Effect of fine ceramic recycled aggregate (RA) and mixed fine RA on hardened properties of concrete

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The ceramic industry is well known for producing large amounts of rejected ceramic waste. During the construction and demolition waste crushing process, a large amount of fine recycled aggregates (FRA) are usually produced. However, little research work has been carried out employing those types of aggregates in recycled aggregate concrete (RAC) production. In this research work, mixed and ceramic FRA in partial replacement of 10, 20, 35 and 50% of natural fine aggregates were used in order to verify their applicability in RAC manufacturing. All the concretes were produced to have the same workability. The physical, mechanical and durability properties of the RAC were determined and compared with the results obtained for conventional concrete. The results showed that an increase in the percentages of FRA used in the concrete production led to a decrease in density and an increase in water absorption. The mechanical and durability properties of all the concretes produced with fine ceramic recycled aggregates were similar to those of conventional concrete at 28 days. However, after 1 year, the compressive strength and chloride diffusion of the RAC mixtures produced using fine ceramic recycled aggregates were considerably higher than those of conventional concrete.

Introduction

Over the past century there has been a tremendous degradation of natural areas due to the large expansion of the construction industry and its use of natural resources. The concrete industry in particular is one of the major global consumers of natural resources. In order to minimise this impact, experts consider the manufacture of concrete a possible destination for waste and also a source for new aggregates to be used in new concrete life cycles.

Spain produced around 40 Mt of construction and demolition waste (CDW) per year during the Spanish building boom, with a corresponding decrease during the period between 2008 and 2013 (Jimenez *et al.*, 2010). Approximately 75% of CDW is composed of mixed ceramic fractions such as bricks, tiles and concrete (European Commission, 1999; MMAMRM, 2009). It has been reported that the majority of these wastes are directly landfilled, with only 40% appropriately treated in recycling plants (Jimenez *et al.*, 2010). In order to foster the use of larger amounts of recycled aggregates (RAs) in concrete, knowledge of the effect of RAs in cement-based materials is necessary.

Aggregates account for some 70–80% of the total volume of concrete and consequently any reduction in the consumption of natural aggregates would have a significant beneficial impact on

the environment. For this reason, the use of recycled CDW as concrete aggregate has been studied in recent years. Recycled concrete aggregates have been extensively studied for concrete production for more than 50 years (Etxeberria *et al.*, 2007; Hansen, 1986, 1992; Limbachiya *et al.*, 2000; Poon *et al.*, 2004; Sague-Crentsil *et al.*, 2001; Silva *et al.*, 2014), but studies on the utilisation of ceramic or mixed coarse RAs are relatively new. According to de Brito *et al.* (2005), Correia *et al.* (2006) and Gomes and de Brito (2009), concretes produced with recycled ceramic coarse aggregates achieve suitable mechanical properties, although the reduction in compressive strength is larger than that of flexural strength. The abrasion resistance of such concretes is higher than that of concrete made with limestone aggregate. From a durability point of view, concretes made with partial substitution of natural aggregates for ceramic aggregates obtained adequate properties.

According to Medina *et al.* (2012, 2013), RA concretes produced with ceramic aggregates exhibit superior mechanical behaviour compared with conventional concrete. It was also reported that the microstructure in the interfacial transition zone (ITZ) between the recycled ceramic aggregate and the paste was more compact than in the case of natural aggregate and paste. However, concretes containing recycled ceramic aggregate reveal greater sorptivity than conventional concretes. According to Senthamarai

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and Devadas Manoharan (2005) and Senthamarai *et al.* (2011), ceramic electrical insulator waste coarse aggregate can be used for the production of concrete that complies with the requirements of permeation characteristics set by the relevant standards.

It is also known that between 30% and 50% of the RA produced in the recycling process is fine aggregate (Vegas *et al.*, 2011). However, due to its high absorption, low density and the potential presence of impurities, little research has been carried out with respect to its use in concrete manufacturing. The suitability of fine ceramic RAs for use in different low- or moderate-grade applications (lower compressive strength than that defining high-performance concrete (HPC), 62 MPa according to ACI), has been verified by several authors (Alves *et al.*, 2014; Binici, 2007; Halickaa *et al.*, 2013; Khatib, 2005; Pacheco-Torgal and Jalali, 2010; Torkittikul and Chaipanich, 2010).

