Effect of tiles, bricks and ceramic sanitary-ware recycled aggregates on structural concrete properties

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Abstract

In this paper, tile ceramic waste (TCW)[1], red clay bricks (RCB) and ceramic sanitaryware (CSW) were used as the partial replacement (14-30 wt.%) of natural limestone aggregates to produce structural concrete. The natural and recycled aggregates were characterised, and the strength and density of the hardened concrete were investigated after 7 and 28 curing days at room temperature. The TCW concrete obtained the best compressive strength results (strength gain of up to 7% with 20 wt.% waste after 28 curing days). The mechanical properties of the CSW recycled concrete were similar to those of traditional samples, and slightly diminished with curing time and aggregate substitution, with a maximum strength loss of 5.77% for the 30 wt.% replacement. Although the RCB concrete presented the greatest strength loss (up to 18.4% after 7 curing days), it exhibited the best improvement of the strength with curing time, which resulted in a strength loss of only 11% in the 30 wt.% RCB concretes cured for 28 days. These results demonstrate the feasibility of using TCW and CSW as recycled aggregates in structural concrete production without significantly affecting the developed recycled concrete's compressive strength.

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[1]List of non common abbreviations used in this paper: TCW: Tile ceramic waste; RCB: Red clay bricks; CSW: Ceramic sanitaryware; EHE-08: Spanish Structural Concrete Code; SI: Shape Index; w/c: effective water to cement ratio; (w'/c): total water to cement ratio; SAI: Strength Activity Index; SG: Strength gain

1. Introduction

In recent years, concern about the environment has progressively increased. Thus it is important that the construction industry sector pays attention to this matter given the large amounts of waste it generates. According to the data provided by the Spanish Association of Recycling of Construction and Demolition Waste (RCDA) [1], it is estimated that 14,862,442 tonnes of construction and demolition waste (CDW) were produced in Spain in year 2015, which implies approximately 0.32 tonnes per inhabitant/year. CDW is selected and classified in recycling plants. As explained by the RCDA, the vast majority of the 74 recycling plants analysed in [2] followed these processes to produce recycled aggregates from CDW: admission control, classification and first separation (stone materials such as concrete, bricks or ceramics are separated from the non-stone ones, like wood, steel or plastics; this can be done manual or mechanically), grinding (reducing particle size, with separation of ferrous materials), cleaning (by air or water) and screening (separation of particles by particle size ranges). Recycling plants present a wide variation of processes, equipment and technical characteristics, which may vary from simple mobile crushing units to installations with different production lines and cleaning systems. This implies that a wide range of recycled aggregates, with different qualities, may be produced. The recycled aggregates to be used in structural concrete require a more intensive classification (to obtain a more homogeneous material), and cleaning (to reduce the content of non-stone materials and contaminants). According to the data reported in [3], although 80% of construction and demolition waste is composed of ceramic materials, e.g., bricks and concrete, only 17% is recycled and the remaining 83% is simply dumped. Ceramic waste is not only generated during building processes (54% of construction and demolition waste) [3], but is also produced by the ceramic industry. As previously reported in [4], the Spanish production of structural ceramics (bricks, etc.) reached a maximum of almost 30 million tons in 2006, which progressively diminished to the 7.7 million tons recorded in 2010. Similarly, 9,515 million m^2 of ceramic tiles were produced worldwide in 2010, of which 3.8% were manufactured by the Spanish industry, which ranked seventh in the list of manufacturers. According to the data provided by Stock [5], 420 million m^2 of tiles were produced in Spain in 2013, which respectively represents 34.6% and 3.5% of production in Europe and the world. As explained by Medina et al. [6], Spain was the world leader of ceramic sanitaryware production in 2008, e.g., washbowls, lavatory pans or bidets. Indeed 5-7% of the 7 million produced pieces were rejected for sale due to product requirements and technical considerations. As Halicka et al. [7] point out, the biodegradation period of ceramics is very long, possibly up to 4,000 years. This, together with

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the increased demand for environmentally responsible construction, means that it is necessary to seek alternatives to reuse and evaluate ceramic waste materials.

The scientific community, together with the ceramic industry, have done studies to reuse ceramic waste in cement and concrete production. Some of this research has been conducted by Pereira de Oliveira et al. [8] and Pacheco-Torgal and Jalali [9], who have analysed the use of ceramic materials as pozzolanic admixtures. Authors like Puertas et al. [10,11] have studied the suitability of red and white fired waste tiles to produce Portland cement clinker. Alternative binders have been developed by the alkali-activation of bricks or porcelain stoneware tiles in the studies by Reig et al. [4,12]. Ceramic materials have also been used as recycled aggregates in concrete production. As observed by Xiao et al [13] and Alves et al. [14], this alternative diminishes the amount of waste deposited in dumps or landfills, and reduces the amount of natural resources used. Additionally, no special processing is required as the applied concrete-producing technology is the same as that of natural aggregates. Although the Spanish Structural Concrete Code contemplates the use of recycled aggregates (EHE-08, Annexe 15) [15], it considers only those that originate from healthy or high-strength structural concrete, and recommends replacing maximum 20 wt.% of natural gravel.

Reusing ceramic materials as recycled aggregates in concrete is not a new research area in concrete technology. As summarised in (Table 1), many good references exist on using ceramic waste materials as an admixture or completely replacing fine or coarse fractions of traditional aggregates. As Kisku et al. [16] and Elchalakani and Elgaali [17] observed, the effect of recycled aggregates on strength depends mainly on the quality of the recycled material rather than on its quantity. This has been confirmed by the different results reported in the literature since. Some studies [14,18,19] have indicated that substituting natural aggregates for ceramic waste generally diminishes concrete compressive strength. Other works have reported that mechanical properties do not vary significantly with the use of ceramic waste aggregates [20,21], or even improve when waste is added [22-26]. Such variations in previously reported literature results suggest that in order to entirely embrace ceramic waste materials for their use as recycled aggregates in concrete production, it is necessary to fully understand the properties of the recycled concrete being developed.

