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Influence of low content of steel fibre on concretes produced with recycled coarse aggregates with varying densities

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ABSTRACT

The use of construction and demolition (C&D) waste as aggregate in concrete results in a reduction in strength due to its porosity. To compensate, mix designs often require higher cement contents, which increase the material's environmental impact. This study presents an experimental and numerical analysis of the effect of steel fibres on the mechanical properties of the concrete produced with recycled C&D aggregates with varying densities. The variation in fibre content did not present any influence on the compressive strength of concrete, which is significantly affected by the lower density of the recycled C&D aggregate. The fibres collaborate to mitigate the loss of flexural strength of the steel fibre reinforcement in recycled coarse aggregate concrete (SFRRCAC) provoked by lower density of recycled aggregates when the water-to-cement ratio is lower. When the water-to-cement ratio is above 0.65, there is a great reduction of the matrix strengths due to the paste porosity and the influence of aggregate density and fibre content was insignificant.

Keywords: concrete; recycled aggregates; steel fibres; experimental tests; numerical analyses.

1. INTRODUCTION

One of the main aspects that should be considered with regard to sustainable development is the preservation of natural resources and the reduction of waste disposal in landfills [1]. In this regard, initiatives have historically been undertaken to find viable applications for construction and demolition (C&D) waste to avoid its disposal and reduce the consumption of natural materials by industry [2–5].

Usually, the use of C&D recycled aggregates reduces the concrete strength proportionally to the aggregate's porosity [6], which may have resulted from the strength class of the concrete that gave rise to the waste [7] or the waste composition that influences the oven-dry (OD) density and water absorption of the aggregates [8]. This decrease in strength is typically considered a problem that requires action to circumvent, and researchers have investigated it experimentally [9, 10] and numerically [11]. One immediate alternative is to increase the cement and/or mineral admixtures content to compensate for the strength reduction [12] and minimise negative impacts on durability [13]. However, this impacts the material's cost and eco-efficiency and requires strategies to control cement content to reduce this drawback [14]. Another possibility is to limiting recycled aggregates' content as proposed by DAMDELEN [15], which minimises the need to increase cement content. On the other hand, some research has focused on aggregate treatments to improve concrete strength [16]. Whatever the solution, there is a risk of increasing costs and the need to control the overall environmental impact [17].

Studies have focused on a new strategy based on the use of fibre reinforcement [9, 10]. The idea is to explore the possibility of enhancing flexural strength [18] while reducing Young's modulus provided by the recycled aggregates [6, 19]. This combination may be helpful for specific applications such as rigid pavements [18, 20]. However, the study by AHMADI *et al*. [18] on the viability of using steel fibre reinforcement in recycled coarse aggregate concrete (SFRRCAC) was inconclusive regarding flexural strength (or modulus of rupture) due to some limitations of the experimental study. The study by GAO and ZHANG [21] on the analysis of SFRRCAC flexural performance defined the composite as a non-obvious material when low contents

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of steel fibre (less than 0.5%) were used, which cannot be interpreted as conclusive. Although that conclusion, posterior studies, such as the one performed by SABIREEN *et al*. [22], obtained interesting findings but were limited to a single fibre content used in the mixtures tested, which is a limitation to understand the potential of the composite better. This difficulty in concluding these studies may be due to the fact that the modulus of rupture is less predictable when non-concrete aggregates are present [14]. Also, the improvement in the fracture properties of concrete with recycled aggregates could be associated only with high fibre contents, such as 1.5% by volume of steel fibres [23], which can make its application unfeasible due to increasing costs and impairing workability [24].

In light of the above, an experimental study was conducted to better understand the behaviour of SFRRCAC with varying aggregate composition and density. The main objective of this study is to establish relationships between the matrix characteristics and the effect of steel fibre reinforcement on the flexural strength of the composite. In addition, numerical analyses were carried out to understand better the influence of fibres on the composite behaviour for some mixtures considered in this research and provide a reliable way to predict the material's behaviour.

2. EXPERIMENTAL PROGRAM

This experimental study aimed to assess the mechanical behaviour of concrete with recycled coarse aggregate reinforced with steel fibre and compare it with conventional coarse aggregate concrete. To accomplish this, the C&D waste recycled aggregates were prepared and characterised to determine whether the OD density could be employed as a parameter to anticipate the mechanical behaviour of the SFRRCAC, as previously established for compressive strength [18]. The next section provides information on the preparation and characterisation of the C&D waste.

2.1. Preparation of recycled aggregates

This experimental study was based on the potential variation in the density of coarse aggregates. The recycled aggregates were processed to separate them into different density ranges. This separation was achieved using a heavy media separation process, which is typically used to separate minerals based on their densities using organic liquids, solutions of inorganic salts, or stable suspensions of predetermined densities. The heavy media used in the process must have an intermediate density between the mineral species to be separated, causing the lighter material to float and the heavier material to sink. The procedure used in this study was similar to the one used by ANGULO *et al.* [6].

A sample of approximately one cubic meter of recycled aggregate was obtained from the Itaquera Recycling Plant, located in the city of São Paulo, Brazil. The aggregates were produced by crushing C&D waste in a primary impact crusher. From there, the material was taken by a conveyor belt to a sieve used to separate it into different granulometries. The residue used in the study was then collected from the corresponding to the characteristic size of 19 mm stock pile. The retained 19.1 mm fraction was further crushed in a lab jaw crusher to achieve the specified particle size distribution. The aggregates were then sieved, and the fraction below 9.5 mm was discarded to ensure similar mixture conditions to ordinary crushed stone aggregate. The coarse fraction (19.1–9.5 mm) was washed to remove any fine particles adhering to the outer surfaces and then dried in a ventilated oven at 110 °C for 24 h. This coarse recycled aggregate is shown in Figure 1.

