realizaron ensayos no destructivos mediante pruebas de velocidad de pulso ultrasonido y resistividad eléctrica. Los resultados indican que la presencia de PRH y AR-RCD provoca un descenso de las propiedades mecánicas inferior al porcentaje de incorporación respecto a los hormigones fabricados con áridos naturales. Estos resultados se atribuyeron a losa: i) una mayor relación agua/conglomerante (cemento + PRH); ii) al efecto de dilución como consecuencia de un menor contenido en cemento; y iii) a las propiedades intrínsecas (absorción de aguay resistencia a la fragmentación) de nuevos componentes reciclados. Sin embargo, las mezclas con un 10 % de PRH y un 50 % de AR-RCD mostraron prestaciones mecánicas similares y misma clase resistente que los hormigones fabricados solo con un 50 % de AR-RCD. Además, según los resultados de resistividad eléctrica y velocidad de ultrasónicos, la incorporación de PRH muestra un efecto inferior al 14 % independiente del tipo de árido (natural o reciclado). Finalmente, los resultados obtenidos son prometedores y abren el camino hacia una gestión más eficiente y conjunta de los RCD en la búsqueda de implementar en la industria de la construcción el modelo de economía circular.

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Mechanical behaviour of structural concrete with ground recycled concrete cement and mixed recycled aggregate

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ABSTRACT

This article analyses the combined effect of valorising ground recycled concrete (GRC) as 10% or 25% cement replacement and 0% or 50% mixed recycled construction and demolition waste aggregate (RA-CDW) in structural concrete. An exhaustive experimental programme was designed to assess the variation in compressive and tensile strength, modulus of elasticity and hardened concrete density. Non-destructive ultrasonic pulse velocity and electrical resistivity tests were also conducted. The concrete mixes prepared with GRC and RA-CDW exhibited lower mechanical performance than those manufactured with natural aggregate and cement only (although the difference was smaller than the respective replacement ratios). These findings were attributed to: a higher water/binder (cement + GRC) ratio, the dilution effect resulting from a lower cement content in the new mixes and the intrinsic properties (water absorption and abrasion resistance) of the new recycled components. The mixes with 10% GRC and 50% RA-CDW, however, showed similar mechanical performance and remained in the same strength class as those with 50% RA-CDW and 100% Portland cement. In terms of the electrical resistivity and ultrasonic pulse velocity tests, the effect of replacing OPC with GRC was below 14%, irrespective of whether natural or recycled aggregates were used. Such promising findings pave the way for more efficient and global C&DW management with a view to steering the construction industry toward the circular economy.

1. Introduction

Construction is a key industry worldwide, accounting in the European Union for 10% (European Commission, 2012) and in China for over 26% (Zheng et al., 2017) of the GDP. Given that in the EU it employs over 20 million people (European Commission, 2012), developments in the industry have a significant impact on the European economy and its citizens' quality of life.

Concrete is still the construction material most widely used around the world and universally acknowledged by engineers and architects as one of the best building materials on the market (Monteiro et al., 2017). Total concrete output in 2017 amounted to ~27 Gt (Li et al., 2019). Given an estimated average composition, that translated into the consumption of ~19 Gt of aggregate, ~4 Gt of Portland cement and 2 Gt to 3 Gt of fresh water (Miller et al., 2018). According to the latest research on world economic growth, the planet's built area will double in the next 40 years and concrete production will have to rise by 25% by 2030 (Miller, 2018). Quarrying the enormous amounts of stone needed for concrete entails the destruction of natural environments and air pollution due to the dust generated. Producing clinker, a key cement component formed when limestone and clay are burnt at 1450 °C, calls not only for huge kilns that consume vast amounts of energy (Miller, 2018), but generates surprisingly high levels of CO_2 emissions, accounting for 8% of the worldwide total (Monteiro et al., 2017). Given these facts, the construction industry must commit to adopting measures to tackle climate change and guaranteeing concrete and cement manufacture sustainability for future generations (Rahla et al., 2019).

The concrete industry in particular is seeking alternative raw materials sourced from industrial by-products, both as aggregates for concrete manufacture and partial cement substitutes (Cantero

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et al., 2019). One option is to reuse the waste generated during the construction and demolition of infrastructures and buildings, which constitutes the heaviest flow of waste worldwide. Over 10 Gt of construction and demolition waste (C&DW) are generated yearly around the globe, with output in the U.S. at 0.7 Gt, in the EU at over 0.9 Gt and in China at around 2.3 Gt. Given the predictions on future urban growth, these figures are expected to rise. Two main types of recycled aggregate can be obtained from selective demolition and C&DW management plant processing: i) recycled aggregates from concrete structures (RCA) and ii) recycled mixed aggregate (RMA), comprising a combination of concrete, and masonry debris (brick, roof/wall/floor tiles) and pollutants (plaster, plastic, glass and similar).

The scientific community has conducted considerable research on the effects of using RCA as a coarse aggregate in concrete manufacture. Andreu and Miren (2014) concluded that concrete with 100% RCA could reach up to 40 MPa with no need to adjust the amount of cement. De Juan and Gutiérrez (2009) reported that structural concrete could be manufactured with RCA provided the aggregate was sorted to ensure water absorption lower than 8 wt% and a Los Angeles coefficient under 40 wt%. Matías et al. (2013) observed that the greater contact area in RCA than in NA provided a closer bond to the cement paste, which raised splitting tensile strength in recycled aggregate concrete. Although RCA output is less than half that of RMA (Asensio et al., 2020), it is generally more uniform, less water-absorbent and harder. Those properties favour its use as replacement of natural aggregate in concrete manufacture (Silva et al., 2014). Consequently, RMA is more widely used as landfill after excavation or landscape restoration (European Commission, 2016), which limits opportunities for valorisation. Some researchers have nonetheless shown that RMA can generate high quality concrete (Bravo et al., 2015; Cantero et al., 2018; Medina et al., 2014).

Recent years have also witnessed a quest for new supplementary cementitious materials (SCMs) to lower natural resource consumption in the cement and concrete industries. To that purpose, studies have focused on valorising industrial biomass waste (Lv et al., 2019; Medina et al., 2019; Nakanishi et al., 2014), ornamental quarry sludge (Mármol et al., 2010; Medina et al., 2017; Sáez del Bosque et al., 2018), burnt clay (Scrivener et al., 2018) and similar. In light of the aforementioned issues on construction and demolition waste, few articles have also been published on the viability of using ground concrete as partial substitute of cement.

A number of researchers (Diliberto et al., 2017; S. Li et al., 2019) have studied the composition of some types of concrete dust generated during RCA production. They found that the dust analysed contained some active materials such as non-hydrated cement particles and a high SiO_2 content that may favour cement hydration when ground to the necessary fineness. Kwon et al. (2015) studied the chemistry of waste cementitious powder (WCP) with a view to manufacturing recycled cement. Based on the quantity of free CaO, X-ray diffraction and thermal analysis, they concluded that up to 30% WCP can be used as a main constituent in recycled cement and that such use would prompt a 46% fall in CO_2 emissions. Kim and Choi (2012) also prepared cement pastes from waste concrete powder (WCP) of varying fineness. They reported up to 62% reduction in viscosity and ~2 h delay in initial setting time in cement pastes with waste concrete powder at a replacement ratio of 45% or lower. In their conclusions, they stressed that, as the replacement had a coarser Blaine fineness and a larger particle size than OPC, less mixing water was involved in the chemical hydration reactions. According to their findings, the replacement ratio for this material should be no higher than 15%.

Much has yet to be understood about the use of ground recycled concrete as a cement replacement in mortar and concrete manufacture. Most of the literature focuses on the use of recycled cement paste (Prošek et al., 2019), mortar (Bogas et al., 2019) and concrete (Letelier et al., 2017) which, after crushing, milling and high-temperature (400 °C–900 °C) thermal treatment for up to 4 h (Bogas et al., 2019; Letelier et al., 2017; Shui et al., 2008) yields a dehydrated powder that could be used to replace a given fraction of cement. From the standpoint of sustainability and low carbon models, the thermal process involved is contrary to the objectives of low energy consumption and cutting of CO_2 emissions.

In contrast, Kim (2017) manufactured self-consolidating concrete with waste concrete powder obtained directly from RCA production as OPC replacement. That author designed mixes with 15%, 30% and 45% of the powder to replace OPC, using 466 kg/m^3 of binder and a constant water/binder (w/b) ratio of 0.38, varying the amount of superplasticiser (SP) from 1% to 1.5% depending on the amount of replacement in the new binder. The 28-day compressive strength was observed to decline in the same proportion as the replacement ratio. Tensile strength, in turn, declined by 40% and the modulus of elasticity by 20% in the mixes with 45% waste concrete powder, which the author argued is a non-reactive substance with no impact on concrete strength.

Xiao et al. (2018) also assessed the mechanical behaviour of concrete mixes made with recycled concrete and brick powder (RP) as OPC replacement. They prepared mixes with 15%, 30% and 45% RP, maintaining the same workability (90 mm) and a w/b ratio of 0.4 for 380 kg/m^3 and 0.5 for 360 kg/m^3 of binder. Workability was kept constant by raising the amount of superplasticiser from 2.0 kg/m^3 to 8.7 kg/m^3 as RP increased in the new binder. The authors concluded that replacing OPC with up to 30% RP had a minimally adverse effect on compressive strength (declines of $\leq$7.7%) and a beneficial effect on tensile strength. They attributed those good results to the presence of SiO_2 in RP. The beneficial filling and pozzolanic (reaction with hydrated $Ca(OH)_2$) effects induced allegedly offset the adverse effects of lower quantities of C–S–H due to the smaller amount of OPC. The RP used by these authors had a smaller mean particle size and a larger specific surface (640 m^2/kg vs 350 m^2/kg) than OPC, which greatly enhanced the aforementioned beneficial effects.

In that context, further scientific and technical knowledge is required on the viability of using ground recycled concrete as an OPC replacement in new concrete with recycled aggregate. Such a novel approach has not yet been adopted in international research in the field, nor has any study been published on the combined valorisation of ground recycled concrete (GRC) as an OPC replacement and MRA in concrete manufacture. The present article analyses the effect of the combined use of cement with 10% (RC_{10}) or 25% (RC_{25}) GRC and 50% RMA from C&DW as a partial replacement of natural coarse aggregate in structural concrete. The ambitious experimental programme designed explored the impact of such replacements on concrete compressive and tensile strength, modulus of elasticity and hardened density. The physical properties of the mixes were also analysed with non-destructive ultrasonic pulse velocity and electrical resistivity tests.

2. Materials and methods

2.1. Materials

2.1.1. Binders

Three binders were used to prepare the concrete mixes: i) type I, strength class 42.5 (CEM I 42.5 R) ordinary Portland cement (OPC); ii) a blend of 90% OPC and 10% GRC (RC_{10}); and iii) a blend of 75% OPC and 25% GRC (RC_{25}).

2.1.2. Source and preparation of ground recycled concrete

The ground recycled concrete (GRC) obtained by crushing and grinding laboratory-prepared concrete specimens was batched to a Faury method with 300 kg/m^3 of CEM II/A-L42.5 R cement and an effective water/cement ratio (w/c_{eff}) of 0.55. Concrete was designed for an XC3 environment and a target workability of S3 as defined in European standard EN 206–1 (European Committee for Standardization., 2013, p. 206). Four natural aggregates were used: i) coarse-crushed limestone gravel (12/22 mm); ii) medium-crushed limestone gravel (6/12 mm); iii) coarse siliceous coarse sand (2/4 mm); and fine siliceous sand (0/2 mm). Concrete was poured into 150 mm cubic and 150 × 300 mm prismatic moulds, demoulded after 24 h and subsequently cured in a humidity chamber (RH>95%) for 28 d. The 28-day concrete had a mean compressive strength of 39.8 MPa, a mean tensile strength of 2.75 MPa and a modulus of elasticity of 38.9 GPa.

The four stages involved in GRC preparation (Fig. 1) were: i) mixing, curing and testing the aforementioned specimens to breakage; ii) jaw crushing the cubic and prismatic specimens to a particle size of <16 m; iii) roll crushing the jaw-crushed particles to <5 mm; iv) ball-grinding the crushed concrete to the intended fineness at 60 rpm and a milling load of 56 kg per 20 kg of material for 2 h. The particle size distribution of the materials after each stage is plotted in Fig. 1.

2.1.3. Aggregates

The coarser of the two coarse natural crushed limestone aggregates (12/22 mm) was labelled NC-G and the medium aggregate (4/12 mm) NC-M, whilst the coarser (2/4 mm) of the two natural siliceous river fines was labelled NS-C and the finer (0/2 mm) NS-F. The particle size of the recycled aggregates (labelled RA-CDW) supplied by a C&DW recycling plant at Lisbon, Portugal, ranged from 0 mm to 25 mm. These aggregates were subsequently sieved at the laboratory, and sizes <4 mm and >22 mm were rejected.

2.2. Concrete design

The six concrete mixes prepared comprised two groups: i) mixes containing natural aggregates only, with OPC (NAC), 10% GRC (N10/0) or 25% GRC (N25/0); and ii) mixes containing 50% RA-CDW with OPC (R0/50), 10% GRC (R10/50) or 25% GRC (R25/50). The first group was designed to determine the effect of GRC as an addition and the second to ascertain the combined effect of GRC and RA-CDW.

All the mixes were designed as specified in European standard EN-206-1 (2013) for durability class XC2 and strength class C25/30, using 300 kg/m^3 of binder (OPC + GRC), i.e. >280 kg/m^3 set out in the standard. The composition of the six mixes used in the study is given in Table 1. Those of the reference NAC and RA-CDW were fitted to a Faury curve (J. Faury, 1958) for a maximum particle size of 22 mm. All the mixes were set to a target workability of S2 as defined in EN-206-1 (2013), equivalent to 70 ± 20 mm slump.

The amount of water required for the target workability was adjusted empirically in a preliminary stage. The total amount used in each mix (Table 1) was defined as the effective water plus the water needed to offset the amount absorbed by aggregate soaked

Table 1
Concrete mix design.

Mix	Component (kg/m^3)					
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
Cement	300.0	270.0	225.0	300.0	270.0	225.0
GRC	–	30.0	75.0	–	30.0	75.0
Total water	171.3	177.1	183.3	205.2	211.2	217.2
NS-F	154.0	150.0	154.0	154.0	154.0	154.0
NS-C	754.5	754.5	754.5	754.5	754.5	754.5
NC-M	367.0	367.0	367.0	183.6	183.6	183.6
NC-G	653.0	653.0	653.0	326.5	326.5	326.5
RA-CDW	–	–	–	449.0	449.0	449.0

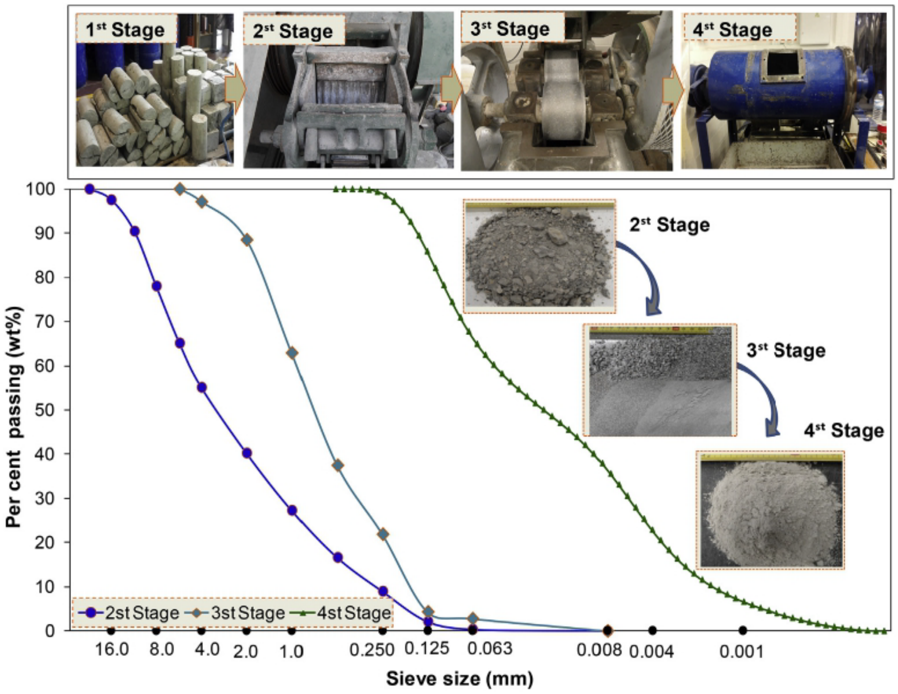

Fig. 1. Stages of recycled cement preparation (above) and particle size distribution in each stage (below).

for 10 min (approximately the mixing time). All the aggregates were used moist, subtracting the existing water from the total required in the mix.

2.3. Sample preparation and testing procedure

All the mixes were prepared in an 85 L revolving drum mixer with a constant volume to ensure comparability. All the aggregates were stored under laboratory conditions. The mixer and the laboratory materials used to estimate the fresh state properties were pre-dampened. The materials were mixed in three stages: i) the coarse (recycled and natural) aggregate was mixed for 4 min with two-thirds of the mixing water plus the amount of water to be absorbed by the aggregate; ii) the fines were added and the materials mixed for 2 min; iii) the binder plus the remaining one-third of the water were mixed for a further 4 min, for a total mixing time of 10 min. The specimens were prepared and cured as per European standard EN 12390−2 (2009d). After moulding, performed with particular care to minimise pouring and consolidation times, the specimens were wrapped in plastic and stored for 24 h. The demoulded specimens were stored in a humidity chamber at 20 ± 2 °C and 95 ± 5% humidity until tested. The physical and mechanical properties analysed in the fresh and hardened mixes are listed in Table 2.

2.4. Experimental design

A total of 24 specimens per mix were prepared to assess the effects of including GRC and RA-CDW on concrete density, compressive strength, ultrasonic pulse velocity and electrical resistivity. An additional 16 specimens per mix and batch, the maximum number possible given the volume accommodated by the laboratory mixer, were prepared to test for tensile strength. Monte Carlo simulations assuming a normal distribution and pessimistic estimates of variation in mechanical strength were conducted to ensure the sample size was suitable and the experimental design representative of 28-day properties. The experimental findings for the 246 specimens were tested statistically for normal distribution prior to calculating the coefficients of variation (CoV). All the tests were performed with the 5% maximum experimental error recommended in Model Code (2010) (2010).

3. Results and discussion

3.1. Aggregate properties

3.1.1. Composition

The compositional analysis of 4/22 mm RA-CDW (Table 3), conducted as specified in standard EN 933−11 (2010b), revealed that mortar and concrete (Rc) accounted for 47.1 wt%, fired clay ceramics (Ru: brick, roof, wall and ceiling tiles) for 22.6 wt% and natural aggregate for 25.2 wt%. The impurities identified included plaster (X_1, 1.8 wt%), glass (Rg, 1.7 wt%) and floating particles (FL, 1.0 wt%). Given that the Rcu (Rc + Ru) was over 70 wt% and the ceramic materials (Rb) under 30 wt%, the RA-CDW used was a type B RA, as defined in British standard BS EN 206−1 (BSI Standards Publication, 2013). It also qualified as recycled mixed aggregate (RMA) as per Spanish structural code EHE-08, as it contained $R_{cu} \leq 95$ wt% and Rb > 5 wt%.

Table 3
Coarse recycled aggregate composition.

Constituent	Amount (wt%)
Concrete and mortar (Rc)	47.1
Natural stone (Ru)	25.2
Clay materials (Rb)	22.6
Bituminous materials (Ra)	0.2
Glass (Rg)	1.7
Floating particles (FL)	1.0
Plaster (X_1)	1.8
Metals (X_2)	0.4
EN 12620 designation	Type BS EN-206−1
$Rc_{declared}$* Rcu_{70}, Rb_{30}-, Ra_{1-}, FL_{2-}, XRg_{2-}*	Type B

*incomplete values

3.1.2. Physical and mechanical properties

The properties of all the aggregates used to prepare the concrete mixes are listed in Table 4, according to which RA-CDW exhibited lower density and higher water absorption than NC-M and NC-G due to the higher porosity of its components (bound mortar, brick, tile) (Cantero et al., 2020a). The 24 h absorption coefficient found for RA-CDW (9.1 wt%, greater than 5 wt% recommended in EHE-08 (Comisión Permanente del Hormigón, 2008), is one of the major limitations to the use of recycled aggregate in concrete manufacture. It was nonetheless within the 5.5 wt% to 9.9 wt% range reported by Bravo et al. (2015) and Cantero et al. (2018) in their research on C&DW recycled aggregate, which contained 11 wt % to 29 wt% fired clay and 69 wt% to 87 wt% mortar and concrete particles.

At 44%, the Los Angeles coefficient (LA) found for RA-CDW was higher than 26 wt% for NC-G and 28 wt% for NC-M, denoting a lower abrasion resistance in the former, possibly due to the lesser hardness of some of its components (such as concrete and brick). The LA range reported in the literature for C&DW is 32 wt% to 52 wt % (Bravo et al., 2015; Cantero et al., 2019; Medina et al., 2014). The 20 wt% flakiness index (FI) observed for RA-CDW, compared with 16 wt% found for NC-G and NC-M, was attributed to the sharp edges on the brick, tile and other fired clay materials in C&DW.

3.2. Binder properties

Density and X-ray fluorescence (XRF)-determined chemical

Table 2
Concrete properties characterised and standards applied.

Test method	Standard	Curing time (d)	Specimen shape and size
Slump test	EN 12350:2 (European Committee for Standardization, 2009a)	Fresh concrete	–
Fresh density	EN 12350−6 (European Committee for Standardization, 2009b)		
Air content	EN 12350−7 (European Committee for Standardization, 2009c)		
Hardened density	EN 12390−7 (European Committee for Standardization, 2001)	28	Cubic: 150 × 150 × 150 mm
Compressive strength	EN 12390−3 (European Committee for Standardization, 2009d)	7, 28, 56, 91	
Ultrasonic pulse velocity	EN 12504−4 (European Committee for Standardization, 2004)		
Electrical resistivity	UNE 83988−2 (Spanish Committee for Standardization, 2014)	28	
Splitting tensile strength	EN 12390−6 (European Committee for Standardization, 2010a)	28	Cylindrical: 150 mm Ø x 300 mm
Modulus of elasticity	EN 12390−13 (European Committee for Standardization, 2014a)		

Table 4
Physical and mechanical properties of the aggregates.

Property	ρ_{ssd} (kg/m^3)	ρ_{od} (kg/m^3)	W_{24h} (wt%)	W_{10min} (wt%)	LA (wt%)	FI (wt%)
NS-F	2601	2583	0.4	0.2	–	–
NS-C	2609	2599	0.5	0.3	–	–
NC-M	2630	2599	1.3	0.5	28	13
NC-G	2670	2640	1.3	0.6	26	16
RA-CDW	2256	2068	9.1	8.1	46	20

Note: ρ_{ssd}: saturated surface dry density, ρ_{od}: oven dry density, W_{24h}: 24 h absorption coefficient (European Committee for Standardization, 2014b), W_{10min}: 10 min absorption coefficient (Rodrigues et al., 2013), ***LA:*** Los Angeles coefficient (European Committee for Standardization, 2010c), ***FI:*** flakiness index (European Committee for Standardization, 2012).

Table 5
Chemical components and physical properties of OPC and GRC.

Component (wt%)										
Binder		Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	LoI*
OPC**		0.20	1.80	5.10	18.70	3.00	0.50	65.10	2.60	2.50
GRC		0.30	0.50	3.80	46.10	0.40	1.20	40.00	1.50	6.20
WCP (literature)	min	0.13	1.24	3.84	18.20	0.44	0.35	11.82	1.34	6.00
	max	3.02	3.53	13.55	58.55	1.47	3.53	47.70	6.37	28.93

Density (g/cm^3)			
OPC	**GRC**	**Literature on waste concrete powder**	
		min	max
3.11	2.54	2.40	2.63

Note. - *LoI: loss on ignition; **CEM I 42.5 R ordinary Portland cement.

composition of the binders used are listed in Table 5, along with the findings reported by earlier authors using waste mortar or concrete powder as a binder for pastes (Prošek et al., 2019; Li et al., 2019), mortars (Bogas et al., 2019; Diliberto et al., 2017) and concrete (Kim, 2017; Kim and Choi, 2012; Kwon et al., 2015 and S. Xiao et al., 2018). As the XRF data show, the majority oxides in GRC were SiO_2, which at 46.10 wt% was higher than in OPC (18.70 wt%) and CaO with 40.00 wt%, a value lower than observed in OPC (65.10 wt%). The higher SiO_2 in the GRC was attributed to the presence of siliceous sand in the source concrete. Density was lower in GRC (2.54 g/cm^3) than in OPC (3.11 g/cm^3).

The crystalline phases in GRC (Fig. 2) included quartz, calcite, feldspars, muscovite and plagioclase, along with the alite and belite present in the anhydrous cement.

The particle size distribution of OPC and GRC plotted in Fig. 4 shows that D_{90} (90th percentile particle size) in GRC was 147 µm compared to 46 µm in OPC. At 10 µm and lower (D_{10}), GRC exhibited a smaller particle size than OPC, attributed to the bound mortar in recycled aggregate, which is not as hard as the natural aggregates in the source concrete. GRC morphology (see micrographs in Fig. 3) comprised larger, irregularly shaped particles - aggregates with bound mortar - and smaller clusters with a rough surface - the mortar and paste fraction.

Table 6 lists the initial setting times, water demand for a normal consistency and soundness (EN 197-3, 2017) of the binders used in this study (OPC, RC_{10} and RC_{25}). The data showed that, although including GRC lengthened the initial setting time due to the lower reactivity of GRC and its larger particle size than in OPC, the end concrete was European standard 197-1-compliant for this property. Water demand rose with the incorporation of GRC, due in particular to the greater sorptivity of the mortar present and the larger percentage of particles <10 µm. The use of ground concrete had no adverse effect on soundness, which was also EN 197-1-compliant.

Table 6 also gives the compressive strength of the cements used, all of which complied with the requirements for strength class 42.5 R cement. Strength declined by 7.43% with the incorporation of 10% GRC and by 23.9% with 25% GRC relative to OPC, an indication of the low reactivity of this addition.

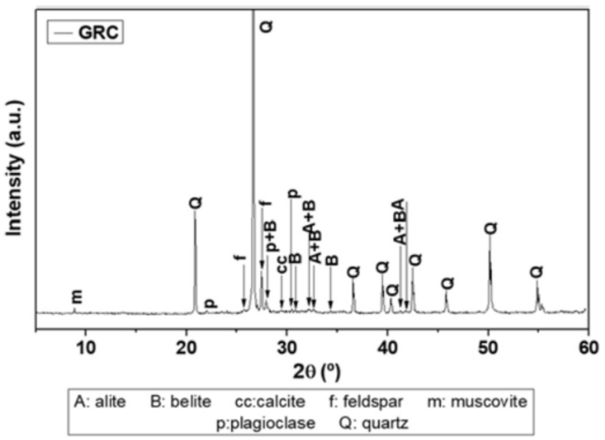

Fig. 2. Mineralogical composition of GRC.

3.3. Fresh concrete properties

3.3.1. Workability

The effective water/binder ratio (w/b_{eff}) found in the preliminary workability trials and the slump values for each mix listed in Table 7 show that the w/b_{eff} ratio had to be raised for higher GRC contents in the mixes with natural and RA-CDW aggregates both: from 0.56 to 0.60 in the NA mixes (NAC, N10/0 and N25/0) and from 0.59 to 0.63 in the RA-CDW mixes (R0/50, R10/50 and R25/50). This may be associated with the presence of more irregularly shaped, < 6 µm particles in GRC than in OPC (Kim, 2017; Zhu et al., 2016) and the greater water demand exhibited by the new binders (RC_{10} and

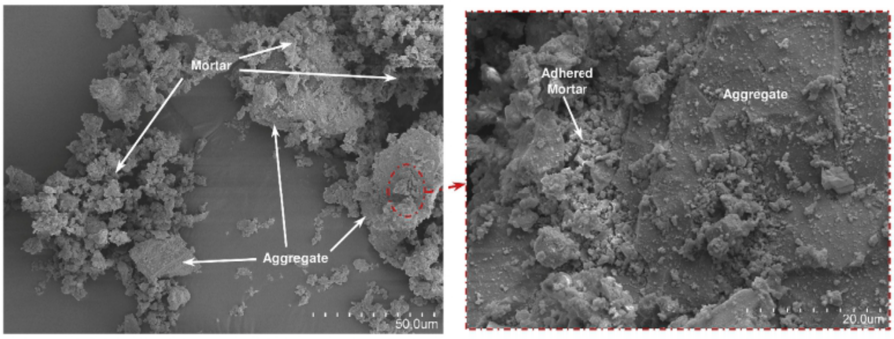

Fig. 3. Ground recycled concrete morphology.

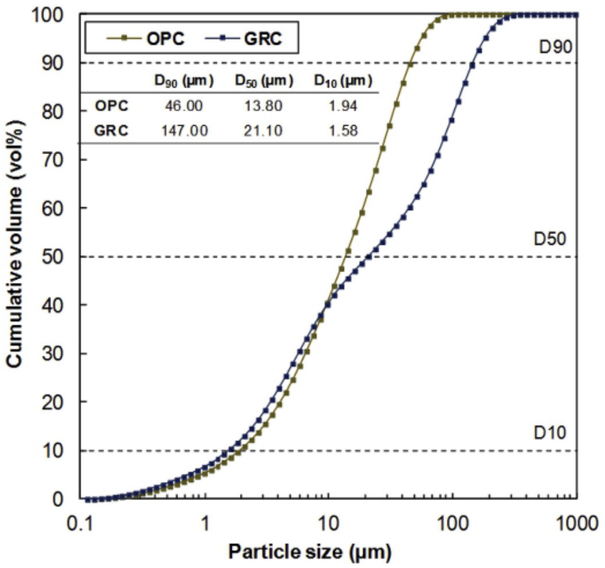

Fig. 4. Laser diffraction particle size distribution in OPC and GRC.

RC_{25}). The data also indicated that the rise in w/b_{eff} prompted by including RA-CDW could be due to the greater flakiness (flat surfaces and sharp edges) of RA-CDW than the NA particles (Table 4). The concomitant decline in workability would have to be offset with a higher water content. These findings were consistent with earlier reports by Xiao et al. (2018) studying concrete mixes prepared with up to 45% concrete and brick powder (RP) as OPC replacement, in which workability was observed to be lower in RP than in OPC concrete due to the higher sorptivity and irregular shape of the former. That lower workability was offset by increasing the amount of (water-reducing) plasticiser with rising contents of the addition to retain a constant w/b_{eff}.

3.3.2. Fresh concrete density and air content

The fresh mix density (ρ) and air content (Ac) values for all the mixes studied (Table 8) declined with rising contents of GRC and the presence of recycled aggregate. That decline, directly related to the lower density of the latter and the nature (irregular shape, porosity) of the former, as well as to the lower cement content, translated into a smaller volume of hydration products. The data also showed that including GRC led to a steeper decline in NA ($\leq$2.5%) than in RA-CDW ($\leq$1.4%) fresh mix density and that the use of RA-CDW (mixes R0/50, R10/50 and R25/50) played the predominant role on the decline of that parameter. Those observations were attributed to the up to 4.9% lower density of RA-CDW (Table 4) compared to the reference mix (NAC). The values recorded nonetheless fell within the 1%–5% range for mixes made with 25% ground C&DW and 50% RMA (Cantero et al., 2019).

The use of GRC and RA-CDW raised the air content in all the mixes, due primarily to the greater porosity of the majority components (mortar, fired clays and concrete) present in the latter and the porosity of the former. Higher air content was observed by Tahar et al. (2017) in recycled aggregates, and attributed to the air bubbles in recycled sands not present in natural fines. The steepest rise recorded here, up to 19%, was exhibited by the RA-CDW mixes. That behaviour was consistent with the findings reported by Cantero et al. (2019) in their study of mixes prepared with both 25% ground C&DW (RC-CDW) and 50% RMA. A 17% greater air content was observed in mixes made with both 25% RC-CDW and 50% RMA than in those prepared with 50% RMA and a conventional binder.

Table 7
Effective water/binder ratio (w/b_{eff}) and slump in the mixes (±denotes standard deviation).

Mix	w/b_{eff}	Slump (mm)
NAC	0.56	65 ± 2.8
N10/0	0.58	74 ± 2.5
N25/0	0.60	65 ± 3.7
RA-CDW	0.59	75 ± 3.1
R10/50	0.61	61 ± 3.7
R25/50	0.63	63 ± 4.2

Table 6
Binder characteristics and standard requisites.

Property	OPC	RC_{10}	RC_{25}	EN 197–1*
Initial setting time (min)	84	90	91	≥60
Water demand (g)	143	144	147	–
Soundness (variation, mm)	0	0	0	≤10
28 d compressive strength (MPa)	67.5 ± 1.0	62.6 ± 1.0	51.39 ± 2.2	≥42.5

Note. - *Strength class defined as 42.5 R.

Table 8
Fresh concrete density *(ρ)* and air content *(Ac)*.

Property	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
ρ (kg/m^3)	2367 ± 8	2340 ± 9	2309 ± 10	2251 ± 11	2244 ± 12	2219 ± 10
Effect of GRC (%)[a]	–	−1.1	−2.5	–	−0.3	−1.4
Effect of RA-CDW (%)[b]				−4.9	−4.1	−3.9
Effect of GRC + RA-CDW (%)[c]					−5.2	−6.3
Ac (vol%)	2.6 ± 0.1	2.7 ± 0.2	2.9 ± 0.2	3.2 ± 0.2	3.4 ± 0.3	3.8 ± 0.2
Effect of GRC (%)[a]	–	3.8	11.5	–	6.2	18.8
Effect of RA-CDW (%)[b]				23.1	25.9	31.0
Effect of GRC + RA-CDW (%)[c]					30.8	46.2

[a] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50.
[b] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50.
[c] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

All the air content values were under 4%, in keeping with earlier studies on mixes made with up to 70% RCA (Tahar et al., 2017).

Fig. 5 plots density against air content in the fresh NA and RA-CDW mixes. The graph shows a high linear correlation between the two properties ($R^2 \geq 0.97$), particularly in the GRC + RA-CDW mixes due to the greater impact of RA-CDW porosity in such cases (Table 7).

3.4. Hardened concrete properties

3.4.1. Hardened concrete density

The 28-day bulk density (ρ_b) in the hardened mixes is depicted in Table 9. The use of GRC in the mixes with natural aggregate only (mixes N10/0 and N25/0) led to slight declines (<2%) relative to the reference NAC. Density declined linearly with rising GRC due to the lower density and reactivity of that material than of anhydrous OPC and the smaller volume of hydration products (due to the lower percentage of cement). The result was a more porous cementitious matrix (see section 3.2). Whilst the combined incorporation of GRC and RA-CDW induced no decline in mix R10/50's density relative to mix R0/50, mix R25/50 was lightly less dense. These findings were consistent with the fresh state density values given in Table 8, where the simultaneous incorporation of 10% GRC and 50% RA-CDW (mix R10/50) lowered the value less (by 4.5%) than the use of 50% RA-CDW only (down by 5.1%), a development not observed for the mix with 25% GRC and 50% RA-CDW (R25/50).

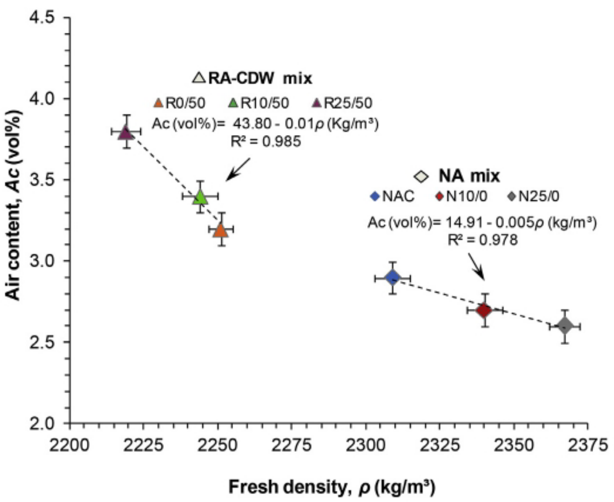

Fig. 5. Variation in fresh state density (ρ) with fresh state air content (Ac) in mixes.

3.4.2. Compressive strength

Further to the 28-day compressive strengths listed in Table 10, mix N10/0 had 19% and mix N25/0 40% lower compressive strength than the reference NA (NAC). As Fig. 6 shows, the decline was gradual and linear with rising GRC replacement ratio, a result attributed primarily to the lower amount of cement, low GRC reactivity and higher effective w/b_{eff} ratio. It was also consistent with the lower compressive strength of the new binders prepared with 10% (RC_{10}) and 25% (RC_{25}) GRC (Table 6). On the other hand, Kim, 2017 prepared concrete mixes replacing 15% and 30% of the OPC with waste concrete powder generated during RCA production. These authors reported declines of 15% and 30% because their study used a constant w/b_{eff} ratio. Workability consequently varied between the two mixes, while strength fell in the same proportion as the replacement ratio.

The 25% lower compressive strength observed here in mix R0/50 relative to the reference NAC was due primarily to the intrinsic characteristics of RA-CDW, especially its higher porosity and lower abrasion resistance [60, 61] associated with the bound mortar and fired clay material in its composition, and to the rise in w/b_{eff} required to obtain the desired workability.

When the two wastes (GPC + RA-CDW) were combined (mixes R10/50 and R25/50), the strength recorded was 29.5% (R10/25) and 49.9% (R25/5) lower than in NAC. Those lower values were attributed primarily to three factors: i) the incorporation of GRC; ii) the incorporation of RA-CDW, which was more porous and hence weaker than NA; and iii) the presence of a new ITZ between the RA-CDW and mortar weaker than the ITZ between NA and mortar. When the effect of the first two factors was analysed separately, GRC was found to prompt 5.8% lower strength in R10/50 and 33.1% lower in R25/50, whereas RA-CDW induced a 13.1% decline in R10/50 and a 15.9% decrease in R25/50. The inference is that compressive strength in mix R10/50 was more highly impacted by the use of 50% RA-CDW than by the incorporation of 10% GRC. Those values were consistent with earlier observations by Letelier et al. (2017) for mixes made with 5%, 10% and 15% recycled hydrated cement (RHC) and 30% RCA. Those authors found that in mixes with up to 15% RHC and 30% RCA. the factor with the greatest impact on the mechanical performance of the mixes was the presence of low quality RCA. Such earlier findings revealed the implications on the compressive strength of mixes made with low quality (Letelier et al., 2017) RA containing a high percentage of impurities (such as plaster or floating particles) (Medina et al., 2015).

The standard deviation, coefficient of variation (CoV) and normal quantile plots at 95% confidence in the 28-day mixes are plotted in Fig. 6. Both standard deviation (error bars) at < 1.5 MPa and coefficient of variation (CoV) at <4% denoted slight differences between the reference and the experimental mixes, as well as 'very good' or 'good' laboratory preparation of the mixes as defined in

Table 9
28-day bulk density in the concrete mixes studied.

Property	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
ρ_b (kg/m^3)	2370 ± 12	2339 ± 14	2332 ± 13	2253 ± 12	2261 ± 12	2225 ± 10
CoV (%)	0.7	0.6	0.6	0.7	0.6	1.0
Effect of GRC (%)[a]	–	−1.1	−1.6	–	0.6	−1.1
Effect of RA-CDW (%)[b]				−5.1	−3.4	−4.6
Effect of GRC + RA-CDW (%)[c]					−4.5	−6.1

[a] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50.
[b] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50.
[c] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

Table 10
28-day compressive strength of the concrete mixes.

Property	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
f_{cm} (MPa)	46.6 ± 1.2	37.8 ± 1.4	27.7 ± 0.9	34.8 ± 1.2	32.8 ± 1.4	23.3 ± 0.9
Effect of GRC (%)[a]	–	−18.9	−40.4	–	−5.8	−33.1
Effect of RA-CDW (%)[b]				−25.2	−13.1	−15.9
Effect of GRC + RA-CDW (%)[c]					29.5	49.9

[a] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50.
[b] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50.
[c] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

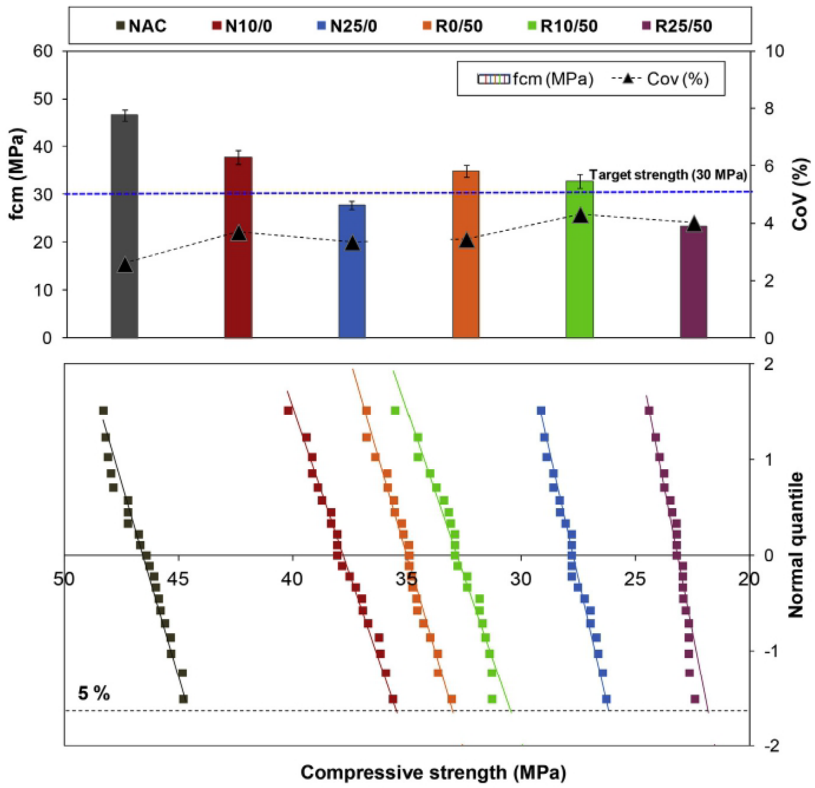

Fig. 6. Statistical parameters (above) and normal quantile plots (below).

ACI-214R-11 for mixes with strength < 35 MPa. Three main conclusions can be drawn from the quantile plots: i) the results were uniformly distributed along the theoretical normal distribution; ii) the standard deviations were small and the normality curves had high slopes; and iii) some data (dotted line) were near the 5% characteristic strength referenced in Eurocode 2 (European Committee for Standardization, 2016) (EC-2) to estimate characteristic compressive strength (fck) in construction design. These data were consistent with the normal data distributions observed by Pacheco et al. (2019) in mixes with 100% RCA and Cantero et al. (2018) in mixes made with 50% RMA.

Further to the variation in strength with age plotted in Fig. 7, the incorporation of GRC and the combined use of GRC + RA-CDW had no effect on new concrete hardening, for all the mixes followed a pattern similar to that of the reference NAC.

Table 11 lists the 28-day compressive strengths for the cubic and cylindrical specimens, along with the strength class as per EC-2. All the mixes except N25/0 and R25/50 met the design phase requirements for strength class C25/30. The mix with 10% GRC (N10/0) qualified for an even higher strength class, 30/37. Based on these criteria, mixes N10/0, N25/0, R0/50 and R10/50 could be used in structural and mix R25/50 in non-structural applications.

3.4.3. Splitting tensile strength

As the data in Table 12 show, the incorporation of GRC induced a decline in 28-day splitting tensile strength of 13% in mix N10/0 and 20% in N25/0 relative to the reference NAC. That effect was again due to dilution and the lower reactivity resulting from the incorporation of GRC. The non-reactive particles in GRC may lead to higher porosity and therefore to lower concrete strength (Qin and Gao, 2019). The use of RA-CDW alone (R0/50) induced a 17.5% decline in tensile strength relative to NAC, a value within the 9%–21% range reported for mixes made with 50% C&DW RA (Bravo et al., 2015).

Tensile strength was 21% (R10/50) and 48% (R25/50) lower than in mix NAC when GRC and RA-CDW were combined. A separate analysis of each factor showed that the effect of GRC was 4% lower strength in R10/50 and a 37% drop in R25/50, whereas RA-CDW led to a 9% decline in R10/50 and a 36% decrease in R25/50. This shows that using 10% GRC in mixes prepared with 50% RA-CDW had no significant impact on tensile strength. Those patterns were consistent with the compressive strength findings discussed in item 3.4.2, with mix R10/50 strength impacted more intensely by the incorporation of 50% RA-CDW than by the use of 10% GRC. Earlier studies also reported small amounts (<15%) of mineral additions (fly ash, (Kou et al., 2007); metakaolin, (Bui et al., 2019); and paper sludge ash (Bui et al., 2019)) to have no significant adverse effect on the mechanical performance of concrete with up to 100% RCA compared to mixes with 100% RCA and a conventional binder.

The 28-day tensile strength, standard deviation, coefficient of

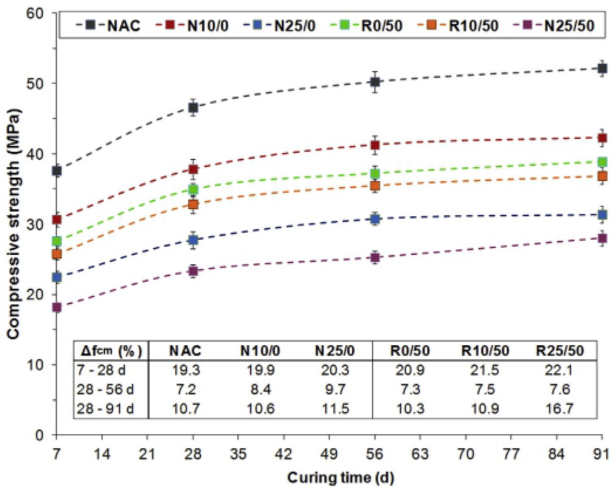

Fig. 7. Variation in compressive strength with curing time.

Table 11
28-day compressive strength and EC-2 strength class in cubic and cylindrical specimens.

f_{cm} (MPa)	Mix					
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
$f_{cm,cube}$	46.6	37.8	27.7	34.9	32.8	23.3
$f_{cm,cylinder}$	42.8	34.8	26.5	28.5	26.9	18.3
EC-2[a]	C35/45	C30/37	C20/25	C25/30	C25/30	C12/15

[a] **Note:** strength class in EC-2 is designated CX/Y, where X is the characteristic 28-day compressive strength value in 15 × 30 cm cylindrical specimens and Y the characteristic compressive strength in 15 × 15 cm cubic specimens.

variation (CoV) and normal quantile plots at 95% confidence are plotted in Fig. 8. The data showed that CoV tended to decline with tensile strength in both the NA and RA-CDW mixes, a pattern generally observed for this parameter and reported earlier for mixes made with 25% recycled ground C&DW and up to 50% RMA (Cantero et al., 2019). The CoV values were within the normal 5%–30% range established for splitting tensile strength tests on mixes with up to 25% FA and 100% RCA (Pacheco et al., 2019; Xiao et al., 2016). All the normal quantile plots on the lower part of the figure attested to a good fit to the normal distribution.

Tensile strength is commonly expressed in terms of compressive strength. Further to EC-2 (2016), in structural concrete for normal use and a strength class of ≤ C50/60, 28-day tensile strength can be expressed as: $f_{ctm} = 0.30 \times f_{ck}^{\frac{2}{3}}$, where f_{ck} is the characteristic 28-day compressive strength in cylindrical concrete specimens.

Fig. 9 plots 28-day f_{ctm} against 28-day f_{ck} for the NA and RA-CDW mixes, along with the EC-2 (2016) equation and the 95% confidence intervals ($f_{ctk,095}$ and $f_{ctk,0.05}$) for the characteristic tensile strength specified in the code. As the graph shows, as both the NA and the RA-CDW mixes stood above the lower limit ($f_{ctk,0.05}$) for tensile strength, they are useable in the manufacture of structural concrete, for the design value specified in EC-2 is calculated with the following equation (Equation (1)):

$$f_{ctd} = \frac{\alpha_{ct} \times f_{ctk,0.05}}{\gamma_c} \quad (1)$$

Where f_{ctd} is the design tensile strength, $f_{ctk,0.05}$ is the characteristic 28-day tensile strength in concrete, α_{ct} is a coefficient that factors in the long-term effects on tensile strength (with a recommended value of 1.0) and y_c is a partial safety factor for concrete whose value is 1.50.

These findings are consistent with the results of Silva et al. (2015), who studied the effect of using RA on concrete tensile strength by analysing 590 samples of RA concrete reported in the literature. They observed that 97.5% of all the mixes lie above the lower limit defined for tensile strength and concluded that neither RA nor mineral additions used in concrete had any effect on the 28-day tensile or compressive strength and that the specifications presently in place for conventional concrete are applicable to such materials.

3.4.4. Modulus of elasticity

The 28-day modulus of elasticity (E_{cm}) values of the mixes are listed in Table 13. Incorporating GRC lowered E_{cm} by 7% in mix N10/0 and by 13% in N25/0 relative to the reference NAC, values that fall within the same range (6%–15%) as reported by Kim (2017) for mixes with up to 30% waste concrete powder. With the incorporation of RA-CDW, mix R0/50 exhibited E_{cm} 25% lower than NAC, a decline similar to 22% observed by. Bravo et al. (2015) in mixes with 50% RA with a composition similar to that of RA-CDW. The

Table 12
28-day tensile strength of the concrete mixes.

Property	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
f_{ctm} (MPa)	3.1 ± 0.5	2.7 ± 0.4	2.5 ± 0.2	2.6 ± 0.3	2.5 ± 0.3	1.6 ± 0.1
Effect of GRC (%)[a]	–	−12.9	−19.9	–	−4.0	−37.1
Effect of RA-CDW (%)[b]				−17.5	−9.0	−35.7
Effect of GRC + RA-CDW (%)[c]					−20.8	−48.2

[a] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50.
[b] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50.
[c] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

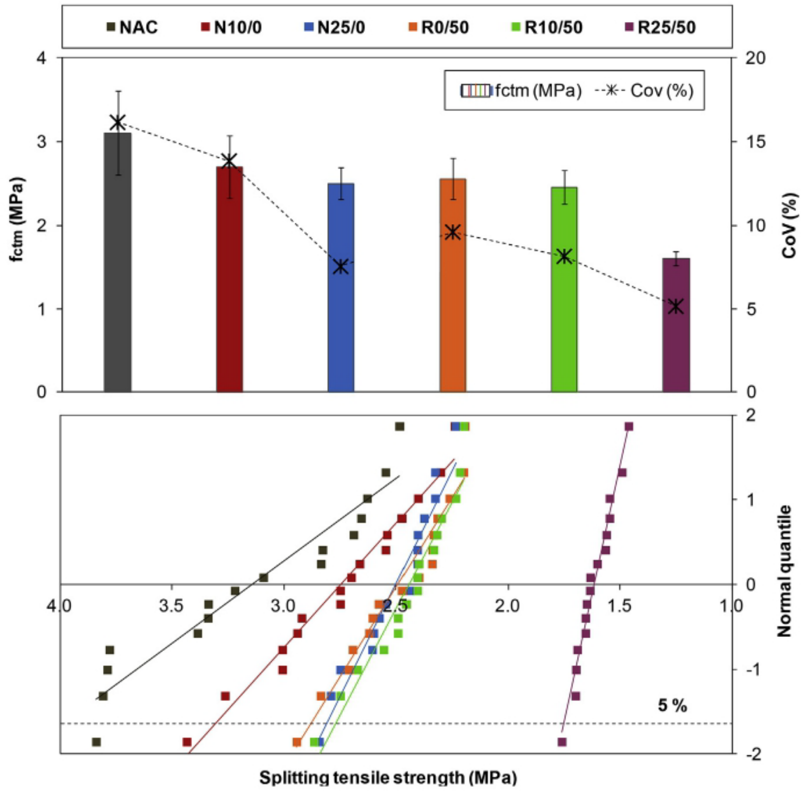

Fig. 8. Statistical parameters (above) and normal quantile plots (below) for 28 day tensile strength.

combined use of GRC + RA-CDW brought E_{cm} down by 27% in R10/50 and by 35% in R25/50 relative to the reference NAC.