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Table 1. Literature review on the use of recycled aggregates in concrete

Author and reference	Year	Waste	Replacement, %	
			Fine	Coarse
Zhou and Chen [26]	2017	Recycled concrete	-	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Suárez-González et al. [27]	2017	Ceramic pieces from ventilation conducts	0, 20, 35, 50, 70 and 100	
Faella et al. [28]	2016	Recycled concrete	0, 30, 60 and 100	
Hakan Elçi [29]	2016	Floor and wall tiles	100	100
Medina et al. [30]	2016	Sanitaryware	-	20 and 25
Etxeberria and Vegas [31]	2014	Construction and demolition and brick waste	0, 10, 20, 35 and 50	-
Alves et al. [14]	2014	Bricks and sanitaryware	0, 20, 50 and 100	-
Medina et al. [19]	2014	Construction and demolition waste	-	25 and 50
Tavakoli et al. [32]	2013	Ceramic tiles	0, 25, 50, 75 and 100	0, 10, 20, 30 and 40
Halicka et al. [7]	2013	Sanitaryware	100	100
Medina et al. [6,24]	2011 2012	Sanitaryware	-	15 to 25
Gonzalez-Corominas et al. [33]	2016	Precast concrete Construction and demolition waste	15 and 30	20, 50 and 100
Malesev et al. [23]	2010	Concrete	-	0, 50 and 100
Bezerra Cabral et al. [34]	2010	Construction and demolition waste	Up to 100	Up to 100
Torkittikul and Chaipanich [25]	2010	Ceramic earthenware	0, 10, 20, 30, 40, 50, and 100	-
Guerra et al. [35]	2009	Sanitaryware	-	3 to 9
Cachim [22]	2009	Brick	-	50 and 100
Ismail and Al Hashmi [20]	2009	Glass	10 to 20	-
Debieb and Kenai [36]	2008	Brick	0, 25, 50, 75 and 100	0, 25, 50, 75 and 100
Etxeberria et al. [37]	2007	Concrete	-	0, 25, 50 and 100
López et al. [38]	2007	Ceramic industry	10 to 50	-
Evangelista and de Brito [21]	2007	Concrete	0 to 100	-
Brito et al. [18]	2005	Clay bricks	-	Up to 100
Khatib [39]	2005	Brick	25 to 100	-
Limbachiya [40]	2004	Construction and demolition waste	-	0 to 100
Park et al. [41]	2004	Glass	0 to 70	-

This study analyses the properties and suitability of different ceramic waste materials (tiles, red clay brick and ceramic sanitaryware) as a recycled aggregate in structural concrete production. Although some of the above-discussed studies have been conducted on concrete with incorporated recycled ceramic aggregates, very few works maintain the workability of concrete, which renders directly comparing the obtained results inadvisable as different workability levels may not offer the same range of applications. Very few studies have simultaneously compared the use of various types of ceramic materials as recycled aggregates. Alves et al. [14] evaluated the effect of recycled bricks and sanitaryware as fine ceramic aggregates (replacement ratios of 0-100%) on concrete's mechanical properties. They concluded that the recycled concrete produced with crushed bricks exhibited adequate structural performance, but the concrete prepared with fine sanitaryware aggregates performed poorly compared to the reference concrete (RC). Pacheco-Torgal and Jalali [9] also used different types of ceramic wastes (bricks, stoneware tiles and sanitaryware) to partially replace cement with ceramic powder and natural aggregates with crushed ceramic. They concluded that both recycled concretes developed with 100% ceramic sand and those made replacing the natural granite gravel by coarse ceramic aggregates, presented higher compressive strength results than traditional concrete. However, it is unclear whether recycled sand or gravel was composed of a combination of the different ceramic materials used in the study or only one of them. This experimental programme intends to bridge these gaps by investigating the feasibility of incorporating ceramic tiles, bricks and sanitaryware as a partial substitute of natural aggregates into structural concrete production. The characteristics of natural and recycled aggregates, and the influence of the type and amount of ceramic waste on fresh and hardened concrete's properties, were analysed.

2. Material and Methods

2.1. Materials used

Natural limestone and three different types of ceramic waste materials were used as aggregates in the present study. The tile ceramic waste (TCW) was provided by ceramic tiles companies and contained different types of tiles, e.g., stoneware and porcelain stoneware tiles. The red clay brick (RCB) waste and ceramic sanitaryware (CSW) pieces, such as basins and lavatory pans, were taken from dumps filled with construction waste. Two different granulometric TCW fractions were supplied and were used as received. The RCB and CSW wastes were broken with a hammer and crushed in a jaw crusher BB200 (Retsch) to obtain a granular material. Crushed particles were sieved through 4 mm and 16

mm openings to prepare two different granulometric fractions for each waste material (0/4 and 4/16).

Three different granulometric fractions were used for the natural limestone aggregate (10/20, 4/11 and

0/4 mm). The morphology of the TCW, RCB and CSW coarse recycled aggregates (4/16) is shown in

Fig. 1. All the materials presented irregular particles with sharp edges. The CSW aggregates exhibited

the smoothest surface, whereas brick particles had a rough surface, which was attributed to their

greater porosity.

INSERT FIGURE 1

Portland cement type CEM II/A-V 42.5 R, which complied with European Standard UNE-EN 197-1,

was provided by the company Elite Cementos S.L. (Grao de Castellón, Spain). Tap water was used to

prepare and cure the developed concrete. A polymeric superplasticiser in an aqueous solution (SIKA

SKM230) was used in the prepared mixes.

2.2. Characterisation of aggregates

The test methods employed in this study to characterise the natural and recycled aggregates, together

with the applied standards, are summarised in (Table 2).

Table 2. The test methods and standards used to characterise the natural and recycled aggregates

Property	Test	Standard	Aggregates	
			Coarse	Fine
Particle size distribution	Sieve analysis	UNE-EN 933-1	X	X
Percentage of fines (<0.063 mm)	Sieve analysis	UNE-EN 933-1	X	X
Assessment of fines	Sand equivalent	UNE-EN 933-8	-	X
Specific weight	Pycnometer	UNE-EN 1097-7	-	X
Specific weight	Water displacement	UNE-EN 1097-6	X	-
Loose bulk density	Mass per Volume	UNE-EN 1097-3	X	X
Water absorption	Sand absorption cone	UNE-EN 1097-6	-	X
Water absorption	Water immersion	UNE-EN 1097-6	X	-
Resistance to wear	Micro-Deval	UNE-EN 1097-1*	X	-
		UNE 83-115-89**	-	X
Particle shape	Measure particle dimensions	UNE-EN 933-4	X	

* 500 g material, 5 kg stainless steel balls, 2.5 kg water, 12,000 revolutions at 100±5 rpm
** 500 g material, 2.5 kg stainless steel balls, 2.5 kg water, 1,500 revolutions at 100±5 rpm

The particle shape index (SI) indicates the percentage of particles with a length to thickness ratio higher than 3 (non-cubic particles). The material was sieved to determine the SI for granulometric fractions 4/8 and 8/16 mm. The average percentage of non-cubic particles was determined according to Equation 1:

[Equation 1]

where $V_{4/8}$ and $V_{8/16}$ were the percentages of particles of granulometric fractions 4/8 and 8/16 mm, respectively (per unit); $SI_{4/8}$ and $SI_{8/16}$ were the SI of granulometric fractions 4/8 and 8/16 mm, respectively.

