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Influence of steam curing on the pore structures and mechanical properties of fly-ash High Performance Concrete prepared with recycled aggregates

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Abstract

In this research work, High Performance Concrete (HPC) was produced employing 30% of fly ash and 70% of Portland cement as binder materials. Three types of coarse recycled concrete aggregates (RCA) sourced from medium to high strength concretes were employed as 100% replacement of natural aggregates for recycled aggregate concrete (RAC) production. The specimens of four types of concretes (natural aggregate concrete (NAC) and three RACs) were subjected to initial steam curing besides the conventional curing process. The use of high quality RCA (>100MPa) in HPC produced RAC with similar or improved pore structures, compressive and splitting tensile strengths, and modulus of elasticity to those of NAC. It was determined that the mechanical and physical behaviour of HPC decreased with the reduction of RCA quality. Nonetheless steam-cured RACs had greater reductions of porosity up to 90 days than NAC, which led to lower capillary pore volume.

1. INTRODUCTION

Construction and demolition waste (C&DW) is one of the most voluminous and heaviest waste streams generated in the European Union. C&DW accounts for approximately 33% of all waste generated in the EU [1] and it consists of several materials, including concrete, bricks, gypsum or metals, many of which can be recycled. European Union countries encourage reusing and recycling in construction by publishing C&DW recycling targets. According to the Waste framework Directive 2008/98/EC [2], the minimum recycling percentage of C&DW by the year 2020 should be at least 70% by weight. In spite of the variability on recycled aggregate properties, proper treatment and categorization of the C&DW allow recycled aggregates to be more efficiently employed [3].

Over the past twenty years, many studies concerning the effects of using recycled coarse aggregates as a replacement of natural aggregates in concrete have been published [3–8]. Generally, recycled aggregates have higher porosity, water absorption capacity and contaminant content and also lower density and abrasion or impact resistance than natural aggregates. The use of RCA for the production of low and medium strength concretes (up to 50-60 MPa according to ACI [9] and BS EN 206-1) decreases the compressive strength and modulus of elasticity of the concrete. Recycled aggregate concretes show increased shrinkage, creep and water sorptivity in comparison with those of natural aggregate concrete (NAC). Nevertheless, the use of appropriate mix design methods with the addition of mineral admixtures can mitigate the negative influence of recycled aggregates [10,11].

But relatively few investigations [11–18] have been published about using recycled aggregates for High Performance Concrete (HPC) production. Some studies [11,14,18] revealed that the quality of the parent concrete, from which source the recycled aggregates are derived, is a crucial factor affecting the properties of the resulting HPC produced. It has been reported that the use of RCA, sourced from crushing original HPC, for the production of new HPC can improve mechanical and durability properties even at high replacing ratios [14]. Limbachiya [13] concluded that only 30% of coarse RCA could be used to produce HPC. Tu et al. [16] and Pacheco-Torgal et al. [17] affirmed that recycled aggregates were not suitable for high strength concrete applications due to compressive strength reduction and poorer long-term durability.

Fly ash represents a beneficial mineral admixture, especially when incorporated in Recycled Aggregate Concrete (RAC). Certain studies [14,19,20] have reported three possible mechanisms which could cause an enhancement in the RAC ‘s behaviour: part of the mineral admixtures penetrates into the RCA’s pores causing a subsequently improvement in the interfacial transition zone (ITZ) bonding between the paste and the aggregates; the cracks originally present in the aggregates being filled by hydration products; RCA would have a residual binding ability which could be activated by using Fly-Ash (FA).

The use of fly ash has been widely accepted in recent years and its influence on many properties of concrete in both fresh and hardened states have been studied [21–24]. Equally, fly ash ensures economic benefits through saving cement, environmental benefits by using industrial wastes, and technical improvements because of the higher concrete durability [22]. Certain authors [21,24] attempted to produce concrete with high volumes of fly ash, but the most common replacement ratios used in low water/binder ratio concretes are 25-30% [25,26]. On the whole, the long term mechanical and durability properties of fly ash concretes are higher than those of ordinary Portland cement concretes. However, the extended hydration period required for fly ash concrete intensifies dependence on curing conditions. Moreover, for fly ash concrete, at early ages, the heat generation is reduced but the setting and hardening time are increased.

Steam curing at ambient pressure is the most common technique among the accelerated curing methods of concrete. In applications, such as pre-cast concretes and pre-stressed reinforced concretes, which require high mechanical performances at very early ages, the steam curing enables concretes which normally have slower strength gain, such as fly ash concretes, to achieve faster strength gain at the required levels [21]. A typical steam curing cycle consists of a pre-curing treatment of up to 4 hours and a heating and cooling rate of 10-45ºC/h. The maximum temperature reached in steam curing is usually limited to 60±5ºC and this temperature is kept constant at the maximum value for 6-18h [21–23,26,27].

When concrete is subjected to steam curing, the hydration of cement proceeds quickly, the speed of CSH gel formation also increases and the gel wraps round the cement or fly ash particles [22]. The acceleration of compressive strength gain eases the production of pre-cast and pre-stressed concrete elements in the pre-casting plants. The required early compressive strength for formworks demolding and bar stress transmission is in general at more than 30 and 50 MPa respectively [27,28]. Nevertheless, heat and moisture treatment of the concrete also increases the proportion of large pores in the cement paste [29]. Inadequate steam curing regimes can lead to detrimental changes in porosity and pore size distribution of concrete which can significantly reduce mechanical and durability properties, especially over the long term [26].

The total pore volume, pore size distribution and pore interconnection are the main properties influencing the mechanical and durability behaviour of concretes. Several investigations [30,31] have inferred that the mechanical properties and permeability of concrete are principally dependent on the meso and macrocapillary pores. Porous structures in cementitious materials have been widely investigated by using the Mercury Intrusion Porosimetry (MIP) technique [26,32–34]. Nevertheless, this technique has been criticized due to the fact that the pore structures characterized by the MIP method are based on improper assumptions. These assumptions on pore connectivity and pore dimensions can produce differences in the measured MIP values to those of the real pore network [34]. Besides these limitations, MIP is still considered as an appropriate technique used to compare the pore structures of cementitious systems.

This paper details research on the influence of initial steam curing on the pore structures and mechanical properties (compressive strength, splitting tensile strength and modulus of elasticity) of Portland-Fly Ash HPCs containing recycled concrete aggregates. Three different qualities of original concretes (40, 60 and 100MPa of characteristic compressive strength) were crushed to obtain coarse recycled aggregates which were used to replace 100% of the natural coarse aggregates. After concrete casting, the specimens of each type of concrete were exposed for the first 24 hours to two different initial curing regimes, air curing and steam curing, in order to assess the influence of steam curing on the pore structures and the mechanical behaviour.

2. EXPERIMENTAL DETAILS

2.1. Materials

2.1.1. Binders and admixture

The cement used was a commercially available Portland cement (CEM I 52.5R) equivalent to ASTM Type I cement. The Portland cement had a Blaine's specific surface of 495 m^2/kg and a density of 3150 kg/m^3. A rapid-hardening Portland cement was used in order to achieve concretes of 1-day compressive strength which were higher than 50 MPa, thus meeting the requirements for precast and prestressed concrete [27,28]. The FA used had a specific surface of 336 m^2/kg and a density of 2320 kg/m^3, was equivalent to ASTM class F. The chemical compositions of the Portland cement and the FA are given in Table 1.

A high performance superplasticizer based on polycarboxylate ether (PCE) with a specific gravity of 1.08 was used for concrete production. The dosage used was at a constant percentage of binder weight (1.5%) following the manufacturer's recommendations.

2.1.2. Aggregates

Two types of 4-10 mm coarse natural aggregates (rounded siliceous and crushed dolomitic) and two siliceous river sands (size fractions of 0-2 mm and 0-4 mm) were used for the production of the natural aggregate concrete (NAC). The natural aggregates were those used in previous research [18] and selected for being those used in HPC to produce commercially-available prestressed concrete elements from a Spanish factory.

The recycled aggregates, RCA100, RCA60 and RCA40, which were used in complete replacement by volume of the natural coarse aggregates, were obtained from crushing three parent concretes of different qualities (of 100, 60 and 40MPa of characteristic compressive strength). The three recycled aggregates mentioned were employed in a previous research [18] with maximum sizes of 10 mm. The RCA100 were sourced from rejected 100 MPa compressive strength concrete specimens obtained from the same Spanish prestressed concrete manufacturer. The parent concrete used to produce RCA100 was the same as the NAC of this study. The 60 MPa parent concrete was especially produced in the laboratory to achieve 60 MPa at 28 days, after which it was crushed for RCA60 production and stored for a minimum of 180 days before using in concrete fabrication. The RCA40 were sourced from crushing 3-year old precast beams with a compressive strength of 40MPa at 28 days. The parent concretes of 60 MPa and 40 MPa were composed of crushed fine (0-4 mm) and coarse limestone aggregates (4-10 mm and 10-20 mm) and Ordinary Portland cement (CEM I 42.5, type I according to ASTM specifications).

