Word count: 9577~~382~~

Mechanical and microstructural characterization of non-structural precast concrete made with recycled mixed ceramic aggregates from construction and demolition wastes.

Juan-Valdés*, Andrés; Rodríguez-Robles, Desirée; García-González, Julia; Guerra-Romero, Manuel Ignacio; Morán-del Pozo, Julia María.

Escuela Superior y Técnica de Ingeniería Agraria. University of León. Avenida Portugal 41, León, 24071, Spain.
* andres.juan@unileon.es

Field Code Changed

Abstract

The pressure caused by the construction activities has begun to take its toll on the environment. One option to alleviate the negative impacts is to reuse the construction and demolition wastes as recycled aggregate in the manufacture of non-structural concrete. Therefore, this research compares the recycled kerbstones and paving blocks made with a 50% replacement ratio of pre-saturated recycled mixed ceramic aggregates to the conventional non-structural precast concrete elements. Although some decreases in compressive (-25.47%) and flexural strength (-5.77%) were observed, the splitting tensile strength (0.53%), the strong bond exhibited by the ITZ between the recycled aggregates and the cement paste and the relatively low porosity (12.44% with a small volume of pores greater than 2 µm) showed promising results; thus proving the viability of using recycled kerbstones and paving blocks.

Keywords: precast, kerb, paving block, recycled concrete, recycled mixed ceramic aggregates, mechanical and microstructural characterization

1. INTRODUCTION

Despite the recent economic crisis, the construction industry continues to be one of the principal drivers of the worldwide development. For instance, in the European Union, the construction sector provides 13 million direct jobs in around 3 million enterprises and represents a 10% of the total gross domestic product by generating an annual turnover of around 16000 billion of euros (EBC, 2015).

The so-called cementitious materials are the most used substances in the construction works. Indeed, concrete -both in mass and reinforced form- is the man-made material more employed in the world (Fernández-Canovas, 2013). The production of construction materials entails an intense demand for non-renewable natural resources to be used as raw materials that causes an enormous negative environmental burden, both directly and indirectly. Although the raw materials used in the concrete production constitute some of the most abundant resources in the Earth’s crust (siliceous aggregates, clay, limestone…), the pressure caused by the intensiveness of the construction activities has begun to take its toll on the environment. In fact, some countries have already reported a certain scarcity in the natural aggregate extraction (EEA, 2008) and the United Nations Environment Programme has warned about a possible risk of exhaustion (UNEP, 2014).

The associated negative impacts may be partially alleviated by using the generated wastes as secondary materials that can be reincorporated into the construction sector as inputs in the manufacture of recycled materials destined for a similar or new use (Spanish Ministry of Environment, 2001). Thus, in the concrete manufacture, the construction and demolition wastes (CDW) can be used as a replacement of the natural aggregates or as a cement addition due to the pozollanic properties that these wastes exhibit -especially when they consist of a significant ceramic fraction- (Lavat et al., 2009; Pacheco-Torgal and Jalali, 2010; Sánchez de Rojas et al., 2014). These types of valorisation techniques are based on the circular economy principle, which promotes the reduction of the natural resources consumption and the wastes generation by maintaining the product value beyond their first life span through sequential reutilization (European Commission, 2014).

One option to reuse the CDW is incorporating them as recycled aggregates in the manufacture of non-structural concrete. Due to the society concerns regarding the quality of this type of materials, the non-structural application should be proposed as the first step in the challenge to overcome those suspicions. Moreover, despite this type of concrete constitutes much smaller percentage of the total based-cement materials used in the construction sector, the mechanical and durability specifications for this type of elements are widely known to be less demanding than those required for structural concretes.

Based on the classification proposed by the Spanish Association of CDW Managers (Güell-Ferré et al., 2012), it is possible to ascertain that the majority (85%) of recycled aggregates from CDW produced in Spain are recycled mixed ceramic aggregates (RMAc), that is recycled aggregates composed of a heterogeneous mixture of unbound natural aggregates, concrete and ceramic waste materials; the latter ranging from 30% to 70%. Nowadays, recycled aggregates are mostly used as filling in trenches and wells or as bases and sub-bases in construction works, which entails a downcycling of the materials. In this regard, the Spanish Code on Structural

Concrete (Permanent Commission on Concrete, 2008), namely EHE-08, can be held responsible for this situation. Since the current legislation does not contemplate the use of RMAc in concrete applications, these recycled aggregates are legally relegated to the aforementioned uses. Therefore, the present work aims to delve into the reutilization possibilities of RMAc as a partial replacement of the coarse natural aggregates in concrete mixes suitable for the production of non-structural precast elements. To date, some research efforts have been made in the viability assessment of the use of recycled aggregates from CDW to produce non-structural precast concrete elements of different types (kerbs, paving blocks, stones and flags, concrete blocks and floors, prestressed joists for flooring systems, terrazzo and hollow tiles and concrete pipes). Due its relevance, the results from the studies conducted on kerbs (de Guzmán Báez, 2010; López Gayarre et al., 2013; Özalp et al., 2016; Rodríguez et al., 2016) and paving blocks (Jankovic et al., 2012; Poon et al., 2002; Poon and Chan, 2006, 2007; Poon and Lam, 2008; Rodríguez et al., 2016; Soutsos et al., 2011a) will be used for comparison within this research.

In this paper, two types of non-structural precast elements with a wide use in construction, such are kerb units and paving blocks were manufactured to assess the effect that the use of commercially available RMAc -i.e. directly obtained from recycling plants and containing a significant contents of ceramic (>30%)- had on the behaviour and performance of the recycled concrete resulting from a 50% replacement ratio of the coarse natural aggregate by pre-saturated recycled aggregates according to the protocol established by García-González et al. (2014). In general, it is recognised that the high porosity and water absorption of the recycled aggregates originating from CDW is the principal disadvantage of this type of secondary material as greatly increases the water absorption of the recycled concrete mixture. Nonetheless, the basic properties of the concrete can be maintained, or even improved in some aspects, with an appropriate mix design accounting for the specific characteristics of the by-products used.

Moreover, the results obtained were compared with those achieved by the commercially available non-structural precast concrete elements produced by the company *Prefabricados de Hormigón Pavimentos Páramo S.L.*, member of the Spanish Association of the Precast Concrete Industry (ANDECE), which has selflessly collaborated in this study.

2. MATERIALS

2.1. CONCRETE RAW MATERIALS

For the manufacture of the recycled concrete mixture, the following materials have been employed in this research: commercially available Portland blended cement (CEM III/A 42.5

N/SR) conforming to the Spanish (Royal Decree 256, 2016; UNE 80303-1, 2013) and European (EN 197-1, 2011) standards. Besides the environmental advantages, a blended cement including blast furnace slag was selected based upon the recommendations of Mas et al. (2012b). The authors reported that sulphate-resistant CEM III/A was especially suitable in the manufacture of recycled concrete since resulted in mixes with lower strength declines compared to the conventional concrete, as well as due to its resistance against the greater sulphate content associated to the use of recycled aggregates. The 42.5 N strength class was chosen to match the one used by the local precast concrete company. Tap water was used, complying with the EHE-08 (Permanent Commission on Concrete, 2008) recommendations. Natural aggregates, both fine and coarse natural aggregates presented a siliceous nature and complied with the requirements of the EHE-08 (Permanent Commission on Concrete, 2008) and the European standard EN 12620+A1 (2008) establishing the properties that aggregates used in the manufacture of concrete must fulfil. In addition, they have the CE marking of construction products (certificate number: 1035-CPR-ES033899). All natural aggregates are commonly used in the production of precast specimens: 0/4 mm crushed sand, 0/5 mm rounded sand, 4/10 mm gravel and 6/12 mm gravel. Figure 1 displays the particle size distribution (EN 933-1, 2012) of the four fractions of natural aggregates.

Regarding to the recycled aggregates, these were obtained through a mechanical treatment (crushing, sieving and removal of impurities) of the CDW in a recycling plant located in the Autonomous Community of Madrid (Spain). Figure 1 displays the particle size distribution of the 4/20 mm recycled aggregates. The aggregate characterization carried out revealed the most significant differences between the recycled aggregates and natural aggregates. A comparison between the particle size distribution (EN 933-1, 2012) of the recycled and natural aggregates can be observed in Figure 1. Regarding physical and mechanical properties such as D/d ratio (EN 933-1, 2012), fines content (EN 933-1, 2012), flakiness index (EN 933-3, 2012), Los Angeles coefficient (EN 1097-2, 2010), RMAc performed similarly to the natural aggregates and the results were within the suitable parameters established by EHE-08 (Permanent Commission on Concrete, 2008) for the concrete manufacture. However, results obtained for the EN 1097-6 (2013) showed the most variation compared to the natural aggregates. The presence of attached mortar and ceramic materials in the recycled aggregates caused a 2.1% reduction of density (EN 1097-6, 2013) of RMAc in comparison with natural aggregates (2.5%). Nonetheless, the main difference between the RMAc and the natural aggregates was the water absorption (EN 1097-6, 2013), which will be significantly affected by the properties of the original attached mortar (Abbas et al., 2007; Shi et al., 2016; Tam et al., 2007; Zhang et al., 2015a; Zhang et al., 2015b). In this case, RMAc showed an 8.5% water absorption higher than the water absorption of the natural aggregates (1.2%), which is attributed due to the presence of old mortar and clay materials (Poon and Chan, 2006; Yang et al., 2011). Despite the commonly dry consistencies used in the manufacture of precast concrete elements, the use of aggregates with high water absorption could result in a workability drawback. Hence, a technique to solve this problem was required. Previous studies developed using the same recycled aggregates employed in this paper showed that the pre-saturation technique of the recycled aggregate is a suitable method to manufacture quickly, easy and inexpensive recycled concrete with low strength requirements and maintain a suitable workability (García-González et al., 2014).

