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An eco-friendly self-compacting concrete with recycled coarse aggregates

Un hormigón autocompactante eco-amigable con áridos gruesos reciclados

L.A. Pereira-de Oliveira(*), M. Nepomuceno(*), M. Rangel(*)

SUMMARY

The potential uses of coarse recycled aggregates in the composition of SCC increases the ecological value and partly solve the issues of waste disposal sites generated by construction and demolition of structures. Thus, this paper present an experimental study of SCC properties where the normal coarse aggregates were replaced by different percentages of recycled aggregates, i.e., 0% (SCC), 10% (SCCR10), 20% (SCCR20), 30% (SCCR30) and 40% (SCCR40). The results from fresh concrete (rheological properties and self-compactability) as the hardened concrete properties (compressive strength, density and dynamic modulus of elasticity), show only minor discrepancies. From the standpoint of mechanical behaviour, the results confirm the viability to incorporate coarse recycled aggregates in the SCC demonstrating the conservative character of the currently recommended limits.

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Keywords: Self-compacting concrete; recycled coarse aggregate; rheological properties; sustainable concrete.

RESUMEN

Los usos potenciales de áridos gruesos reciclados en la composición del hormigón autocompactante (SCC) aumenta el valor ecológico y en parte resuelve los problemas de los sitios de disposición de residuos generados por la construcción y la demolición de las estructuras. Por lo tanto, este trabajo presenta un estudio experimental de las propiedades de SCC en el cual los áridos gruesos naturales fueron reemplazados por distintos porcentajes de áridos reciclados, es decir, 0% (SCC), el 10% (SCCR10), el 20% (SCCR20), el 30% (SCCR30) y el 40% (SCCR40). Los resultados del hormigón fresco (propiedades reológicas y la auto-compactación), como las propiedades de hormigón endurecido (resistencia a la compresión, densidad y módulo de elasticidad dinámico), muestran sólo pequeñas discrepancias. Desde el punto de vista del comportamiento mecánico, los resultados confirman la viabilidad de incorporar áridos gruesos reciclados en los SCC demostrando el carácter conservador de los límites actualmente recomendados.

Palabras clave: *Hormigón autocompactante; árido grueso reciclado; propiedades reológicas; hormigón sostenible.*

(*) University of Beira Interior, (Portugal).
Persona de contacto/Corresponding author: luiz.oliveira@ubi.pt (L.A. Pereira-de Oliveira)

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1. INTRODUCTION

The potential uses of recycled aggregates in the self-compacting concrete (SCC) composition increase the ecological value and partly solve the issues of waste disposal sites generated by construction and demolition of structures. In general, recycled aggregates derived from crushed concrete consist of 65-70% by volume of natural coarse and fine aggregates, and 30-35% by volume of old cement pastes (1). The amount of cement paste present is crucial for the performance of recycled concrete aggregate added to concrete (2); Angulo *et al* found a content of porous cement paste in recycled aggregates around 19.3% (w/w) (3).

In the last two decades, the properties of normal concrete with recycled aggregates were extensively studied (4) (5) (6) (7) (8) (9). From these studies, it is known that comparing with the natural aggregates, the recycled aggregates density is lower and the water absorption is higher. In fact, the recycled coarse aggregates surface texture is more porous and rough when compared to natural aggregates; these characteristics increase the water demand and reduce the workability of normal concrete (10). A unanimous opinion was found in the literature, here cited, that these characteristics are responsible by the mechanical properties decreases. Tabsh and Abdelfatah (11) found that replacing natural coarse aggregates by recycled coarse aggregates (RCA) in concrete requires 10% of extra water in order to achieve the same slump. Owing to this particularity, the water withdrawal of unit volume of concrete with recycled aggregates should be increased on the basis of that of ordinary concrete (12).

It has been observed that recycled coarse aggregates exert greater influence on the normal concrete compressive strength and elastic modulus than the recycled fine aggregates (13). As the replacement ratio increases, the compressive strength and elastic modulus decrease, and the drying shrinkage strain increases (14) (15). However, at low level of replacement, i.e. less than 20%, this effect is negligible (16). When 100% coarse recycled aggregates are added to the mixture the concrete resistance reduction could attain, at 28 days, around 40% (17) (18). It had been found a correlation between elastic modulus and compressive strength of recycled aggregate, showing that 15% lower elastic modulus is achieved by using 30% recycled aggregates (19).

