Cement & Concrete Composites 40 (2013) 21–29

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Properties of recycled ceramic aggregate concretes: Water resistance

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ARTICLE INFO

Article history:
Received 25 January 2012
Received in revised form 5 April 2013
Accepted 8 April 2013
Available online 17 April 2013

Keywords:
Sanitary ware ceramic waste
Recycled aggregates
Sorptivity
Porosity
Water resistance
Concrete

ABSTRACT

Water permeability is a durability indicator, for it quantifies concrete resistance to penetration by external agents, due to that water is one of the main carriers of aggressive substances. The present study explores whether substituting 20% and 25% recycled sanitary ware for gravel in coarse aggregate affects structural recycled concrete resistance to water. The findings reveal that the slightly higher porosity in the recycled concrete does not translate into greater permeability. These new recycled concretes, which prove to be as durable as the conventional material, will therefore perform well throughout their design service life.

1. Introduction

Concrete [1,2] is a porous material open to attack throughout its service life by physical and chemical agents present in the medium, in particular sulphate or chloride ions or carbon dioxide, whose ingress into the concrete as aqueous solutions or gases causes cracking, microstructural changes and other damage such as corrosion due to the depassivation of reinforcing steel. The result [3–5] of chemical reactions between these external agents and the hydrated phases of the cement, such damage compromises the useful life of concrete.

Durability is one of the most important properties of concrete from the standpoint of safety, as well as for economic and environmental reasons [6]. According to the Eurocode 2 definition [7] "A durable structure shall meet the requirements of serviceability, strength and stability throughout its intended working life, without significant loss of utility or excessive unforeseen maintenance".

This property [8] is closely related to the quality of the outer few centimetres of concrete. Water permeability [9–13] is a durability indicator, for it quantifies concrete resistance to penetration by external agents. The importance of ascertaining this parameter lies in the fact that water is one of the main carriers of aggressive substances and is also directly related to freeze–thaw cycle-induced damage. Penetration [14,15] depends primarily on concrete pore structure, aggregate characteristics and moisture content.

It is of particular importance today [16–18], since the use of recycled materials as active additions or aggregate is becoming more and more widespread in concrete manufacture, especially where for reasons of location or availability the use of natural aggregates is not economically viable due to the need for long distance haulage to the worksite [19]. At the same time, the re-use of waste contributes to the sustainable management of natural resources and the reduction of CO_2 emissions.

The research conducted to date on the re-use of ceramic and fired clay waste (such as electrical insulation, porcelain and blocks) as recycled coarse aggregate in concrete manufacture, which has focused primarily on mechanical performance [20–27], has systematically reported declines in strength. The degree of that decline depends on the type of waste and replacement ratio used. Durability [28–30], in turn, has been observed to decline in most cases due primarily to the variation in the pore size distribution attendant upon the use of recycled aggregate.

In the absence of codes and specifications on the subject, the water resistance of structural concrete made with ceramic or fired clay materials as coarse aggregate is an innovative line of research of international interest. The only references to the subject found in the literature are the papers published by the authors of the present study [31–34] in which these new recycled concretes were reported to exhibit better mechanical behaviour than the conventional material.

The present study therefore explores the effect of the use of ceramic sanitary ware waste as a partial replacement for natural coarse aggregate on mechanical strength and water resistance in these new concretes. To that end, compressive and tensile strength,

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http://dx.doi.org/10.1016/j.cemconcomp.2013.04.005

pore size distribution, total water absorption by total immersion, capillary sorptivity and water penetration under pressure are addressed.

2. Materials

The natural aggregate used can be classified into two fractions, the coarse fraction or gravel, with a particle size of 4–20 mm, and the fines, with particles under 4 mm in diameter. This rounded gravel had a smooth surface and no sharp edges (Fig. 1).

XRF analysis conducted to determine the chemical composition of this natural aggregate showed that 97 wt% consisted of SiO_2, and the rest of other minority (primarily aluminium and iron) oxides.

The sanitary ware waste used as a partial replacement for coarse natural aggregate was crushed with a jaw crusher to a size of 4/12.5 mm. This recycled aggregate was irregularly shaped and had sharp edges (Fig. 2b), due both to the original shape of the thin waste (Fig. 2a) and the crushing process. Morphologically, the inner and outer parts of this waste could be clearly distinguished (Fig. 2c), for the rough inner matrix was covered by an essentially smooth vitreous outer layer less than 0.3 mm thick.

The aggregate size grading curves found by sieving are shown in Fig. 3. Note that all the curves were continuous, which would facilitate concrete casting. Furthermore, the shape of the recycled and natural coarse aggregate curves was very similar and the latter was coarser than the former, as the fineness modulus (see Table 1) for the two aggregates show. These values are within the usual range of fineness modulus (5.5–8.5) for the coarse aggregate used in concrete manufacture [35].