The chemical composition of the recycled aggregates was determined by X-ray fluorescence (XRF) in a Philips Magix Pro spectrometer.

2.3. Composition of concrete mixes

The purpose of the study was to produce a concrete with a target mean strength of 30 MPa and an average workability of 50±10 mm, defined by the slump test. To investigate the influence of recycled aggregates on the properties of the fresh and hardened concretes, cement content (320 kg/m³), the effective water to cement ratio (w/c = 0.55) and the amount of superplasticiser (0.6% of cement weight) were constant in all the designed concretes, and only the type and amount of ceramic waste used to replace the natural aggregates varied. The prepared concretes complied with the requirements set out in 'Chapter 37.3. Durability of Concrete' of the Spanish Structural Concrete Code (EHE-08) [15], where a maximum w/c ratio of 0.55 and minimum 300 kg/m³ of cement are specified to ensure the durability of reinforced concrete to be used in normal environments with medium humidity (designed as IIb in Table 8.2.2 of EHE-08). A concrete with no ceramic waste (Reference Concrete, RC) was prepared for comparison purposes. The RC concrete combined three different granulometric fractions of the limestone aggregates (41.2% coarse, 14% medium, 44.8% fine). The natural coarse fraction was not replaced with recycled aggregates because it was not possible to prepare regular particles bigger than 10 mm due to the thickness of the ceramic aggregates used was less than 1 cm. Percentages of substitution of the natural for recycled aggregates of 14%, 20% and 30% were used (in weight). As reported in Table 3, the 14% substitution comprised the medium-sized limestone particles. Further replacements of the natural aggregates (20% and 30%) were selected to also investigate the partial substitution of natural sand.

To maintain the level of workability, the total water to cement ratio was adjusted in each concrete mix according to the amount of recycled aggregates and their water absorption. Water was added to the ceramic particles before being mixed with the binding paste. Although the total amount of water added to the system increased, the effective amount of water (that used in the hydration process of cement, defined in UNE EN 206-1 as the total amount, minus that absorbed by aggregates) was kept constant. The substitution percentages, together with the designation of the developed mixes, the total and effective w/c ratios (total one indicated in parentheses, (w'/c)) of the developed mixes, are summarised in Table 3.

Table 3. Concrete mix proportions

Aggregate Material	Substitution %	Designation	Cement kg/m³	Effective w/c	Total (w'/c)	Natural limestone kg/m³			Recycled ceramic kg/m³	
						10/20	4/11	0/4	4/16	0/4
Limestone	0	RC			0.60		288	927	0	0
Tile Ceramic waste	14	TCW14			0.68			927		0
	20	TCW20			0.70		0	871	288	56
	30	TCW30			0.74			779		148
Red Clay Brick	14	RCB14	320	0.55	0.76	852		927		0
	20	RCB20			0.82		0	871	288	56
	30	RCB30			0.92			779		148
Ceramic Sanitary-ware	14	CSW14			0.61			927		0
	20	CSW20			0.61		0	871	288	56
	30	CSW30			0.61			779		148

2.4. Preparation and characterisation of concrete

Concretes were mixed according to Standard BS 1881-125:2013. Fresh concrete workability was examined by the slump cone test in accordance with Standard UNE EN 12350-2. Samples were demoulded after being cured for 24 h and were placed in a temperature and humidity-controlled chamber at 20ºC and 98% relative humidity until the testing age was reached. The density and compressive strength of the concrete samples were determined after 7 and 28 curing days. Cylindrical samples (15 cm diameter, 30 cm height) were used to assess compressive strength, which was tested according to Standard UNE EN 12390-3 in an Ibertest MEH-3000 PT/W testing machine. The results are also presented in terms of the relative strength (RS) and strength gain (SG, %). The RS (%) is the

ratio between the strength of the recycled aggregate concrete and that of the RC, and the SG (%) compared to the RC was calculated according to [Equation 2].

[Equation 2]

where σ_{CW} is the compressive strength of the concrete that contained ceramic waste, and σ_{RC} is the compressive strength of the RC.

3. Results and Discussion

3.1. Aggregate properties

3.1.1 Chemical composition of ceramic aggregates

The chemical composition of the ceramic waste materials is presented in (Table 4). All the ceramic wastes presented high levels of SiO_2 and Al_2O_3, together with moderate amounts of CaO, Fe_2O_3 and K_2O. The CSW had the highest SiO_2 and Al_2O_3 contents (89.6 wt.%, the sum) and the smallest amounts of CaO (1.2 wt.%) and iron oxide (1.3 wt.%), whereas RCB contained the biggest quantities of these compounds (CaO, Fe_2O_3, MgO). High SiO_2 and Al_2O_3 contents (88%, the sum) have also been previously reported by Pacheco-Torgal and Jalali [9] for CSW waste, used both as pozzolan and to replace traditional aggregates in concrete production. Similarly, the chemical composition of the TCW came close to that previously recorded by Tavakoli et al. [32] for the ceramic tiles (68.85 SiO_2, 18.53% Al_2O_3 and 4.81% Fe_2O_3) used to replace coarse and fine aggregates in recycled concrete. Similar values have also been found by Puertas et al. [11] for red and white tiles (66.0% SiO_2, 14.2% Al_2O_3, 3.31% Fe_2O_3 and 6.1% CaO) used as alternative raw materials to produce Portland cement. However, slightly higher silica contents have been published by Hakan [29] for wall and floor tiles used as recycled aggregates in concrete production, where values came close to 70% SiO_2, 15% Al_2O_3, 2% Fe_2O_3 and 3.3% CaO.