Usually, it happens that the crushing process applied to produce recycled aggregates from concrete structures demolition provoke mechanical damage forming lots of micro-cracks and aggregates edge-angles. In this fragmentation process some concrete matrix incrustation remains on the aggregates surfaces, which results in increased of specific surface area and surface porosity of recycled aggregates. These aspects are reflected in recommendations and standards that define the composition of potentially recyclable materials from construction and demolition.

In Portugal, the most used demolition processes are based on the simultaneous destruction of the entire building, which results in waste rather heterogeneous. Taking into account the heterogeneity of construction demolition wastes, the Portuguese recommendation E 471 (20) limits the incorporation of recycled coarse aggregate in structural concrete production. The replacement of natural aggregates by recycled aggregates is limited by this document in order to avoid large variations of the modulus of elasticity, creep, shrinkage and durability. The limit is 25% of aggregates composed of 90% minimum of particles from concrete demolition (ARB1) that can be used up to concrete strength class C40/50. When the recycled aggregates composition has a value between 70% and 90% of particles from concrete demolition (ARB2), this can be used up to concrete class C35/45.

As previously mentioned there are many works on the use of recycled aggregates in normal concrete, but very few are those reporting the self-compacting concrete behaviour with recycled aggregates.

According Grdic *et al* (21), the total replacement of the natural coarse aggregates by recycled aggregates from demolition of concrete structures reduce the compressive and tensile strength of SCC in order of only 9% and 13% at 28 days, respectively. The authors also observed that the water absorption of self-compacting concrete with recycled aggregates was 0.77% for SCC with 50% recycled aggregates and 0.92% for SCC with 100% recycled aggregates.

Regarding that E 471 recommendation was elaborated for normal concrete and that there are few studies about self-compacting concrete with recycled aggregates incorporation, this study aims to observe the mechanical behaviour of SCC with partial natural coarse aggregates replacement by recycled aggregates from local concrete structures demolition. The obtained results can be very significant from the aspects of practical use.

The development of SCC and the first mixture design method, namely that proposed by Okamura, Maekawa and Ozawa, later improved by the contribution of Ouchi *et al* (22) (23), represented an important step for concrete technology. Furthermore, the guidelines proposed by the JSCE (24) establish a basis for generalising its use. The method proposed by Okamura was developed for general application and has the advantage of simplicity. However, this method is considered conservative and, in general, it leads to a self-compacting concrete mixture with higher volumes of paste than an optimised mixture (25). Afterwards, the general tendency was to focus on optimising mixture proportions, aiming to reduce paste volume. The research done by Petersson *et al* (26) (27), Tangtermsirikul and Bui (28), Bui and Montgomery (29), Sedran and Larrard (25) should be recognized. Sonebi (30) has also investigated the effects of the content of cement, additions and superplasticizer on the fresh and hardened properties of SCC and proposed a statistical model to simplify the test protocol required to optimise a given mix. Many of the models described are based on a given set of materials and correlations and cannot be generalised to other materials unless new correlations are generated. As a result of this analysis, a different simple approach to the SCC mix design developed by Nepomuceno (31) was considered.

A piece of data which is important for the design of SCC mixture with recycled coarse aggregates is the quantity of water absorbed by the recycled aggregate, which is always higher in comparison to the same fraction of the natural coarse aggregate. Normally, the water requirement of normal concrete with recycled aggregates is increased, resulting in significant high total water/cement ratio (W/C), regardless of the use of water-reducing admixtures (32). The amount of water absorbed by the aggregate was taken into account separately by some researchers (33), in addition to its wetness before mixing and the free water that formed part of the mixture. Others researchers (32) (34) considers, the total water content for W/C ratio, because it is impossible to separate the effective water content (water absorbed by recycled aggregate and mixing water) from the total water content in the fresh concrete, especially in the case of recycled sand. In the case of SCC with recycled aggregate, Grdic *et al* (21) observed small variations in the quantity of water for SCC mixtures achieve the equal consistency. The highest porosity of the concrete ITZ microstructure around the pre-soaked lightweight aggregate compared with the dry aggregate is an interesting observation in the point of view of the concrete durability properties (35). Some authors (36) (37) argue that this difference on ITZ microstructure leads to a slightly higher capillary suction or water absorption of concrete when pre-soaked lightweight aggregates are used.

