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Utilisation of Ceramic Stoneware Tile Waste as Recycled Aggregate in Concrete

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Abstract: The construction industry has a significant environmental impact and concrete production is responsible for a large part of CO_2 emissions and energy consumption. This study focused on the reutilisation of a specific type of tiles ceramic waste (TCW), composed only of stoneware and porcelain stoneware tiles, hereafter referred to as ceramic stoneware (CS), as recycled aggregate in concrete. Natural limestone and CS aggregates (sand and gravel) were characterised (particle size distribution, water absorption, resistance to wear, density and X-ray diffraction analyses) and recycled aggregate concrete (RAC) was prepared by replacing 20, 50 and 100 vol.% of sand and gravel, separately. Concrete workability generally improved with CW addition, especially when replacing natural gravel. Although the compressive strengths of the concrete specimens prepared with recycled sand were slightly lower than those of the reference specimens, similar or better results were recorded with the recycled CS gravel. In consonance, the RAC developed with recycled gravel obtained lower water penetration depths than the reference concrete. No significant variation in tensile strength was observed when varying CS content (values within the 2.33–2.65 MPa range). The study contributes to sustainable construction practices and circular economy by promoting the valorisation and reutilisation of industrial waste and reducing the consumption of natural resources.

Keywords: circular economy; recycled aggregate concrete; ceramic waste aggregate; workability; mechanical properties

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1. Introduction

More than 35% of the CO_2 emissions and 40% of the energy consumed worldwide are associated with the construction industry [1], and concrete is the most widely used construction material [2]. It is estimated that 30,000 million tonnes of concrete are annually produced, which corresponds to 3% of the global energy demand and 8% of greenhouse gas (GHG) emissions [3]. Approximately 60–75% of concrete is composed of aggregates, which are usually natural and non-renewable materials [4]. According to Struble and Godfrey [5], replacing natural aggregates does not imply a significant reduction in the energy demand because, of the 0.893 MJ required to prepare 1 kg of conventional concrete (30 MPa after 28 curing days and 0.48 w/c ratio), only 0.056 MJ are attributed to aggregates (6.3%). Similarly, Samadi et al. [6] did not observe a significant reduction in GHG emissions when replacing up to 100% of natural sand with tiles ceramic waste (TCW) in mortars. This was also explained by the low energy required to crush aggregates (0.003 and 0.009 tonnes of CO_2 emitted per ton of ceramic waste (CW) and natural sand, respectively). However, apart from the involved energy, reusing industrial by-products in concrete minimises the consumption of natural resources and landfilling waste [7]. Furthermore, transport emissions may also be reduced if waste is close to the concrete production plant. In this regard, according to the Spanish Ceramic Tile Manufacturers' Association (ASCER), 94%

of ceramic tiles and intermediate products (special pieces, ceramic powder produced by atomisation, etc.) made in Spain in 2021 were produced in the province of Castellón (eastern Spain). The fact that 80% of the 137 registered Spanish companies were located in this area, where this study was conducted, makes reusing TCW in recycled aggregate concrete (RAC) a very interesting valorisation alternative.

Ceramic tiles production has significantly increased in recent years from the 8581 million m^2 globally manufactured in 2009 to the 16,093 million m^2 produced in 2020 [8]. In 2020, Spain was the largest ceramic tiles producer in the European Union, the second exporting country in the world (415 million m^2 exported, 81.4% of its national production), and the fifth manufacturing country worldwide. Although reusing TCW could significantly contribute to circular economy, reducing the consumption of natural resources and the visual impact when landfilled, according to the European Environment Agency (EEA) [9], most CW is simply landfilled or used in low-value applications, such as road sub-bases. Additionally, according to Article 30.8 of the Spanish Structural Code [10], only recycled aggregates from concrete can be used in structural concrete, replacing up to maximum 20 wt.% of natural coarse aggregates. Thus, the current regulation does not allow the replacement of natural sand with recycled aggregates in structural concrete. However, several studies on TCW use in RAC [11–14] reported similar or even better mechanical properties with contents significantly above this limit. In most of these studies, workability was reduced with increasing CW contents [12–14], which is attributed to higher water absorption (WA) of CW recycled aggregates.