The C&D aggregates were classified into two porosity classes using a sink-and-float technique. This process allowed for the separation of the C&D aggregate particles into different OD density classes, enabling analysis of the influence of aggregate density on composite behaviour. The equipment used in this experimental study was the same as that used by ANGULO *et al.* [6]. The sink and float separation procedure provided two specific weight ranges: between 1.9 and 2.2 g/cm^3, and between 2.2 and 2.5 g/cm^3. The phase composition (cement-based, ceramic, ordinary rocks) of each density class was determined through hand sorting, and the results are presented in Table 1. The main differences in composition between the aggregates are associated with the higher amount of mortar and ceramic material in the less dense aggregate. Conversely, the denser aggregate has a considerable share of almost 45% granite, equivalent to the composition of conventional crushed aggregate.

The determination of the OD densities of coarse aggregates follows the Equation (1). The physical characterization of the recycled aggregate is presented in Table 2, together with the ordinary coarse aggregate. The characterization was made accordingly to the Mercosur standard NM 53 [25].

$$ODdensity = \frac{Md}{MSSD - MW} \tag{1}$$

In Equation (1), the *ODdensity* is the density (kg/dm³); *Md* is the aggregate mass dried at 110 °C for 24 hours (kg); *MSSD* is the mass at saturated surface-dry (SSD) condition (kg); and *MW* is the mass under water (kg).

Figure 1: Coarse recycled aggregate used in the study.

Table 1: Characteristics of recycled aggregates used in the experimental program.

PHASE	1.9 < D < 2.2 (%)	2.2 < D < 2.5 (%)
Concrete and mortar	92.37	53.15
Red ceramic	2.43	0.18
White ceramic	2.81	0.17
Granite	0.48	44.91
Bitumen	1.73	1.59
Asbestos	0.18	0.00
Total	100.00	100.00

D* = density.

Table 2: Composition of recycled aggregates used in the experimental program.

COARSE AGGREGATE	RECYCLED 1.9–2.2 g/cm³	RECYCLED 2.2–2.5 g/cm³	ORDINARY
Density (g/cm³)	2.07	2.50	2.63
Water absorption (%) in 24 hours	6.75	2.16	0.03
Maximum size (mm)	19	19	19

Figure 2 shows the curves obtained for water absorption over time for both classes of C&D aggregates, which were measured using a hydrostatic balance. Saturation was achieved by introducing the aggregates into a mixer filled with water, and the mass increase was measured progressively to obtain the results presented in Figure 2. Although the denser aggregate reached saturation earlier due to its lower porosity, it can be concluded that most of the water absorption occurs within the first 10 minutes, since the water absorption level of the recycled aggregate no longer shows any perceptible change. It is important to point out that this time must be verified

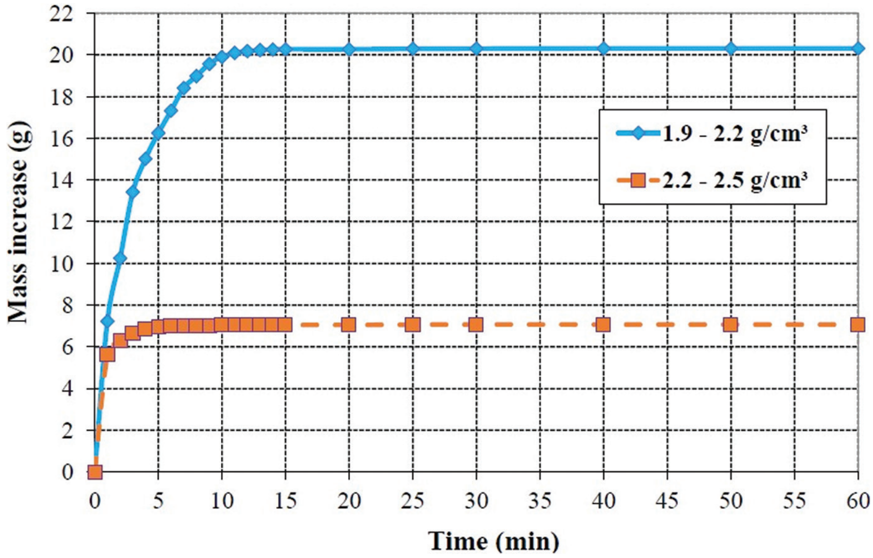

Figure 2: Water absorption of the recycled coarse aggregate versus time during the mixing with water.

experimentally, as described here, since variations in the composition of the recycled aggregate will affect the saturation time. As a result, the recycled aggregates were pre-saturated in water for 10 minutes to prevent their influence on the concrete's water demand [26, 27] and ensure consistent workability conditions.

2.2. Ordinary materials

The ordinary crushed aggregate (granite), ordinary quartz river sand, Portland cement blended with approximately 35% blast furnace slag (CP II E type with a 28-day compressive strength of 32 MPa), and the dispersion admixture (Lignosulfonate) were sourced from the local market. The hooked-end fibres used were produced by cutting steel sheet (fibre type A II according to the Brazilian standard ABNT NBR 15530:2019 [28]) and were also obtained from the local market (Figure 3). The producer reported an average yield strength of 600 MPa for the fibres, with a length of 49 mm and a rectangular cross-section of 0.45 mm by 1.84 mm.

2.3. Concrete mix proportions

The matrix mix-design was conducted using the same methodology employed by other Brazilian researchers [24, 28] to assess the effectiveness of recycled aggregates in plastic concretes with regards to their mechanical strength and durability while maintaining consistent workability conditions [29]. This requires an increase in the mortar volume of the concrete matrix to allow for the addition of a greater quantity of fibres.

The optimum proportion of mortar is determined in terms of dry materials (α) using Equation (2) in this mix-design method. This determination is made for each density range of recycled aggregate and ordinary aggregate. The α value is usually assessed visually, after checking the surface condition in terms of finish with a trowel, with the optimum α being the minimum value that gives concrete a smooth appearance when removing the slump cone mould (Figure 4a). The level of slump is also verified (Figure 4b). The α value is responsible for the cohesive properties of the concrete and is related to the volume of mortar that fills the voids in the coarse aggregate. Hence, it is dependent on the characteristics of the aggregates. Once the α value is determined, it is kept constant for all mixtures in the study.

