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Experimental Evaluation of the Potential use of Waste Recycled Concrete Fine Aggregates to Produce Self-compacting Concrete

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Abstract. The current concern with sustainability in the construction sector has led to the adoption of processes to minimise the impact on the environment. The use of recycled concrete aggregates in self-compacting concrete (SCC), as an alternative to natural aggregates, seems to be a solution with great potential. However, it is common knowledge that the use of recycled aggregates in the production of SCC instead of natural aggregates may causes changes in some of its properties, both in the fresh and hardened state, and that the magnitude of those changes will depend on the percentages of incorporation and the nature of recycled aggregates. When using the mix design methodology proposed by Nepomuceno *et al*, SCC is assumed to be consisted basically of two phases, namely, the liquid phase (mortar phase) and the solid phase (coarse aggregates), being the main SCC properties controlled by the mortar phase. In this perspective, this research work reports the results obtained when testing mortars with flow properties appropriate to produce SCC, when binary and ternary blends of powder materials were used and natural fine aggregates were partially replaced by recycled concrete fine aggregates. The experimental program carried out involved, in a first stage, the production and testing of 11 binary mortar mixtures suitable for the production of SCC, with replacement percentages of natural fine aggregate by recycled concrete fine aggregate varying from 0% (reference mixture) to 50%, in 5% increments. Subsequently, 6 ternary mortar mixtures were produced and tested for the same purpose, with replacement percentages of natural fine aggregate by recycled concrete fine aggregate varying from 0% (reference mixture) to 50%, in 10% increments. Binary mortars included Portland cement type I 42.5R and limestone powder, while ternary mortars included Portland cement type I 42.5R, limestone powder and fly ash. In both cases, the dosages of superplasticizer and mixing water were determined experimentally to obtain the required fresh properties suitable to produce SCC. The results indicate that the 28 days age compressive strength and density of the mortars decrease with the increase in the percentage of incorporation of recycled concrete fine aggregates, regardless of whether they are mortars with binary or ternary blends of powders. In binary mixtures, the mixing water dosage increases with the percentage of incorporation of recycled aggregates, while in ternary mixtures the opposite occurs, at least up to a percentage of 40% of incorporation of recycled aggregates. The superplasticizer dosages, necessary to obtain the appropriate flow properties, were always higher in the ternary mixtures compared to the binary mixtures, even comparing only the reference mixtures. It can be concluded that mortars with the incorporation of recycled concrete fine aggregates constitute a viable material with potential for use in the construction industry, provided that the necessary adjustments to its performance are considered, thus contributing to the sustainability of construction.

INTRODUCTION

Construction and demolition waste (C&DW) comprises the largest waste stream in the European Union, with stable production in recent years and high recovery rates [1]. However, the destination of this waste has been a matter

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of concern due to the damage it can caused to the natural environment. Thus, the construction sector has sought sustainable alternatives, such as the use of powder wastes as mineral additions or the use of recycled aggregates in concrete mixtures as an alternative to natural aggregates. It has been reported that the use of recycled aggregates in the production of concrete, to replace natural aggregates, causes changes in some of its properties [2-10]. Brito [3] has stated that the overall performance of a concrete mixture incorporating recycled aggregate can result as similar to those produced with conventional natural aggregates as lower is the rate of incorporation of recycled aggregates, as better the characteristics of the recycled aggregates, as lower the amount of impurities transported to the mixture by recycled aggregates, as lower the strength class of the concrete produced and as higher the paste strength phase to compensate for the worst characteristics of recycled aggregates. The increasing of the paste phase strength is achieved by combining the use of water reducing admixtures and binders of higher strength classes [3].