The particle size distributions are shown in Fig. 1 and their physical properties are shown in Table 2. The natural aggregate had better physical properties than those of the recycled concrete aggregates. Nonetheless, the physical and mechanical properties of the RCA improve as the original concrete quality increases.

According to Jennings [31], pore structure is the most important feature which may act as flaws in cement based materials. The porosity of recycled aggregates was determined by Mecury Intrusion Porosimetry (MIP) using a 'Micromeritics Poresizer 9320' in samples taken from the RCAs of approximately a total weight of 5.5 g. Each mean value was calculated from testing three RCA samples and each sample was composed by three Ø 1 cm RCA particles. The pore size diameter can be divided into four pore size ranges, following Mindess [35] classification; >10μm (air), 10-0.05 μm (macropores), 0.05-0.01μm (mesopores) and <0.01μm (micropores). As can be seen in Fig. 2, some differences in the range of 0.01 to 10 μm were found, RCA-60 showed the lowest percentage of pore volumes in the range of 0.05-10 μm, while RCA-100 contained the lowest percentage of pore volumes of smaller than 0.05 μm. RCA-40 showed significantly higher pore volumes than those RCA-100 and RCA-60 at all the pore size ranges. The total porosity results from the MIP of the RCA100, 60 and 40 were 4.88, 5.73 and 8.63% respectively (see Table 2). The detailing of the standard deviations were 0.31, 0.25 and 0.40%. The reduction on the quality of the parent concrete led to higher total porosity of the RCAs.

2.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory. The NAC proportioning was provided by a Spanish HPC manufacturer and followed the Fuller's dosage method [36]. Following previous research [12,18], the three types of recycled coarse aggregate were used to substitute (by volume) 100% of the natural aggregates in each RAC series (RAC were referenced as 100, 60 and 40, according to the strength of the parent concrete). The concrete proportioning parabola correctly fitted the Gessner parabola provided by the Fuller's method in both cases, when using NA and RCA.

The moisture content of the fine and coarse aggregates was reproduced following the moisture conditions defined in previous studies [12,18]. The fine aggregates were over-saturated (3-4% of moisture content). In order to control the concrete production, the recycled coarse aggregates were nearly saturated, at 80-90 % of their water absorption capacity. In general the higher water absorption of the RCAs reduces the workability of the concrete mixtures, however in this case the moisture content in the RCAs neutralized such effect. In addition, the high moisture states enabled higher control on the reacting water with the binder and avoided problems derived from water on the RCAs surface or bleeding [37].

As shown in Table 3, 380 kg of binder (266 kg of cement and 114 kg of fly ash) and a constant effective water - binder ratio of 0.285 were used in all concrete productions (considering as being effective water that water which reacted with the binder). The volume of mixing water was determined before concrete production, in order to maintain constant the water amount reacting with the binders (effective water). The volume of mixing water was compose of the effective water and the water absorbed by the aggregates at concrete production (effective absorption capacity). The effective absorption capacity of aggregates was determined by submerging the aggregates in water for 20 minutes.

The total water amount of the concrete was considered as the total amount of effective water, effective absorption capacity of aggregates and moisture water (water inside the aggregates) [38]. The total water amount in the RAC studied was found to be higher as a result of its higher absorption capacity which initially provided the same cement paste conditions to NAC and RAC.

The amount of chemical admixture added was kept constant at 1.5% of the cement weight in all concrete mixtures. The mix proportioning and the admixture amount produced dry consistencies of fresh concrete, between 0-20 mm in the concrete slump test (S1 class following the EN 206-1:2000 standard).

2.3. Specimens casting and curing

For each concrete mixture, 100 mm cubic specimens were used to determine the compressive strength at the age of 1, 28 and 90 days and 200 x Ø100 mm cylindrical specimens were used for the splitting tensile strength and the modulus of elasticity tested at 28 days. Samples extracted from 100mm concrete cubic specimens were used for the Mercury Intrusion Porosimetry (MIP) test. The specimens were compacted using a vibrating table during two stages of 30 seconds each.

The concrete specimens were divided into two series, air-cured (AC) and steam-cured (SC). The air-cured specimens were stored in the laboratory at ambient conditions for 24 hours. A wet burlap and a plastic sheet being used to cover the specimens to ensure a reduction in water evaporation. The other concrete series was cured in a steam bath 4 hrs after casting (without demolding). Both the steam curing temperature and its duration have important effects on the progress of the hydration reaction and product formation [38]. The steam curing cycle used, which followed the method of Poon and Kou [39] and Ramezanianpour et al. [27], is shown in Fig. 3. After the initial curing stage of 24 hours, the specimens from both series were demolded and three cubes of each series were tested for the 1-day compressive strength. The rest of the specimens were further cured in a curing chamber at constant conditions of 23ºC and 95% humidity until the other test ages were reached.

2.4. Tests of hardened properties of concrete

The compressive strength and the porosity and pore size distribution analysis were determined at the ages 1, 28 and 90 days after the concrete casting. The splitting tensile strength and the modulus of elasticity were tested at the age of 28 days.

2.4.1. Pore structure

The testing of porosity and pore structure was performed by Mercury Intrusion Porosimetry (MIP) with a 'Micromeritics Poresizer 9320' mercury intrusion porosimeter according to BS7591 Part 1. This test was carried out on small concrete pieces, weighing approximately 5.5 g. The crushed samples were obtained from the 100 x 100 x 100 mm cubic specimens. The samples were first immersed in acetone for 4 days to stop the cement hydration and then introduced in a vacuum drier for 2 hours to extract the remaining acetone. Before testing, the samples were dried in an oven at 50ºC for 4 days. Using the MIP technique, a measure of the total porosity of the sample as well as the surface area of the pore network was also obtained. The MIP test was conducted on the concrete samples cured at ages 1, 28 and 90 days and each result represents the average of three tested samples.

2.4.2. Compressive strength, splitting tensile strength and modulus of elasticity

The mechanical properties of concretes were determined using a compression machine with a loading capacity of 3000 kN. The compressive strength was measured using 100 mm cubic specimens following the UNE-EN 12390-3. The splitting tensile strength and the modulus of elasticity were tested at 28 days employing 200 x Ø100 mm cylindrical specimens in accordance with UNE-EN 12390-6 and UNE 83-316-96 specifications, respectively. Each presented value is the average value taken from 3 specimens.

3. RESULTS AND DISCUSSION

3.1. Pore structure

The porosity, average pore diameter and threshold diameter obtained by the MIP test at the ages of 1, 28 and 90 days are presented in Table 4. The standard deviations, which are also reported, were lower than 0.6%. The variability of results between NAC and RACs was similar, however the steam cured concretes' results showed slightly higher variability than those of conventional air curing.

Fig. 4 shows the cumulative mercury intrusion volume after 1, 28 and 90 days of curing employing both curing methods (AC and SC). The pore size distributions of all the samples followed a similar pattern, each curve having three distinct regions: one with a gentle increase of pore volume of pore sizes of up to 0.1 µm; the second within the pore size range between 0.1-0.01 with a significant increase in pore volume; and the last being between pore size of 0.01–0.005 µm with a gentle slope. The majority of the intrusion volume in the first range is due to macropores and macrocracks and the filling of the non-wetting liquid (mercury) into the rough texture of the exterior surface of the crushed sample [32,40]. The majority of the intrusion in the second range is due to capillary pores and the last one due to some parts of gel pores [35].

3.1.1. Effect of original quality of RCA on pore structure

After 1 day of curing, the RAC-100 had significant lower average pore diameters than those of the NAC, in both curing methods. Likewise Fig. 4a show that the RAC-100-AC had slightly lower cumulative intrusion (pore volume) at any pore size than the NAC-AC. In steam curing concretes (Fig. 4b), the RAC-100-SC and the RAC-60-SC had finer pore distributions from 1 to 0.05 µm, but the total cumulative intrusions were similar to those of the NAC-SC.

The porosity reduction observed in RAC, containing recycled aggregates sourced from high quality parent concrete (> 60 MPa), when compared to the results of the NAC can be explained by an ITZ improvement. Such early-age improvements in recycled aggregate concretes were attributed by Poon et al. [41] to the reduction of the water-cement ratio in the ITZ at early hydration, a similar behaviour pattern also observed in lightweight aggregates[42,43]. The partially saturated aggregates absorb a certain amount of water, lowering the w-c ratio in the ITZ at early age, and the newly formed hydrates gradually fill the pores in the ITZ.

Nevertheless the RAC-40 concretes had the highest pore volume at all pore sizes. The RAC-40-AC and the RAC-40-SC had total intrusions of 0.053 and 0.048 mL/g, respectively and capillary pore intrusions (between 10-0.01 µm) of 0.046 and 0.042 mL/g, respectively. Park et al. [44] and Igarashi et al. [30] measured the total pore intrusion of cement pastes and capillary pore intrusion of concretes, respectively, using OPC also at early ages (1 day) by the MIP method. According to their results, the total porosity of OPC mixtures with a low water/cement ratio was approximately 0.080 mL/g [44] and the capillary pore volume was in the region of 0.100 mL/g at 24 h [30]. The early-age total pore volume and the capillary pore volume of all the concretes produced in this study, even those RAC containing the RCA-40MPa, were lower than those reported by Park et al. [44] and Igarashi et al. [30] due to the refinement of the porous structure on account of the 30% fly ash replacement of rapid-hardening Portland cement [45,46].