A similar approach was taken by other researchers, known as the equivalent mortar volume method [30], for recycled aggregate concretes. This approach maintains a constant relative volume proportion of coarse aggregates to mortar in the concrete. In this case, the constant volume of coarse aggregates prevents the influence of different aggregate densities on the mix proportions. Table 3 presents the results of an optimum mortar obtained for each coarse aggregate.

$$\alpha = \frac{1+\alpha}{1+\alpha+b} \tag{2}$$

In Equation (2), α is the mortar content in terms of dry materials; *a* is the fine aggregate mass proportion to cement; and *b* is the coarse aggregate mass proportion to cement.

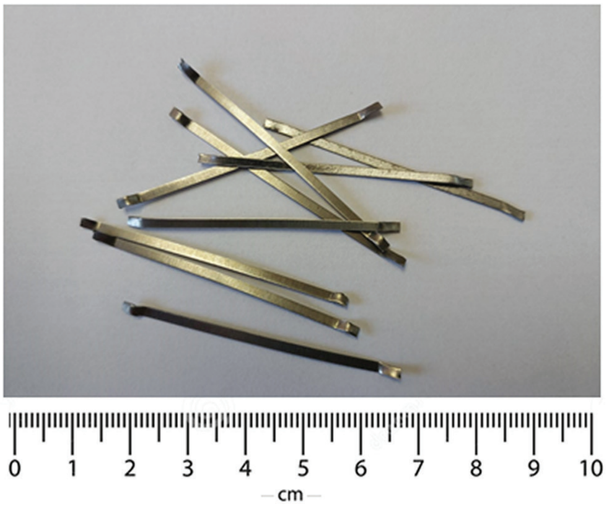

Figure 3: Steel fibres used in this experimental study.

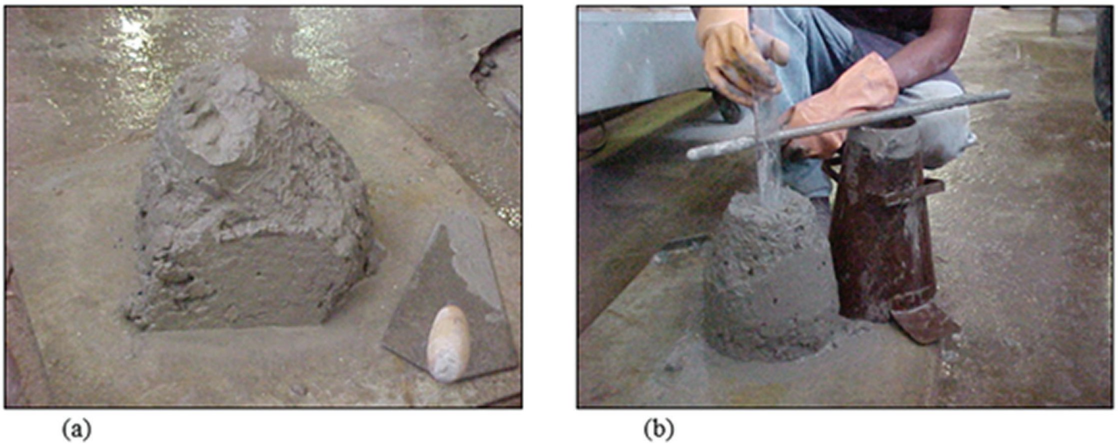

Figure 4: Visual aspect of concrete: (a) verification of the optimum mortar proportion with the use of a trowel; and (b) the slump test measurement.

Table 3: Optimum mortar (α) for each coarse aggregate used.

COARSE AGGREGATE	RECYCLED 2.07 g/cm³	RECYCLED 2.50 g/cm³	ORDINARY 2.63 g/cm³
α	54%	52%	48%

One of the principles of this method is to create three concretes with the same workability conditions (fixed slump and mortar content) by varying the cement content. Therefore, three concrete mix proportions were produced by adjusting the amount of water to achieve consistency in the slump range of 80 ± 10 mm for all of them. As a result, families of concretes with constant consistency and cohesive characteristics but different compositions were defined, as presented in Table 4. The adjustment of each matrix was obtained for each fibre content used in the study: 0, 10, 20, and 40 kg/m^3. Where the addition of fibres resulted in a decrease in slump, water consumption was adjusted to achieve a slump equal to 80 ± 10 mm. The slump was measured using the standard slump test accordingly to the Mercosur standard NM67 [31] for each batch.

2.4. Specimens casting and testing

For each mixture, the specific gravity weight of the concrete was measured in its fresh state using a recipient with a known volume. Five cylindrical specimens (10 × 20 cm) were created from a single batch of each mixture

Table 4: Mix proportions used in the experimental study.

AGGREGATE ENVELOPE DENSITY	MIX PROPORTION NUMBER	CEMENT CONSUMPTION (kg/m³)	MATERIAL MASS PROPORTION TO CEMENT				FIBRE CONTENT (kg/m³–%)
			CEMENT	AGGREGATES		WATER	
				FINE (A)	COARSE (B)		
Recycled 2.07 g/cm³	1	474	1	1.16	1.84	0.41	0 – 0%
	2	346	1	1.97	2.53	0.57	
	3	269	1	2.78	3.22	0.74	
	4	474	1	1.16	1.84	0.43	10 – 0.13%
	5	346	1	1.97	2.53	0.57	
	6	269	1	2.78	3.22	0.74	
	7	474	1	1.16	1.84	0.47	20 – 0.25%
	8	346	1	1.97	2.53	0.57	
	9	269	1	2.78	3.22	0.75	
	10	474	1	1.16	1.84	0.47	40 – 0.51%
	11	346	1	1.97	2.53	0.60	
	12	269	1	2.78	3.22	0.79	
Recycled 2.50 g/cm³	13	533	1	1.08	1.92	0.36	0 – 0%
	14	391	1	1.86	2.64	0.45	
	15	301	1	2.64	3.36	0.64	
	16	533	1	1.08	1.92	0.36	10 – 0.13%
	17	391	1	1.86	2.64	0.46	
	18	301	1	2.64	3.36	0.65	
	19	533	1	1.08	1.92	0.37	20 – 0.25%
	20	391	1	1.86	2.64	0.48	
	21	301	1	2.64	3.36	0.63	
	22	533	1	1.08	1.92	0.37	40 – 0.51%
	23	391	1	1.86	2.64	0.48	
	24	301	1	2.64	3.36	0.65	
Ordinary 2.63 g/cm³	25	543	1	0.92	2.08	0.35	0 – 0%
	26	395	1	1.64	2.86	0.48	
	27	310	1	2.36	3.64	0.61	
	28	543	1	0.92	2.08	0.34	10 – 0.13%
	29	395	1	1.64	2.86	0.48	
	30	310	1	2.36	3.64	0.61	
	31	543	1	0.92	2.08	0.36	20 – 0.25%
	32	395	1	1.64	2.86	0.48	
	33	310	1	2.36	3.64	0.60	
	34	543	1	0.92	2.08	0.39	40 – 0.51%
	35	395	1	1.64	2.86	0.48	
	36	310	1	2.36	3.64	0.61	