The lower quality of the recycled aggregates and the increase in the percentage of substitution of natural aggregates by recycled aggregates will affect negatively the concrete performance, by decreasing its compressive strength [4, 5]. Pedro *et al*. [6] have studied concrete mixtures with simultaneous incorporation of fine and coarse recycled concrete aggregates and have reported a greater reduction in compressive strength of mixtures with 100% recycled fine aggregates, compared to that with 100% recycled coarse aggregates, for different ages of concrete. The inclusion of recycled fine aggregates in concrete mixtures is less common due to the difficulty of satisfactorily controlling their properties during the production process. However, Evangelista and Brito [7] have shown that, when using recycled fine aggregates produced in the laboratory with controlled granulometry and crushing, its incorporation in concrete does not significantly affect the compressive strength if the replacement rate does not exceed 30%. However, the use of recycled fine aggregates to produce structural concrete is generally restricted in normative documents due to the uncertainty regarding the presence of harmful impurities, as a result of less quality control of the origin of the materials. Evangelista and Brito [7] have suggested that the use of precast concrete for the production of recycled fine aggregates would easily overcome such problems with regard to the quality control of the materials.

According to Rahul *et al*. [8] the compressive strength of concrete with recycled fine aggregates is mainly affected by the replacement ratio of natural by recycled fine aggregates and the water absorption of recycled fine aggregates. Hassan *et al*. [10], have also studied the mechanical properties of concrete made with coarse and fine recycled aggregates, and have attributed the reduction in compressive strength to the heterogeneity between the components of the concrete mixture and the presence of voids formed, due to the lack of connection between the structural materials. The biggest limitation of concrete with recycled fine aggregates is its higher water absorption, agglomeration of particles and adhesion of the mortar, all interfere with its properties [5,11,12]. The higher water absorption of recycled aggregates implies an effective compensation of the water in the mixture [5]. Therefore, it is necessary to estimate the amount of additional water and define methods to determine it [8].

Considered one of the greatest advances in the construction sector due to its properties, self-compacting concrete (SCC) has been increasingly used in high quality structures, where conditions for compaction are difficult. The SCC is characterized by flowing inside the reinforcement, filling the formwork in a natural way, without loss of homogeneity, compacting under the action of its own weight maintaining its homogeneity, without the need for any vibration [5,13-15]. To obtain an SCC, a high amount of powder materials is required. The use of cement as the only powder material implies the use of high dosages, resulting in a high cost. In this sense, more sustainable additions have been tested to replace part of the cement [14]. Other studies have been developed regarding the replacement of natural aggregates by recycled aggregates in SCC, either as fine aggregates [4] or coarse aggregates [16]. In general, as for normal vibrated concrete, the mechanical performance of SCC decreases with the increase in the incorporation of recycled aggregates [4, 5, 16-18]. According to Revilla-Cuesta *et al*. [19], the literature does not recommend the use of structural SCC with recycled fine aggregates with a percentage higher than 50%, due to its mechanical characteristics. Barbosa *et al*. [20], measured the water absorption of SCC with recycled fine aggregates and confirmed that the absorption is higher than in SCC with recycled coarse aggregates, being both higher than that of natural ones.

The present study aims to analyse the impact on SCC mechanical properties resulting from the incorporation of recycled fine aggregates in partial replacement of natural fine aggregates. When using the mix design methodology proposed by Nepomuceno *et al*. [14], SCC is assumed to be consisted basically of two phases, namely, the liquid phase (mortar phase) and the solid phase (coarse aggregates), being the main SCC properties controlled by the mortar phase. In this perspective, this research work reports the results obtained when testing mortars with flow properties appropriate to produce SCC, when binary and ternary blends of powder materials were used and natural fine aggregates were partially replaced by recycled concrete fine aggregates. The recycled concrete fine aggregates used in the study reported here were produced under controlled laboratory conditions. The experimental program carried out involved, in a first stage, the production and testing of 11 binary mortar mixtures suitable for the production of SCC, with replacement percentages of natural fine aggregate by recycled concrete fine aggregate varying from 0% (reference mixture) to 50%, in 5% increments. Subsequently, 6 ternary mortar mixtures were produced and tested for the same purpose, with replacement percentages of natural fine aggregate by recycled concrete fine aggregate varying from 0% (reference mixture) to 50%, in 10% increments. Binary mortars included Portland cement type I 42.5R and limestone powder, while ternary mortars included Portland cement type I 42.5R, limestone powder and fly ash. In both cases, the dosages of superplasticizer and mixing water were determined experimentally to obtain the required fresh properties suitable to produce SCC. The fresh and hardened properties of the produced mixtures were studied and the viability of using recycled concrete fine aggregates in the construction industry was analysed.