Correia *et al.* (2006) and Silva *et al.* (2014) concluded that RA concrete could achieve the properties of conventional concrete for a replacement of natural aggregates with fine ceramic aggregates up to 50%. Torkittikul and Chaipanich (2010) also established 50% of fine ceramic aggregates as the optimum replacement ratio in order to maintain similar workability and compressive strength to those of conventional concrete. However, Khatib (2005) reported that even at 100% of fine aggregate replacement the reduction in strength was only 10% and indicated that this could be due to a cementing action in the presence of fine ceramic aggregates. Furthermore, Khatib (2005) and Pacheco-Torgal and Jalali (2010) showed that the increase in compressive strength over time for all mixes containing crushed bricks was higher than for mixes just containing crushed concrete and natural aggregates. All samples showed a high resistance to chloride penetration and durability, confirming the positive impact of using these aggregates. Higashiyama *et al.* (2012a, 2012b) also came to the same conclusions with respect to durability.

Some authors (Suzuki *et al.*, 2009; Vejmelková *et al.*, 2012) have suggested that the use of recycled ceramic materials could enhance HPC, offering an additional value to ceramic waste. Suzuki *et al.* (2009) used porous coarse ceramic waste aggregates for the internal curing of HPC. Their research found a high effectiveness of ceramic aggregates in the reduction or even complete elimination of autogenous shrinkage. The incorporation of 40% coarse mixed aggregate led to a non-shrinking HPC accompanied by a significant increase in compressive strength. For HPC incorporating waste sanitary ceramic aggregate, Halickaa *et al.* (2013) found the concrete elements to have the properties necessary for high-temperature applications.

There is a need to extend current knowledge regarding the use of fine RAs. In the work reported here, mixed fine RAs obtained from a CDW treatment plant and fine ceramic RA obtained from crushed rejected bricks were used as partial replacements (10%, 20%, 35% and 50%) of natural fine aggregates in order to verify their applicability in concrete manufacture. The physical, mech-

anical and durability properties of the RA concretes were determined and the results were compared with those of conventional concrete.

Experimental details

Materials

Cement

Type I Portland cement (CEM I 52.5 R) was used in all the concrete mixtures. The high strength and rapid hardening cement presented a specific surface of 4600 cm²/g. Its chemical composition is given in Table 1.

Natural quarry aggregates

The raw crushed aggregates used in the experimental phase were fine aggregate (FA 0–4 mm), coarse aggregate type 1 4–12 mm (CA1) and coarse aggregate type 2 12–20 mm (CA2) from a limestone quarry. Densities and absorption were determined according to UNE EN 1097-6:2001 and are presented in Table 2. The particle size distribution of the natural aggregates (see Figure 1) was determined according to UNE EN 933-2:1996 (BSI, 1996). All fractions of natural aggregates satisfied the requirements specified by the Spanish standard for structural concrete (EHE, 2008).

Recycled aggregates

The following two types of fine RAs were used as partial substitutions for natural sand.

- Ceramic recycled sand. Rejected bricks were collected from the Piera Ecocerámica company and were crushed in the

Silicon dioxide (SiO ₂): %	20.0
Iron oxide (Fe ₂ O ₃): %	3.4
Aluminium oxide (Al ₂ O ₃): %	5.3
Calcium oxide (CaO): %	62.5
Magnesium oxide (MgO): %	2.0
Potassium oxide (K ₂ O): %	0.9
Sodium oxide (Na ₂ O): %	0.1
Sulfur trioxide (SO ₃): %	3.2
Loss on ignition: %	2.5

Table 1. Chemical composition of the cement used

	CA2 12–20 mm	CA1 4–12 mm	FA 0–4 mm
Dry density: kg/dm ³	2.65	2.64	2.58
Water absorption: %	0.67	0.87	1.68

Table 2. Properties of natural aggregates

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Figure 1. Particle-size distribution of natural and RAs

university's laboratory using an impact crusher; this aggregate was called PCS (Piera ceramic sand) and was composed of 100% ceramic material.

- Fine mixed RA. This was produced in a recycling plant in Montoliu (Barcelona) managed by Gestora de runes de la construcció S.A. It was produced by crushing mixed CDW and its composition was approximately 70% ceramic, 20% concrete, 9.4% natural aggregate, 0.5% gypsum and 0.1% other. This aggregate was called MMS (Montoliu mixed sand).

The physical properties of these fine RAs are listed in Table 3.