to measure compressive strength and water absorption. Compressive strength tests [32] were conducted using a Shimadzu® hydraulic testing machine with a capacity of 2000 kN using three cylindrical specimens for each mix composition. The other two were used for the water absorption determination was performed after 72 hours of the sample saturation following the procedure of the Brazilian standard ABNT NBR9778:2005 [33]. Additionally, using the same testing machine, four prismatic specimens (10 × 10 × 40 cm³) were produced for each mixture to obtain the flexural strength [34]. All the casted specimens were left in their moulds for 24 h before being cured in a moist chamber with a temperature of 23 ± 2 °C and relative humidity equal to or greater than 95% for 28 days. Finally, the specimens were tested at the age of 28 days.

3. NUMERICAL ANALYSIS

Numerical analysis was carried out to investigate the effect of fibres on the flexural performance of composite materials that contained recycled coarse aggregates (2.07 g/cm^3) and ordinary crushed aggregates (2.63 g/cm^3). A numerical model proposed by BITENCOURT JUNIOR *et al.* [35] was used to construct a discrete and explicit representation of the fibres for steel fibre contents of 40 kg/m^3 as represented in Figure 5. This numerical model was successfully applied recently to predict the behaviour of pullout steel fibres from cementitious matrix [36, 37], to obtain the post-cracking parameters of steel fibre reinforced concrete (SFRC) [38], and to predict the behaviour of beams under Serviceability and Ultimate Limit States [39]. The model employed a mixture theory to evaluate the effective mechanical properties of the homogenised aggregates in the matrix, considering the porosity of these inclusions.

Steel fibres were modelled using two-node finite elements (truss elements) with an elastic perfectly plastic constitutive model with Young's modulus of 210 GPa and yield stress of 1200 MPa. The fibres were randomly positioned, considering the wall effect of the mould.

To describe the concrete behaviour under tension and compression, a continuum damage model with two independent scalar damage variables was applied. The concrete was discretised into finite elements using three-noded triangular finite elements, with material parameters listed in Table 5. Young's modulus was estimated based on the results of previous experiments that used the same raw materials [6], as presented in Table 6.

The concrete-fibre interaction is described by utilizing a non-rigid coupling scheme proposed by BITENCOURT JUNIOR *et al.* [35]. A suitable constitutive damage model is adopted to describe the correlation between shear stress (adherence stress) and the relative sliding between the concrete and each fibre. The material parameters adopted are listed in Table 7. More details about the numerical model employed can also be found in BITENCOURT JUNIOR [40].

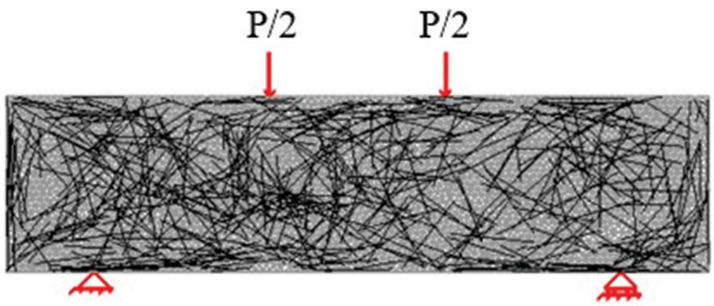

Figure 5: Numerical model to study the contribution of the fibres on the flexural behaviour of the composite.

Table 5: Parameters adopted for the concrete in the numerical analyses considering the results presented by ANGULO *et al*. [6].

CONCRETE PARAMETERS	RECYCLED 2.07 g/cm³	ORDINARY 2.63 g/cm³
Young's modulus (MPa)	21000	35000
Poisson's ratio	0.2	0.2
Fracture energy (N/mm)	0.15	0.15
Tensile strength (MPa)	2.10	2.88
Compression stress damage threshold (MPa)	21.0	28.8
Compressive parameter A-	0.89	0.89
Compressive parameter B-	1.16	1.16

Table 6: Young´s modulus estimated based on the parameters of ANGULO *et al*. [6].

AGGREGATE DENSITY (g/cm³)	CEMENT CONSUMPTION (kg/m³)	YOUNG'S MODULUS (GPa)
2.07	474	20.8
	346	19.4
	269	15.8
2.50	533	27.1
	391	26.4
	301	21.1
2.63	543	30.8
	395	27.6
	310	22.8

Table 7: Parameters adopted for the concrete-fibre interaction in the numerical analyses.

CONCRETE-FIBRE INTERACTION PARAMETERS	RECYCLED 2.07 g/cm³	ORDINARY 2.63 g/cm³
Maximum shear stress (MPa)	12.0	12.0
Residual shear stress (MPa)	4.5	4.5
α	0.4	0.4
Slip s_1 (mm)	0.01	0.01
Slip s_2 (mm)	6.5	6.5
coupling constant (normal) (MPa/mm)	10^9	10^9
coupling constant (tangential) (MPa/mm)	10^3	10^3

4. RESULTS AND DISCUSSION

4.1. Concrete density and porosity

Table 8 presents the results obtained for the specific gravity weight of concrete in its fresh state, along with the average water absorption values and their respective standard deviations. Both properties are strongly affected by the OD densities of coarse aggregates. The specific gravity weight remained relatively constant for each level of OD density of the aggregates. Specifically, the specific gravity weight of the concrete made with recycled aggregates with envelope densities of 2.07 g/cm^3 and 2.50 g/cm^3, as well as the ordinary aggregate, was 2.12 ± 0.05 g/cm^3, 2.29 ± 0.05 g/cm^3, and 2.37 ± 0.04 g/cm^3, respectively. Therefore, it can be concluded that the OD density of the aggregates is the primary factor influencing the specific gravity weight of the concrete in its fresh state, and these parameters can be correlated, as presented in Figure 6.