This waste was highly acidic, with a predominance of silica (66.57%) and alumina (21.60%). Lesser quantities of iron (1.41%), calcium (2.41%), sodium (1.41%), potassium (2.79%) and zirconium (1.48%) oxides were also present. This waste contained no chlorides, soluble sulphates or sulphur compounds.

The total porosity of this recycled ceramic aggregate was greater than in the natural material (Table 1), although it was lower than reported for aggregate drawn from fired clay waste such as roof tiles or block [23,36]. Moreover, Fig. 4 shows that this ceramic sanitary ware industry waste had a larger volume of pores with a diameter of under 10 μm.

Table 1 compares the physical and mechanical properties of the two types of coarse aggregate.

The table shows that water absorption was 2.4 times greater in the recycled than in the natural aggregate as a result of the greater porosity of the former, although both were comfortably below the ceiling (<5 wt%) stipulated in Spanish Code Structural Concrete (EHE-08) [37], Chapter VI, Materials, item 28.6. The value found was similar to the 0.72% found for ceramic electrical insulator waste [21] and much lower than reported for other types of ceramic or fired clay waste [22,29,30,38,39], with values of 6–20%.

Table 1 also shows that the recycled aggregate had a flakiness index eight times greater than gravel, but this value was likewise lower than the ceiling (<35 wt%) laid down in Spanish Code Structural Concrete (EHE-08), Chapter VI, Materials, item 28.5. This is a direct consequence of both aggregate morphology, with its preferred planes of failure due to the shape of the original waste, and the crushing process [40].

According to the Los Angeles abrasion test findings (Table 1), this recycled sanitary ware aggregate was 39% more fragmentation resistant than gravel, complying with yet another Spanish Code Structural Concrete (EHE-08) requisite (<40 wt%), likewise laid down in item 28.5 of Chapter VI, Materials. Such improved performance was also reported by Debieb and Kenai [23], who observed that fired clay block exhibited greater resistance to wear (31.6 wt%) than natural aggregate (36.3 wt%).

Portland cement: high strength, rapid hardening CEM I 52.5 R ordinary Portland cement (OPC), as defined in the existing standard [41], was used in all the concrete mixes.

Its chemical composition is given in Table 2.

3. Experimental program

The concrete was designed using the La Peña dosage method [36] aiming for a 28-day compressive strength of 30 MPa. This method establishes amount of water constant because the necessary volume of water is function of the maximum size aggregates (20 mm) and consistency (soft).

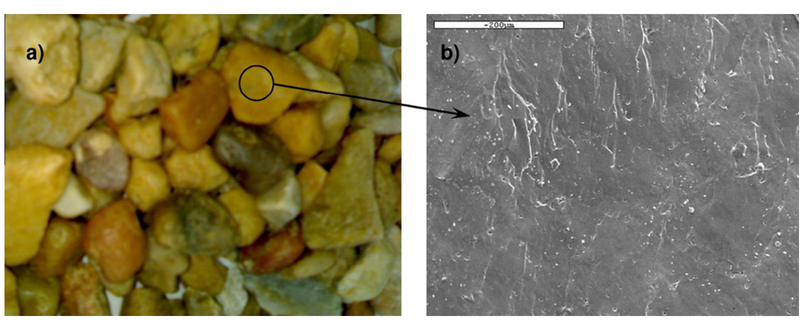

Fig. 1. Natural coarse aggregate: (a) overall appearance; (b) surface texture (200×).

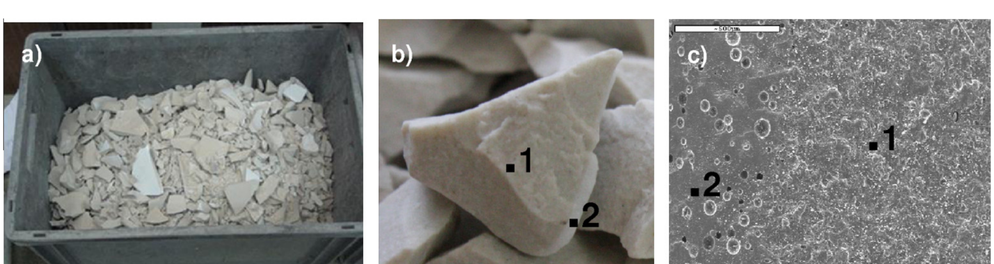

Fig. 2. Recycled ceramic aggregate (1. Internal part and 2. External part): (a) original shape; (b) overall appearance; and (c) surface texture (75×).