Table 4. Chemical composition of the TCW

	wt.%		
	TCW	RCB	CSW
Al_2O_3	18.6	16.6	23.6
SiO_2	61.2	49.9	66.0
CaO	5.8	9.7	1.2
MgO	1.8	5.5	0.7
K_2O	3.3	4.4	2.9
Fe_2O_3	5.0	6.5	1.3
SO_3	0.09	3.3	0.07
LOI*	0.7	2.4	0.3
Other	3.5	1.7	4.0

* Determined at 1,000ºC

3.1.2. Particle size distribution of aggregates

The particle size distribution curves of the natural and recycled aggregates are plotted in (Fig. 2). The limestone aggregates presented the coarsest and finest particle size distributions, and the granulometric curves of the recycled aggregates fell in between. The TCW (0/4) presented a larger amount of particles < 1 mm compared with the fine fractions of the RCB and CSW recycled aggregates. The coarse CSW aggregates (4/16) had the highest percentage of particles bigger than 8 mm (≈44%). This percentage was 22% and 35% for the RCB and TCW coarse aggregates, respectively. Limestone, RCB and CSW gravel did not contain particles smaller than 2 mm, and only the TCW gravel presented particles within the 2-0.125 mm range.

INSERT FIGURE 2

The fineness grading modulus (FM), the percentage of fines and the quality of fine particles (sand equivalent test) determined for each material used as aggregate and granulometric fraction (D/d), are summarised in Table 5. These results complete and corroborate the particle size distribution curves. The coarse limestone aggregates obtained the highest FM values (7.92 and 6.89 for the 10/20 and 4/11 fractions, respectively). The CSW gravel, which contained the highest percentage of particles > 8 mm of all the recycled aggregates, presented an FM value of 6.38. On the contrary, an FM value of 5.95 was obtained for the recycled TCW gravel, which is attributed to its relatively large amount of particles below 2 mm. The smallest grading modulus obtained for the natural sand (3.64) corroborated

the smaller size of the 0/4 limestone particles. A close value was recorded for the TCW sand (3.76), which progressively increased up to the 4.04 FM value obtained for the RCB sand, the coarsest of all the fine aggregates.

The TCW gravel contained a considerable amount of fine particles (1.98% below 0.063 mm) compared with the other coarse aggregates used (0.01 to 0.03%). Similarly, the limestone sand presented a larger quantity of fine particles (6.50%) compared with the recycled sand (1.11% to 3.71%). All the values, except that presented by the TCW (4/16), complied with the specifications set by the Spanish Structural Code for Concrete (EHE-08) [15] for natural aggregates to be used in structural concrete (Table 28.4.1.a) as they were lower than 1.5% for gravel, 6% for non-limestone sand and 10% for limestone sand. The sand equivalent test results, all above 88 units, revealed that particles were clean and had a very low clay content. The obtained positive sand equivalent test results allow to use any of the studied aggregates in structural concrete placed under any environmental class related to the corrosion of reinforcements specified in Table 8.2.2 (general classes, e.g., non-aggressive, regular, marine or environments with chlorides) or the specific exposure classes defined in Table 8.2.3a (chemical, frost or erosion) of EHE-08 [15]. These results well agree with those previously reported by Debieb and Kenai for crushed brick used as a recycled aggregate in concrete [36], where a sand equivalent value of 84.02 was obtained for the ceramic aggregates.

Table 5. Particle size distribution parameters and the quality of fine particles

Property	Coarse Aggregate					Fine Aggregate			
	Natural (10/20)	Natural (4/11)	Recycled (4/16)			Natural (0/4)	Recycled (0/4)		
			TCW	RCB	CSW		TCW	RCB	CSW
FM	7.92	6.89	5.95	6.19	6.38	3.64	3.76	4.04	3.84
Percentage of fine particles, wt.%	0.01	0.02	1.98	0.03	0.02	6.50	3.71	1.11	2.28
Sand equivalent	-	-	-	-	-	89	88	90	98

3.1.3. Particle size distribution of the combined aggregates

The particle size distribution of the different compositions of aggregates, according to the mix proportions indicated in Table 3 (Section 2.3), is plotted in (Fig. 3). The FM is indicated in parentheses. The different compositions presented close granulometric distributions and FM values, which varied within a narrow range (5.73 to 5.84). This minimised the influence of particle size variations on the developed recycled concrete characteristics. The higher FM value of the RC was attributed to its higher percentage of particles larger than 4 mm and 8 mm.

INSERT FIGURE 3

3.1.4. Physico-mechanical properties of aggregates

The physico-mechanical properties of the natural and recycled aggregates are summarised in Table 6. The recycled ceramic aggregates presented close specific weight values, which ranged from 2,414 to 2,477 kg/m^3 for the fine particles, and from 2,280 to 2,350 kg/m^3 for the coarse fraction. These values were lower than those obtained for the natural limestone aggregates (2,790 and 2,780 kg/m^3 for sand and gravel, respectively), which denotes a greater porosity of the ceramic particles. Similarly, the natural aggregates obtained higher loose bulk density values (1,698 and 1,530 kg/m^3 for the fine and the coarse fractions, respectively) than those shown by ceramic particles, which ranged from 1,056 to 1,422 kg/m^3 for sand and from 966 to 1,265 kg/m^3 for gravel. As all the materials were irregularly shaped, which implies similar voids between particles, differences were attributed to the heavier specific weight of the natural particles. These results agree with the higher water absorption values generally obtained for the recycled aggregates compared with the natural particles. The water absorption results widely varied depending on the ceramic material, and ranged from 0.69-15.76% and from 1.83-18.31% for the recycled sand and gravel, respectively. The RCB recycled aggregates presented the highest water absorption values, whereas the results obtained for the CSW particles came close to those recorded for the natural limestone aggregates.

