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Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates

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Abstract

In order to reduce the volume of ceramic waste from the construction industry, it is possible, among other applications, to use it as aggregates in the production of non-structural concrete artefacts. The main characteristics of such aggregates as well as those of the fresh and hardened concrete made with them (after a standardized pre-saturation procedure) are presented here and compared with those of conventional materials (primary stone aggregates and the concretes made exclusively with them), within a larger experimental investigation to maximize the reuse and reutilization of construction and demolition waste. The results show that there is a potential for the use of these ceramic aggregates in elements in which the primary requirement is not compressive strength but tensile strength and abrasion resistance, such as for concrete pavement slabs.

Keywords: Sustainable construction; Ceramic waste; Aggregates; Non-structural concrete

1. Introduction

Ceramic materials, such as roof tiles and hollow bricks in façades and partition walls, are one of the mainstays in terms of construction materials in Mediterranean countries. Their factory production and construction procedures, however, produce a large amount of waste in addition to those resulting from demolition of existing buildings [1]. Ceramic wastes thus form one of the most important construction and demolition wastes (CDW) worldwide. Nevertheless, the reuse and recycling of these materials outside the strict factory production cycle is still not a common practice, especially in Portugal, where more than 95% of the total CDW volume produced is deposited in dumping grounds.

In the present paper, the Portuguese experience in recycling ceramic hollow bricks fragments as aggregates for the production of non-structural concrete for pavement slabs is described. The experimental results presented include the aggregate characteristics and the properties of fresh and hardened concrete. The results obtained with recycled ceramic waste are compared with those of conventional aggregates and concrete.

2. General description of the tests performed

The experimental work reported in the present paper involved the use of crushed hollow bricks waste coming from the building of partition walls as a replacement of coarse primary limestone aggregates in making 50 mm thick pavement slabs. Four different types of concrete with a replacement rate of 0 (reference concrete—BR), 1/3 (B1), 2/3 (B2) and 3/3 (B3), were cast. The mix design of all concretes is shown in Table 1.

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Table 1
Concrete mix design details

Component	Sieve limits (mm)	Weight (kg/m^3)
Coarse aggregates	2.38–4.76	206.8
	4.76–6.35	337.8
	6.35–9.52	508.9
Sand		633.8
Cement		346.7
Water		208.0
Admixtures		–

Table 2
Volume index of each fraction of aggregates

Type of aggregates	Sieve limits (mm)	I_v
Primary	6.35–9.52	0.162
	4.76–6.35	0.149
	2.38–4.76	0.239
Ceramic	6.35–9.52	0.202
	4.76–6.35	0.144
	2.38–4.76	0.153

The most relevant characteristics of the aggregates used were analysed, including the river sand common to all the mixes, the coarse primary limestone aggregates and the coarse recycled ceramic aggregates resulting from grinding the fragments of brick waste. An empirical process of pre-saturation of the ceramic aggregates, described later, reproducible both in a ready-mixed concrete plant and in a building site was proposed and implemented.

The workability (slump) and specific density of fresh concrete as well as the water absorbed in the pre-saturation process of the ceramic aggregates were measured for all mixes. Mechanical behaviour tests (compression, tension in bending and abrasion) on standard specimens of hardened concrete for all mixes were performed. The details and results of these tests are reported in the paper.

3. Aggregate characterization

3.1. Volume index

The volume index of each fraction of primary and secondary coarse aggregate was determined in accordance with LNEC (the Portuguese National Laboratory of Civil Engineering) standard E 223. [1] The procedure includes weighing the aggregates according to its size (in pre-established quantities), measuring their biggest dimension (50 particles per sieve), saturating them, drying the surface and measuring the volume taken by the aggregates in a calibrated recipient.

The volume index of each fraction of the aggregates I_v is given in Table 2 and determined according to the following formula:

$$\frac{V_2 - V_1}{\sum V} \tag{1}$$

where $\sum V$ is the sum of the volumes of the spheres with diameter equal to the length of each particle, rounded to the units; V_1 the volume of the water contained in the calibrated recipient; V_2 the volume of the water and the aggregates contained in the calibrated recipient.

The volume index indicates the shape of the particles: aggregates nearly spherical have an index near 1, compared to elongated ones with a smaller index. The analysis of the results leads to the following conclusions:

- in this work the smaller ceramic aggregates (fraction 2.38–4.76 mm mostly but also fraction 4.76–6.35 mm) were obtained by crushing bigger fragments that had been ground in a Los Angeles test machine (which rounded their borders), thus obtaining more elongated shapes and sharper borders; under normal circumstances and similar to what happened with the primary aggregates, finer aggregates should have bigger indexes;
- also because of the particular grinding procedure used the volume index of the ceramic aggregates were not always smaller than the corresponding values for the primary aggregates; in real applications this reduction will lead to smaller resistance and higher permeability in the concrete made with ceramic aggregates;
- the grinding process of the recycled aggregates is a critical parameter since it strongly affects the results and therefore deserves further study.