The TCW used in the present study was an industrial by-product provided by a company located in Onda, the Castellón province of eastern Spain. It was composed of only stoneware and porcelain stoneware ceramic tiles (hereafter referred to as CS) and did not contain other types of construction waste, such as gypsum, concrete or cement. In previous studies, Mas et al. [15] and Pitarch et al. [16] explored the pozzolanic activity of this specific type of TCW, and observed that its chemical composition ((SiO_2 + Al_2O_3 + Fe_2O_3) > 70%) and amorphous content (60%) conferred it some pozzolanic activity, which became significant after longer curing periods. When finally divided, this CW partially reacted with the portlandite released during the hydration of Portland cement to generate compounds with cementitious properties. Therefore, when used as recycled aggregate, this pozzolanicity is expected to improve the interfacial transition zone between recycled CS aggregates and the binding matrix, enhancing the properties of RAC [17–19].

In short, the large volumes of TCW that arise from the current linear economic model are generally landfilled, and the structural code only considers the possibility of reusing small amounts (max. 20 wt.% of natural gravel and no sand) of concrete waste as recycled aggregate in structural concrete. Although previous studies have successfully proven that TCW can be used to partially replace natural aggregates in concrete, there is a wide variety of ceramic tiles, whose properties (WA, hardness, chemical and mineralogical composition, etc.) markedly depend on their manufacturing process. As the properties of RAC very much depend on the characteristics of the employed CW, this research aimed to explore the use of CS, an industrial by-product only composed of stoneware and porcelain stoneware tiles, as recycled aggregate in concrete. This TCW is homogeneous, free of impurities, with low water absorption and high mechanical strength and hardness. Therefore, it is expected to provide a good performance when used as recycled aggregate in concrete. The provided information may significantly contribute to a circular economy by promoting the reutilisation and valorisation of industrial CW generated in large quantities.

2. Materials and Methods

This research work was divided into three main stages: aggregates characterisation; concrete design and samples preparation; and developed concrete characterisation.

2.1. Aggregates Characterisation

The natural calcareous and recycled CS aggregates were characterised by particle size distribution (UNE 933-1:2012, [20]), WA (WA, UNE 1097-6:2014, [21]), resistance to wear, density (UNE 1097-6:2014, [21]) and X-ray diffraction (XRD) analyses. Wear resistance tests were conducted in a Micro-Deval testing machine by adapting the processes from standards UNE 1097-1:2011 for coarse aggregates (500 g of material; 5 kg of stainless steel balls; 2.5 kg of water and 12,000 revolutions at 100 ± 5 rpm) and UNE 146404:2018 for fine aggregates (500 g material; 2.5 kg of stainless steel balls; 2.5 kg of water and 1500 revolutions at 100 ± 5 rpm). To determine the mineralogical composition by XRD, the particle size of aggregates was reduced by crushing and milling, as described in [16], up to a mean diameter of approximately 20 microns. XRD tests were performed within the 5–70 2θ degrees range, with Cu Kα radiation at 20 mA and 40 kV in a Brucker AXS D4 Endeavor diffractometer.

Figure 1 shows the aggregates used in the present study: natural fine (NFA), natural coarse (NCA), ceramic stoneware fine (CSFA), and ceramic stoneware coarse (CSCA) aggregates. The particle size of gravel ranged from 4 to 12 mm, and sand particles were smaller than 4 mm.

(a) (b)

Figure 1. Aggregates used in the study: (**a**) natural limestone; (**b**) recycled CS.

Table 1 summarises the physico-mechanical properties of the natural and recycled aggregates. The recycled CS particles were lighter than the natural ones, and sand was slightly denser than gravel. These differences were considered when designing the concrete mixes, and the substitution percentages were established as volume (vol.%) rather than as weight. The WA of sand was greater than that of gravel, which was attributed to the smaller particle size, which implies a bigger specific surface area. The CS absorption results fell in line with those previously reported by Medina et al. [22] for different types of ceramic tiles used as recycled aggregates in concrete, whose WA values ranged from 1.4 to 11.6% and 2.0 to 17.2% for coarse and fine aggregates, respectively. The authors in [20] attributed this broad amplitude to variations in tile production processes. The results recorded for CS particles are also similar to those reported by Silva et al. [23], who found a strong influence of both sintering temperature and tile thickness on the bulk density and WA of ceramic tiles. The authors in [23] reported the highest WA values (over 3%) when sintering at 1180 °C, while the absorption of the tiles sintered at 1200 °C and 1220 °C was lower than 0.5%. The results of the present study corroborate that the used CW was a mixture of ceramic tiles with low or medium-low WA (as defined in ISO 13006 [24] and UNE-EN 14411 [25] specifications), which, according to the Ceramic Tiles Guide of the Generalitat Valenciana [26], generally corresponds to stoneware and porcelain stoneware tiles.