The particle-size distributions of the PCS and MMS aggregates were coarser than those of the natural fine aggregates (see Figure 1) and slightly coarser than the requirements of the Spanish standard for structural concrete (EHE, 2008) for use in concrete production. However, given that the fine RAs were used as partial replacements (10%, 20%, 35% and 50%) of natural sand, the particle-size distribution of the final aggregate complied with the EHE standard.

	PCS	MMS
Apparent density: g/cm ³	2.78	2.78
Dry density: g/cm ³	1.98	1.94
Saturated surface-dry (SSD) density: g/cm ³	2.27	2.24
WA ₂₄ : %	14.72	15.8

WA₂₄, water absorption in 24 h

Table 3. Physical properties of the fine RAs

Admixture

The chemical admixture used in the manufacture of the concrete was polycarboxylate-based, especially designed for applications in concrete and prepared to improve workability even for low cement contents.

Concrete mixtures

Nine different types of concrete were produced, namely a conventional concrete (CC) and eight RA concretes. Partial substitution of 10%, 20%, 35% and 50% of the conventional sand (FA 0–4 mm) by the two types of fine RAs (PCS and MMS) was carried out. According to the different percentages of the fine RAs used, the concrete mixes containing PCS aggregate were called CP10, CP20, CP35 and CP50 and the concretes with MMS aggregates were denoted CM10, CM20, CM35 and CM50 (Table 4).

Concrete mix proportions were defined according to their maximum volumetric compaction. This mix proportion for conventional concrete was defined as 50% fine aggregate and 50% coarse aggregate. The distribution of coarse aggregate was 30% CA1 (4–12 mm) and 70% CA2 (12–20 mm). Some 375 kg of cement and an effective water/cement (w/c) ratio of 0.40 were used in order to produce 1 m³ of all defined concrete mixes. The concrete mix proportions used are defined in Table 4. The effective w/c ratio of conventional concrete was determined and maintained constant for all concrete mixes (the effective water was the water reacting with the cement). Aggregates were used in a dry condition in order to control the effective w/c ratio in all the other concretes. The natural coarse aggregates absorbed 20% of their total water capacity (which was the water absorption capacity of aggregates submerged for up to 20 min), the fine natural aggregates absorbed 50% of their absorption capacity and the fine RAs 80% of their absorption capacity. The total water amount of the concrete was considered as the amount of effective water weight plus the absorbed water for the aggregates (see Table 5). The amount of admixture used varied from 0.8% to 1.0% with respect to cement weight and the slump of all concretes were liquid (14–20 mm) determined by UNE EN 12350-2:2006 (Aenor, 2006). More water and a higher quantity of admixture were added to the mixer for concrete production due to the higher absorption capacity of the mixed RAs. However, due to this larger amount of added water, the initial slump of concrete produced with high percentages of mixed RAs was considerable. Tavakoli and Soroushian (1996) found that no detrimental effect in slump value occurred in concrete containing 50% of ceramic waste aggregate where the slump values were similar to the conventional control.

Specimen casting and curing

For each concrete mixture, 100 mm cubes were prepared to determine the hardened concrete density, absorption, accessible air voids and capillary absorption capacity. Cylinders (100Ø/200 mm) were used to evaluate compressive and splitting tensile strengths, elastic modulus and resistance to chloride ion penetration of concrete.

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	Material: kg/m ³ of concrete						Admixture: %	Effective w/c ratio	Slump: cm
	CEM	FA 0–4 mm	PCS/MMS 0–4 mm	CA1 4–12 mm	CA2 12–20 mm	Total water			
CC	375	955	0	287	669	161.5	0.8	0.40	14
CP10	375	860	71	287	669	168.9	0.8	0.40	15
CP20	375	764	143	287	669	176.4	0.7	0.40	14
CP35	375	621	250	287	669	187.5	0.8	0.40	20
CP50	375	478	357	287	669	198.6	0.8	0.40	18
CM10	375	860	70	287	669	169.4	1.0	0.40	15
CM20	375	764	140	287	669	177.3	1.0	0.40	20
CM35	375	621	245	287	669	189.1	1.0	0.40	21
CM50	375	478	350	287	669	200.9	1.0	0.40	21