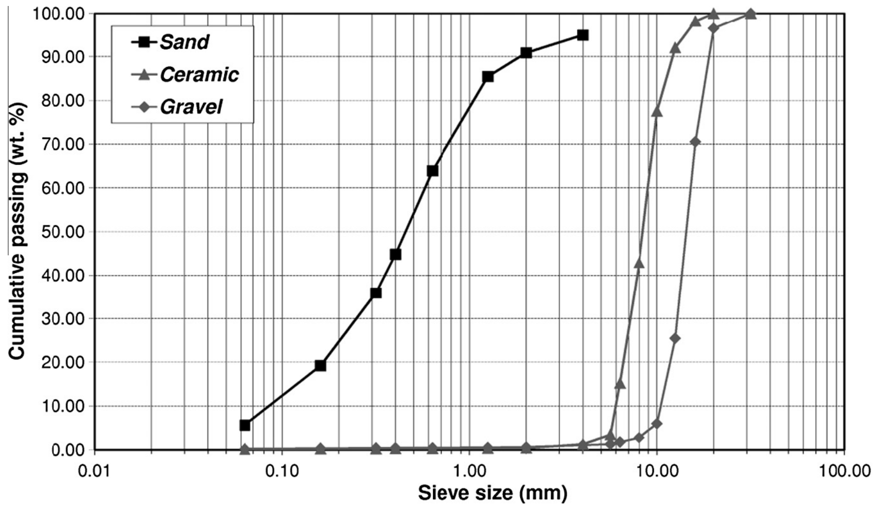

Fig. 3. Aggregate size grading curves.

Table 1
Physical and mechanical properties of natural and recycled coarse aggregate.

Characteristic	Gravel	Ceramic
Grading modulus	6.93	6.17
Fines content (wt%)	0.22	0.16
Total porosity (vol.%) (ASTM D 4404-84)	0.23	0.32
Real density of dry samples (kg/dm^3) (EN 1097-6)	2.63	2.39
Water absorption at 24 h (wt%) (EN 1097-6)	0.23	0.55
Flakiness index (wt%) (EN 933-3)	3	23
Los Angeles coefficient (wt%) (EN 1097-2)	33	20

Table 3 gives the batching for the concretes used.

Three types of concretes were prepared for this study: a reference concrete (RC) and two recycled concretes, in which 20 (CC-20) or 25 (CC-25) wt% of the natural coarse aggregate (gravel) was replaced with crushed ceramic sanitary ware waste.

To ensure durability, the w/c ratio and cement content in all concretes conformed to the maximum w/c ratio ($\leqslant$0.65) and minimum cement content ($\geqslant$250 kg/m^3) requirements set out in Spanish Code Structural Concrete (EHE-08).

The testing program included determination of slump, density, compressive and splitting tensile strength, pore size distribution, effective porosity, total water absorption, sorptivity and resistance to water penetration under pressure.

3.1. Compressive and splitting tensile strength

The compressive (20 specimens) and splitting tensile (6 specimens) strength test was performed according to EN 12390-3 [42] and EN 12390-6 [43] respectively, using cylinders with the dimension 300 mm $\varnothing \times$ 150 mm to obtain an average value. These tests were carried out on the specimens at the age of 28 days.

3.2. Mercury intrusion porosimetry

The analyser used was a Micromeritics Autopore IV 9500 mercury porosimeter able to operate at pressures of up to 33,000 psi (227.5 MPa) and measure pore diameters of 0.006–175 μm. This trial was conducted to ASTM standard D 4404 [44].

The samples were obtained by shear to prevent internal cracking and, prior to testing, were dried at 40 °C to a constant weight and degassed for 30 min with a vacuum pump.

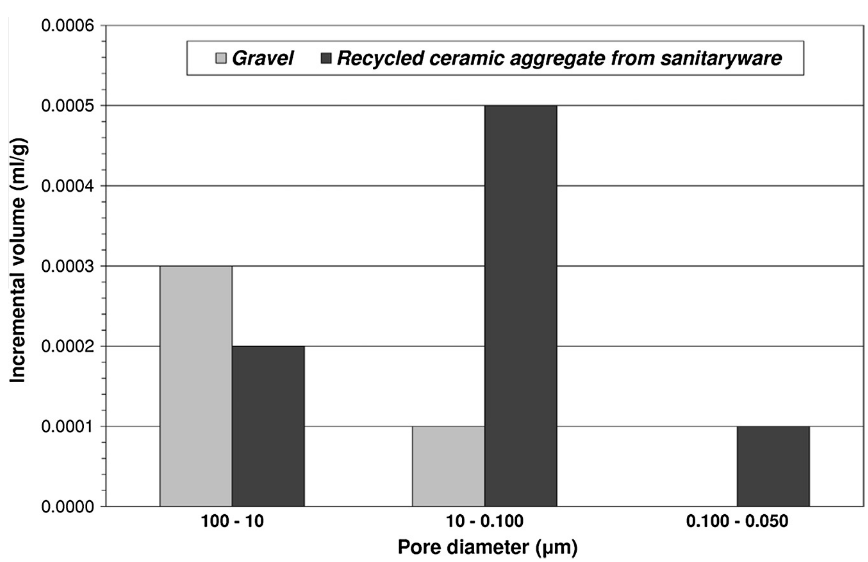

Fig. 4. Coarse aggregate pore diameter distribution.

Table 2
Chemical composition of ordinary Portland cement.