3.2. Bulk density

The bulk density of the compacted coarse aggregates (primary and ceramic) used was determined. For the primary aggregates only the density after they were dried in an oven was measured, contrary to the ceramic aggregates for which, due to its high water absorption, the air-dried and water saturated densities were also of interest. The procedure followed was based on the Portuguese standard NP 955. [2]

As expected, the bulk density of the ceramic aggregates dried in an oven (1159 kg/m^3) was smaller than the corresponding value for the limestone aggregates (1542 kg/m^3), something necessarily translated into lesser resistance in concrete made with ceramic aggregates. Also expected were the increasing values of the bulk density of the ceramic aggregates from dried in an oven

[1] Roughly equivalent to BS EN 1097-3:1998.

[2] Roughly equivalent to BS EN 1097-3:1998.

to dried in the open air (1167 kg/m^3) and to saturated (1265 kg/m^3), the latter of which shows the high water absorption to be expected in these aggregates, clearly demonstrating the need to pre-saturate them before mixing.

3.3. Specific density and water absorption

The specific density and water absorption ratio of the coarse aggregates were measured according to Portuguese standard NP 581. [3]

The specific density varied from 2029 kg/m^3 to 2626 kg/m^3 (dried) and from 2273 kg/m^3 to 2657 kg/m^3 (saturated, surface dry), for the ceramic and limestone aggregates, respectively.

The water absorption ratio, referred to the oven-dried aggregates, was 12% for the ceramic aggregates and 1% for the primary ones, a high disparity that was predictable and clearly points towards the greatest difficulty/limitation of the use of ceramic aggregates in the production of concrete or mortar without loss in one or several of the following characteristics: mechanical resistance, workability and durability. Pre-saturation is a way of minimizing these consequences. According to Devenny and Khalaf [2], approximately 30 min are necessary to saturate ceramic aggregates, the time-period adopted in the pre-saturation procedure throughout this investigation that also included spreading the aggregates in plastic sheets and leaving them to surface dry for a further 30 min before mixing. This procedure was made as simple as possible since it is meant to be reproduced in building site conditions.

To make sure that the pre-saturation procedure was reliable, the weight of water absorbed by the ceramic aggregates was measured by deducting the total weight of the aggregates just before they were mixed from their weight before saturation. The following water absorption values (in volume) were obtained: 2.3891 for B1 mix, 4.9781 for B2 mix and 7.1671 for B3 mix. The results showed that the water absorption was almost proportional to the quantity of ceramic aggregates in each concrete mix (0.136 l/kg of ceramic aggregate before pre-saturation, for B1 and B3 mixes), with a very slight increase in the B2 mix (0.142 l/kg), probably due to the fact that the aggregates were not as evenly spread in the plastic sheets to dry, an increase that is the most probable reason for a slight change in the water/cement ratio in that mix.

4. Properties of fresh concrete

As referred above, a grading curve for both the fine aggregates (river sand) and the coarse ones (primary or secondary) was devised to maximize the concrete compaction (Fig. 1). An important aspect is that, even though different aggregates were used in the four mixes under analysis (BR, B1, B2 and B3) the grading curve was always the same.

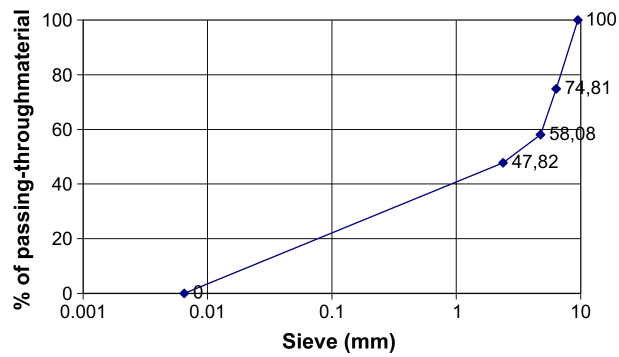

Fig. 1. Grading curve of aggregates for all concrete mixes.

4.1. Workability

In order to have comparable concrete mixes, the mix compositions were pre-tested in order to obtain the same slump value in the Abrams cone test: 80 ± 10 mm.

4.2. Specific density

The specific density of all the concrete mixes was determined, and it varied from 2349 kg/m^3 for mix BR to 2123 kg/m^3 for mix B3. As expected, since the density of the ceramic aggregates is smaller than that of the limestone aggregates, the specific density of the fresh concrete mixes decreases as the percentage of replacement of limestone aggregates by ceramic aggregates increases, according to a nearly-linear correlation.