At 28 and 90 days of curing, the RAC-100 generally had similar or lower average pore diameters and threshold pore diameters to those of the NAC at 28 and 90 days of curing (for both curing methods). The pore size distributions of the RAC-100 at 28 days of curing were lower than those of the NAC in all pore sizes (see Fig. 4c) for air-cured concretes. The NAC-SC and the RAC-100-SC also showed similar pore volumes (0.025 mL/g) in the steam curing concretes (see Fig. 4d). Fig. 4e and 4f show the results of the 90-day cured samples in which the RAC-100 showed a finer pore structure and lower pore volumes to those of the NAC. The RCA100 had similar pore size distribution (see Fig. 2) to that of NAC due to the similar quality of the mortar paste. The finer pore structures of the RAC-100 could be explained by an improvement of the ITZ and the new mortar paste through internal curing [15,47].

The total porosities and threshold values of the RAC-60 were higher than those of the NAC, whose average pore diameters were generally very similar at the ages of 28 and 90 days. The RAC-60-AC had slightly lower large macrocapillary pores (10-0.1 μm) than the NAC-AC, but the amount of mesocapillary pores (0.05-0.01 μm) rapidly increased (Fig. 4c and 4e). The RAC-60-SC had slightly higher pore volume (0.028 mL/g) despite showing lower macrocapillary pore (10-0.05 μm) volume than that of NAC-SC (Fig. 4d and 4f).

The porosity, the average pore diameter and the threshold diameter at 28 and 90 day were increased with the reduction of the RCA quality, irrespective of the curing method used (see Table 4), due to the influence of the aggregate type used. Also the concretes produced employing the lowest quality RCA had a coarser pore size distribution (Fig. 4d and 4f).

It must be noted that the steam-cured RAC showed higher reduction (between 16 and 36%) of the total cumulative intrusion volume from 28 to 90 days in comparison with the NAC (5%). Such higher reductions are more than likely caused by the original higher porosity of the RCA which permitted a time-extension of hydration and a more effective water transport through the pore structure in steam curing concretes [15,48]. The RAC showed similar or lower macrocapillary pore volumes to those of the NAC-SC but their meso and microcapillary pore size volumes were similar or slightly higher than those of the NAC-SC.

3.1.2 Effect of steam curing on pore structure

Despite the fact that steam curing generally produces larger capillary pores in NAC [49], the pore structure of the steam-cured concretes with 1 day of curing (Fig. 4b) was improved by the use of recycled aggregates due to a denser ITZ [41]. The use of RCA mitigated the increase of macrocapillary pores due to steam curing, which had been typically observed in steam-cured natural aggregate concretes [29]. After 1 day of curing, the steam-cured concretes obtained lower porosity, average pore diameter and threshold pore diameter than those concretes cured in air for a given aggregate type (Table 4 and Fig. 5). The influence of steam curing was especially positive in the reduction of the average pore size, which was between 12-34% lower in comparison to those of the air-cured concretes.

The steam curing process enhanced the pozzolanic reactions which led to refinements of the pore structure of the RAC [50]. This reaction was clearly observed in the higher reduction of the average pore diameter of the RAC-60-SC when compared with the same concrete subjected to air curing. Several studies [14,39] have confirmed that the use of RAC can improve the binder's hydration by containing higher amount of portlandite and unreacted cement particles. The parent concrete from RCA60 was the youngest concrete used in recycled aggregates production, consequently having more portlandite, due to a lower carbonation ratio, reacting with the pozzolans from FA and increasing CSH formation.

The MIP results at 28 and 90 days still showed lower average pore diameter for steam-cured concretes (Fig. 5). In addition it must be noted that the RAC-60 and the RAC-40 had lower relative average pore diameters, when comparing steam-cured and air-cured concretes, than NAC after 90 days of curing. Moreover the porosity increase, which was due to the use of lower quality aggregates, was lower when they were exposed to steam curing than when they were air-cured. The porosities of the RAC-60-SC and the RAC-40-SC were 10 and 21% higher, respectively, than that of the NAC-SC; while the porosity of the RAC-60-AC and the RAC-40-AC was 17 and 34% higher, respectively, than that of the NAC-AC after 90 days of curing. Also pore size distributions revealed that steam cured concretes had similar distributions even when using medium quality RCA (RCA-40) and that the RAC-100 and the RAC-60 kept lower capillary pore volumes than the NAC after 90 days of curing (Fig. 4f).

3.2.2. Effect of concrete's age on pore structures

Fig. 6 shows the porosity reduction according to three pore size ranges from ages 1 to 90 days of the concretes. When using steam curing, the RAC experienced higher reductions of pore volumes than the NAC from 1 to 90 days age, with respect to all the pore size ranges. Typically, steam-curing produces diminished hydrations of binders due to the isolation of the unreacted binder particles and disruption of the water circulation [22]. The use of porous RCA may permit an enlarged and continuous hydration of binders which led to higher refinement of the pore structure. The highest reductions, especially with respect to the capillary pores (10-0.01µm) were observed in the RAC-40-SC. The RCA40 had the highest porosity which could act as internal curing reservoir and enlarge the binder hydration. A fact that has been reported in other studies using recycled aggregates and lightweight aggregates [15,47,51].

3.2. Compressive strength

The compressive strength test results at the ages of 1, 28 and 90 days are presented in Table 5. The employment of steam curing proved to be essential in the production of concrete for prestressed concrete elements. The use of fly ash diminished the early-age compressive strength, which was detrimental for concrete mixtures containing RCA60 and RCA40. However, the concrete mixtures containing these two lower-quality aggregates could only reach the minimum of compressive strength at 1 day of curing (50 MPa [27,28]) by undergoing the steam curing regime. The standard deviations indicated in Table 5 were lower than 7.5 MPa and the compressive strength results fulfilled the tolerance values required by the Spanish technical specification on prestressed concrete sleepers [28]. The only concrete mixture showing higher standard deviations than NAC was RAC60. RAC60 had been prepared with the youngest parent concrete which appeared to be more influential on the variability of compressive strength due to the remaining reactivity of the RCAs [14,52].

3.2.1. Effect of original quality of RCA on compressive strength

The compressive strength results show that the use of lower quality RCA reduced the compressive strength of the RAC when compared with the NAC. However, with respect to the high quality RCA, after 1 day of curing, the study determined that the RAC-100-SC produced with RCA sourced from 100MPa recycled concrete and steam-cured, obtained the highest compressive strength. These values being similar to that of the NAC-SC, steam-cured concrete prepared with natural aggregates. Furthermore, with respect to air-cured concretes, the RAC-100-AC attained a higher 1-day compressive strength than the NAC-AC.

After 28 and 90 days of curing, the RAC-100-AC achieved the highest compressive strengths which were slightly higher than those of the NAC for both ages (see Table 5). The results revealed that the use of the RCA-100 increased the mechanical behaviour. The improvement of the compressive strength of HPC by using high quality have been previously reported by other studies [11,14,18].

Despite the fact that the 28-day compressive strength of the RAC-60 was slightly lower than that of the NAC, this small decrease was in line with the values determined in other studies [14]. However, it should be noted that the RAC-60-AC achieved similar compressive strengths to those of the NAC-AC at 90 days, highlighting the higher potential of the recycled aggregates in reacting with fly ash due to the higher pozzolanic enhancement [53].

A severe decrease on the RCA quality caused notable reductions on compressive strength, the RAC-40 compressive strengths were, on average, 13 and 15% lower in comparison with the NAC-AC at the ages of 28 and 90 days respectively. In line with those findings from Etxeberria et al [8] and Tabsh and Abdelfatah [6], the compressive strengths from RAC60 and RAC40 were lower than NAC due to the poorer mechanical properties of RCAs than those of natural aggregates. In all probability the mechanical properties of RCAs were due to the lower quality of the old adhered mortar in comparison to the new mortar paste [54]. The old ITZ between the aged mortar paste and the raw aggregates from RCA60 and RCA40 is expected to be weaker than the new ITZ between the new mortar and the RCA. The old ITZ could be the first surface in which the crack develops [8,54].

3.2.2. Effect of steam curing on compressive strength

The steam-cured concretes showed 4 to 15% higher 1-day compressive strength than their air-cured counterparts due to the acceleration of the CSH gel formation (Fig. 7). The obtained compressive strength was higher than that required in pre-cast and pre-stressed reinforced concrete [27,28], even using the lowest RCA quality (aggregates sourced from 40MPa concretes). Concrete mixtures subjected to steam curing suffered an acceleration of binder hydration and CSH gel formation [22,26,29] a fact which is in accordance with the porosity reduction at very early age mentioned previously. But amongst the air-cured concretes, the RAC-40-AC could not be used in pre-stressed concrete due to the negative influence on compressive strength of the poorer quality RCA.