Chemical constituent	wt%
SiO_2	19.39
TiO_2	0.20
Al_2O_3	5.22
MgO	1.38
CaO	62.07
Na_2O	0.36
K_2O	0.89
P_2O_5	0.07
SO_3	3.33
SrO	0.81
Cl	0.01
LOI	3.27
C_3S	67.35
C_2S	8.71
C_4AF	8.03
C_3A	7.42
CaO/SiO_2	3.20

Table 3
Mix proportion of concretes.

Concrete mix	Material (kg/m^3)				
	Sand	Gravel	Ceramic	Cement	Water
Reference concrete (RC)	716.51	1115.82	0.00	398.52	205.00
Concrete containing 20% recycled aggregate (CC-20)	725.81	892.66	216.43	387.64	205.00
Concrete containing 25% recycled aggregate (CC-25)	728.14	836.87	270.53	384.91	205.00

3.3. Water absorption

Water absorption resulting from total immersion, effective porosity and sorptivity were found as described in Italian standard Normal 7/81 [45] and Spanish standard UNE 83982 [46] respectively, using three 28 day, 75 mm ∅ × 150 mm specimens for each concrete type and test.

Sorptivity was determined by placing the bottom of the specimens in contact with the water flow.

Cumulative water absorption was recorded at intervals of up to 2 h by weighing the specimen after removing the surface water with a moist cloth. The amount of water absorbed was calculated and normalised to specimen cross-section area.

Sorptivity is the slope of the curve of the water absorbed by unit surface area versus the square root of time (from 5 to 120 min). This trial was not interrupted until the specimen reached a constant mass to thereby plot the capillary water absorption curve and effective porosity for the concretes tested.

3.4. Water penetration depth under pressure

Water penetration under pressure was determined in accordance with the procedure specified in European standard EN 12390-8 [47] using three 150 mm ∅ × 300 mm specimens for each type of concrete. This trial was conducted on a BEH3-LDN device.

4. Results and discussion

4.1. Consistency and density

Table 4 gives the consistency and density values for the fresh concretes.

All the concretes were observed to have a slump of 6–9 cm (soft consistency), as initially planned (see item 3). This value declined as the replacement ratio rose, by 5% in CC-25 compared to RC, due to the differences between the physical properties of the natural and recycled ceramic aggregates.

Density, in turn, was also observed to decline with rising proportions of recycled aggregate as a result of the lower density of this product compared to the natural material. The value for CC-25 was 0.84% lower than for RC.

Table 4
Physical properties of fresh concretes.

Concrete	Slump (mm)	Bulk density (kg/m^3)
RC	75 ± 0.64[a]	2390 ± 10.2
CC-20	72 ± 0.58	2370 ± 9.7
CC-25	71 ± 0.61	2360 ± 6.8

[a] The ± represents one standard deviation.

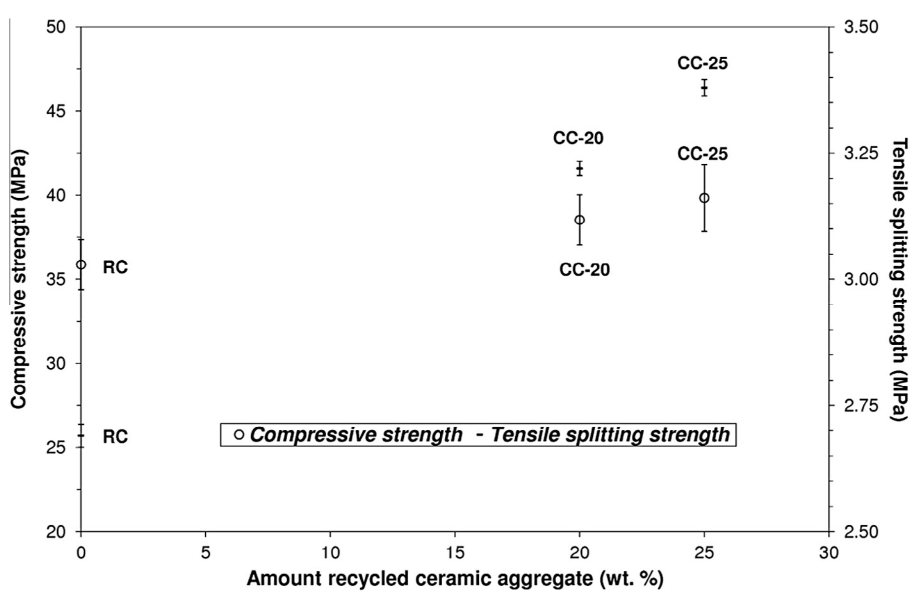

Fig. 5. Compressive and tensile splitting strength of the concretes at 28 days.

4.2. Mechanical properties

Fig. 5 shows the 28-day compressive and tensile splitting strength values for the concretes studied. The use of recycled aggregate in CC-25 was found to improve compressive and tensile splitting strength by 12% and 26%, respectively, compared to the reference concrete.

These results are consistent with findings reported by other researchers [25,39,48] using fired clay waste (blocks, roof tiles) at replacement ratios of 15% and 100%.