Table 4. Mix proportions of concretes

	CC	CP10	CP20	CP35	CP50	CM10	CM20	CM35	CM50
SSD density: g/cm ³	2.46	2.45	2.42	2.38	2.37	2.41	2.42	2.37	2.37
Dry density: g/cm ³	2.43	2.41	2.38	2.33	2.33	2.37	2.38	2.32	2.32
Water absorption: %	1.48	1.54	1.78	1.97	1.88	1.53	1.65	2.03	2.06
Accessible air voids: %	3.59	3.72	4.24	4.58	4.38	3.63	3.92	4.7	4.79
Sorptivity: mm/min ^{1/2}	0.0338	0.0533	0.5320	0.5510	0.6330	0.0422	0.0425	0.5100	0.0457

Table 5. Density, water absorption, porosity and sorptivity coefficient of the hardened concretes

The concrete specimens were kept in their moulds for 24 h. The moulds were covered with wet burlap and plastic to ensure that the temperature and wet conditions would remain stable between 18°C and 26°C with a high moisture content. After demoulding (24 h after casting), the specimens were cured in a humidity-controlled room at 23°C and 95% humidity until the age of testing.

Tests of hardened concrete properties

Physical properties

The density, absorption and voids were measured following ASTM C 642-97 (ASTM, 1997) (standard test method for density, absorption, and voids in hardened concrete) at 28 d. Three cube specimens were used in this test for each type of concrete produced.

Mechanical properties

The compressive strengths of the concretes were determined using a compression machine with a loading capacity of 3000 kN. The compressive strength of the cylindrical specimens was measured at the ages of 7 d, 28 d and 365 d (1 year) following UNE EN 12390-3 (Aenor, 2011). Each presented value is the average of three measurements. The splitting tensile strength and elastic modulus were tested at 28 d, following UNE EN 12390-6 (Aenor, 2010) and UNE 12390-13 (Aenor, 2013)

specifications respectively. Three specimens were used for each type of concrete produced.

Durability properties

CAPILLARY WATER ABSORPTION

The concrete's capillary water absorption was assessed using 100 × 100 × 100 mm cubic specimens at 28 d after mixing following the Swiss standard SIA 162/1 (SIA, 1989). For sorptivity determination, the specimens were previously oven-dried at 40°C until a constant weight was obtained. The bottom face of the specimens was then submerged in water to a depth of 5 mm (the lateral surfaces were impregnated with impermeable resin). The cumulative water absorbed was recorded at different time intervals up to 120 min by weighing the specimen after removing surface water using a dampened tissue. The results of capillary water absorption are the average of three measurements.

CHLORIDE ION PENETRABILITY

The rate of chloride ion ingress into concrete is primarily dependent on the internal pore structure. The pore structure is defined by the type of cement paste, the quality of the ITZ and the porosity of the aggregates. It is considered that concrete should be evaluated for chloride permeability wherever there is a potential risk of chloride-induced corrosion (Joshi and Chan, 2002).

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The chloride penetrability of concrete was determined in accordance with ASTM C1202 (ASTM, 2012) using a 50 mm long, 100 mm diameter concrete section cut from the middle of a 100Ø/200 mm concrete cylinder. The three middle sections obtained from one cylinder were tested at different ages. The external 20 mm sections of the cylinder were rejected. The resistance of concrete to chloride ion penetration is represented by the total charge passed, in coulombs, through a water-saturated concrete section during a test period of 6 h. In this study, the chloride ion penetrability test was carried out on concrete specimens at the ages of 28 d, 6 months and 1 year; each result is the average of three measurements.

Results and discussion

Physical properties

Density, water absorption and accessible pore tests

The obtained results are presented in Table 5. The replacement of natural sand by fine RAs (PCS or MMS) produced a reduction in density and an increase in absorption capacity and accessible air voids of the hardened concrete. Similar results were reported by Khatib (2005) and López *et al.* (2007). The higher the percentage of RA used, the greater the difference between the values for the RA concrete and conventional concrete. Due to the lower density of the MMS aggregates, concrete mixes produced with those aggregates obtained lower density than those made with PCS aggregates. Nevertheless, the decrease in the density of concrete produced with 50% MMS aggregates was lower than 5% when compared with that of conventional concrete.

Figure 2 shows the influence of the use of fine RAs on the absorption capacity and accessible porosity. The influence of fine RAs on these properties was greater than on the density of the recycled concrete because the difference in absorption capacity of RAs and natural aggregates was higher than the difference between their densities. The increase in absorption capacity of concretes made with 35% and 50% fine RAs was

Figure 2. Water absorption and accessible porosity of RA concretes (CP or CM) compared with conventional concrete (CC) at 28 d

similar. The absorption capacity of CM50 concretes increased by 40% with respect to that of conventional concrete after 28 d of curing.

