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Mechanical properties of structural concrete with fine recycled ceramic aggregates

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HIGHLIGHTS

- Recycled aggregates obtained from crushed bricks and crushed sanitary ware.
- Influence of aggregates incorporation in mechanical properties of concrete.
- Concrete with recycled crushed bricks presents adequate structural performance.
- Concrete with recycled sanitary ware performs poorly.

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ABSTRACT

The objective of this research is to evaluate the effect of the incorporation of recycled ceramic fine aggregates, obtained from crushed bricks and crushed sanitary ware, on the mechanical properties of concrete. The effects of such incorporation on properties such as compressive strength, splitting tensile strength, modulus of elasticity and abrasion resistance were investigated and are discussed. Seven different concrete mixes were cast to test these hardened properties: a conventional reference concrete and six concrete mixes with replacement ratios of 20%, 50% and 100% of natural fine aggregates by either fine recycled brick aggregates or fine recycled sanitary ware aggregates. All mixes were prepared with the same workability and the same aggregates' size gradation to allow for a valid comparison of results. Results obtained show that concrete with recycled crushed bricks exhibits adequate structural performance. Conversely, concrete with recycled sanitary ware performed poorly compared to the reference concrete, even though this limitation may be offset by the use of superplasticizers.

1. Introduction

Consumption of natural resources and energy has increased proportionately to civilization development and world population growth, and this is one of the biggest environmental concerns today. In addition to the increasing emission of greenhouse effect gases, unbalanced consumption of natural resources will eventually lead to their exhaustion, as in the case of ceramic materials.

According to the Portuguese Centre of Ceramics and Glass,[1] the Portuguese ceramic industry produced, in 2012 only, 10,000 tons of sanitary ware waste and 35,000 tons of brick waste. Adding to this, there is ceramic waste resulting from construction and demolition operations. So, a large quantity of ceramic waste is produced and just a small quantity is recycled, leading to an enormous waste disposal.

The use of recycled aggregates, namely ceramic, in new structural concrete, is beneficial from the viewpoints of environmental protection and reduction in the consumption of natural resources. However, to entirely embrace the use of recycled aggregates in the production of new concrete, it is necessary to fully understand the performance of this type of concrete.

This research addresses the important environmental problem of how to dispose of the waste generated by the ceramic industry and by construction and demolition operations and analyses the feasibility of incorporating fine aggregates from that waste in concrete production, with respect to mechanical performance. Although some studies discussed below have been performed on concrete with incorporated recycled ceramic aggregates, in most of them only the coarse fraction is involved. As a matter of fact, no studies about concrete with fine sanitary ware aggregates were found. So, this experimental programme intends to fill this gap, contributing to the analysis of the viability of the use of this type of aggregates in structural concrete.

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[1] http://www.ctcv.pt/index_eng.html.

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An additional part of the innovation of this research has to do with keeping constant both following factors (unlike most similar studies published in the literature): (i) Size distribution of the aggregates (when replacing natural aggregates with recycled aggregates this distribution was kept constant in order to avoid difficult-to-interpret changes in almost every relevant property of concrete); (ii) Workability (for practical purposes, concrete mixes with different workability levels may not have the same range of applications and therefore should not be directly compared).

2. Literature review

The literature review showed there is a lack of information regarding the influence of the incorporation of recycled ceramic fine aggregates on the mechanical behaviour of concrete, especially for fine sanitary ware aggregates.

The general features of a few selected experimental researches concerning the properties of concrete with recycled ceramic aggregates analysed in the present article are briefly described next.

Mansur et al. [1] tested four families of concrete mixes, each one defined by a given water/cement ratio and consisting of one conventional concrete (concrete made with natural aggregates only) and one concrete with a 100% replacement ratio of coarse natural aggregates by coarse recycled ceramic aggregates (from crushed clay bricks). The compressive and tensile strengths, the modulus of elasticity, the drying shrinkage and the creep of those concretes were determined.

De Brito et al. [2] tested replacement ratios of 1/3, 2/3 and 3/3 of coarse limestone aggregates by coarse recycled ceramic aggregates (from crushed standard hollow red clay wall bricks from a single batch) to determine the compressive and flexural tensile strengths, the abrasion resistance, and the water absorption by capillarity and immersion of concrete.

Khatib [3] tested replacement ratios of 25%, 50%, 75% and 100% of fine natural aggregates (class M sand) by fine recycled ceramic aggregates (bricks obtained from demolished structures, which were then crushed in the laboratory) to determine the compressive strength, the ultrasonic pulse velocity, the density, the dynamic modulus of elasticity, the shrinkage and the expansion of concrete; he made the same analysis for concrete with fine recycled concrete aggregates.

Senthamarai and Manoharan [4] tested six families of mixes, each one defined by a given water/cement ratio and consisting of one conventional concrete (with no recycled aggregates) and one concrete with a replacement ratio of 100% of coarse natural aggregates by coarse recycled ceramic aggregates (from ceramic electrical insulator industrial wastes) to determine the compressive and tensile strengths and the modulus of elasticity of concrete.

Debieb and Kenai [5] tested replacement ratios of 25%, 50%, 75% and 100% of fine natural aggregates by fine, coarse and both simultaneously, recycled ceramic aggregates (crushed bricks) to determine the compressive and tensile strengths, the modulus of elasticity, the water absorption by capillarity, the water permeability and the shrinkage of concrete.

Gomes and de Brito [6] tested replacement ratios of 25% and 50% of coarse limestone aggregates by coarse recycled ceramic and mortar aggregates (from demolished standard partition walls made of hollow red clay bricks and cement-based renders of previously known characteristics) to determine the compressive and tensile strengths, the modulus of elasticity, the water absorption by capillarity and immersion, and the carbonation and chloride penetration of concrete; they made the same analysis for concrete with coarse recycled concrete aggregates.

López et al. [7] tested replacement ratios of 10%, 20%, 30%, 40% and 50% of fine natural aggregates by fine ceramic aggregates (obtained from recovered floor and wall tiles) to determine the compressive and tensile strengths of concrete.

Guerra et al. [8] tested replacement ratios of 3%, 5%, 7%, 9% of coarse natural aggregates by coarse ceramic aggregates (obtained from industrial rejects of sanitary ware) to determine the compressive and tensile strengths of concrete.

Medina et al. [9] tested replacement ratios of 15%, 20% and 25% of coarse natural aggregates by coarse ceramic aggregates (obtained from industrial rejects of sanitary ware) to determine the compressive and tensile strengths of concrete.

The results obtained by these authors, regarding both aggregates' and concrete's properties, are described next. There are other studies on the use of ceramic recycled aggregates in the production of concrete which are focused on durability aspects (e.g. Correia et al. [10], Senthamarai et al. [11], Kenai and Debieb [12], Medina et al. [13]), outside the scope of our paper.

2.1. Aggregates' properties

Mansur et al. [1] stated that coarse recycled ceramic aggregates show higher water absorption when compared to coarse natural aggregates. The values reported are 6.1% and 0.7%, respectively. Regarding the bulk density, they reported that this property is lower for the coarse recycled brick aggregates (2.21 kg/dm^3) than for coarse natural aggregates (2.66 kg/dm^3).

According to de Brito et al. [2], coarse recycled ceramic aggregates have high water absorption (12.0%). They stated that this property is probably the greatest limitation to the use of this type of aggregates in the production of concrete, without loss in mechanical strength, workability or durability. They also reported a lower bulk density for recycled brick aggregates (1159 kg/m^3) than for coarse natural aggregates (1542 kg/m^3).