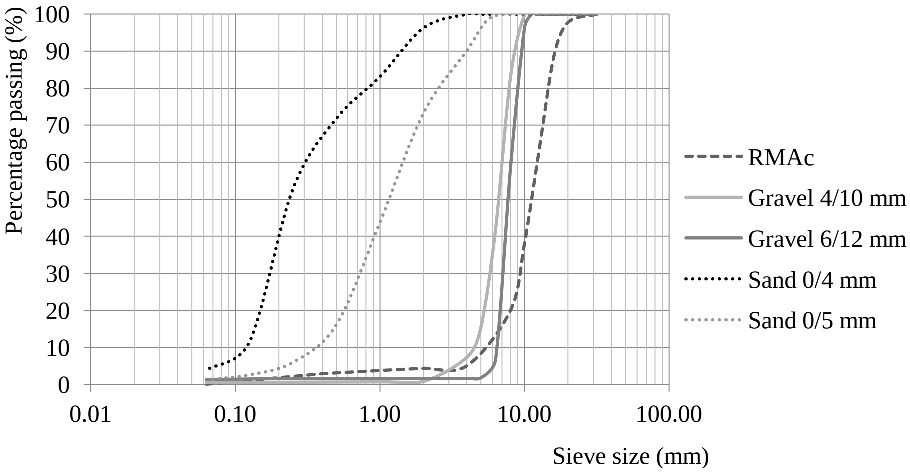

Figure 1: Particle size distribution of the recycled mixed aggregates

The composition of the recycled aggregates was determined according to EN 933-11 (2009). The different fractions of the non-floating components are shown in Table 2.

Table 1~~2~~: Non-floating components of the recycled aggregates

Component	**Percentage (wt%)**
Unbound aggregates (natural aggregates without cement mortar attached)	44.11
Ceramics (bricks, tiles, stoneware and sanitary ware…)	33.56
Concrete and mortar (natural aggregates with cement mortar attached)	17.51
Asphalt	0.44
Glass	0.75
Gypsum	3.48
Other impurities (wood, paper, metals, plastic…)	0.16

The recycled aggregates were composed of the following materials: concrete and mortar, unbound natural aggregates, ceramics, asphalt, glass, gypsum, and impurities, such as wood, plastic, and metal. The data showed that the predominant material were unbound natural aggregates (44.11%) followed by materials of a ceramic nature, which constituted a 33.56%, and the concrete and mortar fraction (17.51%). In terms of impurities, such as glass, asphalt, wood, paper, metals and plastic, no significant problems should be expected based on the quantities obtained. However, the great content of gypsum (3.48%) could generate some problems since its incorporation could cause expansions in the recycled concrete due to the delayed formation of ettringite (Neville, 1995). Nevertheless, as it can be observed in the accompanying SEM images, such problems were not identified for the recycled mixture assessed in this paper.

Due to the important role of attached mortar in the recycled aggregate properties (Abbas et al., 2007; Shi et al., 2016; Tam et al., 2007; Zhang et al., 2015a; Zhang et al., 2015b), the recycled aggregates were subjected to three different tests, which quantified their adhered mortar content (García-González, 2016). For to date no standard procedure has been established for quantifying adhered mortar in recycled aggregates. The first test followed the method described in the article of Tam et al. (2007), based on treating the aggregate by soaking in solutions of 0.1 M HCl, the second test increased the concentration of HCl until 10 M. The third method applied freeze-thaw cycles (-15/80 °C) in the presence of a 26% sodium sulphate solution, being based on the procedure followed by Abbas et al. (2007). The method at low HCl concentrations proved to be best suited for this type of aggregate, for the other two methods proved to be overly aggressive. According this method, the adhered mortar accounted for 4% of the total material, an acceptable value for a recycled aggregate processed by secondary crushing.

Considering the extensive use of ceramic materials in the building practices of many Mediterranean countries such as Spain, it is expected that the generated CDW contain, on average, 54% of these materials according to the 2001-2006 National CDW Plan (Spanish Ministry of Environment, 2001). Hence, the study of the valorisation opportunities that CDW containing significant amounts of ceramic materials acquires a special interest, especially those focused in their reutilization as a substitute for the coarse natural aggregates in the concrete manufacture. The recycled aggregates used in this research work were selected due to its particular ceramic content composition.

2.2. CONCRETE MIX PROPORTION

Although some efforts have been made on the definition of a specific mix design for recycled concrete, the common practice is based on the substitution, in terms of weight or volume, of the natural aggregates by the recycled ones. However, it is recognized that the greater water absorption of recycled aggregates is one of the main responsible for the differences between mixes and may cause problems in the recycled concrete, especially if not considered during the mixing stage.

Ideally, recycled concrete should be able to replace the equivalent commercially available conventional concrete option. Therefore, the proportions of the conventional concrete (CC) mix used by *Prefabricados de Hormigón Pavimentos Páramo S.L.* in the manufacture of commercially available kerb units and paving blocks was used as a model in the dosage of the recycled concrete (RC) specimens. In order to produce recycled non-structural precast elements that can economically compete with the conventional products, the cement content for both mixtures should be the same, as that constitutes the greatest part of the total manufacture cost. In addition, since this investigation is solely focus on the effect of the coarse RMAc, the content of natural fine aggregates was maintained.

Thus, water, cement and fine aggregates content remained unaltered, whereas the 50% of the total weight of the coarse natural aggregates was replaced by 4/20 mm recycled mixed ceramic aggregates that were pre-saturated before its incorporation to the mix. A 50% replacement ratio was chosen based on the limit replacement values suggested in the literature review (de Guzmán Báez, 2010; López Gayarre et al., 2013; Poon et al., 2002; Rodríguez et al., 2016; Soutsos et al., 2011b). Regarding the need to taking into account the greater water absorption of the RMAc, the pre-saturation technique was preferred to the mixing water compensation, since the latter could lead to bleeding risks that alter the interfacial transition zone (ITZ) (Poon et al., 2004a, 2004b). Nonetheless, in order to ensure a correct pre-saturation practice, a detailed study regarding the absorption properties of the recycled aggregates must be performed on a case by case basis. In a previous investigation (García-González et al., 2014), it was found that, in order to achieve improvements in the consistency of the recycled concrete, the RMAc employed in this study require from a 3 minute pre-saturation in potable water to reach a 47.5% of the water absorbed at maximum saturation, which would require a 10 days immersion.

Table 3 shows the detailed proportion of the different raw components used in the manufacture of the recycled concrete mixture (RC).

Table 2~~3~~: Mix proportions per cubic metre of recycled concrete

	RC
fck (MPa)	25
Total w/c (-)	0.5
Water (l)	155.21
Cement (kg)	312.5
Sand 0/4 mm (kg)	96.98
Sand 0/5 mm (kg)	441.81
Gravel 4/10 mm (kg)	242.46
Gravel 6/12 mm (kg)	80.82
Recycled mixed ceramic aggregate 4/20 mm (kg)	323.28

2.3. NON-STRUCTURAL PRECAST CONCRETE ELEMENTS

Both kerb units and paving blocks were produced with a single concrete throughout and thus are considered monoblock non-structural precast elements (UNE 127340, 2006). The test concrete specimens were manufactured following the instructions outlined in EN 12390-1 (2012) and EN 12390-2 (2009). After casting, all tests specimens were finished with a steel trowel and were immediately covered with plastic film to avoid any water loss due to evaporation. After 24 hours, all the specimens were demoulded and cured under water at 20±2ºC.

The produced kerbstones presented a 200x100 mm cross section and 1000 mm length with an intended use as delimitation of the pedestrian walkaways -Class A2 conforming to UNE 127340 (2006)-. Figure 2a illustrates both the general appearance and the cross-sectional dimensions of a kerb unit for use in pedestrian sidewalks. The paving blocks were manufactured following the dimensions suggested by *Prefabricados de Hormigón Pavimentos Páramo S.L.* Hence, paving blocks of 200 mm length, 100 mm width and 80 mm height were produced (Figure 2b) since this typology is one of the most employed.

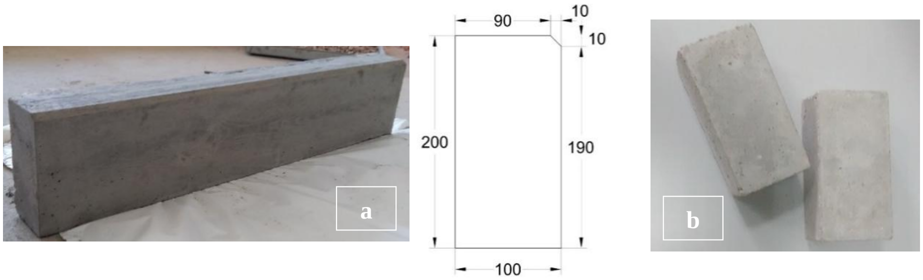

Figure 2: a) General appearance and cross-sectional dimensions (mm) of the recycled kerbstone. b) General appearance of the recycled paving blocks.

3. METHODS

An experimental programme was carried out in order to evaluate the mechanical and microstructural properties of the recycled concrete made with a 50% substitution of coarse natural aggregates by RMAc. To compare the performance of the recycled concrete, commercially available conventional non-structural precast elements produced by *Prefabricados de Hormigón Pavimentos Páramo S.L.*, i.e. analogous kerb units and paving blocks to those produced in the laboratory, were employed.

3.1. CONSISTENCY

The workability of the recycled concrete was determined by means of the Vebe test (EN 12350-3, 2009). This test was performed on a sample obtained in accordance with EN 12350-1 (2009) immediately after the mixing stopped.

3.2. DENSITY

The hardened density of recycled concrete, both in the saturated and oven-dried state, was determined as the average value from four prismatic specimens (200x100x80 mm) made with RMAc after 28 days of curing in water according to EN 12390-7 (2009).