Recycled aggregate concretes exhibit better strength values due primarily to the intrinsic characteristics of ceramic sanitary ware aggregate (shape and surface texture), which improve the aggregate-paste interface, due to the more irregular shape it presents, resulting in a superior specific surface area than natural aggregate (gravel), which is rounded and thus lacks edges. Moreover, this irregular shape and rough surface provides the higher bond between recycled ceramic aggregate and the paste, as observed earlier by Medina et al. [34,49].

4.3. Porosity

4.3.1. Total porosity and pore diameter distribution

Total porosity, average pore diameter and pore size distribution were analysed to determine the effect of the recycled aggregate on microstructure. The total porosity findings (Table 5) showed that porosity rose with the percentage of the ceramic aggregate. Nonetheless, in CC-25 the increase over the reference concrete was only 4.16%. This slight rise was due to the greater porosity of the ceramic aggregate (see Table 1), offset by the smoother interface between ceramic aggregate and paste than between gravel and paste [34]. The values obtained were within the expected range (10–20%) [40], and similar to the range for recycled concretes (10–23%) [50–53].

Table 5
Total porosity and average pore diameter of concretes at 28 days.

Concrete	Total porosity (vol.%)	Average pore diameter (μm)
RC	15.72 ± 0.32[a]	0.0669 ± 0.0031
CC-20	16.21 ± 0.48	0.0560 ± 0.0016
CC-25	16.38 ± 0.59	0.0459 ± 0.0030

[a] The ± represents one standard deviation.

Table 5 also gives the average pore diameter values for the concretes: the greater the replacement ratio, the more refined was the pore system. This finding can be attributed to two factors: the difference in pore size distribution in the waste aggregate (see Fig. 4), which had pores smaller than 0.10 μm, and the smoother interface between recycled aggregate and paste.

According to Fig. 6, which shows the effect of recycled aggregate on concrete pore size distribution, the reference concrete (RC) had a higher proportion of pores larger than 0.05 μm in diameter (macropores), while the recycled aggregate concretes had a larger volume of pores under that size (capillary pores).

4.3.2. Effective porosity

Fig. 7 shows the effective porosity for the concretes, which was observed to rise with the percentage of ceramic aggregate. The value for CC-25 was 15% greater than for RC. This rise was attributed to the higher total porosity in the recycled aggregate concrete, as attested to by the linear relationship between effective and total porosity visible in Fig. 7. This relationship was previously reported in a paper by Lian et al. [54], although the value of the equation parameters varied depending on the type of concrete used.

The effective porosity values obtained were 38%, 41% and 42% of total RC, CC-20 and CC-25 total porosity, respectively. These findings were consistent with the values reported by Wen et al. [55], according to which effective porosity ranged from 25% to 50% of total porosity measured by MIP.

4.4. Total water absorption

Table 6 gives the total water absorption values found for the concretes, which rose with the percentage of recycled ceramic aggregate (Fig. 8). The increase over RC was 36% for CC-20 and 46% for CC-25.

This increase was due to both the higher water absorption coefficient in recycled aggregate and the effect of this RCA on the pore system. Fig. 8 shows the linear relationship between this property and total porosity versus the percentage of recycled aggregate, as reported in earlier papers [28,29,56].

These findings are consistent with the pattern observed in concretes made with other types of recycled aggregate (fired clay,

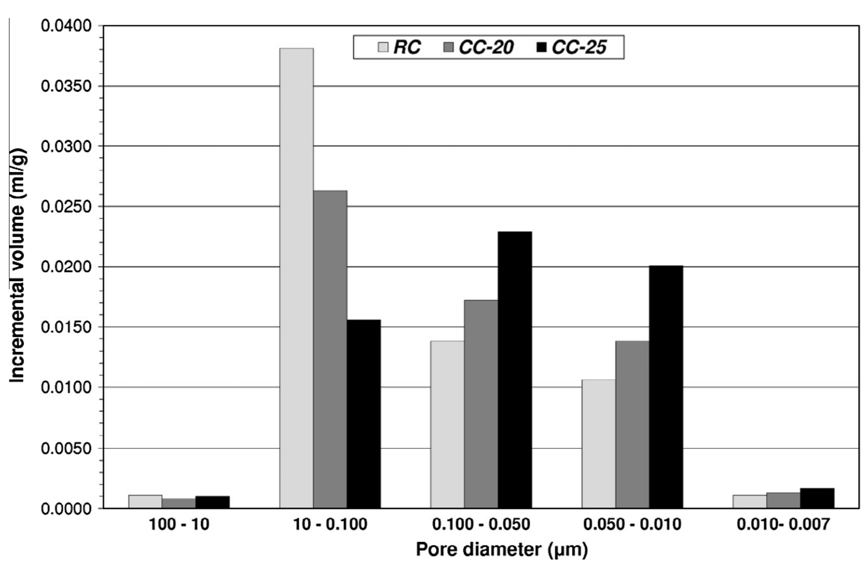

Fig. 6. Pore size distribution at 28 days.