EXPERIMENTAL PROGRAM

In the present study, the following materials were used: a Portland cement (C) type CEM I 42.5R in accordance with NP EN 197-1 [21]; a calcium carbonate limestone filler (LM) with the reference MICRO 100 AB, supplied by OMYA COMITAL, SA; a commercial fly ash (FA) supplied by a local ready-mix concrete company; a polycarboxylate-based superplasticizer (SP) with the commercial reference Sika Viscocrete 3005, supplied by SIKA, a tap water (W), a fine-grained natural rolled sand (S2); an intermediate-grained natural rolled sand (S4) and, finally, a recycled concrete fine aggregate (RA) obtained directly from the crushing of concrete cubic specimens stored in laboratory. In the present research work, it was decided to use the fine aggregates resulting directly from the grinding process, without separating the powder particles. Properties of the constituent materials are presented in Table 1, while the grading distribution of fine aggregates are shown in Figure 1. The use of two different natural fine aggregates had the purpose of allowing the combination of the fine aggregates to obtain the same grading curve in all the produced mixtures, as close as possible to the reference curve. Thus, all the mortars produced have approximately the same particle size distribution of fine aggregates. All the mortars were produced following the methodology proposed by Nepomuceno *et al*. [14], that makes use of the parameters presented in Table 2. The volume of voids in the mortar calculation and the contribution to the volume of powdered materials from fine aggregates were both neglected.

TABLE 1. Mortars constituent materials and properties.

Property	C	LM	FA	SP	S2	S4	RA
Density [kg/m^3]	3140	2720	2380	1050	2600	2630	2310
Specific surface area [cm^2/g]	3848[a]	5088[b]	4009[b]	---	---	---	---
Fineness modulus	---	---	---	---	2.104	3.035	3.166
Maximum particles size [mm]	---	---	---	---	1.19	2.38	4.76
Water absorption [%]					0.43	0.93	9.19

[a] Blaine; [b] Coulter LS200-Laser particle analyser

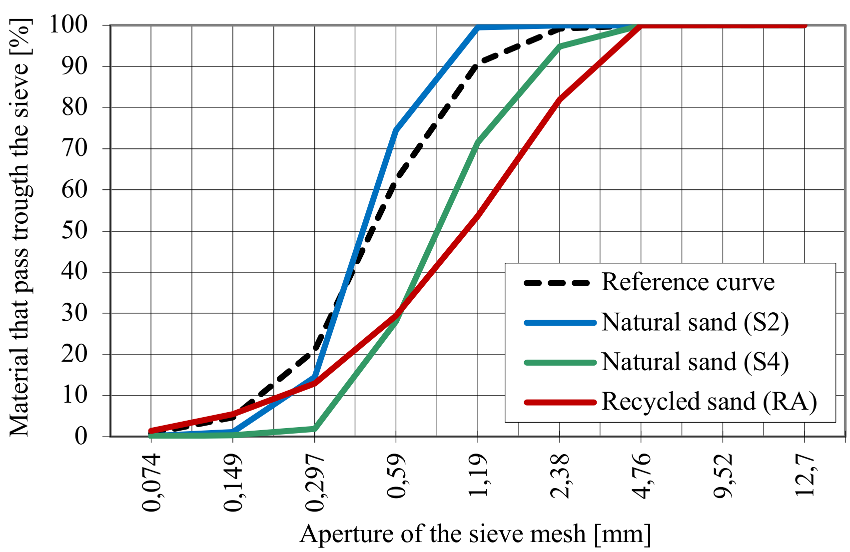


FIGURE 1. Grading distribution of fine aggregates.

TABLE 2. Mix design parameters used in the methodology proposed by Nepomuceno *et al*. [14].

Parameter	Description
Vp/Vs	Ratio in absolute volume between powder materials and fine aggregates
Vw/Vp	Ratio in absolute volume between water and powder materials
Sp/p%	Ratio in percentage between the amounts in mass of superplasticizer and powder materials
fc	The unit percentage of cement in the total absolute volume of powder materials (Vp)
flm	The unit percentage of limestone in the total absolute volume of powder materials (Vp)
ffa	The unit percentage of fly ash in the total absolute volume of powder materials (Vp)
fs2	The unit percentage of sand S2 in the total absolute volume of fine aggregates (Vs)
fs4	The unit percentage of sand S4 in the total absolute volume of fine aggregates (Vs)
fra	The unit percentage of recycled sand RA in the total absolute volume of fine aggregates (Vs)

Two series of mortars were produced, namely a binary mixture (Serie 1) and a ternary mixture (Série 2). Mixtures were classified as binary when they associated a cement with one mineral addition, and ternary when they associated a cement with two mineral additions.

