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Mechanical behaviour of concrete made with fine recycled concrete aggregates

L. Evangelista [a], J. de Brito [b,*]

[a] Instituto Superior de Engenharia de Lisboa, R. Conselheiro Emídio Navarro, 1, 1950-062 Lisboa, Portugal
[b] Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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Abstract

This paper concerns the use of fine recycled concrete aggregates to partially or globally replace natural fine aggregates (sand) in the production of structural concrete. To evaluate the viability of this process, an experimental campaign was implemented in order to monitor the mechanical behaviour of such concrete. The results of the following tests are reported: compressive strength, split tensile strength, modulus of elasticity and abrasion resistance. From these results, it is reasonable to assume that the use of fine recycled concrete aggregates does not jeopardize the mechanical properties of concrete, for replacement ratios up to 30%.

Keywords: Sustainable construction; Concrete waste; Fine recycled aggregates; Structural concrete

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1. Introduction

Concrete demolition waste has been proved to be an excellent source of aggregates for new concrete production. There are many studies that prove that concrete made with this type of coarse aggregates can have mechanical properties similar to those of conventional concretes and even high-strength concrete is nowadays a possible goal for this environmentally sound practice [1–3].

However, the fine fraction of these recycled aggregates has not been the subject of thorough similar studies since it is believed that their greater water absorption can jeopardize the final results. The results of several studies presented in the past have caused the existing codes concerning recycled aggregates for concrete production to strongly limit the use of these products [4–6].

The investigation conducted, in which the recycled fine aggregates were obtained from laboratory grade concrete and superplasticizers were used, has produced results that contradict these initial perceptions. This paper presents the main results of the research concerning compressive and split tensile strength, modulus of elasticity and abrasion resistance and draws some conclusions on the viability of using fine recycled concrete aggregates in structural concrete, namely by comparing them with conventional concretes with exactly the same compositions with the exception of fine fraction.

2. Experimental research program

2.1. Recycled concrete aggregate production

The fine recycled concrete aggregates that were used during the entire research program were obtained from an original concrete (OC), of standard composition and properties, which was made in laboratorial conditions, solely for the purpose of being crushed afterwards. By using this procedure, it was possible to fully control the concrete's composition and to determine its main

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[*] Corresponding author. Tel.: +351 218419709; fax: +351 218497650.
E-mail address: jb@civil.ist.utl.pt (J. de Brito).

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properties, which, if not known, could become an additional variable, when analysing and concluding about the achieved experimental results. The OC composition can be observed in Table 1. The average compressive strength of the OC, after a 28 day period of wet curing, was 29.6 MPa.

The concrete was crushed on the 35th day, using a small jaw crusher, which produced aggregates with a maximum nominal size of 38.1 mm. The aggregates were then separated according to their dimension, by mechanical sieving, and only the fractions between 0.074 mm and 1.19 mm were used, so the particle size range for both fine natural aggregates (FNA) and fine recycled aggregates (FRA) would be the same. In spite of this, the grading curves of the natural and recycled were different (Fig. 1), and therefore, it was necessary to adjust the latter to match the former to achieve a similar fineness modulus. To accomplish this, it was necessary to separate the recycled aggregates according to their different particle sizes. After separation, the aggregates were stored in tight containers to avoid moisture exchanges with the environment. Although this type of procedure is too difficult for practical application, it enables comparisons between mix compositions with the same particle size distribution, even though the replacement ratios differ.

The main properties of the fine natural and recycled aggregates (after correction of its grading curve) were studied and are displayed in Table 2. FRA present a lower density than FNA, due to its greater porosity, that leads to much higher water absorption.

Table 1
Original concrete composition

	OC
CEM II 32.5N cement (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* ratio	0.52

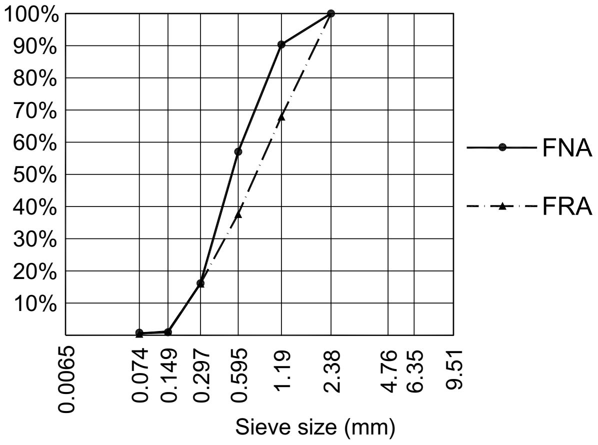

Fig. 1. Grading curves for FNA and FRA.