Since one of the goals of this study was to identify the influence of coarse recycled aggregates in SCC workability, the total water content was considered in the mixtures water/cement ratio.

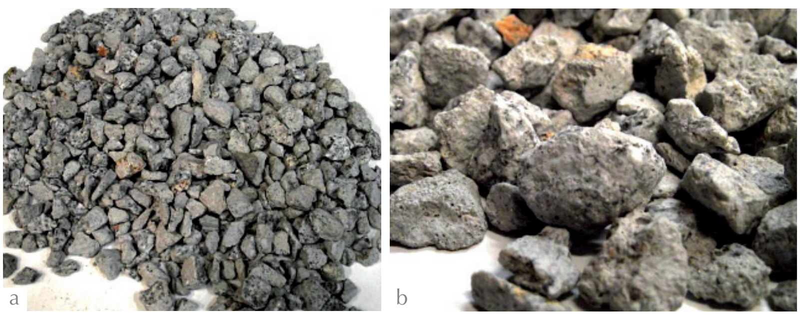
2. EXPERIMENTAL PROGRAMME

2.1. Materials

A Portland cement type CEM I 42.5R with density of 3140 kg/m^3 and a mineral addition of limestone powder with density of 2720 kg/m^3 were used as powder materials. The mineral addition was used for the purpose of increasing the viscosity of SCC mixtures.

A modified polycarboxylate based superplasticizer (Sika ViscoCrete 3005) was used to control the shear stress for attaining self-compacting rheological desired characteristics. The superplasticizer was supplied in liquid form and had a density of 1.05 kg/dm^3 and 25.5% of solid content. The superplasticizer saturation dosage determined with the Marsh cone test was 3.0% of cement weight.

Six different aggregates were selected for the experimental programme here described and include two fine aggregates of natural sand (S1 and S2), two natural coarse aggregates crushed from granite (CA1 and CA2) and two recycled coarse aggregates (RA1 and RA2) from a local construction and demolition waste recycling facility. The coarse recycled aggregates were sourced from a C30/37 strength class concrete manufactured with crushed granite stones and can be classified according to E471 as ARB1 aggregates. Figure 1 shows the elongated shape of the recycled aggregates particles after the concrete demolition, crushing and sieving process. The sieve analysis and the fineness modulus of those six aggregates are shown on Table 1, while the density and water absorption are shown on Table 2.



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1. Recycled coarse aggregates from demolition waste:
a) predominance of elongated particles shapes.
b) concrete matrix incrustations on aggregates.

Table 1. Sieve analysis and fineness modulus of aggregates.

Mesh aperture (mm)	Fine and coarse aggregates sieve distribution					
	S1	S2	CA1	CA2	RA1	RA2
25.400	100.00	100.00	100.00	100.00	100.00	100.00
19.100	100.00	100.00	100.00	100.00	100.00	99.27
12.700	100.00	100.00	100.00	86.90	100.00	46.02
9.520	100.00	100.00	100.00	48.48	99.20	13.98
4.760	100.00	99.85	61.61	5.10	21.25	0.28
2.380	99.90	77.95	5.20	2.58	5.74	0.12
1.190	99.50	42.81	1.13	2.10	0.74	0.08
0.590	82.80	18.22	0.49	1.62	0.44	0.07
0.297	20.50	5.29	0.30	1.05	0.25	0.06
0.149	1.20	1.41	0.20	0.60	0.06	0.05
0.074	0.20	0.37	0.12	0.26	0.05	0.03
Residue	0.10	0.00	0.00	0.00	0.00	0.00
Fineness modulus	1.961	3.545	5.311	6.385	5.723	6.861

Table 2. Density and water absorption of aggregates.