Khatib [3] achieved water absorption of 14.8% for fine recycled ceramic aggregates, a significantly higher value than the one obtained for natural aggregates (0.8%). He obtained lower bulk density for fine recycled brick aggregates (2050 kg/m^3) than for coarse natural aggregates (2650 kg/m^3) and fine recycled concrete aggregates (2340 kg/m^3).

Senthamarai and Manoharan [4] reported that ceramic waste has lower water absorption than natural aggregates. The values reported are 0.7% and 1.2%, respectively. Regarding the bulk density, they obtained lower bulk density for coarse recycled ceramic aggregates (2.5 kg/dm^3) than for coarse natural aggregates (2.7 kg/dm^3).

Debieb and Kenai [5] reported water absorption of 14.0% for fine recycled ceramic aggregates and of 1.0% for natural aggregates. They concluded that the higher water absorption of crushed brick aggregates is due to their high porosity. The authors reported a lower bulk density for fine recycled brick aggregates (2496 kg/m^3) than for fine natural aggregates (2978 kg/m^3).

Gomes and de Brito [6] obtained 16.3% for the water absorption of coarse recycled ceramic and mortar aggregates whereas a value of 2.3% was reported for coarse natural aggregates. The values of bulk density were 2160 kg/m^3 for coarse recycled aggregates and 2616 kg/m^3 for coarse natural aggregates.

López et al. [7] and Guerra et al. [8] stated that, despite being similar, the bulk density of natural aggregates is higher than the one of recycled ceramic aggregates.

Medina et al. [9] stated that coarse sanitary ware aggregates has higher water absorption than coarse natural aggregates. However, the results reported, respectively 0.6% and 0.2%, showed that these properties are very similar for recycled and natural aggregates. Regarding bulk density, they reported that this property is higher for coarse natural aggregates (2630 kg/m^3) than for coarse recycled ceramic aggregates (2390 kg/m^3).

Analysing the results reported by these authors, one can conclude that recycled brick aggregates presents significantly higher water absorption than natural aggregates and recycled sanitary ware aggregates. The last two types of aggregates have small and similar values of water absorption. Regarding bulk density, recycled brick aggregates have lower bulk density than natural aggregates and recycled sanitary ware aggregates. The last two types of aggregates have similar values of bulk density. One can conclude also that water absorption and bulk density display dissimilar trends. In fact, Angulo [14] reported this type of relationship between these properties.

2.2. Properties of concrete

The results of the tests performed to determine the properties of concrete made with recycled ceramic aggregates are described next. The values obtained by the different authors for the different tests will be presented in Section 4, along with the results of this experimental programme. Results of Mansur et al. [1] are not illustrated because the authors did not report them.

2.2.1. Workability

Mansur et al. [1] stated that the use of coarse recycled brick aggregates gives consistently lower workability than the corresponding mix with natural aggregates. They attribute this result to the rough surface of the recycled aggregates.

Khatib [3] kept constant the water/cement ratio of all concrete mixes produced. With an increase in the replacement of fine natural aggregates by fine recycled brick aggregates, he obtained a decrease in the slump value due to the high water absorption of these latter aggregates.

Senthamarai and Manoharan [4] obtained higher slump values for concrete mixes with full replacement of coarse natural aggregates by coarse recycled ceramic aggregates. The authors stated that this result is due to the lower water absorption and smooth surface texture of the ceramic aggregates.

Debieb and Kenai [5] reported an increasing linear trend between water/cement ratio and replacement ratio, in order to have the same slump value for all compositions produced. They stated that this result is due to an inefficient pre-saturation process.

Results reported by López et al. [7] and Guerra et al. [8] are not clear about the relationship between replacement ratio and workability.

2.2.2. Fresh density

Gomes and de Brito [6], de Brito et al. [2] and Medina et al. [9], reported a linear decrease in the fresh density of the concrete mixes produced, with an increase in the replacement ratio of natural aggregates by recycled ceramic aggregates. They justified this trend with the lower bulk density of the recycled aggregates when compared to the natural aggregates.

Debieb and Kenai [5] stated that the fresh density of the concrete mixes produced decreases as the incorporation of recycled brick aggregates increases. However, they did not report on the type of relationship prevailing between these two variables.

2.2.3. Compressive strength

Mansur et al. [1] reported that, within the strength range tested, concrete made with coarse brick aggregates achieved a higher strength level than conventional concrete. The authors justified this higher strength with the higher angularity and rougher surface of the recycled aggregates, when compared to the natural ones, which improved the strength development by better mechanical interlocking and better adhesion, on a greater available surface area. No appreciable changes in the rate of strength development between the two types of concrete were found.

De Brito et al. [2] stated that, as the replacement ratio increases, the concrete compressive strength decreases linearly. This strength reduction is justified due to the fact that recycled coarse brick aggregates are lighter and less resistant than natural aggregates.

Khatib [3] reported a systematic decrease in compressive strength as the fine recycled brick aggregates content increases. However, for the same replacement level and test age, mixes with brick aggregates achieved higher strength than those with recycled concrete aggregates. Between the age of 28 and 90 days, the rate of compressive strength gain for all mixes containing crushed bricks is higher than that of those containing crushed concrete and natural aggregates only. This result is justified with pozzolanic reactions caused by the silica and alumina contents of crushed bricks.

Senthamarai and Manoharan [4] reported lower compressive strength in concretes with total replacement of coarse natural aggregates by coarse recycled ceramic aggregates than the one obtained for conventional concrete, for all families tested. However, this decrease was very small.

Debieb and Kenai [5] stated that the higher the replacement ratio of fine natural aggregates by fine recycled brick aggregates, the lower the compressive strength. No appreciable changes in the rate of strength development were found.

Gomes and de Brito [6] stated that with an increase in the replacement ratio, the concrete compressive strength decreases.

López et al. [7] reported an increase in compressive strength with an increase in the replacement ratio.

Results obtained by Guerra et al. [8] are not clear about the influence of the incorporation of coarse sanitary ware aggregates on the compressive strength. All the compositions tested have higher strength than conventional concrete except the one with 3% replacement ratio.

Medina et al. [9] reported an increase in the compressive strength with the replacement ratio. They justified this result with narrower, more compact, less porous and less marked interfacial transition zone for mixes with ceramic incorporation than for conventional concrete.

2.2.4. Tensile strength

Mansur et al. [1] reported that concrete made with coarse brick aggregates achieved higher splitting tensile strength than conventional concrete. According to them, this is due to a more angular shape and rougher surface texture of brick aggregates, which possibly may have enhanced the interfacial bond, resulting in a higher strength.

Results obtained by de Brito et al. [2] and Gomes and de Brito [6] indicate a linear decrease in both the splitting tensile strength and flexural strength with the replacement ratio. However, this reduction is less than the one for compressive strength. The justification given by de Brito et al. [2] for this result is the same as for compressive strength.

Senthamarai and Manoharan [4] found that concrete mixes with full replacement of coarse recycled ceramic aggregates present lower splitting tensile strength than conventional concrete. However, the difference is very low.

Debieb and Kenai [5] stated that, although the angular shape of the crushed material and its rough surface are generally beneficial for a good bond between the crushed brick aggregates and the cement paste, which could enhance the flexural strength, a decrease in resistance was observed. This reduction was similar to that in compressive strength.

Results obtained by López et al. [7] and Guerra et al. [8] are not clear about the influence arising from the incorporation of recycled ceramic aggregates on splitting tensile strength.

Medina et al. [9] reported an increase in the splitting tensile strength with replacement ratio for the same reason described about compressive strength.