Table 2
Properties of FNA and FRA

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

2.2. Mix compositions

The different mixes' compositions were designed using Faury's method [8], with a common target slump of 80 ± 10 mm. The mix design was primarily conceived for the reference concrete (RC), made only of natural aggregates. It was then adapted for the remaining mixes, taking into account the different water/cement ratios, expected to increase along with the recycled aggregates replacement ratio. The increase of water has to do with FRA's greater absorption and to the greater need of mixing water, on account of the greater particle friction that recycled aggregates generate [7].

To estimate the water that the FNA would absorb during the mixing, the relationship proposed by Leite [3] was considered, which established the FRA water absorption through time. The author concluded that during the period of 10–30 min of mixing, the FNA water absorption stabilizes, reaching around 50% of its maximum capacity. Leite also proposed, based on Neville's observations [9], that after introducing the binder in the mixture, the recycled aggregates absorption was significantly reduced, because it seals the aggregates pores, limiting water exchanges.

The experimental research was divided in three distinct stages: in the first stage, different concrete compositions were studied and tested in order to fine-tune the mix proportions to comply with the stipulated workability; the goal of the second stage was to perform a preliminary evaluation of the concrete mixes, based on parameters both mechanical (compressive strength and shrinkage) and durability-related (water absorption); the third stage's main purpose was to evaluate, as thoroughly as possible, the mixes that presented the most promising results at the second stage.

To check the suitability of Leite's proposal, two different techniques for mixing the fine aggregates (both natural and recycled) with water were used. In the first technique, applied at the first stage of the campaign, the fine aggregates were inserted into water (2/3 of the required mixing water, plus the water that was estimated to be absorbed), and were mixed during a period of 10 min, after which the remaining constituents were placed. In the second technique, used at both second and third stages, the same mixing procedure was used, except that the duration of mixing was extended to 20 min.

It was expected that the replacement of FNA with the correspondent FRA would cause a large increase in the *w*/*c* ratio [10,11]. In order to keep it at an acceptable level (below 0.45 since, for a 100% replacement ratio, existing

Table 3
Concrete composition (1 m^3)

	RC	C10R	C20R	C30R	C50R	C100R
% of replacement	0	10	20	30	50	100
Cement CEM I 42.5R (kg)	380	380	380	380	380	380
Water (l)	155.8	160.6	165.4	170.2	175.6	180.9
w/c ratio	0.41	0.42	0.44	0.45	0.46	0.48
$(w/c)_{ef}$ ratio	0.41	0.42	0.43	0.44	0.45	0.45
FNA (kg)	668	598	529	460	327	0
FRA (kg)	0	52	103	154	254	509
Coarse aggregate 1 (kg)	409	407	404	402	400	400
Coarse aggregate 2 (kg)	382	380	378	376	374	374
Coarse aggregate 3 (kg)	397	395	393	390	388	388
Superplasticizer (kg/m^3)	4.9	4.9	4.9	4.9	4.9	4.9

literature predicted a huge increase in the water content necessary to keep the workability of the mix constant), a modified carboxylate based superplasticizer was used, 1.3% by weight of cement. A CEM I 42.5R Portland cement (380 kg/m^3), and three different crushed limestone coarse aggregates were used. Table 3 shows the mixture compositions for all concretes, for all stages.

2.3. Testing

Compressive strength tests were carried out on 150 mm cubes, according to NP EN 12390-5 [12]. Tested specimens were subjected to 28-day wet curing, for first and second stages, while for third one, 7, 28, and 56 days wet-cured specimens were evaluated. For split tensile strength and modulus of elasticity tests, 150 mm diameter cylinders 300 mm tall 31 days wet-cured were used, according to NP EN 12390-6 [13] and LNEC E397 [14], respectively. As for abrasion resistance, 71 × 71 × 40 mm prisms were tested, using a grinding wheel, according to DIN 52108[1] [15].