The CS aggregates exhibited significantly greater wear resistance than the natural limestone particles, which was evidenced by the lesser loss of mass recorded after the Micro-Deval tests (3.76% and 17.20% for the coarse and fine CS versus 24.05% and 28.75% for natural gravel and sand, respectively). Figure 2 shows the particle size distribution of the natural and recycled aggregates. The CS and calcareous gravel had similar particle sizes, and the recycled gravel was slightly coarser than the natural one. On the contrary, the recycled sand was significantly coarser and less uniform than natural sand. This falls in line with the wear resistance results reported in Table 1, since the greater hardness of the CS particles compared to the natural ones implies using larger amounts of energy to reach a similar particle size, and this is counterproductive from environmental and economic perspectives.

Table 1. Physico-mechanical properties of aggregates.

	Coarse Aggregates (4/12)		Fine Aggregates (0/4)	
	Natural (NCA)	**Recycled (CSCA)**	**Natural (NFA)**	**Recycled (CSFA)**
Particle apparent density (kg/m^3)	2771.2	2373.7	2843.0	2423.3
Water absorption, WA (wt.%)	1.60	1.76	3.43	2.49
Wear resistance (wt.%)	24.05	3.76	28.75	17.20

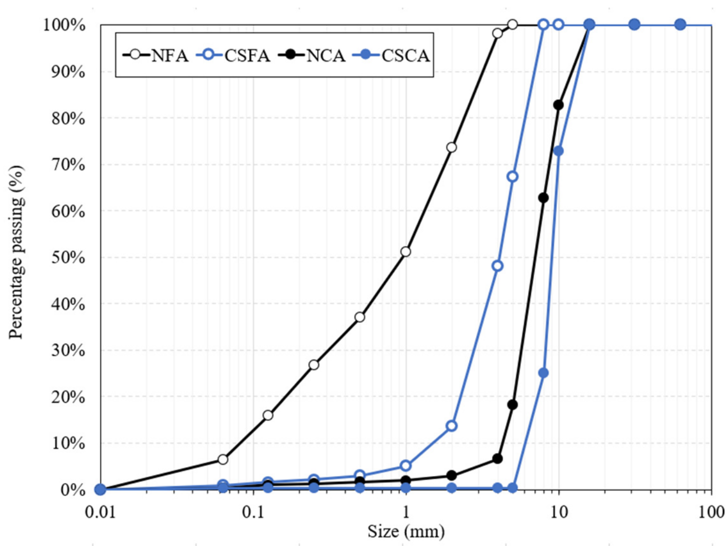


Figure 2. Particle size distribution of the natural and CS aggregates.

The X-ray diffractograms of the CS and natural limestone particles are plotted in Figure 3. For a given material, the same phases were identified in gravel and sand. Calcite (C, $CaCO_3$, PDFcard 83-578) and dolomite (D, $CaMg(CO_3)_2$, PDFcard 75-1760) were the crystalline phases identified in the natural aggregates, while quartz (Q, SiO_2, PDFcard 46-1045), the sodium feldspar albite (A, $NaAlSi_3O_8$, PDFcard 9-466) and mullite (M, $Al_6Si_2O_{13}$, PDFcard 79-1455) were distinguished in the CS particles. The CS diffractogram deviates from the baseline from 15 to 30 2θ degrees, which denotes the presence of amorphous compounds. This falls in line with the previous research by Zanelli et al. [27], who observed the formation of amorphous phases in stoneware tiles from approximately 1050 °C. Microstructural studies in porcelain stoneware tiles have also observed crystalline phases embedded in substantial amounts of amorphous phases [28].