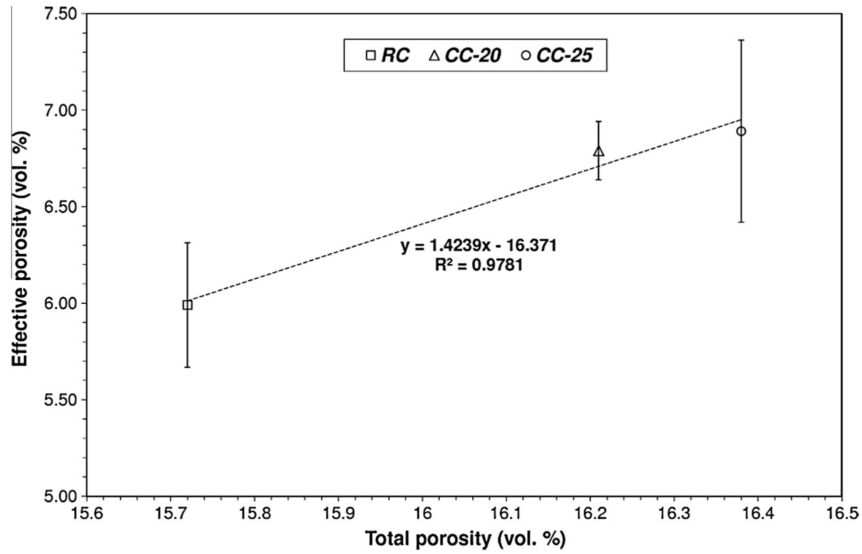

Fig. 7. Effective porosity of concretes.

Table 6
Total absorption water of concretes.

Concrete	Total water absorption (wt%)
RC	2.11 ± 0.048[a]
CC-20	2.87 ± 0.064
CC-25	3.08 ± 0.071

[a] The ± represents one standard deviation.

CDW) [38,57–60]. The higher absorption values exhibited by that waste can be explained by the difference between its water absorption coefficient (4–12%) and the coefficient for the waste used in the present study (Table 1).

According to the classification proposed by CEB-FIP [61] concrete quality can be estimated from total water absorption. Pursuant to that classification, RC and CC-20 were of high quality (Ab < 3%), while CC-25 was of medium quality (3% < Ab < 4%); i.e., the inclusion of recycled aggregate had no substantial effect on quality. At the same time, other authors [62,63] have contended that concretes with total water absorption values of under 10% are of good quality.

4.5. Sorptivity

Fig. 9 shows the amount of water absorbed by unit area versus the square root of time, as well as the trend line equations from which the sorptivity values were calculated for concretes RC, CC-20 and CC-25 (Table 7).

Table 6 gives the water sorptivity values obtained for the concretes, which were observed to rise with the percentage of ceramic aggregate. The values for CC-20 and CC-25 were 11% and 38% higher than in conventional concrete, respectively.

These results were the direct consequence of the effect of ceramic sanitary ware aggregate on the pore size distribution in concrete (see Fig. 6), i.e., of the increase in the volume of capillary pores (∅ < 0.05 μm). This can be seen in Fig. 10, which shows

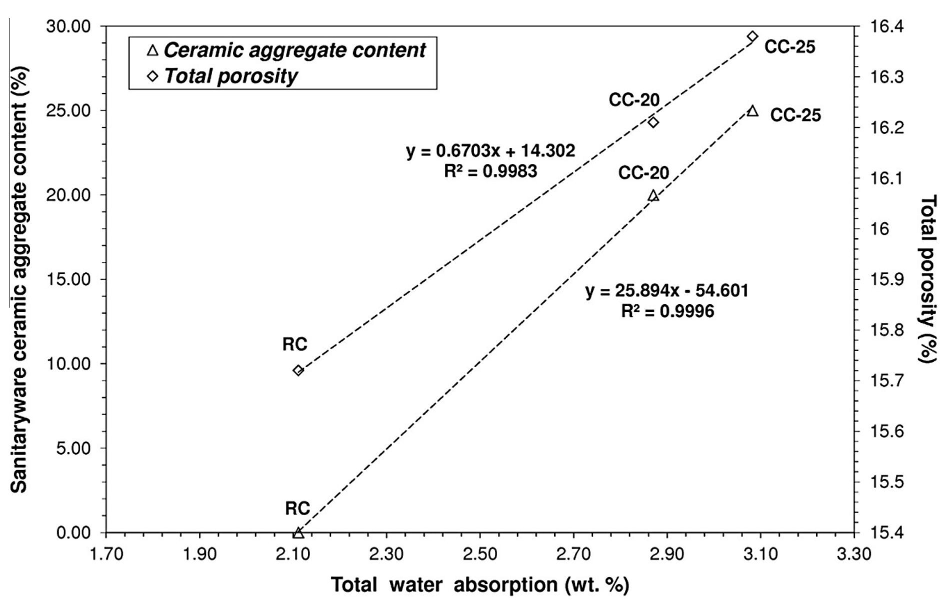

Fig. 8. Total water absorption: total porosity ratio versus the percentage of recycled ceramic aggregate.