Notation	Density (kg/m^3)	Water absorption (%)
S1	2570.0	0.3
S2	2610.0	0.4
CA1	2710.0	0.15
CA2	2700.0	0.14
RA1	2509.0	4.10
RA2	2485.0	4.05

2. Reference curve and resultant grading curve of fine aggregates.

3. Reference curve and resultant grading curves of coarse aggregates.

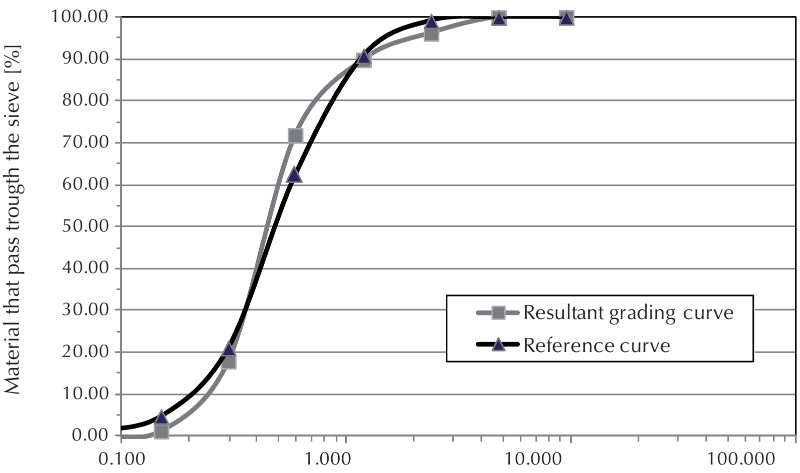

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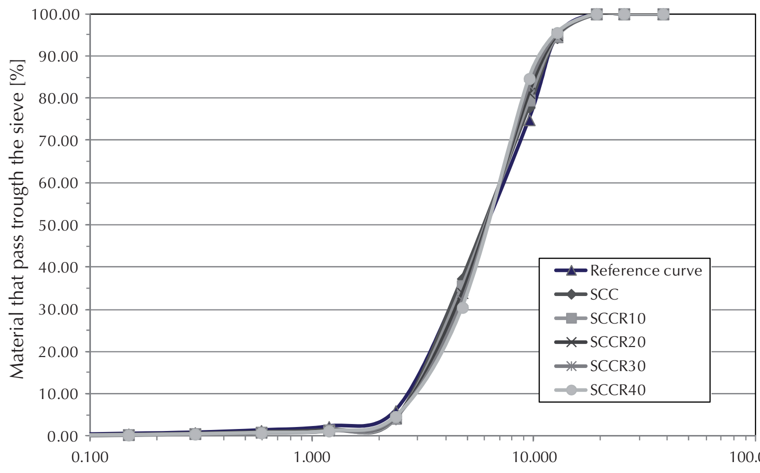
Table 3. Coarse aggregates volume fractions.

Mixture	Coarse aggregates volume fractions				Fineness modulus
	CA1	CA2	RA1	RA2	
SCC	0.570	0.430	---	---	5.773
SCCR10	0.513	0.387	0.095	0.005	5.773
SCCR20	0.456	0.344	0.190	0.010	5.774
SCCR30	0.399	0.301	0.285	0.015	5.775
SCCR40	0.342	0.258	0.380	0.020	5.776



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The two fine aggregates were combined in the volume proportions of 83% of S1 and 17% of S2 to achieve the grading reference curve proposed by Nepomuceno *et al* (38) for the mortar phase of self-compacting concrete. The resultant grading curve of fine aggregates is shown on Figure 2.

The coarse aggregates were combined to produce five different mixtures with a constant grading curve as close as possible to a reference curve defined as adequate to produce SCC and, at the same time, with the incorporation of different volume fractions of recycled coarse aggregates. Such combination of the volumetric fractions of the coarse aggregates is shown on Table 3. Figure 3 shows de reference curve and the resultant grading curves of coarse aggregates.

2.2. Mixture design

In this study, five types of concrete were made: a reference mixture SCC produced only with natural aggregates, SCCR10, SCCR20, SCCR30 and SCCR40, i.e. self-compacting concrete with 10%, 20%, 30% and 40% of natural coarse aggregates replaced by recycled aggregates. The fine and coarse aggregates were previously dried on laboratory environment. The reference SCC mix was designed in order to comply with EN 206-9 (39) and fits in a concrete strength class C45/50 and in accordance with the requirements concerning the properties of fresh concrete of the same standard. It should be noted that the SCC strength class chosen is the maximum strength class permitted, on the recommendation E471, for the application of recycled aggregates from concrete demolition. A pan mixer with a rotating cylindrical pan was used to mix a volume of 25 litters, per batch, of SCC with the mixing process shown in Figure 4. Table 4 shows the composition of self-compacting concrete mixtures.

