Construction and Building Materials 153 (2017) 129–138

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Superplasticizer's efficiency on the mechanical properties of recycled aggregates concrete: Influence of recycled aggregates composition and incorporation ratio

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HIGHLIGHTS

- Four different untreated CDW sources.
- Influence of CDW composition on the performance of polycarboxylic superplasticizers.
- Superplasticizer effect on workability, compressive and tensile strengths, and Young's modulus.
- Recycled aggregate characteristics limit the efficiency of superplasticizers.
- Superplasticizers lose efficiency when used with CDW aggregates instead of concrete waste.

ARTICLE INFO

Article history:
Received 3 May 2017
Received in revised form 4 July 2017
Accepted 10 July 2017

Keywords:
Recycled aggregates concrete
Untreated construction and demolition waste
Superplasticizer
Mechanical properties

ABSTRACT

Most research on recycled aggregates concrete concern aggregates produced from concrete waste, rather than actual construction and demolition waste. Different investigations have assessed that sulfonated-based superplastizers are not as efficient in recycled aggregates concrete than on natural aggregates concrete, but no significant loss of polycarboxylic-based superplasticizer efficiency has been reported. This may not be valid when the aggregates are sourced from actual construction and demolition waste, due to the higher porosity, roughness, and weaker mechanical properties of aggregates produced from this source. This paper analyses the mechanical properties of superplasticized concrete with the incorporation of construction and demolition waste. Recycled aggregates produced from construction and demolition waste were taken directly from plants and used as aggregates without screening or treatment, emulating what would happen in a practical application by the concrete industry. The results of the tests and the superplasticizer's efficiency are compared with results on natural aggregate concrete compositions and on analogue recycled concrete aggregate concrete compositions with and without superplasticizers. The composition of the different construction and demolition waste aggregates is considered during the analysis of results. Evidence was found that when recycled aggregates are sourced from construction and demolition waste, polycarboxylic-based superplasticizers perform satisfactorily but may not be as efficient as in natural aggregate concrete compositions.

1. Introduction

The state-of-the-art on recycled aggregates concrete (RAC) argues in favour of the use of construction and demolition waste (CDW) as aggregates for concrete. However, most studies are focused on the use of recycled aggregates (RA) produced from a single source of waste – in most cases concrete. Different types of waste will lead to RA with different compositions, physical and mechanical properties. In general terms and irrespective of the type of CDW waste used as RA, RAC tends to have worse mechanical and durability properties mainly because the increased porosity, roughness, and water absorption of the RA leads to higher w/c ratios, resulting in weaker and more porous cementitious

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.103
0950-0618/

Acronyms

w/c ratio	water/cement ratio;
CDW	construction and demolition waste
CRA	coarse recycled aggregate
CRAC	coarse recycled aggregates concrete
CRCAC	coarse recycled concrete aggregate concrete
FRA	fine recycled aggregate
FRAC	fine recycled aggregates concrete
ITZ	interfacial transition zone
NA	natural aggregate
NAC	natural aggregate concrete
RA	recycled aggregates
RAC	recycled aggregates concrete
RCA	recycled concrete aggregate
RCAC	recycled concrete aggregate concrete
SP	superplasticizer

pastes. Since superplasticizers (SP) reduce the w/c ratio of concrete compositions, their joint use with RA is a natural solution to offset the negative effects caused by RA incorporation. Nevertheless, studies have found that water reducing admixtures may be less efficient on RAC when compared to their effect on natural aggregates concrete (NAC) [1,2].

Despite studies focused on a single type of CDW allowing the direct understanding of the effects of each particular type of CDW on concrete properties, an important aspect hinders the replicability of research on RAC by the concrete industry: CDW, either available on plants or directly on site after demolition/deconstruction, is typically a mix of different construction materials, with a highly variable composition, and it is not practical or economically viable to completely screen it. Only limited screening is typically made, mostly concerning the removal of organic materials, as well as reinforcement bars. Since CDW are highly variable, RA with different properties will be produced from different CDW facilities and it is necessary to evaluate the extent of the difference in RAC properties caused by the use of CDW from different sources.

This paper is focused on the application of CDW on RAC by the industry: an SP is used in different RAC mixes made with direct application of minimally-treated CDW as aggregates. Concrete mixes without SP are compared with compositions with SP and the efficiency of the SP is evaluated. The RA are unscreened and produced from four CDW processing facilities from different regions and with different processing methods to account for the effect of CDW compositions and processing on concrete properties.

2. Recycled aggregates concrete

Different waste has been tested as aggregates for concrete: Topçu and Canbaz studied recycled glass concrete [3], Martínez-Garcia et al. [4] RAC with mussel shell as RA, Senthamarai and Manoharan [5], the behaviour of RAC with ceramic RA.

Agrela et al. [6] reported that the composition of CDW, despite variable, is mostly composed of concrete and masonry waste. The most investigated type of RAC tested so far is RAC resorting to recycled concrete aggregates (RCA). The material and mechanical [7,8], the durability [9,10], and the structural [11,12] properties and behaviour of recycled concrete aggregates concrete (RCAC) advocate for its use as a structural material. The knowledge on CDW RAC is more limited. CDW RA result in concrete with worse properties than NAC and RCAC and the extent of this decrease is dependent on the composition of the CDW RA used [6,13,14].