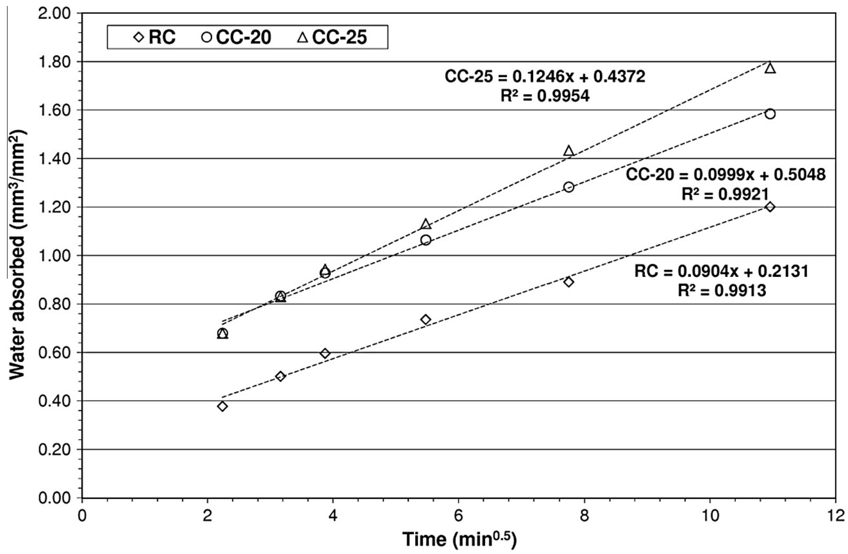

Fig. 9. Capillary suction curves (for determining sorptivity) in 2-h concretes.

Table 7
Concrete sorptivity.

Concrete	Sorptivity (mm/h$^{0.5}$)
RC	0.6999 ± 0.0578[a]
CC-20	0.7740 ± 0.0298
CC-25	0.9652 ± 0.0668

[a] The ± represents one standard deviation.

the linear relationship between the increase in the volume of this pore fraction and capillary sorptivity in the concretes. These findings were concurrent with reports by other authors [64–66].

The increase in sorptivity is consistent with the upward trend observed by other authors using ceramic or fired clay waste [23,28,38,63] or construction and demolition waste [49,66–68] as coarse aggregate in concrete manufacture. It might be mitigated, however, with active additions such as silica fume or fly ash as partial substitutes for OPC, or by using some other type of blended cement, for these materials are known to lower concrete sorptivity [69].

The capillary water absorption curves for the three concretes studied were similar, as shown in Fig. 11. At the same time, as a result of the larger volume of capillary pores in the recycled aggregate, the amount of water absorbed rose with the percentage of ceramic aggregate and saturation time [56]. These curves exhibited an initial rapid absorption stage (first 24 h), after which the rate declined due to hydration and rehydration of the paste components, modifying the microstructure and therefore pore connectivity [70,71]. In the final stage the specimens reached saturation and a constant weight, as diffusion air filled the pores [64].

Further to the classification proposed by Alexander et al. [13] and Ho et al. [72], concrete durability can be determined from its water sorptivity values. In that classification, concretes with a water sorptivity of under 6 mm/h$^{0.5}$ are durable, although other authors [73] have proposed lowering that value to 3 mm/h$^{0.5}$ for reasons of safety. On the grounds of these classifications, concretes made with the ceramic sanitary ware aggregate studied here (CC-20 and CC-25) may be regarded as durable.

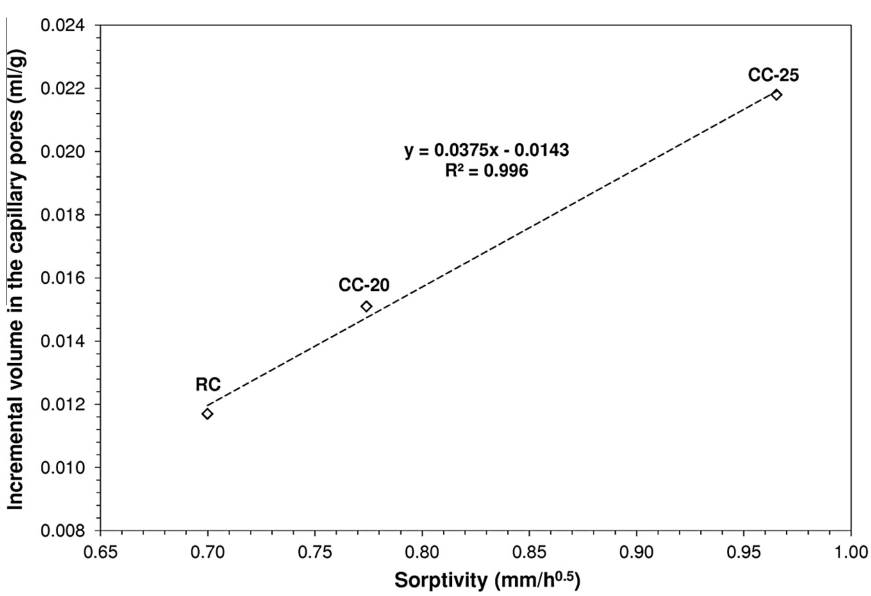

Fig. 10. Increase in capillary pore volume versus concrete sorptivity.