Mechanical properties

Compressive strength

Table 6 shows the compressive strength values obtained by all the concretes studied at 7 d, 28 d and 365 d. At 7 d, the conventional concrete exhibited similar strength to that of the concretes made with PCS aggregates but, after 28 d of curing, all the concretes made with fine RAs (CP and CM concretes produced with all the percentages of aggregates indicated) showed a higher compressive strength than the conventional concrete. The medium-low w/c ratio and adequate bond strength of the fine RAs (PCS and MMS) enabled the RA concretes to show comparable behaviour

	Compressive strength: MPa			Splitting tensile strength at 28 d: MPa	Modulus of elasticity at 28 d: MPa
	7 d	28 d	365 d		
CC	51.0	52.5	63.2	4.51	39 546
CP10	47.7	56.2	66.2	4.57	38 776
CP20	52.7	56.9	69.5	4.63	40 410
CP35	51.5	58.3	79.3	4.84	38 750
CP50	48.7	57.2	69.0	4.90	40 942
CM10	55.9	61.1	70.8	4.30	37 346
CM20	56.2	57.8	71.9	4.15	39 311
CM35	51.2	52.0	71.4	4.40	34 126
CM50	50.3	54.5	68.0	4.65	35 298

Table 6. Mechanical properties of concretes

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to that of conventional concrete (Neville, 1995). According to some researchers (Higashiyama *et al.*, 2012a, 2012b; López *et al.*, 2007; Pacheco-Torgal and Jalali, 2010; Torkittikul and Chaipanich, 2010) an improved interfacial zone due to the use of rough ceramic, as well as the strength of the sintered ceramic (mullite), contributes to this increase in strength. Taha and Nounu (2008) also reported that aggregate texture plays an important role in the compressive strength of concrete. The presence of water in the PCS and MMS aggregates allowed adequate hydration of the cement through internal curing, improving the cement hydration and consequently the concretes' properties (ACI, 1997; Suzuki *et al.*, 2009). The microstructures of the improved ITZ and the ITZ in lightweight aggregate concrete showed similarities. Moreover, several authors have found higher compressive strength results through the use of lightweight aggregates (Bentz, 2007; Espinoza-Hijazin and Lopez, 2011; Golias *et al.*, 2012) or self-healing effects (Şahmaran *et al.*, 2014) as internal curing agents contribute to better hydration of the cementitious system.

An analysis of the highest compressive strengths obtained indicates that concretes made with 20% and 35% of either type of fine RA were adequate for use. The highest compressive strength was obtained in concretes made with 35% of PCS (fine ceramic) aggregate. The lower strength of the CM concretes is probably due to the more heterogeneous composition of the MMS (mixed) aggregate and the presence of soft material.

Figure 3 shows that the concretes made with more than 20% of fine RAs achieved a higher increase in compressive strength from 28 d to 365 d than conventional concrete. Concretes made with 35% of PCS and MMS obtained the highest increase over that period, which could be attributed to the pozzolanic effect of the ceramic aggregates (Vegas *et al.*, 2011) (the MMS aggregate also contained 70% ceramic material). The good results obtained with the MMS aggregates could also be due to the estimation of a lower water absorption rate (80%) than the aggregates actually had (80%) was the absorption capacity of aggregates submerged for 20 min).

Figure 3. Compressive strength increase from 28 d to 365 d of curing

Although the compressive strength decreased with an increase in the replacement ratio of recycled brick aggregates in the study of Alves *et al.* (2014), a higher rate of strength development occurred for mixes incorporating brick aggregates compared with the reference concrete. The same behaviour was reported by Khatib (2005) and was attributed to possible pozzolanic activity of the brick aggregates. Another reason for the higher rate of strength development reported by Cachim (2009) is that the higher water content of the mixes (in order to maintain the same workability) leads to later hydration of the cement (internal curing); this was also described by Pacheco-Torgal and Jalali (2010).