5. Mechanical behaviour of hardened concrete

Four concrete types were tested: BR, without any recycled aggregates; B1, with one third of the limestone coarse aggregates replaced with the same quantity of ceramic aggregates with exactly the same grading; B2 and B3, similar to B1 but with replacement ratios of two and three thirds, respectively.

The concrete mixing composition, as detailed earlier, was kept constant except for the water/cement ratio that was made to depend upon maintaining approximately the same slump value (Abrams test) for every fresh concrete mix, as stated above. The (apparent) w/c ratio was 0.60 for the BR mix and, due to the pre-saturation procedure adopted, was kept constant in all but the B2 concrete mix, where it was reduced to 0,55 to meet the slump value criterion. As referred above, this was probably due to a slight deficiency in the air drying part of

[3] Roughly equivalent to BS EN 1097-6:2000.

Table 3
Strength and abrasion resistance of the concretes

Concrete mix	Compressive strength (MPa)	Flexural[a] strength (MPa)	Average loss of thickness by abrasion (mm)
BR	23.3	3.50	4.45
B1	18.2	3.20	4.20
B2	17.7	2.95	3.70
B3	13.0	2.60	3.30

[a] Span = 540 mm.

the pre-saturation process for the ceramic aggregates of that particular mix.

5.1. Compressive strength

To measure the compressive strength three 150 mm cubes were made of each concrete type. The procedure followed LNEC standard E 226 [4] that includes demoulding the cubes 24 h after casting, storing them in a humid chamber (average temperature and RH of 20 °C and 100% respectively) for a further 27 days. The results for all concrete types are shown in Table 3 and represent an average value of three tests.

As expected, as the percentage of ceramic aggregates (with less density and compressive strength than the limestone aggregates) increases, the concrete compressive strength decreases. The limited number of specimens tested indicates that the relationship between compressive strength and percentage of ceramic aggregates is approximately linear. In relative terms, the total replacement of limestone primary aggregates with ceramic recycled ones caused a 45% decrease in compressive strength.

5.2. Flexural strength

More important than compressive strength in pavement slabs is the flexural strength. To assess flexural strength, three prismatic specimens of $50 \times 400 \times 600$ mm were made of each mix. The experimental procedure followed was the one presented in the LNEC standard E 227, [5] with third point loading and a 540 mm span. The results for all concrete types are shown in Table 3 and represent an average value of three tests.

The flexural strength, as compressive strength, decreased with the percentage of replacement of limestone aggregates with ceramic aggregates increase. Again, these results indicate an approximate linear relationship between the two factors. Additionally, the relative reduction in flexural strength when all coarse primary aggregates are replaced is only 26%, much less than that for compressive strength.

Fig. 2. Abrasion resistance test.

5.3. Abrasion resistance

Also very important for pavement slabs is the resistance to abrasion. To assess this property, three prismatic specimens, $50 \times 70 \times 70$ mm, were made of each mix, by sawing the prismatic specimens used in the flexural tests. The experimental procedure followed was the one presented in the DIN standard 52108, [6] which includes the following steps: before the test, the specimens were kept in the same humid chamber and then dried until their mass stabilized; then they were measured, the testing machine was cleaned and a known quantity of abrasive sand was positioned in the disk; the specimen was positioned over it with and under a calibrated weight; four cycles of a pre-determined number of rotations, measurement of the dimensions of the specimen and weighing them were performed (Fig. 2). The results for all concrete types are shown in Table 3 and represent an average value of three tests.

The results again show nearly-linear increase in abrasion resistance, as measured by the loss of thickness of the specimens, with the percentage of ceramic aggregates, a trend most significantly positive in pavement slabs. This can be explained by the better adhesion between the mortar paste and the ceramic aggregates, caused by their greater porosity as compared with the limestone aggregates. The abrasion resistance is controlled fundamentally by the wear of the matrix and its bonding to the coarse aggregates, as opposed to the wear of the coarse aggregates.

6. Conclusions

This experimental study indicates that the recycling of ceramic waste from construction and demolition sites as coarse aggregates for the production of non-struc-

[4] Roughly equivalent to BS 1881-116:1983.
[5] Roughly equivalent to BS 1881-118:1983.
[6] Roughly equivalent to BS EN 13892-4:2002.

tural concrete artefacts is feasible. The main problem with these aggregates is their high water absorption, even though this can be partly solved by resorting to a pre-saturation procedure easily reproducible in a building site.

Strength decreases as the quantity of ceramic aggregates in concrete increases, since they are lighter and less resistant than the primary stone aggregates. The decrease in compressive strength is higher than that in the flexural strength. Furthermore, the abrasion resistance of concrete made with ceramic recycled aggregates is higher than that of concrete made with limestone aggregates.

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