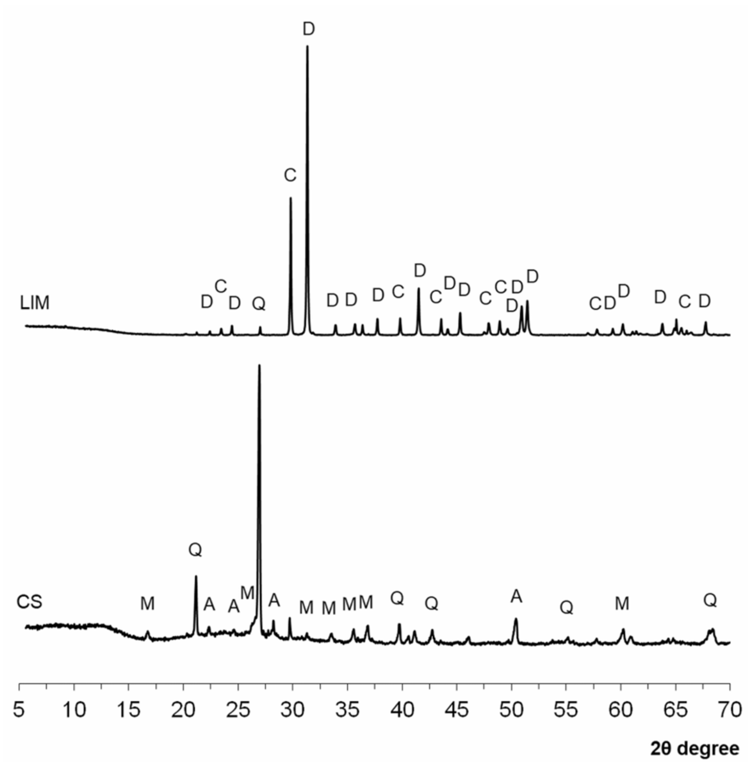


Figure 3. X-ray spectra of the CS and limestone aggregates. C: Limestone ($CaCO_3$); D: dolomite ($CaMg(CO_3)_2$; Q: quartz (SiO_2); M: mullite ($Al_6Si_2O_{13}$); A: albite ($NaAlSi_3O_8$).

2.2. Concrete Design and Sample Preparation

The components and proportions of the different developed concrete mixes are summarised in Table 2. A constant effective water-to-cement ratio of 0.44 was used in all the mixes. This value is often used to guarantee the strength and durability of concrete in common applications. The total amount of water was corrected for each mixture, depending on the WA of aggregates (Table 1) and their moisture content (relative humidity, RH: 1.9%, 0.4%, 1.3% and 0.2% for the NFA, NCA, CSFA and CSCA aggregates, respectively). Aggregates were pre-soaked with a partial amount of the corresponding water to achieve their saturation and to avoid the absorption of the water required to hydrate Portland cement. Given the density differences between the natural and recycled particles (Table 1), the substitution percentages were established as volume (vol.%) rather than as weight (the same volume of particles). The designation of the RAC samples was established according to the type of aggregate used and its substitution percentage. Thus, CSFA20 refers to a RAC in which 20 vol.% of natural sand was replaced with the same volume of recycled CSFA. A reference mix (Ref.), containing only natural calcareous aggregates, was also prepared for comparison purposes. A constant amount of a polycarboxylate-based superplasticiser (MC-Powerflow 3200 from MC-Bauchemie) was used in all the prepared mixes to enhance their workability. The CEM II/B-L 32.5N cement employed in the study was supplied by Élite Cementos S.L., a company located in Castellón (Spain). Its lower clinker content compared to CEM I, as defined in Standard UNE-EN 197-1 [29], increases the sustainability of the developed concrete.

Concrete samples were prepared in a pan concrete mixer. Forty-two cubes of 100 mm side (6 per mix) were developed for compressive strength tests (three tests per curing age, 7 and 28 days), and the same amount of cylindrical specimens (100 mm diameter and 300 mm height) was produced to evaluate tensile strength evolution and resistance to water penetration (three samples per test, cured for 28 days). After casting concrete into the corresponding moulds, they were covered with plastic sheets for 24 h to prevent water evaporation. Then, samples were demoulded and placed inside a curing chamber with controlled temperature and humidity (20 °C and 100% RH) until the testing age.

Table 2. Concrete mix proportions.

ID	Cement (kg)	Fine Aggregates		Coarse Aggregates		Water			Super-Plasticiser (kg)
		NFA (kg) Natural	CSFA (kg) Recycled	NCA (kg) Natural	CSCA (kg) Recycled	Effective Water (L)	Ratio w/c	Total Water (L)	
Ref.		651	-	1082	-			207.7	
CSFA20		520.8	110.9	1082	-			207.1	
CSFA50		325.5	277.3	1082	-			206.2	
CSFA100	425	-	554.6	1082	-	185	0.44	204.6	2.89
CSCA20		651	-	565.6	184.3			208.1	
CSCA50		651	-	541.0	460.9			208.6	
CSCA100		651	-	-	921.7			209.5	

2.3. Fresh and Hardened Concrete Characterisation

The workability of the different developed mixes was assessed by the Abrams cone test according to UNE-EN 12350-2 [30] (Figure 4a,b). To determine the evolution of consistency, this test was conducted 10 and 30 min after the mixing process began.

(**a**) (**b**)

Figure 4. Abrams cone slump test: (**a**) before lifting the mould; (**b**) consistency measurement.