A separate analysis of the effect of each factor (GRC and RA-CDW) revealed that incorporation of the former linearly lowered the modulus of elasticity in both the NA ($R^2 = 0.96$) and RA-CDW ($R^2 = 0.94$) mixes (Fig. 10). In this figure, the vertical distance (ordinates) between the NA and RA-CDW values for a given GRC content is indicative of the effect of adding RA-CDW, whereas the vertical distance (ordinates) between the points for a given family (NA or RA-CDW) reveals the effect of replacing cement with GRC. The findings showed that the effect of using RA-CDW, at 26%, was much greater than that of using GRC (13%) (Table 13) Alnahhal et al. (2017) studied the effect of manufacturing concrete with 100% RCA and 10%, 20% or 30% of rice husk ash, palm oil ash or palm oil clinker powder to replace OPC. They found RCA to have a much more significant effect, of up to 23%, on the decline in E_{cm} than replacing OPC with up to 30% of any of the by-products, which was consistently under 12%. The effect was attributed primarily to the greater stiffness and porosity of RCA relative to NA. In an earlier study, Corinaldesi and Moriconi (2009) explored the effect of fly ash and silica fume (<35%) as OPC replacements in mixes with 100% RMA. They likewise found E_{cm} to depend more heavily on the lower compressive strength prompted in the concrete by 100% RMA and to be insignificantly impacted by the presence of the mineral additions.

As per EC-2 (2016), E_{cm} can be expressed in terms of mean concrete compressive strength as follows (Equation (2)):

$$E_{cm} = 22 \times \left(\frac{fcm}{10}\right)^{0.3} (f_{cm} \text{ in MPa}) \quad (2)$$

EC-2 recommendations that call for increasing E_{cm} by 20% for basalt aggregate and lowering it by 10% for limestone and by 30% for sandstone are depicted in the curves labelled 'EC2-Basalt

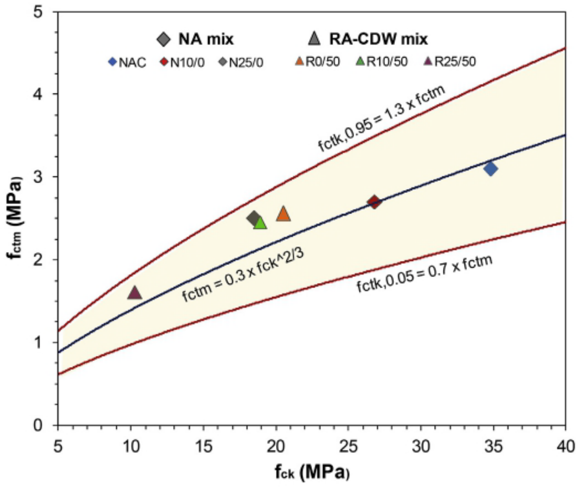

Fig. 9. Variation in 28 day tensile strength (f_{ctm}) with 28 day compressive strength (f_{ck}).

aggregates' and 'EC2-Sandstone aggregates' in Fig. 11. The figure also plots E_{cm} against the f_{cm} values from the literature for mixes with natural ('NAC from literature') or 50% recycled ('R50 from literature') aggregates (De Juan and Gutierrez, 2004; Kou et al., 2007), where the authors assessed the effect of using NA and coarse RCA on mixes made with a wide range of w/c ratios.

As the figure shows, both the NA (NAC, N10/0, N25/0) and the RA-CDW (R0/50, R10/50, R25/50) mixes fall within the ranges observed in the literature for the corresponding materials. The mixes with GRC as well as those containing both GRC and RA-CDW yielded E_{cm} values lying above the curve proposed in EC-2 for mixes made with sandstone. The inference is that even when the two types of waste (GRC + RA-CDW) were combined to manufacture concrete, the modulus of elasticity of the resulting mixes complied with the EC-2 specifications for NAC.

3.4.5. Ultrasonic pulse velocity

As the 28-day ultrasonic pulse velocity (UPV) readings listed in Table 14 show, using GRC lowered the values by 2% in N10/0 and by 6% in N25/0 relative to the reference NAC. Those findings are related to the lower density of concrete (Table 9) in N10/0 and N25/0 due to the lower density of GRC relative to OPC (Table 5). The present values were 10% lower than those observed by Sasanipour et al. (2019) for concrete mixes made with up to 25% SF as OPC replacement, although those authors also attributed the reduction found in the UPV to the lower density of SF relative to OPC. The UPV of the mix prepared here with 50% RA-CDW (R0/50) fell by 8% relative to the reference NAC, a decline related to the higher porosity observed for RA-CDW relative to NA (Kwan et al., 2012). It nonetheless fell within the 5%–20% range reported for mixes made

Table 13
28-day modulus of elasticity values of the concrete mixes studied.

Property	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
E_{cm} (GPa)	35.0 ± 0.9	32.5 ± 1.1	30.6 ± 1.5	26.3 ± 1.1	25.7 ± 1.1	22.8 ± 1.0
Effect of GRC (%)[a]	–	−7.3	−12.7	–	−2.3	−13.1
Effect of RA-CDW (%)[b]				−24.9	−26.4	−25.3
Effect of GRC + RA-CDW (%)[c]					−26.7	−34.8

[a] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50.
[b] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50.
[c] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

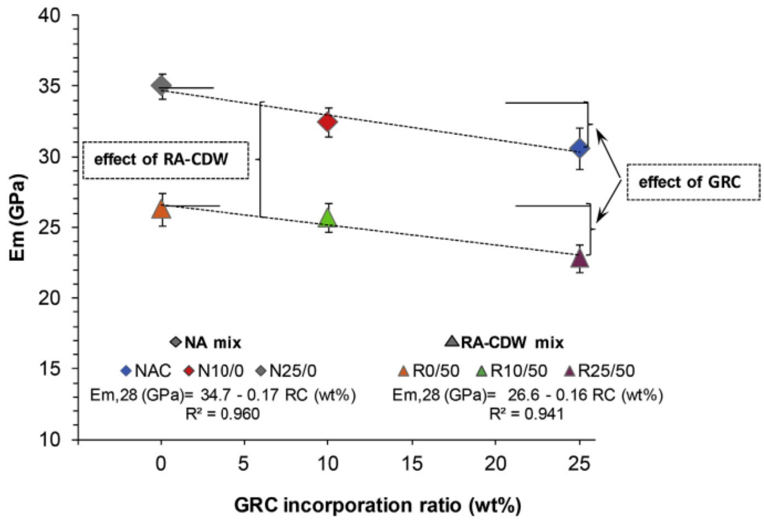

Fig. 10. Effect of including GRC on 28 day E_{cm} in NA and RA-CDW mixes.

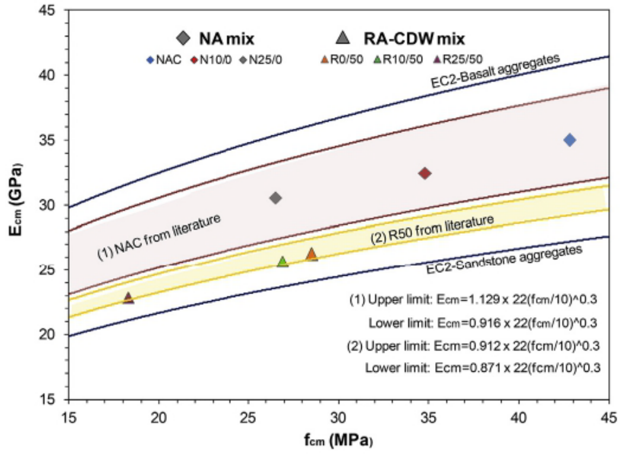

Fig. 11. Variation in E_{cm} with f_{cm} for RA and RA-CDW mixes.

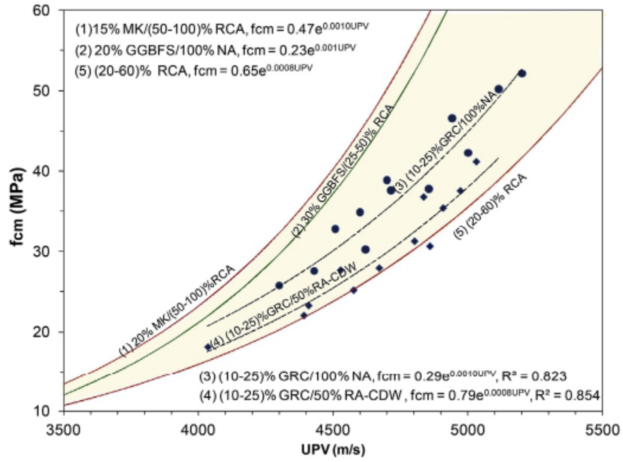

Fig. 12. UPV *versus* compressive strength (f_{cm}) in concrete.

with up to 60% RCA (Muduli and Mukharjee, 2019; Sasanipour et al., 2019; Tuyan et al., 2014). The combined use of GRC and RA-CDW induced a decline in UPV of 9% in R10/50 and 11% in R25/50 relative to the reference NAC. The breakdown of those values by factor (Table 14) showed that the use of GRC in the RA-CDW mixes reduced the adverse effect of replacing 50% of the natural with recycled aggregate.

A number of authors (Alnahhal et al., 2017; Costa and Marques, 2018; Saint-Pierre et al., 2016) deem UPV values of over 4500 m/s to denote excellent quality concrete and those between 3600 m/s and 4500 m/s good quality concrete. As the data in Table 14 show, all the mixes could be regarded as excellent quality concrete, with the exception of R25/50, which exhibited a UPV indicative of a good quality material.

UPV is plotted against compressive strength in Fig. 12 at 7, 28, 56 and 91 days. The figure also shows the relationship between the two parameters for: 1) mixes with 50% or 100% RCA plus 15% metakaolin “15% MK/(50–100)% RCA” (Kou et al., 2011)); 2) mixes with 100% NA and 20% ground granulated blast furnace slag “20% GGBFS/100% NA” (Shariq et al., 2013)); 3), 4) the present experimental data and 5) mixes with 20% or 60% RCA and no additions “(20–60)% RCA” (Tuyan et al., 2014).

As the data in the figure show, the exponential relationship between UPV and compressive strength in the mixes studied here had a high correlation coefficient ($R^2 > 0.82$), in keeping with the values reported by other authors (Alnahhal et al., 2017; Kou et al., 2011). All the values fall within the limits found for mixes with 60% RCA or containing either 50% or 100% RCA with 15% MK or 20% GGBFS with 100% NA.

3.4.6. Electrical resistivity

The 28-day electrical resistivity (ER) findings for 150 cm cubic specimens are given in Table 15. Using GRC lowered ER by 8% in N10/0 and by 15% in N25/0 relative to the reference NAC as a result of the greater porosity of the new mixes, attributed in turn to the dilution entailed by the partial replacement of OPC with GRC and the higher water/cement ratio required to maintain the target workability. The electric current flowed more readily through the more porous cementitious matrices, lowering ER (Cantero et al., 2020b; Sengul, 2014). With the incorporation of RA-CDW, ER declined by 9% in R10/50 and 12% in R25/50 relative to the reference NAC. The effect of combining GRC and RA peaked at a moderate 12% in R25/50.

3.5. CO_2 emissions from concrete

The environmental impact of the mixes designed is given in Table 16 in terms of the CO_2 emitted by the materials. Manufacturing- and transport-related emissions, which according to Yang et al. (2015) are generally smaller than those generated by material production, were disregarded.

The values shown were taken from Damtoft et al. (2008) for cement, Fib (2012) for natural river sand (NS–F and NS-C) and natural coarse aggregate (NC-M and NC-G) and Hossain et al. (2016) for recycled aggregate (RA-CDW). The CO_2 emissions owing to GRC were calculated from electric power consumption as described in item 2.1.2. As total consumption was 0.140 kWh/kg and 1 kWh is deemed to generate 1.35 kg CO_2 (Turner and Collins, 2013), the CO_2 emitted by GRC came to 0.188 kg/kg. In earlier research, Tan et al. (2020) reported a slightly higher value (0.245 kg/kg) for recycled

Table 14
28-day UPV values in concrete mixes.

Property	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
UPV (m/s)	4941 ± 89	4855 ± 72	4626 ± 59	4532 ± 71	4508 ± 71	4407 ± 88
CoV (%)	1.8	1.5	1.3	1.6	1.6	2.0
Effect of GRC (%)[a]	–	−1.7	−6.4	–	−0.5	−2.7
Effect of RA-CDW (%)[b]				−8.3	−7.1	−4.7
Effect of GRC + RA-CDW (%)[c]					−8.8	−10.8

[a] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50.
[b] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50.
[c] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

Table 15
28-day ER values of the concrete mixes.

	NA mix			RA-CDW mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
ER (Ωxm)	75 ± 3.0	69 ± 3.0	64 ± 2.0	72 ± 4	68 ± 3	65 ± 3
CoV (%)	4.3	4.2	3.6	5.4	5.1	4.0
Effect of GRC (%)[2]	–	−8.0	−14.6	–	−5.1	−9.1
Effect of RA-CDW (%)[3]				−3.6	−0.6	2.6
Effect of GRC + RA-CDW (%)[3]					−8.6	−12.4

Notes: [1] Effect of GRC (%) found by comparing NAC to N10/0, NAC to N25/0, R0/50 to R10/50 and R0/50 to R25/50. [2] Effect of RA-CDW (%) found by comparing NAC to R0/50, N10/0 to R10/50 and N25/0 to R25/50. [3] Effect of GRC + RA-CDW (%) found by comparing NAC to R10/50 and NAC to R25/50.

Table 16
CO_2 emitted by concrete mixes.

Material	CO_2 emitted (kg/kg)	CO_2 emitted by mixes (kg/m^3)					
		NAC	N10/0	N25/0	R0/50	R10/50	R25/50
Cement	0.860	258.00	232.20	193.50	258.00	232.20	193.50
GRC	0.188	0.00	5.46	13.65	0.00	5.46	13.65
Water	0.00020	0.03	0.03	0.04	0.04	0.04	0.04
NS-F	0.004	0.62	0.60	0.62	0.62	0.62	0.62
NS-C		3.02	3.02	3.02	3.02	3.02	3.02
NC-M	0.008	2.94	2.94	2.94	1.47	1.47	1.47
NC-G		5.22	5.22	5.22	2.61	2.61	2.61
RA-CDW	0.003	0.00	0.00	0.00	1.35	1.35	1.35
Total		269.83	249.65	218.43	267.10	246.94	216.70
Δ CO_2 emission (%)		–	−7.5	−18.7	−1.0	−8.5	−19.7

powder derived from mixed recycled aggregate. The lower value observed here may be attributed to the longer milling time deployed in that study than in this one, as well as to differences in milling facility specifications.

Further to the data in Table 16, the use of GRC lowered CO_2 emissions by 7.5% in N10/0, 18.7% in N25/0, 8.5% in R10/50 and 19.7% in R25/50. Those declines were similar to the 9.7%–19.4% range reported by Song et al. (2019) in concrete containing from 10% to 25% granulated blast furnace slag.

4. Conclusions

The conclusions that may be drawn from this study are set out below:

- The GRC used had a higher SiO_2 and a lower CaO content than OPC. The values for both compounds fall within the range for this type of waste reported in the literature. Due to the presence of natural aggregates in the source concrete, 60% of the GRC particles were larger than the OPC particles, possibly lowering new binder (RC_{10} and RC_{25}) reactivity;
- The w/b_{eff} ratio had to be raised in the preliminary design stage to maintain the workability of the GRC + NA and GRC + RA-CDW mixes, due to: i) the greater water demand attributed to the bound mortar present in GRC, which was more porous than OPC; and ii) the greater angularity of the RA-CDW compared to the NA particles:
- Compressive strength was more heavily impacted by the use of 50% RA-CDW than by the incorporation of 10% GRC. Based on the present findings, the mixes prepared with 50% RA-CDW and those made with both 10% GRC and 50% RA-CDW would be apt for structural applications, as they met the requirements for EC-2 strength class C25/30;
- The incorporation of GRC lowered tensile strength by 20% in the NA mixes and by 37% in the RA-CDW mixes due to the dilution effect and the lower reactivity of the new recycled binders (RC_{10} and RC_{25});
- The relationship between modulus of elasticity and compressive strength appeared to be unaffected by GRC or the combined presence of GRC and RA-CDW. Given that many standards estimate both tensile strength and modulus of elasticity from concrete compressive strength on the grounds of that relationship, that lack of variation should favour the wider use of such mixes in structural concrete;
- Based on their ultrasonic pulse velocity readings, all the mixes prepared with both GRC and RA-CDW could be deemed excellent quality concrete, with the sole exception of the mix with 25% GRC and 50% RA-CDW, which exhibited good quality. Ultrasonic pulse velocity findings can be used to compute compressive strength in the mixes with GRC and RA-CDW from the equation relating the two parameters;
- The electrical resistivity analyses showed that readier ion mobility across the pore structure in the new mixes lowered ER values by no more than 14%, even in the mix with 25% GRC and 50% RA-CDW;
- In combination with RA-CDW, the use of GRC enhanced concrete environmental performance. At 10% replacement, it lowered the CO_2 emitted in concrete manufacture by 8.5% and at 25% GRC by 19.7% relative to concrete made with OPC and 100% NA.

In short, mixes with 10% ground recycled concrete and 50% recycled aggregate met the mechanical performance requisites for strength class 25/30 structural concrete. Those findings may be extrapolated to concrete with recycled aggregate of a similar quality to those used in this study, bearing in mind that quality is closely related to their constituents (concrete, unbound aggregate, clay-based materials…). Such findings will help the construction industry design concrete with a smaller carbon footprint and contribute to reducing the volume of construction and demolition waste presently stockpiled in recycling plants.

CRediT authorship contribution statement

B. Cantero: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **M. Bravo:** Methodology, Validation, Resources, Writing - review & editing. **J. de Brito:** Conceptualization, Formal analysis, Writing - review & editing, Supervision, Funding acquisition. **I.F. Sáez del Bosque:** Conceptualization, Investigation, Writing - review & editing. **C. Medina:** Conceptualization, Supervision, Methodology, Project administration, Funding acquisition, Writing - review & editing.

Declaration of competing interest

The authors have no interest that may have influenced the research described in this paper.

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Capítulo 8

Water transport mechanisms in concretes bearing mixed recycled aggregates

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Water transport mechanisms in concretes bearing mixed recycled aggregates

Resumen

La entrada de agentes agresivos del medio ambiente a través de la estructura porosa del hormigón induce procesos de degradación que comprometen la vida útil de las estructuras de hormigón. La viabilidad de incorporar materiales reciclados en el diseño de hormigones estructurales requiere un conocimiento previo de su efecto en los mecanismos de transporte de agua, al tratarse del medio que actúa como vehículo principal de los agentes agresivos externos (sulfatos, ácidos…) que penetran a través de su estructura porosa. En el presente trabajo de investigación se presentan los resultados de varios indicadores de durabilidad tales como resistividad eléctrica, permeabilidad de agua bajo presión, absorción de agua total, absorción de agua capilar y porosidad accesible al agua que permiten evaluar directa e indirectamente la penetración de agua, y consecuentemente predecir el comportamiento a lo largo de la vida útil de los hormigones reciclados que incorporan entre un 20 % - 100 % de áridos reciclados mixtos (ARM). Los resultados revelan que la incorporación de ARM a los 28 días de curado en hormigones con hasta un 75 % de ARM muestran valores de absorción de agua, porosidad y profundidad máxima de agua a presión por debajo del 7 % en peso, 15 % en peso y 30 mm, respectivamente, correspondientes a hormigones de buena calidad. Adicionalmente, si consideramos una mayor edad de curado, hasta 90 días, estos valores se reducen hasta en un 40 %. En cuanto, a la resistividad eléctrica la incorporación de hasta un 100 % de ARM no modifica el riesgo de corrosión de los nuevos hormigones, encontrándose todos valores entre 50 Ω.m - 100 Ω.m a los 28 días. Finalmente, y la vista de los resultados presentados en esta investigación, la incorporación de hasta un 75 % de ARM, es viable para el diseño de nuevos hormigones estructurales más sostenibles y de buena calidad, desde una perspectiva de sus propiedades durables.

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Water transport mechanisms in concretes bearing mixed recycled aggregates

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ABSTRACT

Aggressive agents present in the environment that penetrate concrete through its pore structure induce deterioration, compromising the service life of concrete members. Determining the viability of using recycled materials in structural concrete calls for a prior understanding of their effect on water transport, the primary vehicle for external agent ingress. This article describes durability indicators such as electrical resistivity, water permeability (pressure testing), total water absorption, effective porosity and sorptivity that directly or indirectly measure water penetration and consequently performance across the service life of concrete bearing 20% to 100% mixed recycled aggregate (MRA). The 28 d concretes studied here with up to 75% MRA exhibited <7% weight gain due to water absorption, <15 vol% porosity and <30 mm maximum depth of water penetration under pressure, all indicative of high quality concrete. In 90 d materials, the values of the aforementioned parameters were 40% lower. Even in concrete with up to 100% MRA (with 28 d readings of 50 Ω m to 100 Ω m), electrical resistivity remained unaffected, The present findings reveal that high quality high durability structural concrete can be viably manufactured with up to 75% MRA.

1. Introduction

The deterioration-mediated shortening of the service life of concrete structures carries social, environmental and economic consequences. Huge investment is often required in industrialised nations to repair and maintain existing structures when concrete durability is compromised. An understanding of the agents involved in concrete deterioration is therefore of cardinal importance in structural design able to guarantee a long service life.

Specific indicators are used to quantify properties that determine concrete capacity to resist attacks by external agents that shorten its service life. Indicators measuring the attack itself are deemed to be direct, whereas those that measure the transport of agents into and through concrete are regarded as indirect. The properties associated with aggressive agent ingress into concrete include water absorption, permeability to water and air, porosity and sorptivity [1,2].

These considerations are of particular significance under the present circumstances, in which the construction industry is making efforts to move toward greater sustainability and a circular economy by reusing construction and demolition waste (C&DW) [3]. According to Eurostat [4], C&DW accounts for over one-third of all the waste generated in the European Union. Two main types of recycled aggregate (RA), which together account for approximately 70% of the total [5], are presently in use. The first, recycled concrete aggregate (RCA), is processed from crushed concrete waste, whilst the second, mixed recycled aggregate (MRA), is based on mixed C&DW waste. The latter category can be divided into two sub-categories, mixed recycled aggregate per se and ceramic (burnt clay) mixed recycled aggregate.

The use of coarse RA in concrete manufacture is subject to constraints due to the material's higher porosity and water absorption and lower density than natural aggregate (NA), which translate into lower durability in recycled [6–8] than in conventional concrete [9–12]. That notwithstanding, RCA has become a new alternative raw material in some countries and its use is envisaged in standards dealing with the design and construction of concrete structures [13–17], in particular in scantly aggressive environments. Further to a consensus opinion in the literature, the use of small percentages (~30%) prompts no rise in permeability, whereas at higher values RCA induces a decline in

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performance which must be borne in mind so as not to compromise service life [18–22].

Both subcategories (mixed and ceramic) of mixed recycled aggregate are used primarily as landfill for landscape restoration, pipe ditches and road base and sub-base layers [23–25]. Nonetheless, although some research today is focusing on the mechanical performance of new concretes [26–33], only a short number of studies on how MRA affects concrete durability has been published [26,28,34,35]. The resulting gap in the scientific-technical understanding research of water transport mechanisms and their interaction with other properties in new recycled concretes calls for research in that area.

Medina et al. [26] observed that the use of MRA had no adverse effect on capillary absorption in concretes with up to 25% MRA, whereas at replacement ratios of around 50% values rose by 10% to 20% relative to conventional concrete. The authors concluded that based on their strength and durability, recycled concretes with up to 50% MRA were apt for housing construction. Medina et al. [36], studying the effect of 20% and 25% ceramic sanitary ware waste on water penetration in concretes, also found that the use of such aggregate induced a slight rise in total porosity and altered the pore size distribution. They further reported that in concretes with up to 25% recycled ceramic aggregate the maximum penetration depth of water under pressure was below the 30 mm ceiling laid down in Spanish structural concrete code EHE-08 [13]. They consequently deemed concretes in which NA was replaced with ceramic industry rejects to be viably impermeable to water.

Bravo et al. [28] studied the effect of different types of C&DW containing 4% to 29% ceramic waste on the total and capillary water absorption of concretes prepared with replacement ratios of 10% to 100%. They found that including 25% to 100% RA induced a 20% to 70% rise in total and a 5% to 41% rise in capillary water absorption, although no such increases were observed in those properties at 10% replacement. They concluded that at ratios of 25% or higher RA had an adverse effect on concrete durability and that the presence of significant fractions of ceramic materials in RA should be avoided in concrete subject to strict durability requirements. Along the same lines, González-Corominas and Etxeberria [37] concluded that capillary absorption was the property most severely affected in recycled concretes bearing 100% MRA due to the higher porosity and water absorption of that material, in which ceramics account for ~67 wt%. Concretes prepared with up to 50% MRA exhibited suitable durability, however.

Alexandridou et al. [35] studied the effect of RA containing 70% to 90% concrete waste and ~10% ceramic waste from different Greek C&DW management plants on total water absorption, effective porosity and sorptivity in concretes with 25% to 75% recycled aggregate. Their findings showed that in concretes with up to 75% RA total water absorption rose by 30% and sorptivity by 52% relative to conventional concrete. These authors concluded that the use of RA lowered concrete durability but that recycled concrete with up to 50% of the material was sufficiently durable.

The inter-relationships between the water transport mechanisms directly affecting recycled concrete durability were explored and modelled in this study to advance the understanding of the viability of including MRA in such materials. That entailed determining the durability of mixes with 20% to 100% MRA by analysing effective porosity as well as durability indicators such as penetration depth of water under pressure, water absorption, sorptivity and electrical resistivity. The interaction among the aforementioned properties was also studied to shed light on the overall effect of using MRA on concrete durability and assess its possible applicability in the design of full-scale concrete members, to ultimately favour the use of recycled concretes in certain types of civil works and building construction.

2. Materials and methods

2.1. Materials

The MRA used in this study consisted in coarse (12/22 mm, MRA-C) and medium (6/12 mm, MRA-M) gravel furnished by the ARAPLASA C&DW management plant at Plasencia in the Spanish region of Extremadura.

Further to the composition of the MRA given in Table 1, >88 wt% consisted in concrete, mortar and unbound aggregate, irrespective of particle size distribution. Fired clay blocks, roof tiles, sanitary ware and similar accounted for around 7 wt% and other materials for <1 wt%.

A commercial NA used, siliceous crushed graywacke, contained sand (NS, 0/6 mm) and coarse (12/22 mm, NG-C) and medium (6/12 mm NG-M) gravel. The particle size distribution of the aggregate studied, graphed in Fig. 1 along with the limits specified in ASTM standard C33 [39] for the use of aggregate in concrete manufacture, shows that with the exception of the coarsest fraction of the natural sand used (sieve size >4.75 mm), all the coarse aggregates were standard-compliant. Table 2 lists the physical and mechanical properties of the NA and MRA used, along with the respective requirements in European standard EN 12620 [40] and Spanish structural concrete code EHE-08 [13].

The cement used, a 42.5 R conventional Portland cement (CEM I 42.5 R) furnished by a Lafarge Holcim cement plant located in the Spanish province of Toledo, conformed to the physical, chemical and mechanical requirements laid down in EN 197-1 [41]. It exhibited 2 day compressive strength of 31.5 MPa, 7 day strength of 57.2 MPa and 28 day strength of 64.8 MPa. Water demand for a normal slump was 149 g, setting time was 2 h 45 min and Le Chatelier mould expansion was 1 mm.

BRYTEN NF, the water-based modified polycarboxylate superplasticiser used in all the mixes, had a density of 1.1 g/cm^3 and a solids content of 20%.

2.2. Experimental program, testing procedure and specimen preparation

Six concrete mixes were prepared: a conventional concrete with natural aggregate (the reference concrete, RC) and concretes with 20% (R20), 25% (R25), 50% (R50), 75% (R75) and 100% (R100) MRA.

The strength, resistivity and water transport coefficients of the concretes prepared are given in Table 3, together with the standard defining the procedure used, test age and specimen size. Each test was conducted on four specimens per mix and age.

The specimens for the capillary absorption test were pre-conditioned to ensure the same starting moisture in all and hence their comparability. Pre-conditioning consisted in laboratory oven drying at 50 ± 2 °C for 4 d, subsequent wrapping in steam-proof polyethylene and return to the oven for a further 3 d. The specimens were then set in an airtight container and stored at 20 ± 2 °C and 70 ± 5% relative humidity for 21 d. Moisture was guaranteed with a sodium chloride-saturated solution further to the procedure set out in Spanish standard UNE 83966 [42].

Finally, during the test specimens were sealed with adhesive tape on all but the side in direct contact with the water to ensure a one-

Table 1
Coarse recycled aggregate constituents (EN 933-11 classification [38]).

Class	Type	Amount (wt%)	
		MRA-C	RMA-M
Rc	Concrete and mortar	46.98	43.98
Ru	Natural stone	44.92	43.84
Rc + Ru		91.90	87.82
Rb	Fired clay materials	7.15	10.93
Ra	Asphalt	0.56	0.87
FL	Floating particles	0.17	0.02
X	Plaster	0.04	0.34
X + Rg	Others and glass	0.19	0.02

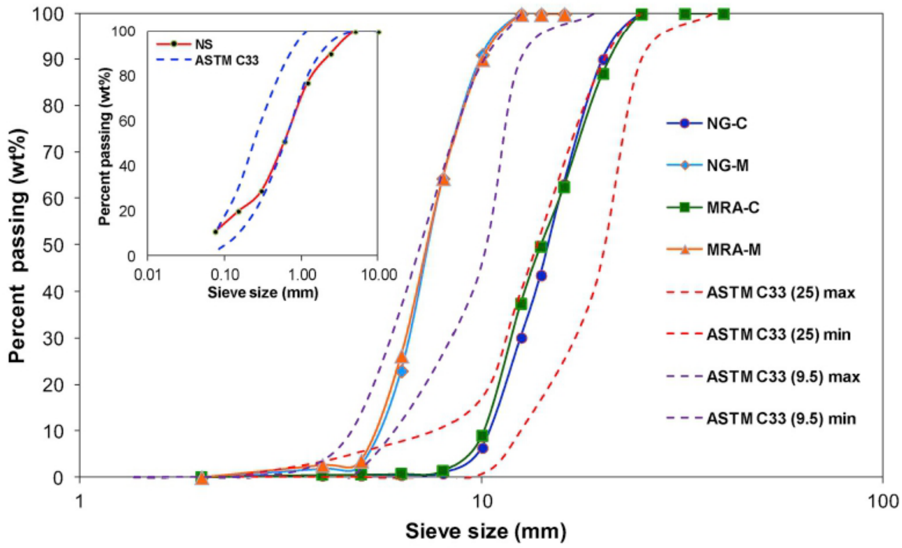

Fig. 1. Particle size distribution of the NA and RA studied and the limits specified in ASTM C33 for use in concrete manufacture.

Table 2
Physical, mechanical and chemical properties of the aggregates.

Property [reference No. for standard]	Aggregate					
	NS	NG-C	NG-M	MRA-C	MRA-M	EN-12620/ EHE 08
SSD[a] density (kg/m³) [41]	2760	2740	2740	2450	2420	–
Relative particle density (kg/m³) [41]	2.82	2.77	2.78	2.65	2.66	–
Absorption coefficient (wt%) [41]	1.18	0.78	0.88	5.27	6.28	<5
Los Angeles coefficient (wt%) [42]	–	18	16	36	32	40
Flakiness index (wt %) [43]	–	25	21	10	10	35

[a] ***Note.*** *- SSD: Saturated surface dry.*

Table 3
Concrete properties characterised and standards followed.

Test method	Standard	Curing time in days	Specimen shape and dimensions
Slump test	EN 12350:2 [46]	–	–
Compressive strength	EN 12390-3 [47]	28	Cubic: 150 x 150 × 150 mm
Electrical resistivity	UNE 83988-2 [48]	1, 3, 7, 14, 21, 28 and 90	Cylindrical: 100 mm Ø x 200 mm
Water penetration depth under pressure	EN 12390-8 [49]	28 and 90	Cylindrical: 150 mm Ø x 300 mm
Total water absorption	UNE 83980 [50]	28 and 90	Cylindrical: 100 mm Ø x 200 mm

dimensional water flow.

2.3. *Concrete design*

The mixes were batched to the British method [43], i.e., using the following starting conditions: 28 d concrete characteristic strength in cylindrical specimens (15Φ cm x 30 h cm), f_{ck} = 30 MPa; cement strength class, 42.5 R; effective w/c ratio, 0.45; and aggregate with a maximum size of 20 mm, considering its natural moisture and water absorbed. The theoretical composition of the mixes designed, after correcting the water content for the moisture present in the aggregate when the concrete was prepared, is given in Table 4.

The concretes were prepared in the laboratory as follows. The coarse and fine aggregate were blended in the mixer for 30 s. The cement was then added and the mixer rotated for 60 s to ensure a uniform blend of the three solid components. The admixture was dissolved in 10% of the total water content and mixed with the solids for 45 s. With the mixer still in operation, 70% of the total volume of water was added and mixed for 120 s, after which (with the mixer running), the remaining 20% of the water was added and mixed for 240 s. The mixer was then switched off, the fresh state properties were determined and the mix poured into the respective moulds [44].

3. Results and discussion

3.1. *Workability and compressive strength in cubic specimens*

The slump and 28 d compressive strength values in Table 5 show that the use of MRA induced no loss in concrete workability: all the values (11 cm–14 cm) lay within the range for fluid consistency defined in EHE-08 [12] (10 cm–15 cm) and the range for consistence class S3 (likewise 10 cm to 15 cm) established in European standard EN 206-1 [45]. The findings were in keeping with the pattern reported by other authors [26, 44] for MRA, in which the use of RA had no adverse effect on the workability of concretes prepared with a constant effective w/c ratio.

Replacing up to 50% of NA with MRA induced no decline in new concrete compressive strength. At 100% replacement (R100), compressive strength was at most 7% lower in those materials than in the conventional concrete (RC). Those findings were consistent with the results reported by Bravo et al. [28] for the mechanical properties of concretes made with several types of recycled aggregate sourced from different C&DW treatment plants. Those authors observed declines in 28 d compressive strength ranging from 5% to 34% in concretes prepared with up to 100% RA, which they attributed to the compositional non-uniformity of the different types of RA used. From the mechanical standpoint, then, these concretes would be apt for building structural members.

Table 4
Concrete batching.

Mix	Component (kg/m³)								
	NS	NG-C	NG-M	MRA-C	MRA-M	Cement	Water	w/c_{eff}[a]	SP[b]
RC	732.36	766.69	382.96	–	–	400.00	193.03	0.45	6.20
R20	720.79	603.66	301.53	146.24	72.60	400.00	200.21	0.45	6.20
R25	720.79	565.94	282.69	182.80	90.75	400.00	202.08	0.45	6.20
R50	705.38	369.22	184.43	357.77	177.62	400.00	210.63	0.45	6.20
R75	693.81	181.58	90.70	527.86	262.06	400.00	219.02	0.45	6.20
R100	678.39	–	–	688.17	341.65	400.00	226.83	0.45	6.20

[a] **w/c_{eff}:** effective w/c ratio.
[b] **SP:** superplasticiser.

Table 5
Workability and strength of the 28 d mixes studied.

Mix	Property	
	Slump (cm)	Compressive strength (MPa)[a]
RC	11 ± 1.08	51.16 ± 0.12
R20	13 ± 1.28	51.56 ± .0.81
R25	12 ± 1.78	51.69 ± .0.45
R50	13 ± 2.04	51.56 ± 0.41
R75	13 ± 2.28	49.69 ± 0.69
R100	14 ± 2.38	47.78 ± 0.35

±: standard deviation.
[a] tested in 15 cm cubic specimens (further to European standard EN 206-1 [55], a conversion factor of 0.80 must be applied to these values to find the reference strength in 15 × 30 cm cylindrical specimens).

3.2. *Electrical resistivity*

Further to the electrical resistivity (ER)/MRA content plots in Fig. 2, all the saturated concretes exhibited higher ER at 28 d than at 90 d. That behaviour was related to cement hydration processes and gradual densification of the cementitious matrix over time that induced a change in concrete pore structure, as observed earlier in concretes made with RA derived from concrete [46–48,52], ceramic sanitary ware [49], crushed brick waste [50] or recycled glass sand [51].

Two stages can be distinguished in Fig. 2: up to 7 d and from 8 d to 90 d. ER rose most steeply in the first week in all the concretes, by 69% to 76% of the 28 d value. That was due primarily to the rapid early age formation of hydration products. After the first week, ER continued to rise steadily but more moderately up to 90 d.

As Fig. 3 shows, replacing NA with MRA in the concretes prompted a decline in ER, a finding consistent with earlier observations for recycled concretes made with 10% to 100% RCA [18,57,59] containing 25% to 50% crushed brick [50]. The authors attributed the declines observed primarily to the higher porosity of the bound mortar and ceramic material in the recycled aggregate and the higher water absorption in RCA than in natural aggregate, which affected the degree of saturation of the concrete pores.

The ER findings for 28 d and 90 d concretes shown in Fig. 3 revealed that ER was indirectly related to the MRA replacement ratio (28 d $R^2 = 0.890$; 90 d $R^2 = 0.930$). That linear decline with rising RA is consistent with earlier observations for concretes prepared with 25% and 100% RCA [53].

The ER values for the 28 d materials, which ranged from 86 Ω m to

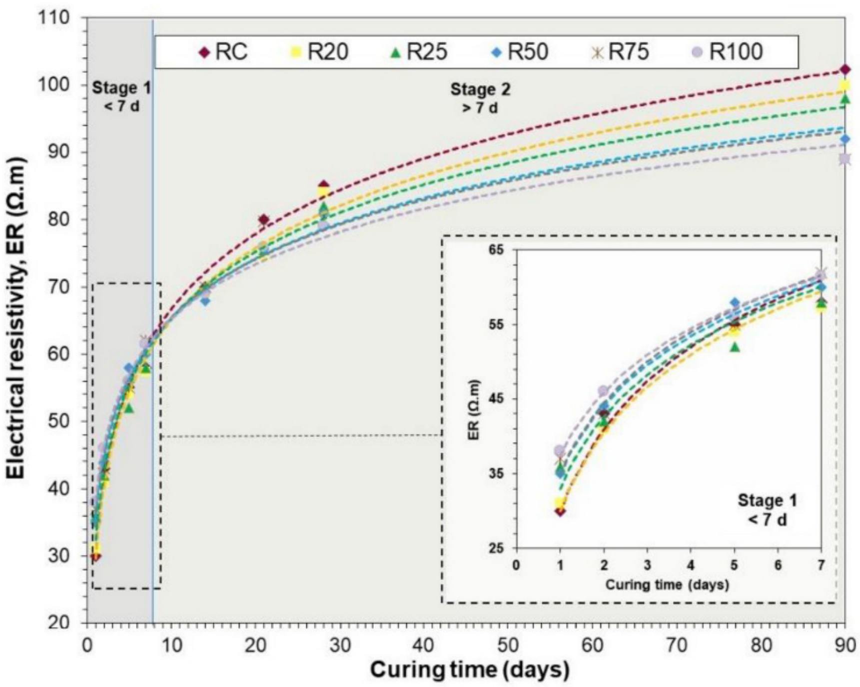

Fig. 2. ER vs time in the concretes studied.

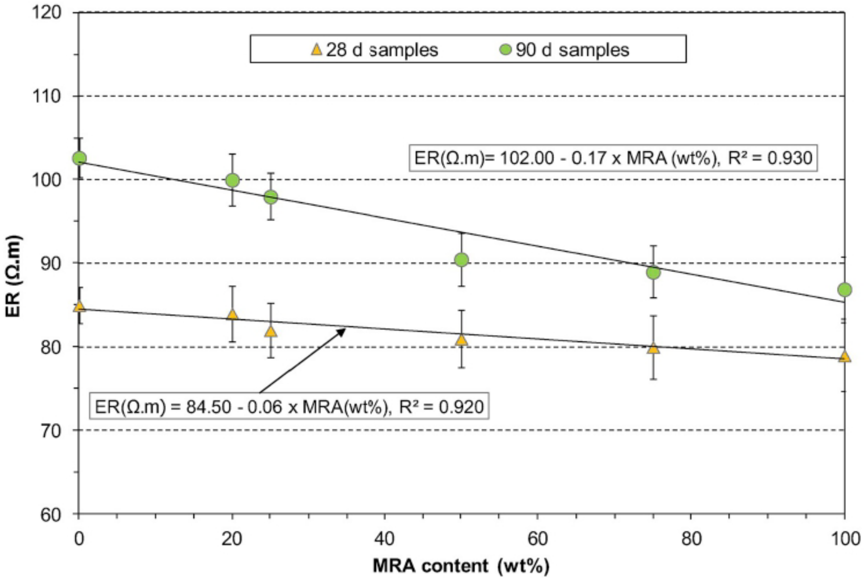

Fig. 3. ER vs MRA content in 28 d and 90 d concretes.

79 Ω m, declined by 1% in mix R20, 6% in R25, 8% in R75 and 10% in R100 relative to the reference concrete (RC). Dodds et al. [56] reported declines in ER of 3% to 30% in concretes bearing 30% to 100% RCA. The dips found here lay at the lower end of that range, inferring that on the whole the concretes studied here exhibited higher performance.

The 90 d concretes exhibited ER values of 102 Ω m to 89 Ω m. The decline in ER was greater than in the 28 d concretes, the mix R20 dipping by 3%, R25 by 5%, R50 by 12%, R75 by 14% and R100 by 16% relative to RC. However, these declines were lower than the 13% to 49% range observed in concretes containing between 25% and 100% RCA [57].

Fig. 4 shows that ER was linearly related to compressive strength in 7 d, 28 d and 90 d cubic specimens (see supplementary data, Annex I). ER rose with curing age and aligned with the compressive strength results, as per Equation (1) below. The respective R^2, at 0.920, attested to the good correlation between the two properties.

$$ER_{cube} = 1.260 \times fcm_{cube} - 7.242 \quad (1)$$

where ER_{cube} is electrical resistance in Ω·m and fcm_{cube} is concrete compressive strength in MPa, both measured in 150 mm cubic specimens.

The foregoing is in keeping with earlier reports [58] on 7 d to 90 d concretes made with natural aggregate, according to which ER was linearly related to compressive strength.

3.3. Water penetration depth under pressure

Fig. 5 shows the 28 d and 90 d maximum (D_{max}) and mean (D_a) water

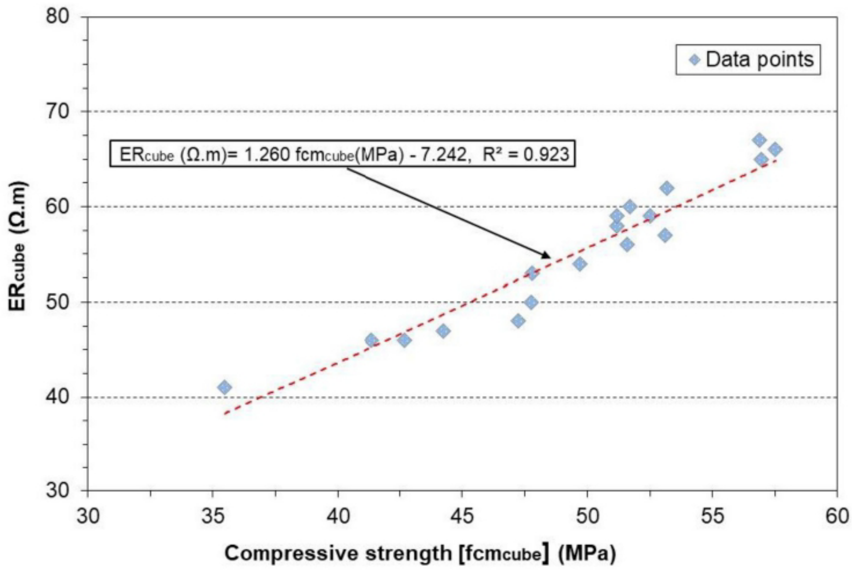

Fig. 4. Compressive strength vs ER.

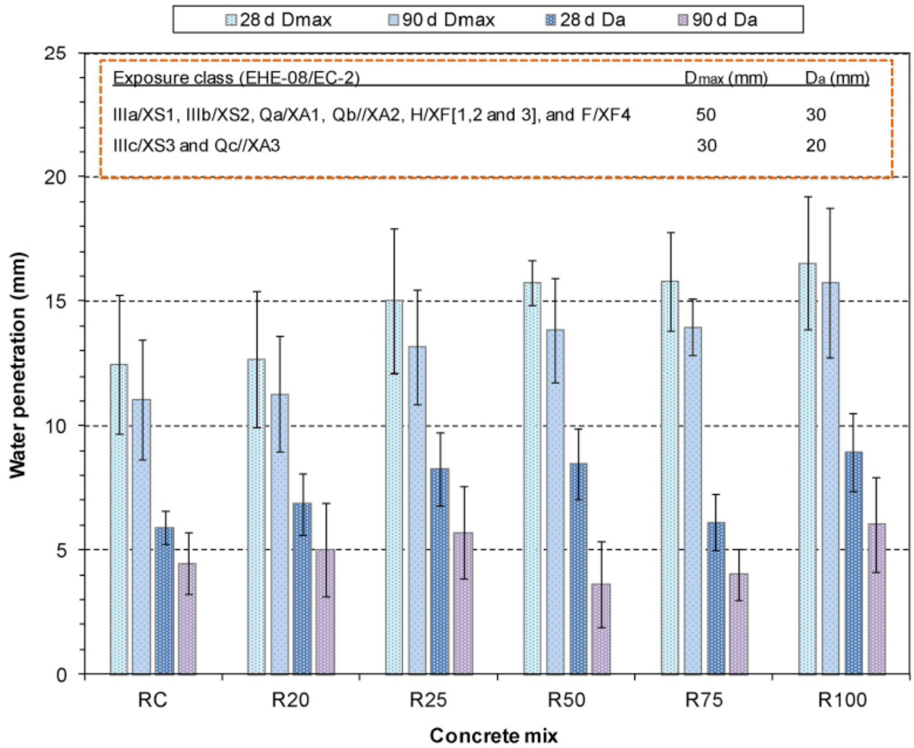

Fig. 5. Maximum and mean 28 d and 90 d depth of water penetration under pressure in concretes and EHE-08 and EC-2 requirements.

penetration depths, along with the EHE-08 specifications for those parameters. The data show that all the concretes, irrespective of the percentage of MRA involved, were standard-compliant in terms of pore structure impermeability.

The 28 d D_{max} values ranged from 13 mm to 17 mm, with rises of 2% in R20, 20% in R25, 26% in R50, 27% in R75 and 32% in R100 relative to RC. Those results were similar to the rises of up to 35% observed in recycled concretes manufactured with 10% to 100% RCA [49,59] and 25% to 100% MRA [5]. The deeper water penetration in the recycled than in the conventional concrete was related to the greater water absorption (see section 3.4) and effective porosity (see section 3.5) in the former due to the intrinsic properties of the new aggregate. The same findings were observed [27,59] in materials bearing 20% and 100% concrete and mixed recycled aggregates.

The D_{max} values were also below the depths recorded in concretes bearing 25% to 75% RCA and 25% to 100% MRA by Zega et al. [60] and Martinez-Lage et al. [5], respectively. These authors reported D_{max} values of 12 mm to 32 mm, irrespective of the type and percentage of RA used, attributable primarily to the design of the recycled concretes with low effective w/c ratios and the use of dry RA.

The 90 d D_{max} declined relative to the 28 d values in all the concretes, ranging from 11 mm to 16 mm. The range for the concretes bearing MRA (5%–12%) as well as the 11% for the conventional material were similar to the 10% to 15% range observed in 56 d concretes made with 25% to 75% RCA [65], an effective w/c ratio of 0.45 and similar cement content.

The D_a values in turn were lower than the 30 mm ceiling for exposure classes IIIa/XS1, IIb/XS2, Qa/XA1, Qb/XA2, H/XF [1,2and3] and F/XF4 and the 20 mm upper limit for class IIIc/XS3 and Qc/XA3 defined by EHE-08. The rises relative to RC observed in D_a in the 28 d MRA concretes, which ranged from 16% to 50%, dropped to 12% to 34% in the 90 d materials bearing the same 20% to 100% MRA. The smaller reduction in D_a at the later age might be associated with the hydration of the residual anhydrous cement present in the bound mortar in the RA and directly related to the steeper downturn in water absorption and porosity with age in recycled than in conventional concrete (see sections 3.4 and 3.5). D_a was not observed to rise progressively with the replacement ratio, for the value remained unchanged from 50% to 75% replacement and was practically the same as for RC.

The water penetration fronts in the 90 d RC, R25, R50 and R100 concretes in Fig. 6 show that the shape of the penetration lines were similar, with scant differences between the mixes bearing MRA and those containing NA.

As the ER vs D_{max} plots for 28 d and 90 d concretes in Fig. 7 show, the two properties were directly related, with R^2 equal to 0.989 for the 28 d mixes and to 0.887 for the 90 d materials. Those findings revealed that higher electrical resistivity (lower conductivity) inferred lower water penetration and were consistent with earlier reports of a close relationship between these two indirect indicators of durability that depend in particular on pore system connectivity [61].

3.4. Total water absorption

According to the total water absorption (W_a) data given in Table 6 for the 28 d and 90 d concretes after 24 h immersion, W_a rose linearly with the MRA replacement ratio, with R^2 values of 0.962 for the 28 d and 0.944 for the 90 d concretes. Linearity was similarly observed by Bravo et al. [34] in concretes with 10% to 100% C&DW aggregates (R^2 = 0.935) and Medina et al. [26] (R^2 = 0.998) in concretes with 25% to 50% MRA.

