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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 (>100 MPa) 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

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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 h and a heating and cooling rate of 10–45 °C/h. The maximum temperature reached in steam curing is usually limited to 60 ± 5 °C and this temperature is kept constant at the maximum value for 6–18 h [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 100 MPa 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 h 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.

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

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 40 MPa 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 40 MPa 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 Mercury 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; >10 μm (air), 10–0.05 μm (macropores), 0.05–0.01 μm (mesopores) and <0.01 μm (micropores). As can be seen in Fig. 2, some differences in the range of 0.01–10 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

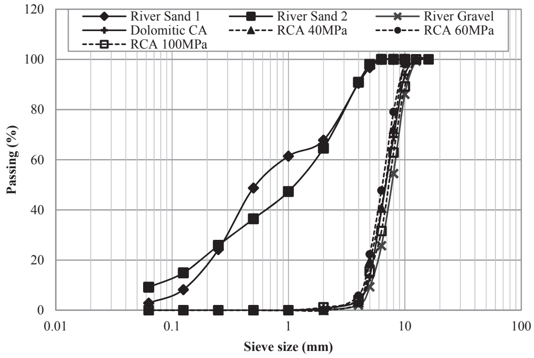

Fig. 1. Particle size distributions of fine and coarse aggregates.