The methodology of SCC mix design applied in this study was developed by Nepomuceno *et al* (31) (38) and considers the concrete as a two phase material, the matrix (mortar phase) and the incrustations of coarse aggregates on the matrix (concrete phase). The design parameters of the mortar phase should be defined to obtain simultaneously the desired fresh and hardened properties of self-compacting concrete. For each of these two phases, an adequate reference curve of granular skeleton was defined. Thus the general approach consists of the following stages: selection of the materials; definition of the reference grading curves for the fine and coarse aggregates; studies in mortars and studies on concretes.

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At the first stage, the powder materials (cement and additions) should be selected taking into account the level of compressive strength to achieve on hardened concrete. The fine and coarse aggregates should have adequate grading curves to enable the best approximation to the proposed reference curves. Preferably, a modified polycarboxylate based superplasticizer should be selected.

On the second stage, the unit volume percentage of fine aggregates and the unit volume percentage of coarse aggregates must be determined separately.

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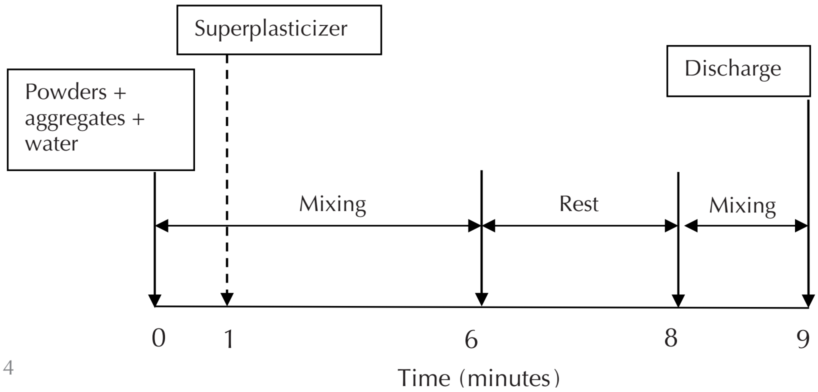

4. Mixing schedule.

Table 4. Mix proportion (kg/m³)

Mix	W/C (kg/kg)	Total Water	Cement	Limestone powder	S1	S2	CA1	CA2	RA1	RA2	SP (l/m³)
SCC	0.559	159.3	284.9	370.2	604.9	125.8	461.0	346.5	-	-	3.12
SCCR10	0.559	159.3	284.9	370.2	604.9	125.8	414.9	311.9	71.2	3.7	3.12
SCCR20	0.560	159.5	284.9	370.2	604.9	125.8	368.8	277.2	142.3	7.5	3.12
SCCR30	0.562	160.1	284.9	370.2	604.9	125.8	322.7	242.5	213.4	11.2	3.12
SCCR40	0.562	160.1	284.9	370.2	604.9	125.8	276.6	207.9	284.6	14.8	3.12

The third stage corresponds to the definition of the adequate parameters for the mortar phase, that includes the unit volume percentage of each powder material in the total volume of the blend of powder materials (Vp), unit volume percentage of each fine aggregate in the total volume of fine aggregates (Vs), as previously defined on the second stage, Vp/Vs (ratio in absolute volume between powder materials and fine aggregates), Vw/Vp (ratio in absolute volume between water and powder materials) and Sp/p% (ratio in percentage between the amounts in mass of superplasticizer and powder materials). For the mortar phase, an interval of variation was defined for the parameters that characterize the flow behaviour of mortars (Gm, Rm), in such a way that it leads to self-compacting concrete. The Gm parameter is measured on mortar spread test and Rm is measured on a v-funnel test. Adequate correlations between concrete compressive strength and water to cement ratio are proposed for two types of cements. Since the water to cement ratio is the same for concrete and mortar phases, this parameter can be defined on the mortar phase design. The Vp/Vs ratio should be defined from 0.6 to 0.8, but a value between 0.7 and 0.8 is recommended. Correlations are proposed to estimate the percentage of cement replacement by the addition for different combinations of powder materials as a function of the Vp/Vs ratio and the water to cement ratio previously established. The Vw/Vp and the Sp/p% ratios can be also estimated for preliminary tests based on proposed correlations. However, since the superplasticizer can differ from different suppliers, the water content Vw/Vp and the superplasticizer dosage Sp/p% have to be experimentally adjusted until the mortar presents the adequate flow properties, evaluated in terms of relative spread area (Gm) and the relative flow velocity (Rm). Usually only superplasticizer dosage needs to be adjusted.