Compressive strength was determined in the samples cured for 7 and 28 days according to UNE-EN 12390-3 [31] in a hydraulic press with a maximum capacity of 1500 kN at 6 KN/s until failure. The same equipment was used to evaluate the tensile strength of concrete by means of indirect splitting tensile tests (Figure 5), which were performed according to UNE-EN 12390-6 [32] on cylindrical specimens cured for 28 days (100 mm diameter and 300 mm height). For every test, three specimens were evaluated per concrete mix and curing age, and the mean compressive and tensile strength values, together with the corresponding standard deviations, were calculated.

Water penetration tests were run to assess the durability of concrete mixes. They were conducted according to UNE-EN 12390-8 [33] by applying pressurised water at 500 kPa for 72 h to the lower surface of the hardened concrete (Figure 6a). Samples were then divided into two halves by indirect tensile stress, and the maximum and mean water penetration depths were measured (Figure 6b) following the procedure described in Annexe A of the standard.

Figure 5. Splitting tensile strength test.

(**a**) (**b**)

Figure 6. Water penetration test: (**a**) application of pressurised water; (**b**) penetration depth measurement.

3. Results and Discussion

3.1. Fresh Concrete Workability

The workability of the different developed concrete mixtures, as determined by the Abrams cone test, is presented in Figure 7. The slump values obtained immediately after mixing concrete (10 min) varied between 9 and 23 cm and, after 30 min varied between 7 and 17 cm, which denotes loss of workability with time. The slump values determined immediately after mixing concrete (10 min) generally diminished with increasing recycled sand (CSFA) contents and progressively rose with increasing amounts of recycled gravel (CSCA, improved workability). This variation was attributed to the shape differences between the natural and recycled aggregates (rounder particles improve workability) and to the corrections of the total amount of water in the system (smaller in CSFA and larger in the CSCA concretes, Table 2), made to compensate for both WA and RH to maintain a constant w/c effective ratio. The humidity of the used aggregates affects workability, even if water is corrected to maintain a constant effective water content. In addition, the WA tests of sand have inherent difficulties to determine the amount of water required to have saturated aggregates with a dry surface. In any case, all the obtained values are feasible for construction applications.

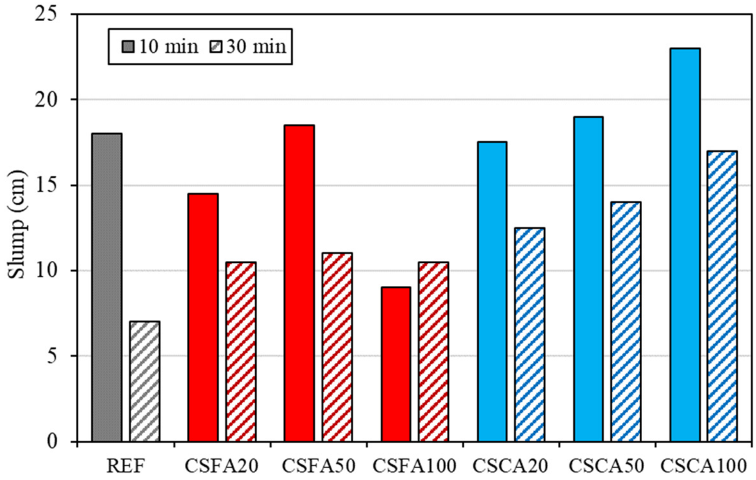


Figure 7. Workability of the different RACs developed with CS aggregates. Solid and striped bars indicate the results obtained 10 and 30 min after mixing, respectively.

It is remarkable that after 30 min, the workability of RACs was always better than that of the Ref. concrete (7 cm, soft consistency, as defined by the Spanish Structural code [10]). Although the slump recorded with increasing amounts of recycled sand was almost constant (close to 10 cm, fluid consistency), workability progressively improved with increasing amounts of the CS recycled gravel (up to 23 cm with 100 vol.% CSCA, liquid consistency). The improved workability of the RAC is attributed to the lower water absorption of the recycled sand compared with the NFA (Table 1), which implies lower loss of humidity over time. Most of the studies that have used CW as recycled aggregates in concrete have evaluated workability immediately after mixing, and generally report loss of workability with increasing CW contents [12–14], which was attributed to the higher WA values than the natural particles. More specifically, Rashid et al. [13], who replaced up to 30% natural gravel with TCW recycled aggregates (17.39% WA), observed a progressive reduction in the slump values with increasing amounts of CW. Similar findings have been reported by Goyal et al. [12] in RAC developed by replacing up to 25% of natural gravel with TCW aggregates (2.7% WA) because, to maintain constant workability, larger amounts of superplasticisers were required with rising CW contents. Sivakumar et al. [14] applied a constant w/c ratio of 0.55 in their study and replaced up to 50% natural sand and gravel (two series separately and one series simultaneously) with TCW fine and coarse aggregates (0.86% and 2.35% WA, respectively). Workability reduced in all the developed RACs, especially in those containing recycled sand, which was attributed to the porosity and WA of CW. The differences between the evolution of workability recorded with the CS aggregates used herein and results previously reported in the literature are attributed mainly to the relatively low WA values of the CS recycled particles, the correction of the total water applied, and the presaturation of aggregates before being mixed with Portland cement.