In the 28 d materials the W_a values ranged from 4.1% to 7.3% in the MRA-bearing materials, compared to 3.1% in the conventional concrete. These values were 10% lower than W_A, the ceiling for high quality concrete apt for structural applications. The rises in MRA-containing concrete W_a were 1.3- to 2.4-fold the increase in RC, values very similar to the range (1.3–2.2) found for concretes with 15% to 80%

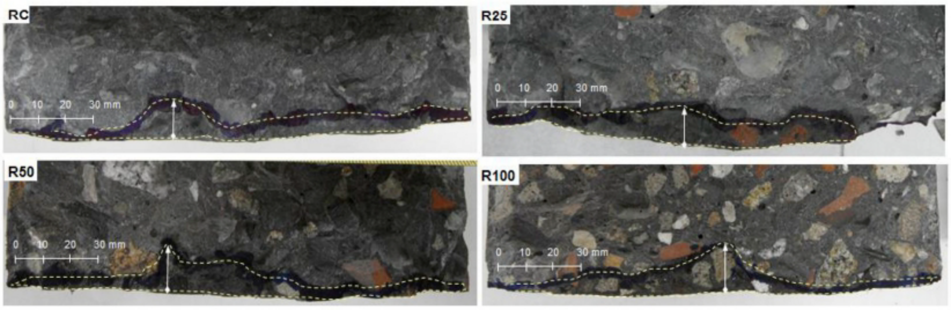

Fig. 6. Water penetration fronts in 90 d RC, R25, R50 and R100 (arrows show D_{max}).

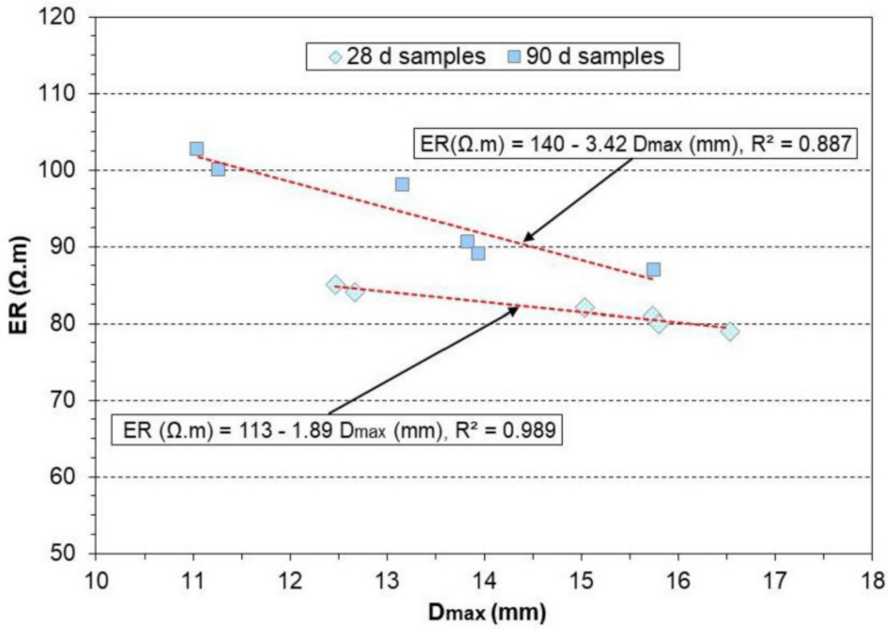

Fig. 7. Relationship between D_{max} and ER for 28 d and 90 d mixes.

Table 6
Total water absorption (W_a) in 28 d and 90 d concretes and capillary water absorption (WA_{cap}) in 90 d mixes.

Mix	W_a (wt%)		WA_{cap} (mg/mm^2)
	28 d	90 d	90 d
RC	3.10 ± 0.20	3.00 ± 0.10	1.37 ± 0.11
R20	4.10 ± 0.10	3.30 ± 0.10	1.59 ± 0.28
R25	4.40 ± 0.10	3.50 ± 0.10	1.67 ± 0.25
R50	5.90 ± 0.20	4.20 ± 0.10	1.77 ± 0.13
R75	6.10 ± 0.20	4.10 ± 0.20	1.84 ± 0.20
R100	7.30 ± 0.10	4.40 ± 0.10	1.88 ± 0.15
Correlation[a]	*W_a(wt%)=3.31 + 0.04xMRA(wt%)* R^2=0.962	*W_a(wt%)=3.10 + 0.01xMRA(wt%)* R^2=0.944	*WA_{cap}(mg/mm^2)= 1.47 + 0.004xMRA(wt%)* R^2=0.845

± Standard deviation.
[a] Between property and MRA replacement ratio.

concrete waste [20] and 25% to 100% ceramic waste (brick and tile) [62,63] aggregate. That effect was attributable to the greater permeability (see section 3.3) of the recycled concretes due to the quality (composition)-mediated intrinsic properties of recycled aggregate, which exhibits higher absorption coefficients than natural aggregate (see Table 2); its greater effective porosity (see section 3.5); and the intrinsic properties of the ITZ between the MRA and the paste, which, as observed by Djerbi [64], was 1.6- to 1.9-fold more porous than the NA/paste ITZ. All the 28 d W_a values fell within the 3.9% to 7.5% range recorded for concretes made with 20% to 100% RA from C&DW [25,35].

In the 90 d concretes, W_a varied from 3.3% to 4.3% in the MRA-bearing mixes and was 3.0% for the mix with NA. As expected, those values were lower than for the 28 d materials, by 3% in RC, 20% in R20, 21% in R25, 23% in R50, 29% in R75 and 40% in R100. Those findings, which revealed a steeper decline in W_a with age in the MRA concretes, were consistent with both the results on impermeability (see section 3.3) and earlier observations on concrete bearing 15% to 80% RCA [30].

3.5. *Effective porosity*

Effective porosity (P_{wa}) in the 28 d and 90 d concretes is plotted against MRA content in, which shows that the two parameters were linearly related (R^2 = 0.957 at 28 d; R^2 = 0.965 at 90 d). That pattern was consistent with earlier reports for concretes prepared with RA from

C&DW [19,65–67]. With the exception of 28 d R100, all the mixes exhibited $P_{wa}<15\%$, conforming to the Comité Euro-international du Béton (CEB, 1998) [74] definition of good quality concrete.

In the 28 d materials the P_{wa} values ranged from 9.5% to 15.7% in 20% to 100% MRA-bearing materials, compared to 7.5% in the conventional concrete. P_{wa} was 1.2–2.0 times higher in the MRA than in the reference concrete, values that were in keeping with the findings for W_a (see section 3.4). The P_{wa} observed for the MRA-bearing concretes also lay within the 8% to 16% range reported for RA with 20% to 100% concrete- or ceramic-waste RA and an effective w/c ratio similar to the one used in this study [19,50,62,68,69].

Porosity was lower in the 90 d materials than in the 28 d mixes (see Fig. 8) due to the intrinsic effect of cementitious matrix hydration on pore system connectivity, which grew with curing time, increasing the effectiveness of the matrix as a barrier to diffusion. The declines between 28 d and 90 d were steeper in the MRA concretes, dropping by 19% to 38% compared to 4.6% for conventional concrete. Those values were related to the propensity of W_a to slide with time (see section 3.4). The 97% correlation coefficient for the regression equation ($W_a = 2.11 + 1.69\ P_{Wa}$) relating the two properties was an indication that they were directly related 97% of the time.

3.6. Water absorption coefficient due to capillary action and sorptivity

Further to the data in Table 5, the capillary absorption coefficient ($WA_{cap.}$) in 72 h concretes rose linearly with the MRA replacement ratio ($R^2 = 0.845$). That pattern was in keeping with observations reported by Bravo et al. [34] for concretes bearing 10% to 100% concrete and C&DW mixed recycled aggregates. The R^2 found by those authors, at 0.860, was very close to the value calculated here.

Using MRA induced a 16% rise in WA_{cap} in concretes with 20% (R20), and 37% increase in those with 100% recycled aggregate relative to the conventional material (RC). That compares to the 12% to 49% range reported by Bravo et al. [34] for recycled concretes bearing 10% to 100% of such aggregates.

The variation in capillary absorption over time in 90 d MRA-bearing concretes depicted in Fig. 9 and supplementary data, Annex II was similar to the pattern for conventional concrete (RC), although with slightly higher values. That difference was due to the greater P_{wa} and W_a in recycled concretes, as discussed in sections 3.4 and 3.5. The figure further shows that in both the conventional concrete (RC) and the recycled materials (R20, R25, R50, R75 and R100) capillary absorption over time exhibited a nearly perfect fit to the Hall model [71] ($0.993 \leq R^2 \leq 0.995$). That finding was consistent with observations reported by Evangelista and De Brito for concretes in which the some of the natural fines were replaced with recycled aggregate [72].

Two stages can be distinguished in these curves: an initial or primary stage in the first 6 h of immersion in water when sorptivity was more intense and a second after 6 h through the end of the 8 d test when capillary diffusion-mediated weight gain was slower.

The sorptivity values for the primary and secondary stages are given in Table 7. Primary and secondary sorptivities were found as the slopes of the experimental capillary water absorption/square root of time ($t^{0.5}$) curves, as specified in ASTM standard C1585-13 [73]. The high correlation coefficients for those expressions ($R^2 > 0.99$) denoted high reliability and was compliant with the requirement laid down in the standard ($R^2 > 0.98$). As Table 7 shows, like WA_{cap}, primary and secondary sorptivity rose linearly ($R^2 > 0.890$) with the MRA replacement ratio.

Primary sorptivity was the result of diffusion-driven water absorption by the capillary pores. The primary sorptivity values in concretes with 20% to 100% MRA (R20 to R100) ranged from 0.213 mm/h$^{0.5}$ to 0.268 mm/h$^{0.5}$, compared to the 0.198 mm/h$^{0.5}$ observed for conventional concrete (RC). Concretes made with 25% MRA (R25) exhibited values less than 7% higher than the mix containing NA (RC), whilst the materials with replacement ratios of over 25% (mixes R50, R75 and R100) had values 23% to 28% higher than RC. Those increases were closely related to the higher volume of permeable pores in the recycled concretes, as discussed in section 3.5, and consistent with the Medina et al. [26] finding that sorptivity remained practically constant in concretes with up to 25% MRA. Those authors also observed that raising replacement to 50% induced sorptivity rises of up to 28% relative to the reference concrete.

Secondary sorptivity in turn depended on pore volume and size as well as on pore system tortuosity and connectivity [78]. The secondary sorptivity values in concretes with 20% to 100% MRA (R20 to R100)

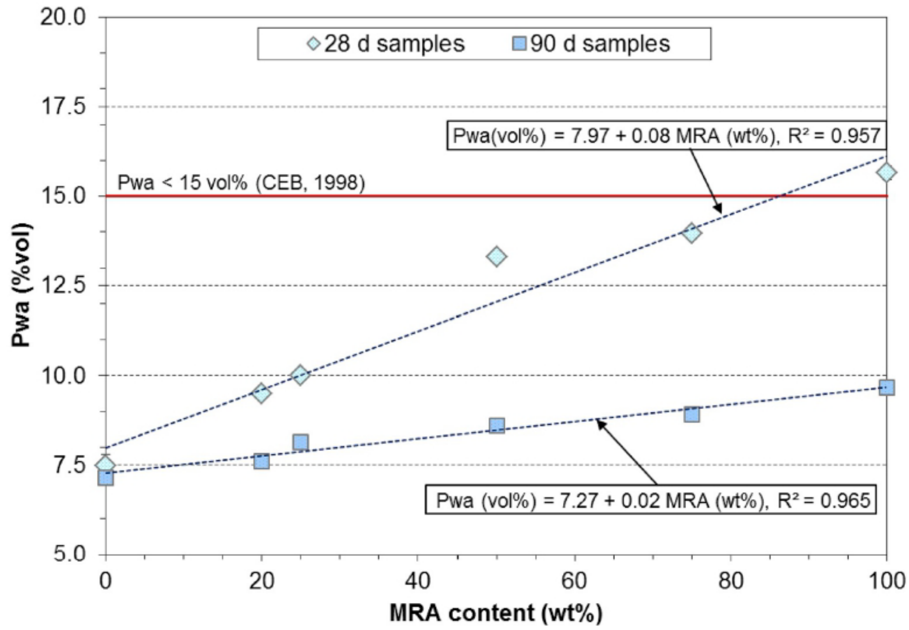

Fig. 8. Effective porosity (P_{wa}) in 28 d and 90 d concretes and the CEB [70] ceiling for good quality concrete.

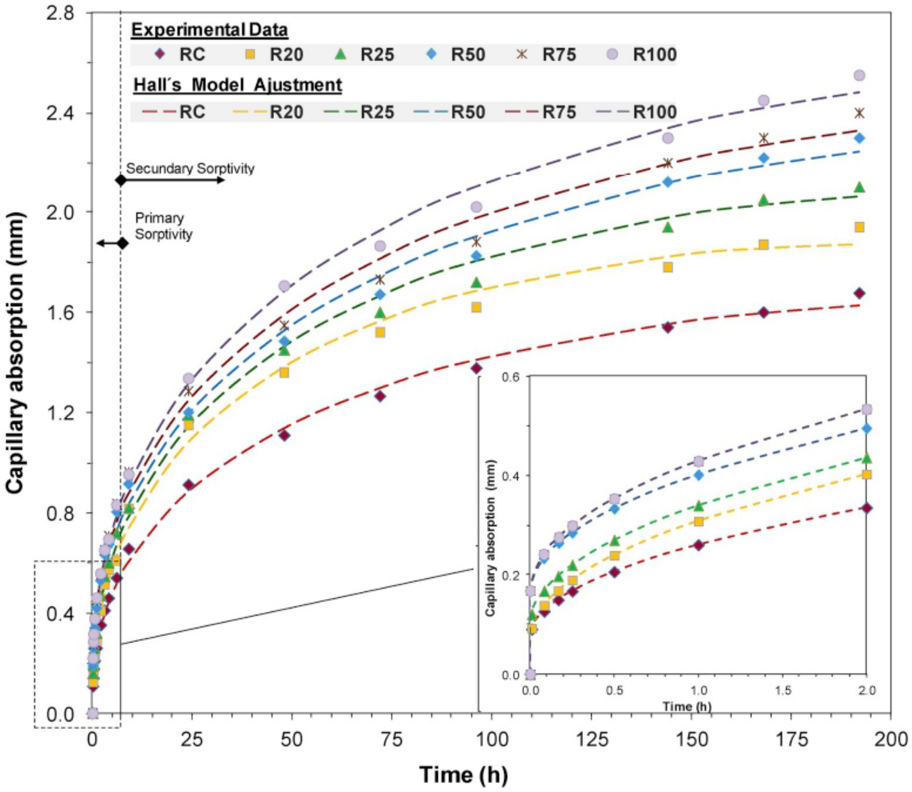

Fig. 9. Capillary absorption vs time.

Table 7
Sorptivity in 90 d concrete mixes.

Mix	Primary (5 min-6 h)		Secondary (1 d–8 d)	
	Sorptivity (mm/$h^{0.5}$)	R^2	Sorptivity (mm/$h^{0.5}$)	R^2
RC	0.198 ± 0.012	0.994	0.084 ± 0.003	0.996
R20	0.213 ± 0.013	0.993	0.097 ± 0.010	0.993
R25	0.232 ± 0.019	0.993	0.101 ± 0.007	0.995
R50	0.251 ± 0.015	0.993	0.129 ± 0.007	0.996
R75	0.262 ± 0.018	0.994	0.134 ± 0.009	0.995
R100	0.268 ± 0.019	0.995	0.138 ± 0.008	0.997
Correlation[a]	*S (mm/$h^{0.5}$)=0.210 + 0.0007xMRA(wt%)* *R^2=0.917*		*S (mm/$h^{0.5}$)=0.087 + 0.0006xMRA(wt%)* *R^2=0.898*	

± Standard deviation.
[a] For sorptivity vs MRA replacement ratio.

ranged from 0.097 mm/$h^{0.5}$ to 0.138 mm/$h^{0.5}$, compared to the 0.084 mm/$h^{0.5}$ observed for conventional concrete (RC). In other words, the secondary sorptivity values were 57% to 42% lower than observed for primary sorptivity, denoting the barrier effect of the cementitious matrix over time. That pattern was consistent with findings reported for concretes with 10% to 30% RCA [74].

Zaccardi et al. [75] recently proposed a new theoretical model for calculating sorptivity from the slope of the experimental WA_{cap} data vs the fourth root of time ($t^{0.25}$) plot and the alteration in the pore system induced by C–S–H gel swelling with water penetration. This new model solves the problem of $t^{0.5}$ non-linearity, reducing sorptivity to a single durability indicator that can be related to other deterioration-inducing parameters that impact the service life of concrete structures. In a nutshell, it circumvents the need to determine two kinetic parameters for the predictive model, primary and secondary sorptivity, as specified in ASTM standard C1585-13 [73], while also affording a better fit to the experimental data. Moreover, as primary sorptivity is found over a very short test period (5 min–6 h), it furnishes information on the outer layer of concrete only, and none on its inner structure [76].

Table 8 compares the sorptivity values and correlation coefficients calculated for 90 d specimens in one-sided contact with water for 35 h using the $t^{0.25}$ and $t^{0.5}$ approaches. As the table shows, the R^2 values calculated with the $t^{0.25}$ model were >0.994, higher than obtained with the $t^{0.5}$ model (see Table 8). In both cases sorptivity rose linearly with MRA content (R^2 > 0.910). Although the sorptivity values found with the $t^{0.25}$ model were 10% to 44% higher in the concretes bearing 20% to 100% MRA (R20 to R100) than in the conventional concrete (RC), they were smaller than observed with the $t^{0.5}$ model (32%–63%) for the same materials. According to earlier studies, the higher sorptivity values delivered by the $t^{0.5}$ model were attributable to its lesser accuracy [75, 77].

All the sorptivity values recorded lay below the 3 mm/$h^{0.5}$ recommended by Ho and Lewis [78] for concretes subject to aggressive

Table 8
Water sorptivity in concrete mixes.

Mix	Sorptivity (mm/$h^{0.25}$)	R^2	Sorptivity (mm/$h^{0.5}$)	R^2
RC	0.532 ± 0.018	0.997	0.088 ± 0.004	0.977
R20	0.582 ± 0.006	0.997	0.111 ± 0.018	0.965
R25	0.637 ± 0.012	0.994	0.118 ± 0.002	0.975
R50	0.723 ± 0.014	0.996	0.124 ± 0.004	0.978
R75	0.745 ± 0.010	0.997	0.136 ± 0.038	0.978
R100	0.769 ± 0.008	0.998	0.144 ± 0.078	0.975
Correlation[a]	*S (mm/$h^{0.5}$)=0.552 + 0.002xMRA(wt%)* *R^2=0.912*		*S (mm/$h^{0.25}$)=0.097 + 0.0005xMRA(wt%)* *R^2=0.918*	

± Standard deviation.
[a] For sorptivity vs MRA replacement ratio.

exposure, ensuring an acceptable service life in concrete structures and showing that the use of MRA did not alter capillary diffusion-mediated penetration.

3.7. Inter-property relationships

3.7.1. Electrical resistivity and effective porosity

The ER vs P_{wa} plots for 28 d and 90 d concretes in Fig. 10 show that ER declined with rising porosity in keeping with Archie's law (Equation (2)), which describes the relationship between electrical resistivity and porosity in porous materials [79]:

$$ER = A \times P_{wa}^{-m} \quad (2)$$

where *ER* is electrical resistivity in Ω·m, *A* is a constant that depends on the pore structure and P_{wa} is concrete effective porosity in vol%.

The correlation coefficients were observed to be over 0.920 at the ages studied, suggesting that this law, generally accepted for conventional concretes, would also be applicable to concretes bearing mixed recycled aggregate. That behaviour is consistent with the findings reported by Omary et al. [66] who, using Archie's law, obtained a correlation coefficient of $R^2 = 0.90$ for the relationship between porosity and ER in recycled concretes bearing 30% to 100% RCA, irrespective of the concrete strength class. Those findings confirmed the dependence of ER on pore system characteristics, which can be directly evaluated with P_{wa}.

3.7.2. Sorptivity ($t^{0.25}$ model), effective porosity and total water absorption

Sorptivity calculated with the $t^{0.25}$ approach is plotted against P_{wa} and W_a for 90 d concretes in Fig. 11, which also shows the respective regression equations and correlation coefficients. As the figure shows, the three properties were linearly related ($R^2 > 0.930$), an indication that sorptivity depends on both P_{wa} and W_a. Those findings are consistent with the relationships observed earlier [18,34,36] between sorptivity calculated with the $t^{0.5}$ method, total water absorption and porosity found from the microstructure of concretes bearing 10% to 100% aggregate processed from ceramic [36], concrete [18] or mixed concrete and ceramic [80] waste.

3.7.3. Sorptivity ($t^{0.25}$ method), electrical resistivity and maximum depth of water penetration

Sorptivity calculated with the $t^{0.25}$ approach is plotted against ER and D_{max} for 90 d concretes in Fig. 12, which also shows the respective regression equations and correlation coefficients. The correlation coefficients for the regression equations ($R^2 \geq 0.891$) denoted a clearly linear relationship between sorptivity and the other two properties. The effect of MRA varied with the parameter involved. Sorptivity declined at higher ER and rose at higher D_{max} values. Those findings were attributable to the greater porosity and more effective pore system connectivity in concretes made with MRA than with NA and their consequently higher permeability and lower electrical resistivity (see sections 3.3 and 3.5).

4. Conclusions

The conclusions that may be drawn from this study are set out below.

- Regardless of the replacement ratio used, the concretes exhibit S3 consistence.
- While compressive strength declines in concretes with a 100% replacement ratio it does so by less than 10%.
- Electrical resistivity follows a similar pattern in MRA-bearing and conventional concretes.
- Electrical resistivity is 5% to 16% lower in both 28 d and 90 d concretes containing 25% to 100% MRA than in mixes with NA: i.e., the declines are in all cases less than relative volume of the MRA replacement ratio.
- Irrespective of the replacement ratio, the new recycled concretes exhibit an impermeable pore structure that conforms to the mean and maximum depth ceilings set out in Spanish code EHE-08 for exposure classes IIIa, IIIb and IIIc and EC-2 for classes XS1, XS2 and Cx3.
- In recycled concretes both water absorption and effective porosity rise linearly with the MRA replacement ratio. The 28 d concretes prepared with under 75% MRA and an effective w/c ratio of 0.45 meet good durability standards, with <15% porosity and <7% water absorption.

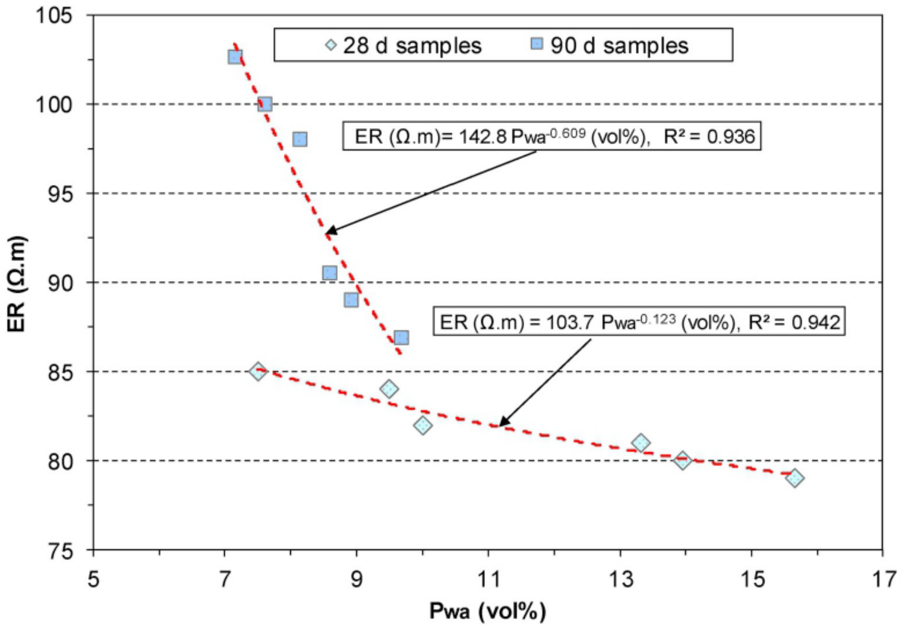

Fig. 10. ER vs porosity (P_{wa}) in 28 d and 90 d mixes.

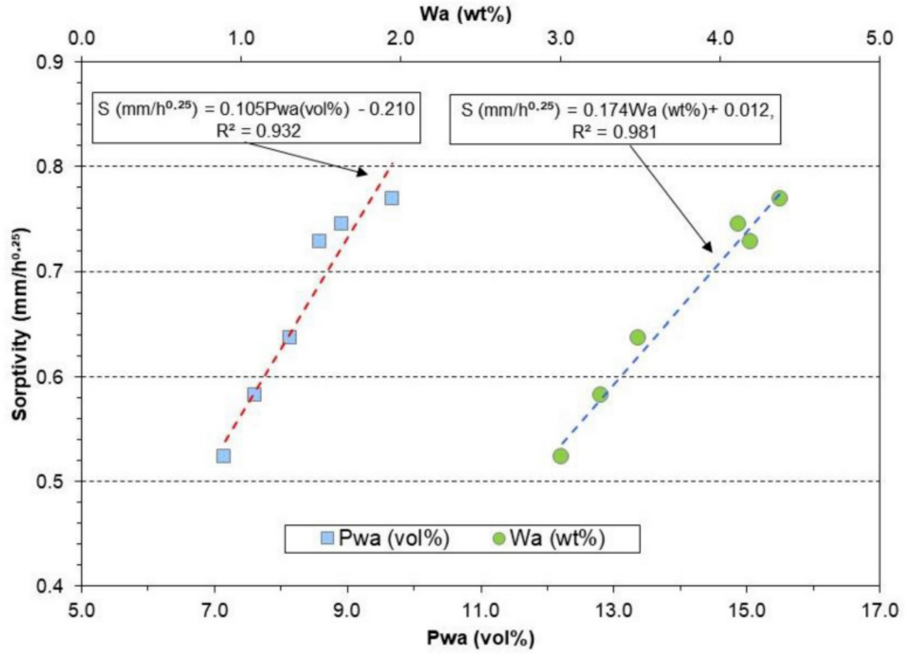

Fig. 11. Sorptivity (S) versus water absorption (W_a) and effective porosity (P_{wa}) in 90 d concretes.

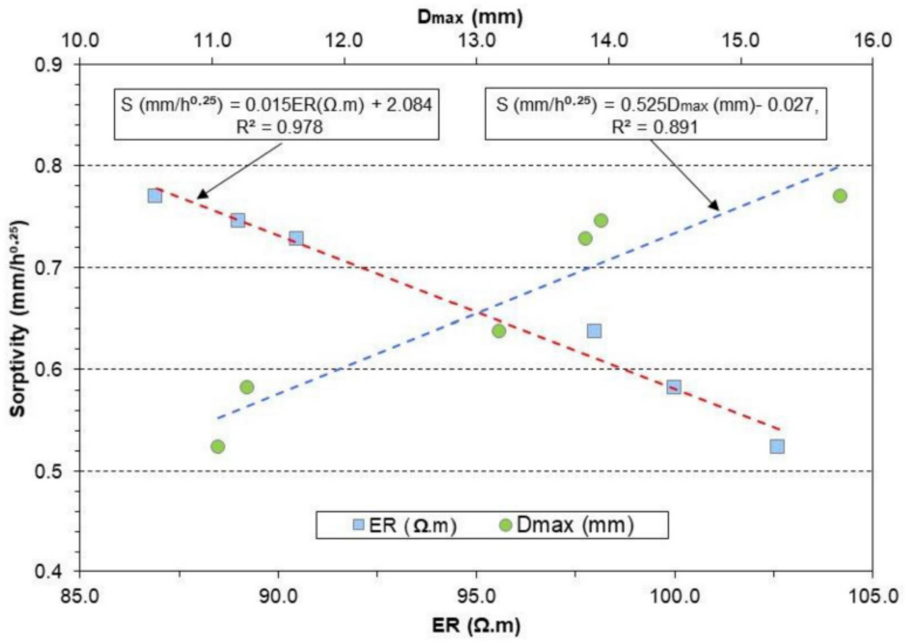

Fig. 12. Sorptivity (S) vs electrical resistivity and maximum depth of water penetration (D_{max}) in 90 d mixes.

- The change in mechanical strength over time, which explains the enhancement of durability with curing time, is not affected by the presence of MRA in new concretes.
- All the sorptivity values obtained in concretes with MRA and same effective w/c (0.45) are lower than the 3 mm/$h^{0.5}$ recommended for aggressive environments. Sorptivity calculated with the $t^{0.25}$ approach, which affords a more realistic description of capillary suction than the traditional $t^{0.5}$ method, shows a determination coefficient of >99.5%. With the $t^{0.25}$ procedure, the capillary diffusion process is expressed with a single kinetic parameter, which may be used in future service life models based on that transport mechanism.
- The close inter-relationships between sorptivity, electrical resistivity, water absorption, effective porosity and penetration depth of water under pressure are unaltered by the presence of mixed recycled aggregate. Consequently, Archie's law can be used in these

new MRA-bearing concretes to predict porosity from electrical resistivity at different curing times.

– In light of the findings and from the standpoint of water permeability, natural aggregate can be viably replaced with up to 75% mixed recycled aggregate from construction and demolition waste to produce structural concretes with a characteristic strength of 30 MPa.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cemconcomp.2019.103486.

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Capítulo 9

Water transport and shrinkage in concrete made with ground recycled concrete-additioned cement and mixed recycled aggregate

Capítulo 9

Water transport and shrinkage in concrete made with ground recycled concrete-additioned cement and mixed recycled aggregate

Resumen

Este estudio de investigación explora las propiedades de transporte de agua en hormigones que incorporan entre un 10 % y un 25 % de ultra finos reciclado de hormigón (PRH) como remplazo del cemento Portland de manera individual y conjunta, con un 50 % de áridos reciclados mixtos (ARM). Para ello se estudiaron los principales indicadores de durabilidad relacionados con la movilidad de fluidos: i) porosidad abierta, ii) penetración de agua bajo presión, iii) coeficiente de permeabilidad al agua, y iv) absorción de agua capilar y movilidad iónica como la resistividad eléctrica. Además, se realizó un seguimiento de la contracción en todos hormigones diseñados. Los resultados revelan que la incorporación de hasta un 25 % PRH conduce a un aumento lineal de la porosidad abierta de hasta un 11.4 % en hormigones con un 100 % de AN y de un 33 % en hormigones con un 50 % de ARM respecto al hormigón convencional. Además estos hormigones tienen una estructura porosa más interconectada que reduce la resistividad eléctrica entre un 14 % y un 23 % respectivamente. A pesar de ello, los hormigones que incorporación de PRH y/o ARM mantienen una estructura porosa lo suficientemente impermeable que garantiza valores de profundidad máxima de agua bajo presión inferiores a 30 mm, coeficientes de permeabilidad al agua inferiores a 10^{-12} m/s y valores de sortividad inferiores a 1 mm/$h^{0.5}$ asegurando una adecuado comportamiento durable. El análisis ANOVA de tres vías determino que la incorporación GRC fue el factor que más afecta a la penetración de agua bajo presión, coeficiente de permeabilidad al agua y sortividad. El tiempo de curado es el efecto estadísticamente más significativo en los hormigones que incorporaran conjuntamente PRH y ARM como resultado de la hidratación anhidra del PRH y el mortero residual presente en los componentes del ARM. Finalmente, y en base a los resultados de esta investigación, es posible concluir que la incorporación de hasta un 10% de PRH como remplazo parcial al cemento en el diseño de nuevos hormigones reciclados no compromete su comportamiento durable respecto los hormigones convencionales.

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Water transport and shrinkage in concrete made with ground recycled concrete-additioned cement and mixed recycled aggregate

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ABSTRACT

This article reports on analytical research into water transport in concrete with 10%–25% ground recycled concrete (GRC) as partial Portland cement replacement and 0% or 50% mixed recycled aggregate (MRA). It included analyses of durability indicators associated with water transport: effective (or open) porosity, penetration depth of water under pressure, permeability coefficient, capillary water absorption and electrical resistivity. Shrinkage was also monitored in all concrete samples. The findings showed that replacing up to 25% OPC with GRC induced a linear rise in effective porosity of up 11.4% in concrete with 100% NA and 33% in mixes with 50% MRA, relative to conventional concrete. The outcome, a tightly interconnected pore structure, lowered electrical resistivity by 14% in NA and 23% in MRA GRC-additioned cement concrete. That pore structure was nonetheless sufficiently impermeable to ensure suitable concrete durability, with penetration depth of water under pressure below 30 mm, a permeability coefficient below 10^{-12} m/s and sorptivity below 1 mm/$h^{0.5}$. The three-way ANOVA conducted revealed that adding GRC was the factor with the greatest impact on penetration depth of pressurised water, permeability coefficient and sorptivity. Curing time was the most statistically significant factor for electrical resistivity and shrinkage in both mix families (NA and GRC), inasmuch as it determined the degree of hydration of the anhydrous phase in GRC and in the residual mortar bound to MRA components. Further to the present findings, the use of GRC at a replacement ratio of up to 10% does not lower recycled material concrete's durability relative to the mixes made with ordinary Portland cement.

1. Introduction

The ingress of aggressive agents present in the environment into concrete structures is instrumental in their deterioration and integrity. Durability depends largely on the ease with which water and gas can penetrate the material, hence the need to understand how such agents access the pore system and capillaries that serve as entranceways. Water absorption, porosity, water permeability and sorptivity, as good indicators of such durability-related transport properties, provide insight into concrete resistance to the ingress of such detrimental external agents [1].

Greater emphasis must be given to factors such as service life, durability and the use of waste as raw materials in structural system design to enhance construction sustainability [2]. Such consideration is of vital importance in the transition to a circular economy in light of the rising worldwide volumes of construction and demolition waste (CDW), which in the last 10 years have been the highest of all flows of solid waste.

Over 12 Gt of CDW are generated yearly, a figure expected to continue increasing in the wake of expected urban growth [3]. The scarcity of landfill space and strict environmental legislation in developed and developing economies have led to worldwide regulation of the methods for recycling and reusing CDW. Concrete continues to be the construction material most widely used around the world [4]. One of the most promising options for implementing a circular economy and meeting the sustainable development goals laid down in Agenda 2030 [5] is to process CDW for application as recycled aggregate (RA), partially replacing natural aggregate (NA) in concrete, and as a supplementary cementitious material (SCM) in cement clinker manufacture.

CDW-sourced RA can be divided into two main groups: recycled

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Abbreviations

GRC	ground recycled concrete
NA	natural aggregate
MRA	mixed recycled aggregate
OPC	ordinary Portland cement
ANOVA	analysis of variance
CDW	construction and demolition waste
RA	recycled aggregate
SCM	supplementary cementicius material
RCA	recycled concrete aggregate
CRA	coarse recycled aggregate
RBA	recycled brick aggregate
FRCA	fine recycled concrete aggregate
ITZ	interfacial transition zone
RCPF	recycled cement powder fines
TGA	thermogravimetric analyzer
CKD	cement kiln dust
CSW	concrete slurry waste
SEM	scanning electron microscope
RP	recycled powder
RFA	recycled fine aggregate
NAC	natural aggregate concrete
EC2	Eurocode 2
RILEM	Réunion Internationale des Laboratories et Experts des Matériaux (in French)

concrete aggregate (RCA) processed by selective crushing of used concrete, which accounts for ~40% of the total; and mixed recycled aggregate (MRA), the result of jointly crushing used concrete, masonry materials (brick, roof and ceramic tile) and some minor components including plaster, wood, plastic and glass that comprise the remaining ~60%. Tam et al. [3] argued that the use of coarse recycled aggregate (CRA) is a promising solution to the CDW problem. One outcome of the huge scientific and administrative effort invested has been the enactment of legislation [6–9] establishing 20%–30% CRA replacement ratios as ceilings below which RCA can be safely used in concrete manufacture without compromising the mechanical strength or durability of the end product. However, further research is still in order to acquire a deeper knowledge of durability, carbonation, permeability, shrinkage and creep to dispel consumers' concern on the durability of concrete made with CRA.

Unfortunately, very little research has been conducted on the durability of concrete with MRA, because it s more varied composition and higher water sorptivity than RCA that have limited its use in construction [10]. Authors such as Zhang et al. [11] recently concluded that further research into the use of MRA as CRA in concrete is called for to contribute more effectively to construction sustainability and lower the enormous demand for NA. Later on, Cantero et al. [12] studied water transport as an indicator of concrete durability in mixes in which 20%, 25%, 50%, 75% and 100% of the NA was replaced with MRA. They observed effective porosity to rise linearly with the MRA content ratio, from 7.5% in conventional concrete to 9.5% in concrete with 20% MRA, and to 15.7% with 100% MRA. Despite that increase in porosity, all the concrete mixes with MRA exhibited values under the 30 mm maximum and 20 mm mean penetration depth of pressurised water stipulated in Spain's structural concrete code [6] for aggressive exposure classes. The authors concluded that structural concrete with up to 75% MRA, which is sufficiently impermeable to guarantee durability, can be viably manufactured. Mas et al. [13] also found penetration depth of pressurised water to rise linearly with MRA replacement ratio, while also observing that the presence of 20 wt% to 30 wt% masonry materials in MRA significantly raised the recycled aggregate concrete's water sorptivity.

Medina et al. [14], studying water and capillary absorption in concrete with 25%–50% MRA with high percentages of floating particles and asphalt, observed that, due to the high water sorptivity of those components, absorption rose with their content in concrete with MRA. All the sorptivity values found were nonetheless less than the 10% value recommended by Neville [15] for concrete with a variety of structural applications. Medina et al. also reported that 25% MRA had no adverse effect on capillary absorption whilst at 50% replacement absorption grew by just 20% relative to conventional concrete. Authors such as Alexandridou et al. [16] also observed that concrete with 15%–75% MRA exhibited total water sorptivity 30% and effective porosity 52% higher than conventional concrete. They concluded that, even though the use of MRA lowered concrete's durability, sufficiently durable concrete could be manufactured with MRA incorporation values of up to 50%.

After analysing shrinkage in concrete with 20%, 35%, 50%, 70% or 100% recycled brick aggregate (RBA), Gayarre et al. [17] concluded that the greater shrinkage observed in concrete with crushed brick aggregate (RBA) was due to the lower modulus of elasticity in the resulting material. They consequently recommended that, whilst concrete containing 35% RBA exhibited shrinkage values acceptable for structural concrete, the decline in the modulus of elasticity would have to be monitored. Etxeberria and González-Corominas [18], while determining the effect of ratios below 30% of recycled masonry and mixed recycled aggregate as NA replacement in high-strength concrete, observed porosity to rise and density to decline due to the lower density and higher water sorptivity of both the used mortar and the masonry (roof tile, brick) particles present in MRA. They found a very similar pattern in respect of shrinkage in MRA compared to conventional concrete, with shrinkage in the former up to 35% greater than in the latter. They attributed that finding to the greater presence of cement paste and a larger proportion of interconnected pores in recycled aggregate concrete. Bravo et al. [19] in turn, noted that, although the incorporation of MRA raises total shrinkage, no consensus has yet been reached on the extent of that rise. According to these authors, two factors may explain the scatter observed in the shrinkage values reported: the higher porosity and lower Young's modulus in MRA; and the greater water absorption by MRA during mixing, which induces an internal curing mechanism that mitigates early-age evaporation-induced shrinkage. The remarks made in this and the preceding paragraphs should boost greater effort on the part of the scientific community to fill some of the knowledge gaps on MRA concrete's durability.

However, CDW processing itself also generates large volumes of fine recycled concrete aggregate (FRCA), the fraction hardest to valorise due to the especially high water sorptivity of these materials, which can undermine fresh and hardened concrete properties [20]. Their high sorptivity may be attributed to their large specific area and the presence of used bound mortar that weakens the interfacial transition zone (ITZ) and hinders bond between the cementitious matrix and the fines [20–22]. As a result, these materials are used primarily as fill in ditches and other activities of similarly low economic value [23].

One potential approach to valorising FRCA could be to use it, after additional grinding, as a SCM partially replacing ordinary Portland cement (OPC) [24]. Such an innovative solution might prove to be an eco-friendlier course to manufacture cement with a smaller environmental impact, for it would entail reusing construction waste while at the same time lowering the clinker content in cement, the major source of CO_2 emissions in concrete manufacture [25]. Further to recent physical-chemical analyses of the cementitious powder generated during paste, mortar and concrete crushing [24,26–29] as a new SCM in cement design, it can be viably used at ratios of 5%–25% as a new addition to lower cement clinker content.

To date, a few studies have assessed the durability of cement-based materials (mortar, concrete) containing cementitious powder as a partial cement replacement. Bordy et al. [30] designed mortars made with laboratory-prepared, crushed and ground cement paste containing recycled cement powder fines (RCPF). Further to thermogravimetric (TGA) findings, the RCPF bore around 24% residual reactive anhydrous clinker that might exhibit some hydraulic reactivity. The authors also observed a rise in porosity with RCPF content due largely to the lower clinker content and consequently lower volume of hydrated products. Najim et al. [31], in turn, used 10%, 20% and 30% cement kiln dust (CKD) to replace cement in concrete manufacture, reporting that CKD concrete exhibited lower fresh state workability, greater hardened state porosity and a predominance of larger pore sizes as a result of the higher CKD capacity to absorb mixing water. They attributed that effect to the higher a lime content of CKD, which altered cement paste's microstructure. Maslehuddin et al. [32] studied electrical resistivity and drying shrinkage in concrete with 5%, 10% or 15% CKD as OPC replacement. They found that whereas concrete with 5% CKD did not differ significantly from the reference in terms of electrical resistivity or drying shrinkage, adding 10% CKD raised drying shrinkage by 19% and lowered electrical resistivity by 8%, whilst at 15% CKD the former rose by 38% and the latter declined by 22%. The decline in electrical resistivity was attributed to a higher chloride ion content in the pore solution in CKD concrete.

Similarly, Anastasiou et al. [33] designed concrete containing concrete slurry waste (CSW) as cement replacement. They recorded a rise in porosity and a decline in hardened state dry density. Porosity rose by up to 47% in concrete with 20% CSW due to the lesser quantity of cement and greater porosity of the hydrated cement mortar present in CSW. Sun et al. [34] ran a scanning electron microscope (SEM) study of the ITZ in concrete with CRA sourced from coarse and fine concrete in conjunction with recycled concrete powder (RP). Their findings showed that concrete with 20% RP contained unhydrated particles in the mortar paste bound to the aggregate surface that reduced the degree of hydration and densification of the new cementitious matrices. They also reported a higher pore volume in the microstructure of concrete with a higher presence of recycled materials (100% RCA, 10% recycled fine aggregate (RFA) and 20% RP), contending that would lower mechanical strength and durability in the new recycled material concrete.

According to this state of the art analysis, there is a pressing need to fill the scientific and technical knowledge gaps of the effects of the use of these new SCM on durability indicators such as penetration depth of water under pressure, permeability coefficient and capillary absorption and their relationship to porosity and electrical resistivity. Moreover, to date no study has been conducted jointly valorising ground recycled concrete (GRC) and MRA in concrete production. The originality of this research therefore lies in its study of the effects of using ground recycled concrete as an SCM in concrete made with coarse aggregate containing construction and demolition waste. It purposed to enhance the scientific and technical understanding of the combined use of such waste and contribute to its valorisation, while heightening the cost-effectiveness and reducing the environmental footprint of concrete manufacture. With that purpose in mind, this study analysed the effect of using recycled material-incorporated cement containing 10% (R_{10}) or 25% (R_{25}) GRC in concrete mixes prepared with 100% NA or 50% NA and 50% MRA. The experimental programme designed assessed the water transport properties directly affecting recycled material concrete's durability by analysing the effective porosity, capillary water absorption, penetration depth of pressurised water, water permeability coefficient, electrical resistivity and shrinkage. A three-way analysis of variance (ANOVA) was run to determine the impact of three factors: age, GRC incorporation ratio and MRA content, and their interaction on the dependent variables associated with water transport and shrinkage.

2. Materials and methods

2.1. Materials

2.1.1. Binders

The three binders used were: a type 1 42.5 R (CEM I 42.5 R) OPC; a blend of 90% OPC and 10% GRC labelled R_{10}; and a blend of 75% OPC and 25% GRC, labelled R_{25}. GRC was obtained by crushing and grinding laboratory-prepared concrete specimens, batched as per the Faury method [35] (Fig. 1). The majority chemical species present in GRC were SiO_2 (46.10 wt%), CaO (40.0 wt%) and other oxides such as Al_2O_3 and Fe_2O_3(<5 wt%). Powder morphology was characterised by large (<147 μm), irregularly shaped particles resulting from crushing and grinding aggregate with bound mortar, along with fractions consisting of smaller (<1.58 μm) particles with a rougher, more porous surface. The GRC used was less dense (2.54 g/cm^3) than OPC (3.11 g/cm^3) [36] (Table 1).

2.1.2. Aggregates

The particle size distribution of the aggregate used in the mixes studied, classified as set out in European standard EN 933-1 [37], is shown in Fig. 2.

The coarse NA used, crushed limestone, exhibited two particle size fractions, 4/12 mm (NG-M) and 12/22 mm (NG-G). The natural fines consisted of two siliceous river sands, 0/2 mm (NS-F) and 2/4 mm (NS-C). The single fraction (0/32 mm) MRA supplied by a CDW recycling plant at Lisbon, Portugal was sieved and classified at the laboratory, where sizes <4 mm and >22 mm were discarded (see Fig. 1). The composition of the 4/22 mm coarse MRA aggregate ultimately used, found as recommended in European standard EN 933-11 [38], is given in Table 2. As the data in the table show, the major components were Rc (47.1 wt%), Rb (22.3 wt%) and Ru (25.2 wt%), although minor components (<2 wt%) such as glass and plaster were also present. Based on those data and Spain's structural concrete code (EHE-08) [6], with its ≤ 95 wt% R_{cu} (R_{cu} = Rc + Ru) content and >5 wt% Rb content, MRA can be classified as a mixed recycled aggregate. It also qualifies for that category according to the Agrela et al.'s [10] proposal, which specifies $R_{cu} > 70\%$ and $Rb < 30\%$. Its values also lies within the 68%–88% for R_{cu} and the 5%–29% for Rb cited in the literature [12,13,37–41] to define recycled aggregate as MRA. According to the physical and mechanical properties of the aggregates in Table 3, MRA met code EHE-08's recommendations for use as coarse RA in the manufacture of structural concrete ($f_{ck} \leq 30$ MPa).

2.2. Experimental programme

In the experimental programme designed, the independent variables were GRC (r_{GRC}) and MRA (r_{MRA}) replacement ratios. Table 4 lists mix design parameters and the respective labels. Combining these variables yielded a total of six mixes using three r_{GRC}, (0 wt%, 10 wt% and 25 wt %) to replace OPC and two r_{MRA} (0 vol% and 50 vol%) to replace NA. The mixes with 100% NA (r_{MRA}: 0%) were designed to study the effect of GRC on conventional concrete, and those with 50% MRA (r_{MRA}: 50%) to determine the joint effect of the two recycled materials.

2.3. Concrete design and sample preparation

The composition of the mixes studied is given in Table 5. The particle size distribution of all the (fine + coarse) aggregates, irrespective of whether they were natural or recycled, fit the theoretical curve defined by Faury [35] (Fig. 2), assuming a maximum size of 22 mm, the maximum compactness ratio and the same fraction (by volume) of each type of aggregate in all the mixes. All the mixes were batched as set out in European standard EN 206-1 for durability class XC2 and strength class C25/30, although, slightly more binder (300 kg/m^3 of OPC + GRC) was used than the specified minimum 280 kg/m^3 for that exposure class. All were also prepared for a target workability of S2 as defined in

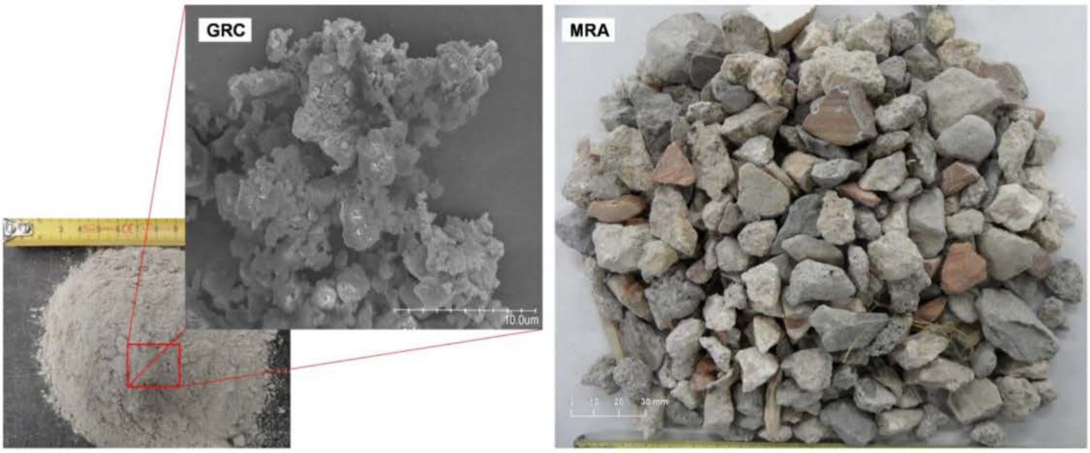

Fig. 1. (a) Ground recycled concrete (GRC) and (b) mixed recycled aggregates (MRA).

Table 1
Physical and chemical properties of the binders used.

Chemical composition		
Oxide (wt%)	OPC	GRC
SiO_2	18.70	46.10
CaO	65.10	40.00
Al_2O_3	5.10	3.80
Fe_2O_3	2.60	1.50
LOI	2.50	6.20
K_2O	0.50	1.20
MgO	1.80	0.50
SO_3	3.00	0.40
Na_2O	0.20	0.30
Particle size distribution		
Percentage passing (%)	Sieve size (μm)	
10	1.94	1.58
50	13.80	21.21
90	46.00	147.00
Sieve size (μm)	Percentage passing (%)	
<63 μm	97.88	67.84
Density		
ρ (g/cm^3)	3.11	2.54

EN-206-1 [46], equivalent to 70 ± 20 mm slump [47].

2.4. Tests and methodology

Mix fresh state properties, namely slump, air content and density, were determined as specified, respectively in European standards EN 12350-2 [47], EN 12350-7 [48] and EN 12350-6 [49]. Compressive strength was found on 28 d, hardened concrete specimens as recommended in EN 12390-3 [50].

The water transport properties relevant to durability found were:

Table 2
MRA composition.

Component	Class	Amount (wt%)
Concrete and mortar	Rc	47.1
Natural stone	Ru	25.2
Clay materials	Rb	22.6
Glass	Rg	1.7
Gypsum	X1	1.8
Floating particles	FL	1
ituminous materials	Ra	0.2
Metals	X2	0.4

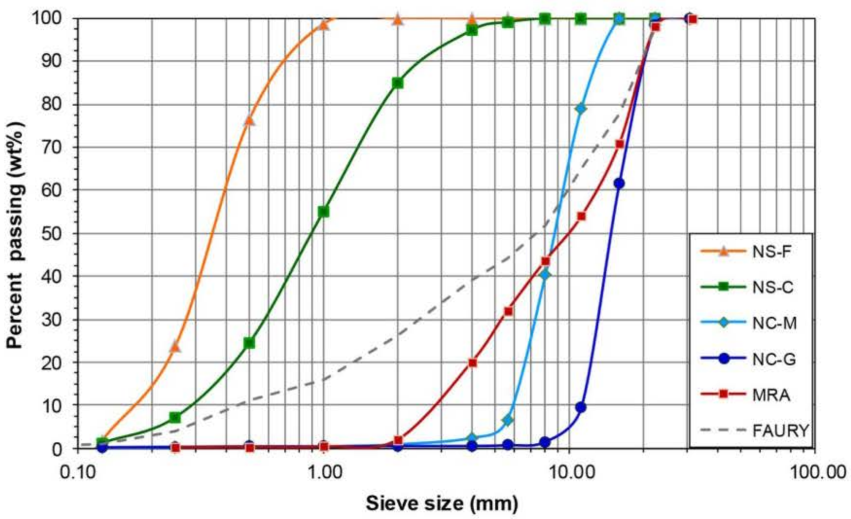

Fig. 2. Particle size curves for the aggregate used in the concrete mixes analysed.