3.3. SURFACE FINISH AND DIMENSIONS

For both kerb units and paving blocks, the requirements for visual aspects (appearance, texture and colour) and dimensions were verified following the guidelines established in EN 1340 (2003; 2006) and EN 1338 (2003; 2006), respectively.

3.4. COMPRESSIVE STRENGTH

According to the standard EN 12390-3 (2009; 2011), the average compressive strength of the recycled mixture was determined at 7, 21, 28 and 365 days for three cylindrical specimens (150 mm diameter and 300 mm height) meeting with the shape and size requirements of EN 12390-1 (2012) by means of a hydraulic press conforming to EN 12390-4 (2000). The compressive test was always preceded by a capping process with pure sulphur into the trowelled surface to achieve a smooth surface for uniform distribution of the load during testing.

3.5. FLEXURAL STRENGTH OF KERBSTONES

The flexural strength of eight kerb units was assessed conforming to EN 1340 (2003; 2006) and the Spanish national complement (UNE 127340, 2006) to the aforementioned standard on 28 days old specimens.

3.6. SPLITTING TENSILE STRENGTH OF PAVING BLOCKS

The mechanical characterization of the recycled paving blocks, i.e. the average splitting tensile strength of eight paving blocks, was carried out according to EN 1338 (2003; 2006) on 28 days old specimens.

3.7. MICROSTRUCTURE

The microstructural studies, both SEM images and EDX elemental mappings, were conducted by using a Hitachi S-4800 scanning electron microscope with tungsten as X-ray source, a Si/Li detector and a Brucker XFlash 5030 EDS analyser. The preparation of the samples consisted on their placement in a metallic holder by means of a bi-adhesive graphite film and a subsequent carbon coating to ensure conductivity and avoid signal masking.

3.8. POROSITY

Mercury Intrusion Porosimetry (MIP) was used to determine the porosity and pore size distribution of 28-days concrete samples. The tests were conducted using a Micromeritics AutoPore IV 9500 porosimeter, which operates in the pressure range 0.0034-227.5270 MPa over a pore diameter range from 0.006 µm to 175 µm. The samples were dried to constant weight at 40 ºC and degassed with a vacuum pump for 30 minutes in order to ensure moisture removal.

4. RESULTS AND DISCUSSION

4.1. CONSISTENCY

A Vebe time of 9 s was registered, which is indicator of a dry consistency. Dry workabilities are typical of concrete mixes where more roughened surface texture of recycled aggregate particles increase the inter-particle friction (Butler et al., 2014). However, no problems in workability were detected when placing, compacting or casting the test specimens. According to Khayat (1999), the true significance of this property relates to the future field application of the concrete mix, the type of construction, the placement method, the shape of the formworks and the structural design. In fact, rather low consistencies are preferred in the precast industry (Jankovic et al., 2012; Xiao et al., 2011). Hence, the effect of the RMAc on the workability of the mixture after using the pre-saturation technique seems to be acceptable for mass concrete employed in the manufacture of kerbs and paving blocks without causing the satisfactory filling and vibration of the specimens to be more energy-intensive.

4.2. DENSITY

Numerous researches have reported density losses when comparing the recycled mixtures to concretes made with coarse natural aggregates. For similar conditions to those tested in the present investigation -i.e. a 50% replacement ratio of coarse natural aggregates by recycled mixed aggregates- the reported decreases range from around 2.1% on saturated state (Medina et al., 2015, 2014; Rodríguez-Robles et al., 2015) to 6.4% on oven-dried state (Gonzalez-Corominas and Etxeberria, 2016). Specifically, the study conducted by Medina et al. (2015) showed that the presence of floating particles or asphalt in the recycled mixed aggregates was responsible for 20% of the reduction in density compared, whereas the influence of the ceramic materials in the recycled mixed aggregates accounted for 40% of the density loss.

Figure 3 illustrates the saturated and oven-dried density values of the recycled mixture. As expected, the lower density exhibited by the RMAc due to the presence of adhered mortar, clay-based particles and floating materials, which are responsible for the higher porosity of RMAc, resulted in lower hardened density values of the recycled concrete compared to those typically accepted for conventional mixtures (around 2500 kg/m^3). For kerbstones made with a 50% substitution of recycled mixed aggregates (74.3% unbound aggregates, 11.8% concrete, 5.6% masonry and 8.3% other impurities), Rodríguez et al. (2016) reported a density of 2240 kg/m^3, which is similar to the results achieved in this research work.

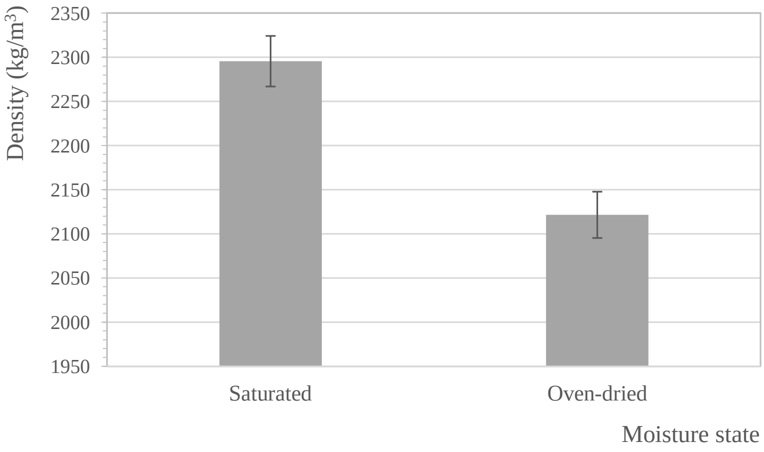

Figure 3: Density values of the recycled concrete

4.3. SURFACE FINISH AND DIMENSIONS

The surface finish of kerb units and paving blocks was assessed in natural daylight conditions. The finishing was deemed satisfactory as none of the specimens evaluated presented any cracks or flaking. Thus, the partial substitution of the coarse natural aggregate by RMAc did not alter the fulfilment of the visual requirements. This observation is in accordance with the remarks of López-Gayarre et al. (2013), who stated that the recycled mixed aggregate replacement should not exceed 50% in order to achieve a good superficial finish. Moreover, the texture and colour was similar to the specimens industrially produced by *Prefabricados de Hormigón Pavimentos Páramo S.L.*, which will assure a good acceptance in the precast market.

Regarding the dimensional requirements, both kerb units and paving blocks complied with the tolerance limitations established in their respective standards, EN 1340 (2003; 2006) and EN 1338 (2003; 2006).

4.4. COMPRESSIVE STRENGTH

Figure 4 illustrates the evolution of the compressive gain throughout a year, which follows a similar asymptotical pattern to that of a conventional concrete. Nonetheless, Mas et al. (2012a) and González-Corominas and Etxeberria (2014) have noticed that strength development of recycled concretes with recycled mixed coarse aggregates is higher than that of conventional concrete. The authors pointed at the strength contribution of the unhydrated cement particles present in the recycled mixed aggregates as cause of the mechanical improvement. Similarly, Rodríguez et al. (2016) stated that the reduction in the mechanical properties of precast elements made with recycled mixed aggregates compared to those made of natural aggregates were decreased with the age of the specimen. The authors attributed this occurrence to the improvement in the microstructure and the self-curing effect promoted by the higher water absorption of recycled mixed aggregates during the mixing stage that is slowly released back to the mixture later on. Conversely, Brandes and Kurama (2016) reported that the rate of compressive strength gain with time was not significantly affected by the use of recycled concrete aggregates in the precast industry.

Despite the current EHE-08 (Permanent Commission on Concrete, 2008) is too restrictive and does not allow the use of recycled mixed aggregates, not even for non-structural purposes, it is worth mentioning that the recycled concrete exhibited a characteristic compressive strength of 29.70 MPa at 28 days of curing.

Regarding the conventional mixture employed by *Prefabricados de Hormigón Pavimentos Páramo S.L.*, the characteristic compressive strength was 39.85 MPa. Therefore, the use of a 50% replacement of the coarse natural aggregates caused a 25.47% reduction of the compressive strength in the recycled concrete compared to the conventional mixture. This poorer mechanical behaviour can be attributed to the presence of adhered mortar, ceramic materials, as well as some other impurities (wood, plastic, gypsum…) present in the RMAc, as they are responsible for the higher porosities and weaker bonds between the aggregates and the cement paste in the recycled mixtures. Although there is no consensus regarding the performance reduction resulting from a recycled mixed aggregate substitution in the manufacture of concrete, González-Corominas and Etxeberria (2014) observed a similar decline in the 28-days compressive strength (26.79%) of cylindrical concrete specimens manufactured with a 50% replacement of coarse gravel by recycled mixed aggregates containing 67.3% of ceramic materials, 22.2% concrete products, 9.8% unbound aggregates and 0.8% impurities. On the contrary, for recycled concretes exhibiting compressive strength values around 29-30 MPa, de Guzmán Báez (2010) observed lower strength reductions. The author reported decreases up to 4.9% for a 50% replacement ratio with recycled mixed aggregates, which were comprised of 51% unbound aggregate, 18.5% ceramic materials, 25% cementitious materials and 5.5% other materials. Shaikh and Nguyen (2013), who replaced 50% of natural coarse aggregate by CDW with 78.7% cementitious materials, 13% ceramic materials, 2.3% asphalt and 5.7% others, obtained a compressive strength 10% lower in recycled concrete than in conventional concrete. Nonetheless, it has been noticed that replacements up to 60% of the coarse natural fraction with recycled aggregates derived from masonry did not affect significantly the mechanical performance of the recycled concrete (Soutsos et al., 2011a). In view of these results, overall differences can be attributed to the compositional variations of the recycled aggregates employed in the different research works.