3.2. Compressive and Tensile Strength of the hardened Concrete

The compressive strength evolution with the curing age of the concrete samples developed with different amounts of recycled sand and gravel is summarised in Figure 8 (mean and standard deviation values). After seven curing days, compressive strength ranged between 24.7 and 32.2 MPa, and these values increased to 33.4–39.1 MPa after 28 curing days. The strength of the RACs prepared with the recycled CS sand was slightly lower than that presented by the reference concrete, and scarcely varied with the CSFA content, no matter what the curing age was. This slight strength reduction was attributed to loss of workability (Figure 7), together with the coarser and discontinuous particle distribution of CSFA (Figure 2). The high concentration of CSFA particles within the

1–5 mm range is expected to increase porosity because the voids left by larger particles cannot be progressively filled by smaller ones. On the contrary, the compressive strength results obtained by replacing natural gravel with CSCA progressively improved, and were similar to those presented by the reference concrete, or even better with complete substitution (CSCA100). As both natural and recycled gravels exhibited similar particle size distributions (Figure 2) and WA values (Table 1), enhanced strength was attributed not only to the greater hardness of the CSCA particles, but also to the improved workability with increasing substitution percentages.

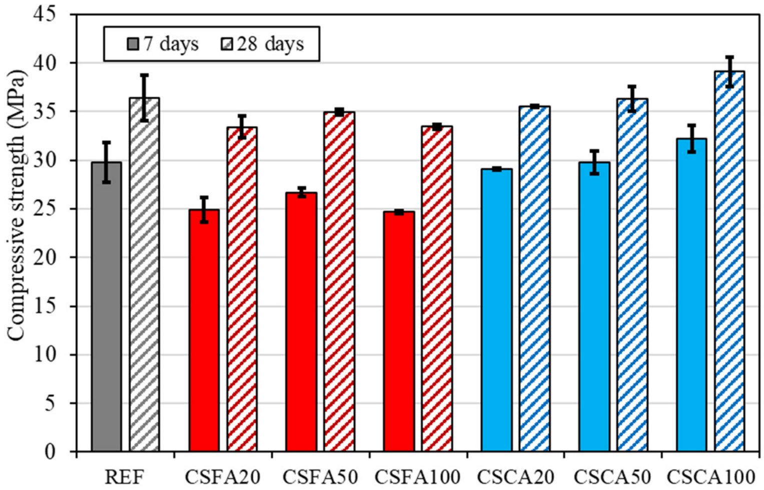


Figure 8. Compressive strength of the RACs developed with the CS aggregates (mean values and standard deviation). Solid and striped bars indicate the results obtained after 7 and 28 curing days, respectively.

The tensile strengths (f_{ct}) of the developed concrete samples ranged between 2.33 and 2.65 MPa (Figure 9). No significant variation was observed between the tensile strength of the reference concrete and those developed with the CS recycled aggregates, and differences were attributed mainly to the heterogeneous nature of concrete and the inherent dispersion of the results. Some surfaces of the CS aggregates were coated with glaze, which is distinguishable by a change in colour. Although this raised concerns about their adherence to the cement matrix, the obtained positive tensile strength results suggest that those surfaces did not degrade the adherence between aggregates and the binding matrix.