2.2.5. Modulus of elasticity

Mansur et al. [1] reported a decrease in this property when coarse natural aggregates were replaced by coarse brick aggregates. They also obtained results which indicate that, for both types of concrete, an increase in compressive strength is matched by an increase in the modulus of elasticity.

Khatib [3] stated that replacing fine natural aggregates with crushed brick results in a decrease in the dynamic modulus of elasticity. In addition, an increase in the replacement level is associated with a decrease in the same property. He also observed that concrete mixes containing crushed bricks yielded higher modulus of elasticity than those incorporating crushed concrete, for the same replacement ratio.

Senthamarai and Manoharan [4] obtained a reduction in modulus of elasticity with replacement ratio. Their results also indicate that an increase in the water/cement ratio leads to a decrease of this property.

Gomes and de Brito [6] reported a linear decrease in modulus of elasticity with the replacement ratio.

2.2.6. Abrasion resistance

This property has only been studied by de Brito et al. [2]. The results indicate a nearly-linear increase in abrasion resistance with the replacement ratio. They justified this result with the better adhesion between the mortar paste and the ceramic aggregates, caused by their greater porosity as compared to the limestone aggregates.

3. Experimental programme

3.1. Materials used

Primary aggregates in this experimental programme are limestone gravel and siliceous river sand. The secondary aggregates are crushed brick powder, provided by Grupo Tábuas e Leite & Co., Lda, and crushed sanitary ware, obtained with a jaw crusher from rejected sanitary pieces provided by Grupo ROCA. CEM II A-L 42.5 R cement from the SECIL cement plant in Outão, Setúbal was used as binder. Tap water was used.

3.2. Characterization of the aggregates

The following tests were performed to characterize the aggregates, enabling the correct design of concrete mixes and the in-depth understanding of the results: sieve analysis – EN 933-1 [15] and EN 933-2 [16]; bulk density and water absorption – EN 1097-6 [17]; apparent bulk density – EN 1097-3 [18]; shape index – EN 933-4 [19] (coarse aggregates only); Los Angeles test – LNEC E237 [20], similar to EN 1097-2 [21] (coarse aggregates only).

Due to the high water absorption of the recycled brick aggregates, one must compensate for the water absorbed in order to have the same workability for all compositions produced. Ferreira et al. [22], who studied the influence of pre-saturation of recycled aggregates (coarse recycled concrete aggregates were used in this study) on concrete properties in which they are incorporated, concluded that this methodology negatively (but not significantly) affects the concrete behaviour, especially the durability performance. So, they concluded that adding an adequate amount of water during the mixing procedure is the best way to offset the negative effects of the high water absorption of the recycled aggregates. A similar procedure was thus followed in our research.

In this experimental programme, the methodology proposed by Rodrigues et al. [23] was used. According to this methodology, when determining the mixing water content, it is possible to take into account that recycled brick aggregates have much higher water absorption than natural aggregates. The test procedure consists in determining the increase of water absorbed by an immersed fine recycled brick aggregates sample, previously oven dried, by means of a hydrostatic balance. In order for the various mixes to have the same effective water/cement ratio (i.e. the same free water for cement hydration and workability purposes), the extra amount of water that recycled brick aggregates absorbs during mixing was added to the mixer.

3.3. Composition of concrete mixes

Considering standard EN 206-1 [24], the purpose was to produce a concrete with an average cube compressive strength of approximately 37 MPa (C25/30) and with workability defined by the slump range of 125 ± 10 mm. Table 1 presents the composition of the materials used.

Faury's method was used to determine the mixes' composition, assuming a target slump of 125 ± 10 mm.

The replacement ratios were set at 0%, 20%, 50% and 100% of the total aggregate volume. Fine aggregates are particles below 4 mm, while "rice grain", gravel 1 and gravel 2 are coarse aggregate particles with maximum dimension of 8 mm, 11.2 mm and 22.4 mm, respectively.

Both the natural fine and coarse aggregates were replaced by equivalent recycled aggregates. In order to eliminate the influence of the gradation on the results, the size distribution of the natural aggregates was reproduced in the equivalent recycled aggregates for all the mixes.

Finally, the water/cement ratio was calibrated so as to maintain the level of workability, which was expected to be affected as the amount of recycled ceramic aggregates incorporated increases (Table 2).

In order to understand the viability of the use of fine sanitary ware aggregates in concrete, additional specimens of SWC100 were produced with superplasticizer, aiming at offsetting the increase of effective water/cement ratio (to keep the same workability as the reference concrete).

3.4. Testing of fresh concrete

The following tests were carried out in fresh concrete: Slump test (Abrams cone) – EN 12350-2 [25]; Bulk density – EN 12350-6 [26].

3.5. Testing of hardened concrete

The following tests were carried out in hardened concrete: (i) compressive strength at 7, 28 and 56 days – EN 12390-3 [27]; (ii) splitting tensile strength at 28 days – EN 12390-6 [28]; (iii) modulus of elasticity at 28 days – LNEC E397 [29]; and (iv) abrasion resistance at 91 days – DIN 52108 [30].

The compressive strength test method is specified in EN 12390-3, using a total of ten $15 \times 15 \times 15\ cm^3$ wet-cured specimens, three for tests at 7 days, five for tests at 28 days and three for tests at 56 days.

Table 1
Composition of the reference concrete mix.

Size grading (mm)			Volume (m^3/m^3)	Weight (kg/m^3)
Fine aggregates	<0.063	0.063	0.0000	0.0
	0.063	0.125	0.0142	36.1
	0.125	0.25	0.0430	109.3
	0.25	0.5	0.0493	125.3
	0.5	1	0.0567	144.1
	1	2	0.0651	165.5
	2	4	0.0748	190.1
Coarse aggregates	"Rice grain"		0.0570	146.4
	Gravel 1		0.0223	56.8
	Gravel 2		0.2923	734.3
Cement			0.1150	350.0
Water			0.1930	193.0

Table 2
Water/cement ratio (w/c) and identifying acronym of all concrete mixes.

Mix	Acronym	Apparent w/c	Effective w/c
Reference concrete	RC	0.53	0.53
Brick concrete with 20% aggregate replacement	BC20	0.56	0.53
Brick concrete with 50% aggregate replacement	BC50	0.61	0.53
Brick concrete with 100% aggregate replacement	BC100	0.64	0.53
Sanitary ware concrete with 20% aggregate replacement	SWC20	0.76	0.76
Sanitary ware concrete with 50% aggregate replacement	SWC50	0.78	0.78
Sanitary ware concrete with 100% aggregate replacement	SWC100	0.86	0.86

Table 3
Aggregate tests results.

Property	Gravel 2	Gravel 1	"Rice grain"	Coarse river sand	Fine river sand	Brick aggregate	Sanitary ware aggregate
Bulk density (kg/m^3)	2512	2546	2569	2554	2529	1948	2969
Water absorption (%)	1.7	1.7	1.6	0.6	0.3	12.2	0.2
Apparent bulk density (kg/m^3)	1450	1438	1416	1579	1556	1032	1319
Los Angeles abrasion test (%)	28.4	25.8	22.7	–	–	–	–
Shape index (%)	14.8	17.0	17.8	–	–	–	–

The method described by standard EN 12390-6 was used to determine the splitting tensile strength. Tests were performed on wet-cured specimens: three cylinders 30 cm tall and of diameter 15 cm per concrete mix analysed.

The modulus of elasticity method is specified in the standard LNEC E397, using two cylinders 30 cm tall and of diameter 15 cm per concrete mix analysed.