Our results are in line with previously reported literature data, where lower particle density and higher water absorption values have been recorded for other ceramic aggregates, such as crushed bricks [22,31,36], ceramic tiles [29] and sanitaryware [7,14,24], compared to those of the natural aggregates. More specifically, Debieb and Kenai [36] have reported specific weight values of 2,232 kg/m^3 and 2,496 kg/m^3 for gravel and sand obtained from crushed bricks, which were used to partially or totally

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replace limestone aggregates in concrete. Similarly to our obtained results, Alves et al. [14] have published higher loose bulk density values for sanitaryware sand (1,319 kg/m³) than for brick aggregates (1,032 kg/m³). The water absorption value obtained for the recycled brick gravel (18.31%) is also similar to the values previously reported by Cachim [22] for two different brick types (15.81% and 18.91%), which were used to replace 15% and 30% of natural coarse aggregates. Our results also fall in line with those previously obtained by Etxeberria and Vegas [31] for fine brick waste (14.72%), which was used to replace limestone sand. Slightly lower water absorption values have been reported by Alves et al. [14] for brick (12.2%) and sanitaryware (0.2%) aggregates used to replace natural sand. The CSW water absorption values obtained in our study came close to those previously reported by Halicka et al. [7] for CSW (1.53%), which was used as the only concrete aggregate to replace natural sand and gravel. Slightly lower values were obtained in other studies [24,30] for CSW aggregates with a maximum particle size of 12.5 mm (0.55%).

The ceramic aggregates used herein presented relatively high water absorption values compared with different traditional natural aggregates, such as granite, basalt, quartz (absorption values within the 0.1-0.5% range) or limestone (0.3-1.5%) [7]. The limestone and CSW aggregates comply with the maximum water absorption value set by the Spanish Structural Concrete Code for natural aggregates to be used in structural concrete (5 wt.%, as defined in Chapter 6, Section 28.6, EHE-08) [15]. According to the Spanish Standard (Annexe 15, Section 28.6.1, EHE-08) [15], recycled aggregates that present up to 7 wt.% water absorption can be used to replace a maximum of 20 wt.% of natural coarse aggregates, provided that the water absorption of natural aggregates is below 4.5 wt.%. When recycled particles are used to substitute more than 20 wt.% of natural gravel, the water absorption of the mixed aggregate (natural and recycled) should not exceed 5 wt.%.

As described in Section 2.2, resistance to wear tests were run following different standards for coarse and fine aggregates. A larger number of both revolutions and mass of stainless steel balls was used for the coarse aggregates test. The CSW particles exhibited the lowest loss of mass after the Micro-Deval test (21.8% and 7.3% for the fine and the coarse particles, respectively), which denoted greater resistance to wear among the aggregates used herein. Similar resistance to wear values were recorded for the RCB, TCW and limestone sands (≈42%), whereas bigger differences were found among the coarse aggregates, with values ranging from 7.3% for the CSW recycled particles to 42.2% for the RCB waste. Our results for the CSW aggregates are consistent with those previously reported

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by Medina et al. [24], who also observed greater resistance to fragmentation for the CSW aggregates (determined by the 'Los Ángeles' test) compared with that presented by the natural particles.

Table 6.Physico-mechanical properties of natural and recycled aggregates

Property	Coarse Aggregates				Fine Aggregates			
	Natural (4/11)	Recycled (4/16)			Natural (0/4)	Recycled (0/4)		
		TCW	RCB	CSW		TCW	RCB	CSW
Specific weight, kg/m³	2,780	2,280	2,350	2,283	2,790	2,463	2,477	2,414
Loose bulk density, kg/m³	1,530	1,265	966	1,246	1,698	1,422	1,056	1,236
Water absorption, wt.%	0.25	8.93	18.31	1.83	0.43	6.28	15.76	0.69
Resistance to wear, wt.%	20.0	15.5	42.2	7.3	47.6	43.8	41.4	21.8

The particle Shape Index (SI) results, which indicate the percentage of particles with a length to thickness ratio above 3 (non-cubic particles), are presented in Table 7. As observed, the limestone and TCW aggregates exhibited regular shapes, and RCB and CSW contained more non-cubic particles. The SI of RCB was higher for the particles within the 8-16 mm range, which was attributed to the shape of the used bricks, that had walls between hollows. When broken by a hammer, pieces had the thickness of these walls, with different lengths and widths. On the contrary, higher SI values were obtained for the finer CSW fraction used in the test (4-8 mm), which was attributed to the laminar shape of the crushed particles. Similar results have been reported by Hakan [29] for wall and floor tiles used as recycled aggregates, with SI values that came close to 10% for particles with sizes ranging from 6.3-10 mm and from 10-14 mm. As reported in [29], the SI value considerably increased, up to 100%, for bigger ceramic tiles recycled aggregates (14-20 mm). This agrees with the criteria considered in the present study, according to which the coarse fraction of the natural aggregates (10/20) was not replaced with ceramic particles because of their flat elongated shape. SI values of 30% and 16% have been reported by Cachim [22] for two different types of recycled brick aggregates, both with a maximum particle size of 8 mm, which they used to replace the fine fraction of natural coarse aggregates. The results obtained for the CSW particles also fall in line with those previously observed by Medina et al. [24], who obtained a flakiness index of 23% (percentage by weight of particles whose thickness is less than 0.6 times its mean dimension, evaluated according to UNE EN

933-3) for CSW recycled aggregates with a maximum particle size of 12.5 mm, used to replace natural gravel.

Table 7. Particle shape index (SI) of natural and recycled aggregates

Aggregate Material	Granulometric fraction	Volume %	SI %	SI %
Limestone	(4/8)	48.3	10	9
	(8/16)	51.7	9	
TCW	(4/8)	46.6	9	9
	(8/16)	53.4	9	
RCB	(4/8)	42.4	13	25
	(8/16)	57.6	34	
CSW	(4/8)	47.2	35	29
	(8/16)	52.8	24	

3.2. Workability of fresh concrete

The slump cone test results of the developed concrete mixes are presented in Table 8. Values varied from 3 cm to 5 cm for all the developed mixes which, according to Section 31.5 of the Spanish Structural Concrete Code [15], corresponds to a plastic consistency. The narrow variation of the workability results confirmed that the adopted mixing procedure was appropriate and indicated that the water used during the mixing process was that required for the hydration reactions of cement. Thus no excess water was added to the system, which would have led to greater porosity and the consequent loss of mechanical properties.