Splitting tensile strength and modulus of elasticity

All the RA concretes studied achieved similar splitting tensile strengths to that of conventional concrete, as shown in Table 6. All the concretes made with PCS (fine ceramic) aggregates obtained a higher splitting tensile strength than did the conventional concrete. This is probably due to the rougher surface of this type of RA (López *et al.*, 2007; Mansur *et al.*, 1999) and a higher pozzolanic effect and thus the production of an effective ITZ (Khatib, 2005). Among the RA concretes, those produced with 50% fine RA showed the highest splitting tensile strength. The fine RAs were used in a dry condition and their absorption capacity facilitated the adequate adherence of the cement to their surface when water was absorbed (Etxeberria *et al.*, 2006).

Figure 4(a) shows the ITZ of concrete made with PCS aggregate; the fine ceramic aggregate marked by the square is detailed in Figure 4(b). The fine ceramic grain had an adequate ITZ due to cement accumulation on the interface. Torkittikul and Chaipanich (2010) also reported that concretes made with 50% of ceramic waste aggregate had no cracks between the interfaces of the ceramic aggregate particles and the cement paste. This is consistent with the fact that the compressive strength of the specimens containing ceramic waste aggregate was higher than that of the control mix.

The modulus of elasticity of the concrete made with fine RAs was similar to that of the conventional concrete – expected behaviour due to the fact that the modulus of elasticity is determined by the coarse aggregate used in the manufacture of the concrete (Neville, 1995). The concretes produced with 35% and 50% MMS aggregates suffered a slight reduction in elastic modulus (see Table 6); this is probably due to lower stiffness of the mortar adhered to the MMS aggregates. Similarly, Evangelista and de Brito (2007) concluded that the elastic modulus values of concretes made with 30% of fine concrete RAs as a substitute of natural sand were significantly lower than those of conventional concrete.

Figure 5 shows that the concretes made with PCS aggregates achieved the splitting tensile strength values obtained by the conventional concretes. Concretes produced with mixed fine

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(a)

(b)

Figure 4. The ITZ of concrete made with PCS aggregate. (a) Concrete sample. The ITZ of the ceramic aggregate was adequate (a fine ceramic aggregate is marked inside the square, detailed in (b)). (b) The fine ceramic aggregate. The ITZ was much denser than the aggregate. The ITZ of natural aggregates can be the weakest zone in concrete

aggregates (MMS) showed decreases in splitting tensile strength of 5% and 8% for 10% and 20% replacements respectively, but the 50% MMS concrete (CM50) achieved a slightly higher splitting tensile strength than the conventional concrete. According to Alves *et al.* (2014), the use of superplasticiser eliminates the effect of agglutination between the fine RAs, thus improving

Figure 5. Splitting tensile strength and modulus of elasticity (28 d of age) of RA concretes compared with conventional concrete

the compressive and splitting strength. Concretes produced with more than 35% mixed RAs showed a reduction of 13–10% of the modulus elasticity with respect to that of conventional concrete.

Durability

Capillary water absorption

The results of assessing the concrete specimens' capillary water absorption over a period of 2 h are shown in Figure 6: the capillary water absorption of the conventional concrete was lower than that of any of the RA concretes, as also noted by other researchers (Debieb and Kenai, 2008; Evangelista and de Brito, 2010). The concretes made with fine ceramic PCS aggregates (CP concretes) showed a greater capillary absorption capacity than the concretes made with fine mixed RAs (CM concretes). This is most probably due to the grading size distribution of the fine ceramic RA: the PCS had 25% of aggregates greater than 4 mm compared with 14% for MMS and 1% for natural aggregate). The larger aggregate size produced a connectivity between grains and thus increased the capillary absorption capacity; this

Figure 6. Capillary water absorption

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has also been reported by other researchers (Levy and Helene, 2004; Wirquin *et al.*, 2000; Zega and Di Maio, 2011). It should also be taken into account that the absorption capacity of RAs was considered to be 80% at concrete production, but was probably higher, resulting in a lower effective w/c ratio of recycled concrete than was expected and consequently a denser cement paste.

The sorptivity values (Table 5) of all concretes ranged from 0.0338 mm/min^{1/2} for conventional concrete to 0.0633 mm/min^{1/2} for CP50 (produced with 50% fine ceramic aggregate). The sorptivity values obtained in the first 2 h can be correlated with concrete w/c ratios. According to Neville (1995), values of 0.09 mm/min^{1/2} and 0.17 mm/min^{1/2} correspond to concretes with w/c ratios of 0.4 and 0.6 respectively. Gonzalez-Corominas and Ettxeberria (2014) found a sorptivity value of 0.016 mm/min^{1/2} for concrete made with 15% ceramic fine aggregate in place of natural sand using an effective w/c ratio of 0.0285; the concrete made with 15% of fine aggregates achieved a similar sorptivity to that of conventional concrete. Discontinuity of the pores due to the homogeneous distribution of sand grains through the cement paste had little influence on this property. However, the tests affirmed that the quality of the cement paste and w/c ratio had more influence on sorptivity than the replacement level of the RAs.

