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Durability performance of structural concrete containing fine aggregates from waste generated by marble quarrying industry

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ABSTRACT

The aim of this research is to assess the durability performance of concrete containing various percentages of fine aggregates produced from the waste generated by the marble quarrying industry (0%, 20%, 50% and 100% of the total volume of fine aggregates). The workability and bulk density of fresh concrete were measured and the water absorption by capillary action and immersion, together with the carbonation, chloride penetration and drying shrinkage of hardened concrete, were determined.

It was concluded that the durability properties of concrete containing fine aggregates of granite, basalt and river sand tend to improve, remain constant and decrease, respectively, with the incorporation of fine aggregates from marble quarrying waste. However, these changes do not compromise the use of these secondary aggregates in structural concrete.

1. Introduction

1.1. Preliminary remarks

Humans have always consumed natural resources to meet their needs. However, their importance in terms of environmental sustainability has only recently been appreciated. It is reckoned that 80% of all the rock extracted in the Estremoz, Borba and Vila Viçosa districts in Portugal, is treated as waste. It has therefore become necessary to create sustainable destinations for this material to mitigate or eliminate this trend and to improve its economic value. However, to assess the usability of this waste in the building industry we must ensure that all quality parameters are satisfied, as well as accurately defining the performance of the concrete produced with such waste fine aggregates.

This paper examines the durability related properties of concrete made with these aggregates and supplements the results of Silva et al. [42] that focused on the mechanical performance of the same mixes. It follows on from a previous programme of work on coarse marble aggregates from the same locality [3,27].

1.2. Research significance

This research addresses the sustainable exploitation of marble by ensuring the proper utilisation of the waste and by-products generated by quarrying, the environmental recovery of the areas affected and the prevention of adverse environmental impacts. Part of the innovation of this research lies in the formulation of the mixes by a direct replacement of the fine aggregates (in volume), keeping their size grading and the concrete workability class constant. Any entropic influence of the aggregates' size distribution, water/cement ratio (w/c) and other composition related aspects on the experimental results was thus avoided.

2. State of the art

For a better understanding of the properties and performance of the mixes to be produced, the related research done so far was reviewed. Although some studies in this area have been published there remain several gaps in the information, especially in terms of the durability-related properties.

Coutinho and Gonçalves [11] report that workability is related to the physical properties of concrete such as segregation and exudation, cohesion, viscosity, bulk density and the friction angle of the mix. Aïtcin [1] and Ramachandran et al. [40] consider that these physical properties result from the physical and chemical nature of the materials present in concrete. They single out the reactivity of the cement and additives, the amount of aggregates in the mix, the coarse/fine aggregate ratio, the size grading curve and the shape of the aggregates as the chemical and physical aspects to take into account for workability.

According to Hebhoub et al. [20], the bulk density of concrete does not significantly vary with the proportion of aggregate replaced because the bulk density of all the aggregates was similar. Their study notes that the bulk density of concrete is a function of the density of its components, the proportions of each material

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used in the mix, the initial and final water content and the concrete's hydration level.

Verbeck [47] states that the amount and characteristics of the pores of the cement paste and aggregates influence the most important properties of hardened concrete. Given the influence that the aggregates' pore size has on this property, Basheer et al. [4] observed that increasing the coarse aggregate ratio increases the permeability of concrete.

Concerning the porous structure and permeability of concrete, Coutinho and Gonçalves [11] say that the concrete's water absorption varies with its w/c ratio, the fineness and content of the cement, age, curing conditions, compactness, workability and water absorption of the aggregate. Permeability mechanisms are absorption and diffusion and they can be measured by capillary action and immersion test methods.

The permeability of concrete is a transport mechanism associated with two degradation mechanisms, i.e. carbonation and chloride penetration. According to Neville [31], the presence of CO_2 in the porous structure of reinforced concrete leads to a large pH reduction, compromising the steel's protection against the corrosive effect of water and oxygen. When it comes to concrete's resistance to chloride penetration, Ferreira [15] states that this phenomenon consists of a molecular reaction of the chloride ions, leading to the destruction of the passive rebar layer.

An important aspect of the durability of concrete is shrinkage control. According to Coutinho and Gonçalves [11], this phenomenon depends on the mix's water content, the amount of cement used and its properties, the aggregates' rock type and size distribution and the concrete's curing conditions. Troxell et al. [45] found that shrinkage increased in their test samples over 30 years, concluding that after the second year this mechanism was due to carbonation. Their study also found a strong influence of the aggregates' rock type on concrete shrinkage, due to their shape and texture which consequently affects the compactness of the mixes.