Figure 7 demonstrates three main water absorption levels depending on the OD densities of coarse aggregates. The figure also depicts the correlations between the water absorption and the w/c ratio for each OD density of coarse aggregate. While the w/c ratio influences the water absorption, it is not as intense as the OD densities of the aggregates. This influence is due to the fact that a higher w/c ratio leads to a more porous hardened cement paste. However, the volume of the aggregates is greater than the volume of the paste, which justifies the higher influence of the OD density parameter. Therefore, the primary correlation is obtained between the water absorption and the OD density of the coarse aggregates, as presented in Figure 8. These results present the same tendency as those obtained by SILVA *et al.* [8] and clearly demonstrate that the porosity of the aggregates is the primary factor influencing water absorption.

The fibre consumption did not affect water absorption, as expected due to the workability control, where the slump was kept constant, and the volume of the fibre could not interfere with the compaction [24]. However, it is important to note that water absorption must be considered an important factor related to concrete durability. The higher porosity of C&D recycled aggregate concretes will lead to an increase in permeability, turning the material more susceptible to aggression by external agents such as chloride ions, reducing the durability of the reinforced structures [41]. Although that, the durability of recycled aggregate concrete could be comparable

Table 8: Results obtained in terms of average values and their standard deviations.

AGGREGATE ENVELOPE DENSITY	MIX PROPORTION NUMBER	SPECIFIC GRAVITY MASS OF CONCRETE (g/cm³)	WATER ABSORTION (%)	COMPRESSIVE STRENGTH (MPa)	FLEXURAL STRENGTH (MPa)
Recycled 2.07 g/cm³	1	2.08	8.90 ± 0.25	38.47 ± 0.06	4.27 ± 0.11
	2	2.03	9.46 ± 0.11	29.20 ± 1.04	3.75 ± 0.25
	3	2.05	9.78 ± 0.17	20.38 ± 0.03	3.01 ± 0.17
	4	2.17	9.34 ± 0.01	38.83 ± 0.88	4.50 ± 0.46
	5	2.11	9.80 ± 0.04	28.46 ± 0.17	3.99 ± 0.32
	6	2.07	10.10 ± 0.16	21.16 ± 0.68	3.05 ± 0.34
	7	2.17	9.41 ± 0.22	35.51 ± 3.60	4.58 ± 0.41
	8	2.13	9.54 ± 0.15	29.15 ± 0.20	3.96 ± 0.14
	9	2.09	9.96 ± 0.11	21.48 ± 1.26	3.19 ± 0.08
	10	2.19	9.22 ± 0.25	35.80 ± 0.66	4.90 ± 0.45
	11	2.16	9.62 ± 0.29	29.14 ± 2.48	3.98 ± 0.10
	12	2.14	10.47 ± 0.01	19.55 ± 1.48	3.17 ± 0.20
Recycled 2.50 g/cm³	13	2.33	6.49 ± 0.17	52.70 ± 2.53	5.70 ± 0.14
	14	2.29	6.72 ± 0.02	44.16 ± 4.49	4.60 ± 0.15
	15	2.24	7.04 ± 0.01	25.77 ± 0.16	3.52 ± 0.34
	16	2.35	6.75 ± 0.12	53.56 ± 3.57	6.11 ± 0.31
	17	2.27	7.21 ± 0.09	43.32 ± 1.27	4.63 ± 0.12
	18	2.20	7.39 ± 0.12	25.31 ± 0.02	3.52 ± 0.32
	19	2.34	6.77 ± 0.21	53.29 ± 4.19	5.95 ± 0.53
	20	2.29	7.10 ± 0.25	39.74 ± 0.70	5.05 ± 0.11
	21	2.26	7.36 ± 0.26	29.22 ± 1.79	3.84 ± 0.31
	22	2.35	6.68 ± 0.27	50.71 ± 1.15	6.12 ± 0.16
	23	2.33	6.81 ± 0.02	41.45 ± 1.43	5.28 ± 0.42
	24	2.27	7.23 ± 0.05	26.36 ± 2.91	3.70 ± 0.09
Ordinary 2.63 g/cm³	25	2.40	5.55 ± 0.05	54.79 ± 1.30	6.51 ± 0.65
	26	2.30	5.88 ± 0.16	40.24 ± 1.87	4.67 ± 0.21
	27	2.33	5.92 ± 0.06	31.09 ± 1.24	4.12 ± 0.42
	28	2.42	5.53 ± 0.15	55.44 ± 0.95	6.52 ± 0.45
	29	2.35	5.87 ± 0.14	43.72 ± 1.01	5.25 ± 0.05
	30	2.33	5.98 ± 0.01	30.67 ± 1.59	4.11 ± 0.21
	31	2.43	5.59 ± 0.23	54.10 ± 1.87	6.44 ± 0.66
	32	2.37	5.64 ± 0.09	41.66 ± 1.53	5.34 ± 0.21
	33	2.33	5.73 ± 0.24	30.51 ± 1.79	4.21 ± 0.42
	34	2.43	5.55 ± 0.29	49.15 ± 1.87	6.42 ± 0.14
	35	2.39	5.64 ± 0.19	43.90 ± 0.37	4.77 ± 0.45
	36	2.37	5.84 ± 0.09	30.86 ± 0.44	4.29 ± 0.47

to conventional concrete [42] when precautious measurements such as the reduction of the maximum water absorption limit specifications for concretes using recycled aggregates [41].