Moreover, the water compensation of the recycled aggregate has also been held responsible for some of the mechanical performance declines of recycled concrete (Ferreira et al., 2011; García-González et al., 2014; Mefteh et al., 2013; Poon et al., 2004b) as the technique affect the effective water/cement ratio. However, the need of such techniques is justified by the greater water absorption of the RMAc and its effect on the consistency and workability of the resulting recycled concretes.

Despite it is widely recognised that the strength reduction problem can be solved by increasing the cement content, such practice goes against the environmental principle that the reutilization of recycled aggregates in the concrete manufacture attempt to achieve. Nevertheless, the use of the use of a slag blended cement allowed the filling of part of the pores and micro-cracks in the recycled aggregates which resulted in a better ITZ (Mas et al., 2012a). In addition, the proven pozollanic activity of the CDW (Medina et al., 2014, 2015), particularly that of the ceramic particles, also played a positive role in the compressive strength of the recycled mixture.

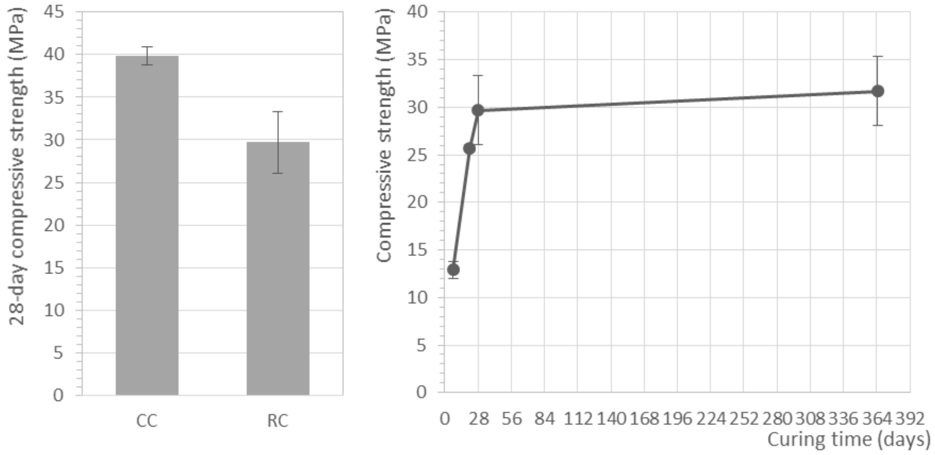

Figure 4: Compressive strength of the conventional and recycled concretes at 28 days of curing. Evolution of the characteristic compressive strength of the recycled concrete mixture

4.5. FLEXURAL STRENGTH OF KERBSTONES

Figure 5 illustrates the flexural performance of the recycled concrete kerbstones. Based on the criteria established in the Spanish national complement (UNE 127340, 2006) of the kerb units standard, the recycled non-structural precast elements are categorised in Class S since all individual results of failure load were over 4.65 kN and the average failure load, which was of 7.7 kN, exceeded the 5.81 kN threshold value for A2 kerbstones. Regarding the flexural strength, which was determined based on a 100 mm span conforming to (UNE 127340, 2006), the individual values obtained for all specimens exceeded the 2.8 MPa (dashed line in Figure 5) and 4 MPa (dotted line in Figure 5), which are considered the limit values for consideration in Class 1 and Class 2, respectively, according to the criteria exposed on EN 1340 (2003; 2006). Nonetheless, the average flexural strength of the 8-set sample of recycled kerbstones was 4.71 MPa. Therefore, the recycled concrete kerb units must be considered Class 1 and will exhibit an S marking that indicates a mechanical performance over 3.5 MPa, which qualifies them for use in pedestrian zones or areas with light traffic.

Conversely, the kerb units made with natural aggregates manufactured by *Prefabricados de Hormigón Pavimentos Páramo S.L.* belong to Class 2, display a T marking, which refers to a flexural strength greater than 5 MPa, and accordingly made them suitable for greater level applications. Whereas the mechanical decrease observed between conventional and recycled non-structural precast elements was around 5%, the normative thresholds place the resulting kerbstones in two different application categories. Thus, the use of a 50% substitution of the coarse natural aggregate by RMAc resulted in a slightly poorer performance of the recycled kerbstones when compared to those made with conventional concrete.

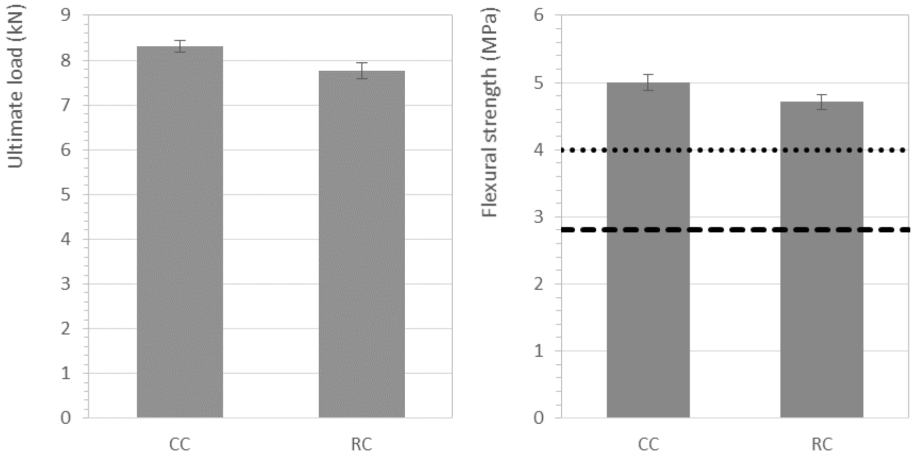

Figure 5: Mechanical characterization of the conventional and recycled kerb units where the dashed and dotted lines represent the Class 1 and 2 thresholds respectively.

Similar mechanical performance and strength reductions can be found in the literature. For 30% and 50% replacements with recycled mixed aggregates, de Guzmán Báez (2010) reported reductions of 9.4% and 5.9% in the flexural strength of recycled kerbstones respect to the conventional concrete. The control concrete displayed a flexural strength of 4.25 MPa, while the recycled concrete reached 3.85 MPa and 4 MPa, respectively. Özalp et al. (2016), who replaced 25% of both fine and coarse natural aggregates by CDW (which are assumed recycled mixed aggregates due to their origin despite the lack of a compositional disclosure) in the manufacture of kerbstones, reported a 12% reduction in the bending strength at 28 days. Nonetheless, recycled kerb units displayed an average strength of 4.4 MPa.

For substitutions up to 25% of the coarse natural aggregates by recycled mixed aggregates, Rodríguez et al. (2016) stated that recycled kerbstones showed a comparable flexural strength to that of conventional kerb units (around 5.25 MPa at 28 days). However, the increase in the recycled aggregate content up to 50% and 75% led to loses around 12%, whereas a complete replacement resulted in a strength reduction of 31.6% compared to the control concrete. Thus, only recycled concrete mixtures made with a 25% replacement ratio fulfilled Class 2 requirements (EN 1340, 2003), while substitutions beyond that value resulted in non-structural precast elements belonging to Class 1 category (EN 1340, 2003). In this sense, the research conducted by Rodríguez et al. (2016) showed similar results to those obtained in this investigation regarding the category demotion caused by the recycled mixed aggregates incorporation, although the actual reduction in flexural strength was lower in the present study, which may be attributed to the compositional differences of the recycled aggregate or the efficacy of the pre-saturation technique.

On the contrary, López Gayarre et al. (2013) only observed decreases in the flexural strength for replacements greater than 70% of recycled mixed aggregates, which were composed of 69% unbound aggregates, 9.33% cementitious materials, 17.67% ceramic materials, 1.33% asphalt and 2.67% other components. So, the authors reported a 33.6% reduction in the flexural strength for a complete substitution.

4.6. SPLITTING TENSILE STRENGTH OF PAVING BLOCKS

The mechanical characterization of the recycled paving blocks was carried out according to EN 1338 (2003; 2006). The results regarding the failure load per unit length and the splitting tensile strength are shown in Figure 6. All of the paving block specimens exhibited a failure load per unit length above 250 N/m (dashed line in Figure 6), which constitutes the minimum admissible load conforming to the requirement in the European standard. In fact, the average failure load per unit length was nearly 500 N/mmm, which doubled the specification. In terms of splitting tensile strength, all paving blocks samples complied with the 2.9 MPa minimum (dotted line in Figure 6) established in the standard, exhibiting results exceeding that value from 10.3% to 65.5% and resulting in an average splitting tensile strength of 3.9 MPa. Therefore, the recycled paving blocks also fulfilled the mechanical requirement of an average splitting tensile strength over the 3.6 MPa threshold.

Regarding the conventional paving blocks manufactured by *Prefabricados de Hormigón Pavimentos Páramo S.L.*, the average failure load per unit weight was 492.5 N/mm and the average splitting tensile strength reached 3.9 MPa. Therefore, the 50% replacement ratio employed in the manufacture of the recycled non-structural precast elements did not negatively affect the mechanical performance of the paving blocks when compared to the conventional concrete option.

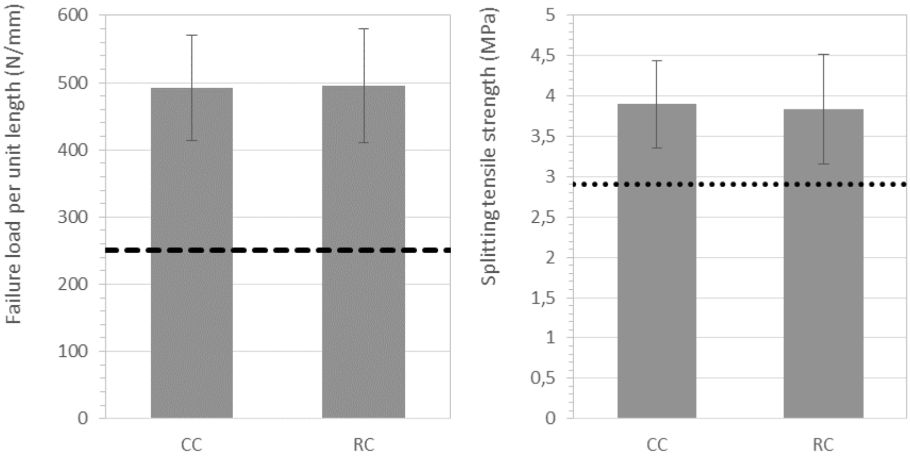

Figure 6: Mechanical characterization of the conventional and recycled paving blocks where the dashed and dotted lines represent the failure load per unit length and the splitting tensile strength thresholds.