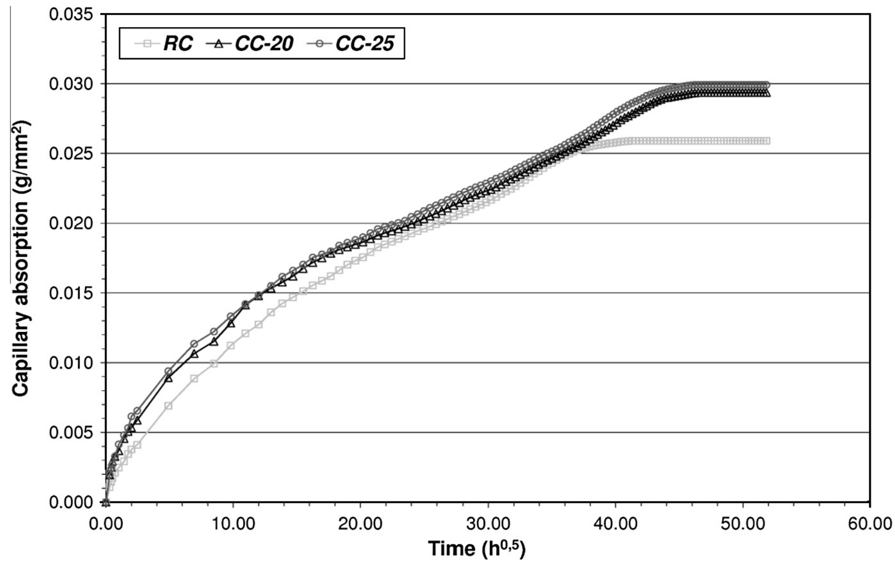

Fig. 11. Capillary water absorption in concretes.

Table 8
Depth of water penetration under pressure.

Concrete	Maximum depth (mm)	Average depth (mm)
RC	27	11.2 ± 0.946[a]
CC-20	26	12.4 ± 1.060
CC-25	27	14.8 ± 1.169

[a] The ± represents one standard deviation.

4.6. Depth of water penetration under pressure

Table 8 gives the maximum and average depth of water penetration under pressure for the concretes studied. While the maximum depth remained constant regardless of the replacement ratio, the average value rose by 11% in CC 20 and 20% in CC 25.

Mas et al. [74], studying small replacement ratios (<25 wt%) of mixed recycled aggregate, also reported that the maximum penetration depth remained constant. These findings are attributed to the fact that penetration depends on factors [75], such as average pore diameter, macropores volume and total porosity. Indeed, the higher total porosity in recycled concretes is offset by the decline in the mean pore size and volume of macropores.

The rise in average depth, in turn, is in line with observations made by authors [74,76] who used other types of recycled aggregate (fired clay or CDW) in concrete manufacture. They also reported an upward trend in permeability with increasing replacement rates.

The values recorded here were nonetheless below the ceilings laid down in Spanish Code Structural Concrete (EHE-08) [37], Chapter VII, Durability, item 37.3.3, Concrete impermeability, according to which plain or reinforced concrete is sufficiently impermeable for classification as IIIa, IIIb, IV, Qa, E, H, F, or Qb when its maximum and mean penetration depths are under 50 and 30 mm, respectively. Therefore, the pore structure of the recycled aggregate concretes studied guarantees impermeability and sufficient durability throughout their service life.

5. Conclusions

The following conclusions may be drawn from the present findings.

1. Mechanical strength is higher in recycled aggregate concretes than in the reference concrete, and rises with ceramic aggregate content.
2. The inclusion of ceramic sanitary ware aggregate raises total porosity slightly and modifies pore size distribution, with an increase in the volume of capillary pores at the expense of macropores.
3. The concretes with recycled ceramic aggregate have greater sorptivity than conventional concretes, since the values are consistently under 3 mm/h$^{0.5}$, these may consequently be regarded as durable materials
4. The maximum depth of water penetration is no greater in recycled aggregate than natural aggregate concretes, and although the average value is somewhat higher in the former, it never exceeds 30 mm.
5. In light of these findings, the replacement of natural aggregate with recycled sanitary ware industry waste is feasible from the standpoint of its resistance to water permeation.

Acknowledgment

The present study was funded by the Spanish Ministry of Science and Innovation under coordinated research Project (BIA2010-21194-C03-01).

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