The 28 and 90-day compressive strengths of the steam-cured concretes were similar to those of air-cured concretes when using the same type of aggregate (Fig. 7). For a given quality of RCA, steam-cured concretes achieved 1-9% and 4-11% lower compressive strength to those of the air-cured concretes at 28 and 90 days of curing, respectively. The negative influence of steam curing was increased at long term, in accord with the results reported by various researchers [39,55].

In this research work, the reduction of compressive strength due to the use of steam-curing for recycled aggregate concrete was lower than that reported by Kou et al. [39] in all probability to the high-medium quality of the RCA used in this study. However Kou et al. [39] found slight improvements in compressive strength when using RCA in steam curing as opposed to standard curing. In this study such improvements were not observed as a consequence of the different cement type used, as in this case, a rapid hardening cement was used and Kou et al. [39] employed a normal hardening cement.

3.2.3. Effect of concrete's age on compressive strength

Fig. 8 shows the increase of compressive strength (in percentage) with respect to the 1-day compressive strength for each concrete mixture produced. It must be noted that the RAC-60-AC and the RAC-40-AC showed the lowest compressive strength at 1 day (see Table 5) but they attained the highest evolutions at 28 and 90 days. The compressive strength increase revealed the positive influence of using FA in RAC as pointed out by other studies [39,56].

A comparison between the steam cured concretes and the air cured concretes revealed that the steam curing regime reduced the long term compressive strength gain. These detrimental effects of steam curing on the long term concrete properties had been reported for natural aggregates concretes [39,55]. Nevertheless for steam-cured concretes, the highest compressive strength gain was achieved by the RCA-40, which signifies that the use of higher porous RCA could contribute to a better binder hydration [15,48]. The compressive strength evolution is in correlation with the pore structure improvements from ages 28-90 days, and also the higher average pore diameter reduction of RCA40 compared to all other steam-cured concrete prepared with the higher quality recycled aggregates. The higher reduction of RAC pore volume compared to that of the NAC could confirm the improvement of the ITZ between the cement matrix and the recycled aggregates, as well as the densification of the binder matrix by internal curing.

3.3. Splitting tensile strength

Table 5 shows the results of the splitting tensile strength of all the concretes at 28 days. The concrete mixtures produced with RCA100 aggregates obtained the highest splitting tensile strength results. This was due to the influence of the high-quality ITZ between the cement paste and the coarse RCA which is especially influential on this property [8]. Certain researchers found that when compared with NAC, the RCAs in fact improved the ITZ quality. This found improvement was due to both the surface irregularities of the recycled aggregates and a certain amount of remaining water absorption which had the effect of reducing the water-cement ration of the ITZ [8,54].

A comparative study between NAC concretes and those of lower quality RCA, revealed that there was a drop in the splitting tensile strength of 0.5-5% in RCA60 and 12-16% in RCA40 with respect to NAC concretes. In these cases, the effect of the lower quality of the old mortar attached to the RCA could be responsible for the splitting tensile strength decrease [54]. Moreover, the standard deviations were proportionally higher than those found in other mechanical tests. The reason could be the higher influence of the old ITZ in the splitting tensile strength results [57].

The steam curing process proved to be beneficial with respect to concrete produced with RCAs. The splitting tensile strengths of steam-cured RACs were approximately 7-5% higher than those concretes which were exposed to conventional curing. However, steam-cured NAC achieved lower results than those of the same concrete cured under conventional conditions. Consequently, it was observed that the RAC concrete proved to have better performance than the NAC concrete when submitted to the steam curing process.

According to Spanish technical specification for prestressed concrete sleepers, the concrete needs to have a minimum of 4.5MPa splitting tensile strength [28]. The air cured concrete had to be produced with RCA100 in order to obtain that value. However, the beneficial effects of using steam curing signify that the quality of RCA could be reduced to RCA60, thus keeping the satisfactory results of splitting tensile strength.

3.4. Modulus of elasticity

The modulus of elasticity test results at the age of 28 days are presented in Table 5. The concrete mixtures designed with RAC obtained lower elastic modulus than that of the NAC mixtures for both curing methods. As certain studies pointed out [12,18], the loss of elastic modulus is especially significant in RAC with replacement levels of 100%. According to Lydon and Balendran [58], the modulus of elasticity of aggregate is proportional to the square of its density. Since RCA have lower density, the density of RAC particles is reduced and its modulus of elasticity is reduced. Concretes with RCA100, RCA60 and RCA40 had on average 5, 13 and 20%, respectively lower modulus of elasticity than that of NAC. However, the drops of elastic modulus as a result of using lower RCA quality were less severe than those registered from studies of Portland cement HPCs [18]. The higher reactivity of fly-ash with RCA and improved ITZ are beneficial factors with respect to binder hydration and cement paste densification in RACs mixtures and certainly influenced the modulus of elasticity results.

The steam curing method had the effect of slightly improving the modulus of elasticity of concrete mixtures. The modulus of elasticity results from steam-cured concretes were up to 7% higher than those of conventional-cured concrete mixtures for the same RCA quality. Kou et al. [39] observed that the use of RCA had a positive influences on the modulus of elasticity in steam-cured mixtures. It should be noted that the use of lower quality aggregates (RCA40) subjected to steam curing obatined the highest improvements (7%).

The modulus of elasticity from all the concrete mixtures proved to be within the range considered by the ACI as the typical values of elastic modulus for HPCs [9]. Nonetheless, the maximum modulus of elasticity were those from NAC (44 – 47 GPa), while the RAC mixtures achieved moduli of elasticity between 35 – 44 GPa. The standard deviations (between 0.1 – 2.5 GPa) did not reveal any relation between the use of RCA and the variability on the modulus of elasticity.

4. CONCLUSIONS

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

1. The total porosity of RAC is higher than that of the NAC concretes due to the porosity of the RCA. However RAC exhibited a greater refinement of the porous structure after the steam curing process. The difference of porosity between RAC and NAC in steam-cured concrete mixtures is lower than that employing air curing.

2. The use of RCA mitigated the macrocapillary pore increase generated by the use of steam curing, which is typically observed in steam-cured conventional concretes. The influence of steam curing was especially beneficial in the reduction of the average pore size of RAC in comparison to those concrete mixtures which only underwent air curing. This reduction was higher in concretes produced with lower quality RCA (RCA40 and RCA60).
3. The RCA prepared from lower original concrete quality (up to 40 MPa) resulted in significant losses on the mechanical properties of RAC. However, the concrete mixtures with RCA, especially those sourced from medium-low quality RCA, were less affected by the long-term compressive strength reduction due to steam curing in comparison with NAC mixtures. It must be noted that compressive strength evolution usually diminishes by the use of steam curing.
4. The steam curing process improved the splitting tensile strength of RAC with respect to that of air curing, though in NAC mixtures the steam curing had negative effects on splitting tensile strength.
5. The modulus of elasticity of the RAC mixtures was considerably lower than that from NAC. However, the modulus of elasticity results from steam-cured RCA mixtures were up to 7% higher than those from conventional-cured concrete mixtures for the same RCA quality.

According to the results, it is observed that RAC mixtures have a more suitable behaviour when undergoing the steam curing process than that of NAC mixtures.

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References

[1] Eurostat, Waste statistics in Europe, (2012).
[2] European Union Parliament, Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain directives (text with EEA relevance), Off. J. Eur. Union. 312 (2008) 3–30.
[3] R.V. Silva, J. De Brito, R.K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, Constr. Build. Mater. 65 (2014) 201–217. doi:10.1016/j.conbuildmat.2014.04.117.

[4] J. Xiao, W. Li, Y. Fan, X. Huang, An overview of study on recycled aggregate concrete in China (1996–2011), Constr. Build. Mater. 31 (2012) 364–383. doi:10.1016/j.conbuildmat.2011.12.074.

[5] C. Thomas, J. Setién, J. a. Polanco, P. Alaejos, M. Sánchez de Juan, Durability of recycled aggregate concrete, Constr. Build. Mater. 40 (2013) 1054–1065. doi:10.1016/j.conbuildmat.2012.11.106.

[6] S.W. Tabsh, A.S. Abdelfatah, Influence of recycled concrete aggregates on strength properties of concrete, Constr. Build. Mater. 23 (2009) 1163–1167. doi:10.1016/j.conbuildmat.2008.06.007.

[7] E.A.B. Koenders, M. Pepe, E. Martinelli, Compressive strength and hydration processes of concrete with recycled aggregates, Cem. Concr. Res. 56 (2014) 203–212.

[8] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (2007) 735–742. doi:10.1016/j.cemconres.2007.02.002.

[9] ACI Committee 363, State of the Art Report on High-Strength Concrete, Farmington Hills, 1997.

[10] V.W.Y. Tam, C.M. Tam, Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach, J. Mater. Sci. 42 (2007) 3592–3602. doi:10.1007/s10853-006-0379-y.

[11] S. Kou, C. Poon, Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete, Constr. Build. Mater. 77 (2015) 501–508. doi:10.1016/j.conbuildmat.2014.12.035.

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

[13] M.C. Limbachiya, T. Leelawat, R.K. Dhir, Use of recycled concrete aggregate in high-strength concrete, Mater. Struct. 33 (2000) 574–580.