Series 1 included a total of 11 mortars with the same binary association of powder materials, incorporating Portland cement CEM I 42.5R (40%) and limestone filler (60%), by absolute volume. In Series 1, the first mortar only includes natural fine aggregates and served as a reference for comparison with the remaining 10 mortars of the same Series that incorporate successively increasing percentages of recycled fine aggregates to replace natural fine aggregates, in increments of 5%, up to a 50% limit, by absolute volume. The resultant grading curve of the fine aggregate's mixtures remained constant in all mortars in this study. The parameters of the produced binary mixtures are listed in Table 3.

Series 2 included a total of 6 mortars with the same ternary association of powder materials, incorporating Portland cement CEM I 42.5R (40%), fly ash (10%) and limestone filler (50%), by absolute volume. Also in this Series, the first mortar only includes natural fine aggregates and served as a reference for comparison with the other 5 mortars of the same Series that incorporate successively increasing percentages of recycled fine aggregates to replace natural fine aggregates, in increments of 10%, up to a limit of 50%, by absolute volume. The resultant grading curve of the fine aggregate's mixtures remained constant in all mortars in this study. The parameters of the produced ternary mixtures are listed in Table 4.

TABLE 3. Parameters of the binary mortar mixtures.

Mortar	Vp/Vs	fc	flm	fs2	fs4	fra
S1-Ref.	0.80	0.40	0.60	0.50	0.50	0.00
S1-5%	0.80	0.40	0.60	0.50	0.45	0.05
S1-10%	0.80	0.40	0.60	0.50	0.40	0.10
S1-15%	0.80	0.40	0.60	0.50	0.35	0.15
S1-20%	0.80	0.40	0.60	0.50	0.30	0.20
S1-25%	0.80	0.40	0.60	0.50	0.25	0.25
S1-30%	0.80	0.40	0.60	0.50	0.20	0.30
S1-35%	0.80	0.40	0.60	0.50	0.15	0.35
S1-40%	0.80	0.40	0.60	0.50	0.10	0.40
S1-45%	0.80	0.40	0.60	0.50	0.05	0.45
S1-50%	0.80	0.40	0.60	0.50	0.00	0.50

TABLE 4. Parameters of the ternary mortar mixtures.

Mortar	Vp/Vs	fc	flm	ffa	fs2	fs4	fra
S2-Ref.	0.80	0.40	0.50	0.10	0.50	0.50	0.00
S2-10%	0.80	0.40	0.50	0.10	0.50	0.40	0.10
S2-20%	0.80	0.40	0.50	0.10	0.50	0.30	0.20
S2-30%	0.80	0.40	0.50	0.10	0.50	0.20	0.30
S2-40%	0.80	0.40	0.50	0.10	0.50	0.10	0.40
S2-50%	0.80	0.40	0.50	0.10	0.50	0.00	0.50

The mix design was carried out assuming that the fine aggregates were in a saturated and surface dry state, and that they neither absorb nor add water to the mix. For this purpose, it was decided to keep all aggregates saturated by frequent sprinkling of water. Before each mixing, at least two measurements of the surface water content of each fine aggregate were taken and the mix dosages were compensated accordingly, namely in the amount of mixing water and the masses of fine aggregates. The mixing sequence followed the protocol suggested by Nepomuceno *et al*. [14].