3. Results and discussion

3.1. Compressive strength

The compressive strength results obtained for the three different stages (the second and third stages' joint results were presented, since there were no differences in their mixing process), at 28 days of age, are shown in Table 4. Strength variations of the various concrete mixes in relation to the reference concrete (designated by Δ) and the strength variations between first and second/third stages (presented in the δ (between stages) column) are also shown. It is possible to realize that, within each stage, the strength resistance had insignificant variations and no visible trend due to the FNA replacement with FRA. When comparing the results of the different stages, the differences between them are also small, although the second/third stages generally present slightly lower compressive strength resistances than the first stage.

Table 4
Compressive strength results

	First stage	Δ (%)	Second and third stages	Δ (%)	δ (between stages)
RC	59.4	–	59.3	–	−0.2
C10R	62.2	4.7	59.0	−0.6	−5.3
C20R	58.4	−1.7	57.3	−3.4	−2.0
C30R	61.3	3.1	57.1	−3.7	−6.8
C50R	60.8	2.3	58.8	−0.8	−3.2
C100R	61.0	2.7	54.8	−7.6	−10.2

A reasonable explanation for the maintenance of the compressive strength with increasing fine aggregates replacement has been proposed by Katz [16], which concluded that recycled aggregates have high levels of cement (both hydrated and non-hydrated), that can reach as much as 25% of its weight, increasing the total amount of cement in the mix.

Although the differences between the first and second/third stages were small, a possible cause for the slight resistance loss has been proposed by Poon et al. [17] and Barra de Oliveira and vasquez [18], that concluded that the saturation level of the recycled aggregates may affect the strength of the concretes, since at higher saturation levels the mechanical bonding between the cement paste and the recycled aggregates becomes weaker. Therefore, as in the second/third stages the mixing period was longer than in the first one, that may have led to a weaker performance of those concretes.

The variation of compressive strength with time (Fig. 2) indicates that the reference concrete's resistance, made exclusively with natural aggregates, almost stabilized after 28 days of age. In opposition, the compressive strength of the concrete mixes made with fine recycled aggregates continues to increase after that age. This result somehow corroborates the assumption that there is non-hydrated cement mixed with the fine recycled aggregates that contributes to the overall resistance. The reference concrete was made of high hydration speed cement (CEM type I), which would justify the rapid stabilization of its compressive strength. On the contrary, the original concrete, used to produce the recycled aggregates, was made with normal hydration speed cement (CEM type II), that takes longer to

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[1] Roughly equivalent to BS EN 13892-4:2002.

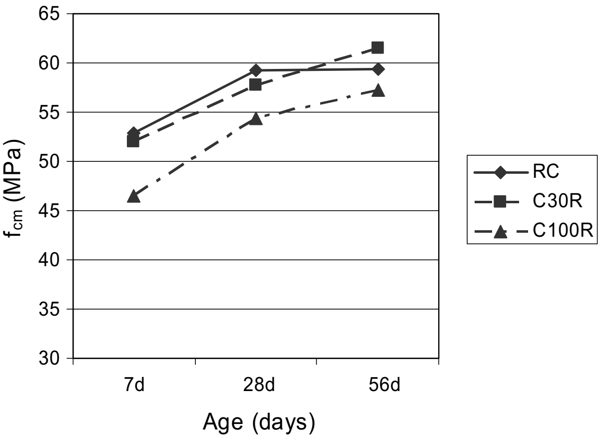

Fig. 2. Compressive strength variation (7, 28 and 56 days).

Table 5
Cement type within concrete mixes

	CEM I 42.5R	CEM II 32.5 N
Original concrete (OC)		*
Reference concrete (RC)	*	
Concretes with FRA (C10R to C100R)	*	*

fully hydrate, and therefore affects the way the compressive strength of the concretes made with it develops through time. Table 5 summarizes the different cement types within each concrete, to better understand the influence over concrete's compressive strength.