Table 3
Physical and mechanical properties of the aggregates studied.

Property	NS-F	NS-C	NC-M	NC-G	MRA	EHE-08[2]
Dry density (kg/m^3) [42]	2581	2583	2600	2620	2069	–
SSD[1] density (kg/m^3) [42]	2601	2609	2630	2670	2256	–
Water absorption 24 h (wt %) [42]	0.4	0.5	1.3	1.3	9.1	≤5 (≤7)[4]
Water absorption 10 min (wt%) [17]	0.2	0.3	0.5	0.6	8.1	–
Open Porosity (vol%) [42]	1.1	1.2	2.5	3	18.7	–
Los Angeles coefficient (wt %) [44]	–	–	28	26	46	< 50[3]
Flakiness index (wt%) [45].	–	–	13	16	20	<35
Fineness modulus	2.1	3.3	7.4	6.5	6.8	–

Note: [1] SSD: Saturate Surface Dry; [2] EHE-08 recommendations; [3] concrete with compressive strength <30 MPa; [4] blended recycled and natural aggregate. Aggregate abbreviations: NS-F: natural fine sand (0/2 mm); NS-C: natural coarse sand (2/4 mm); NC-M: natural medium gravel (4/12 mm); NC-G: natural coarse gravel (12/22 mm); MRA: mixed recycled aggregate (4/22 mm).

Table 4
Experimental programme matrix and mix labels.

$r_{GRC} \setminus r_{MRA}$		MRA (r_{MRA})	
		0%	50%
GRC (r_{GRC})	0%	NAC	R0/50
	10%	N10/0	R10/50
	25%	N25/0	R25/50

Table 5
Concrete mix design.

Material	Mix proportion (kg/m^3)					
Mix	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
MRA replacement	0%			50%		
GRC replacement	0%	10%	25%	0%	10%	25%
OPC	300	270	225	300	270	225
GRC	–	30	75	–	30	75
Total water	168	174	180	205	211	217
Effective water	168	174	180	177	183	189
weff/b(PC + GRC)	0.56	0.58	0.60	0.59	0.61	0.63
NS-F	154	150	154	154	154	154
NS-C	755	755	755	755	755	755
NG-M	367	367	367	184	184	184
NG-G	653	653	653	327	327	327
MRA 16–22.4 mm	–	–	–	109	109	109
MRA 11.2–16 mm	–	–	–	182	182	182
MRA 8–11.2 mm	–	–	–	85	85	85
MRA 5.6–8 mm	–	–	–	59	59	59
MRA 4–5.6 mm	–	–	–	14	14	14

effective porosity (as per Spanish standard UNE 83980 [51]); capillary water absorption (Portuguese guide LNEC E−393 [52]; penetration depth of water under pressure (EN 12390-8 [53]); and water permeability coefficient as per [15]. In the permeability resistance test, water pressurised at a constant 5 bar was applied to the samples for 72 h. The outline of the water penetration front was traced on the two halves of each specimen resulting from the splitting tensile test subsequently conducted and the maximum and mean depths of the water front were recorded.

Ion migration was determined with electrical resistivity readings taken with a Wenner principle-based four-point device, as per Spanish standard UNE 83988-2 [54]. Three specimens were used for this test, with readings taken immediately after removal from the moulds and throughout the 90 d curing period. Specimens were stored in water at 20 ± 2 °C during the entire experimental period. Electrical resistivity was found as the mean of 12 readings (four per specimen).

Shrinkage was measured on prismatic specimens further to standard LNEC-E−398 [55]. After removal from their moulds, these specimens were stored in a dry chamber at constant temperature (20 ± 2 °C) and relative humidity (50 ± 5%). Shrinkage measurements were taken from the outset and across a 120 d period. The physical, mechanical, and durability properties analysed in the fresh and hardened mixes are listed in Table 6.

2.5. *Statistical analysis*

All findings were analysed using a three-way analysis of variance (ANOVA) model to determine the contribution of each factor and their interactions to water transport properties and shrinkage. Three levels of GRC incorporation ratio (0%, 10% and 25%), two of MRA content (0% and 50%) and two of curing age (28 d and 90 d) were analysed. Three-way ANOVA assesses the effect of the explanatory or independent variables on the response or dependent variables, as well as two factor (first order) interactions and three factor (second order) interactions. The model was also applied separately to each mix family (mixes with 100% NA and with 50% MRA) to analyse the same factors and levels: three GRC incorporation ratios (0%, 10% and 25%), two MRA contents (0% and 50%) and two curing ages (28 d and 90 d).

A factor or interaction between factors was deemed to have a significant effect on a property when the p-value associated with the F-statistic (or test) was less than 0.05 (confidence interval of 95%); the higher the test statistic value, the greater the effect of the factor [56]. All statistical calculations were performed using IBM SSPS (v.23) software.

3. Results and discussion

3.1. *Concrete properties*

Further to the data on fresh and 28 d hardened concrete properties in Table 7, the slump of all the mixes was within the 61 mm–75 mm range defined as class S2 (70 ± 20 mm) in standard EN 206-1 [46]. Fresh density was lower in the mixes with GRC and air content higher in concrete mixes with MRA than in the conventional mix. Those findings are directly related to the lower density of the recycled materials (GRC and MRA) than in the conventional ones (OPC and NA).

Twenty-eight day compressive strength declined with rising proportions of GRC as a cement addition and/or the MRA content in concrete. That behaviour was a direct result of the smaller amount of cement used and the intrinsic properties of GRC and MRA.

Table 6
Concrete properties characterised and standards applied.

Test method	Standard	Curing time (d)	Specimen types (*)
Slump test	EN 12350:2	Fresh concrete	–
Fresh density	EN 12350-6		
Air content	EN 12350-7		
Compressive strength	EN 12390-3	28	Cubes 150 × 150 × 150 mm (4)
Effective porosity	UNE 83980	28 and 90	Cubes 100 × 100 × 100 mm (4)
Capillary water absorption	LNEC E−393	28 and 90	Cylinder 150 mm Ø x 100 mm (4)
Penetration depth of water under pressure	EN 12390-8	28 and 90	Cylinder 150 mm Ø x 300 mm (3)
Electrical resistivity	UNE 83988-2	From 1 to 90	Cylinder 100 mm Ø x 200 mm (3)
Shrinkage	LNEC E−398	From 1 to 120	Prisms 100 mm × 100 mm x 500 mm (3)

Note: *number of samples.

Table 7
Fresh and hardened concrete properties.

Property	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
Slump (mm)	65 ± 2.8	74 ± 2.5	65 ± 3.7	75 ± 3.1	61 ± 3.7	63 ± 4.2
[1]Ac (vol%)	2.6 ± 0.2	2.7 ± 0.2	3.0 ± 0.1	3.2 ± 0.1	3.4 ± 0.2	3.8 ± 0.2
[2]ρ_{fresh} (kg/m^3)	2367 ± 21	2340 ± 19	2309 ± 24	2251 ± 28	2244 ± 22	2219 ± 23
28 d [3]f_{cm} (MPa)	46.6 ± 1.1	37.8 ± 1.4	27.7 ± 0.9	34.8 ± 1.2	32.8 ± 1.4	23.3 ± 1.2

Note: [1]Ac: air content, [2]ρ_{fresh}: fresh density and [3]f_{cm}: compressive strength.

3.2. Effective porosity

The 28 d and 90 d effective or open porosity (P_o) findings for all the mixes given in Table 8 attest to a rise in pore volume relative to NAC at both ages in all the experimental concrete mixes. Those results are related to the presence of non-reactive particles in the GRC, the higher effective w/c ratio in the new mixes and the greater porosity that characterises MRA.

The 28 d P_o values were observed to lie from 14.0 vol% to 15.6 vol% in the NA family (NAC, N10/0 and N25/0) and from 16.3 vol% to 18.6 vol% in the MRA mixes (NAC, N10/0 and N25/0). The use of GRC raised P_o by 5.7%–11.4% in mixes N10/0 and N25/0 relative to NAC and by 6.7%–14.1% in mixes R10/50 and R25/50 relative to R0/50. Those findings fell within the 13.0 vol% to 18.1 vol% range found in concrete with: 20%–100% MRA of a composition similar to the material used here (Rc: 44.6 wt%, Rb: 30.2 wt% and Ru: 24 wt%) [57]; 5%–25% rice husk ash [58]; 20%–50% recycled brick and sanitary ware [59]; up to 100% concrete CRA [60]; or 5%–35% rice husk ash and 100% concrete CRA [61].

The 90 d results showed P_o values lower than in the 28 d mixes, as expected, due to more extensive later age cement matrix hydration, with 13.3 vol% to 15.0 vol% in the NA and 14.9 vol% to 17-5 vol% in the MRA families. The somewhat greater decline in the mixes with MRA (≤5.9%) than in the NA concrete (≤4.2%) may have been associated with the pore filling induced by hydration of the anhydrous cement present in the mortar bound to the recycled aggregate. Similar observations were reported by other authors, who recorded declines of 4.0%–5.4% in concrete containing 50% RFA and 100% concrete CRA [62] and in mixes with 30%–100% concrete RFA [63].

The close indirect linear relationship between effective porosity and compressive strength in the mixes made with NA + GRC (NA mix) and concrete containing both MRA + GRC (MRA mix), clearly visible in Fig. 3, was confirmed by the consistently high R^2 values (>0.92 in both). Similar findings were reported earlier for concrete with 5%–30% cement replacements such as rice husk ash ($R^2 = 0.91$) [64], marble dust ($R^2 = 0.78$) [65] or concrete prepared with both rice husk ash and 100% concrete CRA ($R^2 = 0.93$) [61]. These findings likewise attest to the fact that MRA mix mechanical strength depended more on porosity than the same parameter in NA mixes, regardless of the GRC replacement ratio used.

Table 8
Effective (open) porosity in the 28 d and 90 d mixes.

Parameter/Mix	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
28 d effective (open) porosity						
$P_{o,28d}$ (vol%)	14.0 ± 0.1	14.8 ± 0.2	15.6 ± 0.4	16.3 ± 0.4	17.4 ± 0.5	18.6 ± 0.4
Δ GRC (%)[1]	–	5.7	11.4	–	6.7	14.1
Δ MRA (%)[2]				16.4	17.6	19.2
Δ GRC (%) * MRA (%)[3]					24.3	32.9
90 d effective (open) porosity						
$P_{o,28d}$ (vol%)	13.3 ± 0.2	14.2 ± 0.2	15.0 ± 0.4	14.9 ± 0.3	16.3 ± 0.4	17.5 ± 0.3
Δ GRC (%)	–	6.6	12.6	–	5.8	13.6
Δ MRA (%)				15.6	16.2	16.7
Δ GRC (%) * MRA (%)					23.9	31.4

Note: [1] GRC (%): NAC vs N10/0 and NAC vs N25/0 in mixes with NA and N10/0 vs R10/50 and N25/0 vs N25/50 in mixes with MRA; [2] MRA (%): NAC vs R0/50, N10/0 vs R10/50 and N25/0 vs N25/50; [3] GRC + MRA (%): NAC vs R10/50 and NAC vs R25/50.

3.3. Penetration depth of pressurised water

In terms of the maximum (D_{max}) and mean (D_a) 28 d and 90 d penetration depths of pressurised water (Table 9), the incorporation of recycled components GRC and/or MRA raised both parameters in all the mixes to values higher than recorded for the OPC and NA concrete. Those findings were associated with the effect of GRC and MRA on the pore structure of the new concrete. Nonetheless, the D_{max} and D_a values were consistently lower in all mixes (Fig. 4(a)) than the established ceilings (D_{max} = 50 mm or 30 mm; and D_a = 30 mm or 20 mm) for aggressive exposure classes associated with reinforcement corrosion and the specific environmental exposures laid down in code EHE-08 [6]. The experimental data consequently confirmed that the pore structures in all concrete mixes were sufficiently water-impermeable to ensure satisfactory durability [6].

The use of GRC induced a 27.8%–54.5% rise in D_{max} in mixes N10/0 and N25/0 C relative to mix NAC and a 17.7%–39.1% rise in R10/50 and R25/50 relative to R0/50. Rises were smaller in the 90 d concrete, where they came to 19.4%–49.3% in N10/0 and N25/0 relative to NAC and 17.6%–32.9% in mixes R10/50 and R25/50 relative to mix R0/50. That behaviour was a direct result of the slow GRC reactivity [36], whereby the effect of low cement content-induced dilution was more significant at early (<28 d) than at late (≥90 d) ages. Fig. 4(b) also shows the linear relationship ($R^2 \geq 0.98$) between GRC percentage and D_{max} in concrete with cements with recycled additions together with

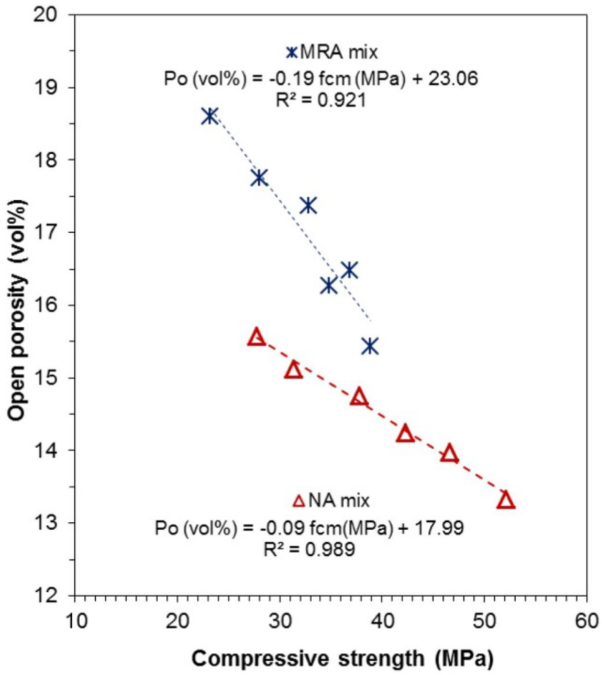

Fig. 3. Variation in compressive strength with effective porosity in (a) mixes with GRC + NA (NA mix); and (b) GRC + MRA (MRA mix).

Table 9
Penetration depth of water under pressure in 28 d and 90 d mixes.

Parameter/Mix	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
28 d penetration depth of water under pressure						
Maximum depth (mm)	14 ± 1	18 ± 2	22 ± 3	19 ± 3	22 ± 4	26 ± 3
Δ GRC (%)[1]	–	27.8	54.5	–	17.7	39.1
Δ MRA (%)[2]				31.3	20.9	18.2
Δ GRC (%) * MRA (%)[3]					54.5	82.6
Mean depth (mm)	11 ± 2	12 ± 2	17 ± 4	14 ± 2	15 ± 4	19 ± 4
Δ GRC (%)	–	9.1	54.5	–	7.1	35.7
Δ MRA (%)				27.3	25.0	18.8
Δ GRC (%) * MRA (%)					36.4	72.7
90 d penetration depth of water under pressure						
Maximum depth (mm)	13 ± 2	16 ± 2	20 ± 3	17 ± 2	20 ± 4	23 ± 3
Δ GRC (%)	–	19.4	49.3	–	17.6	32.9
Δ MRA (%)				26.9	25.0	13.0
Δ GRC (%) * MRA (%)					49.3	69.7
Mean depth (mm)	11 ± 2	11 ± 3	15 ± 3	13 ± 1	14 ± 2	16 ± 3
Δ GRC (%)	–	10.0	50.0	–	7.7	23.1
Δ MRA (%)				30.0	27.3	6.7
Δ GRC (%) * MRA (%)					40.0	60.0

Note::[1] NAC vs N10/0 and NAC vs N25/0 in mixes with NA and N10/0 vs R10/50 and N25/0 vs N25/50 in mixes with MRA; [2] MRA (%): NAC vs R0/50, N10/0 vs R10/50 and N25/0 vs N25/50; [3] GRC + MRA (%): NAC vs R10/50 and NAC vs R25/50.

either 100% NA or 50% MRA. That pattern was consistent with earlier results observed in concrete manufactured with biomass bottom ash replacement of OPC and MRA as NA substitute [66].

MRA at 50% replacement also induced a rise in 28 d D_{max} of ~31% and a ~26% rise in 90 d D_{max} in mixes R0/50, R10/50 and R25/50 relative to mixes NAC, N10/0 and N25/0. This was primarily associated with the presence of bound mortar and masonry material in MRA on permeability and the existence of microcracks in both the MRA microstructure and the MRA component/paste ITZs, which generated more readily accessible ingress pathways [65,66]. The findings likewise showed that this property was less adversely affected by the use of MRA than by the partial replacement of OPC with GRC.

The pattern observed for GRC was again consistent with earlier observations in concrete with 10% or 25% sugarcane bagasse ash [69] or mixes with 10%–20% rice husk ash [70] as replacement for OPC. Jointly including GRC + MRA, in turn, was in keeping with prior reports for concrete with 25% RFA plus 50% concrete CRA [71] and for mixes prepared with 0%–30% biomass bottom ash as an OPC substitute and 100% MRA instead of NA [72].

The D_{max} values recorded lay within the 17 mm–34 mm range observed in concrete with up to 25% sugarcane bagasse ash [69], 20% rice husk ash [70], 50% MRA [73], 50% concrete CRA [67], 75% concrete RFA [63] or 25% RFA in conjunction with 50% concrete CRA [71].

The D_a values followed a pattern similar to the one described for D_{max}. The 28 d D_a values were observed to lie within 11 mm and 17 mm in the NA family (NAC, N10/0 and N25/0) and 14 mm and 19 mm in the MRA mixes (NAC, N10/0 and N25/0). In the 90 d specimens those values declined by a mean 7.5% in mixes N10/0 and N25/0 and 10.5% in the mixes with GRC + MRA. The decline in D_a with curing age in mixes containing GRC and both recycled materials (GRC + MRA) was the result of the greater percentage reduction in effective porosity of these mixes than in the conventional concrete, as observed earlier and discussed in section 3.2.

3.4. Water permeability coefficient

As observed in the 28 d and 90 d water permeability coefficients (k_w) listed Table 10, calculated from Equation (1) [74], all the values were below the 1×10^{-12} m/s ceiling set by the Comité Euro-International du Béton [75] and the 15×10^{-12} m/s laid down in ACI standard 301-89 for high quality concrete and by Metha et al. [68] for moderate strength concrete (maximum aggregate size, 38 mm; 356 kg/m^3 cement; w/c = 0.5):

$$k_w = \frac{d_p^2 \times \delta}{2 \times h \times t} \quad \text{(Eq.1)}$$

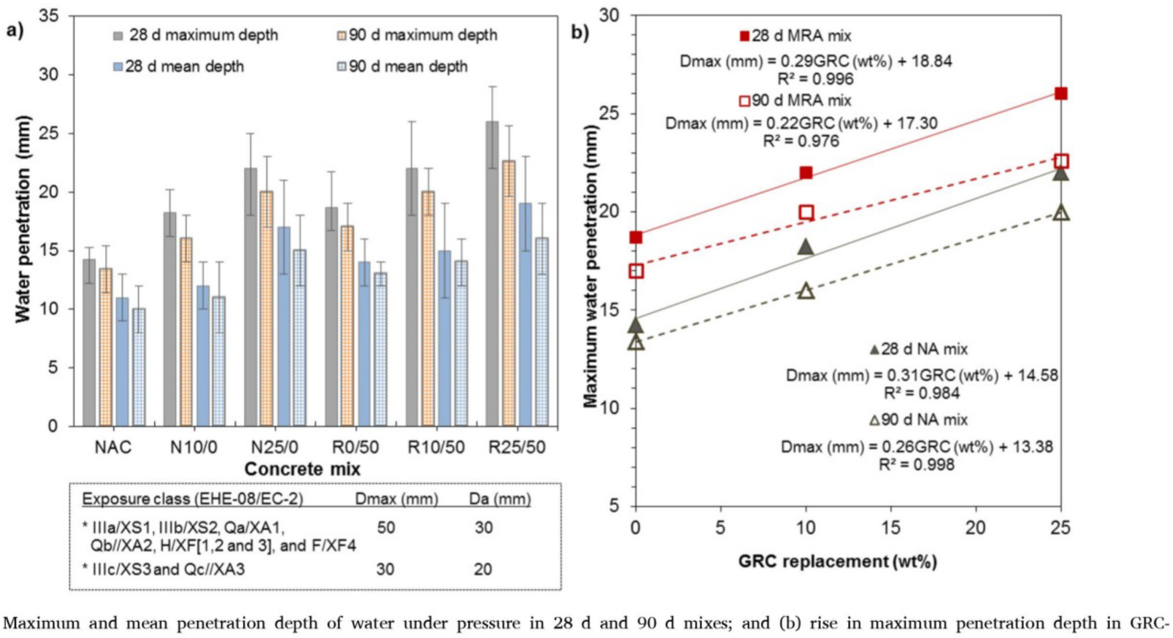

Fig. 4. (a) Maximum and mean penetration depth of water under pressure in 28 d and 90 d mixes; and (b) rise in maximum penetration depth in GRC-additioned mixes.

Table 10
Water permeability coefficient (k_w) in 28 d and 90 d specimens.

Mix	k_{w28d} (10^{-13} m s^{-1})	k_{w90d} (10^{-13} m s^{-1})
NAC	0.65 ± 0.05	0.51 ± 0.04
N10/0	0.86 ± 0.09	0.79 ± 0.07
N25/0	1.54 ± 0.07	1.29 ± 0.05
R0/50	1.23 ± 0.08	1.01 ± 0.07
R10/50	1.51 ± 0.07	1.25 ± 0.04
R25/50	2.59 ± 0.09	1.75 ± 0.07

where k_w is water permeability coefficient in m/s, d_p maximum penetration depth of water (m), δ effective porosity, t time needed to penetrate to d_p and h height of water column (m).

The higher k_w value in mixes R0/50, R10/50 and R25/50 than in N10/0 and N/25/0 was attributable to the better interconnected and more open pore system (see §3.6) in the former three than in the latter two. That behaviour was consistent with earlier observations for concrete with 20%–35% ground bagasse ash as OPC replacement and 100% concrete CRA instead of NA [76] and for mixes in which 50%–70% of the OPC was replaced by blast furnace slag and 100% of the NA with concrete CRA [77].

The close correlation found for the exponential relationship between the water permeability coefficient and mix effective porosity ($R^2 > 0.88$) is illustrated in Fig. 5(a). The correlation coefficient calculated (0.53–0.93) lay within the range found for permeable concrete containing: 20%–100% CRA [78]; 100% recycled aggregate consisting in crushed broken brick sourced from construction sites (RBA) [79]; or 12%–24% limestone powder as OPC replacement [80].

3.5. Capillary water absorption

The variation in 28 d and 90 d capillary water absorption (WA_c) with time in the NA and MRA families of mixes is graphed in Fig. 6, which also shows the Hall model [81] equation for fitting the curves (Equation (2)):

$$WA_c = A + S \times \sqrt{t} - C \times t \qquad \text{Eq.2}$$

where WA_c is capillary water absorption (g/mm^2); S is sorptivity or capillary absorption rate (mm/h$^{0.5}$); t is time (h); and A and C are constants.

The left and right sides of the figure attest to the similarity in the pattern of variation over time between recycled concrete N10/0, N25/0, R0/50, R10/50 and R25/50 and conventional mix NAC. The incorporation of GRC as OPC replacement, separately or in conjunction with the use of MRA as coarse aggregate, induced a gradual rise in WA_c relative to NAC at both ages studied. That behaviour was directly related to the linear relationship between maximum penetration depth and capillary water sorptivity (Fig. 5(b)).

The findings were consistent with observations reported by earlier authors for concrete with: 5%–15% concrete powder as OPC replacement [82]; 30%–100% concrete RFA [21]; 10%–20% limestone powder as OPC replacement in conjunction with 30%–90% concrete CRA to replace NA [83]; 50% or 100% RFA as well as 50% or 100% concrete CRA [62]; or total NA replacement with concrete RFA and CRA [84]. The aforementioned authors contended that the higher WA_c in the recycled material than in the conventional mixes was due to the presence of a greater pore volume, especially as regards the capillary fraction, in the new concrete cementitious matrices as a result of the presence of unbound water not used in cement hydration but required to ensure recycled material concrete's workability, along with the dilution induced by the lower cement content.

The Hall fitting model constants for the 28 d and 90 d concrete and the respective correlation coefficients are listed in Table 11. With values consistently higher than 0.98, all the correlation coefficients found for those relationships lay within the 0.97 to 0.99 range reported by other authors for concrete prepared with up to 100% concrete CRA [62] or up to 100% MRA [12].

The sorptivity (S) values in the 28 d and 90 d mixes calculated with the Hall fitting model are listed in Table 12. The incorporation of GRC induced a rise in that parameter at both ages, amounting to 23.4%–57.7% in N10/0 and N25/0 relative to NAC and 15.5%–51.3% in R10/50 and R25/50 relative to R0/50. The data in the table likewise show that using MRA in the concrete mixes raised sorptivity by 16.7%–26.5% relative to the conventional concrete. Those values lay within the 22%–44% range observed by Bravo et al. [57] for concrete with 10%–100% CDW-derived RA with a composition similar to the MRA studied here.

The variation in 28 d and 90 d sorptivity proved to be linearly related to GRC incorporation ratio in both the NA and MRA families (Fig. 7. ($R^2 > 0.96$). That same effect was observed in concrete where cement was replaced by 5%–40% granite sludge [85]; 5%–20% limestone powder [86]; or 10%–30% coal bottom ash [87].

The figure also shows that in mixes R10/50 and R25/50, which have both recycled materials (GRC and MRA), the decline in sorptivity at a later age ($\Delta_{28d\rightarrow90d} = 19.5\%–22.6\%$) was steeper than observed in the mixes containing GRC only ($\Delta_{28d\rightarrow90d} = 13.5\%–14.4\%$) or prepared with 100% NA and OPC ($\Delta_{28d\rightarrow90d} = 13.3\%$). That was related to the rehydration of the anhydrous cement particles present in both the GRC and in

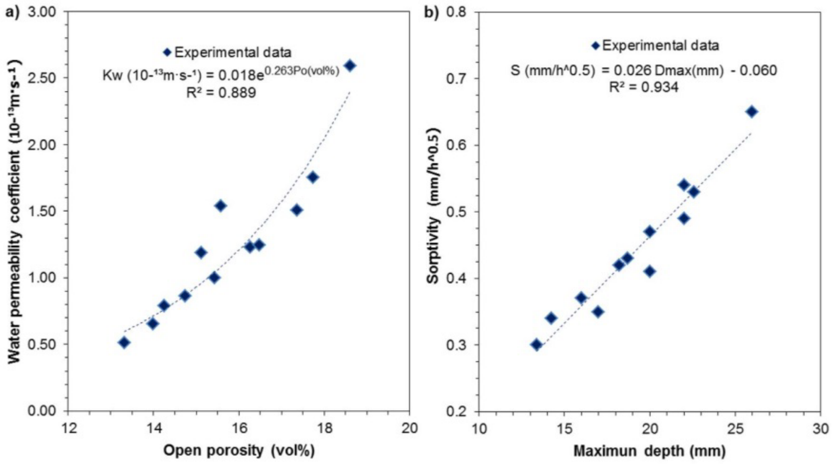

Fig. 5. Variation in (a) effective (open) porosity with the water permeability coefficient; and (b) in maximum penetration depth with sorptivity.

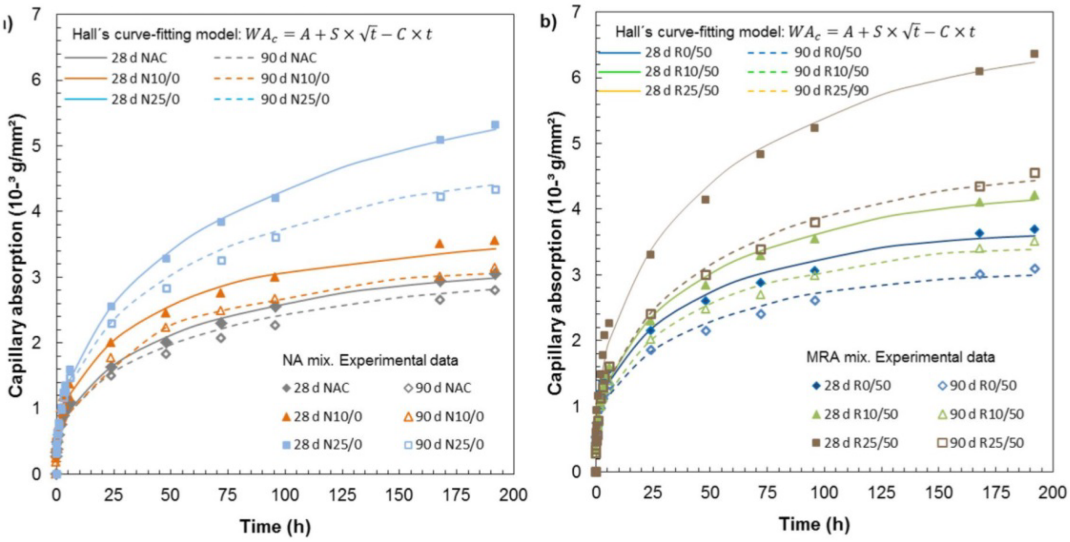

Fig. 6. Variation in 28 d and 90 d capillary water absorption with soaking time in the two families of mixes: (a) NA; and (b) MRA.

Table 11
Hall curve fitting model constants and correlation coefficients (R^2) for 28 d and 90 d concrete.

Hall fitting model constants: $WA_c = A + S \times \sqrt{t} - C \times t$

Mix	28 day mixes			90 day mixes		
	A	C	R^2	A	C	R^2
NAC	0.21	0.010	0.997	0.28	0.008	0.996
N10/0	0.29	0.014	0.989	0.14	0.015	0.992
N25/0	0.21	0.013	0.993	0.25	0.014	0.987
R0/50	0.43	0.014	0.992	0.39	0.012	0.992
R10/50	0.32	0.016	0.991	0.25	0.015	0.988
R25/50	0.40	0.021	0.987	0.23	0.016	0.983

Table 12
Sorptivity in 28 d and 90 d concrete.

Parameter/Mix	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
28 d sorptivity						
S_{28d} ($mm/h^{0.5}$)	0.34 ± 0.01	0.42 ± 0.02	0.54 ± 0.02	0.43 ± 0.03	0.49 ± 0.02	0.65 ± 0.02
Δ GRC (%)[1]	–	23.5	58.8	–	14.0	51.2
Δ MRA (%)[2]				26.5	16.7	20.4
Δ GRC (%) * MRA (%)[3]					44.1	91.2
90 d sorptivity						
S_{90d} ($mm/h^{0.5}$)	0.30 ± 0.01	0.37 ± 0.01	0.47 ± 0.02	0.35 ± 0.02	0.41 ± 0.02	0.53 ± 0.01
Δ GRC (%)[1]	–	23.3	56.7	–	17.1	51.4
Δ MRA (%)[2]				16.7	10.8	12.8
Δ GRC (%) * MRA (%)[3]					36.7	76.7

Note: [1] GRC (%): NAC vs N10/0 and NAC vs N25/0 in mixes with NA and N10/0 vs R10/50 and N25/0 vs N25/50 in mixes with MRA; [2] MRA (%):NAC vs R0/50, N10/0 vs R10/50 and N25/0 vs N25/50; [3] GRC + MRA (%): NAC vs R10/50 and NAC vs R25/50.

the mortar bound to some MRA components. The same pattern was reported by other authors [55,60,86,88] for concrete manufactured with concrete RFA and CRA.

All the sorptivity values recorded were lower than 3 $mm/h^{0.5}$, recommended by Ho and Lewis [89] to ensure a suitable service life for recycled concrete exposed to aggressive environments.

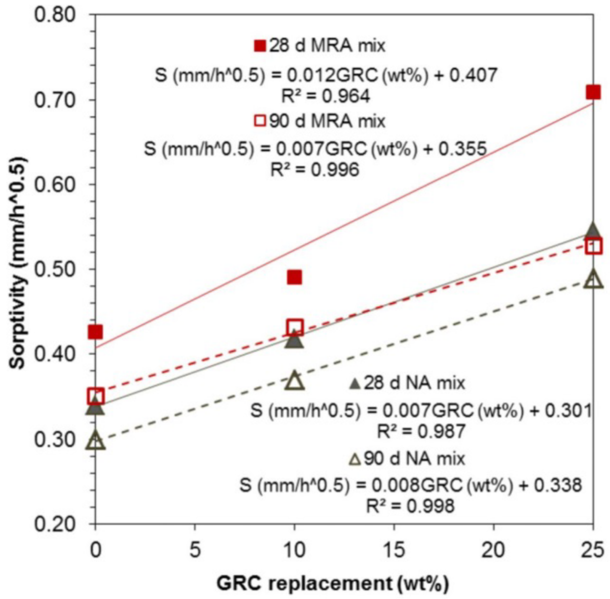

Fig. 7. Variation in 28 d and 90 d sorptivity with GRC incorporation ratio in NA and MRA mix families.

3.6. Electrical resistivity

The variation in electrical resistivity (ER) exhibited a steep early age (<7 d) rise (Fig. 8) irrespective of the type of concrete, which gradually declined [90]. The rapid initial rise was related to hydration product formation and concomitant pore system densification and refinement in concrete, with a decline in connectivity that hindered ion transport while raising mix resistivity [91]. Concrete with GRC exhibited lower electrical resistivity than its OPC counterpart as a result of the dilution associated with the addition. The same effect was observed in earlier studies of concrete prepared with 5%–15% cement kiln powder [32] and

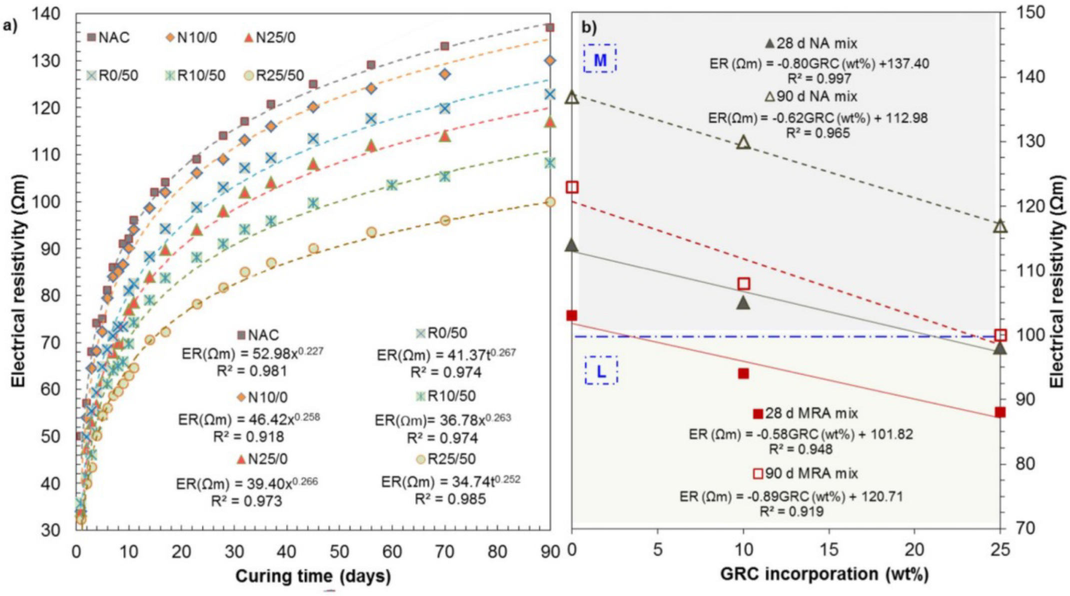

Fig. 8. Variation in 28 d and 90 d electrical resistivity (a) over time; and (b) with GRC replacement ratio for mean (M) and low (L) 'potential' durability.

mixes with 5%–20% limestone powder as cement replacements [86]. Using MRA also induced a decline in resistivity due to its higher porosity and the presence of microcracks in its microstructure. That behaviour was consistent with earlier observations for recycled material concrete with 25%–100% MRA [12] or 25%–100% RBA [92].

The variation in resistivity with curing time (t) is governed by the age factor (q) as per Equation (3):

$$ER_t = ER_0 \times t^q \quad \text{Eq 3}$$

where ER_t is electrical resistivity measured at time (t) and ER_0 at $t=0$.

The curves in Fig. 8(a) attest to a good fit to Equation (3), with correlation coefficients of 0.92–0.98. The age factor values calculated for all concrete mixes with GRC ranged from 0.26 to 0.27, which were slightly higher than 0.23 recorded for OPC concrete. These findings were consistent with earlier observations for type II/A (q = 0.3) and I (q = 0.2) cements reported by Andrade et al. [93].

The ER values for the 28 d and 90 d mixes are listed in Table 13. Adding GRC induced a decline in ER of 5.1%–14.1% in mixes N0/0 and N25/0 relative to mix NAC and of 8.7%–18.7% in mixes R10/50 and R25/50 relative to mix R0/50. The decline in ER translated into readier ion species migration, attributable to a tightly interconnected pore system [94]. The joint use of GRC and MRA, in turn (mixes R10/50 and R25/50), prompted a steeper decline in this property, which was 17%–27% lower than in the NAC reference mix. The decline in all values remained within the 7%–28% range found for concrete mixes with: 25%–50% coarse masonry aggregate [92]; 25%–50% concrete RFA [95]; 5%–15% recycled cement powder as OPC replacement; or 20%–30% palm oil clinker powder as an OPC replacement together with 100% concrete CRA to replace NA [96].

The variation in 28 d and 90 d ER with GRC incorporation ratio in the NA and MRA families graphed in Fig. 9(b) shows that including GRC induced a linear decline in both the NA and MRA families. All the correlation coefficients (R^2) were >0.91. The same pattern was found in concrete manufactured with 5%–25% granite powder [97] or 5%–15% recycled cement powder [32]. According to the 'potential' durability classes proposed by Baroghel-Bouny et al. [98], all the 28 d mixes except R10/50 and R25/50 exhibited mean 'potential' (100 Ω m to 250 Ω m) durability similar to the value observed for the conventional mix (NAC).

The relationship between electrical resistivity (ER) and effective

Table 13
28 d and 90 d electrical resistivity.

28 d electrical resistivity						
Parameter/Mix	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
ER_{28d} (Ω·m)	114 ± 2	105 ± 2	98 ± 3	103 ± 2	94 ± 3	88 ± 2
Δ GRC (%)[1]	–	−7.9	−14.0	–	−8.7	−14.6
Δ MRA (%)[2]				−9.6	−10.5	−10.5
Δ GRC (%) * MRA (%)[3]					−17.5	−22.8
90 d electrical resistivity						
ER_{90d} (Ω·m)	137 ± 1	130 ± 2	117 ± 3	123 ± 3	108 ± 1	100 ± 2
Δ GRC (%)	–	−5.1	−14.6	–	−12.2	−18.7
Δ MRA (%)				−10.2	−16.9	−14.5
Δ GRC (%) * MRA (%)					−21.2	−27.0

Note:* [1] GRC (%): NAC vs N10/0 and NAC vs N25/0 in mixes with NA and N10/0 vs R10/50 and N25/0 vs N25/50 in mixes with MRA; [2] MRA (%): NAC vs R0/50, N10/0 vs R10/50 and N25/0 vs N25/50; [3] GRC + MRA (%): NAC vs R10/50 and NAC vs R25/50.

porosity (Po) in the 28 d and 90 d mixes could be modelled as per Archie's law (Equation (4)) with R^2 values of 0.91–095, indicative of a good fit:

$$ER = A \times P_o^{-m} \quad \text{Eq.4}$$

where ER is electrical resistivity in Ω·m, A is a constant that depends on the pore structure and Po is concrete effective porosity expressed as a decimal.

These findings were consistent with the results of Omary et al. [99] who found an R^2 value of 0.90 for the ER/Po relationships in concrete with 30%–100% concrete CRA, and Cantero et al. [12] who reported correlation coefficients of $0.93 \geq R^2 \leq 0.94$ in concrete with 20%–100% MRA. They also confirmed the dependence of ER on the pore system's characteristics in concrete with GRC as OPC replacement.

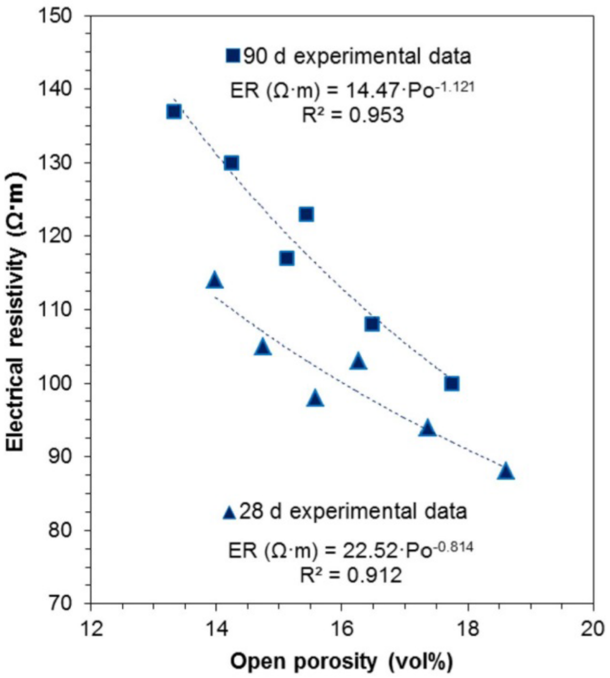

Fig. 9. Variation in 28 d and 90 d electrical resistivity with effective (open) porosity.

3.7. Shrinkage

The variation in shrinkage over time for all mixes is graphed in Fig. 10, according to which the steep decline in specimen size in the first 28 d ultimately waned. That behaviour fit a logarithmic function with correlation coefficients (R^2) over 0.98 and was consistent with findings reported by Bravo et al. [18,100] for concrete with 10%–100% CRA sourced from CDW (R^2 = 0.93 to 0.99) and Cartuxo et al. [101] for concrete with 10%–100% concrete FRA (R^2 = 0.95 to 0.98). The rapid shrinkage in the early weeks (<28 d) and subsequent stabilisation were consistent with previous findings for concrete with: 5%–15% cement kin powder [32]; as cement replacement or 9%–27% recycled CDW powder instead of NA [102]; both 0%–55% biomass bottom ash as OPC replacement and 50%–100% MRA to replace NA [66]; or 50%–75% of a fly ash + slag + silica fume addition and 50%–100% concrete CRA as NA replacement [103].

Further to the shrinkage values of the 28 d and 90 d mixes listed in Table 14, the use of GRC and/or MRA induced 18.7%–35.8% greater shrinkage relative to NAC in the 90 d NA mixes and 11.9%–25.0% in the 90 d MRA mixes relative to R0/50. In addition to the greater porosity of the recycled than the traditional OPC and NA materials, that rise was associated with the presence of a larger number of more tightly interconnected pores, the result in turn of the presence of more unused water that had to be added to the mixes containing GRC and/or MRA to ensure suitable workability. Similar results were observed for concrete with: 5%–15% cement kiln powder to replace OPC [32]; 50% coarse and fine MRA [18]; up to 100% concrete CRA; up to 100% concrete FRA [104]; or 0%–30% biomass bottom ash as cement replacement as well as 0%–50% MRA instead of NA [66].

Mixes R10/50 and R25/50, which contained both MRA and GRC, exhibited 28.5% and 43.5% greater 90 d shrinkage, respectively, than the NAC reference. That difference was wider than observed for the counterpart N10/0 and N25/0 with no MRA because the lower modulus of elasticity in recycled aggregates, attributable to the presence of bound mortar, masonry material and impurities (gypsum and bituminous matter), induces greater shrinkage, as reported earlier by Yanagi et al. [105] and Rosales et al. [66] for concrete manufactured with MRA.

Fig. 10 (b) graphs the variation in shrinkage with GRC incorporation ratio in 28 d and 90 d concrete. The curves show that, irrespective of age and the use or otherwise of MRA, due to the higher water demand in the new binders (R_{10} and R_{25}) containing the addition, shrinkage rose linearly with the GRC ratio with R^2 of 0.98. The same pattern was found in earlier studies for concrete with: 5%–15% cement kiln powder as OPC replacement [32]; 20%–100% MRA as NA substitute [19]; or both 0%–

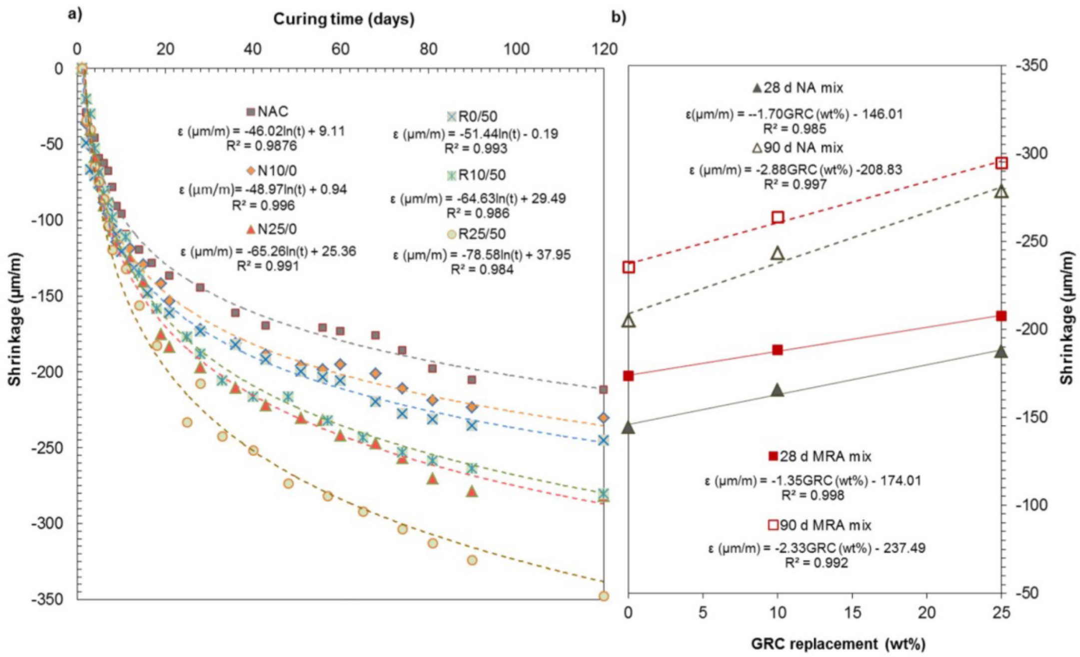

Fig. 10. 28 d and 90 d specimen shrinkage (a) over time; and (b) with GRC incorporation ratio.

Table 14
Shrinkage of 28 d and 90 d concrete.

28 d shrinkage						
Parameter/Mix	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
ε_{28d} (μm/m)	−144.4 ± 4.5	−165.7 ± 5.1	−187.5 ± 4.8	−173.5 ± 6.3	−188.4 ± 7.1	−207.5 ± 6.4
Δ GRC (%)[1]	–	14.8	29.8	–	8.6	19.6
Δ MRA (%)[2]				20.2	13.7	10.7
Δ GRC (%) * MRA (%)[3]					30.5	43.7
90 d shrinkage						
ε_{90d} (μm/m)	−205.3 ± 5.4	−243.6 ± 6.2	−278.7 ± 5.8	−235.7 ± 7.9	−263.8 ± 6.2	−294.6 ± 7.1
Δ GRC (%)	–	18.7	35.8	–	11.9	25.0
Δ MRA (%)				14.8	8.3	5.7
Δ GRC (%) * MRA (%)					28.5	43.5

Note:* [1] GRC (%): NAC vs N10/0 and NAC vs N25/0 in mixes with NA and N10/0 vs R10/50 and N25/0 vs N25/50 in mixes with MRA; [2] MRA (%):NAC vs R0/50, N10/0 vs R10/50 and N25/0 vs N25/50; [3] GRC + MRA (%):NAC vs R10/50 and NAC vs R25/50.

30% biomass bottom ash in the place of OPC and up to 100% MRA instead of NA [66].

Table 15 compares the 90 d shrinkage found experimentally ($\varepsilon_{experimental}$) to the values calculated (ε_{EC2}) as specified in Eurocode 2 (EC2) [106]. All the EC2-calculated values overestimated shrinkage by 106%–140% over the experimental period, an observation consistent with most earlier studies consulted [18,101,105,107]. A review of the literature by Silva et al. [109] found that the calibration models proposed in EC2 to estimate shrinkage were based on RILEM [110] studies conducted as early as 1953, when the characteristics of the concrete used were in all likelihood less favourable than those of the materials in place today. Kurda et al. [108] recently found that the shrinkage values calculated with EC2 [106] and ACI [111] in a considerable number of studies on conventional concrete (OPC + NA) overestimated that parameter relative to the experimental values ($k = \varepsilon_{EC2}/\varepsilon_{experimental}$) by a factor of 1.93 ($R^2 = 0.99$).

The value of the k ratio found in the present study for the conventional mix showed shrinkage to be overestimated by a factor of 1.95, very nearly the same as the 1.93 reported by Kurda et al. [108] (Table 15). Including 10% or 25% GRC raised that overestimate by 5%–9% in mixes N10/0 and N25/0 relative to the value found for the conventional mix (NAC). An even higher rise (11.3%) was found for k relative to NAC in mixes with 50% MRA. The joint inclusion of GRC and MRA, in contrast, lowered the overestimate by 5.1%–8.5% relative to the mix with 50% MRA and 100% OPC, an effect likewise observed in concrete containing 30% biomass bottom ash and 50% MRA [66].

3.8. Significance of factors in water transport and shrinkage

The results of a three-way ANOVA are given in Fig. 11 for the factors analysed: GRC incorporation ratio (GRC (%)); age; and MRA (recycled aggregate) content and their interactions in connection with two properties associated with water transport, namely electrical resistivity and shrinkage (see the supplementary material for the statistical calculations). The statistical models explained from 95.8% to 99.7% of the variation observed in those properties. The GRC ratio (%) explained most (52.2%–65.7%) of the variation in sorptivity, penetration depth of pressurised water and the water permeability coefficient. These findings were attributed to: i) early age GRC activity, which was too low to offset the dilution associated with the lower cement content; ii) the greater GRC than OPC porosity; and iii) the presence of coarse particles >63 μm in the GRC (Table 1). The respective data confirmed the results discussed in sections 3.3, 3.4 and 3.5.

Recycled aggregate content was the factor that affected effective porosity most significantly, explaining 64.8% of the variation. In other words, the use of MRA affected that property more than the GRC ratio, as discussed in the description of the respective results in section 3.2., for two reasons: the MRA replacement ratio in the mix, at 50%, was greater than the 10% and 25% GRC ratios and the aggregate accounted for a larger share of total concrete volume than cement.