Soutsos et al. (2011a), who employed recycled aggregates from masonry-derived construction works, reported that a 28-days tensile splitting strength of 3.6 MPa could be achieved for 50% replacement of coarse aggregates. Moreover, their study concluded that replacements up to 60% allowed to meet the requirements established for paving blocks. Contrarily, Rodríguez et al. (2016), who also manufactured vibro-compressed conventional and recycled paving blocks, observed that only the recycled non-structural precast elements made with a 25% substitution exceeded the 3.6 MPa threshold established in EN 1338 (2003), whereas the conventional paving blocks presented an average splitting strength of 3.5 MPa at 28 days. The authors attributed this finding to the higher percentage of hydrated cement as a result of a greater water content. Nonetheless, it is worth mentioning that the conventional paving blocks exceeded the normative limit at long term (91, 180 and 360 days). However, the opposed results were reported for replacements between 50% and 100% as the recycled paving blocks presented reductions of strength ranging from 14.3% to 31.4% at 28 days of curing and in no case surpassed the strength threshold. For a complete substitution of the coarse natural aggregates by recycled crushed brick aggregates (P3 mixture), Jankovic et al. (2012) reported an average splitting tensile strength 3.2 MPa, which also did not fulfil the strength limit established.

In general, there is a lack of research works in the literature studying the replacement of solely the coarse natural aggregates by recycled aggregates, specifically if those exhibit a significant percentage of ceramic materials. However, several efforts have been made regarding the simultaneous substitution of both the fine and coarse natural aggregates by recycled ones. For instance, Poon et al. (2002) observed gains in transverse strength of paving blocks made with 50% replacement of both fine and coarse natural aggregates by recycled concrete aggregates compared to the control concrete ranging from 12.99% to 14.50% depending on the collection origin of the CDW. Moreover, Poon and Chan (2006) noticed that increasing percentages of brick materials in the recycled aggregates decreased the splitting tensile strength from a 17.2% for a 25% incorporation to a 56.6% for a 75% incorporation when a complete replacement of both fine and coarse aggregates was carried out. Nonetheless, later on, Poon and Chan (2007) reported that recycled concrete incorporating 10% of crushed tiles or 5% of crushed tiles plus 5% of bricks in the total of recycled aggregates resulted in a greater tensile splitting strength of paving blocks compared to those made with 100% recycled concrete aggregates. The authors attributed those results to an improved ITZ due to high water absorption of ceramic materials, which made possible a better penetration of the cement paste, and the increased amount of finer particles that fill voids and reduce the porosity as a consequence of the lower density of ceramic materials in the calculation of the mix design. In any case, the presence of glass or wood had a significant negative effect on the tensile splitting strength.

4.7. MICROSTRUCTURE

The SEM micrograph in Figure 7 shows the microstructure of the recycled concrete. Portlandite crystals were detected in the interfacial transition zone between the cement paste (on the left side of Figure 7) and recycled aggregate (on the right side of Figure 7). These crystals, which have a size higher than 10 μm in most cases, are similar to those reported in different types of concretes (Binici et al., 2009; Henocq et al., 2012; Lee and Yang, 2016; Poon et al., 2009; Rigo da Silva et al., 2002). Moreover, some calcium silicate hydrates formations (C-S-H) were also observed close to the CH crystals. The presence of these two solid phases of the hydrated cement paste, which are the principal cement hydration products in a conventional concrete (Hewlett, 2006; Malhotra and Mehta, 1996; Mindess et al., 2003), reveals that the replacement of coarse natural aggregate by RMAc does not result in a worse cement hydration when the necessary measures are taken (i.e. pre-saturation of the recycled aggregates).

Figure 8 shows the proper covering effect of cement paste around a ceramic recycled aggregate, which is sometimes hard to distinguish between these two concrete components. In Figure 9, the elemental aluminum and silicon maps of the recycled concrete at 28 days are showed. The aluminum is represented by the magenta color and the silicon is signified by the yellow color. Based on the distribution of those two elements, it is possible to identify the natural and recycled aggregates. Likewise, it is possible to observe that both kind of aggregates developed similarly adequate ITZ.

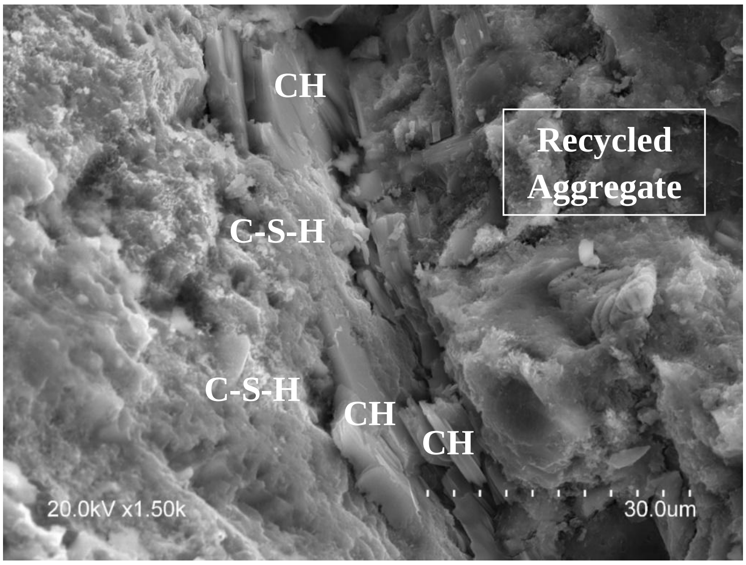

Figure 7: SEM image of the recycled concrete showing the cement hydration products

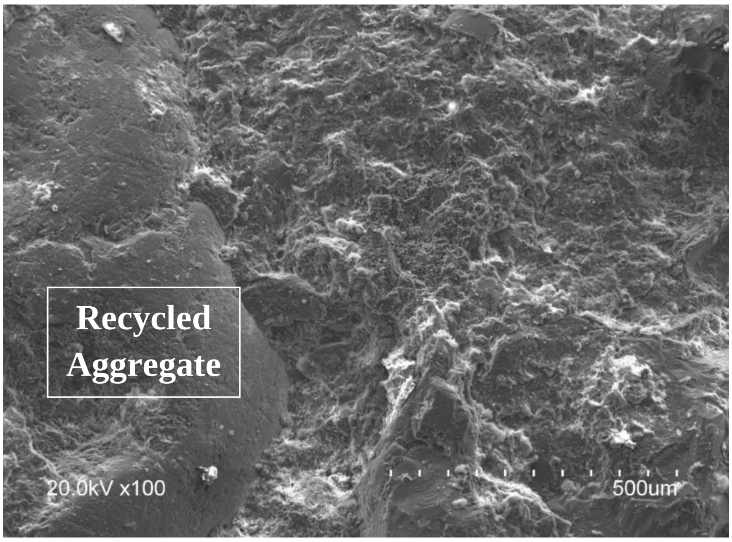

Figure 8: SEM image of the paste-recycled aggregate ITZ

Some authors (Poon et al., 2004b; Sidorova et al., 2014), who made recycled concrete replacing natural aggregates by recycled aggregates without this kind of water compensation, have claimed that the ITZ between recycled aggregates and cement paste is weaker than the bound developed with natural aggregates. The authors attributed this fact to the higher water absorption displayed by the recycled aggregates causing a worse cement hydration around the aggregate. However, in the SEM image illustrated in Figure 10, in which the position of recycled and natural aggregates can be defined by the EDX spectrums, the larger thickness of the ITZ between the recycled aggregate and the cement paste indicates an improved bond with the cement paste in comparison with the interface developed around the natural aggregate. This result was mainly due to the pre-saturation of RMAc before their addition to the concrete mix, which solved the water absorption drawback commonly reported when employing recycled aggregates. Despite the beneficial effect of the pre-saturation of the recycled aggregates in the microstructural development of concrete, the technique is also known for cause a certain decline in the mechanical of recycled concrete (Ferreira et al., 2011; García-González et al., 2014; Mefteh et al., 2013; Poon et al., 2004b), which can also be observed from the results in this investigation. Other studies (Zhang et al., 2015b) showed that the microstructure of the ITZ in cement materials with recycled aggregates was improved by the carbonation of these last ones.