4.2. Compressive strength and young's modulus

The obtained results for compressive strength are presented in Table 8. The results show that the compressive strength does not change with the increasing content of steel fibres. The main parameters that define the compressive strength are the w/c ratio and the aggregates' porosity. Therefore, the analysis of compressive strength behaviour is focused on these parameters. The w/c ratio is a strong influence on compressive strength, as can be

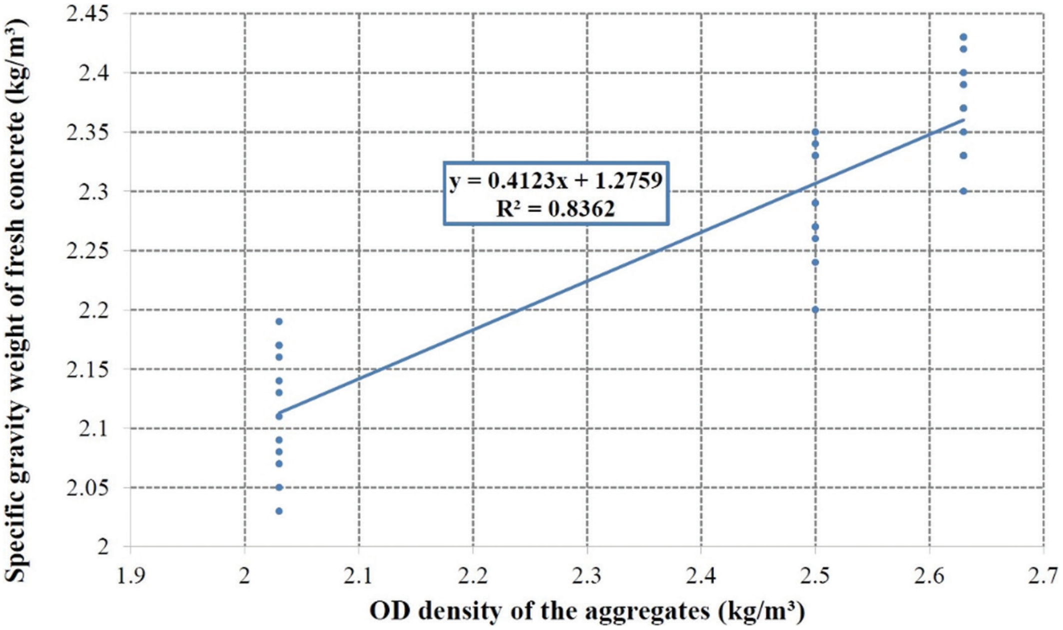

Figure 6: Correlation between the specific gravity weight of fresh concrete and OD density of the aggregates.

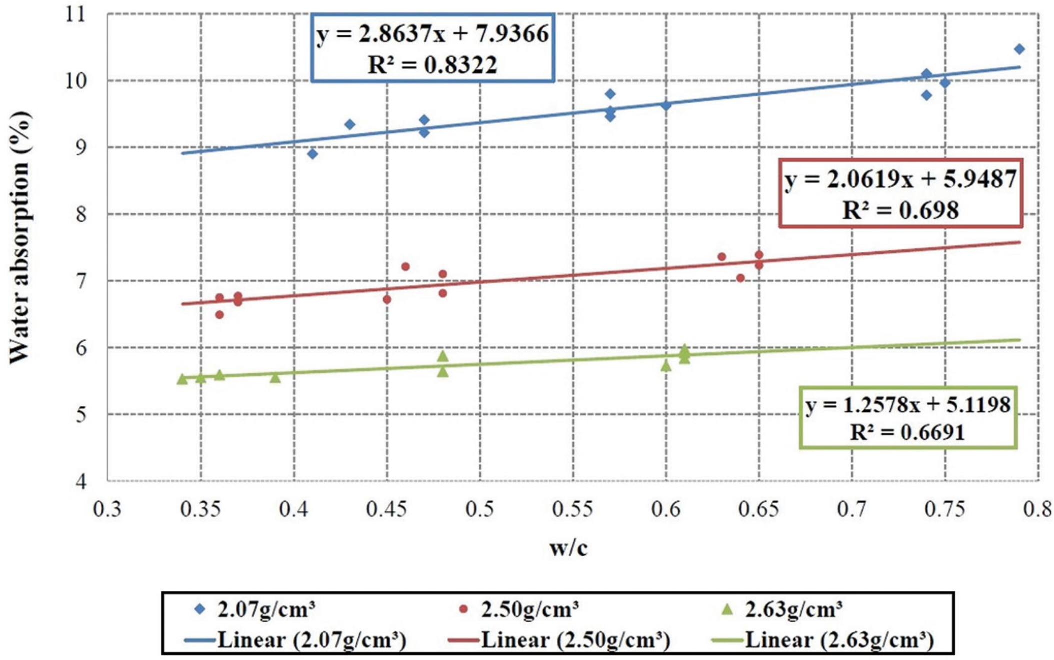

Figure 7: Correlation between the water absorption and w/c ratio for all types of coarse aggregates.

seen in Figure 9. The Abram's Law curves obtained for concretes with ordinary aggregates and recycled with 2.50 g/cm^3 envelop density were almost coincident. Therefore, the total replacement of ordinary aggregates with C&D recycled aggregate with an envelope density of 2.50 g/cm^3 shows equivalent performance to the reference concrete, regardless of the w/c level used. This finding is similar to the results obtained by CHOI and YUN [43] using recycled aggregate with an envelope density as high as 2.50 g/cm^3.The same overlap is observed for the curve associated with recycled aggregates with 2.07 g/cm^3 when the w/c ratio is lower than 0.6.