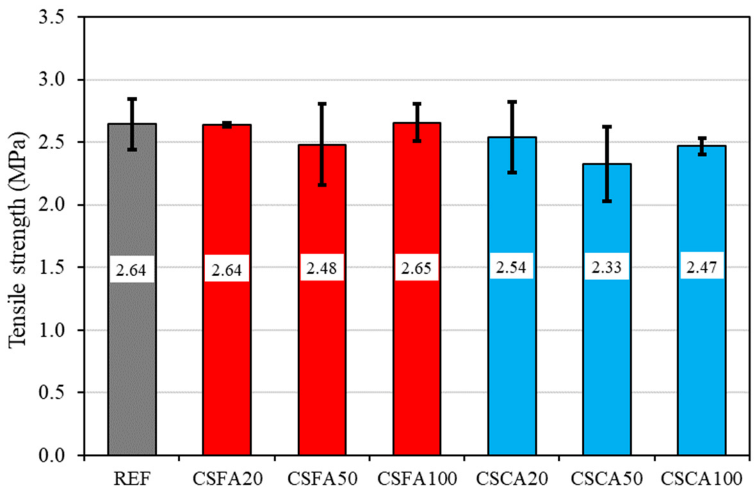


Figure 9. Tensile strength of the RACs developed with the CS aggregates (mean values and standard deviation).

The obtained strength results fall in line with the previous research works reported in the literature on using TCW as a recycled aggregate in concrete. Discrepancies are mainly attributed to the different characteristics of the employed CW, and also to variations when designing or mixing concrete [11–14]. Authors such as Bommisetty et al. [11] and Goyal et al. [12] replaced up to 25% natural gravel with TCW, and reported slightly better mechanical properties than the reference concrete for a given curing period. These authors reported optimum results with substitution percentages of 20% (35.55 MPa after 28 curing days) [11] and 15% (50 MPa after 28 curing days) [12]. Sivakumar et al. [14] replaced up to 50% of natural aggregates (coarse and fine) with TCW. Unlike our study, they did not observe any improvement in mechanical properties when using recycled TCW gravel, but reported better compressive strength values than the reference concrete in the mixes developed with 30% recycled sand and those prepared by replacing 20% natural aggregates with a combination of coarse and fine CW particles. In the study by Rashid et al. [13], the strength of the samples containing 20% and 30% TCW, cured for 28 days, improved by 20% compared to the reference concrete. The authors attributed this improvement to an enhancement in the interfacial transition zone between the recycled particles and the binding paste, and to a partial pozzolanic reaction of the TCW used in their study. This effect may also positively influence the long-term strength of the RAC concretes developed in the present study because, according to previous findings of Mas et al. [15] and Pitarch et al. [16], this particular type of TCW exhibits pozzolanic activity.

3.3. Water Penetration of the Hardened Concrete

The water penetration results are plotted in Figure 10. In line with compressive strength evolution, the maximum penetration depths generally rose when replacing natural sand with CSFA and were significantly reduced when using CSCA. All the concrete samples except CSFA100 could be used in any exposure class established in Table 27.1.a of the Spanish Structural Code because, according to the specifications established in Table 57.5.7 [10], maximum penetration depths were generally lower than 30 mm (no individual values over 40 mm) and medium penetration depths were generally lower than 20 mm (no individual value over 27 mm). CSFA100 could be used in any environment except the most aggressive ones, such as tidal zones (XS3) and soils with marked chemical aggressiveness (XA3). As previously explained (Section 3.1), the greater penetration depths recorded in the CSFA100 concrete were attributed to the larger size of these recycled particles and their lesser continuous particle size distribution (Figure 2) compared to natural sand.

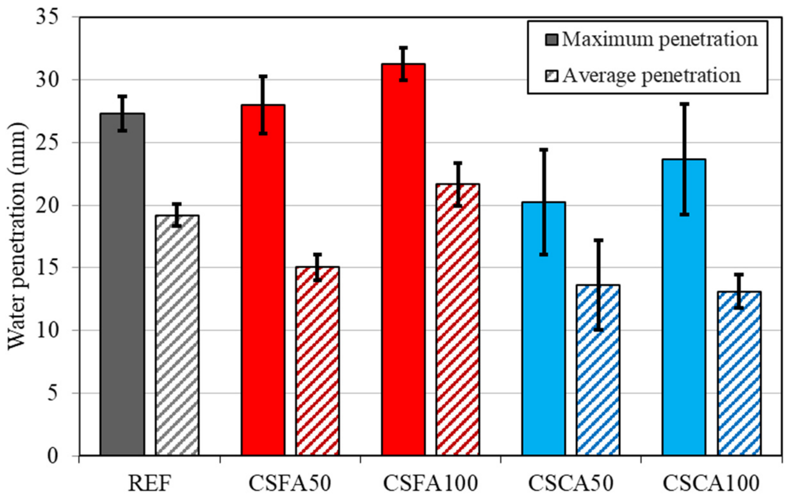
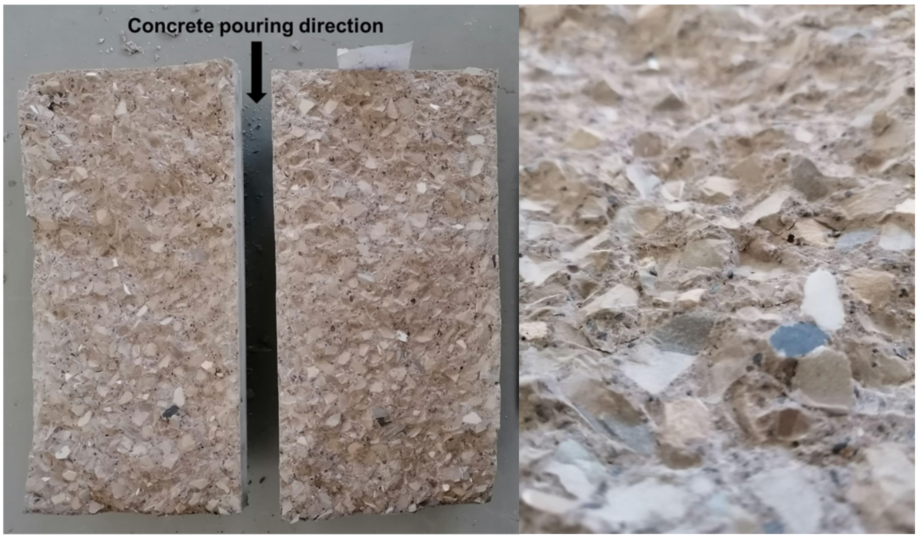