The RC and those prepared with up to 20 wt.% waste maintained a 5.0 cm slump cone test value (except for TCW20, whose workability slightly diminished), which corresponds to an S2 classification according to Standard UNE EN 206-1. Larger amounts of ceramic waste (30 wt.%), which contained bigger quantities of recycled sand, slightly diminished concrete workability. The most significant reduction was presented by the TCW concrete, which was attributed mainly to the higher percentage of fine particles (< 0.063 mm) of this recycled aggregate (see Table 5). According to the high water absorption and SI values presented by the RCB waste, worse workability results were expected for the RCB concretes. However, the slump cone test results only diminished by 1 cm when using 30% RCB, which was attributed to the corrections of the total (w'/c) ratio depending on the water absorbed by

aggregates. The workability results previously reported in the literature for concrete developed with ceramic waste recycled aggregates vary depending on the concrete design, dose method and mixing process used. Recycled concretes with similar or slight variations in the slump test values have been developed in the studies by Alves et al. [14], Medina et al. [19], Cachim [22] or Debieb and Kenai [36], where the total amount of water was also modified according to that absorbed by aggregates. Conversely in other studies [25,32], the amount of water was kept constant no matter what the substitution percentage of natural for recycled aggregates was. Given the greater water absorption generally presented by ceramic recycled particles, the consistency of the recycled concretes developed in these studies generally reduced with increasing contents of recycled aggregates. More specifically, Torkittikul and Chaipanich [25] have observed that the consistency of a recycled concrete diminished by almost 50% when replacing half the amount of natural sand with ceramic waste recycled aggregates. The workability values further lowered, up to 0 cm (slump cone), when traditional sand was completely replaced. Tavakoli et al. [32] have also reported a slight reduction in the slump cone test values with increasing amounts of TCW recycled aggregates, which varied from 6.0 cm for the RC to 4.0 cm for the concretes that contained 100% recycled sand or 40% recycled gravel.

Table 8.Workability of fresh concrete

Concrete Mix	Slump cone test, cm
RC	5.0
TCW14	5.0
TCW20	4.0
TCW30	3.0
RCB14	5.0
RCB20	5.0
RCB30	4.0
CSW14	5.0
CSW20	5.0
CSW30	3.5

3.3. Density and compressive strength of hardened concrete

The density and compressive strength values of the developed concretes, cured for 7 and 28 days, are summarised in Table 9. The density results diminished with increasing ceramic waste contents, which was attributed to the lower density of the ceramic particles. Since substitution of natural

aggregates was done by weight, this implied a larger volume of recycled aggregates and, thus, of prepared concrete, for a given weight substitution. The results are consistent with those reported in previous studies into using different ceramic materials as recycled aggregates in concrete [14,32,36], where the hardened concrete density progressively diminished with increasing amounts of ceramic waste. More specifically, Tavakoli et al. [32] have reported lower density values when replacing up to 40% of natural gravel and up to 100% of natural sand with TCW. Alves et al. [14] have also observed a reduced density for hardened concrete with increasing amounts of brick and CSW aggregates, used to partially or totally replace the fine fraction of natural aggregates in structural concrete production. The density values published by Debieb and Kenai [36] lowered by as much as 17% in a crushed brick concrete compared with that produced with natural calcareous aggregates.

Table 9. Density and compressive strength of the hardened ceramic recycled aggregate concrete cured at 20ºC for 7 and 28 days

Concrete Mix	Density, kg/m^3	Compressive Strength, MPa	
		7 days	28 days
RC	2510 ± 2.85	31.51 ± 0.99	37.80 ± 1.79
TCW14	2472 ± 3.83	33.25 ± 0.61	38.51 ± 0.64
TCW20	2441 ± 4.55	33.75 ± 1.68	40.21 ± 0.35
TCW30	2435 ± 5.03	31.36 ± 0.08	38.25 ± 0.51
RCB14	2481 ± 4.32	27.57 ± 0.21	33.86 ± 0.60
RCB20	2479 ± 4.78	27.70 ± 1.29	34.44 ± 0.11
RCB30	2465 ± 5.79	25.71 ± 0.13	33.62 ± 1.53
CSW14	2450 ± 2.91	31.37 ± 1.13	36.58 ± 0.59
CSW20	2445 ± 4.73	30.40 ± 0.04	35.72 ± 0.37
CSW30	2428 ± 5.18	31.02 ± 0.39	35.62 ± 1.07

The compressive strength results are plotted in Figures 4-6. The strength values are presented in Fig. 4, where error bars are the standard deviation, which represent the dispersion from the mean values. The total (w'/c) ratio is indicated in parentheses, and improvement of strength (IS) that occurred with curing age, from 7 to 28 days, is specified as a percentage (highlighted in dark grey). The concrete developed with the TCW aggregates gave the best compressive strength results, which were maximum for the 20 wt.% substitution. Although the strength values slightly lowered with further amounts of the TCW waste (30 wt.%), they were similar to those obtained for the RC. These results were attributed mainly to the low SI (high % of cubic particles) and the good resistance to wear of the

TCW aggregates. However, the compressive strength of the TCW recycled concretes was also partially attributed to their lower workability compared with the corresponding concretes prepared with the same amount of RCB or CSW waste (see Table 8). The slump cone test results suggested that, although the total (w'/c) ratio progressively increased with the amount of TCW, the amount of water added to compensate for that absorbed by aggregates was still slightly insufficient, which would have reduced the effective water available in the mix.

INSERT FIGURE 4

The relative strength of the mixes (RS), *versus* the RC, is reported in Fig. 5. The recycled concrete developed with up to 20 wt.% TCW obtained positive RS results (over 100%), which came close to 100% with further TCW contents (30 wt.%). The CSW recycled concretes exhibited similar mechanical properties to the reference samples, which slightly diminished with increasing waste contents. The lowest compressive strength results were obtained by the concretes prepared with the RCB aggregates, which was attributed mainly to the high SI and the reduced resistance to wear of these recycled particles, especially those with coarser fractions (see Tables 6 and 7). The RS values of the CSW concretes somewhat lowered from 7 to 28 days, those of the TCW samples remained almost constant with curing time, and the values obtained for the RCB concrete slightly increased from 7 to 28 curing days. This improvement became more pronounced with increasing brick waste contents.