Chloride ion penetrability

The chloride penetration resistance of the concretes was assessed at 28 d, 6 months and 1 year of curing. Figure 7 shows that the resistance to chloride ion penetration at 28 d for the concretes made with mixed recycled fine aggregates decreased with an increase in RA content. The concretes produced with 35% and 50% of ceramic fine RAs had the highest resistance to chloride ion penetration due to the presence of high-density cement paste in the ITZ as shown in Figure 4. The splitting tensile strengths of CP35 and CP50 concretes were also the highest (see Table 6).

Figure 7. Total charge passed through concretes at 28 d, 6 months and 1 year age of curing

After 6 months and 1 year of curing, the concretes with ceramic RA showed a lower chloride penetration than that of conventional concrete, although concretes with 20% of ceramic RAs had a higher resistance to chloride than that of conventional concrete. Pacheco-Torgal and Jalali (2010) and Higashiyama *et al.* (2012a, 2012b) also concluded that the durability of concretes improved significantly in concretes produced with fine ceramic aggregates. Binici (2007) concluded that the use of fine ceramic aggregate as a substitution of up to 60% natural sand strongly improved the chloride penetration resistance of the concretes produced. As shown in Figure 7, the concretes can be classified according to ASTM C1202 (ASTM, 2012) corrosion ranges as between very low and low risk of corrosion after 1 year.

Figure 8 shows the increase of chloride resistance in all the concretes from 28 d to 1 year of age. The conventional concrete achieved an increase of 45% over this time period. All the concretes produced with more than 20% of ceramic or mixed RAs achieved a higher increase of resistance compared with the conventional concrete. Concrete CP20, made with 20% of fine ceramic aggregate, achieved the highest reduction with respect to the electrical charge passed through the concrete. This is probably due to adequate internal curing and some pozzolanic effect (Gonzalez-Corominas and Ettxeberria, 2014): highly hydrated cement paste produces a dense mortar, which is quite impermeable. Zhutovsky and Kovler (2012) also obtained an improvement in chloride penetration resistance in concretes produced with low percentages of fine lightweight aggregates as a substitution for natural aggregates. Due to their water absorption capacity, the lightweight aggregates produced internal curing, which improved the cement hydration. That effect did not appear in the capillary water absorption test, as also confirmed in this research work.

Conclusions

The following conclusions can be made based on the results of this study.

Figure 8. Reduction in charge passed through the concretes at 1 year of age with respect to 28 d value

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- The use of up to 50% of fine ceramic or mixed recycled aggregates as a substitute for natural sand caused a reduction in concrete density of less than 5% compared with conventional concrete. However, the absorption increased by more than 40% in comparison with conventional concrete.
- The early-age compressive strength of concrete made with fine RAs was lower than that of conventional concrete. However, after 28 d of curing, all the concretes produced using up to 50% of fine RAs achieved a higher strength than the conventional concrete.
- Due to the ceramic grains in both types of fine RA used in this work, the increase in compressive strength of the RA concrete from 28 d to 365 d was higher than that of conventional concrete. The concrete made with 35% fine ceramic RA or mixed RA as a substitute for natural sand achieved the greatest increase in compressive strength.
- The values of splitting tensile strength and modulus of elasticity of the RA concretes were similar to those of conventional concrete.
- The chloride resistance of concrete made with up to 50% of ceramic or mixed fine RAs at 1 year was similar or better than that of conventional concrete. The presence of ceramic fine grains caused a reduction of chloride ion penetrability in the concretes.

According to this work, the use of low percentages of ceramic or mixed fine aggregate as a substitution for natural sand could improve the properties of high-strength concretes. Over time, the properties of RA concrete improved more than those of conventional concrete, and consequently similar or better properties were obtained for the RA concrete. As has also been demonstrated by other researchers, the use of low percentages of high absorption capacity aggregates for concrete production allows internal curing of the concrete and mitigates autogenous shrinkage. The use of low percentages of recycled ceramic or mixed fine is thus considered suitable for the production of precast elements and/or high-volume concrete elements.

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