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Durability performance of concrete made with fine recycled concrete aggregates

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ABSTRACT

Fine recycled aggregates are seen as the last choice in recycling for concrete production. Many references quote their detrimental influence on the most important characteristics of concrete: compressive and tensile strength; modulus of elasticity; water absorption; shrinkage; carbonation and chloride penetration. These two last characteristics are fundamental in terms of the long-term durability of reinforced or prestressed concrete. In the experimental research carried out at IST, part of which has already been published, different concrete mixes (with increasing rates of substitution of fine natural aggregates – sand – with fine recycled aggregates from crushed concrete) were prepared and tested. The results were then compared with those for a reference concrete with exactly the same composition and grading curve, but with no recycled aggregates. This paper presents the main results of this research for water absorption by immersion and capillarity, chloride penetration (by means of the chloride migration coefficient), and carbonation resistance, drawing some conclusions on the feasibility of using this type of aggregate in structural concrete, while taking into account any ensuing obvious positive environmental impact.

1. Introduction

It is now well established that the evaluation of the performance of a concrete mix is not limited to the determination of its mechanical properties since it is of paramount importance to characterize the material in terms of the parameters that rate its durability. The service life of a reinforced or prestressed concrete structure and its performance over time are closely connected with the properties that define durability, which include permeability (to various agents), alkali-silica reactivity, reaction to icing-deicing cycles, reaction to sulfates, and others [1].

Concrete made with recycled aggregates is no longer merely a research field; it is already a practical reality and has been used for some years in several countries which lead the way in these matters [2]. Various pilot projects have been implemented in these countries with encouraging results [3,4]. Its use is so widespread there that several of them have developed or are developing normative documents to regulate the use of this type of concrete in order to address its specificities [5].

In most codes the use of fine recycled aggregates in concrete production is restricted or even prohibited because of their unsatisfactory properties [6,7]. There are some studies, however, that suggest their use is not necessarily inauspicious and that good results (similar to those obtained with fine natural aggregates) are feasible in concrete which contain a proportion of this type of aggregate [8,9].

IST (Lisbon, Portugal) has been conducting experimental research to assess the practicality of using fine recycled concrete aggregates to produce new concrete. The experimental program is studying various properties of concretes with different replacement ratios of fine natural aggregates by recycled ones. The results have been compared with those of a reference concrete of identical composition but produced with natural aggregates only. This paper presents the results for water absorption by immersion and through capillarity, the penetration of chlorides, measured in terms of the migration coefficient in a non-steady state, and carbonation resistance.

1.1. Durability parameters

The durability of a concrete element is greatly dependent on the capacity of a fluid to penetrate the concrete's microstructure allowing the introduction of molecules (e.g. carbon dioxide, chloride ions) that react and destroy its chemical stability. This movement is known to occur in three ways: permeation, capillarity and diffusion [10]. The durability of concrete made with fine recycled concrete aggregates (FRA) was analyzed by means of three tests, namely water absorption by immersion, water absorption through capillarity, and chloride penetration in a non-steady state condition.

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Water absorption by immersion measures the permeation capacity of concrete under a given pressure, i.e. the capacity of a fluid to move through the pore structure. This phenomenon depends mostly on the concrete microstructure (especially on the open pore structure), moisture condition and properties of the permeating fluid [11]. Although water absorption by immersion gives an estimate of the volume of a concrete's open pores, it is not a reliable way of determining the concrete's chloride and carbonation resistance, since this depends more on capillary absorption [12].

Water absorption through capillarity is a phenomenon that is due to the difference between the fluid's surface capillary pressure and its gravity pressure, which induces fluid movement until a balance is established. Capillary pressure increases with decreasing capillary diameter and is most relevant at the boundaries of concrete elements. The process is particularly visible in dry–wet conditions and has the most relevance near the element's surface.

The presence of chloride ions in concrete microstructure is known to lead to steel corrosion [13]. Carbonation is a chemical phenomenon where the carbon dioxide that penetrates the concrete structure reacts with calcium hydroxide to drastically reduce concrete alkalinity, enabling steel corrosion by destroying the passive layer. Carbonation depends on the cement's composition, aggregate type and porosity [14]. Together these two phenomena are the main factors in reducing concrete durability [10]. Both chloride penetration and carbonation tend to occur by diffusion, which is the movement of an element due to its concentration gradient within the concrete microstructure. This phenomenon is characterized by Fick's second law:

$$\frac{\partial \phi}{\partial t} = D\frac{\partial^2 \phi}{\partial x^2} \tag{1.1}$$

where φ is the ionic concentration, t is the time, D is the diffusion coefficient and x is the position.