Age, in turn, was the factor contributing most to the variation in electrical resistivity (42.0%) and shrinkage (65.8%), for binder hydration entailed changes in concrete microstructure and a rise in those two parameters, irrespective of the percentage of GRC and/or MRA in the mix. Those findings again supported the results set out in sections 3.6 and 3.7, according to which electrical resistivity was 14.8%–23.8% and shrinkage 65.8%–48.6% greater in the 90 d mixes than in their 28 d counterparts.

Although the interaction between GRC (%) and age had a significant effect, it accounted for less than 3.0% of the variation in all the properties studied, attesting to the low early age (<90 d) reactivity in GRC. None of the other interactions exhibited significant effects (p-value>0.05).

The statistical results for each mix are graphed separately in Fig. 12. Here GRC (%) was also the factor contributing the most to the variation in sorptivity, penetration depth of water under pressure and permeability coefficient, as well as the effective porosity in each family of mixes, with values of 81.8%–91.2% in the NA family and 70.2%–83.6% in the mixes with MRA. Age continued to be the factor accounting for the greatest share of variation in electrical resistivity and shrinkage, with a contribution of 66.19%–70.2% in the NA mixes and 44.7%–76.9% in the MRA family. Its contribution to the other properties also rose, with values of 6.4%–16.5% in the NA family and 14.1%–21.6% in the mixes with MRA. That greater contribution of age to the MRA mixes was attributable to the possible rehydration of the anhydrous particles present in the mortar bound to MRA components. The aforementioned findings are consistent with those described in sections 3.2, 3.3., 3.4 and 3.5. and some earlier studies [23].

Here also, the GRC (%)*age interaction made a minor contribution to variation, with values of 1.3%–3.2% in the NA mixes and 1.9%–5.9% in the MRA mixes. The statistical models explained 95.0%–99.5% of the variation in the properties analysed in the NA mixes and 93.8%–99.6% in the MRA concrete.

Table 15
90 d experimental and EC2-calculated shrinkage values and k factor.

Mix	$\varepsilon_{experimental}$ (μm/m)	ε_{EC2} (μm/m)	k
NAC	−205.3 ± 5.4	−400.3 ± 4.8	1.95
N10/0	−243.6 ± 6.2	−489.0 ± 6.1	2.00
N25/0	−278.7 ± 5.8	−569.7 ± 5.4	2.04
R0/50	−235.7 ± 7.9	−512.2 ± 6.8	2.17
R10/50	−263.8 ± 6.2	−528.2 ± 5.9	2.00
R25/50	−294.6 ± 7.1	−607.8 ± 6.7	2.06

4. Conclusions

The key conclusions to be drawn from the findings discussed in this article are set out below.

- The use of GRC raised effective porosity by 5.7%–11.4% in mixes with 100% NA and by 6.7%–14.1% in mixes containing 50% MRA, both

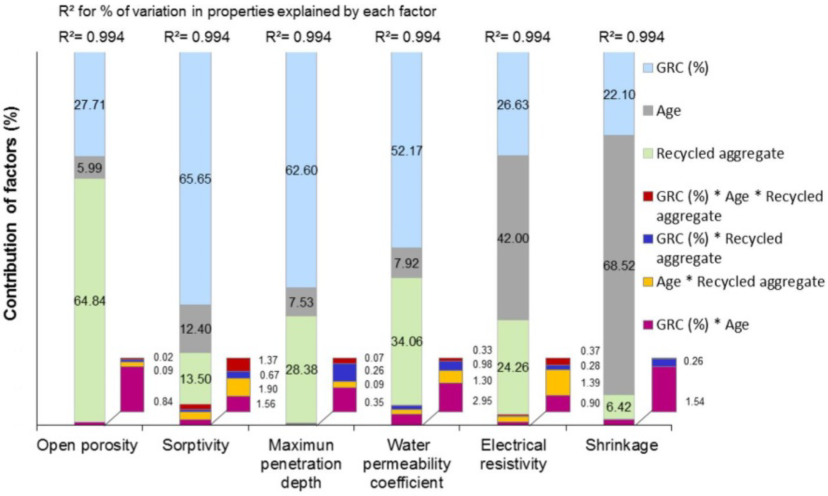

Fig. 11. Three-way ANOVA results for water transport, electrical resistivity and shrinkage -related properties.

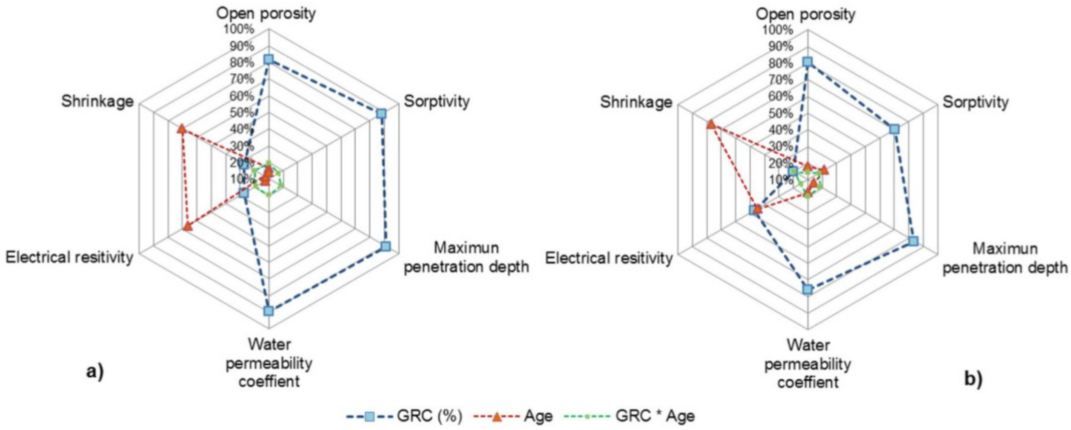

Fig. 12. Two-way ANOVA results for (a) NA mixes; and (b) MRA mixes.

relative to concrete prepared with OPC;

The decline in compressive strength observed in the recycled material mixes containing GRC and/or MRA was directly related to the higher effective porosity in those than in conventional concrete. All the recycled material mixes, whether or not GRC-additioned, complied with the ceiling maximum and mean penetration depths of water under pressure stipulated in the Spanish structural concrete code (EHE-08) for concrete exposed to aggressive environments;

The water permeability coefficient (k_w) in all the mixes was under 10^{-12} m/s, the value specified by the Comité International du Béton as the upper limit for permeability in good quality concrete;

Sorptivity was consistently below the 3 mm/h$^{0.5}$ ceiling recommended for concrete exposed to aggressive environments. Such low sorptivity, which would prevent the ingress of aggressive agents into the pore system and ensure an acceptable service life for recycled material concrete, was very closely and linearly related to the maximum penetration depth of pressurised water;

Enhanced pore system interconnection in mixes containing GRC and/or MRA favoured ion migration, lowering electrical resistivity by a mean of 5.1%–14.6% in mixes with 100% NA and 8.7%–18.7% in those with 50% MRA. Electrical resistivity and effective porosity could be related in keeping with Archie's law;

In the NA family of mixes with GRC, shrinkage was 18.7%–35.8% greater than in the concrete prepared with OPC, and in the MRA family the analogous values were 11.9%–25.0%. Shrinkage calculated as per Eurocode 2 was greater than observed experimentally;

GRC was the factor with the greatest effect on sorptivity, penetration depth of pressurised water and the water permeability coefficient, explaining 52.2%–65.7% of the variation in those properties. MRA, in turn, accounted for 64.8% of the variation in effective porosity;

Most of the variation in electrical resistivity and shrinkage in concrete with both GRC and MRA was explained by curing time, which determined the degree of hydration of the anhydrous cement present in the former and the residual mortar bound to components of the latter.

The present findings support the premise that the pore structure in concrete with 10%–25% GRC as cement replacement in conjunction with 50% MRA is sufficiently impermeable to hinder the ingress of harmful agents and thereby ensure suitable recycled material concrete's durability. Further research is also called for to fully understand the behaviour of these new concrete mixes, including, for instance, carbonation or chloride resistance testing. Another area worth pursuing is the performance of new concrete mixes with other recycled binders, by analysing the interaction, for instance, between pozzolans such as silica fume and fly ash and those present in construction and demolition waste. New specifications or standards governing the use of these new concrete mixes can only be introduced after exhaustive knowledge of their behaviour can be acquired. Recommendations along these lines are essential for engineers, architects and construction companies to understand and confide sufficiently in the behaviour of new concrete mixes to include them in their design.

CRediT: statement of authors' contributions

Blas Cantero: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing· **Miguel Bravo:** Conceptualization, Methodology, Investigation, Writing - review & editing· **Jorge de Brito:** Conceptualization, Methodology, Resources, Writing - review & editing' **Isabel Fuencisla Sáez del Bosque:** Conceptualization, Methodology, Writing - review & editing· **César Medina:** Supervision, Conceptualization, Methodology, Formal analysis Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cemconcomp.2021.103957.

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Capítulo 10

Assessment of the Permeability to Aggressive Agents of Concrete with Recycled Cement and Mixed Recycled Cement and Mixed Recycled Aggregate

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Assessment of the Permeability to Aggressive Agents of Concrete with Recycled Cement and Mixed Recycled Cement and Mixed Recycled Aggregate.

Resumen

La evaluación de la permeabilidad frente a la entrada de agentes nocivos en el hormigón reciclado es fundamental para su incorporación sostenible en la industria de la construcción. Para ello, este estudio analiza los mecanismos de transporte asociados a la entrada de iones cloruros (Cl^-), oxígeno (O_2) y dióxido de carbono (CO_2) en hormigones con un 10 % y un 25 % de cemento reciclado de hormigón (GRC) individual y conjuntamente con un 50 % de áridos reciclados mixtos (MRA). Los resultados revelan que, independientemente del tipo de árido, los hormigones con GRC muestran una menor resistencia a la entrada de agentes nocivos debido a una estructura más porosa y conectada. Sin embargo, todos los coeficientes de permeabilidad al O_2 y penetración de CO_2 se fueron inferiores a $4.5 \text{x} 10^{-17}$ m^2 y 4 mm/año$^{0.5}$ respectivamente, como resultados indicativos de hormigones de buena calidad. Asimismo, los hormigones con un 10 % de GRC y un 50 % de MRA alcanzaron una resistencia a la penetración de CO_2 y Cl^-, similar a la del hormigón convencional. Finalmente y a la luz de estos resultados, la pasividad de las armaduras quedara garantizada en estos hormigones cuando se exponen a entornos normales de carbonatación durante un periodo de vida útil de diseño de hasta 100 años.

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Assessment of the Permeability to Aggressive Agents of Concrete with Recycled Cement and Mixed Recycled Aggregate

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Abstract: Acceptance by the construction industry of recycled concrete as a sustainable alternative material is contingent upon a reliable assessment of its permeability to corrosive agents. This study analyses the transport mechanisms associated with chloride (Cl^-), oxygen (O_2) and carbon dioxide (CO_2) ions in concrete with cement made with 10% or 25% ground recycled concrete (GRC) separately or in combination with 50% mixed recycled aggregate (MRA). The findings show that, irrespective of aggregate type, concrete with GRC exhibited lower resistance to ingress than conventional concrete due to its greater porosity. Nonetheless, O_2 permeability was consistently below 4.5×10^{-17} m^2 and CO_2 penetration, under 4 mm/year$^{0.5}$, indicative of concrete with high quality. Resistance to CO_2 and Cl^- penetration in the materials with 10% GRC was similar to the values observed in conventional concrete. On the other hand, the incorporation of 25% GRC increased the penetration of CO_2 and Cl^- by 106% and 38%, respectively. Further to those findings in normal carbonation environments, reinforcement passivity would be guaranteed in such recycled materials over a 100 year service life.

Keywords: recycled aggregate; recycled concrete; durability; chloride penetration; carbonation

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1. Introduction

The evaluation of the mechanical behaviour of concrete is always considered essential, while the evaluation of the durability of this construction material is sometimes overlooked. Concrete with high porosity allows the entry of external agents, which can lead to durability problems; hence, it is essential to study in detail several properties that are related to the durability of concrete.

The permeability to aggressive agents in concrete can be measured through several tests, such as evaluating the transport mechanisms associated with chloride ions, oxygen and carbon dioxide.

The analysis of the permeability of concrete to gases concerns the entire porous structure of this material, i.e., both small and large pores, due to the reduced size of the oxygen molecules. Therefore, the oxygen permeability test has a higher sensitivity than the water absorption tests, since the water molecules are larger than the oxygen ones [1].

The transport mechanism of chloride ions in concrete is somewhat complex, and may involve diffusion, impregnation and capillary water absorption processes. Transport mechanisms vary widely with the microenvironment in which the structural elements are inserted. The penetration of chlorides into ordinary concrete is usually carried out through the continuous pore structure of the cementitious paste, the interface between the aggregates, and the paste (ITZ) and micro-cracks [2]. The penetration of chlorides is, together with carbonation, the main factor responsible for the depassivation and corrosion of steel reinforcement in reinforced concrete.

In turn, the carbonation process begins with the penetration, by diffusion, of carbon dioxide (CO_2) into concrete, which, in the presence of moisture, reacts with the hydrated cement minerals and gives rise to carbonation. In other words, CO_2 in the atmosphere reacts with the alkaline components of concrete, namely by transforming calcium hydroxide (CH) into calcium carbonate. These chemical reactions of dissolution of the crystalline phases of concrete cause a decrease in the pH of the concrete pores' solution, enabling the corrosion of the steel reinforcement, since the oxide film that protects the steel reinforcement is only stable in very alkaline environments [3]. The carbonation resistance of concrete is generally determined through accelerated tests, in which the concrete specimens are subjected to high concentrations of CO_2 (5%). Thus, one of the problems of this type of test is to understand whether the results obtained evaluate rigorously the behaviour of concrete exposed to atmospheric CO_2 concentrations. It is recalled that the concentration, in volume, of CO_2 in the atmosphere usually varies between 0.03%, in rural areas, and 0.10%, in places with high population density [4].

According to data presented by the United Nations, in 2015 the world population was around 7.3 billion, and this number is expected to reach 9.7 billion in 2050 [5]. That report also indicates that, in 2015, for the first time, the majority of the world's population already lived in cities. The migration of populations to urbanized areas brings benefits for global development, but also implies a significant increase in built parks, with an increase in the production of construction and demolition waste (CDW), whose environmental impact is extremely negative. Although the use of CDW already occurs, as aggregates in concrete in some constructions, the truth is that its incorporation still corresponds to occasional cases and it is not a common reality.

The use of recycled aggregates (RA) in concrete raises some important questions in terms of durability. These aggregates have physical properties and compositions that are very different from those of natural aggregates. The main difference is related to the greater porosity and, consequently, greater water absorption of RA. However, this variation depends on the RA's source and production process. On the other hand, the roughness and specific surface of RA are usually higher and RA typically have more elongated shapes. Due to these factors, the effective water/cement (w/c) ratio of mixes with RA must be increased to maintain a given workability, which then leads to more porous cementitious matrices and interfacial transition zones (ITZs). Given this, the use of RA in concrete can decrease its durability [6].

On the other hand, in the 20th century, the annual emission of carbon dioxide (CO_2) into the atmosphere increased from 1.5 to 25 billion tonnes [7]. This unsustainable rate of emissions comes from several activities, including construction, which alone contributes to more than 6% of the global value through the production of cement. Thus, it is important to investigate the possibility of providing the construction industry with an innovative way of creating structural concrete with a positive environmental impact throughout its life cycle. This can be achieved through the creation of synergies in two distinct areas: replacement of the Portland cement by an alternative binder with lower environmental impact using CDW; and incorporation of RA from CDW.

According to this literature review, there are not many studies on the behaviour in terms of durability of concrete with CDW simultaneously used as aggregates and binders. The use of CDW in concrete has been analysed mainly in two different ways: analysis of the use of RA from crushed concrete; and evaluation of the use of RA from mixed CDW. The latter RA have highly variable composition, which makes their analysis more difficult. On the other hand, RA from CDW generally have higher water absorption, which causes some limitations on their use in concrete.

Torgal et al. [8] analysed the oxygen permeability of concrete with RA and recycled cement from four types of ceramics (ceramic bricks, double-fired white stoneware, sanitary ware and single-fired white stoneware). The authors found that the replacement of 20% Portland cement with recycled cement from ceramics leads to maintaining the oxygen permeability of concrete. For two of the wastes (double-fired and single-fired white stoneware), there was even a slight improvement in this property (lower than 10%). In turn, the authors observed an improvement of 20% and 30% in oxygen permeability with the total replacement of coarse and fine aggregates, respectively. The authors explain this result with the highest degree of hydration in the cementitious paste of concrete with RA.

Thomas et al. [9] evaluated some properties of precast concrete elements in which coarse RA and recycled cement were used. In this experimental campaign, six concrete mixes were characterised: a reference mix; two mixes with 25% and 50% (by weight) RA from mixed CDW; three mixes similar to the previous ones but with recycled cement with low clinker content (cement produced with 25% of ceramic waste). As in other studies [6], it was found that the oxygen permeability coefficient increases with the replacement of natural aggregates with RA. The authors [9] also concluded that this increase is higher in concrete with recycled cement and with the use of 50% of RA (higher than 300%) than in concrete with Portland cement and with the use of 50% of RA (higher than 40%).

Bravo et al. [6] studied the replacement of natural aggregates (fine and coarse) by RA from mixed CDW from four recycling plants. To this end, the authors analysed the oxygen permeability of concrete produced with 0%, 10%, 50% and 100% of fine or coarse RA. Total replacement of the fine and coarse aggregates caused increases in this property of more than 43% and 91%, respectively. Thomas et al. [9] also obtained significant increases in this property with the incorporation of coarse RA from CDW. The authors obtained increases of 50% in the oxygen permeability test performed at 28 days.

Torgal et al. [8] also evaluated the resistance to the penetration of chloride ions in concrete with RA (ceramic) and recycled cement (from four types of ceramic waste). The authors concluded that the use of RA and recycled cement significantly improved this property, obtaining decreases in the diffusion of chloride ions between 12% and 70%, and between 23% and 29%, respectively.

Qin and Gao [10] analysed the influence of the use of recycled cement produced from concrete waste (0%, 10%, 20%, 30% and 50% of the total weight of the binders) on the resistance to the penetration of chloride ions of cementitious composites. The authors concluded that the use of 50% recycled cement increases the permeability to chloride ions by more than 300%. However, the authors found that this increase is reduced to around 200% when the concrete is subjected to accelerated carbonation curing.

Some studies have also analysed the carbonation resistance of concrete with recycled cement. Kim [11] evaluated the behaviour of self-consolidating concrete with recycled cement from concrete (0%, 15%, 30% and 45% of the total mass of the binders). The author found that the use of this recycled cement causes a significant increase in the carbonation depth of the concrete (between 2.3 and 6.9 times).

Sáez del Bosque et al. [12] also evaluated the carbonation resistance of concrete with coarse RA from CDW (25% and 50% of the total coarse aggregates) and recycled cement (with 25% of ceramic wastes). Regardless of the type of cement, the average carbonation depth was slightly higher in materials with 25% or 50% recycled aggregate than in the reference concrete. The use of this partially recycled cement produced from ceramic waste led to an increase in the carbonation depth at 28 days from 4.2 mm to 5.0 mm (increase of 19%).

The present investigation follows previous ones that intended to analyse the mechanical behaviour, water absorption, shrinkage and thermal performance of concrete with RA from CDW and recycled cement [13–15]. In these previous investigations, the authors observed that the use of GRC enhanced concrete environmental performance. At 10% replacement, it lowered the CO_2 emitted in concrete manufacture by 7.5%, and at 25% GRC by 18.7%, relative to concrete made with ordinary Portland cement (OPC).

There are already some studies that address the permeability of concrete with recycled cement (mainly from ceramic wastes) or with RA from CDW. However, no previous study has evaluated the permeability to aggressive agents (chloride ions, carbon dioxide and oxygen) of concrete with simultaneous replacement of the two elements evaluated in this investigation. To fill this scientific and technical knowledge gap, this study analyses the effect of replacing Portland cement with ground recycled cement (GRC), at 10% (R10) or 25% (R25). This assessment was carried out on concrete with 100% NA, 50% NA and 50% mixed recycled aggregates (MRA). This experimental campaign involved the evaluation of the permeability to the aggressive agents of these mixes through the performance of oxygen permeability tests, resistance to the penetration of chloride ions and resistance to carbonation. Finally, the evolution of the carbonation front in these mixes was studied with the increase in the exposure time for mixes in different exposure classes, according to the forecasting model proposed by EHE-08 [16]. This assessment in this type of concrete has not yet been carried out in previous investigations.

2. Experimental Programme

2.1. Materials

2.1.1. Binders

The three types of binders used in this study were as follows: (i) type I 42.5 R (CEM I 42.5 R) ordinary Portland cement (OPC); (ii) a binder with 90% OPC and 10% GRC; and (iii) a binder with 75% OPC and 25% GRC. The GRC was obtained by crushing and grinding laboratory-prepared concrete specimens (stored in a wet chamber at 20 ± 2 °C and relative humidity of 55 ± 5% for 90 days), batched as per the Faury method with 300 kg/m^3 of cement and a water/binder ratio of 0.55. The GRC processing is illustrated in Figure 1: (i) in Stage 1, the specimens were mixed, moulded, cured and subsequently tested to breakage; (ii) in Stage 2, the cubic and prismatic specimens were jaw-crushed to a particle size of <16 mm; (iii) in Stage 3, the particles generated in Stage 2 were roll-crushed to <5 mm; and (iv) in Stage 4, the crushed concrete was ball-ground for 2 h at 60 rpm (ratio between abrasive load and material of 3/1) to the target fineness.

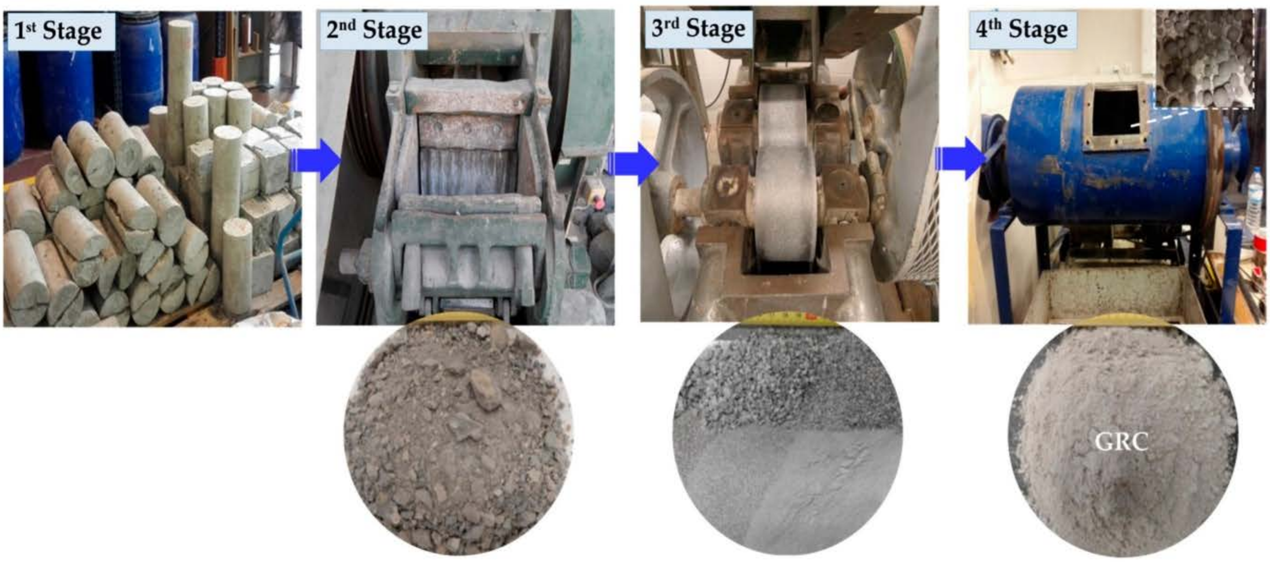

Figure 1. Four stages of GRC preparation.

OPC's and GRC's chemical compositions, particle size distributions and densities are given in Table 1. The main phases in GRC are SiO_2 (46.1 wt%); CaO (40.0 wt%); and Al_2O_3 (5.3 wt%).

D_{90} (90th percentile value for particle diameter) in GRC was 147 μm. The difference from the 46 μm recorded for OPC is associated with the natural aggregate present in the source recycled concrete. In contrast, the lower value of D_{10} in the GRC (1.58 μm) than for OPC may be attributed to the presence of a cementitious matrix in the recycled aggregate used to prepare the former. The GRC used was less dense (2.54 g/cm^3) than OPC (3.11 g/cm^3).

Table 1. Chemical constituents and physical properties of OPC and GRC.

Material	Chemical Constituent (wt%)								
	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	SO_3	LoI *
OPC	18.7	65.1	5.1	2.6	0.2	0.5	1.8	3.0	2.5
GRC	46.1	40.0	3.8	1.5	0.3	1.2	0.5	0.4	6.2
	Physical Property								
	Sieve size (µm)			Per cent passing (%)	Density (g/cm^3)				
	10	50	90	<63 µm					
OPC	1.9	13.8	46.0	97.9	3.1				
GRC	1.6	21.2	147.0	67.8	2.5				

Note. * LoI: loss on ignition.

2.1.2. Aggregates

The coarse natural aggregate (NA) used contained two sizes of limestone gravel, 4/12 mm (NG-M) and 12/22 mm (NG-G), and two sizes of siliceous river sand, 0/2 mm (NS-F) and 2/4 mm (NS-C). The single fraction (0/32 mm) MRA supplied by a CDW recycling plant at Lisbon (Portugal) was sieved and classified at the laboratory, where sizes <4 mm and >22 mm were discarded. The particle size distributions of all the NA and of the 4/22 mm coarse MRA aggregate ultimately used complied with the recommendations of European standard EN 933-1 [17] and are given in Figure 2.

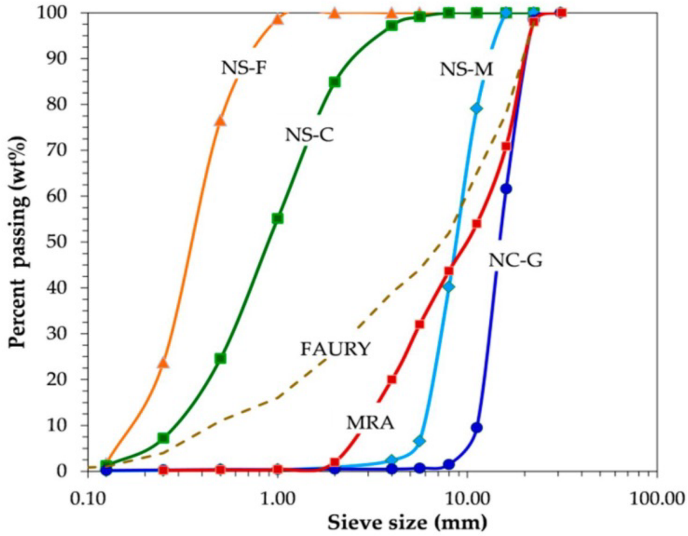

Figure 2. Aggregate particle size distribution and theoretical Faury curve for a maximum aggregate size of 22 mm and 300 kg/cm^3 cement.

The composition of the 4/22 mm coarse MRA aggregate, likewise determined as per standard EN 933-11 [18], is listed in Table 2, according to which the main components were Rc (47.1 wt%), Rb (22.3 wt%) and Ru (25.2 wt%), with glass and plaster (<2 wt%) as minor constituents. On the grounds of those data and the criteria set out in Spain's structural concrete code (EHE-08) [16], with its <95 wt% Rcu (Rcu = Rc + Ru) content and >5 wt% Rb content, MRA qualified for classification as a mixed recycled aggregate. The physical and mechanical properties recommended in standard EN 12620 [19] for coarse aggregates to be used in structural concrete ($f_{ck} \leq 30$ MPa) are listed in Table 3.

Table 2. Composition of MRA as per standard EN 12620.

Class	Rc	Ru	Rb	Rg	Ra	X1	X2	FL
Amount (wt%)	47.1	25.2	22.6	1.7	0.2	1.8	0.4	1.0

Component abbreviations: Rc: concrete and mortar, Ru: natural stone, Rb: clay materials, Rg: glass, Ra: bituminous matter, X1: gypsum, X2: metals, FL: floating particles.

Table 3. Physical and mechanical properties of the aggregates.

Property	NS-F	NS-C	NC-M	NC-G	MRA	EN 12620
Dry density (kg/m^3) [20]	2581	2583	2600	2620	2069	-
SSD [1] density (kg/m^3) [20]	2601	2609	2630	2670	2256	-
$WA_{24\,h}$ [2] (wt%) [20]	0.4	0.5	1.3	1.3	9.1	≤ 5 (≤ 7) [5]
$WA_{10\,min}$ (wt%) [21]	0.2	0.3	0.5	0.6	8.1	-
Open porosity (vol%) [20]	1.1	1.2	2.5	3	18.7	-
LA [3] (wt%) [22]	-	-	28	26	46	≤ 40 [6]
FI [4] (wt%) [23]	-	-	13	16	20	<35

Aggregate abbreviations: NS-F: natural fine sand (0/2 mm); NS-C: natural coarse sand (2/4 mm); NC-M: natural medium gravel (4/12 mm); NC-G: natural coarse gravel (12/22 mm); MRA: mixed recycled aggregate (4/22 mm). **Note.** [1] SSD: saturated surface dry, [2] WA: water absorption, [3] LA: Los Angeles coefficient, [4] FI: flakiness index, [5] concrete with compressive strength < 30 MPa; and [6] blended recycled and natural aggregate according to Spanish concrete code EHE-08 [16].

2.2. Experimental Procedure

2.2.1. Pre-Conditioning

The specimens were prepared and cured for the O_2 permeability and CO_2 and Cl^- penetration tests as per European standard EN 12390-2 [24]. The size of the prismatic specimens for O_2 permeability testing was 150 × 300 mm (∅ × height) and that of the samples for CO_2 and Cl^- penetration was 100 × 200 mm. All of the specimens were cured for 28 d or 90 d in a wet chamber at a relative humidity of 95 ± 5% and a temperature of 20 ± 2 °C. Concrete disks 50 mm thick (measured with a digital calliper with a precision of 0.1 mm) were cut out of the mid-section of each specimen with a water-cooled diamond saw. The samples for O_2 permeability and Cl^- penetration testing were subsequently sealed around the outer rims and the disks for the CO_2 penetration tests at the top and bottom with three layers of epoxy resin to ensure one-dimensional flow.

The samples for the O_2 permeability and CO_2 penetration tests were stored in a wet chamber at 20 ± 2 °C and relative humidity of 55 ± 5% for 3 weeks, in keeping with standardised procedures. The samples for the Cl^- penetration tests were pre-saturated for 4 h in a vacuum container with the top and bottom exposed to the ultra-low pressure (<1 mm Hg). Water was then added to the container, where the vacuum was released after 1 h and the samples left to soak in the water for a further 18 ± 2 h prior to testing.

2.2.2. Oxygen Permeability

O_2 permeability was assessed with a Cembureau apparatus in a room at the controlled temperature (20 ± 2 °C) and relative humidity (50 ± 5%) as specified in Spanish standard UNE 83981 [25]. The O_2 permeability coefficient, defined in terms of Darcy's law, was calculated here with the Hagen–Poiseuille relationship (Equation (1)) for the laminar flow of a compressible fluid across a porous medium under steady flow conditions [26]:

$$K = \frac{2\mu L}{S\left(P_s^2 - P_O^2\right)} P_s Q_s \quad (1)$$

where K (m^2) is the O_2 permeability coefficient; Q_s the outlet flow ($m^3 \cdot s^{-1}$); P_s, the absolute pressure at the sample outlet (Nm^{-2}); P_o, the absolute pressure at the sample inlet (Nm^{-2});

S, the cross-sectional area of the sample (m^2); L, the sample thickness in the direction of the flow (m); and μ, the O_2 dynamic viscosity at 20 °C (2.02×10^{-5} Nsm^{-2}).

2.2.3. Rapid Chloride Permeability (RCP) Test

Cl^- penetration was determined using the electrical procedure described in standard ASTM 1202-97 [27] in a room at a controlled temperature (20 ± 5 °C). The total electric current passing through the samples in 6 h was calculated by integrating current over time (RCP test finding), as in Equation (2):

$$RCP = 900(I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{300} + 2I_{330} + I_{360}) \quad (2)$$

where RCP is total charge (coulombs); I_o, the electric current immediately after applying voltage (Ampere); and I_t, the electric current at time t (Ampere), with subscripts denoting time in minutes.

The empirical formula proposed by Berke and Hicks [28] (Equation (3)) was applied to correlate RCP to the diffusion coefficient (D) in m^2/s $\times 10^{-12}$:

$$D = 0.0103 \times RCP^{0.84} \quad (3)$$

where the unit for RCP is Coulomb.

2.2.4. Accelerated Carbonation Test

The resistance to CO_2 penetration test was conducted as described in Portuguese standard LNEC E391 [29]. The samples were stored for 7 d, 28 d, 56 d or 90 d in an accelerated carbonation chamber with a CO_2 concentration of 3 ± 0.1%, relative humidity of 60 ± 5% and temperature of 23 ± 3 °C. The carbonation depth was found by spraying the two sides of the sample resulting from diametric breakage with a phenolphthalein solution (0.8 g of the indicator in powder form dissolved in a solution containing 70 mL of ethanol and 30 mL of deionised water). As phenolphthalein is purple at pH > 10, the colourless concrete was determined to have been carbonated (pH < 8). Measurements were taken at a total of 12 points in each sample and recorded along with the maximum and minimum CO_2 penetration depths.

2.2.5. Service Life Prediction

Concrete carbonation affects the durability limit states of concrete structures, insofar as it deteriorates the passive cover that protects the reinforcing steel [30]. In the semi-probabilistic approach adopted by Spain's structural concrete code EHE-08, the condition to be met is as follows:

$$t_s > t_d \quad (4)$$

where t_s is estimated service life and t_d service life calculated for the concrete structure.

Calculated service life (t_d) is defined (Equation (5)) as the product of the design service life (t_{SL}) for the type of structure times a service life safety coefficient (γ_i), quantified in the aforementioned code as 1.10. A 50 year design service life is assumed for residential or office buildings, bridges and flyovers less than 10 m long and low- or medium-order engineering structures, whereas monumental buildings or high-order structures are designed for a 100 year service life:

$$t_d = \gamma_i \times t_{SL} \quad (5)$$

Further to the CO_2 penetration model described in code EHE-08 [16], characteristic depth (X_c) can be expressed as in Equation (6):

$$X_c(t_{SL)} = K_n\sqrt{t_d} \quad (6)$$

where X_c is the characteristic depth (mm) for the design service life; K_n is the natural carbonation coefficient listed in Table 8 (mm/year$^{0.5}$) and t_d, the calculated service life.

2.3. Concrete Design

Batching for all the concrete mixes is given in Table 4. In all mixes, irrespective of the MRA and/or NA content, the particle size distribution was fitted to Faury's [31] theoretical curve for a maximum aggregate size of 22 mm, maximum compactness and the same volume of aggregate in all mixes. That called for separating the MRA into sub-fractions: 16/22 mm, 11.2/16 mm, 8/11.2 mm, 5.6/8 mm, 4/5.6 mm. All the mixes were designed to meet the requirements set out in European standard EN-206-1 [32] for durability class XC2 and strength class C25/30. Cement was added at a rate of 300 kg/m^3 and all the mixes were prepared to S2 workability, defined in European standard EN-206-01 [32] as equivalent to a slump of 70 ± 20 mm [33]. Consequently, a higher water/binder ratio was required in the recycled materials than in the conventional materials due to the lower density of the GRC than OPC, and MRA than NA [15,34].

Table 4. Concrete mixes' compositions.

Material	**Proportion (% or kg/m^3)**					
Concrete Mix	**NAC**	**N10/0**	**N25/0**	**R0/50**	**R10/50**	**R25/50**
MRA replacement		0%			50%	
GRC replacement	0%	10%	25%	0%	10%	25%
OPC	300	270	225	300	270	225
GRC	-	30	75	-	30	75
Total water	168	174	180	205	211	217
[w/b(OPC+GRC)]	0.56	0.58	0.60	0.59	0.61	0.63
NS-F	154	150	154	154	154	154
NS-C	755	755	755	755	755	755
NG-M	367	367	367	184	184	184
NG-G	653	653	653	327	327	327
MRA 16–22 mm	-	-	-	109	109	109
MRA 11.2–16 mm	-	-	-	182	182	182
MRA 8–11.2 mm	-	-	-	85	85	85
MRA 5.6–8 mm	-	-	-	59	59	59
MRA 4–5.6 mm	-	-	-	14	14	14
Fresh and hardened concrete properties (±: standard deviation).						
Slump (mm)	65 ± 2.8	74 ± 2.5	65 ± 3.7	75 ± 3.1	61 ± 3.7	63 ± 4.2
Density (kg/m^3)	2367 ± 8	2340 ± 9	2309 ± 10	2251 ± 11	2244 ± 12	2219 ± 10
Strength class [1]	C35/45	C30/37	C20/25	C25/30	C25/30	C12/15
$P_{o,28\,d}$ (vol%) [2]	14.0 ± 0.1	14.8 ± 0.2	15.6 ± 0.4	16.3 ± 0.4	17.4 ± 0.5	18.6 ± 0.4
$P_{o,90\,d}$ (vol%) [3]	13.3 ± 0.2	14.2 ± 0.2	15.0 ± 0.4	14.9 ± 0.3	16.3 ± 0.4	17.5 ± 0.3

Note. [1] Strength class in EC-2 is designated CX/Y, where X is the characteristic 28 day compressive strength value in 15 × 30 cm cylindrical specimens and Y the characteristic compressive strength in 15 × 15 cm cubic specimens. [2,3] Po, 28 d/90 d: 28 d/90 d open porosity (porosity accessible to water).

3. Results and Discussion

3.1. Oxygen Permeability

The graphs in Figure 3 of the 28 d and 90 d O_2 permeability coefficient and standard deviation (error bars) values denote a decline in permeability with curing age, irrespective of the GRC and MRA content. At the same time, the incorporation of the new recycled components induced a rise in O_2 permeability due to (i) the higher porosity of the new cement matrices, attributable to the dilution due to the presence of non-reactive particles in GRC (see item 2.1.1) and (ii) the greater porosity of MRA than NA, induced by the bound mortar and masonry materials found in the former (Table 2). Those findings were consistent with, and within, the range (1.0×10^{-17} to 8.0×10^{-17}) reported for mixes prepared with 50% RCA [35], with 25% masonry aggregate [36], and mixes with 20% masonry waste (in the form of fired clay brick, gloss- or bisque-fired white stoneware or sanitary ware) used as a cement substitute [8].

The use of GRC raised 28 d O_2 permeability by 47.0% in mix N10/0 and 97.3% in mix N25/0 relative to NAC, and by 25.7% in mix R10/50 and 51.9% in mix R25/50 relative to R0/50. These increases were less steep at 90 d: 7.5% in mix N10/0 and 84.1% in mix N25/0 relative to NAC, and 14.9% in mix R10/50 and 47.8% in mix R25/50 relative to R0/50.

Analogously, the use of 50% MRA (mix R0/50) raised 28 d O_2 permeability by 92.7% and the 90 d value by 67.5% relative to the conventional mix with NA. That rise was primarily associated with the effect of the presence of bound mortar and masonry material in MRA (more porous than NA) on O_2 permeability and the more readily accessible ingress pathways generated by microcracks in the MRA microstructure [37,38]. In addition, all the increases lay within the range (18% to 98%) observed in mixes with up to 50% RCA [35,39], with 25% masonry material [36], or prepared with both 25% masonry waste as an OPC replacement and 25% to 50% MRA [9].

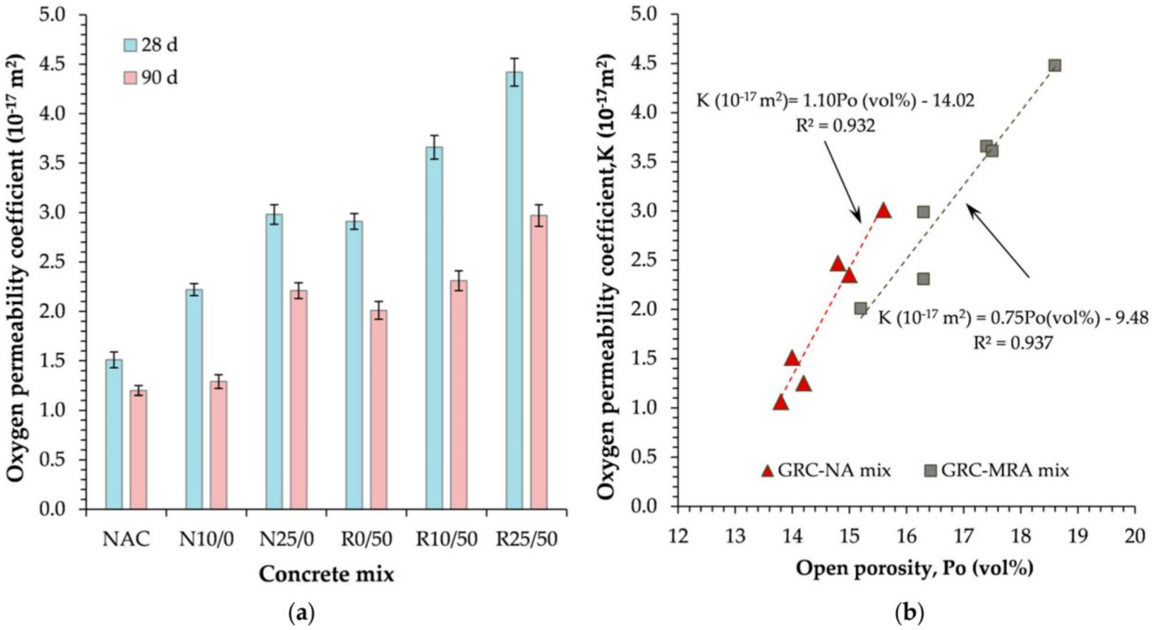

Figure 3. (**a**) 28 d and 90 d oxygen permeability (error bars indicate the standard deviation associated with variability in results); and (**b**) variation in open porosity with oxygen permeability.

Further to the plots in Figure 3b, the O_2 permeability coefficient and open porosity were linearly and closely ($R^2 > 0.91$) correlated in the mixes studied and the former was observed to increase proportionally to the latter. Similar findings were reported for mixes prepared with other additions (fly ash [40], rice husk ash [41] and masonry dust [42]) to replace cement; mixes containing RCA fines and coarse aggregates [43]; and mixes made with masonry aggregate [36]. The inference drawn from such a close correlation indicates that this property may serve as an index for assessing the material's porosity and, consequently, its durability.

3.2. Resistence to Chloride Ion Penetration

The results of the rapid chloride penetration (RCP) test, Berke and Hicks [28] equation-calculated chloride diffusion (D) and the respective standard deviations for the 28 d and 90 d mixes are given in Table 5. The data show a steeper decline in Cl^- penetration with curing age ($\Delta RCP_{28d\rightarrow 90d}$) in the mixes containing recycled materials (GRC and/or MRA) than in the OPC/NA concrete. Similarly, the absolute value of $\Delta RCP_{28d\rightarrow 90d}$ was greater in both the GRC–NA (−13.7% in N10/0 and −14.3% in N25/0) and GRC–MRA (−14.9% in R10/50 and −16.5% in R25/50) families than the −9.3% in the reference NAC.

Table 5. Rapid chloride penetration (RCP) and chloride diffusion in 28 d and 90 d mixes (±, standard deviation).

Concrete Mix	28 d		90 d		$\Delta RCP_{28d\to 90d}$
	RCP (C) *	D ($10^{-12}m^2/s$)	RCP (C)	D ($10^{-12}m^2/s$)	
NAC	3480 ± 258	9.72 ± 0.72	3157 ± 152	8.96 ± 0.84	−9.29
N10/0	3950 ± 245	10.81 ± 0.94	3410 ± 301	9.56 ± 0.91	−13.67
N25/0	4806 ± 453	12.75 ± 1.01	4100 ± 266	11.2 ± 0.98	−14.27
R0/50	4336 ± 361	11.7 ± 0.95	3620 ± 322	10.05 ± 0.81	−16.52
R10/50	4454 ± 284	11.96 ± 1.04	3753 ± 274	10.36 ± 0.92	−15.75
R25/50	4950 ± 181	13.07 ± 0.87	4210 ± 321	11.98 ± 0.82	−14.94

Note. * C: Coulomb.

According to Figure 4a, Cl^- penetration rose linearly ($R^2 \geq 0.949$) with the GRC replacement ratio, irrespective of curing age (28 d or 90 d) and family (GRC-NA or GRC-MRA), with values 8.0% higher in mix N10/0 and 38.1% in N25/10 than in NAC, and 2.7% higher in R10/50 and 16.3% in R25/50 than in R0/50. The incorporation of 50% MRA (mix R0/50) also induced increases of 14.7% to 24.6%, relative to mix NAC. That behaviour can be directly associated with the higher porosity of the new cementitious matrices, given the presence of new recycled materials (GRC and/or MRA). It is also consistent with earlier observations for mixes with additions, such as 10% to 40% cement powder [44], 10% to 50% concrete powder [10], or 5% to 15% cement kiln dust [45] as OPC replacements, and materials containing 15% to 30% biomass bottom ash (BBA) to replace OPC, separately or in combination with 30% MRA as an NA substitute [46].

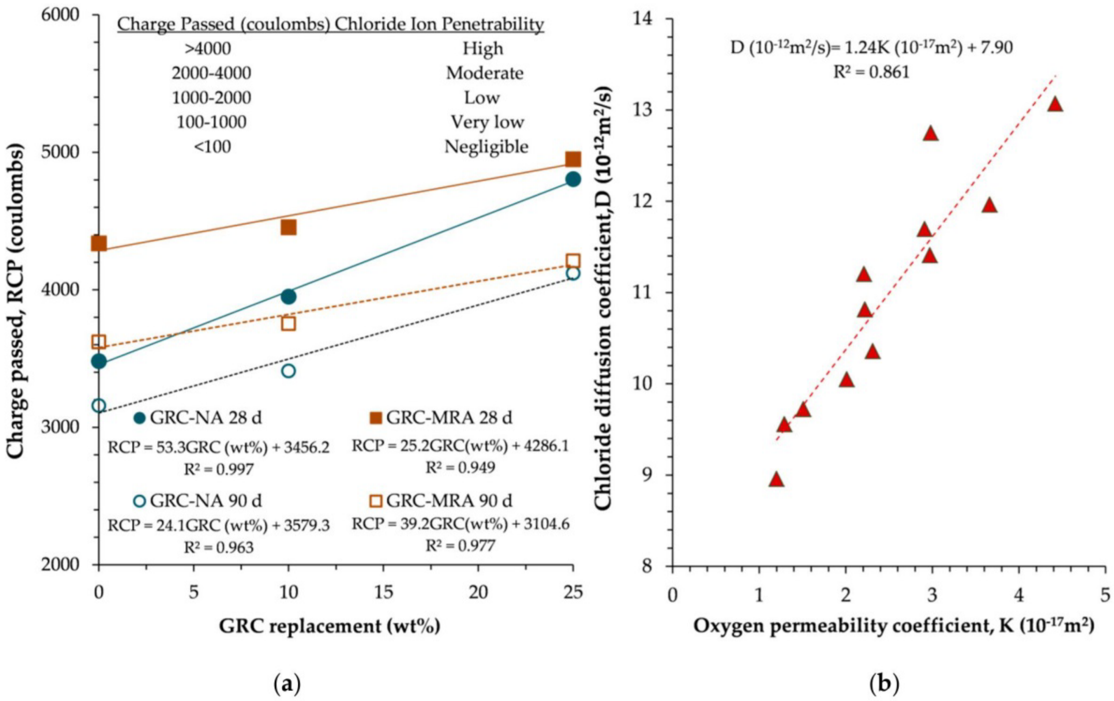

Figure 4. (**a**) Variation in RCP with the inclusion of GRC in 28 d and 90 d mixes; and (**b**) relationship between the chloride diffusion and oxygen permeability coefficients.

The 90 d mixes with 10% GRC, separately or in combination with 50% MRA, qualified for the same 'moderate' corrosion risk class as mix NAC, given that all the rises were observed to lie within the 8% to 30% observed in earlier studies in mixes with 10% to 40% of other inert additions (marble powder and granite dust) [47].

The close linear relationship (R^2 = 0.861 > 0.85 [48,49]) between O_2 permeability and the chloride diffusion coefficient in the mixes studied (Figure 4b) is clear proof that both transport mechanisms depend on pore structure and pore interconnectivity alike [50]. Similar findings were reported earlier for mixes made with additions such as marble powder or granite dust [47], ground granulated blast furnace slag (GGBFS) [51,52] or BBA [46] as cement replacements, mixes with 20% to 100% RCA [43], and mixes where 5% to 10% of the OPC was replaced with silica fume and 50% to 100% of NA with RCA [39].

3.3. Carbonation Resistance

The mean carbonation depths (Cd) of all the mixes after 7 d, 28 d, 56 d or 90 d in an accelerated carbonation chamber and associated standard deviations are listed in Table 6. Carbonation resistance was intensely affected by the porous microstructure of the new recycled concrete mixes with GRC and/or MRA. The use of GRC raised 28 d Cd by +0.8 mm in mix N10/0 and 5.7 mm in mix N25/0 relative to NAC and by 1.0 mm in mix R10/50 and 3.0 mm in mix R25/50 relative to R0/50. Similar findings were observed in mixes prepared with additions such as 5% to 25% marble slurry [53], 25% masonry CDW [12], and 25% to 50% fly ash from biomass-fired power plants [54]. The data in Table 7, in turn, denote the very close (correlation coefficients, R^2, of over 0.89) linear relationship between the Cd and GRC content, irrespective of exposure time and family (GRC-NA or GRC-MRA).

Table 6. Carbonation depth and coefficients in concrete mixes with 7 d, 28 d, 56 d or 90 d exposure to accelerated carbonation (±, standard deviation).

Concrete Mix	Carbonation Depth (mm)				Carbonation Coefficient	
	7 d	28 d	56 d	90 d	K_{ac} (mm/year$^{0.5}$)	R^2
NAC	2.2 ± 0.4	5.4 ± 0.8	6.5 ± 1.1	9.2 ± 1.8	17.95	0.988
N10/0	3.1 ± 0.5	6.2 ± 0.4	7.2 ± 1.4	9.9 ± 1.7	20.55	0.993
N25/0	4.9 ± 0.3	11.1 ± 0.4	14.8 ± 1.7	17.8 ± 2.1	30.0.8	0.994
R0/50	3.9 ± 0.2	8.4 ± 0.8	10.5 ± 1.4	13.5 ± 1.5	27.67	0.987
R10/50	4.1 ± 0.6	9.4 ± 1.1	10.9 ± 1.2	14.9 ± 1.6	29.67	0.994
R25/50	5.1 ± 0.9	11.4 ± 0.5	16.6 ± 1.7	18.0 ± 2.1	38.96	0.982

Table 7. Correlation between mean carbonation depth and GRC replacement ratio.