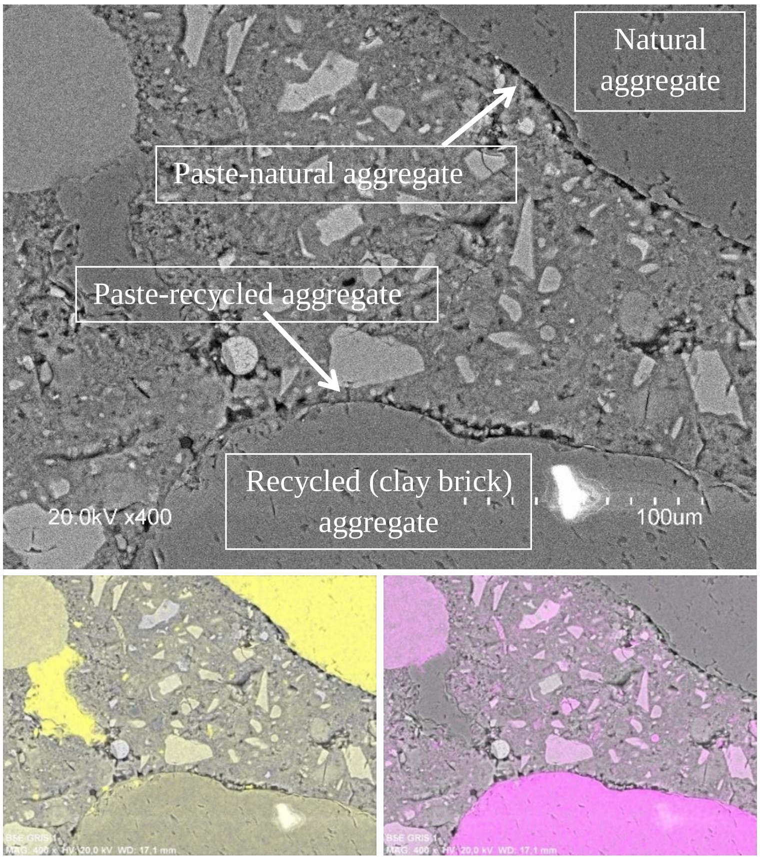

Figure 9: Silicon (yellow) and aluminium (magenta) elemental maps of recycled concrete

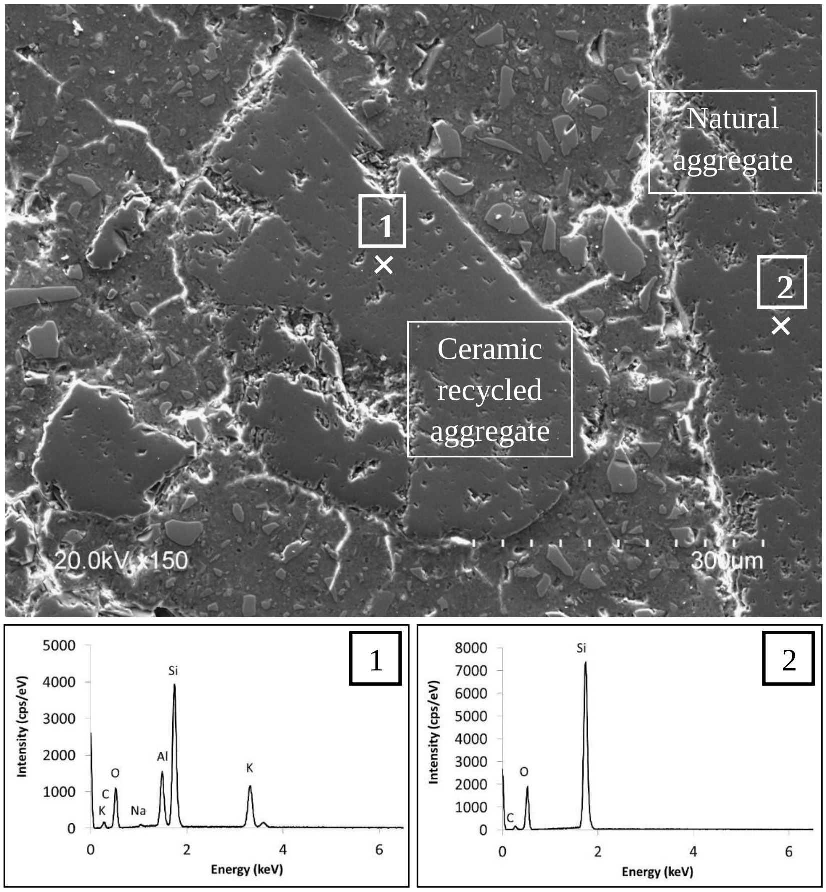

Figure 10: SEM image and EDX spectrums of the recycled concrete

4.8. POROSITY

Figure 11 shows the main pore diameter from the differential intrusion versus the pore size diameter curve of the conventional concrete and recycled concrete by MIP. The pore network on the size diameter range of 0.2 – 439 µm (maximum pore diameter detected) was decreased when recycled aggregates were added and pre-saturation technique was employed. As can be observed in Figure 11, the recycled concrete sample showed a small volume of pores greater than 2 µm. Therefore, the durability of the recycled concrete can be considered suitable, since lower amounts of pores with higher pore diameter are linked to improved effects on concrete durability (Gómez-Soberón, 2002; Kumar and Bhattacharjee, 2003).

Moreover, Cortas et al. (2014), who studied the effect of the aggregates saturation level (0%, 50% and 100%) on the properties of the resulting concrete, stated that the cumulative porosity and the volume of pores with diameters between 0.1 µm and 0.4 µm, i.e. mesoporosity,

Field Code Changed

Formatted: Spanish (Spain, Traditional Sort)

Formatted: Spanish (Spain, Traditional Sort)

Formatted: Spanish (Spain, Traditional Sort)

Field Code Changed

depended on the initial degree of saturation of the aggregates. Their studies concluded that a level of saturation of 50% resulted in the higher strength and the lowest mesoporosity values. Thus, those results support the use of pre-saturation technique followed in this research, which allowed the RMAc to be at a saturation level around 47.5%, linking the mesoporosity results achieved to the good performance of the recycled concrete.

In the recycled concrete sample, the greatest intrusion volume was detected around 0.1 µm, where exceeded significantly the pore volume of conventional concrete sample. However, several studies (Gómez-Soberón, 2002; Kumar and Bhattacharjee, 2003) stated that quantity of pores of size lower than 0.1 µm exerts no important roles in concrete durability. The high amount of pores with 0.1 µm is in concordance with the results published by Moon and Moon (2002), who stated that the volume of pores between 2 µm and 0.05 µm tended to increase with the presence of attached mortar.

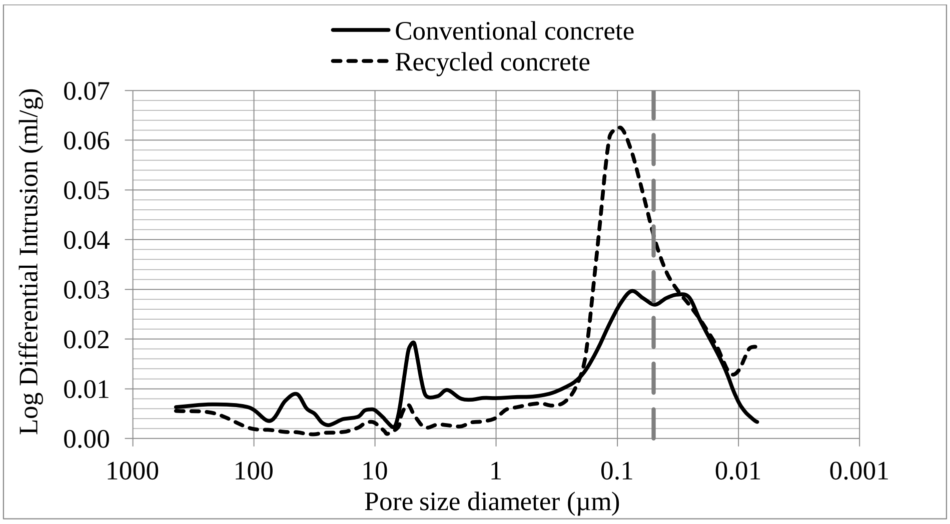

Figure 11: Pore size distribution of conventional and recycled concrete sample at 28 days.

Regarding the value of total porosity, a 12.37% was registered for the conventional concrete and a 12.44% for the recycled concrete, being a minimal variation, which was due to the pick of pores with 0.1 µm in recycled concrete, since the intrusion volume over 0.2 µm pore size was lower in recycled concrete than in conventional concrete, as explained above. Similar results of recycled concrete porosity were obtained by other authors (Buyle-Bodin and Hadjieva-Zaharieva, 2002; Kou et al., 2011) who tested analogous concretes, i.e. presenting w/c ratios ranging from 0.5 to 0.55. However, a slightly greater total porosity has been reported in other research works. For instance, Rübner and Kühne (2008) obtained total porosity values oscillating between 16.9% and 21.5% for recycled aggregate concrete with a 0.5 w/c ratio. Medina et al. (2012), who employed recycled sanitary ceramic aggregates at different replacement ratios -15%, 20% and 25%-, described recycled concretes with values of porosity of 15.98%, 16.21% and 16.38%, respectively. The work of Guo et al. (2013), who manufactured recycled concrete with 30% and 100% recycled concrete aggregates substitution, stated porosity values of 13 and 16%, respectively. Thus, taking into account all of the above, it can be stated that the relatively low porosity value obtained in this study would have a positive effect on durability and mechanical properties of manufactured concrete.

5. CONCLUSIONS

Paving blocks and kerbstones are used worldwide in large quantities for a great number of applications: pedestrian walkways, sidewalks and their boundaries, bicycle paths, service stations, bus lanes, port zones, parking zones… As such, the use of recycled mixed ceramic aggregates in their manufacture represents an interesting sustainable application of recycled concrete as could be the destination for the great volumes of construction and demolition wastes that are generated annually in the world. In view of the results obtained from this investigation is possible to drawn the following conclusions:

- The effect of the recycled mixed ceramic aggregates on the workability of the mixture was acceptable for mass concrete employed in the manufacture of kerbs and paving blocks since rather low consistencies are preferred in the precast industry.
- The 50% replacement of coarse natural aggregates by RMAc allowed a good superficial finish and a texture and colour comparable to the specimens industrially produced.
- The evolution of the compressive gain throughout a year of the recycled concrete was similar to those of conventional concretes. Whereas a characteristic compressive strength reached 29.70 MPa, the use of a 50% replacement ratio caused a 25.47% reduction of the compressive strength of the recycled concrete compared to the conventional mixture.
- Flexural strength was the property most severely affected by the 50% substitution of the coarse natural aggregates. While the conventional kerbstones were classified in Class 2 and displayed a T marking (> 5 MPa), recycled kerb units only fulfilled the requirements for Class 1 and S marking, which qualified then for lesser demanding applications such as use in pedestrian zones or areas with light traffic
- Both recycled and conventional paving blocks exceeded the normative requirements thresholds. In fact, both types of non-structural precast elements reached an average

splitting tensile strength of 3.9 MPa and approximately doubled the failure load per unit weight value.