Figure 10. Water penetration depths of the developed concrete samples (mean values and standard deviation). Solid and striped bars indicate the average "maximum" and "average" penetration, respectively.

3.4. Visual Appearance of Aggregates Distribution

To assess the uniformity of aggregate distribution in the matrix and to identify any potential segregation of the CS aggregates, the fracture surface of the cylindrical specimens used for tensile strength testing was visually monitored and analysed by photographs. As observed in Figure 11a, which shows a section of the CSCA100 mix, no segregation occurred. The same appearance was observed in all the analysed specimens, which indicates that, despite density differences, all the developed RACs were satisfactorily homogeneous. A close-up detail of the CS coarse aggregates on the fracture surface appears in Figure 11b. Glaze coating may be observed in black or white, which indicates that several fractures originated in the interfacial transition zone between the glaze coating and the cementitious paste. Since fracture between aggregates and the cementitious matrix is the usual mode of failure in normal strength concrete and tensile strength values did not significantly vary in RAC (Figure 9), it can be concluded that the glaze coating had no negative effect.



(**a**) (**b**)

Figure 11. Fracture surface of the CSCA100 concrete: (**a**) compounds distribution; (**b**) close-up of the CS coarse aggregates.

4. Conclusions

In this study, CS waste was used to replace natural calcareous aggregates in structural concrete. Based on the obtained results, the following conclusions are drawn:

- The particle size distribution of the CS and natural gravel were similar. The greater hardness of the recycled CS aggregates led to a larger particle size and a more discontinuous distribution in the CS sand compared to natural sand.
- Workability generally improved in RACs, especially in those prepared by replacing natural gravel with CSCA.
- Strength results were comparable to those presented by conventional concrete. Compressive strength of CSFA concretes slightly reduced and was maintained or improved in those prepared with CSCA. The minor variations in the tensile strength values, no matter what the type (CSFA, CSCA) or CW content, were attributed to concrete heterogeneity.
- The water penetration depths of RACs generally reduced and, although they increased in the CSFA100 sample, this concrete could be used in any exposure class except the most aggressive environments.
- The workability, strength and water penetration of the CSFA concrete could be improved by further crushing these aggregates and correcting particle size distribution. However, the additional required energy would reduce sustainability.

– Future studies that simultaneously replace natural sand and gravel with the CS recycled particles would further improve the sustainability of the developed RACs.

This research proves that RACs with similar properties to traditional natural aggregates concrete can be developed by reusing CS recycled aggregates, especially if natural gravel is replaced. This valorisation route offers environmental benefits and contributes to a circular economy because it allows to reuse significant waste material and to reduce the amount of landfilled waste and the consumption of natural resources.

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List of Abbreviations

CS, ceramic stoneware; CSCA, ceramic stoneware coarse aggregates; CSFA, ceramic stoneware fine aggregates; CW, ceramic waste; GHG, greenhouse gas; NCA, natural coarse aggregates; NFA, natural fine aggregates; RAC, recycled aggregate concrete; TCW, tiles ceramic waste; Vol.%, percentage in volume; WA, water absorption.

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