INSERT FIGURE 5

According to the review by Xiao et al. [13], who have examined relevant research on recycled aggregate concrete (RAC) durability, the concretes prepared with recycled gravel generally present lower compressive strength values than those developed with traditional aggregates. Similarly, as summarised in [3], replacing 100% of the natural coarse aggregates usually diminishes the compressive strength of the hardened concrete by 10-20%, depending on the material used as recycled aggregate. Kisku et al. [16] also observed in their review that, for a given w/c ratio, the compressive strength of RAC generally diminishes by up to 10% when compared with that presented by traditional concrete. The results obtained in the present study fall in line with these previous reviews as the mechanical properties diminished by 5-20% when the CSW and RCB recycled aggregates were used. However, they also illustrate that the aggregate type determines the recycled

concrete strength since positive RS results were obtained when using up to 30 wt.% TCW as recycled aggregates. The different influence observed, depending on the ceramic waste used, is also in line with other studies about the use of recycled aggregates in concrete. Thus authors like Cachim [22], Medina et al. [24] or López et al. [38] have observed an improvement in compressive strength results when using ceramic recycled aggregates. According to [16] strength values of some concretes remained unaltered or slightly improved when replacing up to 25 % of the natural aggregates by recycled particles. Other studies, like that performed by Malesev et al. [23] or Evangelista and de Brito [21], have distinguished a slight improvement when replacing natural aggregates with recycled concrete, whereas the compressive strength values lowered in [14,18,19,34] for the concretes developed with recycled aggregates compared with their corresponding samples. More specifically, the study by Hakan [29] has reported similar mechanical properties to those of traditional limestone concrete when using ceramic floor tiles as recycled aggregates, but strength diminished in the mixes made with wall tile aggregates. Tavakoli et al. [32] have noted very little variation in the compressive strength of the concretes developed with increasing amounts of ceramic tiles, and respectively found optimum substitution percentages of 20% and 10% for the sand or gravel replacements [32].

The loss of strength observed with increasing CSW contents was attributed to the high SI, angular shape, smooth surface and reduced water absorption of these ceramic particles. While the first two parameters make the packing of aggregates difficult, the last two are expected to reduce the mechanical adherence between the CSW particles and the binding paste. The CSW results slightly differed from those previously reported by Guerra et al. [35] and Medina et al. [24,30], who have observed some SG when using this ceramic waste as a recycled aggregate. The compressive strength results in the study by Guerra et al. [35] slightly improved with increasing CSW contents; e.g., up to 9.18% for a 9% gravel substitution. However, differences with the results obtained in our study are attributed to the fact that small amounts of natural gravel (3-9%) were replaced with the ceramic waste material in [35]. Medina et al. [24] have reported how the compressive strength of a traditional concrete cured for 28 days increased from 34.7 MPa to 38.2 MPa when replacing 25% of natural siliceous gravel by CSW recycled particles (4-12.5 mm). In later studies [30], the authors attributed the improved compressive strength results with increasing CSW contents to the properties of the ceramic aggregates, and also to the characteristics of the interfacial transition zone (ITZ) with the binding paste.

Previous studies into the use of crushed bricks as recycled aggregates, e.g., those performed by Cachim [22], Debieb and Kenai [36] or Alves et al. [14], have also reported lower compressive strength results compared with the RC. Debieb and Kenai [36] used brick waste to partially replace (25%, 50%, 75% and 100%) natural limestone sand, gravel, and a combination of both. The compressive strength of the concretes cured for 28 days diminished by 30-35% when 25-100% of natural gravel was replaced with coarse crushed brick particles. This reduction ranged from 7-30% in the concrete prepared with 25-100% fine brick aggregates, and diminished by up to 40% when both coarse and fine aggregates were used. Cachim [22] did not observe a significant variation in the compressive strength results when replacing up to 15% of the natural gravel with two different brick types. However, the concrete properties diminished by up to 20% when 30% of the natural aggregates were replaced with one of those bricks. This reduction was attributed to the lower compressive strength and the higher SI of the recycled particles [22]. In the research by Alves et al. [14], recycled bricks and sanitaryware aggregates were used to replace natural sand. The compressive strength results diminished with increasing waste contents, and strength loss values of 9.6% and 42.5% were recorded in concrete samples cured for 28 days when replacing 100% of traditional sand with bricks and sanitaryware aggregates, respectively. These results are contrary to those obtained in the present study. Such discrepancies are partially attributed to the different methods followed to prepare the concrete mixes: water was added during the mixing process in [14], and aggregates were presaturated with water before being mixed with the binding paste in our study. According to [3], presaturating the aggregates increases the amount of cement particles on the recycled aggregate surface, which improves adherence with the binder. Another explanation is that Alves et al. [14] replaced only fine aggregates (in the 0%, 20%, 50% and 100% proportions), while we replaced coarse and fine particles. The lower strength of the recycled brick gravel compared to the natural particles may result in specimens being ruptured through them. Indeed Etxeberria and Vegas [31], who partially replaced limestone sand with brick waste (10%, 20%, 35% and 50% substitutions), have also reported higher compressive strength results for the recycled concrete compared with a traditional one. The best mechanical properties have been obtained for the concrete prepared with 35% recycled brick sand (cured for 28 and 365 days). The authors [31] have attributed the improved compressive strength results to the strength of the bricks used (which contained mullite), and also to the rough surface of the ceramic particles, which improved adherence with the binding paste. As explained in [31], the porosity of brick aggregates also allows water to be present inside particles, which improves cement hydration through internal curing. This is in line with the previous research by Koenders et al. [42], who have

investigated the influence of the water to cement ratio and the initial moisture of recycled concrete aggregates (dry or saturated), and observed a slightly higher hydration rate and better compressive strength results in the samples cured for 28 days when using dry aggregates. Recycled particles are generally more porous than natural aggregates which, according to Xiao et al. [13], modifies the microstructure of the interfacial translation zone (ITZ) compared with that observed in a traditional aggregates concrete.

The SG evolution compared with the RC, calculated as defined in Section 2.4 for the different amounts of ceramic waste materials used and curing times, is presented in Fig. 6. The TCW samples exhibited a positive SG, with a maximum value of 7.11% for the 20 wt.% substitution of the natural aggregates. Although it lowered with further TCW additions, the SG of the TCW30 sample cured for 28 days was still positive, which denotes some contribution of the waste material to strength development. The SG values of the samples developed with the CSW waste progressively lowered with increasing waste contents and curing time, up to a maximum strength loss of -5.77%. However, these negative SG values were considered negligible when considering that up to 30 wt.% of a significant construction waste was being reused, the use of natural raw materials consequently diminished, low energy was required to adapt the ceramic waste to be used in structural concrete (only that needed to crush), and the recycled concrete was developed by the same technology as that used for conventional concrete.