- The SEM analysis revealed that the 3 minute pre-saturation of the recycled mixed ceramic aggregates effectively palliated the greater water absorption and thus a good cement hydration was achieved in the recycled paste. Moreover, an adequate covering effect of the cement paste around a ceramic recycled aggregate were observed and the thickness ITZ between recycled aggregate and cement paste indicated an improved bond compared to the interface developed around the natural aggregates.
- Due to the presence of attached mortar and ceramic materials, the main pore diameter of recycled concrete was around 0.1 µm. In addition, as consequence of the pre-saturation technique, the MIP study reported a small volume of pores greater than 2 µm with and a total porosity of 12.44%, which can be considered relatively low compared to that of other recycled concretes and could be linked to improved effects on concrete durability.

6. ACKNOWLEDGEMENTS

The authors would like to thanks the companies *Prefabricados de Hormigón Pavimentos Páramo S.L.* and *TEC-REC: Tecnología y Reciclado S.L.*, who disinterestedly participated in this study.

7. DECLARATION OF INTEREST

Funding: This work has been financially supported by the Spanish Ministry of Economy and Competitiveness through the research project grant BIA2013-48876-C3-3-R.

Conflict of Interest: None.

8. REFERENCES

Abbas, A., Fathifazl, G., Isgor, O.B., Razaqpur, A.G., Fournier, B., Foo, S., 2007. Proposed method for determining the residual mortar content of recycled concrete aggregates. J. ASTM Int. 5, 1-12. https://doi.org/10.1520/JAI101087

Binici, H., Arocena, J., Kapur, S., Aksogan, O., Kaplan, H., 2009. Microstructure of red brick dust and ground basaltic pumice blended cement mortars exposed to magnesium sulphate solutions. Can. J. Civ. Eng. 36, 1784–1793. doi:10.1139/L09-103

Field Code Changed

Formatted: English (United States)

Brandes, M.R., Kurama, Y.C., 2016. Use of Recycled Concrete Aggregates in Precast/Prestressed Concrete. Procedia Eng., ICSDEC 2016 – Integrating Data Science, Construction and Sustainability 145, 1338–1345. doi:10.1016/j.proeng.2016.04.172

Butler, L.J., West, J.S., Tighe, S.L., 2014. Towards the classification of recycled concrete aggregates: influence of fundamental aggregate properties on recycled concrete performance. J. Sustain. Cem. Based Mater. 3, 140-163. doi:10.1080/21650373.2014.909752

Buyle-Bodin, F., Hadjieva-Zaharieva, R., 2002. Influence of industrially produced recycled aggregates on flow properties of concrete. Mater. Struct. 35, 504–509. doi:10.1007/BF02483138

Cortas, R., Rozière, E., Staquet, S., Hamami, A., Loukili, A., Delplancke-Ogletree, M.-P., 2014. Effect of the water saturation of aggregates on the shrinkage induced cracking risk of concrete at early age. Cem. Concr. Compos. 50, 1–9. doi:10.1016/j.cemconcomp.2014.02.006

de Guzmán Báez, A. de, 2010. Study of the fundamental properties of prefabricated non-structural concrete elements incorporating recycled aggregate in their coarse and fine fraction [in Spanish] (masters). E.U. de Arquitectura Técnica (UPM).

EBC, 2015. Annual report 2014-2015 of the European Building Confederation. European Building Confederation, Brussels, Belgium.

EEA, 2008. Effectiveness of Environmental Taxes and Charges for Managing Sand, Gravel and Rock Extraction in Selected EU Countries. European Environment Agency, Copenhagen, Denmark.

EN 197-1, 2011. Cement. Part 1: Composition, specifications and conformity criteria for common cements. CEN.

EN 933-1, 2012. Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. CEN.

EN 933-3, 2012. Tests for geometrical properties of aggregates. Part 3: Determination of particle shape - Flakiness index. CEN.

EN 933-11, 2009. Tests for geometrical properties of aggregates - Part 11: Classification test for the constituents of coarse recycled aggregate. CEN.

EN 1097-2, 2010. Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation. CEN.

EN 1097-6, 2013. Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption. CEN.

EN 1338, 2003. Concrete paving blocks - Requirements and test methods. CEN.

EN 1338/AC, 2006. Concrete paving blocks - Requirements and test methods. CEN.

EN 1340, 2003. Concrete kerb units - Requirements and test methods. CEN.

EN 1340/AC, 2006. Concrete kerb units - Requirements and test methods. CEN.

EN 12350-1, 2009. Testing fresh concrete - Part 1: Sampling. CEN.

EN 12350-3, 2009. Testing fresh concrete - Part 3: Vebe test. CEN.

EN 12390-1, 2012. Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds. CEN.

EN 12390-2, 2009. Testing hardened concrete - Part 2: Making and curing specimens for strength tests. CEN.

EN 12390-3, 2009. Testing hardened concrete - Part 3: Compressive strength of test specimens. CEN.

EN 12390-3/AC, 2011. Testing hardened concrete - Part 3: Compressive strength of test specimens. CEN.

EN 12390-4, 2000. Testing hardened concrete - Part 4: Compressive strength - Specification for testing machines. CEN.

EN 12390-7, 2009. Testing hardened concrete - Part 7: Density of hardened concrete. CEN.

EN 12620+A1, 2008. Aggregates for concrete. CEN.

European Commission, 2014. Towards a circular economy: A zero waste programme for Europe (COM 398(2014)). European Commission, Brussels, Belgium.

Fernández-Canovas, M., 2013. Concrete [in Spanish]. Colegio de Ingenieros de Caminos, Canales y Puertos, Madrid, Spain.

Ferreira, L., de Brito, J., Barra, M., 2011. Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. Mag. Concr. Res. 63, 617–627. doi:10.1680/macr.2011.63.8.617

García-González, J., Rodríguez-Robles, D., Juan-Valdés, A., Morán-del Pozo, J.M., Guerra-Romero, M.I., 2014. Pre-saturation technique of the recycled aggregates: solution to the water absorption drawback in the recycled concrete manufacture. Materials 7, 6224–6236. doi:10.3390/ma7096224

García-González, J., 2016. Concrete with ceramic mixed construction and demolition waste: optimization of physical, mechanical and durability properties by aggregate pre-saturation, use of superplasticizers and microbially induced carbonate precipitation. PhD thesis. Ghent University. Belgium. http://hdl.handle.net/1854/LU-7238928. University of Leon. Spain. http://hdl.handle.net/10612/5761.

Gómez-Soberón, J.M.V., 2002. Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study. Cem. Concr. Res. 32, 1301–1311. doi:10.1016/S0008-8846(02)00795-0

Gonzalez-Corominas, A., Etxeberria, M., 2016. Effects of using recycled concrete aggregates on the shrinkage of high performance concrete. Constr. Build. Mater. 115, 32–41. doi:10.1016/j.conbuildmat.2016.04.031

Formatted: No underline, Font color: Auto, English (United Kingdom)

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Gonzalez-Corominas, A., Etxeberria, M., 2014. Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. Constr. Build. Mater. 68, 618–626. doi:10.1016/j.conbuildmat.2014.07.016

Güell-Ferré, A., Váquez-Ramonich, E., Varela-Pinto, E., Serna-Ros, P., Martínez-Abella, F., López-Gayarre, F., Barra-Bizinotto, M., Tirado-Alonso, A., Romero-Casado, A., Girbés-Clari, I., 2012. Spanish handbook on recycled aggregates from construction and demolition wastes (CDW) [in Spanish], Fueyo Editores. ed. Madrid, Spain.

Guo, Y., Qian, J., Wang, X., 2013. Pore Structure and Influence of Recycled Aggregate Concrete on Drying Shrinkage. Math. Probl. Eng. 2013, 1–7. doi:10.1155/2013/912412

Henocq, P., Samson, E., Marchand, J., 2012. Portlandite content and ionic transport properties of hydrated C3S pastes. Cem. Concr. Res. 42, 321–326. doi:10.1016/j.cemconres.2011.10.001

Hewlett, P. (Ed.), 2006. Lea’s chemistry of cement and concrete. Elsevier Ltd.

Jankovic, K., Nikolic, D., Bojovic, D., 2012. Concrete paving blocks and flags made with crushed brick as aggregate. Constr. Build. Mater. 28, 659–663. doi:10.1016/j.conbuildmat.2011.10.036

Khayat, K., 1999. Workability, testing, and performance of self-consolidating concrete. ACI Mater. J. 96, 346–353.

Kou, S.C., Poon, C.S., Etxeberria, M., 2011. Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. Cem. Concr. Compos. 33, 286–291. doi:10.1016/j.cemconcomp.2010.10.003

Kumar, R., Bhattacharjee, B., 2003. Porosity, pore size distribution and in situ strength of concrete. Cem. Concr. Res. 33, 155–164. doi:10.1016/S0008-8846(02)00942-0

Lavat, A.E., Trezza, M.A., Poggi, M., 2009. Characterization of ceramic roof tile wastes as pozzolanic admixture. Waste Manag., First international conference on environmental management, engineering, planning and economics 29, 1666–1674. doi:10.1016/j.wasman.2008.10.019

Lee, K.-H., Yang, K.-H., 2016. Development of a neutral cementitious material to promote vegetation concrete. Constr. Build. Mater. 127, 442–449. doi:10.1016/j.conbuildmat.2016.10.032

López Gayarre, F., López-Colina, C., Serrano, M.A., López-Martínez, A., 2013. Manufacture of concrete kerbs and floor blocks with recycled aggregate from C&DW. Constr. Build. Mater. 40, 1193–1199. doi:10.1016/j.conbuildmat.2011.11.040

Malhotra, V.M., Mehta, P.K., 1996. Pozzolanic and Cementitious Materials. Taylor & Francis.