3.2. Split tensile strength

The concrete's split tensile strength is presented in Table 6, which shows a clear decrease of this property with the increase of FNA replacement with FRA, as well as the strength variations relative to the reference concrete, presented in Δ column. According to Coutinho [19], the tensile strength is not as affected by the cement content as the compressive strength, so the tensile strength does not particularly benefit from the additional cement that is incorporated along with the FNA. Therefore, it is perfectly natural that a decrease occurs as the replacement ratio rises, due to the more porous structure of the recycled aggregates.

3.3. Modulus of elasticity

The results achieved for the modulus of elasticity of the different concretes are presented in Table 7, where Δ refers to variations in FRA concrete mixes' modulus of elasticity when compared with the reference concrete. As shown, there is a slight reduction of the modulus of elasticity for the concrete with 30% of FNA replacement with FRA, while for the concrete with full replacement the loss was significant, indicating that the modulus of elasticity decreases with the replacement ratio.

Table 6
Split tensile strength results

	f_{ctm} (MPa)	Δ (%)
RC	3.85	–
C30R	3.65	−5.2
C100R	2.95	−30.5

Table 7
Modulus of elasticity

	E_c (GPa)	Δ (%)
RC	35.5	–
C30R	34.2	−3.7
C100R	28.9	−18.5

The concrete's modulus of elasticity is deeply related to the stiffness of the coarse aggregates, the stiffness of the mortar, their porosity and bond [9,19]. Therefore, for small replacement ratios, it is possible that the overall stiffness is not significantly influenced, because the mortar stiffness is only one of several factors, while for total replacement the mortar withstands such a big stiffness loss that the concrete's modulus of elasticity is considerably affected.

To establish a relationship between compressive strength and modulus of elasticity of concrete mixes made with FRA, a regression based on the model established by Zilch and Roos [20] was used. The authors suggest that the modulus of elasticity is dependant not only on the concrete's compressive strength (f_c) but also on its density (ρ):

$$E_c = a \times (f_c + 8)^{1/3} \times \left(\frac{\rho}{b}\right)^2 \qquad (1)$$

where coefficients a and b are 9100 and 2400, respectively. For this investigation, a and b are regression coefficients determined to be 8917 and 2348, respectively, based on the experimental results for concretes made with FRA. The correlation factor $R^2 = 0.85$.

3.4. Abrasion resistance

The abrasion resistance obtained for the different concrete types analysed is shown in Table 8 (Δ_1 and Δ being respectively the absolute and relative thickness loss of concrete mixes made with FRA in comparison to the reference concrete). It is possible to conclude that the concretes with replacement of FNA with FRA have greater abrasion resistance than the reference concrete. That may have to do with the fact that abrasion resistance is deeply connected with the bond of the cement paste with the fine aggregates,

Table 8
Abrasion test thickness loss

	Δ_1 (mm)	Δ (%)
RC	1.96	–
C30R	1.86	−5.1
C100R	1.37	−30.1

which is better when recycled aggregates are used. Brito et al. [21] obtained similar results when replacing coarse natural aggregates with recycled aggregates of ceramic origin, achieving better abrasion resistances as the replacement ratio increased. Those results are coherent with the present ones, leading to assume that the bond between aggregates and cement has an important role in the performance of concrete to this particular property.

4. Conclusions

An experimental program was conducted to study the use of fine recycled concrete aggregates as partial or global replacements of natural fine aggregates in the production of structural concrete. The experimental results indicate that it is viable to produce concrete made with fine recycled concrete aggregates suitable for structural concrete, considering that:

1. the compressive strength does not seem to be affected by the fine aggregate replacement ratio, at least for up to 30% replacement ratios and the strength levels considered in this study;
2. both tensile splitting [21] and modulus of elasticity are reduced with the increase of the replacement ratio; however, the values obtained for both properties are still acceptable, especially for reasonable levels of the replacement ratio (30%);
3. the abrasion resistance seems to increase with the replacement of fine natural with fine recycled concrete aggregates.

It should be noted that the FRA used were obtained from concrete mixes especially produced in laboratory, which led to controlled crushing and sieving of the recycled aggregates. It is expected that FRA obtained from field structures would likely have particles from debris that might reduce their performance. Nevertheless, the careful extraction of FRA from precast concrete elements would avoid such problems.

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