Fresh state properties were evaluated by performing mini-cone test (Figures 2a and 2b) and mini v-funnel tests (Figures 2c and 2d) in order to determine the values of Vw/Vp and Sp/p% that satisfy the required mortar flow properties to produce SCC, as described by Nepomuceno *et al*. [14]. The mortars should satisfy a Gm value in mini slump-flow between 5.3 and 5.9, corresponding to a spread Dm value between 251 and 263 mm and, simultaneously, a Rm value in mini v-funnel test between 1.14 and 1.30 s^{-1}, corresponding to a flow time t between 7.69 and 8.77 s. In this iterative process, on average, three to four mixtures were necessary to obtain the adequate Vw/Vp and Sp/p% values. Thus, all the mortars have similar rheological properties, as the spread diameter and the flow time can be correlated with the rheological parameters of yield stress and the consistency, respectively [22-24].

(a) (b) (c) (d)

FIGURE 2. Flow tests: (a) Mini cone slump-flow, (b) Measurement of spread diameter, Dm, (c) Filling the mini v-funnel, (d) Measurement of flow time, t.

The obtained values of Vw/Vp and Sp/p% for each mortar adequate to produce SCC, together with the W/C ratio and the mix proportions, are presented in Table 5 and Table 6 for the binary and ternary mortars, respectively.

TABLE 5. Mix proportions to produce a cubic meter of binary mortars (Series 1).

Mortar	Vw/Vp	Sp/p%	W/C (mass)	C [kg]	LM [kg]	W [litres]	SP [litres]	S2 [kg]	S4 [kg]	RA [kg]
S1-Ref.	0.700	0.340	0.56	424	552	237	3.16	549	555	---
S1-5%	0.710	0.330	0.57	423	550	239	3.06	547	498	49
S1-10%	0.710	0.330	0.57	423	550	239	3.06	547	443	97
S1-15%	0.725	0.335	0.58	421	547	243	3.09	545	386	145
S1-20%	0.710	0.335	0.57	423	550	239	3.10	547	277	243
S1-25%	0.705	0.335	0.56	424	551	238	3.11	548	277	244
S1-30%	0.720	0.335	0.57	422	548	242	3.09	545	221	291
S1-35%	0.720	0.335	0.57	422	548	242	3.09	545	166	339
S1-40%	0.725	0.335	0.58	421	547	243	3.09	545	110	387
S1-45%	0.710	0.335	0.57	423	550	239	3.10	547	55	438
S1-50%	0.700	0.335	0.56	424	552	237	3.11	549	---	488

TABLE 6. Mix proportions to produce a cubic meter of ternary mortars (Series 2).

Mortar	Vw/Vp	Sp/p%	W/C (mass)	C [kg]	FA [kg]	LM [kg]	W [litres]	SP [litres]	S2 [kg]	S4 [kg]	RA [kg]
S2-Ref.	0.755	0.385	0.60	417	79	451	250	3.47	539	545	---
S2-10%	0.740	0.385	0.59	419	79	453	247	3.49	542	438	96
S2-20%	0.740	0.385	0.59	419	79	453	247	3.49	542	329	193
S2-30%	0.735	0.385	0.59	419	80	454	245	3.49	543	220	289
S2-40%	0.730	0.390	0.58	420	80	455	244	3.54	543	110	386
S2-50%	0.730	0.390	0.58	420	80	455	244	3.54	543	---	483