On the other hand, when the w/c ratio is higher than 0.6, the compressive strength of concretes produced with aggregates with OD density of 2.07 g/cm^3 is reduced. The difference in compressive strength is greater as

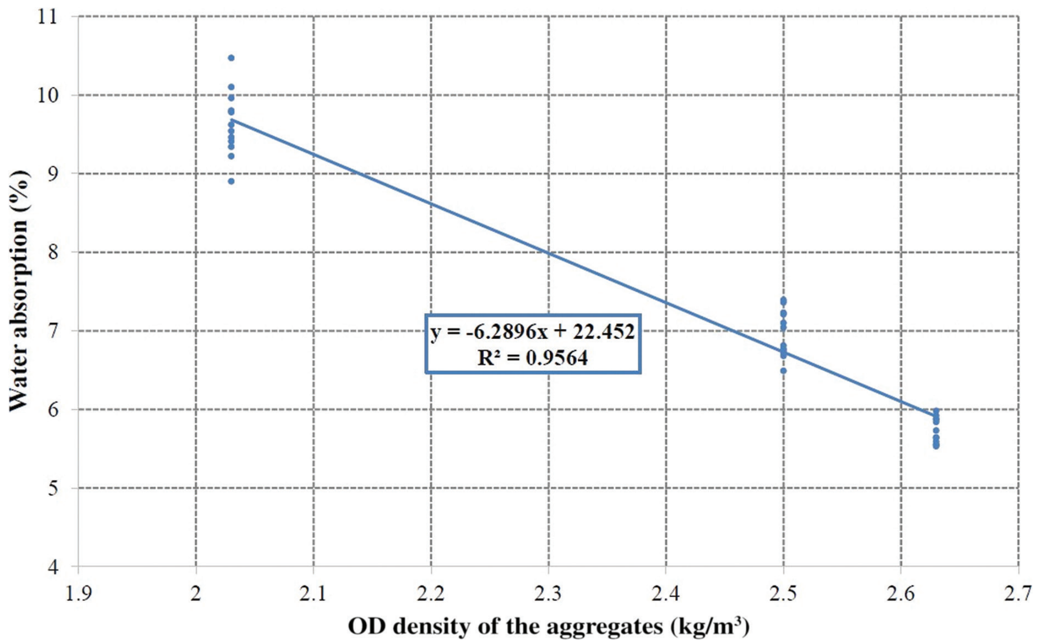

Figure 8: Correlation between the water absorption and OD density of the coarse aggregates.

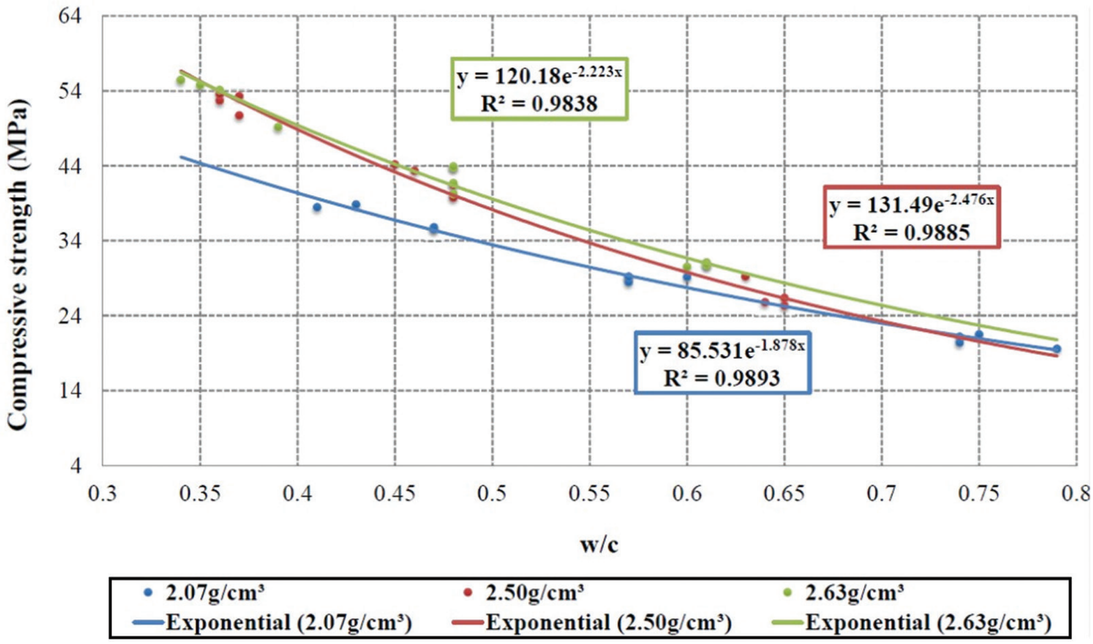

Figure 9: Correlation between the water absorption and w/c ratio for all types of coarse aggregates.

lower is the w/c ratio. In this case, the porosity increased by the lower density aggregates has an important impact on the concrete strength. In contrast, the porosity of the recycled aggregates ceases to be critical, and the porous cement paste controls the material's fracture when the w/c ratio is higher, similarly to the behaviour demonstrated in the work of ANGULO *et al*. [6]. In this condition, the porous paste works as the weakest ring in the chain.

4.3. Flexural strength and numerical simulation

In Figure 10, the correlation between the flexural strength results and the w/c ratio is presented for each coarse aggregate OD density and fibre consumption for an overall visualization of the behaviour. The fibres undoubtedly

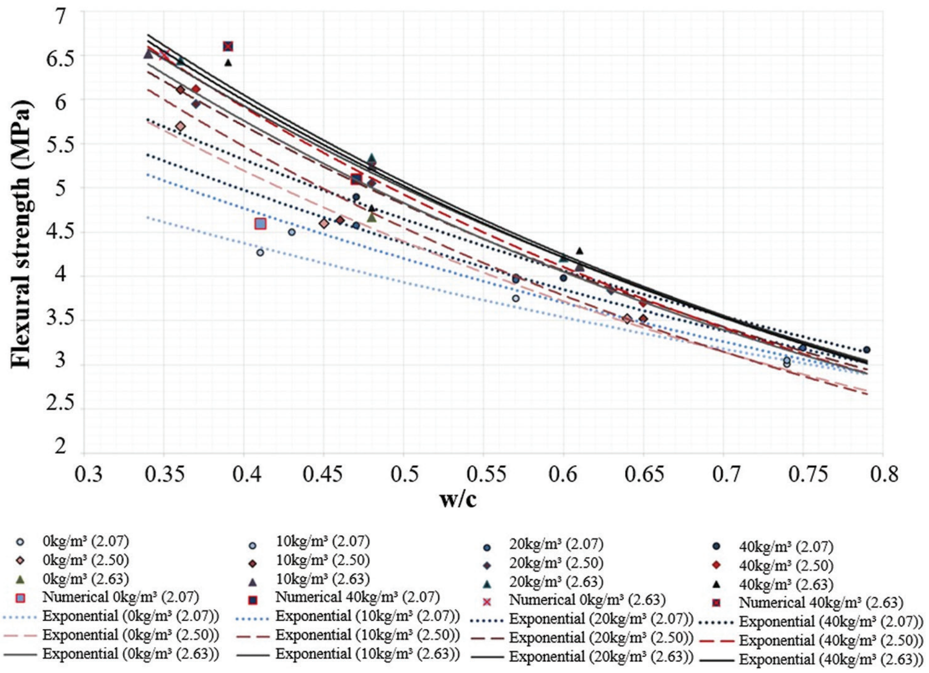

Figure 10: Flexural strength versus w/c ratio for all mix proportions with recycled and ordinary coarse aggregates.