The determination of the wear resistance by abrasion followed the test method specified in the German standard DIN 52108, using three $7.1 \times 7.1 \times 5$ cm^3 specimens.

4. Results and discussion

4.1. Aggregates' properties

Table 3 shows the results of the tests on the aggregates. Fig. 1 shows the grading curves of the different types of natural aggregates.

The fine aggregates with the lowest bulk density are the recycled brick aggregates. Recycled sanitary ware aggregates present the highest bulk density.

Regarding water absorption after 24 h immersion, fine recycled brick aggregates have the highest value (12.2%) and fine recycled sanitary ware aggregates the lowest (0.2%). These values are similar to the ones found by de Brito et al. [2] and Medina et al. [9]. Fig. 2 shows the water absorption of the recycled brick aggregates with time. It is during the first 10 min that most of the water absorption occurs. Accordingly, it was considered that 84% of the maximum absorption potential occurred after this period. This extra water minus the water content already in the aggregates (measured before the mix) was added to the mix.

Analysing the bulk density and the water absorption of the fine recycled ceramic aggregates, one can conclude that recycled brick aggregates have higher porosity than recycled sanitary ware aggregates. This conclusion is in agreement with all the works described in Section 2.

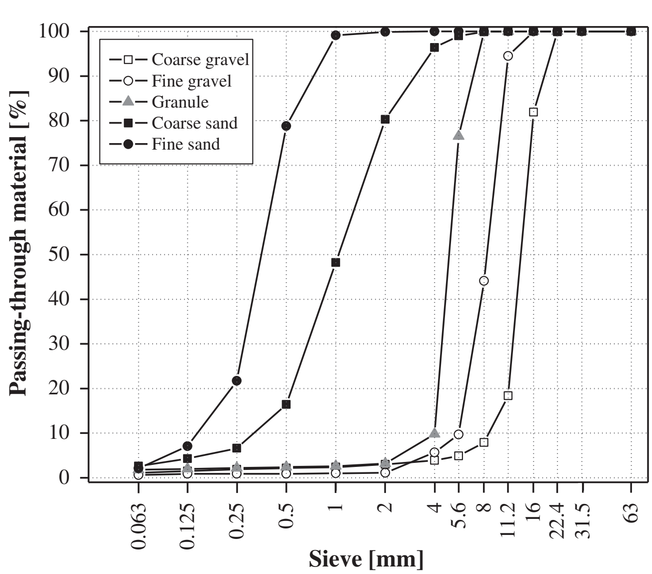

Fig. 1. Grading curves of the natural aggregates.

The Los Angeles abrasion test shows that all the aggregates complied with the limits set in LNEC E 373 [31] for use in structural concrete (50%) – results varied from 22.7% to 28.4%. The shape index results showed a similar geometry for the various types of coarse aggregates.

4.2. Properties of concrete

In this section the results of our experiments are presented and compared with those of the previous researches described in Section 2. Because there are very few similar experiments in the literature, for some properties, the comparison was made with tests performed on concrete with coarse ceramic recycled aggregates, instead of concrete with fine ceramic recycled aggregates.

4.2.1. Workability

Table 4 shows the slump test results and the apparent and effective water/cement ratios for each concrete produced.

This table shows that although recycled ceramic aggregates affect negatively the workability of concrete in which they are incorporated, changing the apparent water/cement ratio is an effective procedure to overcome the problem. In fact, all concrete mixes produced had a slump within the target interval (12.5 ± 1.0 cm), even though the water/cement ratio had to be increased as the percentage of replacement increases.

For concrete mixes incorporating fine recycled brick aggregates, the increase in the apparent water/cement ratio needed to obtain the same workability as that of the conventional concrete, maybe attributed to the higher water absorption of the aggregates. This property implies the migration of water to the aggregates, reducing the quantity of water which contributes to the workability. In their studies, Khatib [3] and Debieb and Kenai [5] obtained the same result. From Table 4 one can conclude that the effective water/cement ratio was kept constant for these compositions.

For concrete mixes with recycled sanitary ware aggregates, the result was not as expected. Despite the low water absorption of these aggregates, a significant increase in the effective water/cement ratio was needed to reach the target slump. This is probably due to the glazed surface together with the referred low water absorption of those aggregates. These two properties were probably responsible for the accumulation of some water at the interface between the fine recycled aggregates and coarse natural aggregates due to liquid bridges between them. Even for small incorporation ratios the recycled aggregates' particles tended to agglutinate. In the literature there is no explanation for this result.

4.2.2. Fresh density

Table 4 shows the results of the bulk density test of fresh concrete. Fig. 3 shows the fresh-state bulk density of each mix relative to the reference concrete (RC), as a function of the aggregate replacement ratio. It shows that incorporating fine aggregates reduces the bulk density in the fresh state of both recycled brick (BC) and sanitary ware concrete (SWC).

In mixes with incorporated fine recycled brick aggregates this is mainly due to the lower bulk density of these aggregates relative to natural ones. De Brito et al. [2] and Debieb and Kenai [5] reported

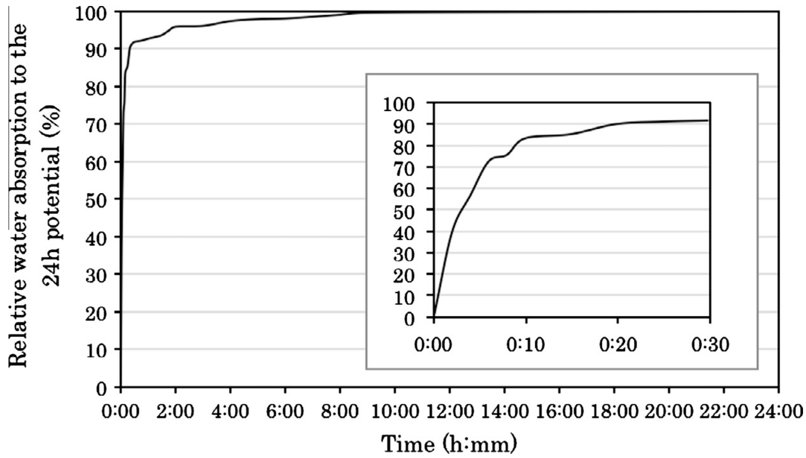

Fig. 2. Absorption of the recycled brick aggregates relative to the 24 h potential as a function of time.

Table 4
Results of tests on fresh concrete: slump (*h*) and bulk density.

Composition	*h* (cm)	Bulk density (kg/m^3)
RC	12.3	2352.7
BC20	12.3	2303.1
BC50	13.4	2250.8
BC100	11.6	2167.4
SWC20	12.0	2248.3
SWC50	11.6	2221.7
SWC100	11.6	2154.6

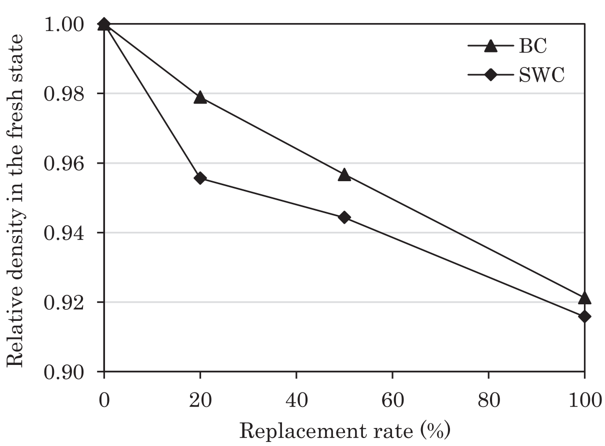

Fig. 3. Density in the fresh state of BC and SWC mixes relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

the same results and the same explanation for the reduction in bulk density with an increase in replacement ratio of recycled brick aggregates.