Exposure Time (Days)	Type of Mix					
	GRC-NA			GRC-MRA		
	m	a	R^2	m	a	R^2
7	0.11	2.13	0.994	0.04	3.79	0.938
28	0.24	4.81	0.924	0.12	8.32	0.994
56	0.34	5.78	0.944	0.25	9.69	0.882
90	0.35	8.11	0.892	0.18	13.34	0.990

Note. Cd= mx + a, where Cd is mean carbonation depth; m, slope on the regression line; x, GRC replacement ratio; R^2, correlation coefficient.

The incorporation of 50% MRA (R0/50), in turn, induced an increase in Cd of 3.0 mm in the 28 d results, relative to the NAC mix. Such deeper carbonation penetration was associated with higher water absorption and porosity in MRA than in NA [6,49]. This was the same pattern as observed in O_2 penetration discussed in Section 3.1, depicted in Figure 3b and observed by other authors [55,56] in mixes with RA.

The linear relationship in the 28 d and 90 d results between carbonation depth and oxygen permeability is depicted in Figure 5a, and between Cd and the chloride diffusion coefficient in Figure 5b. The high R^2 values (all lying between 0.895 and 0.965) denoted a close correlation between those properties and showed that both the O_2 permeability coefficient and the Cl^- diffusion coefficient may serve to predict the carbonation depth [57,58].

Earlier studies with mixes with additions such as fly ash, GGBFS [40,41] or BBA [46] as cement replacements [51,52] together with 25% to 100% RCA [59] yielded similar findings.

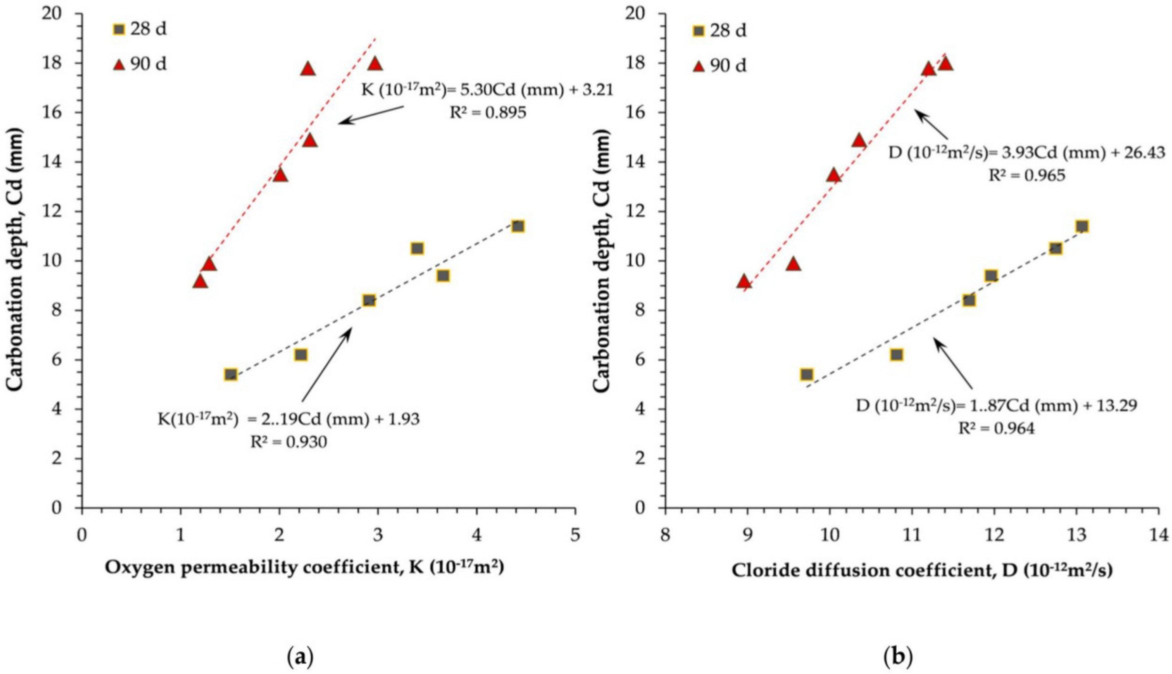

Figure 5. Relationship in 28 d and 90 d mixes between (**a**) carbonation and oxygen permeability coefficient; and (**b**) carbonation and chloride diffusion coefficient.

The accelerated carbonation coefficients (K_{ac}) given in Table 6 were calculated from linear regression of the carbonation depth/square root of time curve and Fick's first law (Equation (7)):

$$C_d = d_0 + K_{ac}\sqrt{t} \quad (7)$$

where *Cd* is the mean carbonation depth at time *t* (mm); K_{ac}, the carbonation rate under the experimental conditions (mm/year$^{0.5}$); d_0, the carbonation depth at time = 0 (mm); and *t*, the exposure time (years).

The reliability of the carbonation coefficients calculated was over 98% in all mixes (see R^2 in Table 6). K_{ac} was 14.5% higher in mix N10/0, 106.6% in N25/0, 54.1% in R0/50, 66.9% in R10/50 and 117.0% in R25/50 than in mix NAC. Those findings denoted a higher rate of carbonation spread in recycled concrete mixes with GRC and/or MRA than in the conventional material. A similar behaviour was reported for mixes with 25% to 50% MRA in combination with 25% fired clay powder processed from CDW and used as a cement substitute [12], and for mixes containing from 50% to 100% RCA, as well as 25% to 55% fly ash [60].

Table 8 lists the carbonation coefficients found for real or natural conditions (K_n) with Equation (8), proposed by Sisomphon and Franke [61] to express the relationship between accelerated and natural carbonation in terms of CO_2 concentration:

$$\frac{K_n}{\sqrt{c_n}} = \frac{K_{ac}}{\sqrt{c_{ac}}} \quad (8)$$

where K_n is the natural carbonation coefficient; K_{ac} the accelerated carbonation coefficient; c_n the CO_2 concentration under natural conditions (~0.04%) [62]; and c_{ac} the CO_2 concentration in the accelerated carbonation test (3%).

Table 8. Natural carbonation coefficients and carbonation resistance classes.

Natural Carbonation Coefficient, K_n (mm/year$^{0.5}$)					
NAC	N10/0	N25/0	R0/50	R10/50	R25/50
2.07	2.37	4.28	3.20	3.46	4.50
Carbonation Resistance Class					
RC2	RC3	RC4	RC5	RC6	RC7
1 < Kn ≤ 2	2 < Kn ≤ 3	3 < Kn ≤ 4	4 < Kn ≤ 5	5 < Kn ≤ 6	6 < Kn ≤ 7
	NAC, N10/0	R0/50, R10/50	N25/0, R25/50		

All the mixes studied exhibited values lower than or similar to the 4 mm/year$^{0.5}$ indicative of quality concrete [63] and none exceeded the critical value (6 mm/year$^{0.5}$), defined to mixes with low carbonation resistance [59]. Further to the classification proposed by Greve-Dierfeld and Gehlen [64], N10/0 would lie within the same carbonation resistance range (RC3) as NAC, whilst mixes R0/50 and R10/50 would be in class RC4, and mixes N25/0 and R25/50 in class RC5.

3.4. Service Life Prediction

Carbonation spread across concrete exposed to different environments is plotted against exposure time in Figure 6, in keeping with the model set out in Spanish structural concrete code EHE-08 [16]. The dashed horizontal lines show the minimum rated cover for each exposure environment, cement type and design service life. The code defines rated cover as the distance between the outer surface of the reinforcement and the closest concrete surface. In light of the resulting curves, mixes in which 10% GRC or 50% MRA were included separately as well as jointly (R10/50) would be at no risk whatsoever of carbonation-induced reinforcement depassivation in structures with a service life of up to 100 years and design the characteristic strength as listed in Table 4. Mixes with 25% GRC, with or without recycled aggregate, would not be apt for reinforced concrete exposed to carbonation.

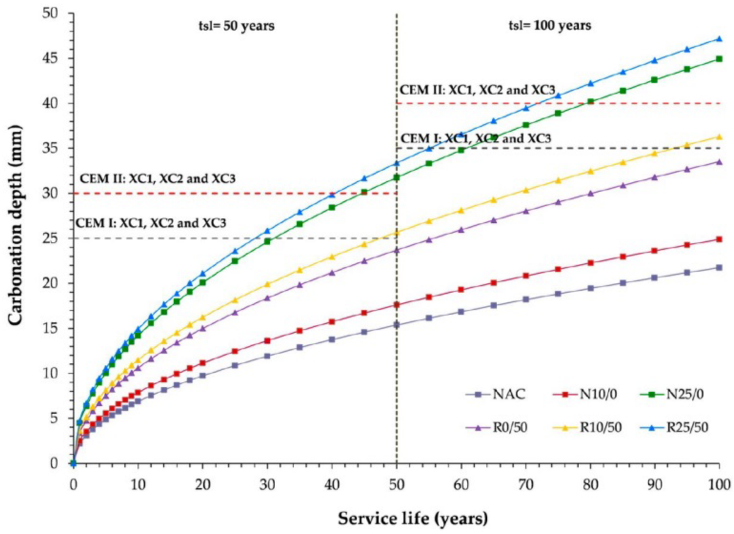

Figure 6. Service life model proposed in Spanish concrete code EHE-08 for carbonation spread in concrete mixes.

4. Conclusions

The conclusions that may be drawn from this study are set out below:

- Incorporating GRC and/or MRA induces an increase in O_2 permeability associated with the greater porosity of these new materials than that found in their conventional counterparts, OPC and NA. Nonetheless, all the O_2 permeability coefficients were below the 4.5×10^{-17} m^2 ceiling for quality concrete;
- Cl^- permeability was not significantly affected (<8%) by the replacement of 10% OPC with GRC, irrespective of the aggregate type present (NA or MRA). The resulting 90 d mixes exhibited the same 'moderate' risk of corrosion as conventional concrete of the same age;
- The high linear correlation between the O_2 permeability and Cl^- diffusion coefficients, irrespective of cement and aggregate type, can be interpreted as proof that these transport mechanisms are governed by both pore structure and interconnectivity;
- The mean carbonation depth in mixes with 10% GRC, separately or jointly with 50% MRA, was 15% to 75% greater than that in mixes prepared with conventional cement and natural aggregate;
- All mixes, irrespective of the GRC replacement ratio and aggregate type, exhibited CO_2 penetration coefficients lower than or similar to 4 mm/year$^{0.5}$;
- The high correlation between O_2 permeability and carbonation depth suggests that the former may be a good indicator for predicting the latter;
- According to the service life prediction model proposed in Spanish structural concrete code EHE-08, incorporating up to 10% GRC as a cement replacement and/or 50% MRA as an NA substitute does not compromise the reinforcement's passivity.

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Capítulo 11

Thermal Performance of Concrete with Recycled Concrete as Partial Cement Replacement and Recycled CDW Aggregate

Capítulo 11

Thermal Performance of Concrete with Recycled Concrete as Partial Cement Replacement and Recycled CDW Aggregate

Resumen

Esta investigación analiza el comportamiento térmico de hormigones fabricados con ultra finos reciclados de hormigón (PRH) como sustituto parcial del cemento en un 10 % y un 25 % en peso, conjuntamente con un 50 % de áridos reciclados mixtos (ARM), ambos procedentes de los residuos de construcción y demolición (RCD). Para este fin, se realizó un programa experimental que evaluó las propiedades físicas (densidad seca, porosidad accesible y conductividad resistividad) y propiedades térmicas (conductividad térmica y calor específico) de los hormigones diseñados. Los resultados indican que la incorporación de un 10 % y un 25 % de PRH con un 50 % de ARM disminuye la conductividad térmica entre un 7.9 % y 11.8 % y aumenta el calor específico entre un 6.0 % y un 9.1 % respecto el hormigón con un 100 % de árido natural. Además, mediante el estudio inter-propiedades se demostró que este mejor comportamiento térmico está directamente relacionado con la menor densidad y mayor porosidad. Finalmente, los resultados obtenidos permiten concluir que estos nuevos hormigones reciclados pueden ser considerados como materiales de construcción energéticamente más eficientes.

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Thermal Performance of Concrete with Recycled Concrete Powder as Partial Cement Replacement and Recycled CDW Aggregate

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Abstract: This novel study was triggered by a lack in the international literature of the simultaneous use of ground recycled concrete (GRC) as a cement replacement and mixed recycled aggregate as part of the granular skeleton in recycled concrete. It explores the thermal behaviour of concrete mixes bearing 10 wt% or 25 wt% GRC as a cement replacement and 25 wt% or 50 wt% mixed recycled aggregate (MRA) sourced from construction and demolition waste (CDW). The experimental programme conducted assessed concrete's dry density, open porosity, electrical and thermal conductivity and specific heat capacity. The findings showed that the use of 10% and 25% GRC, in conjunction with 50% MRA, reduced thermal conductivity by 7.9% to 11.8% and raised specific heat capacity by 6.0% to 9.1% relative to concrete with 100% natural aggregate (NA). A cross-property analysis revealed that improved thermal performance was linearly related to lower density and higher porosity. The results also support the conclusion that these new recycled aggregate concrete mixes are more energy-efficient construction materials than conventional concrete.

Keywords: recycled aggregate; ground recycled concrete; recycled materials concrete; construction and demolition waste; thermal properties

1. Introduction

Concrete production is responsible for serious environmental impacts worldwide. These impacts can be divided into two main problems: use of natural aggregates, and Portland cement production, which leads to an average consumption of 125 kW/h of electricity and results in an emission to the atmosphere of 800 kg of CO_2. Furthermore, the latter also leads to the consumption of a vast number of natural resources [1,2].

In addition to these two problems, the construction industry is also faced with the challenge of adequately disposing the large amount of waste that the industry itself generates. It is recalled that construction and demolition waste (CDW) represents more than 30% of solid waste generated among all economic sectors [3].

It is essential to find, on the one hand, solutions for the use of these CDW, in addition to their use as recycled aggregates (RA), and, on the other hand, sustainable binders that can replace cement. Hence, a hypothesis to solve these environmental problems is the use, in concrete, of binders formed by these CDW.

The use of CDW in concrete as RA has already been proven to be environmentally friendly and cost-efficient [4,5]. However, its evaluation as a substitute material for cement has just begun.

Some studies started by analysing the performance of concrete with different types of ceramic material powders as the replacement of cement. Subaşi et al. [6] found that the use of waste ceramic powders in self-consolidating concrete causes a slight increase in viscosity and a decrease in the mechanical performance of concrete. For example, the use of 20% ceramic powder resulted in a 15% reduction in compressive strength at 28 days.

Ge et al. [7], Kannan et al. [8] and Vejmelková et al. [9] also investigated the durability of concrete with the use of ceramic powders as binders instead of cement, having studied maximum replacement ratios of 30%, 40% and 60%, respectively. These investigations came to the conclusion that the use of ceramic powders can maintain or even slightly improve the durability and shrinkage of the concrete. Kannan et al. [8] states that ceramic powders will provide a relatively high silica environment that might be able to convert calcium hydroxide (CH) into strong calcium silicate hydrate C-S-H. However, it is important to highlight that in all these studies, the ceramic powder used does not have precisely the same particle size of the replaced cement. Therefore, the finer particle size distribution of the ceramic powder, compared to that of the cement, may have caused a greater compactness of concrete and may be the cause of the improved durability of concrete with ceramic powder.

In turn, Cantero et al. [10] analysed the use in concrete of binder and aggregates from CDW. To this end, these authors produced concrete mixes with RA from CDW (0%, 25% and 50%) and recycled cement with CDW (0% and 25%) mixed with Portland cement. The authors found maximum decreases in compressive strength at 28 days of 10% and 20%, when using, respectively, recycled cement alone and recycled cement and RA simultaneously.

Liu et al. [11] evaluated the use of hybrid recycled powder from demolished concrete solids and clay bricks as supplement for cement. This investigation also obtained a decrease in the mechanical performance of these cementitious materials. These authors state that the use of this recycled binder affects the microstructure of the cement paste, changing the size and morphology of C-S-H gels. The nanoindentation test showed that a weaker interfacial transition zone (ITZ) was produced to form the cement paste-recycled particle interface.

It is agreed that the incorporation of CDW powder as replacement of cement in concrete results in worse mechanical properties. However, this decrease appears to vary widely with the nature of the CDW used. Nevertheless, as mentioned, the results obtained in the existing investigations to date on the durability performance of these concrete mixes seem to be even more variable.

To date, there are nearly no studies that analyse the thermal behaviour of concrete with recycled cement from CDW. Only Vejmelková et al. [9] studied the thermal properties of high-performance concrete with ceramic powders, having analysed the thermal conductivity and specific heat capacity. According to the authors, thermal conductivity decreased from 1.69 $Wm^{-1}.K^{-1}$ (reference concrete) to 1.41 $Wm^{-1}.K^{-1}$ (concrete with 60% ceramic powder), due to an increase in open porosity from 11.2% to 15.5%. Additionally, with the replacement of cement, the specific heat capacity increased by about 13%.

Several studies have been published on the thermal performance of concrete containing RA processed from CDW. Bravo et al. [12] evaluated the thermal behaviour of concrete with RA from CDW. The authors produced mixes with 0%, 10%, 25%, 50% and 100% of RA from four different recycling plants where for two mixes the authors only studied coarse RA and two mixes with only fine RA. It should be noted that all mixes were produced with the same workability (100 mm to 150 mm). The authors concluded that the total replacement of fine and coarse aggregates decreased thermal conductivity, respectively, between 22% and 42% and between 17% and 23%. The lower thermal conductivity of concrete with RA was explained by the lower density and thermal conductivity and the higher porosity of these aggregates. Hence, the authors concluded that the effect of using RA is quite variable depending on their nature.

Despite this variation, several other investigations [13–17] also point to decreases in thermal conductivity higher than 20% in mixes with the replacement of natural aggregates with RA from concrete or glass.

This work aims at analysing the thermal behaviour of concrete with recycled concrete powder, as partial cement replacement and RA from CDW, in order to fill the complete lack of information in the literature on this subject. This study started with the collection of CDW from a recycling plant, to be used as RA, and with the production of concrete powder, to be used instead of cement as a binder. In order to carry out this investigation, concrete was produced with RA from CDW (0% and 50%) and recycled cement with recycled concrete powder (0%, 10% and 25%) mixed with Portland cement. The analysis of the thermal behaviour of concrete was carried out through thermal conductivity and specific heat capacity tests, as well as by confronting these properties with the air content, the compressive strength, the open porosity and the electrical resistivity of these mixes. The joint analysis of these concrete properties and the physical and chemical properties of recycled concrete powder allowed a detailed analysis and understanding of the thermal performance of these mixes. The main innovation of this investigation is the analysis of the thermal behaviour of concrete with recycled concrete powder as partial cement replacement, which, as mentioned above, is totally innovative. Furthermore, the present study also evaluates the thermal behaviour of concrete that simultaneously contains recycled cement and recycled aggregates from CDW.

2. Materials and Methods

2.1. Materials

2.1.1. Binders

The three binders used, all European standard EN 197-1-compliant (Table 1), were: a type 1 42.5 R (CEM I 42.5 R) ordinary Portland cement (OPC); a blend of 90% OPC and 10% ground recycled concrete (GRC), labelled RB_{10}; and a blend of 75% OPC and 25% GRC, labelled RB_{25}.

Table 1. Fresh properties in binders.

Property		OPC	RB_{10}	RB_{25}	EN 197-1 [1]
Setting time (min)	**Initial**	84	90	91	≥60
	Final	136	138	141	-
Water content (g)		143	144	147	-
Normal consistency (mm)		36	35	35	34 ± 2
28 d compressive strength (MPa)		67.5 ± 1.0	62.6 ± 1.0	51.39 ± 2.2	≥42.5

[1] Values referred to strength class 42.5 R.

The GRC was obtained by crushing and grinding (to a maximum size of 147 μm) laboratory-prepared concrete specimens, batched as per the Faury method [18]. The composition and fresh and hardened 28-day characteristics of that concrete mix are given in Table 2.

Table 2. Characteristics of the source concrete.

Parameter	Value	Property	Value
Cement type	CEM II/A-L 42.5 R	Slump class [2]	S3
Cement content	300 kg/m^3	Compressive strength [3]	39.8 MPa
w/c_{eff} [1]	0.55	Splitting tensile strength [3]	2.75 MPa
Coarse aggregate	1020 kg/m^3 (crushed limestone)	Modulus of elasticity [3]	38.9 GPa
Fine aggregate	910 kg/m^3 (natural river sand)		

[1] w/c_{eff}: effective water cement ratio; [2] as per European standard EN 206-1 [19]; [3] 28 days.

Further to the X-ray fluorescence (XRF)-determined chemical composition of the GRC and OPC shown in Figure 1a, the major oxides were SiO_2 (46.10 wt%) and CaO (40.0 wt%). The figure also presents graphically the minimum and maximum ground concrete replacement ratios used in earlier studies [20–26] on pastes, mortars and concrete.

The large, irregularly shaped particles visible in the micrograph in Figure 1b were identified as aggregate with bound mortar, and the small clusters with a rough surface as the paste. GRC's density was 2.54 g/cm^3, a value lower than 3.11 g/cm^3 observed in OPC.

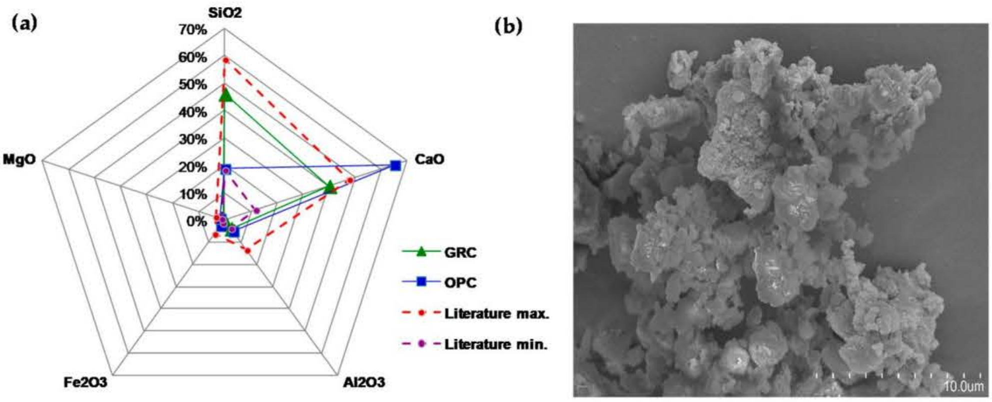


Figure 1. (**a**) Chemical composition of ground recycled concrete (GRC) and ordinary Portland cement (OPC); and (**b**) GRC morphology.

2.1.2. Aggregates

The crushed limestone coarse natural aggregate used was graded in two particle sizes, 4 mm to 12 mm (NG-M) and 12 mm to 22 mm (NG-G). The fines consisted of two siliceous river sands, graded to 0 mm to 2 mm (NS-F) and 2 mm to 4 mm (NS-C).

The mixed recycled aggregates (MRA) supplied by a CDW recycling plant in Lisbon, Portugal, were sieved and classified at the laboratory, where sizes <4 mm and >22 mm were rejected. The composition of the coarse (4 mm to 22 mm) MRA aggregate used, complying with European standard EN 933-11 [27], is given in Table 3. On the grounds of those data and Spain's structural concrete code (EHE-08) [28], the MRA is designated a mixed recycled aggregate for its R_{cu} (R_{cu} = R + Ru) content was ≤95 wt% and its Rb content >5 wt%. It would also be classified under that category in the Agrela et al. [29] proposal, with R_{cu} >70 wt% and Rb <20 wt%.

Table 3. Composition of the source concrete.

Constituent	Label	Content (wt%)
Concrete and mortar	Rc	47.1
Natural stone	Ru	25.2
Clay materials	Rb	22.6
Bituminous materials	Ra	0.2
Glass	Rg	1.7
Floating particles	FL	1
Gypsum	X1	1.8
Metals	X2	0.4

The physical and mechanical properties of the aggregates given in Table 4 show that the MRA was less dense and less abrasion-resistant than the NA (NC-M and NC-G). This was attributed to the higher water absorption of the bound mortar and fired clay materials comprising the MRA. The Los Angeles coefficient (LA), a measure of abrasion fragility, was higher in the MRA (LA = 46 wt%) than in the NA

(LA = 26 wt% to 28 wt%), due to the greater hardness of NA relative to the MRA components such as concrete, brick and tile. The MRA also exhibited a higher flakiness index (FA), 20 wt%, than that of the NA, 13 wt%, likewise attributable to its components, particularly brick and tile, which are flakier than NA.

Table 4. Physical and mechanical properties of aggregates.

Property	NS-F	NS-C	NC-M	NC-G	MRA	EHE 08
Dry density (kg/m³) [30]	2581	2583	2600	2620	2069	-
SSD [1] density (kg/m³) [30]	2601	2609	2630	2670	2256	-
24 h water absorption (wt%) [30]	0.4	0.5	1.3	1.3	9.1	≤5
10 min water absorption (wt%) [31]	0.2	0.3	0.5	0.6	8.1	-
Los Angeles coefficient (wt%) [32]	-	-	28	26	46	≤40
Flakiness index (wt%) [33].	-	-	13	16	20	<35

[1] SSD: saturated surface dry.

2.2. Testing and methodology

Table 5 lists the fresh state and 28-day properties of the concrete mixes analysed and the standards followed to determine them. All the mixes were batched with the same volume to ensure non-interference by parameters irrelevant to the study. The specimens were prepared and cured as per European standard EN 12390-2 [34]. After moulding, performed with particular care to minimise pouring and consolidation times, the specimens were wrapped in plastic and stored for 24 h. The demoulded specimens were subsequently stored in a humidity chamber at 20 ± 2 °C and 95 ± 5% humidity until tested.

Thermal testing was conducted on an Applied Precision Ltd. ISOMET 2114 analyser. Two 100 × 100 × 500 mm prismatic specimens of each mix cured 28 days in a dry chamber (20 ± 2 °C, 50% RH) were analysed in these tests, taking at least three readings per sample.

Table 5. Properties of the concrete mixes analysed.

Parameter Tested	Standard	Specimen Dimensions
	Fresh properties	
Slump	EN 12350:2 [35]	-
Fresh density	EN 12350-6 [36]	
Air content	EN 12350-7 [37]	
	Mechanical properties	
Compressive strength	EN 12390-3 [38]	150 mm Ø × 300 mm
Tensile strength		
	Physical properties	
Open porosity	UNE 83,980 [39]	100 × 100 × 100 mm
Dry density		
Electrical resistivity	UNE 83988-2 [40]	100 mm Ø × 200 mm
	Thermal properties	
Thermal conductivity	ISOMET 2114 [41]	100 × 100 × 500 mm
Volume heat capacity		

2.3. Concrete Design

The six concrete mixes batched for the tests were divided into two groups: mixes containing 100% NA and GRC as OPC replacement at ratios of 0% (labelled NAC), 10% (labelled N10/0) or 25% GRC (labelled N25/0); and mixes with 50% MRA and GRC as an OPC replacement at ratios of 0% (labelled R0/50), 10% GRC (labelled R10/50) or 25% (labelled R25/50). The mixes with 100% NA were designed to study the effect of GRC on conventional concrete prepared with NA, and those with 50% to determine the joint effect of the two recycled materials. No plasticizers were used in any of the mixes.

All the mixes were batched as set out in European standard EN 206-1 [19] to durability class X2 and strength class C25/30, although using 300 kg/m^3 of binder (OPC + GRC), slightly more than the standard minimum of 280 kg/m^3 for that exposure class. All were also prepared for a target workability of S2, as defined in EN-206-1 [19], equivalent to a 70 ± 20 mm slump [32].

The particle size distribution of the (fine + coarse) aggregate, irrespective of whether it was natural or recycled, fit the theoretical curve defined by Faury [18] for a maximum size of 22 mm. The batching for the six materials used in the study is given in Table 6. The total amount of water used in each mix was defined as the effective water plus the water needed to offset the amount absorbed by aggregate when soaked for 10 min (approximately the mixing time) [42]. All the aggregates were used moist, subtracting the water required from the total in the mix.

Table 6. Concrete mix design.

Component	Amount (kg/m^3)					
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
Cement	300.0	270.0	225.0	300.0	270.0	225.0
GRC	-	30.0	75.0	-	30.0	75.0
Total water	171.3	177.1	183.3	205.2	211.2	217.2
NS-F	154.0	150.0	154.0	154.0	154.0	154.0
NS-C	754.5	754.5	754.5	754.5	754.5	754.5
NG-M	367.0	367.0	367.0	183.6	183.6	183.6
NG-G	653.0	653.0	653.0	326.5	326.5	326.5
MRA	-	-	-	449.0	449.0	449.0

3. Results

3.1. Fresh Properties

The fresh-state properties of the mixes are given in Table 7, according to which they all fall in the same workability class, S2 (70 ± 20 mm), defined in European standard EN 206-1 [19].

Table 7. Fresh-state concrete properties (±: standard deviation).

Agg. Group	Mix	w/b_{eff}	Slump (mm)	Density (kg/m^3)	Air Content (vol%)
NA	NAC	0.56	65 ± 2.8	2367 ± 8	2.6 ± 0.2
	N10/0	0.58	74 ± 2.5	2340 ± 9	2.7 ± 0.2
	N25/0	0.60	65 ± 3.7	2309 ± 10	2.9 ± 0.1
MRA	R0/50	0.59	75 ± 3.1	2251 ± 11	3.2 ± 0.1
	R10/50	0.61	61 ± 3.7	2244 ± 12	3.4 ± 0.2
	R25/50	0.63	63 ± 4.2	2219 ± 10	3.8 ± 0.2

Figure 2 shows that fresh-state density ($R^2 > 0.848$) and air content ($R^2 > 0.779$) varied linearly with the w/b_{eff} ratio. Both the rise in air content and the decline in density with rising w/b_{eff} were induced by the use of GRC and MRA, which are respectively less dense than OPC and NA. That behaviour was consistent with the findings reported by Cantero et al. [10] in a study of concrete mixes prepared with both 25% ground recycled CDW (RC-CDW) as a cement replacement and 50% MRA. The authors found a linear rise in fresh-state air content ($R^2 > 0.842$) and a linear decline in density ($R^2 > 0.921$) as a result of using the two recycled materials.

The air content in all the mixes studied here was lower than the 4.5 vol% recommended by ACI [43] for concrete mixes prepared with a maximum aggregate size of 22.4 mm.

3.2. Mechanical Properties

The 28-day mean compressive (f_{cm}), mean splitting tensile (f_{st}), relative compressive (Δf_{cm}) and relative splitting tensile (Δf_{st}) strengths are plotted in Figure 3. In terms of compressive strength, four of the recycled material mixes (R10/0, R25/0, R0/50 and R10/50), which exhibited $f_{cm} > 25$ MPa, would be apt for structural applications in building construction. A value under 25 MPa was found only in the mix with 25% GRC and 50% MRA (R25/50), whose use would be restricted to non-structural purposes.

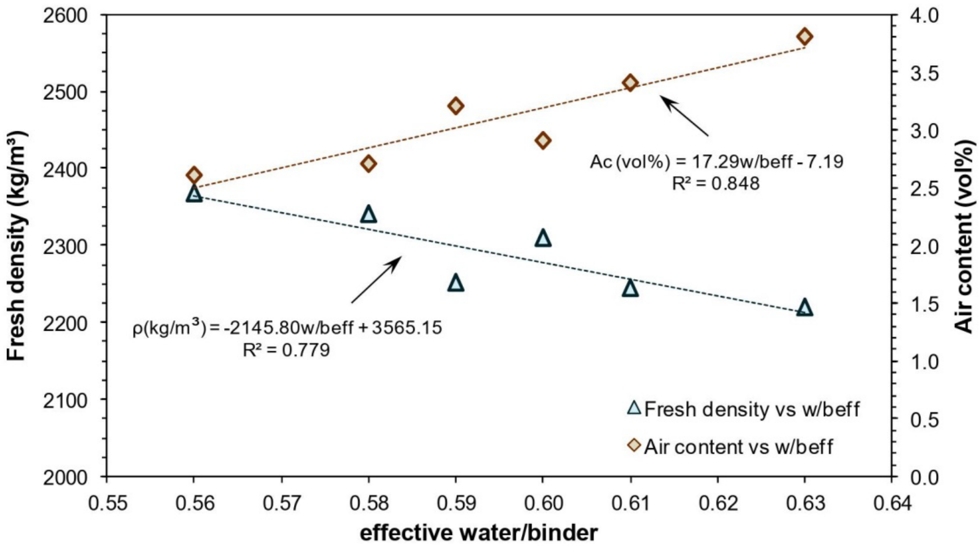
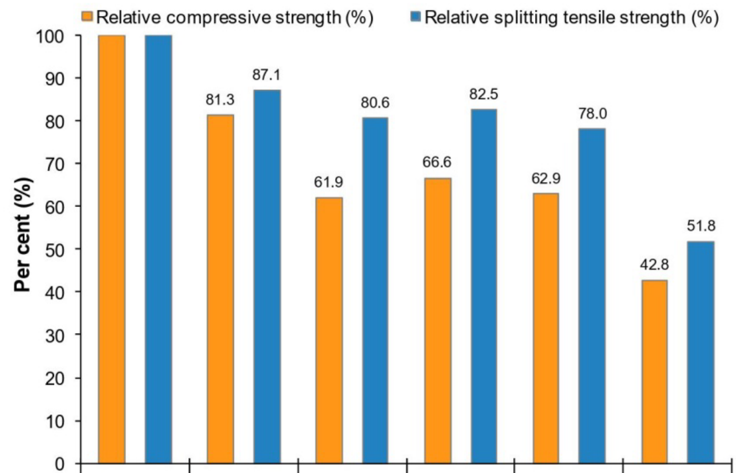


Figure 2. Fresh-state density and air content as a function of the w/b_{eff} ratio.



Mix	NAC	R10/0	R25/0	R0/50	R10/50	R25/50
fcm (MPa)	42.8±1.1	34.8±1.4	26.5±0.9	28.5±1.2	26.9±1.4	18.3±0.9
fst (MPa)	3.1±0.5	2.7±0.4	2.5±0.4	2.6±0.3	2.4±0.3	1.6±0.2

Figure 3. Relative compressive strength (Δf_{cm}), calculated as $\Delta f_{cm_i} = \frac{f_{cm_i}}{f_{cm_{NAC}}} \times 100$, and relative splitting tensile strength (Δf_{st}), as $\Delta f_{st_i} = \frac{f_{cm_i}}{f_{cm_{NAC}}} \times 100$, where subscript i denotes the type of recycled materials mix.

Figure 3 also shows that, irrespective of the GRC replacement ratio and the presence or absence of MRA, the experimental materials had lower compressive and splitting tensile strengths than those of the reference mix. Letelier et al. [44], studying concrete mixes with 10% or 15% ground brick and 30% RCA, found the incorporation of ground brick at both replacement ratios induced declines in 28-day compressive and flexural strength in the mixes, whether made with 100% NA or 30% RCA.

Adding 10% GRC to the NA mix (R10/0) lowered compressive strength by 18.7% and tensile strength by 12.9%, whilst at a replacement ratio of 25% (R25/0) the decline was 38.1% in compressive and 19.4% in tensile strength relative to NAC, due to the lower reactivity of GRC relative to cement and the smaller amount of the latter in the mixes. In a study of the effect of replacing OPC with 15%, 30% or 45% ground crushed concrete, Kim [22] attributed the declines in compressive and flexural strength observed to the lower reactivity of the addition.

With the combined use of GRC and MRA, compressive strength was 33.4% and splitting tensile strength was 17.5% lower in R10/50 than in NAC, whilst in R25/50 compressive strength was 57.2% and splitting tensile strength was 48.2% lower. Those findings were the result of two factors: low GRC reactivity [22] and the lesser density and hardness of MRA than NA [45–47]. The declines recorded were steeper than the up to 20% reported for compressive strength and up to 24% for splitting tensile strength in a study [10] of concrete mixes with ground fired clay-based materials recycled from CDW, which were more reactive than the present GRC, and 50% of a harder MRA (LA < 36 wt%) than the one used here (LA = 46 wt%).

3.3. Physical Properties

Table 8 lists the 28-day dry density (ρ_{dry}), open porosity (P_o) and electrical conductivity (EC) values for all the mixes, as well as the effects of using GRC, MRA and the two jointly.

Table 8. Physical properties of the concrete mixes.

Parameter/Differential	NA mix			MRA mix		
	NAC	**N10/0**	**N25/0**	**R0/50**	**R10/50**	**R25/50**
ρ_{dry} (kg/m^3)	2290 ± 35	2227 ± 20	2158 ± 25	2101 ± 40	2052 ± 38	1990 ± 42
Δ with GRC (%)	-	−2.8	−5.8	-	−2.3	−5.3
Δ with MRA (%)				-8.3	−7.9	−7.8
Δ with GRC (%) × MRA (%)					−10.4	−13.1
P_o (vol%)	12.1 ± 0.2	12.7 ± 0.3	13.7 ± 0.3	15.2 ± 0.4	15.9 ± 0.5	16.9 ± 0.3
Δ with GRC (%)	-	5.0	13.2	-	4.6	11.2
Δ with MRA (%)				26.5	25.2	23.4
Δ with GRC (%) × MRA (%)					31.4	39.7
EC (10^{-3} Ω·m^{-1})	8.8 ± 0.5	9.5 ± 0.3	10.6 ± 0.3	9.9 ± 0.3	10.2 ± 0.2	11.1 ± 0.4
Δ with GRC (%)	-	−7.1	−16.8	–	−3.0	−10.9
Δ with MRA (%)				−10.6	−6.7	−4.3
Δ with GRC (%) × MRA (%)					−13.3	−20.4

Notes: Δ with GRC (%) compares NAC to N10/0 and to N25/0 in mixes with NA; and R0/50 to R10/50 and to R25/50 in mixes with MRA; Δ with MRA (%) compares NAC to R0/50, N10/0 to R10/50 and N25/0 to N25/50; Δ with GRC × MRA (%): compares NAC to R10/50 and to R25/50.

3.3.1. Dry Density

Analysing the data from Table 8, dry density (ρ_{dry}) was lower in all the mixes containing GRC and MRA than in the NAC reference. Figure 4a shows that replacing OPC with GRC lowered ρ_{dry} linearly ($R^2 \geq 0.998$) in the mixes with NA and MRA due to the lower density of the recycled materials (see Section 2.1.1), which also yielded less hydration product (low reactivity) [5,6]. Dry density was 2.8% lower in N10/0 and 5.8% lower in N25/0 than in NAC and 2.3% lower in R10/50 and 5.3% lower in R25/50 than in R0/50. The vertical distance between the two trend lines in Figure 4a, labelled the 'MRA effect', measures the effect of replacing 50% NA with MRA. The mean 8.0% decline in ρ_{dry} in the MRA mixes (R0/50, R10/50 and R25/50) relative to the NA mixes (NAC, N10/0 and N25/0) was attributable to the lower mean dry density of MRA (ρ_{dry} = 2069 kg/m^3) relative to that of NA (ρ_{dry} = 2591 kg/m^3). The joint use of GRC+MRA, in turn, induced declines in dry density relative to NAC of 10.4% in R10/50 and 13.1% in R25/50, findings consistent with earlier observations in concrete made with recycled (coarse and fine) aggregate consisting of crushed waste clay brick [48].

3.3.2. Open Porosity

The open porosity (P_o) data in Table 8 show greater pore volume in all the mixes containing GRC and MRA than in the reference NAC. This was attributed to two factors: the larger w/b$_{eff}$ ratio in the new cementitious matrices associated with the greater water demand in the new binders (RB_{10} and

RB_{25}); and higher water absorption MRA (9.1%) than NA (1.3%) (higher open porosity) primarily due to the presence of bound mortar and fired clay-based material in MRA [49]. Those results are consistent with earlier studies on concrete batched with up to 100% MRA [50], up to 100% RCA [51] and concrete with up to 100% RCA fine and 100% RCA coarse aggregate [52].

The use of GRC raised P_o by 5.0% in N10/0 and 13.2% in N25/0 relative to NAC and by 4.6% in R10/50 and 11.2% in R25/50 relative to R0/50, an indication that the joint use of CDW as additions and aggregates had no adverse effect on open porosity. As Figure 4b shows, a direct linear relationship ($R^2 \geq 0.997$) was observed between open porosity and GRC replacement ratio in all the mixes, whether containing NA or MRA, where it was added. The vertical distance between the two trend lines depicts the impact of replacing 50% NA with MRA, which induced a maximum rise in the mean P_o of up to 25% in the MRA (R0/50, R10/50, R25/50) relative to the NA mixes (NAC, N10/0, N25/0).

All the P_o values lay within the 12.5% to 17% range reported in the literature for concrete made with 50% MRA [52–54] and concrete made jointly with 30% ground granulated blast furnace slag and 50% RCA [55].

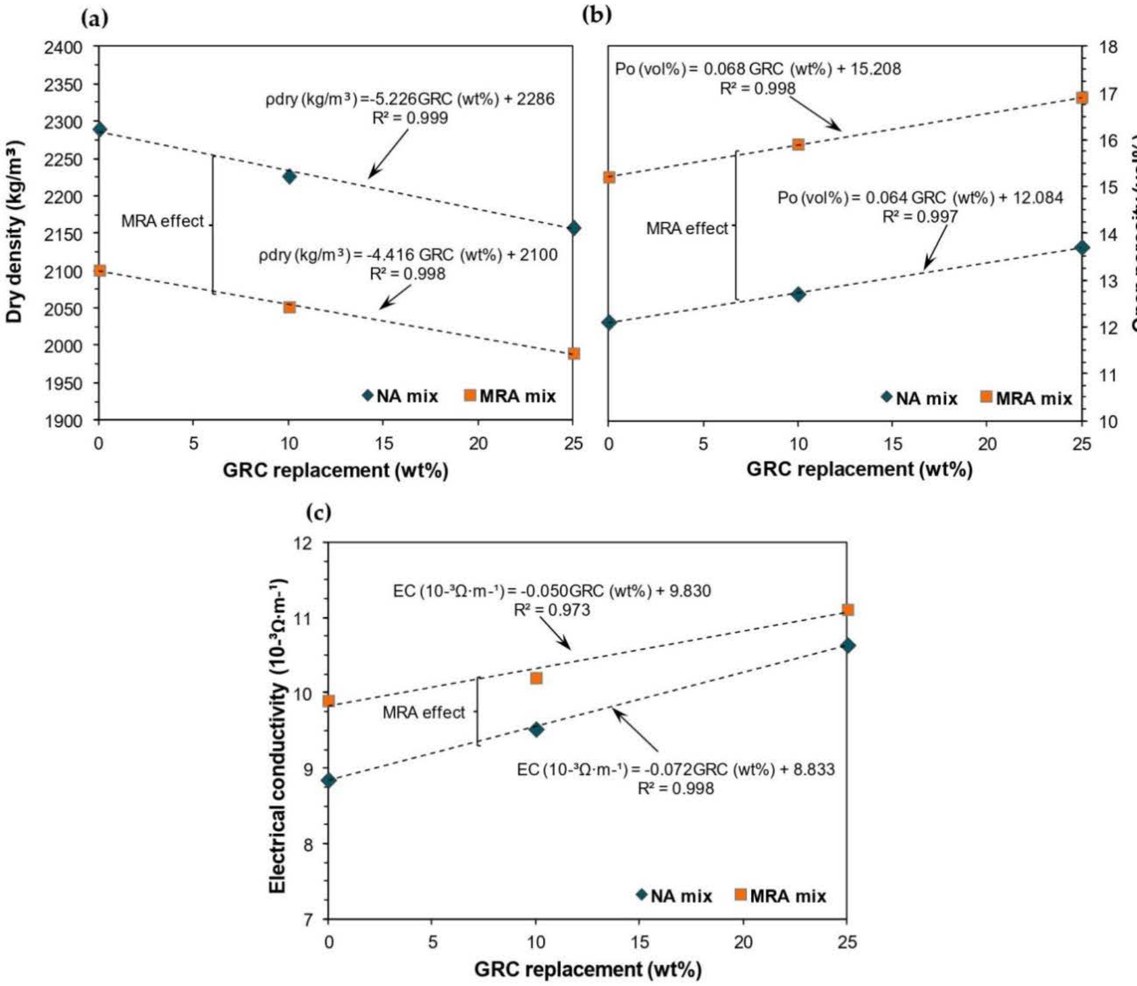


Figure 4. (**a**) Open porosity; (**b**) dry density; and (**c**) electrical conductivity as a function of the GRC replacement ratio.

3.3.3. Electrical Conductivity

The electrical conductivity (EC) values in Table 8 show that the parameter rose with the inclusion of GRC in both the NA and MRA mixes. That observation is related to the greater ion mobility resulting from a more inter-connected saturated pore structure induced by the addition, which in turn raises electrical conductivity [56]. The graph in Figure 5 shows a direct linear relationship ($R^2 \geq 0.978$) between EC and P_o or the volume of permeable pores in the NA and MRA mixes. The use of GRC raised EC linearly ($R^2 \geq 0.980$) (Figure 4c)) by 7.1% in N10/0 and 16.8% in N25/0 relative to NAC and by 3.0% in R10/50 and 10.9% in R25/50 relative to R0/50. Using 50% MRA raised EC by a mean of 7.2% relative to the mixes with 100% NA.

All the increases in EC observed lie within the 7% to 24% range reported in the literature for concrete mixes with 25% or 50% coarse fired clay aggregate [53] and mixes with 25% or 50% RCA fines [57].

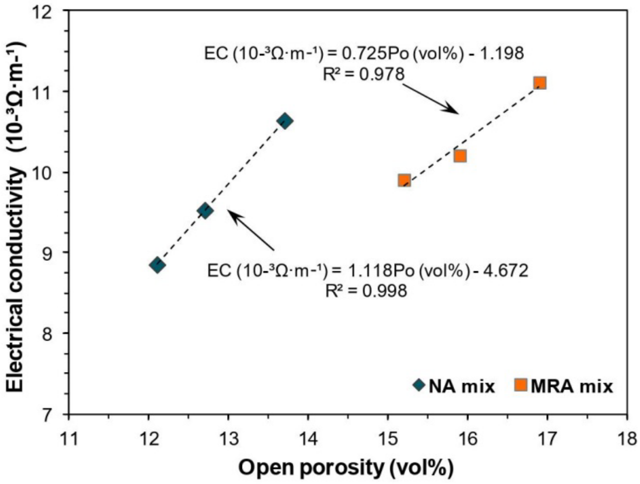


Figure 5. Open porosity versus electrical conductivity.

3.4. Thermal Properties

Twenty-eight-day thermal conductivity (λ) and specific heat capacity (c_p) are given for all the mixes in Table 9, which also lists the effects of including GRC, MRA and the two jointly.

Table 9. Thermal properties of the concrete mixes.

Parameter/Differential	NA mix			MRA mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
λ (W/m·K) [1]	2.064	2.013	1.922	1.963	1.901	1.821
Δ with GRC (%)	-	−2.5	−6.9	-	−3.1	−7.2
Δ with MRA (%)				−4.9	−5.6	−5.3
Δ with GRC (%) × MRA (%)					−7.9	−11.8
Volume heat capacity (MJ/m³·K) [1]	1.864	1.839	1.828	1.781	1.771	1.768
cp (kJ/m³·K)	0.814	0.826	0.847	0.848	0.863	0.888
Δ with GRC (%)	-	1.4	4.1	-	1.8	4.8
Δ with MRA (%)				4.1	4.5	4.9
Δ with GRC (%) × MRA (%)					6.0	9.1

[1] Standard deviation was <0.003 for all parameter values. Notes: Δ with GRC (%) compares NAC to N10/0 and to N25/0 in mixes with NA; and R0/50 to R10/50 and to R25/50 in mixes with MRA; Δ with MRA (%) compares NAC to R0/50, N10/0 to R10/50 and N25/0 to N25/50; Δ with GRC × MRA (%): compares NAC to R10/50 and to R25/50.

3.4.1. Thermal Conductivity

Figure 6 shows that mixes N10/0 and N25/0 exhibited lower thermal conductivity (λ) than NAC and mixes R10/50 and R25/50 lower λ than R0/50, inferring that the recycled material concrete would afford more effective thermal insulation than conventional materials. The use of GRC lowered λ by 2.5% in N10/0 and 6.9% in N25/0 relative to NAC and by 3.1% in R10/50 and 7.2% in R25/50 relative to R0/50. Those values lay in the 2.8% to 6.8% range observed for concrete made with up to 25% RA to replace NA fines [9] and concrete prepared with 10% ground granulated blast furnace slag as an OPC substitute [58].

The inverse linear relationship ($R^2 \geq 0.997$) between λ and GRC in NA and MRA mixes is plotted in Figure 6a. The mean decline of 5.3% in λ (determined as the vertical distance between the two trend lines: the MRA effect) attributed to the use of 50% MRA was very close to the 5.5% decline reported for concrete with 50% RA of a type similar to the RA used in this study [12]. The joint use of GRC and MRA lowered thermal conductivity by 7.9% in R10/50 and by 11.8% in R25/50 relative to the reference NAC.

All the recycled material mixes exhibited λ in the 2.01 W/m·K to 1.60 W/m·K range found for concrete with up to 50% RA fines and up to 50% RA coarse recycled CDW aggregate [12], as well as within the range recommended by Eurocode 2 [59]: 1.95 W/m·K to 1.33 W/m·K.

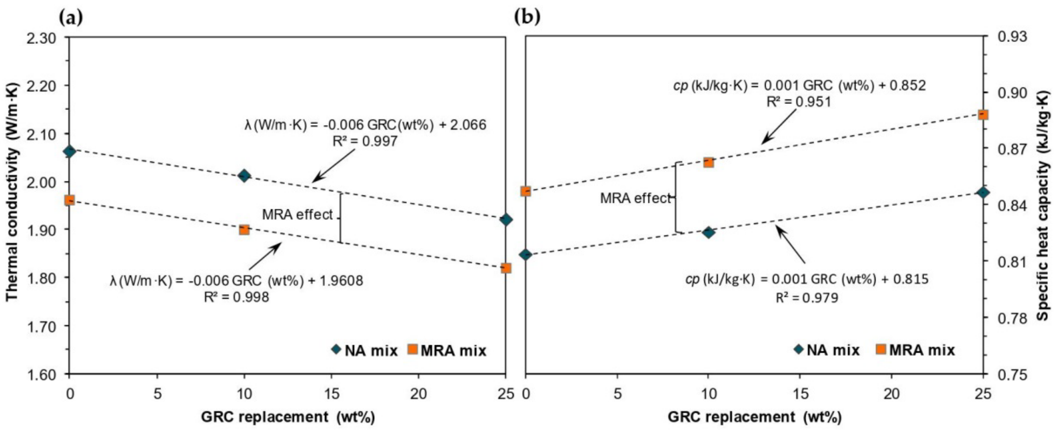


Figure 6. (**a**) Thermal conductivity and (**b**) specific heat capacity as a function of the GRC replacement ratio.

3.4.2. Specific Heat Capacity

Specific heat capacity (c_p in J/kgK) is calculated as $c_p = \frac{c}{\rho_{dry}}$, where c is volumetric heat capacity in J/m^3K and ρ_{dry} is concrete dry density in kg/m^3. Further to the data in Table 9, the use of GRC raised c_ρ by 1.4% in N10/0 and 4.1% in N25/0 relative to NAC and by 1.8% in R10/50 and 4.8% in R25/50 relative to R0/50, an indication that the new mixes would be less affected by abrupt temperature changes than NAC [60]. Figure 6b plots the direct linear relationship ($R^2 \geq 0.950$) between c_ρ and GRC in NA and MRA mixes and shows that the use, in addition, of 50% MRA (MRA effect) raised c_ρ by a mean 4.5% in the MRA mixes relative to the NA mixes, a value similar to the mean 5.3% decline observed for λ.