[14] A. Ajdukiewicz, A. Kliszczewicz, Influence of recycled aggregates on mechanical properties of HS/HPC, Cem. Concr. Compos. 24 (2002) 269–279. doi:10.1016/S0958-9465(01)00012-9.

[15] M. Suzuki, M. Seddik Meddah, R. Sato, Use of porous ceramic waste aggregates for internal curing of high-performance concrete, Cem. Concr. Res. 39 (2009) 373–381. doi:10.1016/j.cemconres.2009.01.007.

[16] T.-Y. Tu, Y.-Y. Chen, C.-L. Hwang, Properties of HPC with recycled aggregates, Cem. Concr. Res. 36 (2006) 943–950. doi:10.1016/j.cemconres.2005.11.022.

[17] F. Pacheco-Torgal, Y. Ding, S. Miraldo, Z. Abdollahnejad, J. a. Labrincha, Are geopolymers more suitable than Portland cement to produce high volume recycled aggregates HPC?, Constr. Build. Mater. 36 (2012) 1048–1052. doi:10.1016/j.conbuildmat.2012.07.004.

[18] A. Gonzalez-Corominas, M. Etxeberria, Experimental analysis of properties of high performance recycled aggregate concrete, Constr. Build. Mater. 52 (2014) 227–235. doi:10.1016/j.conbuildmat.2013.11.054.

[19] S.C. Kou, C.S. Poon, F. Agrela, Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures, Cem. Concr. Compos. 33 (2011) 788–795. doi:10.1016/j.cemconcomp.2011.05.009.

[20] S.C. Kou, C.S. Poon, D. Chan, Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete, Mater. Struct. 41 (2007) 1191–1201. doi:10.1617/s11527-007-9317-y.

[21] H. Yazıcı, S. Aydın, H. Yiğiter, B. Baradan, Effect of steam curing on class C high-volume fly ash concrete mixtures, Cem. Concr. Res. 35 (2005) 1122–1127. doi:10.1016/j.cemconres.2004.08.011.

[22] L. Baoju, X. Youjun, Z. Shiqiong, L. Jian, Some factors affecting early compressive strength of steam-curing concrete with ultrafine fly ash, Cem. Concr. Res. 31 (2001) 1455–1458. doi:10.1016/S0008-8846(01)00559-2.

[23] B. Liu, Y. Xie, J. Li, Influence of steam curing on the compressive strength of concrete containing supplementary cementing materials, Cem. Concr. Res. 35 (2005) 994–998. doi:10.1016/j.cemconres.2004.05.044.

[24] B. Sukumar, K. Nagamani, R. Srinivasa Raghavan, Evaluation of strength at early ages of self-compacting concrete with high volume fly ash, Constr. Build. Mater. 22 (2008) 1394–1401. doi:10.1016/j.conbuildmat.2007.04.005.

[25] C.S. Poon, L. Lam, Y.L. Wong, A study on high strength concrete prepared with large volumes of low calcium fly ash, Cem. Concr. Res. 30 (2000) 447–455. doi:10.1016/S0008-8846(99)00271-9.

[26] M. Ba, C. Qian, X. Guo, X. Han, Effects of steam curing on strength and porous structure of concrete with low water/binder ratio, Constr. Build. Mater. 25 (2011) 123–128. doi:10.1016/j.conbuildmat.2010.06.049.

[27] A.A. Ramezanianpour, M.H. Khazali, P. Vosoughi, Effect of steam curing cycles on strength and durability of SCC: A case study in precast concrete, Constr. Build. Mater. 49 (2013) 807–813. doi:10.1016/j.conbuildmat.2013.08.040.

[28] ADIF, Spanish Technical Specifications of Prestressed Concrete Monoblock Sleepers (ET 03.360.571.8), Madrid, 2009.

[29] S. Erdoğdu, S. Kurbetci, Optimum heat treatment cycle for cements of different type and composition, Cem. Concr. Res. 28 (1998) 1595–1604. doi:10.1016/S0008-8846(98)00134-3.

[30] S. Igarashi, A. Watanabe, M. Kawamura, Evaluation of capillary pore size characteristics in high-strength concrete at early ages, Cem. Concr. Res. 35 (2005) 513–519. doi:10.1016/j.cemconres.2004.06.036.

[31] H.M. Jennings, Design of high strength cement based materials: Part 2 Microstructure, Mater. Sci. Technol. 4 (1988) 285–90.

[32] M. Valcuende, C. Parra, E. Marco, A. Garrido, E. Martínez, J. Cánoves, Influence of limestone filler and viscosity-modifying admixture on the porous structure of self-compacting concrete, Constr. Build. Mater. 28 (2012) 122–128. doi:10.1016/j.conbuildmat.2011.07.029.

[33] R.A. Cook, K.C. Hover, Mercury porosimetry of hardened cement pastes, Cem. Concr. Res. 29 (1999) 933–943. doi:10.1016/S0008-8846(99)00083-6.

[34] S. Diamond, Mercury porosimetry An inappropriate method for the measurement of pore size distributions in cement-based materials, Cem. Concr. Res. 30 (2000) 1517–1525.

[35] S. Mindess, J.F. Young, Concrete, Prentice-Hall, Englewood Cliffs, NJ, 1981.

[36] W.B. Fuller, S.E. Thompson, The laws of proportioniong concrete, Trans ASCE. 59 (1907) 67–143.

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

[38] A.M. Neville, Properties of Concrete, 4th ed., 1995.

[39] S. Kou, C. Poon, D. Chan, Properties of steam cured recycled aggregate fly ash concrete, in: E. Vázquez, C. Hendriks, G. Janssen (Eds.), Int. RILEM Conf. Use Recycl. Mater. Build. Struct., RILEM Publications SARL, Barcelona, Spain, 2004: pp. 590–9.

[40] K.L. Willis, A.B. Abell, D.A. Lange, Image-based characterization of cement pore structure using wood's metal intrusion, Cem. Concr. Res. 28 (1998) 1695–1705. doi:10.1016/S0008-8846(98)00159-8.

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

[42] M.H. Zhang, O.E. Gjørv, Microstructure of the interfacial zone between lightweight aggregate and cement paste, Cem. Concr. Res. 20 (1990) 610–618. doi:10.1016/0008-8846(90)90103-5.

[43] S.L. Sarkar, S. Chandra, L. Berntsson, Independence of microstructure and strength of structural lightweight aggregate concrete, Cem. Concr. Compos. 14 (1992) 239 –48.

[44] K.B. Park, T. Noguchi, F. Tomosawa, A study on the hydration ratio and autogenous shrinkage cement paste, in: E. Tazawa (Ed.), Int. Work. Autogenous Shrinkage Concr. AUTOSHRINK'98, tOKYO, 1998: pp. 281–290.

[45] M. a. Megat Johari, J.J. Brooks, S. Kabir, P. Rivard, Influence of supplementary cementitious materials on engineering properties of high strength concrete, Constr. Build. Mater. 25 (2011) 2639–2648. doi:10.1016/j.conbuildmat.2010.12.013.

[46] P. Chindaprasirt, C. Jaturapitakkul, T. Sinsiri, Effect of fly ash fineness on compressive strength and pore size of blended cement paste, Cem. Concr. Compos. 27 (2005) 425–428. doi:10.1016/j.cemconcomp.2004.07.003.

[47] V. Corinaldesi, G. Moriconi, Recycling of rubble from building demolition for low-shrinkage concretes., Waste Manag. 30 (2010) 655–9. doi:10.1016/j.wasman.2009.11.026.

[48] V. Corinaldesi, Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates, Constr. Build. Mater. 24 (2010) 1616–1620. doi:10.1016/j.conbuildmat.2010.02.031.

[49] A.B. Abell, K.L. Willis, D.A. Lange, Mercury Intrusion Porosimetry and Image Analysis of Cement-Based Materials., J. Colloid Interface Sci. 211 (1999) 39–44. doi:10.1006/jcis.1998.5986.

[50] E.E. Berry, R.T. Hemmings, B.J. Cornelius, Mechanisms of hydration reactions in high volume fly ash pastes and mortars, Cem. Concr. Compos. 12 (1990) 253–261. doi:10.1016/0958-9465(90)90004-H.

[51] S. Zhutovsky, K. Kovler, Effect of internal curing on durability-related properties of high performance concrete, Cem. Concr. Res. 42 (2012) 20–26. doi:10.1016/j.cemconres.2011.07.012.

[52] Z. Shui, D. Xuan, H. Wan, B. Cao, Rehydration reactivity of recycled mortar from concrete waste experienced to thermal treatment, Constr. Build. Mater. 22 (2008) 1723–1729. doi:10.1016/j.conbuildmat.2007.05.012.

[53] S.C. Kou, C.S. Poon, D. Chan, Influence of fly ash as a cement replacement on the properties of recycled aggregate concrete, J. Mater. Civ. Eng. 19 (2007) 709–17.

[54] N. Otsuki, S. Miyazato, W. Yodsudjai, Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete, J. Mater. Civ. Eng. 15 (2003) 443–451. doi:10.1061/(ASCE)0899-1561(2003)15.