In mixes with incorporated sanitary ware aggregates, despite the higher bulk density of these aggregates, when compared to natural ones, the fresh density decreases with an increase in the replacement ratio. This is due to the much higher water content of these mixes.

4.2.3. Compressive strength

The compressive strength test results (mean values – f_{cm} – and standard deviations) for all the mixes, test ages and replacement ratios are given in Table 5, together with the relative percentage difference compared to the reference concrete (Δ). Figs. 4–6 illustrate the relationship between compressive strength of all the mixes and the replacement ratio of fine natural aggregates by fine ceramic aggregates respectively at 7, 28 and 56 days. Figs. 7 and 8 show the development of the compressive strength with age, for each of the families of concrete tested, respectively with recycled brick aggregates and sanitary ware aggregates.

The results show that the compressive strength decreases with an increase in replacement ratio of recycled brick aggregates. Khatib [3] and Debieb and Kenai [5] reported the same conclusion. At 7, 28 and 56 days, the maximum loss of strength, relative to the reference concrete, was 24.9%, 9.6% and 7.1%, respectively.

This reduction in compressive strength is due to the decrease in strength of the paste with an increase in replacement ratio. In fact, de Brito [32] stated that, for the type of coarse aggregates used in the experimental programme, the compressive strength of the concrete is not governed by their strength, but by the strength of the paste. So, introducing fine recycled brick aggregates, with lower strength and more porous structure than the natural ones, decreased the strength of the paste, which led to lower concrete strength.

At 7 days, the maximum loss was reached for the replacement ratio of 50% and not 100%, as expected and observed in the other test ages. In fact, for all test ages, BC50 and BC100 presented similar values of strength. There are two possible reasons for this result: one is that the composition with total replacement displayed a significantly higher standard deviation for all ages; the other is that the higher roughness and specific surface of the recycled brick aggregates, when compared to the natural ones, attenuated the undesirable increase in porosity of the paste, due to better interfacial transition zone.

With an increase in age of the mixes with incorporated recycled brick aggregates, the difference between their strength and that of reference concrete decreases. This result reveals a higher rate of strength development for mixes with incorporated brick aggregates than for reference concrete. In fact, Khatib [3] and Leite [33] reported the same results and attributed thus to a possible pozzolanic activity of the brick aggregates. Another reason for this higher rate of strength development as reported by Cachim [34] is that in order to maintain same workability, the higher water content of the mixes leads to later hydration of the cement. Wild et al. [35] stated that the incorporation of brick aggregates in concrete implies a strength improvement in the long term, when compared to conventional concrete.

In mixes with incorporated sanitary ware aggregates, a considerable decrease in compressive strength with an increase in the replacement ratio was observed, for all test ages. At 7, 28 and 56 days of age, the maximum loss in strength, relative to the

Table 5
Results (average ± standard deviation) of tests on hardened concrete: compressive strength (f_{cm}), splitting tensile strength (f_{ct}), modulus of elasticity (E_c) and abrasion resistance (Δl_m) (Δ is the percentage relative difference to the reference concrete).

Composition	Compressive strength						Tensile strength		Elasticity modulus		Abrasion resistance	
	$f_{cm,7}$ (MPa)	Δ (%)	$f_{cm,28}$ (MPa)	Δ (%)	$f_{cm,56}$ (MPa)	Δ (%)	f_{ctm} (MPa)	Δ (%)	E_{cm} (GPa)	Δ (%)	Δl_m (mm)	Δ (%)
RC	39.0 ± 2.1	–	46.2 ± 0.9	–	47.6 ± 1.5	–	3.60 ± 0.2	–	38.3 ± 1.1	–	4.0 ± 0.1	–
BC20	33.4 ± 0.3	−14.5	42.9 ± 0.4	−7.0	46.8 ± 0.4	−1.7	3.53 ± 0.1	−2.0	32.4 ± 0.3	−2.0	4.4 ± 0.2	9.0
BC50	29.3 ± 0.9	−24.9	41.8 ± 0.6	−9.5	45.5 ± 1.0	−4.4	3.40 ± 0.0	−5.7	31.6 ± 0.3	−5.7	4.7 ± 0.3	15.8
BC100	30.2 ± 2.1	−22.5	41.7 ± 2.0	−9.6	44.2 ± 2.4	−7.1	3.42 ± 0.4	−5.2	27.2 ± 0.5	−5.2	5.3 ± 0.3	31.4
SWC20	25.1 ± 1.2	−35.7	31.2 ± 1.1	−32.5	34.0 ± 0.4	−28.5	2.71 ± 0.2	−24.8	31.3 ± 0.1	−24.8	5.7 ± 0.3	41.0
SWC50	23.6 ± 0.7	−39.6	30.7 ± 0.3	−33.5	33.5 ± 1.5	−29.7	2.60 ± 0.3	−27.7	31.0 ± 0.4	−27.7	5.7 ± 0.2	41.4
SWC100	19.6 ± 0.9	−49.8	26.6 ± 1.5	−42.5	31.0 ± 1.5	−34.9	2.38 ± 0.4	−33.8	28.3 ± 0.6	−33.8	6.0 ± 0.3	49.8

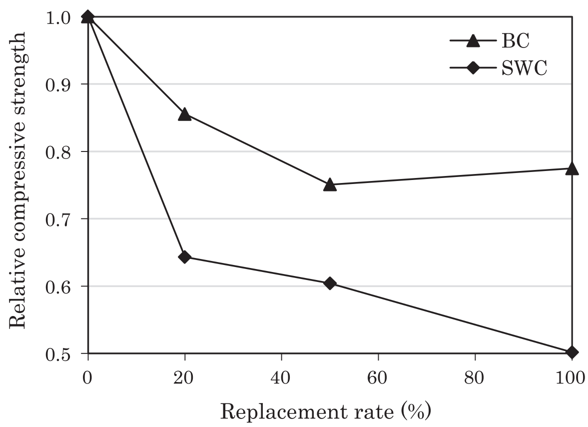

Fig. 4. Compressive strength of BC and SWC mixes (7 days) relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

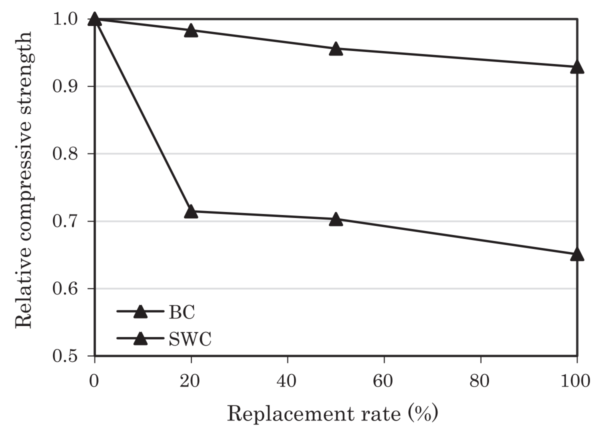

Fig. 6. Compressive strength of BC and SWC mixes (56 days) relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