On the fourth stage the design parameters of concrete are completed by the definition of the unit volume percentage of each coarse aggregate in the total volume of coarse aggregates (Vg) as previously defined on the second stage, the volume of voids (Vv) and the Vm/Vg ratio (where Vm is the volume of mortar excluding air and Vg is the volume of coarse aggregate). For this purpose a mathematical model was developed to estimate de adequate Vm/Vg ratio, which takes into account the properties of the mortar phase (Vp/Vs) and the fresh desired properties for concrete (H2/H1 in L box test and Dm in slump-flow test) and assuming that (t) in the v-funnel test for concrete is between 10 to 20 seconds. The Vm/Vg can vary from 2.00 to 2.60. For the volume of voids it is proposed a constant value of 0.030 m³ per cubic meter, when no air entrainment agent is used.

2.3. Methods

In order to evaluate the rheological and self-compactability properties of fresh concrete, the following methods were used: slump-flow test according to EN 12350-8:2010 (40), v-funnel test according to EN 12350-9:2010 (41) and L box test according to EN 12350-10:2010 (42). The fresh concrete properties measurements were done with two samples of approximately 12 litters of concrete obtained from each mixing.

The rheological properties were evaluated indirectly by means of slump-flow test (Figure 5) and v-funnel test (Figure 6), respectively, expressed in the relative spread area (Gc) and in the relative flow velocity (Rc). The value for (Gc) is obtained by Equation [1], whereas (Rc) is obtained by Equation [2]. The acronym (Dm) stands for the average spread diameter, in mm; the acronym (D_0) stands for the initial diameter at the base of the cone, in mm, whereas (t) stands for the time of flow, in seconds. The variation interval admissible for Gc and Rc was defined by Gc values between 8.0 and 11.3 and Rc values between 0.5 and 1.0 s^{-1}. The self-compactability properties was evaluated by the passing ability ratio H_2/H_1 in L box test, shown in Figure 7 and the SCC mixtures were adjusted in terms of water and superplasticizer amounts to obtain a value of $H_2/H_1 \geq 0.80$.

[1] $$G_c = \left(\frac{Dm}{D_0}\right)^2 - 1$$

[2] $$Rc = \frac{10}{t}$$

The hardened properties of concrete were evaluated at 7 and 28 days age by the density, compressive strength and dynamic modulus of elasticity measurements, according to the following standards: EN 12390-7:2003 (43), EN 12390-3:2003 (44) and BS 1881-203:1986 (45). All SCC hardened properties were determined in 3 concrete specimens for each age and mixture.

3. RESULTS AND DISCUSSION

3.1. Fresh self-compacting concrete properties

The final mix proportions, shown in Table 4, met the limits imposed by Gc and

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5. Determination of self-compacting concrete relative spread area.

6

6. Determination of self-compacting concrete relative flow velocity.

7

7. Determination of self-compacting concrete passing ability ratio.

Rc rheological parameters, described in section 2.3. Overall, the adjustments in terms of superplasticizer were constant in all concretes, but a slight amount of water was added to the mix from the 10% incorporation of recycled aggregates. This water addition is due to the recycled coarse aggregates that show higher water absorption if compared with the natural coarse aggregates, as was shown in Table 2. Although the water absorption of the recycled aggregates have been more than two and a half times higher than for the natural aggregates, the maximum additional water to achieve self-compactability was only 0.5%. This value is lower than that found for the normal concrete, i.e. 10% (11). Thus, the water contents shows in Table 4 are the total water necessary to attain the self-compactability defined by Gc and Rc parameters values presented in section 2.3. It should be noted that for all mixtures the amount of superplasticizer was kept constant. During the slump flow test no segregation was observed with the increase of coarse recycled aggregate in SCC mixtures.