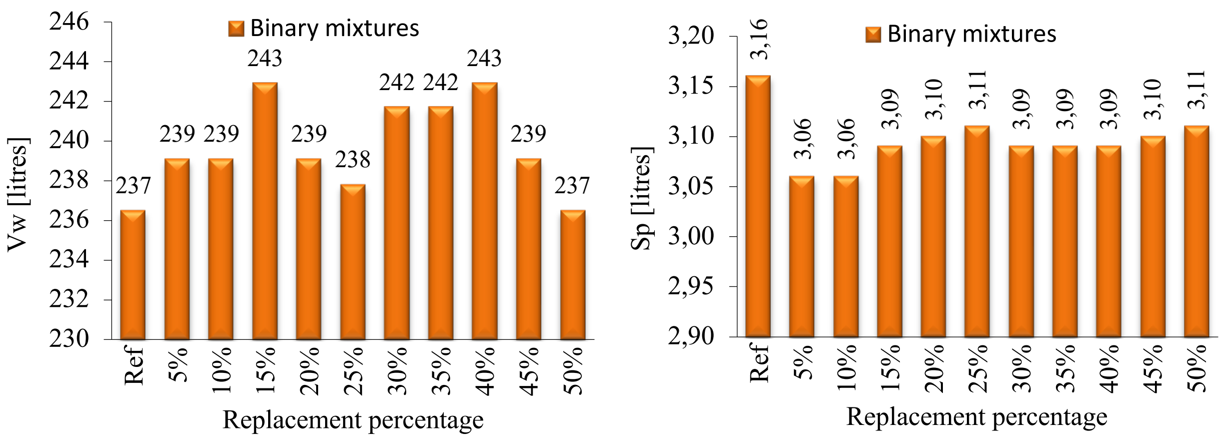
Mortars that fulfil the requirements for the flow properties were sampled in prismatic moulds of 40×40×160 mm^3 without any internal or external vibration (Figure 3a). The specimens were cured under controlled conditions in a curing chamber at a temperature of 20 ºC and approximately 90% relative humidity until they were test. Each of the three samples of the prismatic mould was divided into two halves (Figure 3b). For each mortar, six samples were tested for compressive strength at 28 days age (Figure 3c) and for saturated surface dry (SSD) density. The compressive strength at the ages of 28 and 42 days was measured in accordance with EN 1015-11 [25], while the SSD density of hardened mortars were evaluated based on EN 1015-10 [26].

(a) (b) (c)

FIGURE 3. Test of mortars in the hardened state: (a) Filling of the prismatic mould, (b) Dividing specimens into two halves (f), Testing for compressive strength.

RESULTS AND DISCUSSION

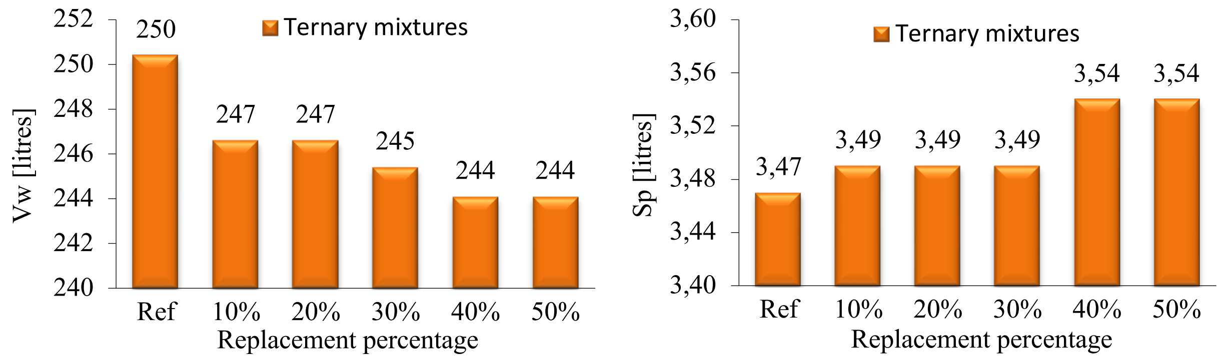
The water content variation on binary mixtures is shown in Figure 4a. The water content varies in a narrow interval, between 237 to 243 litres, presenting a mean value of 240 litres per cubic meter of mortar. Despite the high water absorption value of the recycled aggregates, increasing their percentage of incorporation in the mortars did not produce an increase in the water dosage, and this was due to the fact that the recycled aggregates had been previously saturated. The superplasticizer content variation on binary mixtures is shown in Figure 4b. It is observed that the reference mixture presents a higher dosage of superplasticizer than the mixtures that incorporate recycled aggregates. There is also a slight increase trend in the dosage of superplasticizer as the incorporation percentage of recycled aggregates increases from 5% to 50%. However, the overall variation in superplasticiser content between mixes can not be considered significant. As superplasticizer is usually a very expensive material, it is worth noting that its dosage does not increase as a result of the incorporation of fine recycled concrete aggregates.



(a) (b)

FIGURE 4. Variation of mixing water and superplasticizer contents with replacement percentage in binary mixtures: (a) Mixing water, (b) Superplasticizer content.