The joint use of GRC and MRA induced a rise in c_ρ of 6.0% in R10/50 and 9.1% in R25/50 relative to the reference NAC. Those increases with the use of GRC and MRA infer greater thermal inertia in the new recycled material mixes than in the reference concrete and, consequently, greater thermal stability when exposed to changing outdoor temperatures.

All the c_ρ values lay within the normal range (0.790 $kJ/m^3 \cdot K$ to 0.960 $kJ/m^3 \cdot K$) for concrete used in residential building construction [13].

3.5. Cross-Property Relationships

3.5.1. Thermal Properties and Air Content

Thermal conductivity and specific heat capacity are plotted against fresh-state air content in Figure 7. The linear relationships denote a good correlation between these properties with determination coefficients R^2 of over 0.84, a value higher than $R^2 = 0.57$ reported by Bravo et al. [12] for a study on the thermal behaviour of concrete in which NA was replaced with 10% to 100% (coarse and fine) recycled aggregate from several CDW management plants.

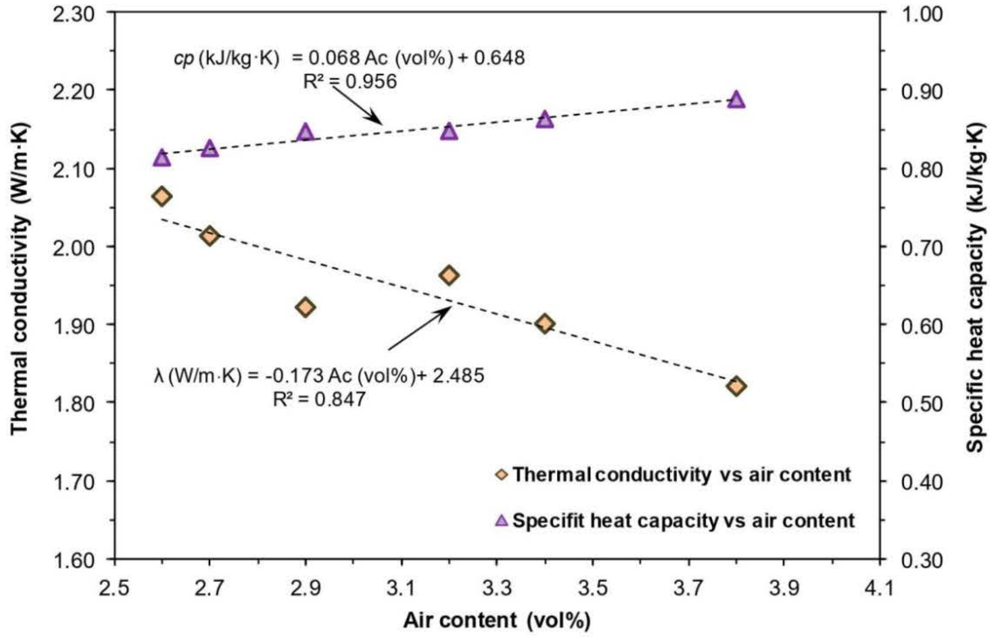


Figure 7. Air content/thermal conductivity and air content/specific heat capacity relationships for all concrete mixes.

3.5.2. Thermal Properties and Compressive Strength

Analysing Figure 8, both thermal conductivity and specific heat capacity were linearly related to compressive strength with determination coefficients R^2 above 0.92, the former inversely and the latter directly, i.e., the lower the thermal conductivity or the higher the specific heat capacity, the higher the compressive strength. Those findings were consistent with the results reported by Bravo et al. [12] and Pavlu et al. [61] for concrete with up to 100% RMA fine and coarse aggregate.

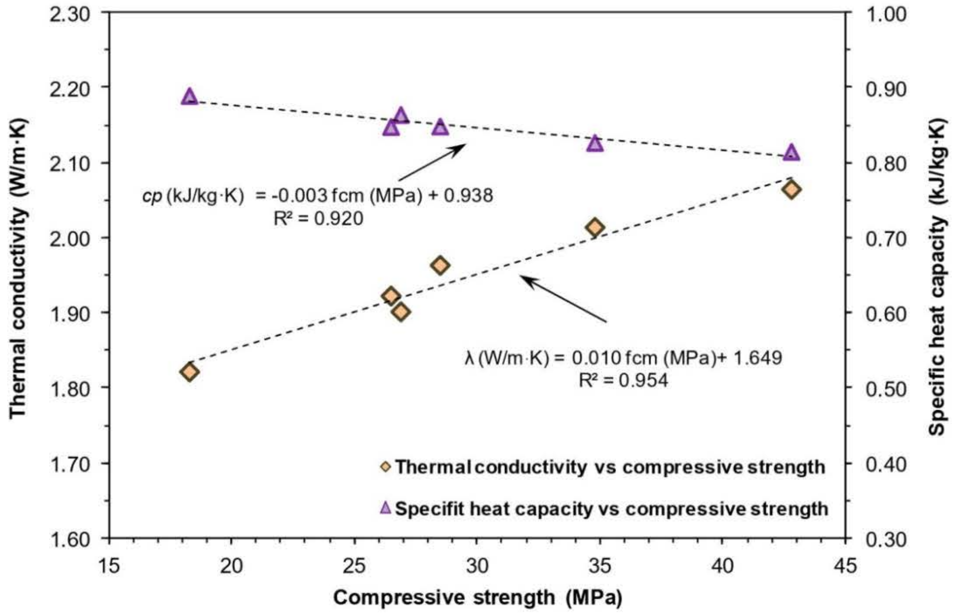


Figure 8. Compressive strength/thermal conductivity and compressive strength/specific heat capacity relationships for all concrete mixes.

3.5.3. Thermal Properties and Open Porosity

Conversely to compressive strength, open porosity was inversely related to thermal conductivity and directly to specific heat capacity (Figure 9) with determination coefficients R^2 for the respective linear relationships above 0.823. According to these data, the larger the pore volume, the more effective the thermal insulation (lower conductivity) is and the greater the thermal stability (higher specific heat capacity) when exposed to abrupt outdoor temperature changes. Earlier studies also related lower concrete thermal conductivity to higher pore volumes [41,44,45,47,48].

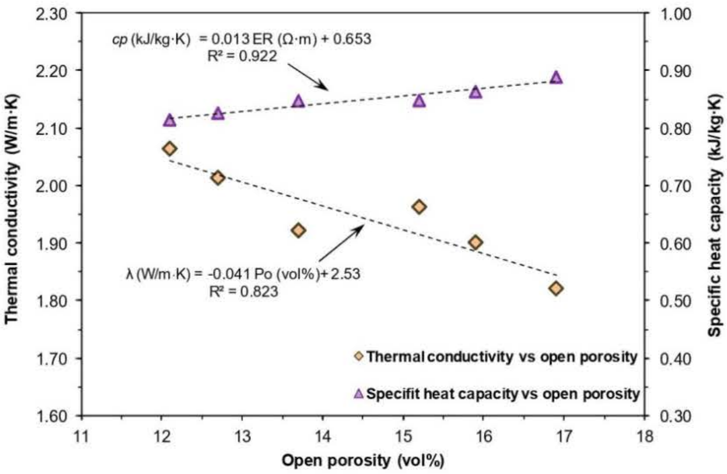


Figure 9. Open porosity/thermal conductivity and open porosity/specific heat capacity relationships for all concrete mixes.

The thermal conductivity of the solid matrix (λs) in concrete mixes is given in Table 10. This parameter separates the effect of the volume of open pores from the effect of adding both recycled materials (GRC and MRA) to the mixes. It exhibited higher values than overall thermal conductivity (Table 9). With GRC, λ_s was 1.8% lower in N10/0 and 5.2% lower in N25/0 than in NAC and, in the mixes with MRA, 2.4% lower in R10/50 and 5.4% lower in R25/50 than in R0/50. The combined use of GRC and MRA lowered the mean λ_s value by 1.7% in (R0/50, R10/50 and R25/50) relative to the reference NAC. In other words, the use of 25% GRC had a greater impact than the use of 50% MRA.

Table 10. Thermal conductivity of the concrete matrices.

Parameter/Differential	NA mix			MRA mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
λ_s (W/m·K) [1]	2.345	2.303	2.223	2.310	2.256	2.186
Δ with GRC (%)	-	−1.8	−5.2	-	−2.4	−5.4
Δ with MRA (%)				−1.5	−2.0	−1.7
Δ with GRC (%) × MRA (%)					−3.8	−6.8

[1] λ_s = ((λ − (P_0i × λ_air)))/V_s, where: λ is overall concrete thermal conductivity; Po is open porosity (expressed as a decimal); λair is the thermal conductivity of air, equal to 0.024 W/m·K; Vi is the volume of the solid matrix for a given total volume defined as Vi = (1 − Poi), where the subscript i denotes the type of concrete mix.

3.5.4. Thermal Properties and Electrical Conductivity

As Figure 10 shows, electrical conductivity, like open porosity, was inversely related to thermal conductivity and directly to specific heat capacity with determination coefficients R^2 for linearity above 0.830. The explanation for these findings lies in the greater electrical conductivity of the recycled materials mixes than the reference mix, resulting from the greater volume of saturated pores in the former (see item 3.3.3). Earlier authors also mentioned a rise in electrical conductivity (reported as a decline in electrical resistivity) with the higher porosity attributed to using MRA coarse aggregate [50], RCA coarse aggregate [62], RCA fines [57] or RCA coarse and fine aggregate jointly [63].

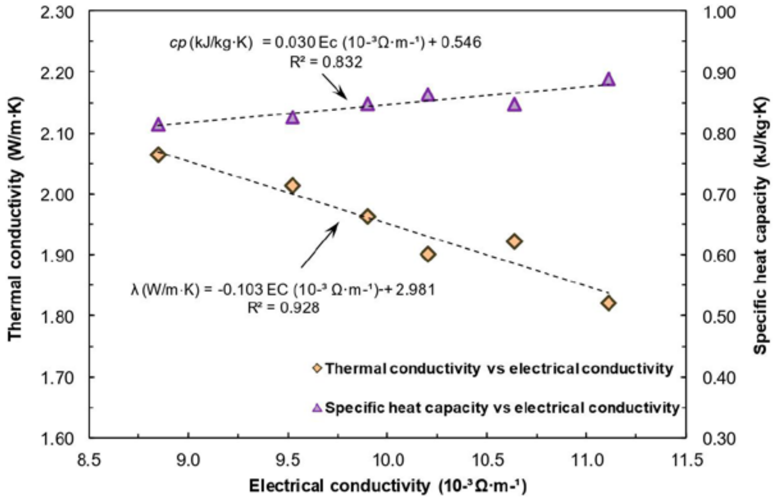


Figure 10. Variation in electrical conductivity/thermal conductivity and electrical conductivity/specific heat capacity relationships for all concrete mixes.

4. Conclusions

The conclusions that may be drawn from this study are set out below:

- The use of GRC to replace 25% of OPC and MRA to replace 50% of NA lowered concrete fresh-state density by 6.2% and raised its air content by 30%. All the recycled material concrete mixes studied had an air content under 4.5%, the upper limit recommended by the ACI committee for structural concrete;
- Porosity rose by 39.7% in the mixes with 25% GRC and 50% MRA and by 13.2% in the mixes with 25% GRC and 100% NA relative to the reference mix made with 100% OPC and 100% NA;
- The decline in dry density and the rise in electrical conductivity were associated with the incorporation of GRC in mixes with 100% NA as well as those with 50% MRA due to the higher porosity in the recycled materials;
- The use of 25% GRC in conjunction with 50% MRA reduced thermal conductivity by 11.8% and raised specific heat capacity by 9.1%, whilst the values for 25% GRC with 100% NA were a 6.9% reduction in thermal conductivity and a 4.1% rise in specific heat capacity, both relative to concrete with 100% natural aggregate (NA);
- Due to their greater porosity, the new recycled materials concrete may provide better thermal insulation and greater thermal inertia than conventional concrete;
- Cross-referencing concrete properties showed that, whereas using GRC and MRA as replacement materials had an adverse effect on concrete's compressive strength, it improved its thermal properties;
- Mixes with 25% GRC and 100% NA and those with 10% GRC and 50% MRA, with compressive strength values of >25 MPa, are not only apt for use in building construction, but afford greater energy efficiency than conventional concrete.

Author Contributions: B.C. performed the experiments; M.B. and B.C. analysed the data and wrote the paper; I.F.S.d.B., C.M. and J.d.B. supervised the research work and revised the paper. All the authors contributed to conceive and design the experiments, and to analyse and discuss the results. All authors have read and agreed to the published version of the manuscript.

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Capítulo 12

Resonance Fatigue Behaviour of Concretes with Recycled Cement and Aggregate

Capítulo 12

Resonance Fatigue Behaviour of Concretes with Recycled Cement and Aggregate

Resumen

El enorme aumento de la producción de residuos de construcción y demolición (RCD) en todo el mundo está llevando a la valorización de áridos reciclados. Una de las alternativas más prometedoras es su uso como árido reciclado en la fabricación de hormigón estructural, lo que motiva el estudio del comportamiento dinámico de estos materiales con el fin de asegurar su idoneidad para su uso en elementos sometidos a cargas dinámicas. Esa investigación evaluó el comportamiento de fatiga por compresión resonante de hormigones estructurales con 25 % o 50 % de agregados mixtos reciclados, individual o en combinación con un 25 % de ultra finos de base cerámica con sustituto del cemento ambos procedentes de los RCD. Todas las mezclas se sometieron a pruebas de fatiga por compresión utilizando el método acelerado de Locati. Según los resultados observados en límite de fatiga de todas las mezclas se encontró entre un 30 % y un 45 % de la resistencia a compresión. Además, también se encontró una correlación entre la frecuencia de resonancia del ensayo y la deformación sufrida por la probeta. Esta correlación permitió la estimación del límite de fatiga a través de un parámetro más estable que la deformación medida por galgas extensométricas, a saber, la frecuencia de resonancia

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Resonance Fatigue Behaviour of Concretes with Recycled Cement and Aggregate

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Abstract: The huge increase in production of construction and demolition waste (CDW) worldwide is leading to the valorisation of as recycled aggregates. One of the most promising alternatives is its use as a recycled aggregate in the manufacture of structural concrete, which motivates the study of the dynamic behaviour of these materials in order to ensure their suitability for use in elements subjected to dynamic loads. This work evaluated the resonant compressive fatigue behaviour of structural concretes with 25% or 50% recycled mixed aggregates, either individually or in combination with 25% recycled cement of clay-based materials both from CDW. All mixes were subjected to compressive fatigue tests using the accelerated Locati method. Regarding the fatigue limit, the results showed that for all mixes, it was between 30% and 45% of the compressive strength. In addition, a correlation was also found between the resonance frequency of the test and the deformation suffered by the specimen. This correlation enabled the estimation of the fatigue limit through a more stable parameter than the strain measured by strain gauges, namely, the resonance frequency. In addition, it was found that the resonance frequency of the test changed as the specimen damage increased. This observation enabled the estimation of the fatigue limit through a more stable parameter than the strain measured by strain gauges, namely, the resonance frequency.

Keywords: recycled concrete; resonant fatigue; Locati method; high frequency

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1. Introduction

Concrete is the most widely used and versatile material in construction [1]. In 2019 ~27 Gt of concrete was consumed worldwide [2], requiring the production of ~19 Gt of natural aggregates (NA) and ~4.1 Gt of Portland cement [3]. With current urban growth expectations, it is estimated that these quantities could increase by as much as 25% by 2030 [4]. Meanwhile, this rapid development is leading to a huge increase in construction and demolition waste (CDW) generated during the construction, remodelling and demolition of buildings and infrastructure, currently representing the world's major waste stream.

Consequently, the construction industry must change its current linear "produce-use-dispose" growth model to a more circular growth commitment by adopting actions that ensure sustainable development for concrete without compromising the needs of future generations.

In this context, many countries are promoting policies that include the circular economy model with the aim of prolonging the useful life of structures, reducing the consumption of natural resources and valorizing the waste generated [5]. To this end, the valorisation of CDW as recycled aggregates (RA) in the design of new concretes is an attractive technique that can bring great economic and environmental benefits, given the possibility of obtaining recycled concretes with good mechanical performance [6–8] and durability [9–12]. In this line, there are other works that attempt to assess CDW as RA together with new recycled supplementary cementitious material (SCM) (ground granulated blast fume [13,14], ceramics recycled [15,16], concrete recycled [17,18] and biomass waste [19,20]) as a partial substitute for cement, providing a double benefit by reducing the consumption of NA and cement, and achieving promising results in the improvement in mechanical and durability performance of concretes made only with CDW.

At present, the fatigue process involving recycled concrete is as yet an inadequately investigated topic [21]. A deeper understanding of this structural behaviour is essential to promote the reincorporation of these new raw materials into the production cycles in the concrete industry.

Fatigue in concrete can be defined as a process of mechanical degradation leading to failure. Due to cyclic loads, crack initiation and propagation within the specimen occur until final failure. However, during the application of the variable loads, a modification of the mechanical parameters of the concrete occurs, progressively varying the structural responses of an element [22]. This behaviour is of great importance in the design of structural elements, such as bridges, airport pavements, roads, marine structures, wind generators, foundations of industrial equipment, etc. Compared to permanent loads, these elements are subjected to a higher number of cyclic loads due to variable loads (transient loads, wind, etc.), and these cyclic loads produce a major reduction in mechanical properties, shortening the service life of this type of structure.

Some researchers have focused their efforts on increasing knowledge about the compressive fatigue behaviour of this new generation of recycled concretes. In this area, Xiao et al. [23] studied the fatigue behaviour of concretes with 100% recycled coarse aggregates (RCA) (>95% waste concrete). For this purpose, they tested cylindrical specimens in cyclic uniaxial compression tests with a constant minimum fatigue load stress and a frequency of 10 Hz. These authors observed that concretes with 100% RCA showed fatigue behaviour in three different stages: (i) cyclic creep stage, (ii) creep coupling stage and (iii) fatigue stage, similar to the behaviour pattern of conventional concrete with NA [24]. Thomas et al. [25,26] carried out an extensive experimental programme (24 mixes) to study fatigue behaviour of concretes made with RCA (20%, 50% and 100%) and different effective water-cement $(w/c)_{eff}$ ratios (from 0.45 to 0.65). In their results, these authors reported that, for same $(w/c)_{eff}$, RCA concretes showed a greater reduction in fatigue life than NA concretes. However, concretes with up to 20% RCA and $(w/c)_{eff}$ showed fatigue behaviour similar to that of NA concrete.

In general, the reduced fatigue life of RCA concretes can be attributed to: (i) greater numbers of micro-cracks in the RCA produced in the crushing process of concrete waste, which are more easily interconnected as a result of cyclic loading [27] and (ii) larger interfacial transition zones between the cement paste and the RCA, which act as additional weak bonds under cyclic loading [28]. Sainz-Aja et al. [29] observed through microstructural analysis with computer microtomography of RCA concretes subjected to compressive fatigue loading that cracks are mostly generated at the aggregate interfacial transition zone (ITZ) and the edges of the flakier aggregates, propagating through the weaker planes until concrete collapse occurs.

Breccolotti et al. [21] researched the experimental results of Xiao et al. [23] and Thomas et al. [26] in order to improve the understanding of the fatigue behaviour of concretes made with RCA. These authors were able to develop a predictive algorithm to estimate the fatigue behaviour of RCA concrete, knowing the compressive strength, the percentage of NA substitution by RCA and the type of concrete mix, obtaining good agreement between the experimental results and the theoretical prediction. Furthermore, these authors verified that the concretes with RCA complied with the fatigue life predictions calculated according to the Model Code 2010 [30].

Recently, Sainz-Aja et al. [31] combined the accelerated Locati fatigue method with 2×10^5 cycles per step with resonant fatigue, minimising the time and cost of fatigue testing. These authors observed more conservative results in the fatigue behaviour of concretes tested at moderate frequency (10 Hz) than in the case of those tested at high frequency (≈90 Hz), this effect being greater in concretes manufactured with RCA. Moreover, they observed an increase in temperature with increasing frequency, which could reduce the fatigue life of the concrete by increasing creep damage.

From all the research carried out to date, great advances have been made in the knowledge of the fatigue behaviour of concrete with RCA. However, this type of recycled aggregate, in Spain only represents between 30% and 40% of CDW [32]. The remainder is represented by mixed recycled aggregates (MRA), the result of jointly crushing used concrete, masonry materials (brick, roof and ceramic tile) and some minor components, including plaster, wood, plastic and glass. MRA are more heterogeneous than RCA, which makes it more difficult to reincorporate them into the concrete production chain. Nevertheless, new scientific contributions are emerging every day that encourage further research in this field, motivated by the possibility of producing concretes with MRA with acceptable mechanical [6,32–34] and durability [10,35–37] results. Furthermore, according to the latest report of the European Commission [38], MRA are the biggest problem within CDW due to their accumulation in recycling plants.

The recent review by Tang et al. [39] shows that the partial substitution of up to 30% by weight of recycled clay waste from CDW as SCM in the manufacture of concrete can improve, if the fineness of the waste is adequate, the properties of new concretes incorporating these new SCMs in the cement with respect to conventional concrete, as well as being an effective solution to mitigate the pollutant emissions associated with cement production, with a reduction of up to 8.1% of cement produced [40].

With this objective, the innovation of this research is to analyse the individual and joint effects of the incorporation of mixed recycled finely ground clay-based waste as SCM to cement (RPW-CDW) and the coarse fraction of mixed recycled aggregates in the study of resonant fatigue behaviour from structural concretes. It purposes to enhance the scientific and technical understanding of the combined use of such waste and contribute to its valorisation. In this context, there are still no research studies on this behaviour with these recycled materials. For this purpose, an experimental programme was designed to carry out resonant fatigue tests using the Locati method with 1×10^5 cycles per step. This technique allowed evaluating the fatigue limit of concretes made with MRA and concretes made with 25% RPW-CDW and (25–50%) MRA, finding that the resonance frequency decreases as the damage in the specimen increases. This observation allows estimating the fatigue limit through a more stable parameter than the strain measured by strain gauges, namely the resonance frequency.

Finally, the results of this research will contribute to a better understanding of the resonant fatigue behaviour of this new generation of concretes with MRA and recycled cement from the integral recovery of CDW.

2. Materials and Methods

2.1. Materials

2.1.1. Binders

The concretes were manufactured with two types of cement: (i) 100% Ordinary Portland cement (OPC), class 42.5 R according to EN 197-1 [41], without additions, supplied by Lafarge Holcim Cement, Toledo, Spain, and (ii) a recycled cement (OPC-25CDW) composed of 75% OPC and 25% recycled ceramic-based waste (bricks, tiles, blocks, etc.) from the crushing and grinding of CDW waste (RWP-CDW). Table 1 shows the chemical composition of RWP-CDW and the resulting OPC-25CDW. This cement is registered by patent Nº ES2512065 [42] and can be classified as CEM II/B or CEM IV/A of strength class 42.5 MPa according to EN 197-1 [41]. Similarly, a water-based modified polycarboxylate superplasticiser (SP) admixture with a density of 1.1 g/cm^3 and a solids' content of 20% from BRYTEN NF furnished by FUCHS Lubricantes was used.

Table 1. Chemical composition of RWP-CDW and OPC-25CDW XRF analysis.

Material	Chemical Composition (%wt.)												LOI
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	Cl-	SiO_2 (1)	
OPC	20.00	6.03	2.57	60.00	1.75	3.90	0.56	1.49	0.15	0.15	0.02	-	3.26
RWP-CDW	59.63	18.51	5.92	4.78	3.08	0.42	0.70	3.58	-	-	-	35.10	2.15
OPC-25CDW	31.30	8.26	3.24	48.99	2.86	2.43	0.51	1.58	0.35	0.19	0.04	-	2.66

Note: (1) Reactive.

2.1.2. Aggregates

The crushed greywacke natural aggregate used comprised three particle sizes: 0 mm to 6 mm (NA-S), 6 mm to 12 mm (NA-M) and 12 mm to 22 (NA-C). The recycled aggregate used, which was supplied by a CDW processing plant located in the Spanish region of Extremadura, had two particle size fractions: 6 mm to 12 mm (MRA-M) and 12 mm to 22 mm (MRA-C). The composition analysis of recycled aggregates (Table 2), conducted as specified in standard EN 933-11 [43], revealed that the main components were concrete and mortar (47.0–44.0 wt%), ceramic (7.2–10.9 wt%) and natural stone (44.8–43.8 wt%), with others (glass and metals) (<0.5 wt%) as minor constituents. On the grounds of these data and the criteria set out in Spain's structural concrete code [44] with its <95 wt% Rcu (Rcu = Rc + Ru) content and >5 wt% Rb content, MRA-M and MRA-G qualified for classification as a mixed recycled aggregate.

Table 2. Composition of recycled aggregates.

Composition (wt%)	MRA-M	MRA-G
Ceramic	7.2	10.9
Concrete and mortar	47.0	44.0
Natural stone	44.8	43.8
Bituminous	0.6	0.9
Others	0.4	0.4

Note: MRA-M: mixed medium recycled aggregate (6/12 mm); MRA-G: mixed gravel recycled aggregate (4/22 mm).

The particle size distribution and the physical and mechanical properties of all the aggregates used to prepare the concrete mixed are listed in Figure 1 and Table 3, respectively. Due primarily to their higher porosity, the recycled aggregates had a lower density than the natural materials in all particle sizes. The saturated surface dry density was found to lie in the 2.42 Mg/m^3 to 2.45 Mg/m^3 range. These aggregates also absorbed more water than the NA, a consequence of the adhered mortar and masonry particles present in the new materials, which exhibited absorption percentages within the range of 4.0 to 10% observed by other authors [7,17,32] for this type of recycled aggregates. As the adhered mortar tended to smooth its sharpest angles, RA had a lower flakiness index than NA. The recycled materials had a higher Los Angeles coefficient than the NA, likewise due to the adhered mortar and the presence of masonry. Here also, the values ranged within the 20 to 40% reported in the literature for recycled aggregate [16,33,45]. Finally, these recycled aggregates complied with the requirements set out in the European standard EN 12620 [46] for use as recycled aggregate in concrete.

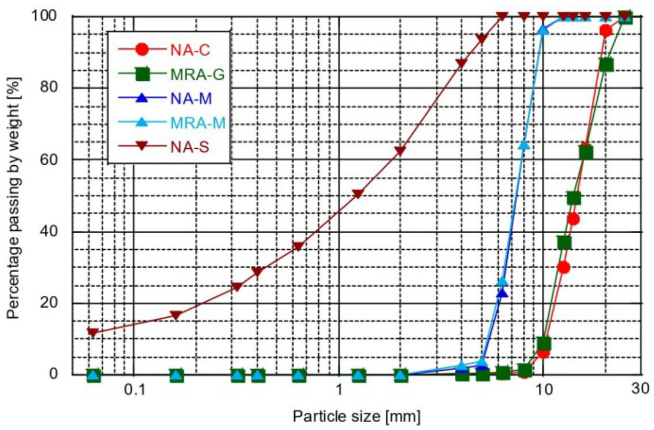

Figure 1. Aggregate particle size distribution. Note: NA-S: natural sand (0/6 mm); NA-M: natural medium gravel (6/12 mm); NA-C: natural coarse gravel (12/22 mm).

Table 3. Physical properties of aggregates.

Property	Aggregates					
	NA-S	**NA-M**	**NA-C**	**MRA-M**	**MRA-G**	**EN 12620**
Dry density (g/cm^3) [47]	2.73	2.71	2.72	2.28	2.32	-
SSD [(1)] density (g/cm^3) [47]	2.76	2.74	2.74	2.42	2.45	-
Water absorption 24 h (%wt.) [47]	1.18	0.88	0.78	6.28	5.27	$\leq$5 ($\leq$7) [(3)]
Open Porosity (vol%) [47]	3.2	2.4	1.9	14.3	12.2	
Los Angeles coefficient (%wt.) [48]	-	16	18	32	36	<50 [(2)]
Flakiness index (%wt.) [49]	-	21	25	10	10	<35

Note: [(1)] SSD: Saturated Surface Dry. [(2)] Concretes with a compressive strength of less than 30 MPa. [(3)] Mixture of recycled aggregate and natural aggregate.

2.2. Experimental Procedure

Table 4 shows the 6 mixes used: a reference concrete (OPC + NA), a concrete with OPC-25CDW and NA, two concretes with OPC with 25% and 50% MRA each and two concretes with OPC-25CDW with 25% and 50% MRA replacement each.

Table 4. Identification of manufactured concrete.

Identification	Description
HP	OPC and 100% NA
HR-25	OPC and 25% MRA
HR-50	OPC and 50% MRA
HP-R	OPC-25CDW and 100% NA
HRR-25	OPC-25CDW and 25% MRA
HRR-50	OPC-25CDW and 50% MRA

Cylindrical specimens of 100 mm diameter and 200 mm height were manufactured according to EN 12390-1 [50] for the resonant fatigue tests. These specimens were demoulded after 24 h and cured at 95 ± 5% relative humidity and a constant 20 ± 2 °C until 180 days of curing. Uniaxial compressive strength according to EN 12390-3 [51] and modulus of elasticity according to EN 12390-13 [52] were also determined.

2.2.1. Resonant Fatigue Test

Resonant fatigue is a technique that allows fatigue testing at the resonant frequency of the system. This resonant frequency depends on the stiffness of the system, and, in the case of concrete, the stiffness is highly dependent on both the load values between which it is being calculated and the degree of cracking of the specimens.

The concrete's compressive resonant fatigue behaviour was studied using the Locati method, which enabled the estimation of the fatigue limit using a single specimen. For this purpose, the minimum stress value (σ_0), corresponding to the lower limit, was fixed, and the upper limit of the maximum stress range (σ_j) was varied in steps, where *j* represents the different steps. Six loading steps with 1×10^5 cycles each were established, and a sinusoidal wave was applied at resonance by means of load control.

The specimens were instrumented with two 60 mm strain gauges to measure the strains. These were placed diametrically opposite to the central axis of the specimen and centred in height, and bonded with two-component epoxy resin. The strains recorded in both gauges were averaged for the calculations.

The test programme for the determination of the resonant fatigue limits is shown in detail in Table 5. Based on the uniaxial compressive strengths ($f_{cd,180}$) of the set of specimens, the minimum stress, σ_{min}, was defined as 2.5 MPa and the maximum initial stress, σ_{max}, as 12.5 MPa, and an increase, Δ, in the maximum stresses of 5.0 MPa was considered in each successive step.

Table 5. Fatigue test parameters by the Locati method.

Step *j*	Cycle *N*	σ_{min}-σ_0 [MPa]	σ_{max}-σ_j [MPa]	Δ [MPa]	σ_{med} [MPa]	Amplitude [MPa]
1	0–1×10^5	2.5	12.5	5.0	7.5	5.0
2	1×10^5–2×10^5	2.5	17.5	5.0	10.0	7.5
3	2×10^5–3×10^5	2.5	22.5	5.0	12.5	10.0
4	3×10^5–4×10^5	2.5	27.5	5.0	15.0	12.5
5	4×10^5–5×10^5	2.5	32.5	5.0	17.5	15.0
6	5×10^5–6×10^5	2.5	37.5	5.0	20.0	17.5

The fatigue limit was established from Equation (1), which was determined by correlating tests on different types of concrete by applying the Locati and Staircase methods [53].

$$L_F = 0.8 * \ \Delta\sigma_L \tag{1}$$

where L_F is the fatigue limit (MPa) and $\Delta\sigma_L$ is the stress range of the Locati test rupture step (MPa).

In addition, the influence coefficient (*IC*) was defined as the ratio of the fatigue limit to the compressive strength in percent.

The resonance frequency tests were carried out with the Zwick/Roell Amsler 400 HFP 5100 Vibrophores (Figure 2), which have a maximum load capacity of 400 kN, maximum mean load of ±300 kN, maximum force amplitude of ±200 kN, and a test frequency range between 35 Hz and 300 Hz.

Figure 2. Zwick Amsler 400 HFP 5100 Vibrophore equipment. Schematic diagram of equipment and test specimen.

2.2.2. Post-Processing Experimental Results

During the fatigue tests, a data acquisition system was programmed to periodically record blocks of 0.03 seconds' duration of the force applied by the resonance machine and the strain recorded by each of the two strain gauges attached to the specimens. In this work, post-processing tasks were carried out to facilitate the interpretation of the results obtained. Specifically, a one degree Fourier regression [54–56] was performed to enable the fitting of the data to a harmonic function (2) [56]:

$$y(t) = a_0 + a_1 * cos(w * t) + b_1 * sin(w * t) \quad (2)$$

where a_0, a_1 and b_1 are regression parameters and w is the angular frequency. This equation can be transformed into a typical sinusoidal Equation (3) by using the following relationships (4) [56]:

$$y(t) = y_0 + A * \sin(w * t + \varphi_0) \quad (3)$$

$$y_0 = a_0; \quad A = \sqrt{{a_1}^2 + {b_1}^2}; \quad \varphi_0 = \frac{\pi}{2} - arctan\left(\frac{b_1}{a_1}\right) \quad (4)$$

where y_0 is the vertical offset, A is the amplitude and φ_0 is the phase shift of the sinusoidal wave. Moreover, the angular frequency and the testing frequency are related by the following Equation (5) [56]:

$$w = 2 * f * \pi * \varphi_0 \quad (5)$$

Figure 3 shows an example comparing the results acquired by raw data (discrete points) and the regression obtained (continuous function).

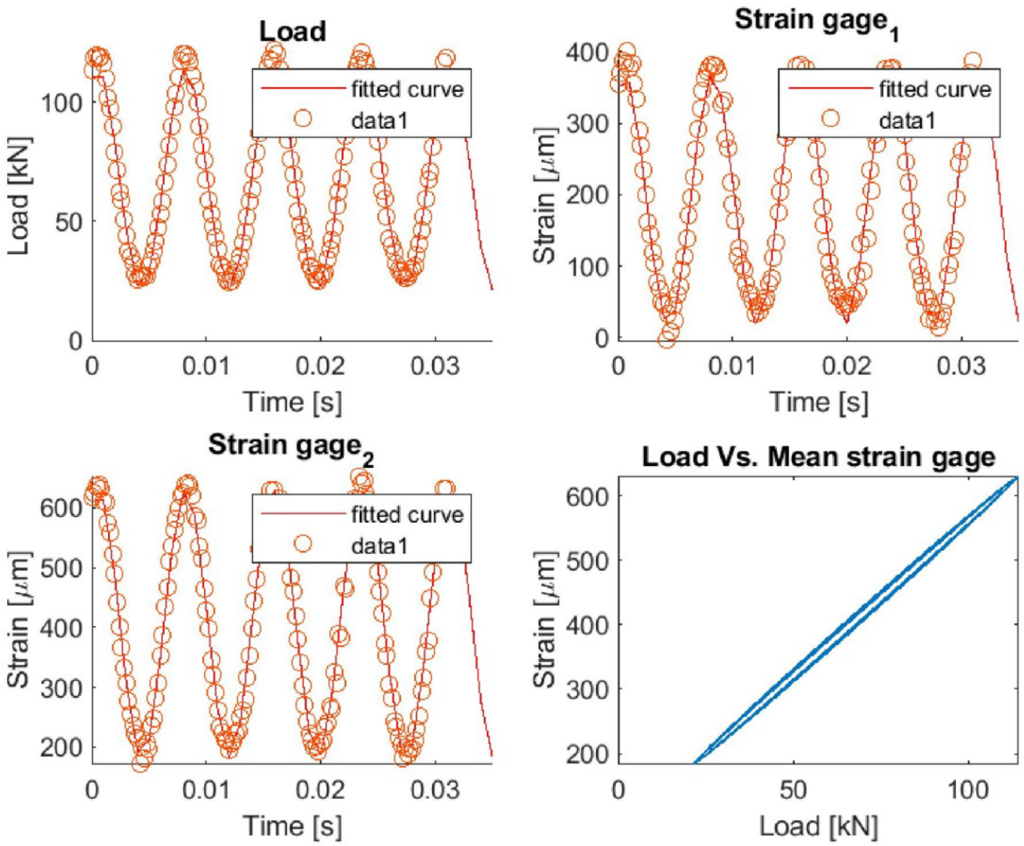

Figure 3. Example of the correlation between the recorded data and fitting values.

2.2.3. Mix Design

Batching for all the concrete mixes is given in Table 6. All mixes, irrespective of the MRA and/or NA content, were designed with the British mix approach [57], using the following starting conditions: (i) concrete compressive strength at 28 days, in 150 mm diameter and 300 mm height specimens, f_{ck} = 30 MPa; (ii) cement strength class, 42.5 R; (iii) effective w/c ratio: 0.45; and (iv) aggregate with a maximum size of 20 mm. The natural moisture content of all aggregates at the time of manufacture of the mixes and the water absorption were also considered. The concretes were prepared in the laboratory as follows: coarse and fine aggregates were mixed for 30 s, then cement was added and mixed for 60 s to homogenise the mixture. The additive was dissolved in 10% of the total water content and mixed with the solids for 45 s. With the mixer running, 70% of the total volume of water was added and mixed for 120 s, after which the remaining 20% of the water was added and mixed for 240 s. The mixer was then switched off, the fresh properties were determined and the mixture was poured into the respective moulds, according to the European standard (EN 12390-1) [50]. Figure 4 shows the modulus of elasticity of the different mixes [16].

Table 6. Concrete mix proportions.

Material [kg/m^3]	Type					
	HP	**HR-25**	**HR-50**	**HP-R**	**HRR-25**	**HRR-50**
NA-S	732.36	720.79	705.38	732.36	720.79	705.38
NA-M	382.96	282.69	184.43	382.96	282.69	184.43
NA-G	766.69	565.94	369.22	766.69	565.94	369.22
MRA-M	-	90.75	177.62	-	90.75	177.62
MRA-G	-	182.80	357.77	-	182.80	357.77
OPC	400	400	400	-	-	-
OPC-25CDW	-	-	-	400	400	400
W	193.03	202.08	210.63	193.03	202.08	210.63
SP	6.20	6.20	6.20	6.20	6.20	6.20
(w/c) $_{effective}$	0.48	0.50	0.53	0.48	0.50	0.53
Physical and mechanical properties						
ρ (kg/m^3)	2340	2310	2290	2350	2310	2240
$f_{cd,180}$ (MPa)	53.5	47.0	48.8	50.2	47.5	47.5

Note: ρ, hardened density and f_{cm}, compressive strength.

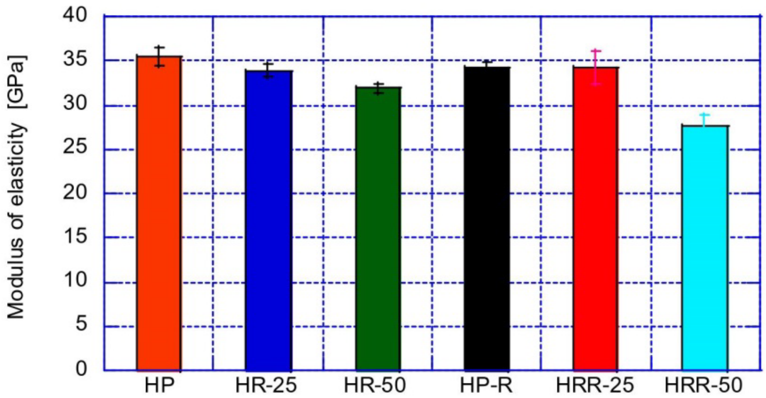

Figure 4. Modulus of elasticity of the different mixes.

3. Results and Discussion

3.1. Fatigue Limit

Table 7 shows the values obtained from the Locati resonant fatigue tests for all mixes. In addition, to complement this parameter, the values of $f_{cd,180}$ (Table 6) and *IC* were added, which enabled the evaluation of the effect of fatigue on each type of concrete.

Table 7. Fatigue limit obtained from Locati Method.

Material	$f_{cd,180}$ [MPa]	$\Delta\sigma_L$ [MPa]	L_F [MPa]	*IC* [%]
HP	53.5	27.5	22.0	41.12
HR25	47.0	18.4	14.8	31.49
HR50	48.8	27.5	22.0	45.08
HRR	50.2	25.3	20.3	40.44
HRR25	47.5	27.5	22.0	46.32
HRR50	47.5	20.6	16.5	34.74

Note: $f_{cd,180}$: uniaxial compressive strength at 180 days; $\Delta\sigma_L$: stress range of the Locati test rupture step; L_F: fatigue limit; *IC*: Influence coefficient ($L_f/f_{cd,180}$ 100).

In all cases, fatigue reduced the strength of the specimens to between 30 and 45% of the $f_{cd,180}$. Regarding the effect of the presence of both MRA and OPC-25CDW on the *IC*, there seemed to be no clear effect. This can be explained mainly by the high dispersion associated with fatigue failure, as this parameter is highly influenced by local phenomena. Furthermore, analysing the strength properties of concrete [15], neither the presence of MRA nor OPC-25CDW produced a significant change in the strength of the material. The little influence of MRA and OPC-25CDW on the *IC* is because, as pointed out by Lantsoght et al. [58], the fatigue strength of a recycled concrete does not depend only on the presence of RA, but also depends to a large extent on water/cement ratio, cement content, concrete type, rest periods, curing conditions and age during loading, and in this case, it was concrete with a high cement content per cubic metre and with high-quality MRA [16]. Furthermore, because the method used for the determination of the fatigue limit was based on a test that applies load steps, the resolution of this method will be similar to the size of the steps used. Therefore, if the differences between mixtures were smaller than the step size, they will be masked by the resolution of the test.

3.2. Strain Evolution Test

Figures 5 and 6 show the evolution of the strain amplitude of the two series of six mixes analysed during the accelerated fatigue test. Figure 4 shows the results corresponding to the OPC mix, and Figure 5 shows the results corresponding to the OPC-25CDW mix.

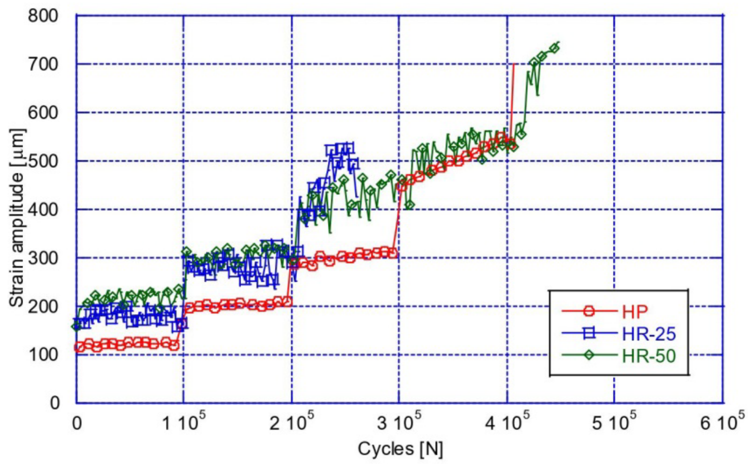

Figure 5. Strain amplitude evolution during a Locati test on the OPC mixes.

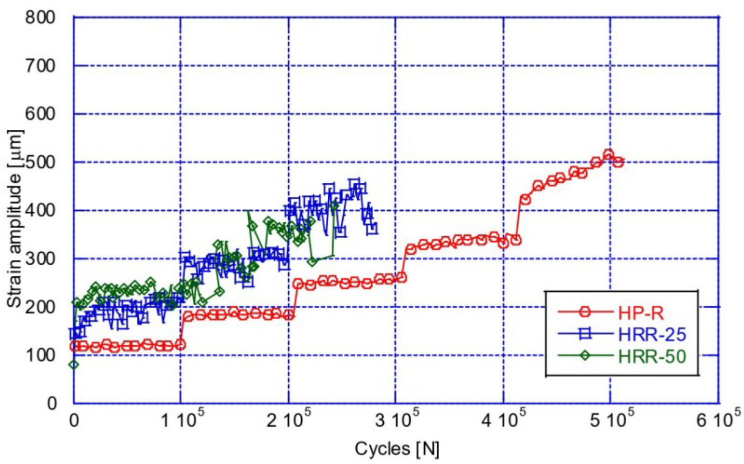

Figure 6. Strain amplitude evolution during a Locati test on the OPC-25CDW mixes.

It can be observed that the presence of MRA increased the strain amplitude recorded for both OPC and OPC-25CDW concretes. This increase in the strain of the concrete with MRA could also be observed in the static tests if we compared the elastic modulus of the different mixes. These results are in agreement with those observed by other authors who have performed fatigue tests on RA concrete analysing the strain evolution [23–26,29,31]. On the other hand, the influence of the type of cement on the strain of the specimens during the fatigue tests was much lower; this effect is also in agreement with the static values obtained in the elastic modulus tests [16]. From Figures 4 and 5, it can also be seen that the presence of MRA resulted in less homogeneous results, which is in agreement with other research [17,59].

In view of the results, which showed both equivalent compressive strength and fatigue strength for both conventional and recycled concretes, it could be considered to use these concretes for the main applications that are susceptible to fatigue damage, such as the railway superstructure, sleepers, or tracks, bridges both for railroad and for road traffic, offshore structures subjected to wind and sea waves and/or wind power tower. Nevertheless, it should be noted that lower modulus results were obtained, which should be taken into account, especially in applications where the concrete is prestressed.

3.3. Frequency Evolution

Figure 7 shows an example of the evolution of the resonant frequency of the set during the fatigue test as a function of the number of cycles. The fatigue testing machine used is characterised by always testing at the resonance frequency of the test machine and specimen assembly, which depends mainly on the stiffness of the assembly; the stiffer it is, the higher the resonance frequency. As shown in this figure, the resonance frequency was not constant throughout the test, which implied that the specimen underwent a series of changes in its mechanical properties during the test. First, it can be seen that when each time a step change occurred, there was also an increase in the resonance frequency. This is because a step-change implies an increase in the stress range applied to the specimen, which generally results in a higher stiffness. Second, it can be seen that, after the first few cycles, there was a reduction in the resonance frequency, corresponding to a stabilisation phase. In the fourth step, this effect was not seen because it is a phenomenon of short duration, which only affects a few cycles, and the data acquisition did not record any of them. However, it is a phenomenon observed by other authors [29,31]. In the first step, it can be seen that, once this first phase was overcome, the resonance frequency remained constant, which means that the specimen was in a stationary state, i.e., the specimen was suffering little damage, and, therefore, it could withstand a large number of cycles without breaking. It was only in the last step that the resonance frequency decreased. This drop in frequency was the consequence of an increase in the specimen deformation, which can be explained by the growth of micro-cracks in the concrete specimen that will lead to specimen failure [60]. For this reason, observing that the resonance frequency decreased (after the initial stabilisation phase) is considered as an indicator of being close to failure of the specimen and that the endurance of the material has been exceeded. Finally, this methodology may be a new way to measure the fatigue limit through resonance frequency monitoring.

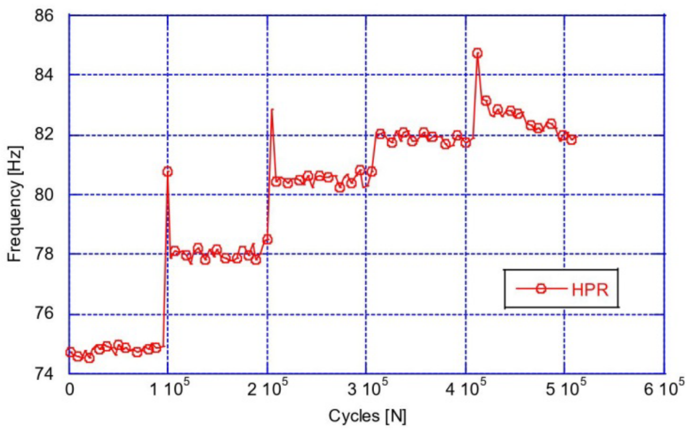

Figure 7. Resonance fatigue frequency evolution during a Locati test.

Figures 8 and 9 show an example of the comparison between the test frequencies obtained for each type of concrete as a function of the percentage of NA replaced by MRA for each type of cement.

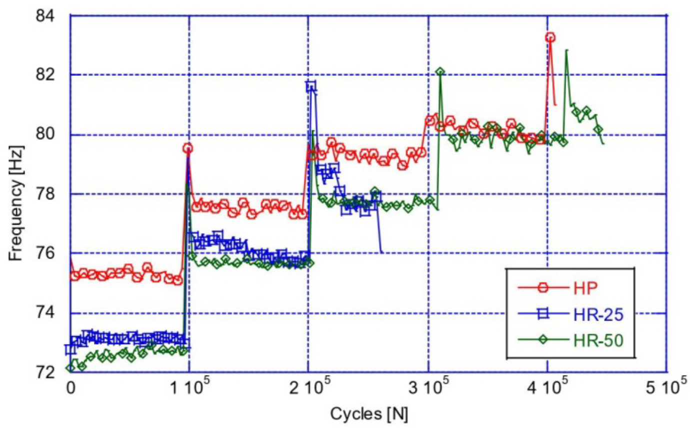

Figure 8. Resonance fatigue frequency evolution during a Locati test for OPC mixes.

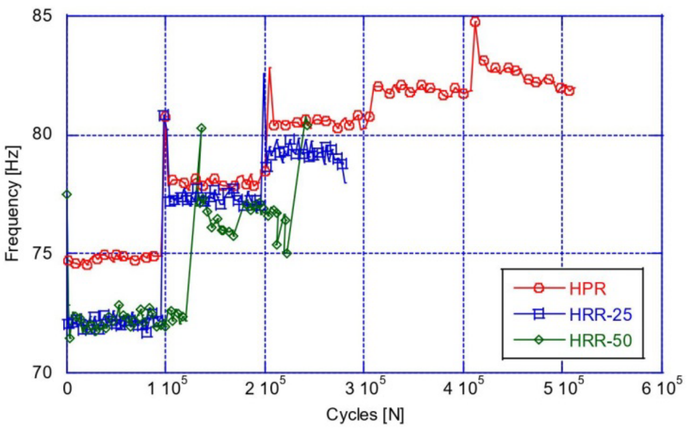

Figure 9. Resonance fatigue frequency evolution during a Locati test for OPC-25CDW mixes.

Figure 7 shows the results for the OPC concretes. It can be seen that the behavioural phases described above were satisfied. As the percentage of replacement increased, the resonance frequency decreased, decreasing the stiffness of the specimen, which was in agreement with the results obtained from the elastic modulus tests and with the strain values previously shown. Figure 8 shows the results of the mixes with OPC-25CDW. As in the case of Figure 7, the phases described above can be seen. In these mixes, it was also observed that in those concretes with MRA, the resonance frequencies were lower than in the case of concretes without MRA. Likewise, these values agreed with the results obtained in the elastic modulus and strain tests.

3.4. Correlation between Strain and Frequency during a Resonance Fatigue Test

In the two previous sections, the evolution of the strain amplitude and the resonance frequency was shown, and it was commented that there is a relationship between the two parameters. Figure 10 shows an example of a comparison between the two parameters for the same test.