Mas, B., Cladera, A., Bestard, J., Muntaner, D., López, C.E., Piña, S., Prades, J., 2012a. Concrete with mixed recycled aggregates: Influence of the type of cement. Constr. Build. Mater. 34, 430–441. doi:10.1016/j.conbuildmat.2012.02.092

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: Spanish (Spain, International Sort)

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: Spanish (Spain, International Sort)

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Mas, B., Cladera, A., Olmo, T. del, Pitarch, F., 2012b. Influence of the amount of mixed recycled aggregates on the properties of concrete for non-structural use. Constr. Build. Mater. 27, 612–622. doi:10.1016/j.conbuildmat.2011.06.073

Medina, C., Frías, M., Sánchez de Rojas, M.I., 2012. Microstructure and properties of recycled concretes using ceramic sanitary ware industry waste as coarse aggregate. Constr. Build. Mater. 31, 112–118. doi:10.1016/j.conbuildmat.2011.12.075

Medina, C., Zhu, W., Howind, T., Frías, M., Sánchez de Rojas, M.I., 2015. Effect of the constituents (asphalt, clay materials, floating particles and fines) of construction and demolition waste on the properties of recycled concretes. Constr. Build. Mater. 79, 22–33. doi:10.1016/j.conbuildmat.2014.12.070

Medina, C., Zhu, W., Howind, T., Sánchez de Rojas, M.I., Frías, M., 2014. Influence of mixed recycled aggregate on the physical – mechanical properties of recycled concrete. J. Clean. Prod. 68, 216–225. doi:10.1016/j.jclepro.2014.01.002

Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L., Arabi, N., 2013. Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. J. Clean. Prod. 54, 282–288. doi:10.1016/j.jclepro.2013.05.009

Mindess, S., Young, J.F., Darwin, D., 2003. Concrete. Prentice Hall, New Jersey, USA.

Moon, D.J., Moon, H.Y., 2002. Effect of pore size distribution on the qualities of recycled aggregate concrete. KSCE J. Civ. Eng. 6, 289–295. doi:10.1007/BF02829151

Neville, A.M., 1995. Properties of concrete. Harlow, Essex : Longman.

Özalp, F., Yılmaz, H.D., Kara, M., Kaya, Ö., Şahin, A., 2016. Effects of recycled aggregates from construction and demolition wastes on mechanical and permeability properties of paving stone, kerb and concrete pipes. Constr. Build. Mater. 110, 17–23. doi:10.1016/j.conbuildmat.2016.01.030

Pacheco-Torgal, F., Jalali, S., 2010. Reusing ceramic wastes in concrete. Constr. Build. Mater. 24, 832–838. doi:10.1016/j.conbuildmat.2009.10.023

Permanent Commission on Concrete, 2008. Code on structural concrete (EHE-08) [in Spanish]. Spanish Ministry of Public Works, Madrid.

Poon, C.-S., Chan, D., 2007. Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates. Constr. Build. Mater. 21, 164–175. doi:10.1016/j.conbuildmat.2005.06.031

Poon, C.S., Chan, D., 2006a. Paving blocks made with recycled concrete aggregate and crushed clay brick. Constr. Build. Mater. 20, 569–577. doi:10.1016/j.conbuildmat.2005.01.044

Poon, C.S., Chan, D., 2006b. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Constr. Build. Mater. 20, 578–585. doi:10.1016/j.conbuildmat.2005.01.045

Poon, C.S., Kou, S.C., Lam, L., 2002. Use of recycled aggregates in molded concrete bricks and blocks. Constr. Build. Mater. 16, 281–289. doi:10.1016/S0950-0618(02)00019-3

Poon, C.S., Kou, S.C., Wan, H.W., Etxeberria, M., 2009. Properties of concrete blocks prepared with low grade recycled aggregates. Waste Manag. 29, 2369–2377. doi:10.1016/j.wasman.2009.02.018

Poon, C.S., Lam, C.S., 2008. The effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks. Cem. Concr. Compos. 30, 283–289. doi:10.1016/j.cemconcomp.2007.10.005

Poon, C.S., Shui, Z.H., Lam, L., 2004a. Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. Constr. Build. Mater. 18, 461–468. doi:10.1016/j.conbuildmat.2004.03.005

Poon, C.S., Shui, Z.H., Lam, L., Fok, H., Kou, S.C., 2004b. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cem. Concr. Res. 34, 31–36. doi:10.1016/S0008-8846(03)00186-8

Rigo da Silva, C.A., Pedrosa Reis, R.J., Soares Lameiras, F., Vasconcelos, W.L., 2002. Carbonation-Related Microstructural Changesin Long-Term Durability Concrete. Mater. Res. 5, 287–293. doi:10.1590/S1516-14392002000300012

Rodríguez, C., Parra, C., Casado, G., Miñano, I., Albaladejo, F., Benito, F., Sánchez, I., 2016. The incorporation of construction and demolition wastes as recycled mixed aggregates in non-structural concrete precast pieces. J. Clean. Prod. 127, 152–161. doi:10.1016/j.jclepro.2016.03.137

Rodríguez-Robles, D., García-González, J., Juan-Valdés, A., Morán-del Pozo, J.M., Guerra-Romero, M.I., 2015. Effect of mixed recycled aggregates on mechanical properties of recycled concrete. Mag. Concr. Res. 67, 247–256. doi:10.1680/macr.14.00217

Royal Decree 256, 2016. Cement Reception Instruction (RC-16) [In Spanish]. Ministry of Public Works, Madrid, Spain.

Rübner, K., Kühne, H.-C., 2008. Pore Structure of Concrete with Recycling Aggregates [in German]. Presented at the 33rd International Geological Congress, Oslo, Norway.

Sánchez de Rojas, M.I., Frías, M., Rodríguez, O., Rivera, J., 2014. Durability of Blended Cement Pastes Containing Ceramic Waste as a Pozzolanic Addition. J. Am. Ceram. Soc. 97, 1543–1551. doi:10.1111/jace.12882

Shaikh F.U.A. & Nguyen H.L., 2013. Properties of concrete containing recycled construction and demolition wastes as coarse aggregates. J Sustain Cement-Based Mater 2, 204-217. doi: 10.1080/21650373.2013.833861

Shi, C., Li, Y., Zhang, J., Li, W., Chong, L., Xie, Z., 2016. Performance enhancement of recycled concrete aggregate - A review. J. Clean. Prod. 112, 466-472. doi:10.1016/j.jclepro.2015.08.057

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: No underline, Font color: Auto, English (United Kingdom)

Sidorova, A., Vazquez-Ramonich, E., Barra-Bizinotto, M., Roa-Rovira, J.J., Jimenez-Pique, E., 2014. Study of the recycled aggregates nature's influence on the aggregate–cement paste interface and ITZ. Constr. Build. Mater. 68, 677–684. doi:10.1016/j.conbuildmat.2014.06.076

Soutsos, M.N., Tang, K., Millard, S.G., 2011a. Use of recycled demolition aggregate in precast products, phase II: Concrete paving blocks. Constr. Build. Mater. 25, 3131–3143. doi:10.1016/j.conbuildmat.2010.12.024

Soutsos, M.N., Tang, K., Millard, S.G., 2011b. Concrete building blocks made with recycled demolition aggregate. Constr. Build. Mater. 25, 726–735. doi:10.1016/j.conbuildmat.2010.07.014

Spanish Ministry of Environment, 2001. Resolution of 14 June, that approves the National National Plan of Construction and Demolition Waste 2001-2006 [in Spanish], BOE 166, 25305-25313.

Tam, V.W.Y., Tam, C.M., Le, K.N., 2007. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resour. Conserv. Recy. 50, 82-101. doi: 10.1016/j.resconrec.2006.05.012

UNE 80303-1, 2013. Cements with additional characteristics. Part 1: Sulphate resisting cements [in Spanish]. AENOR.

UNE 127340, 2006. Concrete kerb units. Requirements and test methods. National complement to the standard EN 1340 [in Spanish]. AENOR.

UNEP, 2014. Sand, rarer than one thinks. UNEP Global Environmental Alert Service.

Xiao, Z., Ling, T.C., Kou, S.C., Wang, Q., Poon, C.S., 2011. Use of wastes derived from earthquakes for the production of concrete masonry partition wall blocks. Waste Manag. 31, 1859–1866. doi:10.1016/j.wasman.2011.04.010

Yang, J., Du, Q., Bao, Y., 2011. Concrete with recycled concrete aggregate and crushed clay bricks. Constr. Build. Mater. 25, 1935–1945. doi:10.1016/j.conbuildmat.2010.11.063

Zhang, J., Shi, C., Li, Y., Pan, X., Poon, C.S., Xie, Z., 2015a. Performance enhancement of recycled concrete aggregates through carbonation. J. Mater. Civ. Eng. 27, 1-7. doi:10.1061/(ASCE)MT.1943-5533.0001296

Zhang, J., Shi, C., Li, Y., Pan, X., Poon, C.S., Xie, Z., 2015b. Influence of carbonated recycled concrete aggregate on properties of cement mortar. Constr. Build. Mater. 98, 1-7. doi: 10.1016/j.conbuildmat.2015.08.087

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: No underline, Font color: Auto, Spanish (Spain, International Sort)

Formatted: English (United States)

Field Code Changed

Formatted: No underline, Font color: Auto, English (United Kingdom)