Figure 5 shows the water and superplasticizer content variation on ternary mixtures. It is observed that the water content decreases when natural aggregates are replaced by recycled aggregates (Figure 5a), while the superplasticizer content increases (Figure 5b). It is clear that the replacement of limestone powder by 10% fly ash, by absolute volume, has produced changes in water content and, consequently, and increase in the superplasticizer dosage was needed to rebalance the flow behaviour of mortars, as all mortars have the same flow behaviour.



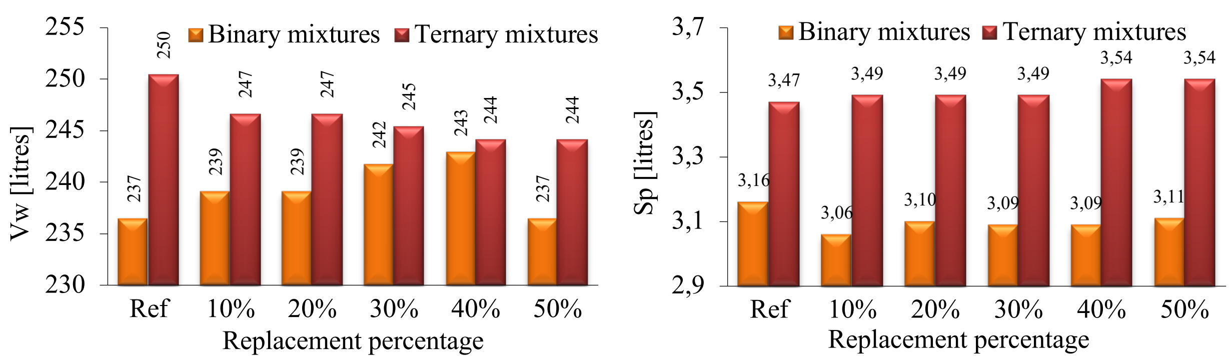
(a) (b)

FIGURE 5. Variation of mixing water and superplasticizer contents with replacement percentage in ternary mixtures: (a) Mixing water; (b) Superplasticizer content.

Figure 6a shows a comparison between binary mixtures (Series 1) and ternary mixtures (Series 2) regarding the variation of mixing water dosage with the increasing percentage of recycled aggregate incorporation. It is observed that binary mixtures always required low water demand to obtain the required flow properties when compared to ternary mixtures. It was also observed that, while in binary mixtures the mixing water dosage increases with the percentage of incorporation of recycled aggregates, in ternary mixtures the opposite occurs, at least up to a percentage of 40% replacement.

Figure 6b shows a comparison between binary mixtures (Series 1) and ternary mixtures (Series 2) regarding the variation of superplasticizer dosage with the increasing percentage of recycled aggregate incorporation. It is verified that for each series there are not very significant differences between the superplasticizer dosages needed to obtain the required flow properties. However, the ternary mixtures always showed higher values for the superplasticizer dosages.

When analysing the influence of recycled aggregates on rheological and mechanical properties of self-compacting concrete, Campos *et al*. [20] have shown that the amount of superplasticizer increases with the increase of recycled aggregates and that the superplasticizer offsets the negative effects of recycled fine aggregates, improving its rheological properties. Although it can be said that the Campos *et al*. [20] results agree with those obtained in the present research work, the increase in the percentage of superplasticizer seems to be small when comparing mixtures with the same constitution of powder materials (binary or ternary), and this can be justified by the differences on the methodology used, since in the present research work all the mortars have the same flow behaviour.



(a) (b)

FIGURE 6. Comparison between binary and ternary mixtures: (a) with respect to variation of mixing water content; (b) with respect to variation of superplasticizer content.

Figure 7a shows the comparison between the binary mixtures (Series 1) and the ternary mixtures (Series 2) regarding the variation of mortar's compressive strength as the percentage of recycled aggregate incorporation increases. A decrease in the compressive strength of the mortars is observed as the incorporation of recycled concrete fine aggregates increases, and this occurs regardless of whether the mortars have binary or ternary powder associations. The reduction in compressive strength as the incorporation of recycled concrete fine aggregates increases is attributed to the greater weakness of recycled aggregates compared to natural aggregates. Figure 7b shows the variation of the mortar's saturated and surface dry (SSD) density at 28 days age as the replacement percentage of natural by recycled aggregate increases, both for binary mixtures (Series 1) and the ternary mixtures (Series 2). A slight reduction in the SSD density of mortars with binary and ternary associations is observed as the incorporation of fine recycled aggregates increases. This reduction is attributed to the lower density of recycled concrete aggregates when compared to natural aggregates. The obtained results corroborate the findings of Bogas *et al*. [9], Salesa *et al*. [11] and Oliveira *et al*. [16]. Figure 7b also shown that, as the incorporation percentage of recycled aggregates increases, the mortars with ternary associations tends to present lower density values compared to the mortars with binary associations. This result was predictable, as fly ash has a lower density than limestone filler.