The concrete prepared with the RCB recycled aggregates gave the lowest SG results, which denotes some reduction in the mechanical properties compared with the RC. The optimum results for the RCB concretes were obtained with the 20 wt.% substitutions, which recorded a 12.0% strength loss after 7 curing days. Although the mechanical properties significantly diminished with further RCB contents (RCB30 concrete exhibited a 18.4% strength loss after 7 curing days), the strength values notably improved with curing time so that the strength loss was of only 11% in the RCB30 sample cured for 28 days. Since higher RCB contents exhibited increasing improvements of strength with the curing time (22.8% and 30.8% respectively for the 14% and 30% wt.% substitutions, see Figure 4) and the 30 wt.% substitutions contained the biggest amounts of recycled sand (16%, as summarized in Table 3), this improvement in strength with the curing time was attributed mainly to a pozzolanic reaction between the fine RCB particles and the portlandite ($Ca(OH)_2$) formed during Portland cement hydration. This reaction generates new hydrates that contribute to the recycled concrete's compressive strength. Previous studies on the use of ceramic waste as pozzolanic admixtures [8-

10,43,44] and as recycled aggregates in concrete [14,31] have shown that the hydraulicity of ceramic materials strongly depends on their sintering process (temperature and time). This determines the type and amount of phases formed and, consequently, their reactivity. Alves et al. [14] have also attributed the higher strength development rate observed with the curing time in a recycled concrete prepared with brick sand to the pozzolanic activity of the brick aggregates, and to the higher water content of the mixes, which favoured later cement hydration. Although the CSW aggregates used in their study [14] also presented pozzolanic activity, the low porosity of these particles prevented pozzolanic reactions from occurring as in the recycled brick aggregates. The pozzolanicity of ceramic waste tiles has also been corroborated in the studies by Ay and Ünal [43], Puertas et al. [10] and Mas et al. [44]. More specifically, the reactivity of the TCW used in the present study has been investigated in [44], which concluded that pozzolanic reactions occur mainly after long curing ages, and that the ceramic material accelerates cement hydration due to the particle effect. Our results are contrary to those previously reported by Pereira de Oliveira et al. [8] who, after investigating the pozzolanicity of red-clay bricks and tiles made in Portugal, concluded that tile waste powder presented potential reactivity, whereas the analysed bricks did not exhibit pozzolanic properties. This was attributed to the lower temperature applied during the production process of bricks compared with that used in the tile industry, which corroborates that the sintering process strongly influences the pozzolanicity of ceramic waste materials. Indeed the results previously reported by Pacheco-Torgal and Jalali [9], who compared the pozzolanic activity of ceramic bricks, white stoneware tiles and CSW, well agree with those obtained herein since ceramic bricks also presented the greatest pozzolanic reactivity in [9]. Etxeberria and Vegas [31] have also noted a higher strength development rate with curing time (28 to 365 days) in the concretes prepared with more than 20% recycled brick aggregates compared with traditional concrete, which they also attributed to the pozzolanic activity of the ceramic particles.

INSERT FIGURE 6

According to the reviews of [3,13], the mechanical properties of recycled aggregates concrete are usually poorer than those presented by traditional concrete. Consequently, the Spanish Structural Code for Concrete, EHE-08 [15] considers only using recycled aggregates obtained from healthy or high-strength structural concrete, and recommends replacing a maximum 20 wt.% of the natural gravel (specific studies must be conducted for further amounts). However, the compressive strength results obtained herein showed that the concrete produced with the TCW or CSW recycled

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aggregates offered better and similar mechanical properties than/to conventional concrete. This makes these ceramic materials promising candidates to be used as recycled aggregates for structural concrete production. Ceramic waste could be provided directly by ceramic companies, or taken from recycling plants, whenever the waste could be easily classified and separated (e.g., ceramic sanitary-ware units). Additionally, since no significant differences were observed among the mechanical properties of the concretes developed with the RCB, TCW or CSW aggregates, it would be interesting to further explore the use of these ceramic waste materials in concrete. Further research that combines these recycled aggregates and compares the properties of the developed concrete with those obtained when using CDW taken from recycling plants (which generally contain impurities such as gypsum, cement, etc.) would provide useful information about the possibilities of use and valorization of this significant construction waste.

4. Conclusions

Tile ceramic waste (TCW), red clay bricks (RCB) and ceramic sanitary ware (CSW) were characterised and used as recycled aggregates for structural concrete production. The conclusions drawn according to the results obtained herein are:

- The TCW, RCB and CSW recycled particles presented lower density values than the natural limestone aggregates, and the water absorption results widely varied, from 0.69% to 18.31%, depending on the material and particle size.

- The limestone and TCW aggregates contained a similar amount of regular particles (SI of 9), whereas the RCB and CSW gravels presented significantly larger quantities of non-cubic aggregates (SI of 25 and 29, respectively).

- The compressive strengths of the TCW and CSW recycled concretes were better than and similar to those presented by the traditional concrete made with the limestone aggregates.

- The RCB recycled concretes cured for 7 days presented the minimum relative strengths (up to -18.4% with 30 wt.% RCB). However, these concretes exhibited the greatest improvement of strength

with the curing time, which originated that relative strength lowered only by 9-11% after 28 curing days. This was attributed to the material's porosity and pozzolanic activity.

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LIST OF FIGURES:

Fig. 1 The ceramic waste used as a recycled aggregate. Coarse fraction: a) Tile ceramic waste, TCW; b) Red clay brick, RCB; c) Ceramic sanitaryware, CSW

Fig. 2 Grading curves of aggregates

Fig. 3 Grading curves of the composition of aggregates: a) general view; b) magnification of the 2.00-31.50 mm area

Fig. 4 Compressive strength of the concrete prepared with 14-30 wt.% of ceramic waste (TCW, RCB and CSW) as recycled aggregates, cured at 20ºC for 7 and 28 days

Fig. 5 Relative strength compared with the RC of the mixes that contained 14-30 wt.% of the ceramic waste (TCW, RCB and CSW) as recycled aggregates, cured at 20ºC for 7 and 28 days

Fig. 6 The SG of the concrete prepared with ceramic waste compared with the RC