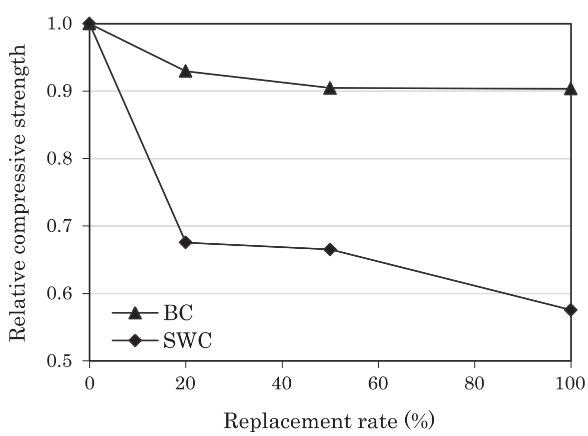

Fig. 5. Compressive strength of BC and SWC mixes (28 days) relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

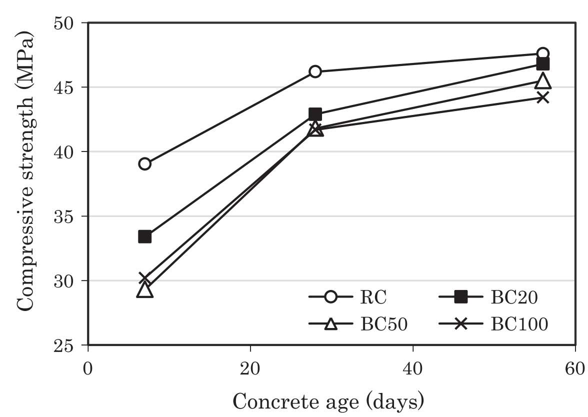

Fig. 7. Compressive strength *versus* time for all replacement ratios of fine natural aggregate by fine recycled brick aggregate.

reference concrete, was 49.8%, 42.5% and 34.9%, respectively. This reduction in compressive strength is due to the increase in the effective water/cement ratio with the replacement ratio, which contributed to the reduction in strength of the paste. In fact, Martins et al. [36] stated that excess water in the mix (more than the one strictly necessary for the hydration reactions) can result in increased workability, but leads to greater porosity and a consequent loss in compressive strength. For these compositions, no relevant changes in the rate of strength development were verified. In fact, Leite [33] stated that, despite the pozzolanic nature of these aggregates, their low porosity does not allow pozzolanic reactions to occur as in the case of recycled brick aggregates. In addition, Levy [37] reported that common bricks are the ceramic material with more pronounced pozzolanic properties.

Comparing the results of brick and sanitary ware concrete mixes one can conclude that the first revealed significantly higher compressive strength than the second. This difference in strength is such that mix SWC20 had a lower compressive strength than mix BC100, at all test ages.

Figs. 9 and 10 shows the results of this experimental programme, together with the results of the experiments described in Section 2.

Fig. 9 shows that the results from BC mixes in this study are higher than the results obtained by other authors, expect for the BC20 composition. One explanation for this result is that de Brito et al. [2], Gomes and de Brito [6] and Debieb and Kenai [5] adopted a pre-saturation procedure instead of adding water during the mixing process. Ferreira et al. [22] concluded in his study that a

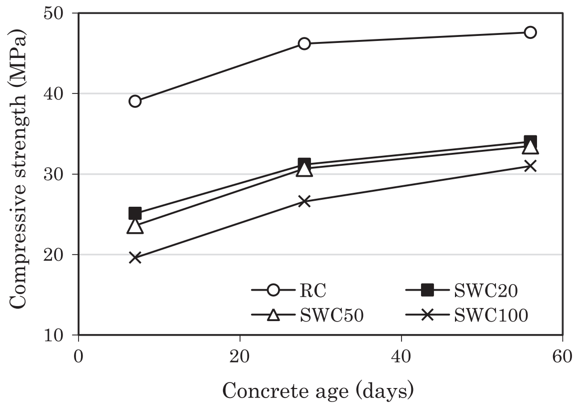

Fig. 8. Compressive strength *versus* time for all replacement ratios of fine natural aggregate by fine recycled sanitary ware aggregate.

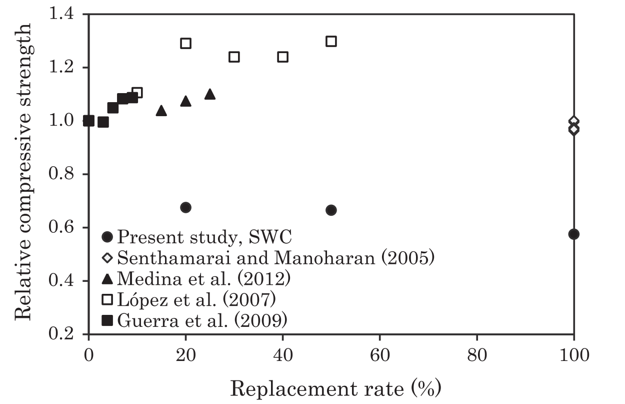

Fig. 10. Benchmarking of the compressive strength test results (28 days) of this experimental programme, for sanitary ware aggregates, and the results of the campaigns described in Section 2.

pre-saturation procedure affects negatively the mechanical behaviour of the concrete. Another possible explanation is that three of these authors replaced coarse natural aggregates by coarse recycled brick aggregates. Therefore, due to the lower strength of these aggregates when compared to the natural ones, the compressive strength of the concrete is limited by the strength of the coarse recycled aggregates (rupture of the specimens goes through them). De Brito [32] stated that when replacing coarse natural aggregates by coarse recycled brick aggregates, concrete strength is highly affected by the strength of these aggregates. The results of Debieb and Kenai [5] illustrate this. Mixes with replacement of the coarse aggregate fraction have lower strength than those with replacement of the fine aggregate fraction.

Fig. 10 shows that no correlation between the results of this work and the results of the experiments described in Section 2 is found. In fact, only the results of this experimental programme showed lower compressive strength of mixes with recycled sanitary ware aggregates than of conventional concrete. This is probably due to the fact that the authors decided to keep the apparent water/cement ratio constant. Therefore, due to higher water absorption of the recycled ceramic aggregates used by the authors, a reduction in the effective water/cement ratio with the replacement ratio occurred, leading to lower compressive strength. Even though López et al. [7] and Guerra et al. [8] did not report the water absorption of the recycled aggregates they used, due to the fact that they have lower bulk density than the natural ones, one can assume that the water absorption is higher [14].

4.2.4. Splitting tensile strength

Table 5 and Fig. 11 show the splitting tensile strength (f_{ct}) test results.

As with the trend shown for compressive strength, the results in this case also reveal a reduction in performance as the replacement ratio of recycled ceramic aggregates increases. The reasons for this strength decrease are the same as those for compressive strength loss, i.e. the increase in porosity of the paste with an increase in the replacement ratio. Evangelista and de Brito [38], who studied the mechanical behaviour of concrete mixes with fine recycled concrete aggregates, also give this explanation for the reduction in splitting tensile strength.

For BC mixes, a maximum loss relative to the reference concrete of 5.7% was found for a replacement ratio of 50%. However, it was expected that the maximum loss would occur in mix BC100. This result can be explained in the same way as for the compressive strength. In fact, de Brito [32] stated that, when comparing conventional concrete with recycled brick aggregates with the same cement content and water ratio, an increase in strength may be obtained due to the rougher surface of this type of recycled aggregates. Mansur et al. [1] also reported this conclusion. For SWC mixes, a maximum loss of 33.8% was found for a replacement ratio of 100%.

Figs. 12 and 13 show the results of this experimental programme and the results of the experiments described in Section 2.