affected the flexural strength resulting in an opposite situation to compressive strength. The coarse aggregate OD density also influenced the flexural strength. The concretes produced with ordinary coarse aggregate (continuous lines) did not present any influence of the steel fibre content on flexural strength. This behaviour is historically observed for concretes reinforced with a low content of fibres [44]. However, the flexural strength increased proportionally to the fibre contents for mix proportions with recycled coarse aggregate. This increase is more intense for the recycled aggregates with lower envelope density (2.07 g/cm^3 presented with dotted lines) and low levels of w/c ratio. This pattern is the same as observed in the study of KAYALI *et al.* [45], where the concrete was produced with lightweight aggregates. The mixtures with envelope density of 2.50 g/cm^3 presented intermediate behaviour but were closer to the mixtures produced with ordinary aggregates. In that sense, the fibres work as a mortar reinforcement, involving the aggregates and minimizing the flexural strength reduction provoked by the aggregate's porosity and poorest surface quality. The poorest quality of the surface is linked to the higher quantities of mortar and ceramic materials present in the lower density aggregate's composition.

The scatter of the results was greater as the w/c ratio used to produce the concrete decreased. The reduced w/c ratio provides an increase in the quality of the paste and better adhesion to the fibre as a consequence. The increased quality of the cement paste allowed an improvement in the bond condition, inducing a greater ability to reinforce the system and inhibit crack propagation. This condition made the behaviour of recycled aggregate concrete closer to that of conventional concrete as the fibre content was increased. Alternatively, for higher w/c ratios, the low paste strength is the critical condition for defining the flexural strength. In this situation, a smaller difference in the flexural strength was observed for the concretes. That is, the scatter of the results is smaller when the flexural strength is reduced due to the high level of w/c ratios and the contribution of the fibre is negligible. The reduced contribution of the fibre is caused by the decrease in bond with the cement paste. The lower strength of the cement paste causes a reduction in the fibre's ability to act as a stress transfer bridge through the cracks. Therefore, the steel fibres could positively affect the SFRRCAC flexural strength, minimizing the negative effect of recycled aggregates' porosity.

The numerical simulation generated flexural strength values very close to the experimental ones for the concretes of lower w/c ratio. In the case of ordinary aggregates, the simulation provided flexural strengths of 6.5 and 6.6 MPa for concretes with 0 and 40 kg/m^3 of fibres, respectively. These values are very close to those obtained experimentally, corresponding to 6.5 ± 0.7 MPa and 6.4 ± 0.2 MPa. The simulation for concretes with aggregates with lower density produced flexural strengths of 4.6 MPa and 5.1 MPa for fibre consumption of 0 and 40 kg/m^3, respectively. These values were also very close to the average test results of 4.3 ± 0.1 MPa and 4.9 ± 0.5 MPa. The flexural strength gain obtained with the fibres was about 10% and 14% for the numerical simulation and experimental results, respectively.

5. CONCLUSIONS AND FINAL REMARKS

The variation in fibre content did not present any influence on the compressive strength of concrete, whatever the density of the aggregates. This property is significantly affected by the lower density of the recycled aggregate and is more intense when the water-to-cement ratio is lower. Although previous studies were inconclusive about the effect of steel fibres on the flexural strength of SFRRCAC, it is possible to confirm that this influence depends on the aggregate's porosity and the w/c ratio. The more porous the aggregates, the greater the reduction in the flexural strength of the SFRRCAC, occurring more significantly at lower water-to-cement ratios. The fibres collaborate to mitigate the loss of flexural strength of the SFRRCAC due to the reduction of the aggregate density when the water-to-cement ratio is lower. When the water-to-cement ratio is above 0.65, the porosity of the paste is very high, greatly reducing the matrix strengths and the influence of aggregate density and fibre content was insignificant.

As final remarks, it can be noted that the use of recycled C&D aggregates with an envelope density closer to that of ordinary aggregates and lower porosity, as a consequence, provides small reductions to the composite mechanical strength. The use of these C&D recycled aggregate caused a slight reduction in flexural strength. However, this loss of performance was fully compensated when a fibre content of 20 kg/m^3 or greater was used. In this case, steel fibre contents above 20 kg/m^3 enable SFRRCAC to exhibit equivalent flexural behaviour to ordinary SFRC.

When the lower density aggregate was used (2.07 g/cm^3), there was a clear impairment to the compressive strength of the material, especially when lower levels of w/c ratio were used. In this case, the fibres did not exhibit any influence as expected. However, the fibres contributed to reducing the negative impact of this aggregate on flexural strength, but they did not show the same effectiveness as with denser recycled aggregates. This was because the reduction in flexural strength was much more pronounced for C&D aggregates with lower density and lower w/c ratio. Therefore, although fibres increase flexural strength, they do not contribute enough to equalize behaviour in this case. In this situation, the use of steel fibre provides only a minor approximation of the behaviour between ordinary SFRC and SFRRCAC. Only when the w/c ratio was higher than 0.6, and the impact of the recycled aggregates was not too pronounced, did the use of higher fibre content (40 kg/m^3) bring the flexural strength of SFRRCAC closer to that of conventional SFRC.

These findings were confirmed not only by the test results but also through numerical analysis. The model used proved to be effective enough to predict the material's behaviour and could provide better analysis conditions for this type of composite. This could be a useful tool to gain a better understanding of the material's behaviour and also to analyse possibilities for practical applications in the future.

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