[55] M. Gesoğlu, E. Güneyisi, B. Ali, K. Mermerdaş, Strength and transport properties of steam cured and water cured lightweight aggregate concretes, Constr. Build. Mater. 49 (2013) 417–424. doi:10.1016/j.conbuildmat.2013.08.042.

[56] M. Limbachiya, M.S. Meddah, Y. Ouchagour, Use of recycled concrete aggregate in fly-ash concrete, Constr. Build. Mater. 27 (2011) 439–449. doi:10.1016/j.conbuildmat.2011.07.023.

[57] S.C. Kou, C.S. Poon, H. Wan, Properties of concrete prepared with low-grade recycled aggregates C & D Waste, Constr. Build. Mater. 36 (2012) 881–889.

[58] F.D. Lydon, R.V. Balendran, Some observations on elastic properties of plain concrete, Cem. Concr. Res. 16 (1986) 314–24.

Table 1. Chemical compositions of binders.

Table 2. Physical and mechanical properties of coarse and fine aggregates.

Table 3. Proportioning of the concrete mixtures (Coded: Natural Aggregate Concrete: NAC; Recycled Aggregate Concrete mixtures, RAC-x-y (x = compressive strength of original concretes reused as aggregates, 100, 60 or 40MPa; y =: initial curing method, air curing (AC) or steam curing (SC)) and the results from the slump cone test.

Table 4. Mercury Intrusion Porosimetry tests results of concrete mixtures at the ages of 1, 28 and 90 days (in brackets, standard deviations).

Table 5. Mechanical properties tests results of concrete mixtures at the ages of 1, 28 and 90 days (in brackets, standard deviations).

Table 1. Chemical compositions of binders.

Composition (%)	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**K_2O**	**TiO_2**	**P_2O_5**	**Na_2O**	**LOI**
Cement	21.91	3.57	4.67	64.98	1.45	0.57	0.18	0.18	0.12	1.05
Fly Ash	55.46	26.94	5.86	5.70	1.50	1.51	1.41	0.83	0.62	3.70

Table 2. Physical and mechanical properties of coarse and fine aggregates.

Physical and mechanical properties	**Dried particle density (kg/dm^3)**	**Water absorption (%)**	**Flakiness index (%)**	**Crushing value (%)**	**LA Index (%)**	**Sand equivalent test (%)**	**MIP Porosity (%)**
River Gravel	2.61	1.29	17.71	18.92	19.61	-	-
Dolomitic Coarse Aggregate	2.68	2.13	7.81	20.15	24.77	-	-
RCA100	2.47	3.74	16.53	22.59	24.01	-	4.88
RCA60	2.39	4.90	13.57	23.36	25.24	-	5.73
RCA40	2.30	5.91	9.59	25.55	24.31	-	8.63
River Sand 1	2.50	1.02	-	-	-	87.88	-
River Sand 2	2.57	1.93	-	-	-	75.00	-

Table 3. Proportioning of the concrete mixtures (Coded: Natural Aggregate Concrete: NAC; Recycled Aggregate Concrete mixtures, RAC-x-y (x = compressive strength of original concretes reused as aggregates, 100, 60 or 40MPa; y =: initial curing method, air curing (AC) or steam curing (SC)) and the results from the slump cone test.

Concrete reference	**Cement (kg)**	**Fly Ash (kg)**	**Admixture (kg)**	**River Sand 1 (kg)**	**River Sand 2 (kg)**	**River Gravel (kg)**	**Dolomitic Coarse Aggregate (kg)**	**Recycled Concrete Aggregate (kg)**	**Total Water (kg)**	**Effective W/B**	**Slump (mm)**
NAC-(AC/SC)	266	114	5.7	711.8	182.5	302.1	784.5	---	135.4	0.285	16
RAC-100-(AC/SC)	266	114	5.7	711.8	182.5	---	---	1010.2	162.3	0.285	10
RAC-60-(AC/SC)	266	114	5.7	711.8	182.5	---	---	975.1	170.4	0.285	11
RAC-40-(AC/SC)	266	114	5.7	711.8	182.5	---	---	938.8	175.3	0.285	20

Table 4. Mercury Intrusion Porosimetry tests results of concrete mixtures at the ages of 1, 28 and 90 days (in brackets, standard deviations).

Mix notation		**Air cured mixtures**				**Steam cured mixtures**			
		NAC-AC	**RAC-100-AC**	**RAC-60-AC**	**RAC-40-AC**	**NAC-SC**	**RAC-100-SC**	**RAC-60-SC**	**RAC-40-SC**
Total Porosity (%)	**1 day**	8.58 (0.11)	7.54 (0.10)	9.36 (0.08)	11.81 (0.07)	7.27 (0.13)	7.36 (0.54)	7.74 (0.32)	10.45 (0.24)
	28 days	4.88 (0.38)	4.85 (0.22)	6.270 (0.15)	8.170 (0.2)	5.810 (0.56)	6.02 (0.55)	6.63 (0.53)	8.85 (0.45)
	90 days	6.46 (0.09)	5.60 (0.11)	7.540 (0.01)	8.690 (0.43)	5.160 (0.46)	4.71 (0.19)	5.69 (0.24)	6.24 (0.36)
Average pore diameter (µm)	**1 day**	0.05 (0.004)	0.04 (0.004)	0.054 (0.002)	0.063 (0.001)	0.046 (0.001)	0.04 (0.003)	0.04 (0.003)	0.06 (0.002)
	28 days	0.04 (0.002)	0.04 (0.003)	0.040 (0.002)	0.044 (0.001)	0.028 (0.002)	0.03 (0.003)	0.03 (0.002)	0.04 (0.000)
	90 days	0.028 (0.000)	0.022 (0.000)	0.035 (0.001)	0.034 (0.003)	0.026 (0.000)	0.023 (0.000)	0.027 (0.000)	0.029 (0.000)
Threshold pore diameter (µm)	**1 day**	111.78 (2.17)	116.98 (5.80)	113.65 (4.69)	218.01 (8.35)	103.95 (1.32)	109.65 (5.06)	113.66 (1.96)	180.04 (4.45)
	28 days	54.48 (2.39)	74.51 (4.78)	91.88 (6.89)	180.13 (10.75)	62.46 (0.89)	68.57 (1.08)	93.62 (1.26)	113.65 (7.43)
	90 days	48.01 (0.55)	36.58 (2.85)	86.53 (1.50)	104.89 (9.56)	38.35 (3.02)	36.7 (2.76)	83.18 (8.06)	91.9 (7.37)

Table 5. Mechanical properties tests results of concrete mixtures at the ages of 1, 28 and 90 days (in brackets, standard deviations).

Mix notation		**Air cured mixtures**				**Steam cured mixtures**			
		NAC-AC	**RAC-100-AC**	**RAC-60-AC**	**RAC-40-AC**	**NAC-SC**	**RAC-100-SC**	**RAC-60-SC**	**RAC-40-SC**
Compressive strength (MPa)	**1 day**	54.11 (0.80)	56.81 (1.12)	46.88 (0.77)	44.23 (1.06)	65.42 (3.48)	66.18 (3.00)	63.03 (2.52)	52.44 (1.66)
	28 days	87.75 (5.38)	91.61 (3.93)	84.06 (4.85)	76.90 (1.07)	86.59 (5.67)	83.69 (2.25)	82.98 (7.42)	75.63 (1.71)
	90 days	102.84 (4.31)	110.88 (3.91)	104.16 (5.89)	88.18 (4.64)	98.05 (4.63)	99.62 (2.76)	93.87 (4.75)	83.18 (1.64)
Splitting tensile strength (MPa)	**28 days**	4.71 (0.31)	4.78 (0.39)	4.47 (0.43)	3.95 (0.35)	4.60 (0.13)	4.97 (0.37)	4.58 (0.10)	4.07 (0.10)
Modulus of elasticity (GPa)	**28 days**	44.43 (2.43)	42.55 (0.26)	39.49 (1.94)	35.34 (1.49)	46.58 (0.38)	43.90 (1.51)	39.80 (1.31)	37.70 (0.11)

Fig. 1. Particle size distributions of fine and coarse aggregates.

Fig. 2. Distribution of pore diameters of recycled concrete aggregates.

Fig. 3. One-day steam curing cycle.

Fig. 4. Pore size cumulative distribution of initially air-cured concretes (left) and initially steam-cured concretes (right) at the ages of 1, 28 and 90 days.

Fig. 5. Relative average pore diameter of steam-cured concretes in comparison with air-cured concretes at the ages of 1, 28 and 90 days.

Fig. 6. Pores volume reduction of concretes produced with 30% FA from 1 to 90 days according to three different pore size ranges; (a) initially air-cured concretes and (b) initially steam-cured concretes.

Fig. 7. Relative compressive strength of steam-cured concretes in comparison with air-cured concretes at the ages of 1, 28 and 90 days.

Fig. 8. Compressive strength increase from 1 to 90 days, highlighting gain ranges from 1 to 28 days and from 28 to 90 days.