Fig. 12 shows that the results obtained in this study for the BC mixes are higher than the results obtained by other authors,

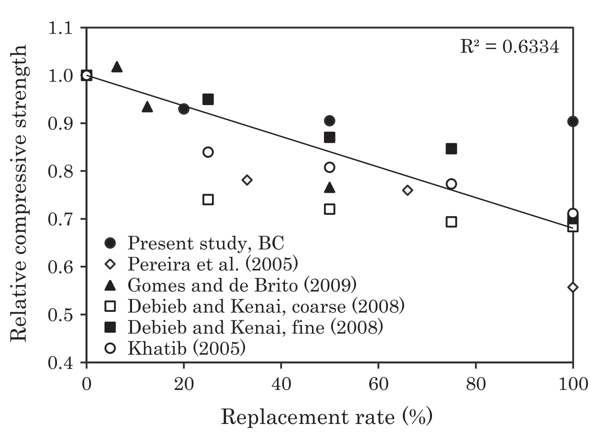

Fig. 9. Benchmarking of the compressive strength test results (28 days) of this experimental programme, for recycled brick aggregates, and the results of the campaigns described in Section 2.

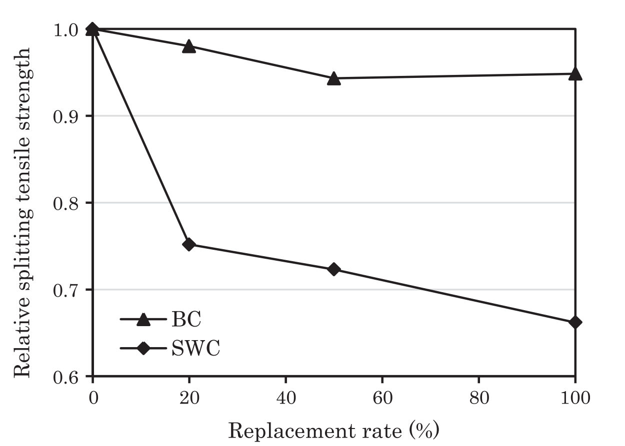

Fig. 11. Splitting tensile strength of BC and SWC mixes relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

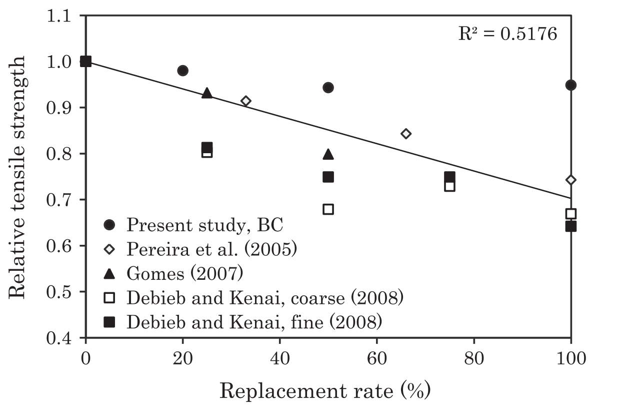

Fig. 12. Benchmarking of the splitting tensile strength test results of this experimental programme, for recycled brick aggregates, and the results of the campaigns described in Section 2.

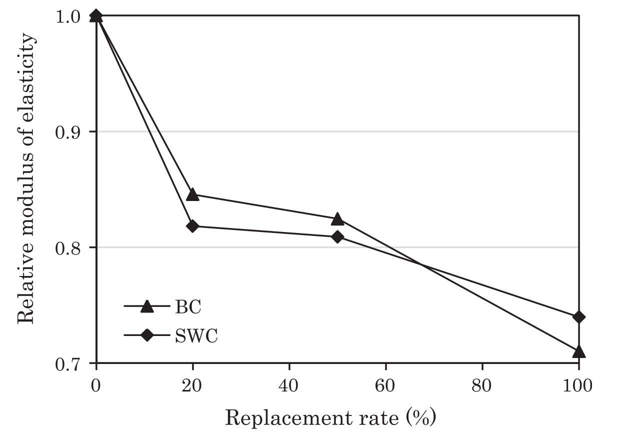

Fig. 14. Modulus of elasticity of BC and SWC mixes relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

similarly to the results obtained for the compressive strength. The reasons stated for compressive strength also justify the results obtained for the splitting tensile strength.

Fig. 13 shows that no correlation between the results obtained in this work for SWC mixes and the results of the campaigns described in Section 2 is found. In fact, only the results of this experimental programme showed much lower splitting tensile strength for mixes with recycled sanitary ware aggregates than for conventional concrete.

4.2.5. Modulus of elasticity

Table 5 and Fig. 14 show the modulus of elasticity (E_{cm}) test results.

The results show that the modulus of elasticity decreases with the replacement ratio of fine recycled ceramic aggregates.

According to Neville [39] and Coutinho and Gonçalves [40], the modulus of elasticity of concrete is strongly related to the stiffness of coarse aggregates, the stiffness of the mortar, their porosity and bond. Of these factors, only the stiffness of the mortar is affected when replacing fine natural aggregates with fine recycled aggregates. So, with an increase in the replacement ratio, the mortar undergoes such a big stiffness loss that concrete's modulus of elasticity is considerably affected. The reduction observed in the BC mixes is mainly due to the fact that fine recycled brick aggregates have lower stiffness than the fine natural aggregates (due to their high porosity) but also due to the increase in apparent water/cement ratio. For the SWC mixes, the reduction stems from the increase in effective water/cement ratio, which improved the porosity of the mortar and prevailed over the higher stiffness of this type of aggregates (due to its low porosity).

For mixes with incorporated recycled brick aggregates, the maximum loss obtained was 29%, for a replacement ratio of 100%. For mixes with incorporated recycled sanitary ware aggregates, the maximum loss obtained was 26%, also for a replacement ratio of 100%.

Fig. 15 shows that the results obtained for BC mixes in this study are higher than the results obtained by Gomes and de Brito [6] and lower than the ones obtained by Khatib [3]. Because Gomes and de Brito [6] replaced coarse natural aggregates by coarse recycled ceramic and mortar aggregates and increased the apparent water/cement ratio in order to keep the workability constant, the decrease in the modulus of elasticity is due to these two factors, i.e. with an increase in the replacement ratio, both the stiffness of the coarse aggregates and mortar decreases. An explanation of Khatib's results, when compared to the ones obtained in this work, is the fact that the author kept constant the water/cement ratio. So, with an increase in the replacement ratio, only the stiffness of the mortar is affected because fine recycled aggregates have a lower stiffness. On the other hand, in the present work, with an increase in the replacement ratio, there are two factors that lowered the stiffness of the mortar, as explained above.

Fig. 16 shows that the results obtained in this work for the SWC mixes are much lower than the ones of Senthamarai and Manoharan [4]. This can be explained by two reasons: the possible higher

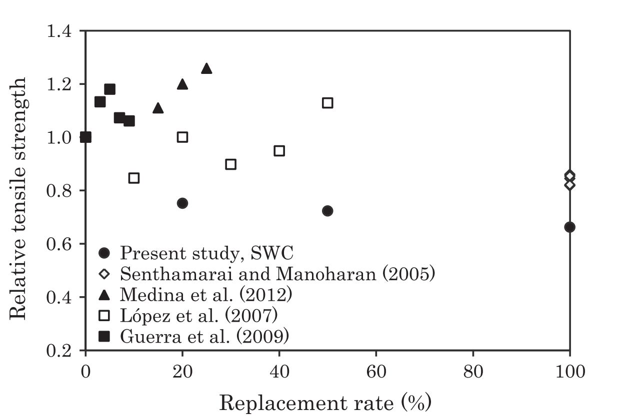

Fig. 13. Benchmarking of the splitting tensile strength test results of this experimental programme, for sanitary ware aggregates, and the results of the campaigns described in Section 2.