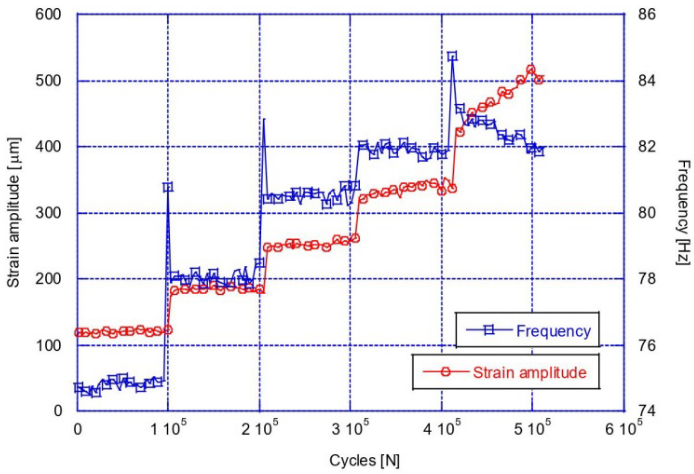

Figure 10. Comparison of the strain amplitude and the resonance frequency during a Locati fatigue test.

Figure 10 show that both parameters suffer abrupt changes at the beginning of each step. In phases where one parameter remained constant, the other also remained constant, although the frequency values seemed to be more stable than the strain values. In phases where changes occurred within the same step, i.e., where the loads remained constant, the effect of the deterioration of the specimens was the inverse for each of these parameters, the frequency decreased and strain increased. At step changes, both parameters underwent punctual increases, while within each step, the change undergone by each parameter was the inverse; this was due to the modifications of the applied stress values. As the applied load amplitude increased, the specimen strained more, and the ratio between force and strain (stiffness) also increased at each step. However, within the same step, as the displacement amplitude increased, the stiffness decreased.

To analyse the ratio between load and strain, Figure 11 shows an example of the evolution of a parameter correlated with stiffness, namely the elastic modulus, during a fatigue test.

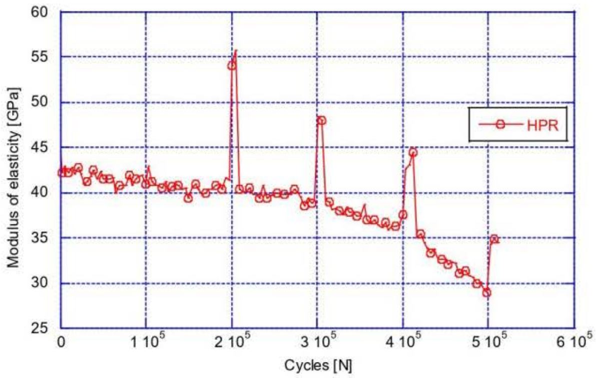

Figure 11. Modulus of elasticity evolution during a Locati test.

Figure 11 shows how, contrary to strain amplitude or resonance frequency, the elastic modulus was a parameter that had a continuous behaviour, if we do not take into account the stabilisation period at the beginning of a step. Moreover, it is a parameter that always decreased [23–25,61]. This is because as the specimen is damaged, the micro-cracks present in the concrete grow, which results in a lower elastic modulus.

3.5. Morphological Analysis of Fractures

Figure 12 shows examples of the failure surfaces of the six types of concretes evaluated in this work. On the left the series of mixes with OPC. On the right, the series of mixes with OPC-25CDW.

Figure 12. *Cont.*

Figure 12. Fracture surface of samples broken during fatigue tests.

Comparing the failure surfaces of those concretes with different degrees of replacement of NA by MRA, different failure mechanisms were observed, similar to those observed by other authors who also performed fatigue tests on concrete [26,61]. In Figure 12, the following patterns were observed on the fracture surfaces of specimens incorporating NA: paste planes were seen, which before fatigue were in contact with aggregates; cracks were seen at the edges of some aggregates; pieces of aggregate were seen protruding above the fracture surface.

Figure 13b shows a detail of the fracture surface of a specimen with MRA. In this figure, the following patterns can be seen: (i) in the case of aggregates from structural concrete, it can be seen that the fracture surface had generated a plane through the aggregate and (ii) in the case of an aggregate of ceramic origin, it can be seen that this aggregate had been pulverized.

(**a**) (**b**)

Figure 13. Fracture surface detail of samples broken during fatigue tests: HP sample (**a**) and HR-50 sample (**b**).

Several authors have concluded that the cracking of the specimens occurs because the cracks propagate through the weaker planes [62–65]. Based on the previously mentioned observations, it is possible to ensure that in those concretes with 0% replacement, and the cracks occur through the paste–aggregate interface (ITZ), i.e., the weakest zone of the specimens is the paste–aggregate interface. It can also be seen that the presence of MRA, especially in those of ceramic origin, can cause the rupture not to occur through the ITZ, because the aggregates have lower mechanical properties so that cracks can advance through them.

On the fracture surface of the fatigue-tested specimens, no different fracture mechanisms were observed in relation to the use of different binders, OPC-25CDW or OPC. It can be observed that the paste had a different colour. It should be noted that, based on the colour of the paste of the concrete with OPC-25CDW, it was possible to estimate that the specimen was "very dry", which is in agreement with what was observed once the test was completed, where the specimens were at a high temperature. This temperature increase has also been detected in other resonant fatigue studies on concrete [29].

4. Conclusions

The main conclusions derived from this research are:

- In the mixtures studied, the resonant fatigue limit was between 30 and 45% of the compressive strength.
- The fatigue results had a large scatter, and no direct influence on the resonant compressive fatigue limit was observed due to the presence of mix recycled aggregate.
- The presence of mixed recycled aggregates in the concretes increased the strain recorded during the resonance compressive fatigue tests. The presence of recycled cement did not affect the strain values.
- The resonance frequencies were lower in the concretes with MRA because the stiffness of the system provided by the presence of MRA increased the strain suffered by the specimen.
- For all cases, it was observed that during resonance fatigue tests with constant load cycles, as the strain increased, the resonance frequency decreased.
- In the compressive resonance fatigue tests, the unmixed MRA specimens exhibited fracture planes across the paste–aggregate interface. While the specimens with MRA showed cracks through the recycled concrete aggregates and pulverisation of the ceramic fractions.
- The strength of all the concretes was similar. The presence of mixed recycled aggregates had a greater effect on the dynamic response (increased strain and decreased resonance frequency) than the presence of recycled cement, which did not show any influence on the dynamic response.
- The characterisation in resonant fatigue allowed a reduction in test durations and the comparison of the fatigue life of different types of recycled concrete, even with recycled cement. However, the dispersion obtained in the results suggests that the more heterogeneous concretes are more sensitive to resonant fatigue. For this reason, for recycled concretes, the method does not seem directly comparable with the classical methods of static characterisation.

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Capítulo 13

Industrial Low-Clinker Precast Elements Using Recycled Aggregates

Capítulo 13

Industrial Low-Clinker Precast Elements Using Recycled Aggregates

Resumen

La utilización de hormigones más sostenibles esta aumentado a media que la sociedad está más concienciada con el medio ambiente. En este trabajo de investigación se ha evaluado las propiedades de elementos prefabricados de hormigón formados con áridos gruesos reciclados y cemento de bajo contenido de clínker utilizando adiciones recicladas. Para tal fin, se diseñaron y caracterizaron seis mezclas diferentes: un hormigón de referencia; dos hormigones con 25 % y 50 % en peso de sustitución de áridos gruesos mixtos procedentes de RCD; y sus homólogos con cemento reciclado con bajo contenido de clínker y áridos reciclados. Los resultados mostraron que la resistencia a la compresión, el módulo elástico y el indicador de durabilidad disminuyen con las proporciones de áridos reciclados que sustituye al árido natural, y estas se acentúan con la incorporación de cemento reciclado. Sin embargo, todos los elementos prefabricados ensayados presentan un buen comportamiento con una ligera reducción de las propiedades mecánicas. Finalmente, se puede confirmar un comportamiento adecuado de las barreras prefabricadas New Jersey, llevado cabo mediante ensayos específicos diseñados laboratorio que simulaba las pruebas reales de impacto de un vehículo.

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Industrial Low-Clinker Precast Elements Using Recycled Aggregates

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Abstract: Increasing amounts of sustainable concretes are being used as society becomes more aware of the environment. This paper attempts to evaluate the properties of precast concrete elements formed with recycled coarse aggregate and low clinker content cement using recycled additions. To this end, six different mix proportions were characterized: a reference concrete; 2 concretes with 25%wt. and 50%wt. substitution of coarse aggregate made using mixed construction and demolition wastes; and others with recycled cement with low clinker content. The compressive strength, the elastic modulus, and the durability indicator decrease with the proportions of recycled aggregate replacing aggregate, and it is accentuated with the incorporation of recycled cement. However, all the precast elements tested show good performance with slight reduction in the mechanical properties. To confirm the appropriate behaviour of New Jersey precast barriers, a test that simulated the impact of a vehicle was carried out.

Keywords: recycled concrete; low clinker cement; precast; mechanical properties; physical properties; New Jersey barriers

1. Introduction

Construction and demolition waste (CDW) is non-hazardous, inert waste generated in any construction, rehabilitation or demolition work. The industrial and construction sectors generate practically the same amount of non-hazardous waste (industry 37,417 kt‡ and construction 35,869 kt‡) in Spain [1]. The European Commission estimates that the volume of CDW comprises one third of all waste generated in the European Union, which constitutes the largest waste stream [2]. Recycling this CDW would lead to more sustainable growth, replacing a linear economy based on use of materials with a more circular economy. This is important, as aggregates are the second-most-used raw material by humans, behind only water [3]. There is European legislation to encourage recycling CDW [4] and many countries have specific norms for the use of recycled aggregates (RA) for concrete [5–8]. In addition, the use of RA could lead to cheaper concrete [9].

Several studies have corroborated that the inclusion of RA produces concrete with a lower density and increased heterogeneity [10–12]. RA normally has a higher porosity than natural aggregate (NA) [13]. In a fresh state, Silva et al. [11] concluded that recycled aggregate concrete (RAC) is less workable and, to achieve a workability equivalent to that of NA, RA could be pre-saturated, or water added during mixing to compensate [14]. However, the incorporation of completely saturated aggregates might cause an excessive water supply [15,16]. Once the RAC hardens, these aggregates make the concrete more susceptible to detrimental environmental effects, resulting in a lower durability [17,18], which should be taken into consideration. Consequently, Annex 15 of the Spanish Instruction for Structural Concrete EHE-08 [19] and other studies [14,20] propose solutions, such as increasing the cement content, reducing the water/cement ratio, or increasing the coating thickness in the case of reinforced concrete.

Generally, it is known that the incorporation of RA into concrete reduces its mechanical properties [21,22], due to the presence of contaminants such as plastics, glass, adhered mortar, etc., ref. [23] and the type of source material (crushed concrete, ceramic or mixed) of the RA [24–26]. The elastic modulus of RAC is lower than that of conventional concrete [15], reaching 45% less for 100% replacement [25]. The results obtained in the characterization of RAC with intermediate replacements present greater variation of results [20]. Other authors have demonstrated the viability of other types of recycled aggregates from waste, such as steel slag [27]. Moreover, the RA affects the fatigue behavior of the concrete [28–32], showing a greater loss of properties than with the static properties. Further research has evaluated the recycling of concrete which incorporates RA [33,34].

With regard to precast concrete elements, it should be noted that, according to the ANDECE (National Association of the Prefabricated Concrete Industry, based in Spain), although the initial cost of elements is higher, the final cost is lower [35]. Other studies such as López-Mesa et al. [36] indicate an almost 18% higher cost of precast slabs versus in situ slabs; although the former have a lower environmental impact and the quality may be higher. Normally, precast elements have a quality seal guaranteeing their properties. Due to a manufacturing process with complete exhaustive control, precast slabs can be: tailored with special properties more easily as they are not manufactured on site; designed with flexibility difficult to achieve in-situ; and incorporate RA in their fabrication. In the case of precast elements using RA, a lower density and strength is observed [37]. Poon et al. [37] investigated the factors that affect the properties of precast concrete blocks with RA, concluding that the compressive strength increases with the reduction in the aggregate/cement ratio (A/C), and that the water absorption of concrete blocks is significantly related to the absorption capacity of the aggregate. Katz [21] investigated the use of precast elements at different ages to produce RA for new precast elements, concluding that the mechanical properties (strength, modulus of elasticity, etc.) when using this type of aggregate in concrete, resemble those when using lightweight aggregates, such as those manufactured using fly ash.

This paper presents the effect on physical and mechanical properties of six types of mixes with different degrees of substitution. The physical properties and durability of these concretes will be analyzed first, then the mechanical properties will be assessed. Finally, the behavior of precast elements will be addressed.

2. Materials and Methodology

The natural siliceous aggregate used in this study is present in three different sizes: 6/0 mm (NS), 12/6 mm (NG-M), and 22/12 mm (NG-C). Mixed recycled aggregates (MRA) were used by substituting NG-M for MRA-M and NG-C for MRA-C. These MRA were obtained from CDW and were principally made up of concrete and mortars (≈ 45%), unbound aggregate, and natural stone (≈ 45%). Figure 1 shows the different size grading for each aggregate.

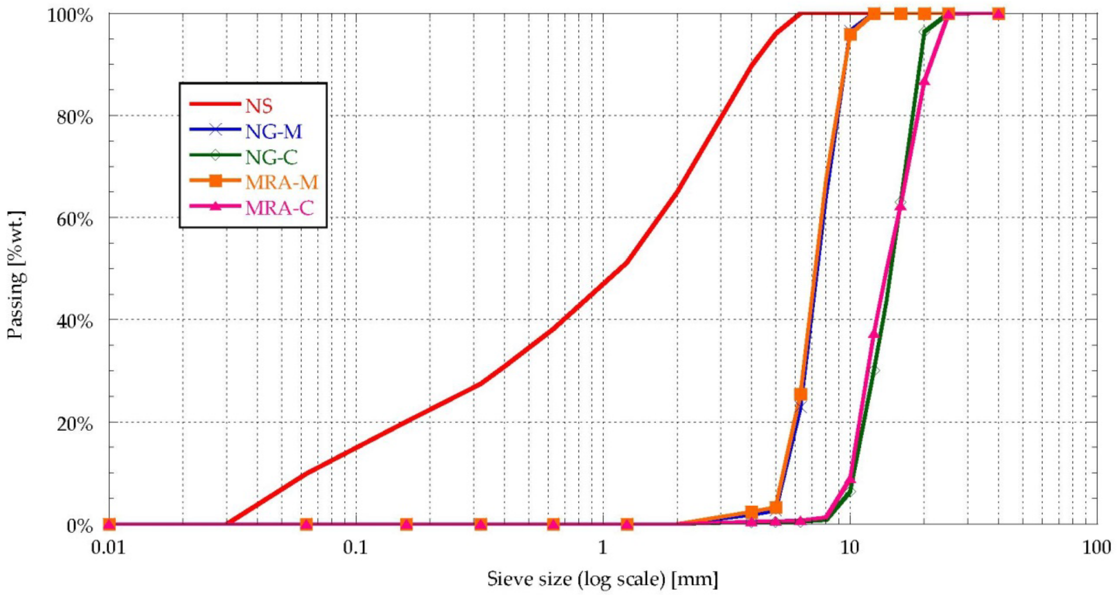

Figure 1. Grading of the aggregates.

Table 1 displays physical and mechanical properties: where *SSS* is the saturated dry surface density according to EN 1097-6 [38]; *A* is the water absorption by weight according to EN 1097-6 [38]; *LA* is the Los Angeles index according to EN 1097-2 [39]; and *FI* is the flakiness index according to EN 933-3 [40].

Table 1. Physical and mechanical properties of the aggregates.

Property	Aggregates				
	NS	**NG-M**	**NG-C**	**MRA-M**	**MRA-C**
SSS [g/cm^3]	2.76	2.74	2.74	2.42	2.45
A [%]	1.18	0.88	0.78	6.28	5.27
LA [%]	-	16	18	32	36
FI [%]	-	21	25	10	10

The conventional cement (OPC) was CEM I 42.5 R, and the low clinker content cement (RC) was constituted of 75% CEM I 42.5 R and 25% ceramic waste from CDW. The tests performed with the cement revealed a compressive strength 20% higher in the case of OPC.

Mixing the aggregates in different proportions with the two existing types of cement produced six concrete mixtures, as shown in Table 2. HP signifies a combination of natural aggregates and conventional cement. HPR is a mixture of natural aggregates and low clinker content cement. HR25 and HR50 were fabricated with conventional cement and substitutions of NA by 25%wt. and 50%wt. proportions of RA, respectively. Finally, HRR25 and HRR50 were obtained by amalgamating low clinker content cement with natural aggregates, substituted by 25%wt. and 50%wt. of recycled aggregates accordingly.

Table 2. Concrete mix proportions (by m^3).

Concrete:	HP	HPR	HR25	HR50	HRR25	HRR50
NS (6/0 mm) [kg]:	732	732	719	705	719	705
NG-M (12/6 mm) [kg]:	382	382	284	184	284	184
NG-C (22/12 mm) [kg]:	766	766	568	369	568	369
MRA-M (12/6 mm) [kg]:	-	-	89	178	89	178
MRA-C (22/12 mm) [kg]:	-	-	178	356	178	356
Cement [kg]:	400	-	400	400	-	-
Low clinker content cement [kg]:	-	400	-	-	400	400
Water [kg]:	193	193	202	211	202	211
Superplasticizer [kg]:	6.2	6.2	6.2	6.2	6.2	6.2
Water/cement ratio	0.48	0.48	0.50	0.53	0.50	0.53

2.1. Physical and Mechanical Properties

Densities were obtained according to EN-12390-7 [41]. Sub-specimens (10Ø × 10 cm) obtained by cutting 10Ø × 20 cm cylindrical specimens were used. The porosity coefficient is the result of comparing the absorbed water and specimen volume, while the absorption coefficient is the result of comparing the absorbed water and specimen weight. Compressive strength was determined using 10Ø × 20 cm cylindrical specimens according to EN-12390-3 [42], with an application strength rate of 0.5 MPa/s. Elastic modulus was determined with 10Ø × 20 cm cylindrical specimens according to EN-12390-13 [43], at a strength rate of 0.5 MPa/s.

2.2. Durability

A water penetration test was performed according to EN-12390-8 [44]. Sub-specimens (10Ø × 10 cm) obtained by cutting 10Ø × 20 cm cylindrical specimens were used. The samples were subjected to a pressure of 5 bar for 72 h. After 72 h water penetration under pressure, it was necessary to analyze how deep the water reached. To be able to observe the interior of the sample, it had to be opened. During this research, the Brazilian method (or indirect tensile strength method) was used to open the sample and analyze its interior. In general, when a cylindrical specimen is subjected to tension along its generatrix, it breaks into two halves, which allows the interior to be analyzed. Once the specimen had been opened, it was possible to measure the penetration depth of the water into the porous concrete. This technique also provided another interesting result: the indirect tensile strength of the concrete. For the determination of oxygen permeability, UNE-83981 [45] was taken as a reference. The 10Ø × 20 cm cylindrical specimens were cut to discard the upper and lower face obtaining a new sample of 10Ø × 10 cm. Silicone was impregnated perimetrically in the samples so that the oxygen could only pass longitudinally. A regulated oxygen pressure was applied on the upper face. Digital flow meters registered the oxygen escaping from the lower face.

2.3. Precast Element Preparation

Two different types of precast elements were manufactured: unreinforced concrete ditches and steel-reinforced New Jersey barriers. Both were manufactured with an industrial concrete mixer, poured in metallic molds and vibrated by hand (Figure 2). In the case of reinforced concrete, reinforcements were set into the mold before the pouring of concrete. In both cases, precast elements were unmolded and cured at ambient temperature.

Figure 2. Precast element manufacturing sequence.

2.4. Precast Element Mechanical Characterization

Concrete ditches have approximate measurements of 50 × 50 × 15 cm. In order to characterize concrete ditches, the tests were carried out by bending. The horizontality of the set was verified, and force was applied by a roller (10Ø × 22 cm) in the central section with a displacement rate of 0.1 mm/s (Figure 3).

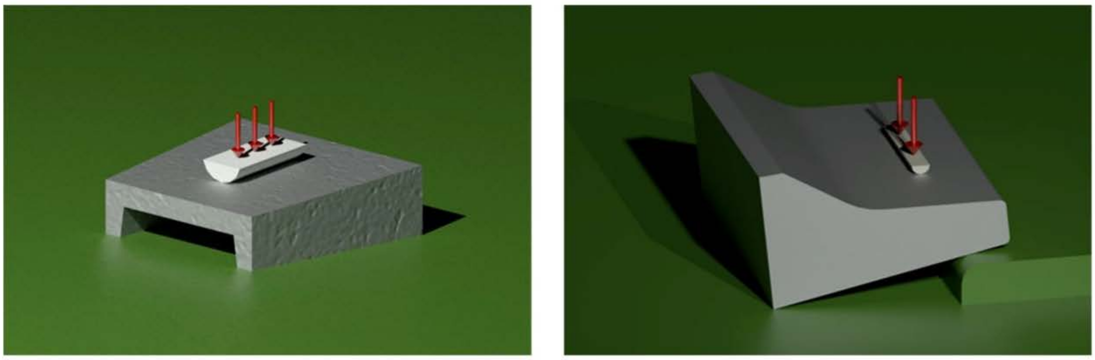

Figure 3. Precast element characterization (concrete ditches left, New Jersey barriers right).

New Jersey barriers have a section with approximate measurements of 47 × 80 cm and a length of 100 cm. In order to characterize New Jersey barriers, a small crane was used to support the precast element on steel beams. These steel beams were placed at one end to correct the inclination of the face on which the test was to be performed, achieving horizontality on that face (Figure 3). The test consisted in applying a stress with a roller (3Ø × 40 cm). The time of the test was very short (0.1–0.2 s) to simulate an impact. The strength and displacement data of the actuator were recorded during the test.

3. Results and Discussion

3.1. Physical Properties

Figure 4 shows the relative and saturated densities of the concretes. As demonstrated, the density decreases as the percentage of NA replaced by RA increases. This is due to the lower density of RA. It also becomes clear that the use of this RC does not affect density significantly.

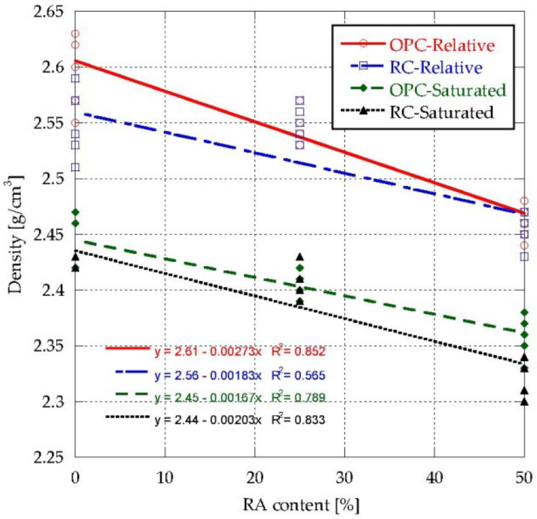

Figure 4. Density vs. RA content.

Figure 5a shows porosity, and Figure 5b shows the absorption coefficient vs. substitution of NA by RA. A decrease in both properties is found in the concretes containing OPC as the percentage of replacement of aggregate increases. However, in the case of concrete made with RC, both properties increase as the percentage of RA increases. This may be because this type of cement interacts more with RAs of different nature, making it difficult to fill all the gaps amongst aggregates. Alternatively, it may be because the RA is able to absorb more water during kneading, causing a small deficit in this type of cement, which is very susceptible to variations in the water dosage. It is possible that there may be another reason that has not been identified.

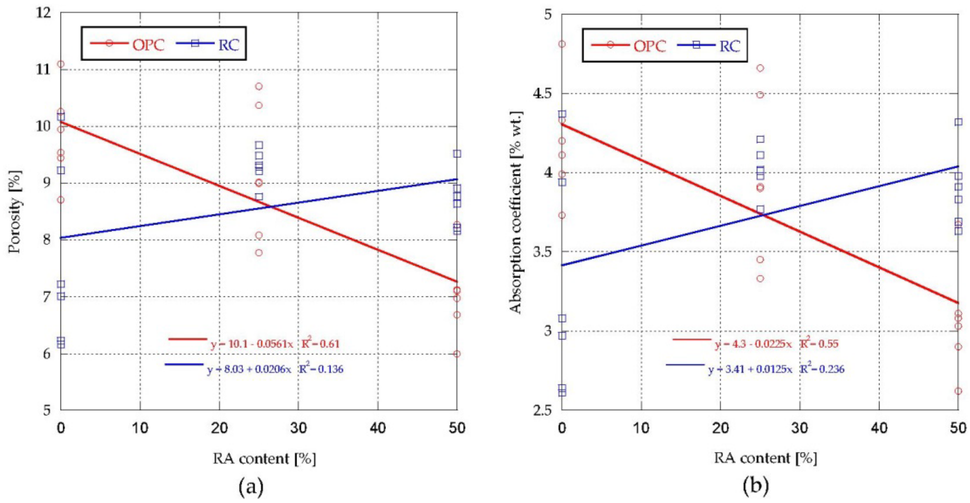

Figure 5. Porosity (**a**) and absorption coefficient (**b**) vs. RA content.

3.2. Compressive Strength and Modulus of Elasticity

Figure 6a shows the compressive strength-strain curves for each concrete at 160 days. Several studies [25,46,47] show that the concrete's compressive strength decreases with the degree of substitution of RA for NA, but in strain terms, concretes show similar values around 2500 μm/m for the failure. The exception is the HRR50 mix, which exceeds the values of the rest by almost 1000 μm/m. Figure 6b shows the same mixtures but at an age of 365 days. The decrease in strength may also be due to the randomness of the type of RA and its distribution into the mortar matrix, which causes greater uncertainty than conventional mixtures.

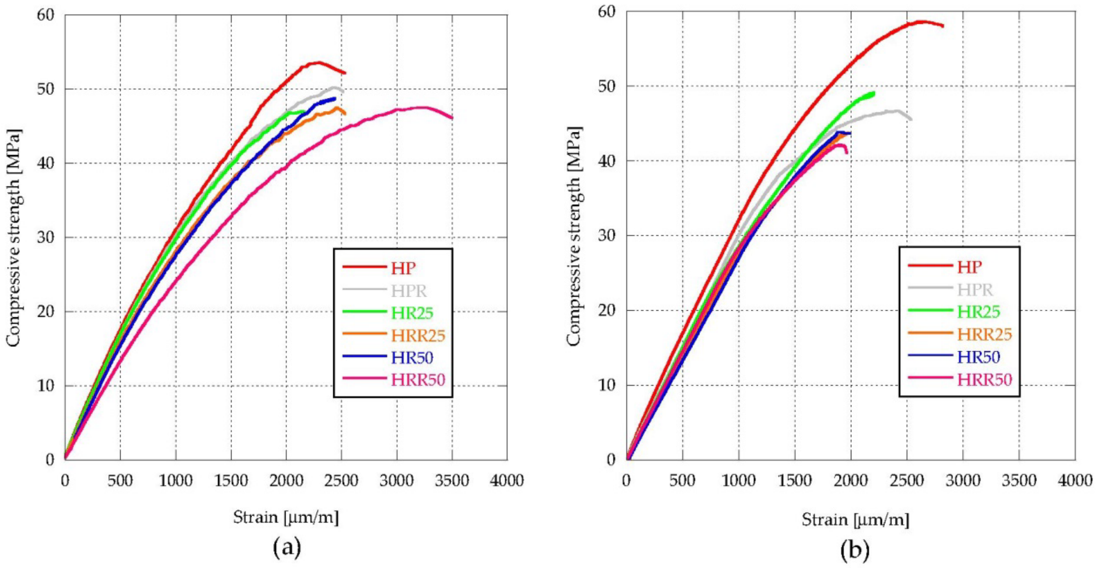

Figure 6. Compressive strength-strain at 160 (**a**) and 365 (**b**) days.

Table 3 shows the different values of compressive strength obtained at different ages.

Table 3. Compressive strength at different ages.

Concrete:	Compressive Strength [MPa]			
	28 days	160 days	365 days	Δ_{36-28} [%]
HP	51.2	53.5	56.8	+10.9
HPR	46.1	50.2	46.6	+1.1
HR25	51.7	47.0	45.1	−12.8
HR50	51.2	48.8	42.1	−17.7
HRR25	45.0	47.5	43.7	−2.9
HRR50	41.2	47.5	42.4	+2.9

Table 4 displays the modulus of elasticity, and shows that when using RC, the decrease in the elastic modulus is around 4%. The substitution of 25% by RA implies a decrease in elastic modulus of 5.6%, while the substitution of OPC in this case does not seem to have an influence. In the case of replacing 50% of aggregate by RA, the influence of the substitution of OPC by RC is meaningful, decreasing the elastic modulus by 15%. As for the loss of elastic modulus over time, a greater influence of the cement is observed than the type of aggregate, with a limit that tends to an asymptotic value of around 27 GPa.

Table 4. Modulus of elasticity.

Concrete:	Substitution [%]	Modulus of Elasticity [GPa]	Modulus of Elasticity at 365 days [GPa]	% of the Initial Elastic Modulus
HP	0	35.5	31.7	89.3
HPR	0	34.1	29.5	86.5
HR25	25	33.9	30.8	90.8
HR50	50	31.9	29.3	91.8
HRR25	25	34.2	27.9	81.6
HRR50	50	27.8	27.4	98.6

Some organizations such as EHE-08, ACI, and Eurocode present their expressions to predict elastic modulus at 28 days from the compressive strength. In Expressions (1)–(3): E is elastic modulus at 28 days [GPa] and f_{28} is the compressive strength at 28 days [MPa].

EHE-08 [48]

$$E = 8.5\sqrt[3]{f_{28}} \quad (1)$$

ACI [49]

$$E = 4.7\sqrt{f_{28}} \quad (2)$$

Eurocode 2 [50]

$$E = 22(f_{28}/10)^{0.3} \quad (3)$$

These expressions can be used to obtain the predictions and comparisons, with the experimental results shown in Table 5. The ACI method fits quite well in most cases but predicts higher values when the percentage of substitution is 50%. The EHE-08 method is safer, although when the substitution is 50% and the OPC is replaced by RC, higher values are produced due to the heterogeneity of the RA affecting the compressive strength. These types of expressions only satisfactorily fit ordinary concrete models.

Table 5. Elastic modulus obtained with different expressions.

Concrete:	Elastic Modulus [GPa]				
	Experimental	EHE-08	ACI	Eurocode 2	$\Delta_{experimental-EHE\text{-}08}$ [%]
HP	35.5	31.6	33.6	35.9	12.5
HPR	34.1	30.5	31.9	34.8	11.9
HR25	33.9	31.7	33.8	36.0	7.1
HR50	31.9	31.6	33.6	35.9	1.1
HRR25	34.2	30.2	31.5	34.5	13.1
HRR50	27.8	29.4	30.2	33.6	-5.3

Figure 7 shows that from approximately 48 MPa, concrete with RA achieved the same compressive strength as concrete with OPC. RA concrete increases its elastic modulus significantly. This might be due to the addition of a new variable, such as RA compared with OPC, which is much more standardized throughout its production process.

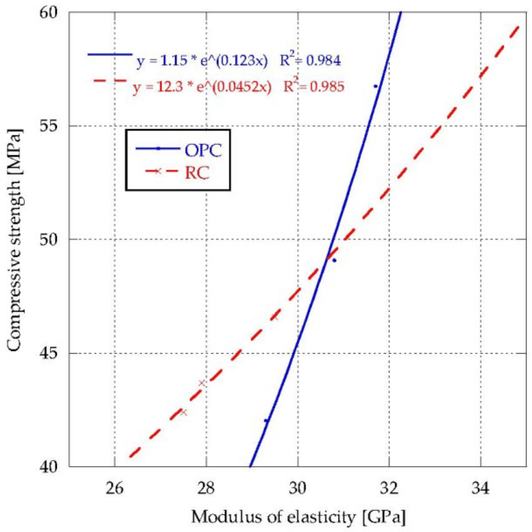

Figure 7. Compressive strength vs. modulus of elasticity.

3.3. Oxygen and Water Permeability

Figure 8a shows the oxygen permeability and Figure 8b shows the maximum penetration of water vs. percentage of substitution, respectively.

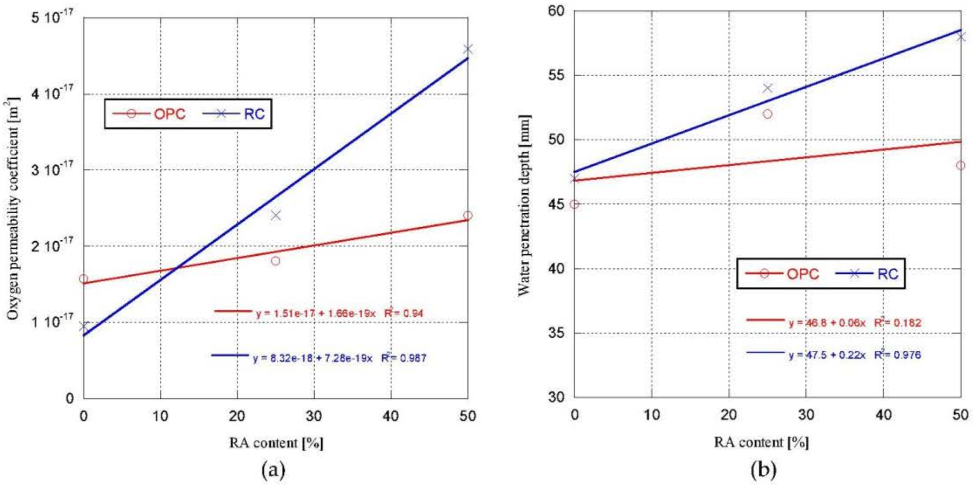

Figure 8. Oxygen permeability coefficient (**a**) and water penetration depth (**b**).

The oxygen permeability coefficient increases with the substitution of the NA by RA. This behavior has been reported in some studies, such as Ismail et al. [51], Medina et al. [52], and Thomas et al. [14]. This increase is higher in concrete with RC than OPC; the type of cement being used is an important factor.

The penetration of water increases with the increase in RA substitution. With these results, only HP and HPR comply with the standard EHE-08 [48] for structural concrete in the case of IIIa, IIIb, IV, etc. environment exposition, which requires an average penetration depth of 30mm, and maximum penetration depth of 50 mm. Penetration of water is related to typology and distribution of the RA, and its impurities with high absorption coefficients.

Figure 9 shows cross-sections of concrete where different colors can be seen. These are caused by the RC in HPR and HRR50 mixtures, and some kind of RA and impurities (such as wood or fired clay) in HRR50 mix.

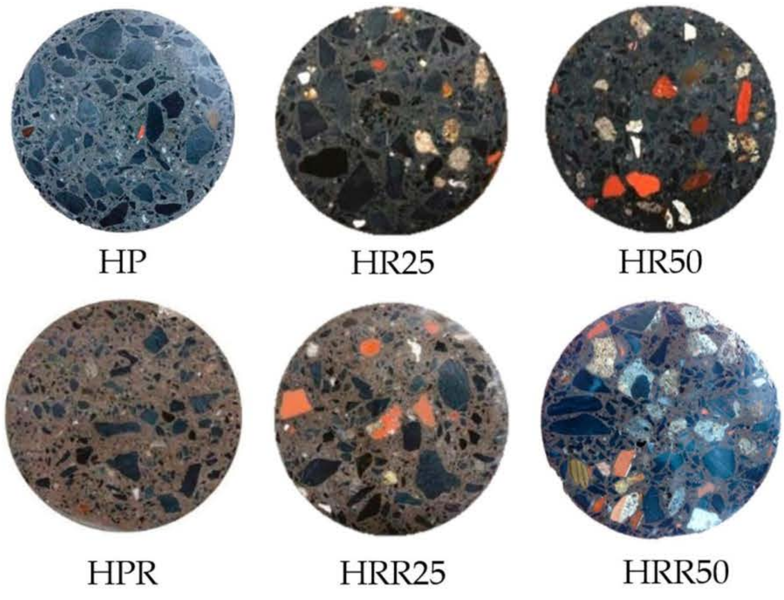

Figure 9. Concrete specimen sections.

3.4. Testing Precast Elements

Figure 10a shows the results of flexural tests on concrete ditches. It can be observed that the concrete composed of RC and RA (HRR50) behaves similarly to HP concrete, which is consistent with the results of splitting tensile strength shown in Table 6. Figure 10b shows the results of the impact test on reinforced precast New Jersey barriers, in which the force applied by the test machine and the position of the actuator are recorded. As expected, the concrete with OPC and NA displayed superior mechanical behavior than concrete with RC and RA. HRR50 could resist only 60% of the force, and 66% of the displacement that HP resisted.

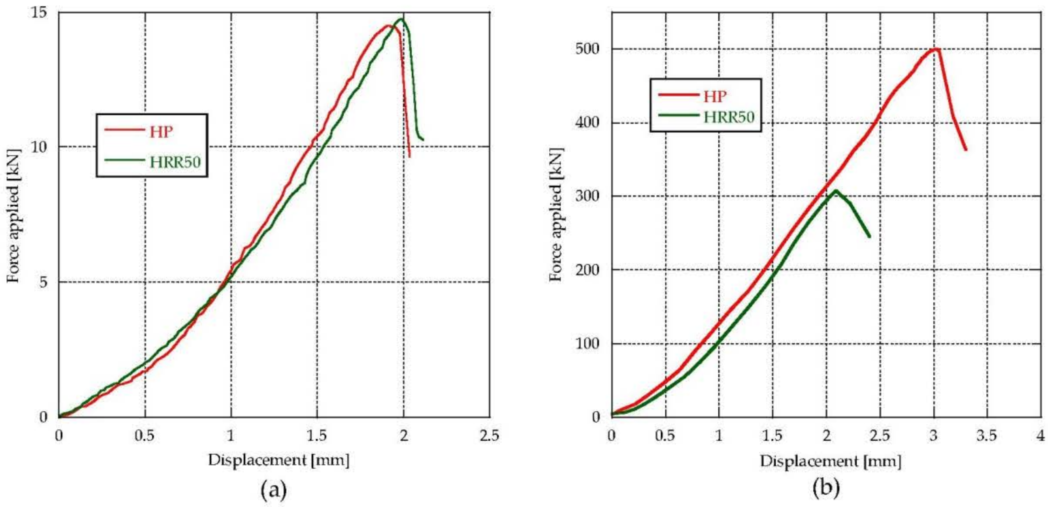

Figure 10. Mechanical characterization of precast elements: Bending test on ditches (**a**), impact test on barriers (**b**).

Table 6. Splitting tensile strength.

Splitting Tensile Strength [MPa]					
HP	**HPR**	**HR25**	**HR50**	**HRR25**	**HRR50**
3.36	3.51	3.48	-	3.30	3.58

Figure 11 shows the results of the test performed with both types of precast elements. Different sections of cracks in OPC and RC concrete ditches, and the fissure produced in a New Jersey barrier are visual results of the tests.

Figure 11. Precast test and cracking.

Equation (4) indicates whether a New Jersey barrier could withstand the perpendicular impact of a vehicle. Velocity and mass are variables, and it would be necessary to incorporate a restitution coefficient in order to avoid the elastic impact.

This coefficient relates the velocity before impact with the velocity after collision, considering the barrier is without velocity before and after impact.

$$C_R = -\frac{V_{1f} - V_{2f}}{V_{1i} - V_{2i}};\, when\ V_{2f}, V_{2i} = 0 \rightarrow C_R = -\frac{V_f}{V_i} \tag{4}$$

García and Cabreiro [53] proposed a method for obtaining the coefficient of restitution based on experimental processes in "*Use of dynamic models in the investigation of road accidents*" (text in Spanish), for which they suggested two equations:

$$C_R = 0.45{\cdot}e^{(-0.040278{\cdot}v)},\ \text{For } v\ <\ 54\ \text{km/h} \tag{5}$$

$$C_R = 0.45{\cdot}e^{(-0.015278{\cdot}v)},\ \text{For } v\ \geq\ 54\ \text{km/h} \tag{6}$$

With Equations (4)–(6), considering the maximum force that a barrier resists, and the duration of the impact as 0.1 s, Equations (7) and (8) are obtained, shown in Figure 12.

$$m = \frac{0.1{\cdot}F}{-\left(\frac{v_i}{3.6}\right){\cdot}\left(0.45{\cdot}e^{(-0.040278{\cdot}v)} + 1\right)},\ \text{For } v\ <\ 54\ \text{km/h} \tag{7}$$

$$m = \frac{0.1{\cdot}F}{-\left(\frac{v_i}{3.6}\right){\cdot}\left(0.12{\cdot}e^{(-0.015278{\cdot}v)} + 1\right)},\ \text{For } v\ \geq\ 54\ \text{km/h} \tag{8}$$

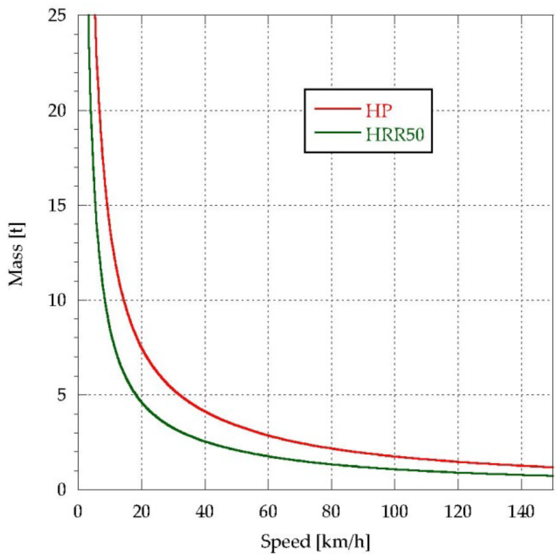

Figure 12. Simulated behavior of reinforced barriers.

These curves are conservative, as the barrier can withstand strains that absorb energy before cracking, and the parapet would not always be immobile (they are only anchored to the ground on viaducts).

4. Conclusions

Characterization tests on concrete specimens and precast elements have been carried out using low-clinker cements and recycled aggregates, obtaining the following conclusions. Firstly, the physical-mechanical properties of mixed recycled aggregates are suitable for the manufacture of concrete and precast elements when the medium and coarse fraction is used. Secondly, the use of mixed recycled aggregates causes a loss of density and compressive strength slightly higher than that which occurs when using recycled concrete aggregates. Recycled concretes made from low-clinker cement are slightly more porous than concretes made with ordinary Portland cement. Finally, regarding the mechanical properties of recycled concrete, a loss of around 10% of the compressive strength is observed when using low-clinker cement. In addition, recycled concrete made with ordinary Portland cement evolves slightly more when over 1 year of curing has elapsed.

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Capítulo 14

Conclusiones Generales

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Conclusiones Generales

En base al desarrollo realizado en la presente Tesis Doctoral, los resultados alcanzados y las conclusiones específicas analizadas en cada uno de los artículos publicados han sido mostradas previamente en los capítulos 4-13. Por este motivo, a continuación, se muestran las conclusiones generales, de acuerdo con los objetivos planteados:

- Los áridos gruesos reciclados mixtos son aptos para su uso en la fabricación de hormigón estructural, a pesar de tener un porcentaje entre un 7 % y un 22 % de residuos cerámicos, superior al límite del 5 % establecido por la actual Instrucción Española de Hormigón Estructural (EHE-08).

- La incorporación de un porcentaje igual e inferior a un 50 % de áridos gruesos reciclados mixtos como sustitutos del árido natural es viable técnicamente, desde un punto de vista mecánico y durable, en el diseño de hormigones reciclados con fines estructurales, siempre y cuando el contenido de impurezas y residuos cerámicos de estas nuevas materias primas recicladas sea inferior o igual a un 1 % y a un 25 % respectivamente.

- El uso simultáneo de áridos gruesos reciclados mixtos (porcentaje de sustitución menor o igual al 50 % del árido natural) como esqueleto granular y los ultra finos de base cerámica (≤25 %) o de hormigón reciclado (≤10 %) procedentes de los residuos de construcción y demolición como adición reciclada en el cemento, es viable técnicamente obteniéndose hormigones reciclados sostenibles de clase resistente C25/30 definida según el Eurocódigo 2 y el nuevo Código Estructural español para fines estructurales.

- Los hormigones reciclados que incorporan menos del 50 % de áridos gruesos reciclados mixtos de forma individual o simultánea con un 10 % o un 25 % de ultra finos de hormigón reciclado y base cerámica de RCD respectivamente, así como adiciones al cemento, presentan una estructura porosa suficientemente impermeable y un comportamiento adecuado frente a la corrosión de armaduras.

- Los hormigones reciclados que incorporan un 50 % de áridos gruesos reciclados mixtos y/o 10 % de ultra finos de hormigón reciclado procedente de RCD, como adición en el cemento han demostrado tener mejores propiedades térmicas respecto el hormigón convencional, y por ende podrían ser hormigones más eficientes energéticamente.

- Los límites a fatiga de los hormigones reciclados que incorporan hasta 25 % de áridos gruesos reciclados mixtos y/o un 25 % de ultra finos de base cerámica procedentes de RCD como adición del cemento fueron semejantes a los del hormigón convencional.

- A nivel industrial y desde un punto de vista técnico, se puede concluir que es posible fabricar piezas prefabricadas sin armadura (bajantes de talud) y piezas armadas (pretiles New Jersey) con porcentaje de hasta un 50 % de áridos reciclados mixtos y/o un 25 % de ultra finos de base cerámica procedentes de los RCD como adición del cemento, cumpliendo con los requisitos mecánicos exigidos en la normativa específica de estas piezas prefabricadas.

Finalmente, a modo de conclusión general se puede señalar que, a pesar de los resultados prometedores obtenidos en la presente Tesis Doctoral, la transferencia tecnológica de estas aplicaciones a la sociedad es aún muy lejana. Hasta la fecha, los áridos gruesos reciclados mixtos y adiciones recicladas procedentes de los ultra finos de base cerámica y de hormigón reciclado procedentes de RCD no se encuentran recogidas en la normativa actual, lo que representa una importante barrera en su utilización en la industria del hormigón. Por lo tanto, aún es necesario una mayor investigación sobre la viabilidad de estos materiales procedentes de los RCD en la fabricación de hormigón con el fin de reducir la incertidumbre vinculada a futuras aplicaciones reales más allá de su uso actual como materiales no ligados al cemento, bases y sub bases de carreteras y rellenos en zanjas, que puedan extender aún más las posibilidades de circularidad y sostenibilidad de estos residuos.

General Conclusions

The results and respective specific conclusions set out in the articles published to date are discussed in Chapters 4 to 13 of this doctoral thesis. This section consequently lists the general conclusions drawn in keeping with the stated objectives.

- Although the masonry waste content (7 % to 22 %) in coarse mixed recycled aggregate is in excess of the 5 % ceiling laid down in Spain's Structural Concrete Code (EHE-08), this material is apt for use in structural concrete manufacture.

- Replacing up to 50 % natural aggregate with coarse mixed recycled aggregate in structural concrete is technically feasible in terms of mechanical performance and durability, providing impurities account for no more than 1 % and masonry waste for not over 25 % of the total.

- The use of recycled mixed aggregate at a replacement ratio of ≤50 % as the granular skeleton in concrete together with masonry (≤25 %) or recycled concrete (≤10 %) ultrafines as cement additions is technically viable. The resulting concretes lie in strength class 25/30 as defined in Eurocode 2 and Spain's Structural Concrete Code.

- Recycled concrete bearing ≤50 % coarse mixed recycled aggregate, alone or in conjunction with 10 % recycled concrete or 25 % recycled masonry waste ultrafines as cement additions, features a sufficiently impermeable pore structure and sufficiently effective anti-corrosion properties to ensure steel reinforcement integrity.

- As recycled concrete with 50 % coarse recycled mixed aggregate and/or 10 % recycled concrete ultrafines as a cement addition performs better than conventional concrete, it constitutes a more energy-efficient alternative to the conventional material.

- The fatigue limits for recycled concretes bearing up to 25 % recycled mixed aggregate and/or 25 % masonry waste ultrafines as a cement addition are similar to the values found for conventional concrete.

- The technical-practical conclusion that can be drawn is that legislation-compliant, precast, non-reinforced (runoff pipes) and reinforced (New Jersey guard rails) elements can be manufactured on an industrial scale with ≤50 % mixed recycled aggregate and/or 25 % masonry CDW ultrafines as a cement addition.

The overall conclusion reached is that despite the promising findings described in this thesis, technology transfer of such applications to society is not expected at any time in the near future. The exclusion to date of mixed recycled aggregate and recycled additions prepared with masonry and concrete CDW from the applicable legislation stands as a substantial barrier to their use in the concrete industry. Further research on the viability of using these CDW-based materials in concrete manufacture is consequently needed to lower the uncertainty around future real-life applications beyond the non-cement uses presently in place such as road bases and sub-bases and ditch fillers. The ultimate aim is to capitalise more broadly on the potential of this waste to enhance concrete circularity and sustainability.

Capítulo 15

Futuras Líneas de Investigación

Capítulo 15

Futuras líneas de Investigación

Las líneas de investigación que podrían ser abordadas en un futuro son:

- Analizar el comportamiento prestacional de los hormigones fabricados con diferentes tipologías de áridos gruesos reciclados mixtos que contenga en su composición diferentes porcentajes de materiales cerámicos. Con ello, se podrían establecer: porcentajes óptimos de incorporación en función de su composición; reducir la incertidumbre vinculada a la presencia de residuos cerámicos en los áridos reciclados mixtos y, finalmente, permitir un mayor campo aplicación más allá de aplicaciones no ligadas al cemento.

- Profundizar en la investigación de nuevas adiciones recicladas procedentes de los ultra finas de origen mixto de RCD. Este análisis permitiría satisfacer la laguna científica – técnica existente en la actualidad y favorecer la valorización de esta fracción reciclada que es acopiada en la planta de reciclaje de RCD.

- Explorar la fabricación de hormigones reciclados de segunda generación con esta tipología de residuos reciclados mixtos. Dentro de la estrategia de la economía circular, y a partir de las probetas de hormigón producidas para llevar a cabo este trabajo, se propone confeccionar nuevos hormigones que puedan dar lugar a futuros estudios de investigación sobre la viabilidad técnica, económica y medioambiental de los productos que con ellos se elaboren. Esto permitiría cerrar el ciclo de los materiales, considerando la pérdida de calidad que pueden llegar a tener tras sucesivos procesos de reciclaje y su posterior fabricación.

Future Lines of Research

Future lines of research that could build on the present findings include the following.

- To analyse the performance of concretes made with different types of coarse mixed recycled aggregate bearing different percentages of masonry materials. The aim would be to establish optimal replacement ratios by recycled CDW composition, reduce the uncertainty around the presence of masonry waste in mixed recycled aggregate and broaden the scope of application beyond non-cement uses.

- To conduct in-depth research into new recycled additions derived from mixed CDW ultrafines. Such analyses would help fill one of today's scientific-technical knowledge gaps and favour valorisation of a fraction of recycled waste that is presently stockpiled at CDW recycling plants.

- To explore second generation recycled concrete manufacture with that fraction of mixed recycled waste. In line with the circular economy strategy, the intention is to recycle the concrete specimens used in the present study to prepare new concretes for future research into the technical, economic and environmental viability of the end products. Such studies would close the circle characterising these materials by exploring their possible decline in quality after successive rounds of recycling and manufacture.

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