Hameed and Sekar [18] investigated the durability-related properties of concrete that incorporated fine recycled marble aggregates and dust from several quarries. They found improvements in the concrete's physical and mechanical characteristics because the particles' bond was more efficient, which resulted in better molecular cohesion. In terms of durability, they found that resistance to sulphate attack improved. A similar conclusion was reached by Binici et al. [5]. They also reported that the incorporation of natural and artificial pozzolan increases concrete's chemical resistance. Binici et al. [6] studied the incorporation of coarse marble aggregates in concrete. In their study, an improvement of chemical resistance to sulphate was noticed and this was due to a better bond between the aggregates and the cement paste, resulting in a more condensed and consistent bonding matrix.

3. Experimental programme

3.1. Materials used

The primary aggregates used were limestone gravel, basalt sand, granite sand and siliceous river sand. The secondary aggregates were sand made from waste generated by the Solubema marble quarrying industry. CEM II 42.5 R cement from the SECIL cement works in Outão, Setúbal, Portugal was used as binder. Tap water was used.

3.2. Characterisation of the aggregates

Some tests were performed to characterise the aggregates to enable the correct design of concrete mixes and to understand any differences in/effects on the results:

- Sieve analysis – NP EN 933-1 [33] and NP EN 933-2 [34].
- Bulk density and water absorption – NP EN 1097-6 [37].
- Apparent bulk density – NP EN 1097-3 [36].
- Shape index – NP EN 933-4 [35] (coarse aggregates only).
- Los Angeles abrasion test – LNEC E237 [21] (coarse aggregates only).

3.3. Concrete mixes composition

Based on Standard NP EN 206-1 [32], ten concrete mixes were produced that had average compression strength, of cube samples of approximately 44 MPa (C 30/37) and workability defined by the slump test in the range 125 ± 15 mm were tested.

The concrete formulations were calculated using Faury's [14] reference curves and are presented in Table 1.

Taking into account that the slump range is 125 ± 15 mm, the replacement ratios were set at 0%, 20%, 50% and 100% of the total aggregate volume. Fine aggregates are particles below 4 mm, "rice grain" has particles below 6 mm, gravel 1 particles are below 12 mm and gravel 2 particles are below 16 mm.

Having optimised and established the reference grading curve, constant for all mixes, the aggregates were replaced in the specified percentages for each grading size within the sieve's size range. The concrete was thus produced in accordance with the reference grading curve and with balanced proportions of aggregates.

However, the fine aggregates' differences in terms of texture and geometry had to be considered, as well as the consequent change of compactness in the mixes produced. Therefore, taking into account the loss of workability caused by the more elongated and angular marble sand, corrections were made to the w/c ratio to maintain the workability, measured indirectly by the slump (Table 2).

Ten mixes were produced (Table 2): three reference mixes (BRB, with basalt sand only; BRC, with river sand only; BRG, with granite sand only); two mixes per family with 20% and 50% replacement ratios of the fine primary aggregates by fine secondary (marble) aggregates (B$/M#, where $ can be B, C or G and # can be 20 or 50); one mix with marble sand only (BRM).

3.4. Testing of fresh concrete

The following tests were carried out on fresh concrete:

- Slump test (Abrams cone) – NP EN 12350-2 [38].
- Bulk density – NP EN 12350-6 [39].

3.5. Testing of hardened concrete

The following tests were carried out on hardened concrete:

- Water absorption by capillary action at 3, 6, 24 and 72 h – LNEC E-393 [23].
- Water absorption by immersion at 28 days – LNEC E-394 [24].
- Carbonation at 7, 28, 56 and 91 days after curing – LNEC E-391 [22].
- Chloride penetration at 28 and 91 days after curing – LNEC E-463 [26].
- Drying shrinkage at 91 days – LNEC E-398 [25].

The water absorption by capillary action test defined by standard LNEC E-393 advocates the use of 250 × 100 × 100 mm samples. Four samples were used for each concrete type and the measurements were taken at 3, 6, 24 and 72 h, after 28 days wet curing.

For the water absorption by immersion test (standard LNEC E-394 [24]), four 100 × 100 × 100 mm cubic samples were