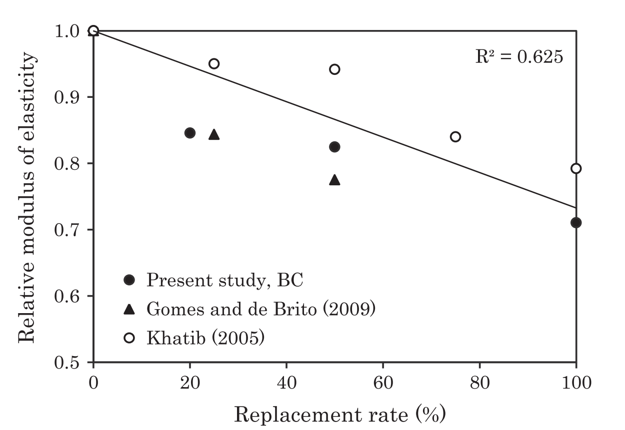

Fig. 15. Benchmarking of the modulus of elasticity test results of this experimental programme, for recycled brick aggregates, and the results of the campaigns described in Section 2.

stiffness of the coarse recycled ceramic aggregates compared to the coarse natural aggregates used in this work; the fact that the mixes produced by these authors had a maximum water/cement ratio of 0.6, lower than that used for the SWC mixes produced in this work, which led to higher stiffness of the mortar in their case.

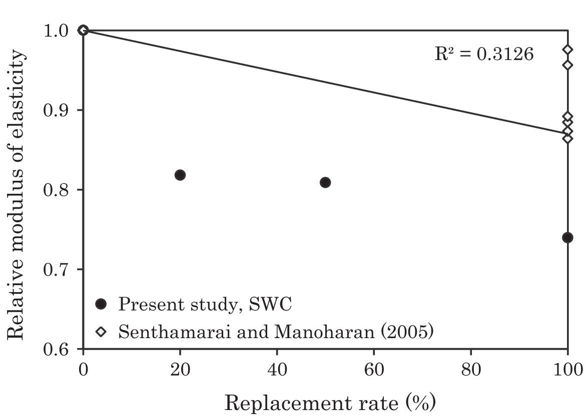

Fig. 16. Benchmarking of the modulus of elasticity test results of this experimental programme, for sanitary ware aggregates, and the results of the campaigns described in Section 2.

4.2.6. Abrasion resistance

The results of the abrasion resistance tests (Δl_m) of all concrete mixes are presented in Table 4 and Fig. 17. Because curing conditions strongly affect the concrete's surface layer, it is worth noting that the test specimens were obtained by sawing larger concrete cubes (100 mm edge) after curing so that the concrete's surface finishing would not be a variable in the test. Thus, the test surface is the cutting surface itself, i.e. an internal plane of the concrete element, composed of aggregate and cement paste, and not an outer surface.

Abrasion resistance is mainly provided by the wear resistance of the paste and by the bond between it and the coarse aggregates. The results show that the abrasion resistance decreases with the replacement ratio. In mixes with incorporated recycled brick fine aggregates, the reduction observed is due to higher porosity of the paste (caused by the porosity of the fine recycled brick aggregates). This contradicts the results of de Brito et al. [32], which were obtained with recycled brick coarse aggregates. The reason for this difference is that in that research the wear resistance of the paste remained basically the same, whilst in our case the fine recycled aggregates are part of the paste and weaken its wear resistance. For mixes with recycled sanitary ware aggregates incorporation, the increase in the effective water/cement ratio with the replacement ratio increased the porosity of the paste, causing a reduction in the abrasion resistance. Additionally, although the glazed part of the aggregates is resistant to abrasion, it more easily detaches from the paste, leading to higher mass losses due to abrasion.

In mixes with incorporated recycled brick aggregates, the maximum loss obtained was 31.4%, for a replacement ratio of 100%. For the same replacement ratio, a maximum loss of 49.8% was observed in mixes with recycled sanitary ware aggregates.

The results indicate also that the differences in resistance between BC and SWC mixes are smaller for higher replacement ratios. This is probably due to the higher abrasion resistance of sanitary ware aggregates, when compared to brick aggregates, which partially offset the higher effective water/cement ratio of the latter.

Results obtained by de Brito et al. [2] are in disagreement with the results of this work. A possible explanation is the fact that the authors kept constant the apparent water/cement ratio for all compositions produced, which, due to the high water absorption of the recycled aggregates, decreased the effective water/cement ratio, reducing the porosity of the mortar. In addition, de Brito et al. replaced only coarse aggregates, so the cement paste itself was produced with natural aggregates only. Another possible explanation is the better bond between the coarse recycled aggregates used by Brito et al. and the mortar, due to their high porosity.

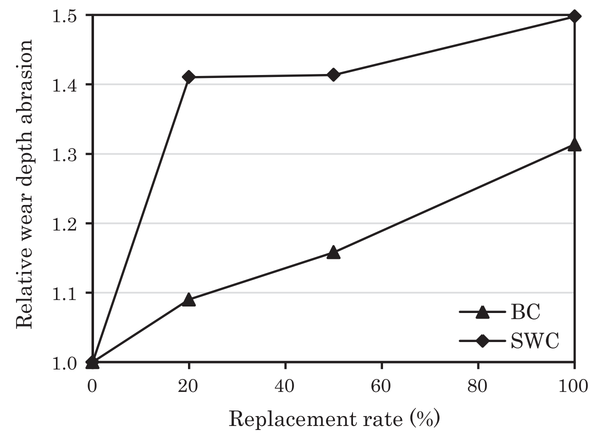

Fig. 17. Abrasion resistance of BC and SWC mixes relative to RC *versus* replacement ratio of fine natural aggregate by fine recycled ceramic aggregate.

4.2.7. Influence of superplasticizers

When a superplasticizer content of 1% of cement mass was added to concrete SWC100 with the same water/cement ratio of the reference concrete, keeping the slump within the target interval, the compressive strength and the splitting tensile strength were respectively 28% and 17% higher than those of the reference concrete.

These results suggest a high potential of fine recycled sanitary ware aggregates to produce structural concrete, provided that superplasticizer is used to eliminate the effect of agglutination between the aggregate's particles.

Pereira et al. [41], who studied the effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates, also found that adding superplasticizers to the mix improved the compressive and splitting tensile strengths of concrete.

5. Conclusions

The use of concrete with recycled aggregates should always take into consideration that it has, in most cases, a lower performance than conventional concrete. This paper presented an experimental programme conducted to study the use of fine recycled ceramic aggregates as partial or total replacements of fine natural aggregates in the production of structural concrete. Within the studied range of strength class, cement type and content, use of additions/admixtures, among other parameters, the experimental results allow drawing the following conclusions:

- Concrete incorporating fine brick aggregates can exhibit adequate quality as structural concrete, unlike concrete with fine sanitary ware aggregates, which does not seem to be adequate for structural purposes.
- Compressive strength and splitting tensile strength do not seem to be significantly affected by fine brick aggregates incorporation, when compared with conventional concrete, but these two properties considerably decrease with the incorporation of recycled fine sanitary ware aggregates.

- The modulus of elasticity decreases with an increase in the replacement ratio of both fine recycled brick aggregates and fine recycled sanitary ware aggregates.
- Abrasion resistance is negatively affected by the incorporation of both types of fine recycled ceramic aggregates.
- From a mechanical performance point of view, a preliminary analysis gave very promising results concerning the use of superplasticizers in the mixes with fine recycled sanitary ware aggregates.

Acknowledgements

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