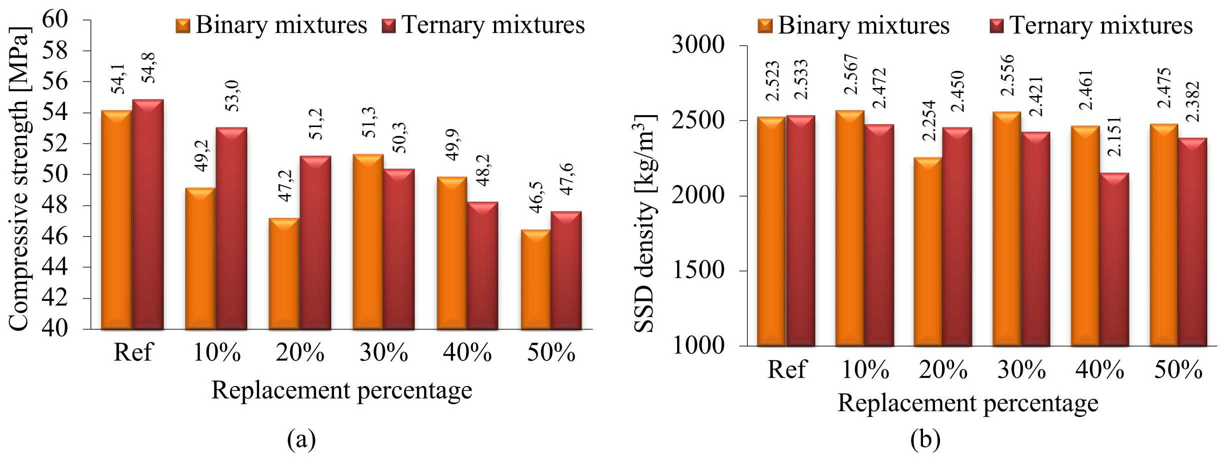


FIGURE 7. Comparison between binary and ternary mortars: (a) with respect to the compressive strength; (b) with respect to the variation of SSD density.

CONCLUSION

Changes in the properties of mortars suitable for the production of SCC as a result of the incorporation of recycled fine aggregates in successively increasing amounts were studied. The main properties evaluated were compressive strength, density and changes in the dosages of water and superplasticizer to obtain the same rheological properties, evaluated directly by the flowability and fluidity tests. The analysis was performed with a binary association of fine materials (CEM I 42.5R Portland cement and limestone filler) and another with a ternary association of fine materials (CEM I 42.5R Portland cement, limestone filler and fly ash). The following conclusions can be stated:

1. The 28 days age compressive strength of mortars decreases with the increase in the percentage of incorporation of recycled fine aggregates, regardless of whether they are mortars with binary or ternary associations;
2. The 28 days age SSD density of mortars decreases slightly with the increase in the percentage of incorporation of recycled fine aggregates, regardless of whether they are mortars with binary or ternary associations;
3. In binary mixtures, the mixing water dosage increases with the percentage of incorporation of recycled aggregates, while in ternary mixtures the opposite occurs, at least up to a percentage of 40% of incorporation of recycled aggregates;
4. The superplasticizer dosages, necessary to obtain the appropriate flow properties, although relatively close to each other, were always higher in the ternary mixtures compared to the binary mixtures, even when comparing only the reference mixtures;
5. Mortars with the incorporation of recycled fine aggregates constitute a viable material with a good potential for use in the construction industry, provided that the necessary adjustments to its performance are considered and that the origin and production of recycled materials can be controlled, as the results of the present research were based on recycled concrete fine aggregates produced under controlled laboratory conditions.

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