Table 5 shows the results obtained by fresh concrete testing. There is a very slight reduction in the Gc and Rc values for maximum recycled aggregates incorporation, but the values obtained are inside the desired values range.

3.2. Hardened self-compacting concrete properties

In Table 6, the average densities, the densities differences related to SCC (ΔSCC, 28 days) and the loss of density between 7 and 28 days (Δdensity) are presented.

Analyzing the results, it appears that the density of hardened concrete decreases as the rate of natural coarse aggregates replacement by recycled coarse aggregates increases. This was expected, since the recycled coarse aggregates present a lower density compared to the natural coarse aggregates due to higher porosity and lower density of cement paste adhering to the aggregates surface. Nevertheless, the incorporation of 40% of recycled aggregates reduces only 1.1% of the SCC density. It could mean that is expected an irrelevant concrete porosity modification with the recycled aggregates incorporation.

About the density loss between 7 and 28 days, it is clear that there is also an insignificant effect of recycled aggregates incorporation in the density loss of concrete with coarse recycled aggregate (0.7% to 0.8%).

Table 7 presents the average compressive strength results obtained with three 150 mm cube specimens at each age test. The compressive strength at 7 and 28 days, the

Table 5. Fresh concrete test results

Mixture	Slump-flow test Dm (mm)	V-funnel test Time (s)	L box test H_2/H_1	Gc	Rc (s^{-1})
SCC	640	14.3	0.89	9.2	0.7
SCCR10	637	14.1	0.87	9.1	0.7
SCCR20	636	15.2	0.88	9.1	0.7
SCCR30	637	14.7	0.89	9.1	0.7
SCCR40	629	15.8	0.87	8.9	0.6

Table 6. Self-compacting concrete density

Mix	Density (kg/m^3)				$\Delta_{SCC,\ 28\ days}$ (%)	$\Delta_{density}$ (%)
	7 days		28 days			
	Mean	Standard Deviation	Mean	Standard Deviation		
SCC	2370.4	33.9	2359.9	23.5	-	- 0.4
SCCR10	2363.3	32.8	2346.9	23.3	- 0.6	- 0.7
SCCR20	2353.8	33.2	2333.9	23.0	- 1.1	- 0.8
SCCR30	2352.6	33.2	2333.7	25.0	- 1.1	- 0.8
SCCR40	2351.4	33.1	2335.0	23.0	- 1.1	- 0.7

Table 7. Compressive strength test results

Mix	Compressive strength (MPa)		Standard deviation (MPa)		$\Delta_{SCC,\ 28\ days}$ (%)	R7/R28 (%)
	7 days	28 days	7 days	28 days		
SCC	43.8	54.2	0.5	0.4	-	80.8
SCCR10	43.3	53.9	0.6	0.6	- 0.5	80.3
SCCR20	43.1	53.7	0.5	0.4	- 1.0	80.3
SCCR30	42.9	53.3	0.3	0.3	- 1.6	80.5
SCCR40	42.5	53.0	0.5	0.7	- 2.2	80.1

Table 8. Results of modulus of elasticity

Mix	Dynamic modulus of elasticity (GPa)				$\Delta_{SCC\ 28\ days}$ (%)	$\Delta_{modulus\ of\ elasticity}$ (%)
	7 days		28 days			
	Mean	SD*	Mean	SD*		
SCC	32.0	0.3	39.5	0.5	-	81.0
SCCR10	32.0	0.4	39.0	0.4	-1.2	82.0
SCCR20	30.2	0.4	38.8	0.5	-1.9	78.0
SCCR30	30.5	0.4	38.6	0.5	-2.4	79.0
SCCR40	30.6	0.4	38.3	0.5	-3.0	80.0

* SD - Standard Deviation obtained with 12 measurements.

strengths standard deviation, the strengths differences related to SCC mix results (ΔSCC, 28 days) and the percentage of compressive strength obtained at 7 days compared with 28 days are shown in this table.