2. Experimental program

2.1. Fine recycled concrete aggregate production

The fine recycled aggregates used in the experimental research reported here were obtained by crushing the original concrete (OC) produced in the laboratory for that purpose in an impact crusher. By choosing this concrete as a source of recycled aggregates two problems were solved: first, it was guaranteed that all the aggregates used came from the same source, thus reducing the scatter that they often exhibit; second, it was possible to determine the main properties of the original concrete thereby permitting a better interpretation of the results. Table 1 gives the composition of the original concrete and some of its properties.

After 35 days, the concrete was crushed. The resulting material was composed of aggregates whose size ranged from 0 to 38.1 mm. Of these sizes only the fractions up to 1.19 mm were used, since this was the maximum dimension of the fine natural aggregates (river sand). After this screening, there were significant differences between the natural and recycled aggregates in terms of their grading curves. The recycled aggregates grading curve therefore had to be converted in order to reproduce that of the natural aggregates (so as to obtain the same fineness modulus for all the mixes with different replacement ratios and eliminate the influence of this parameter on the results). For this, all the recycled aggregates were sieved to obtain the various grading sizes and the different fractions were kept in sealed containers to prevent humidity exchange with the outside environment. Even though the practicability of this procedure leaves much to be desired, it was decided to go ahead with it since it would eliminate unwelcome entropies that would otherwise most surely hinder the analysis of the results obtained.

Table 1
Original concrete composition.

Materials	OC
CEM II 32.5 N (kg/m^3)	362
River sand (kg/m^3)	615
Coarse aggregate 1 (kg/m^3)	717
Coarse aggregate 2 (kg/m^3)	478
Water (l/m^3)	188
W/C	0.52
Slump (mm)	70 ± 10
f_{cm}: 7 days (MPa)	21.0
f_{cm}: 28 days (MPa)	29.6

2.2. Concrete mix design

The calculation of the composition of the various mixes required the characterization of the aggregates used in them, with special emphasis on the properties of the fine aggregates. Table 2 presents the main properties of the fine recycled aggregates (FRA) and compares them with the fine natural aggregates (FNA). In brief, the recycled aggregates have lower specific densities than the natural aggregates because of their higher porosity, resulting in the greater water absorption observed.

The different compositions of concrete in terms of the FNA/FRA replacement ratio (30% and 100%) and the reference concrete (RC) produced with natural aggregates alone were studied in accordance with the methodology proposed by Faury [15], with workability (slump as measured by the Abrams cone) as a common characteristic, within the interval 80 ± 10 mm.

The first mixes were made with the RC, thus determining the composition of the remaining concretes. The W/C ratio (and consequently to calibrate the quantities of the remaining materials) had to be corrected for the subsequent mixes since the more angular shape of the particles of fine recycled aggregates produces higher inner friction [16].

Furthermore, it was necessary to introduce the water that the recycled aggregates were going to absorb during the mixing, to prevent it from being removed in the hydration process which would jeopardize the concretes' performance. Two different W/C ratios therefore needed to be determined: the global W/C ratio, i.e. the ratio between the overall quantity of water introduced into the mix and the amount of binder that, even though very simple to determine, is of no particular interest to the study of the concrete mixes, and the effective W/C ratio, i.e. the ratio between the amount of free water within the mix and the amount of binder whose determination, though fundamental to understanding the concrete's performance, is difficult because the evolution of the water absorption by the recycled aggregates *versus* time has to be known in detail. This particular feature of recycled aggregates is of fundamental importance to the composition and performance of concretes made with them. In a research program at IST and UPC (Barcelona, Spain) under the joint supervision of the second author, the effect of the method of compensating for the coarse recycled concrete aggregates excessive water absorption in concrete

Table 2
Fine recycled and fine natural aggregates' properties.

Properties	FRA	FNA
Dry specific density (kg/m^3)	1913	2544
Surface dry specific density (kg/m^3)	2165	2564
Dry bulk density (kg/m^3)	1234	1517
Water absorption (%)	13.1	0.8
Fineness modulus	2.38	2.38