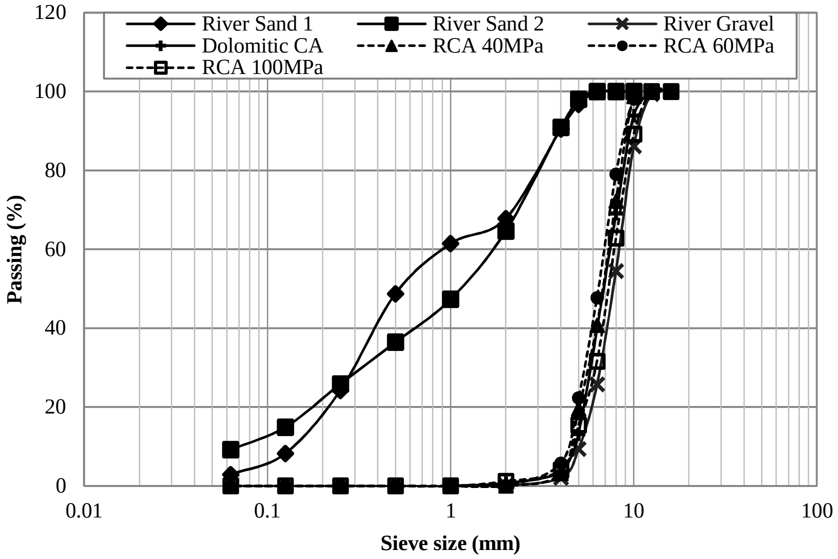


Fig. 1. Particle size distributions of fine and coarse aggregates.

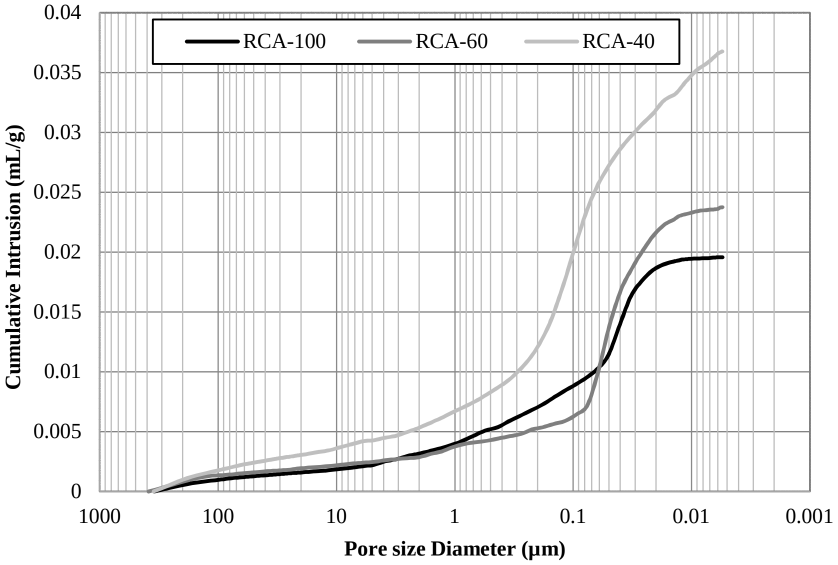


Fig. 2. Distribution of pore diameters of recycled concrete aggregates.

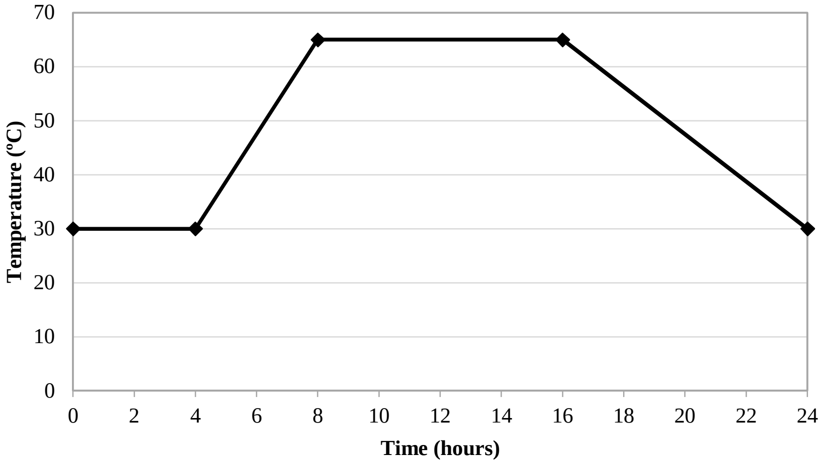
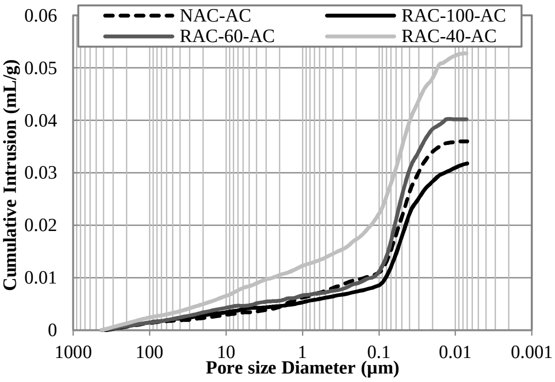


Fig. 3. One-day steam curing cycle.

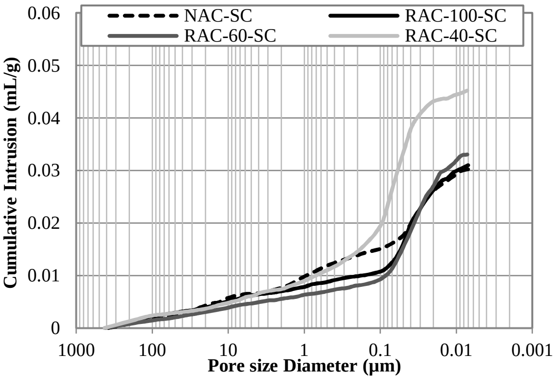
Air-cured concretes

Steam-cured concretes

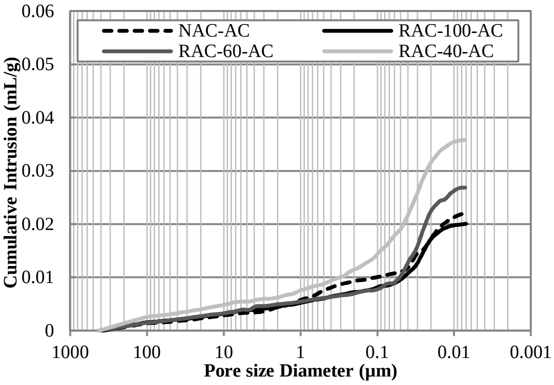
a) 1 day of curing



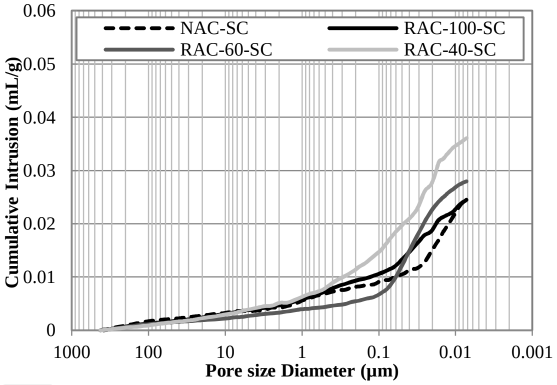
b) 1 day of curing



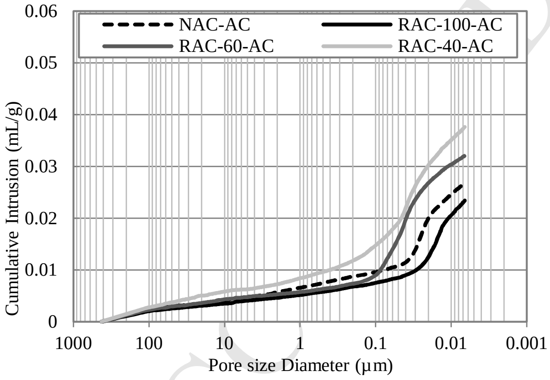
c) 28 days of curing



d) 28 days of curing



e) 90 days of curing



f) 90 days of curing

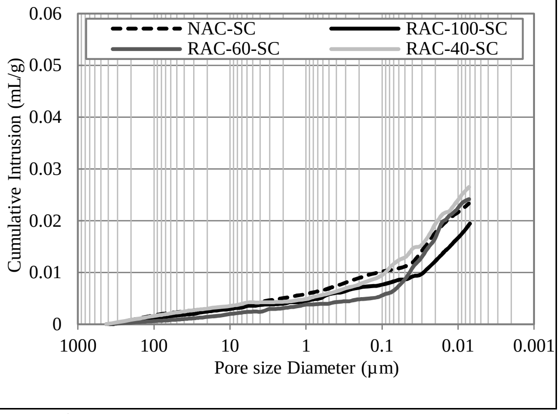


Fig. 4. Pore size cumulative distribution of initially air-cured concretes (left) and initially steam-cured concretes (right) at the ages of 1, 28 and 90 days.