Taking into account the standards deviations results, it was observed that the only significant strength reduction was registered with 40% of recycled aggregate incorporation, which confirms the negligible effect of low level replacement that was observed with the normal concrete (16). It can still be argued that the difference of 2.2% is relatively low than that observed with normal concrete mixtures (17) (18). This strength difference is considered typical for laboratories experimental work, but in real conditions of construction site is normal to tolerate strength variations up to 10%. It was also found that the self-compacting concretes, here studied, achieve at 7 days nearly 80% of compressive strength developed up to 28 days. This strength relationship is consistent with the estimate provided in EN 1992-1-1:2004 (46). Thus, only from the standpoint of compressive strength limits set by the Portuguese recommendation, these limits could be seen as conservative considering the application of recycled aggregates from similar sources to those here studied. Clearly, other assessments such as concern durability properties need to be taken into account in decisions to exceed the limits indicated.

The average dynamic modulus of elasticity results are shown in Table 8, together with the modulus of elasticity differences (ΔSCC, 28 days) related to SCC mix and loss of dynamic modulus of elasticity between 7 and 28 days (Δ modulus of elasticity [%]).

Analyzing the results presented in Table 8, it can be concluded that the dynamic modulus of elasticity was little affected by the incorporation of recycled coarse aggregates. Taking into account the standard deviation values, it was observed at 7 days a slight reduction from SCCR20 to SCCR40. The reductions of 2.4% and 3.0% were confirmed at 28 days for the concrete SCCR30 and SCCR40. These reductions values are significantly low if compared with the values found with normal concrete (19).

A relationship between the incorporation of recycled coarse aggregates and the increase in dynamic modulus of elasticity between 7 and 28 days was unable to establish since there is an uneven variation in the different concretes. Nevertheless, in general, after seven days, the concrete results analysis showed a modulus of about 80% of the value measured at 28 days.

Some studies seems to show that the coarse aggregate has non-significant influence on the durability parameters of SCC concerning to transport properties, such us, air and water permeability (47) (48). Some other authors (8) (21) argue that water permeability, chloride penetrability or drying shrinkage of SCC made with recycled aggregates differs from those made with natural aggregates. Results of air permeability test shows that these SCC mixtures could be considered airtight (47). Even the water permeability coefficient was very low compared with the normal concrete that normally is in the range of 5 to 10 x 10-18 m^2 (48). The incorporation of recycled aggregates seems also not significantly modify the evolution of the capillary water absorption on time. In fact, this behaviour was expected since some related properties measured in this study are particularly dependent on the concrete matrix. Moreover, this SCC matrix dependence is also mentioned in (49) where it is clearly demonstrated that the water absorption by capillarity of SCC mixture is strongly reduced by some kinds of powder additions. However, it was necessary to confirm if an eventual disturbance in the concrete grains packing by the introduction of recycled aggregates did not provoke a significant change in the overall concrete porosity.

4. CONCLUSIONS

With respect to the fresh concrete, the particularity noted during the tests was the need to add more water to mix the concrete with recycled aggregates, compared to concrete without recycled aggregates. This water need can be explained from the higher values of water absorption showed by recycled aggregates if compared with the natural aggregates.

The density of the hardened concrete decreases as the amount of the recycled coarse aggregates increases. This reduction can be explained from the low density values of the recycled aggregates, when compared with natural aggregates.

Regarding the compressive strength, it was observed only 2% of strength loss with the maximum recycled aggregate incorporation of 40%.

The incorporation of recycled aggregate reduced the concrete dynamic modulus of elasticity about only 3% when compared with the natural coarse aggregate self-compacting concrete.

Taking into account the research done and the type of recycled aggregate used, it is possible to conclude that, in general, the self-compacting concrete incorporating local recycled coarse aggregates is a potentially viable material to be used in the construction industry.

Concerning the use of coarse recycled aggregates from concrete demolition in SCC, this work can indicate that, in the case of SCC mixtures similar to these used here, it is possible to increase the limited percentage incorporation imposed by the current recommendation for normal concrete.

Finally the possibility to increase the use of recycled aggregates volume in self-compacting concrete is a great environmental and economical benefit.

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