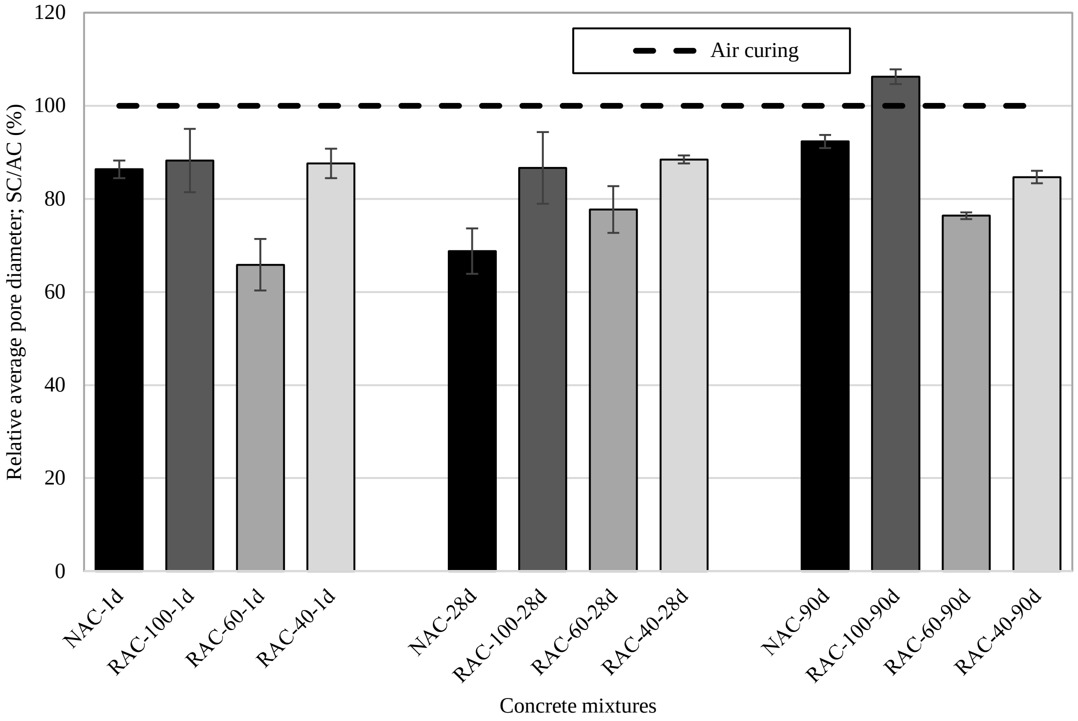


Fig. 5. Relative average pore diameter of steam-cured concretes in comparison with air-cured concretes at the ages of 1, 28 and 90 days.

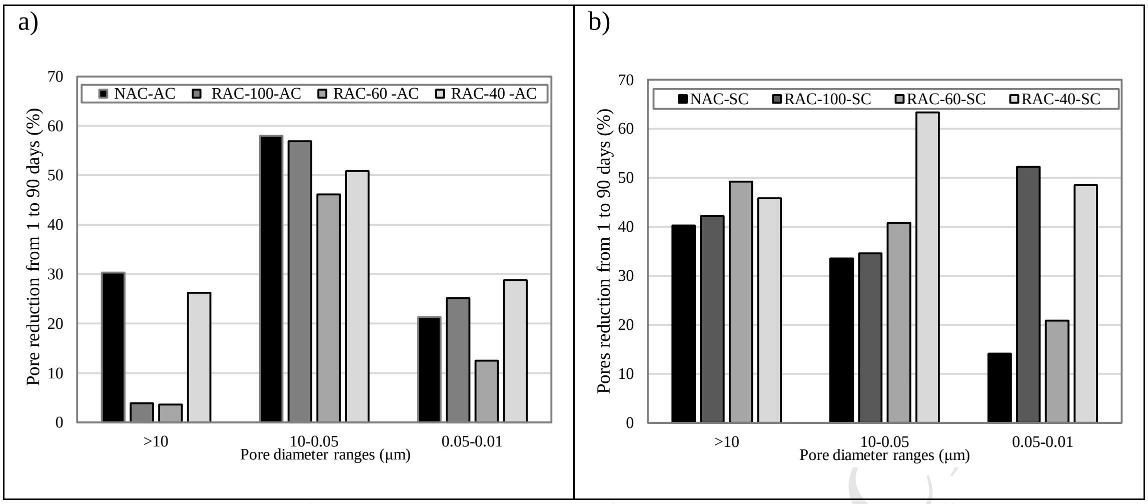


Fig. 6. Pores volume reduction of concretes produced with 30% FA from 1 to 90 days according to three different pore size ranges; (a) initially air-cured concretes and (b) initially steam-cured concretes.

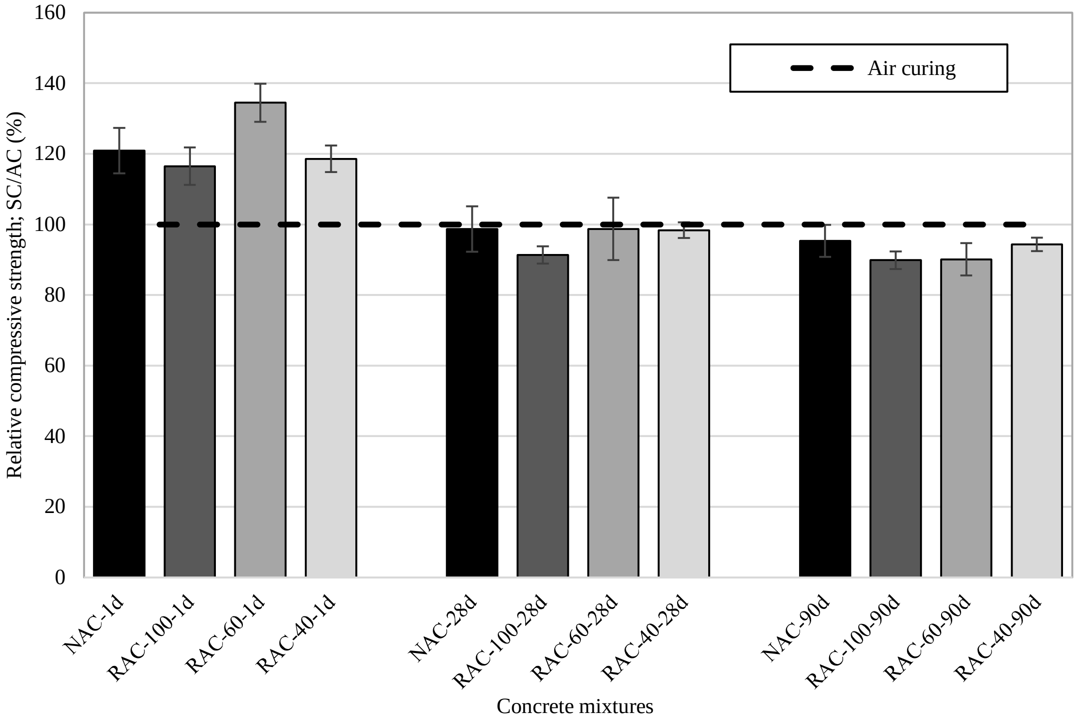


Fig. 7. Relative compressive strength of steam-cured concretes in comparison with air-cured concretes at the ages of 1, 28 and 90 days.

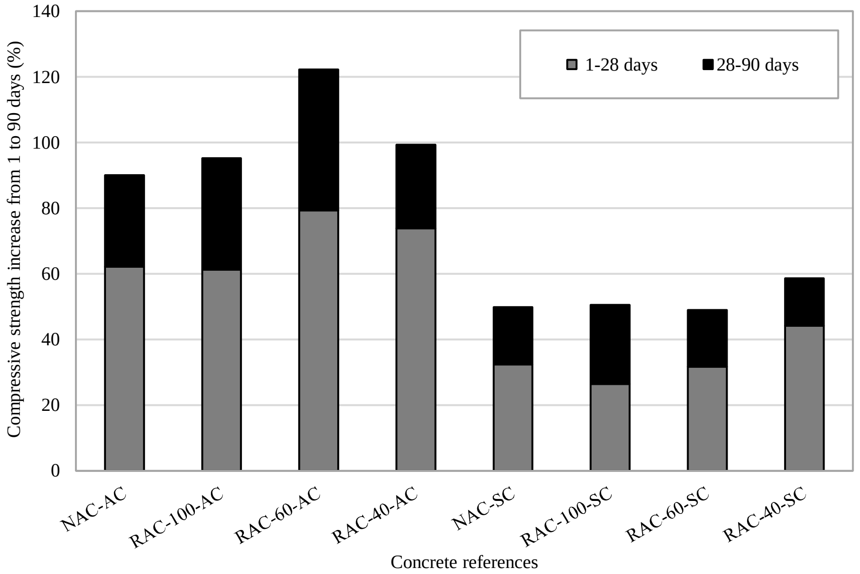


Fig. 8. Compressive strength increase from 1 to 90 days, highlighting gain ranges from 1 to 28 days and from 28 to 90 days.