RA sourced from any of these sources is not as suited to concrete production as NA. The higher porosity, roughness, deformability and worse mechanical strength of RA produced from either concrete or CDW waste results in worse properties than those of NAC. In the case of concrete waste, the attached mortar that involves part of the original NA is responsible for these shortcomings. CDW RA are also partly composed of this attached mortar, but also of ceramics and other materials that have these detrimental characteristics.

Fine recycled aggregates (FRA) typically contain higher contents of these deleterious materials, leading to FRA concrete (FRAC) performing worse than coarse recycled aggregates concrete (CRAC) [12]. Most current regulations do not allow the use of FRA.

3. Superplasticizers

Different SP have different action mechanisms. Nevertheless, they share a common principle: the improvement in fresh-state properties is achieved by preventing the flocculation of cement particles. This flocculation causes water entrapment between cement particles and is caused by Van der Waals and electrostatic interactions between different cement particles and cement particles and water, as well as bridging effects between cement particles and water [15].

Two of the most common SP currently in use are lignosulfate-based and polycarboxylic-based. Both types have been tested on RAC previously in what concerns mechanical [7,16,17] and durability [18,19] properties and it seems that whilst lignosulfate-based SP lose effectiveness with RA incorporation, this effect in polycarboxylic-based SP is, at most, marginal [16]. Hypotheses have been argued to justify these findings [16,20].

Lignosulfate-based SP act mostly by electrostatic repulsion [15]: the SP particles are adsorbed to the surface of the cement particles and the Van der Waals and electrostatic interactions of the latter are neutralized by repulsive effects caused by the negative charge of the SP particles [21]. This repelling effect prevents flocculation and provides pathways for mixing water. Other sulfonated SP, such as melamine and naphthalene-based, share the same mechanism of lignosulfate SP.

Polycarboxylic-based SP are a recent generation of SP, developed in the 1990's. Their main mechanism is steric hindrance [15,22]. The molecular structure of these SP resembles a comb, with a main chain and long-range graft chains. The main chain attaches to cement particles and the anti-flocculation effect is caused by Pauli/Born repulsion of the graft chains: they repel themselves, hence the flocculation of cement particles that are attached to SP particles is hindered.

4. Research significance

The main cause for worse mechanical properties of RAC is the increase in the w/c ratio to offset the losses in workability caused by the higher roughness, elongated shape, and water absorption of RA when compared to NA. The durability performance of RAC is also affected by RA incorporation, partly due to the porosity of RA and partly due to the aforementioned higher w/c ratios of RAC compositions. SP are a natural solution to offset both these detrimental effects.

Experimental data on RA sourced from concrete strongly suggest that lignosulfate-based SP lose their effectiveness on the fresh-state properties of concrete with increasing RA incorporation ratios, whilst most studies with polycarboxylic SP reported, at most, reduced decreases in SP effectiveness [1,2,16,17]. An explanation for these contradictory findings has been put forward:

- Since RA produced from concrete are partly composed of attached mortar, some of the SP particles are adsorbed to the RA instead of to the cement particles. Lignosulfate-based SP act by electrostatic repulsion, which has a short anti-flocculation range, acting only in the vicinities of the surface of the adsorbent particles, hence this type of SP loses effectiveness when used in RAC [2];
- Steric hindrance has a broader influence range, with a main chain that is attached to one or more particles and long graft chains that prevent flocculation. Even if a main chain, or part of it, attaches to part of the specific surface of a RA, since the graft chains extend from it and repel other graft chains, it is possible that they contribute to the overall fluidity of the cementitious paste [20].

Two facts may affect the SP efficiency on the mechanical properties of RAC:

- The loss of SP effectiveness in workability mentioned in the last paragraph leads to higher w/c ratios to reach the target slump, and therefore lower concrete strength and higher porosity;
- Even if no losses of SP efficiency on workability are reported, as the mechanical strength increases, the mechanical properties of concrete start to depend more on the aggregate characteristics; therefore, poor RA quality may hinder the SP positive effects on the mechanical properties of RAC. This often does not have significant influence when the RA are sourced from concrete, but when RA are sourced from CDW, their worse mechanical properties increase this effect.

This experiment investigates the effect of a polycarboxylic-SP on various RAC compositions made with RA sourced from several CDW processing facilities. The goals are to:

- Evaluate the SP efficiency of several RAC compositions by comparing mechanical properties of different compositions with varying RA incorporation ratios with and without SP incorporation;
- Assess whether different RA compositions affect the efficiency of SP. In another study of this experimental campaign, the physical, mineralogical and chemical properties of each RA source were studied [23] and will be referred in the analysis of results;
- Benchmark the SP efficiency reported on experiments with RCAC with the SP efficiency when CDW RA are used. The results on RCAC may overestimate the SP potential on CDW RAC.

Because of the increased popularity of polycarboxylic SP and since it has been consistently reported that polycarboxylic SP are more efficient on RAC mixes than lignosulfate-based SP, this investigation concerns the use of polycarboxylic-based SP only. The SP incorporation was fixed as 1.0% of cement (by weight), a common value. The water part of the SP was included in the SP weight and neglected in the definition of the w/c ratios.

5. Methodology

The assessment of the effect of RA incorporation on RAC properties, including SP efficiency, was made by comparing the mechanical properties (compressive strength, Young's modulus and splitting tensile strength) of several RAC mixes with and without SP with analogue NAC compositions. Various ratios of RA incorporation were tested, trends were reported, and the results were benchmarked with studies on RCAC made with the same commercial polycarboxylic-SP of our study. The experimental results were justified based on physical considerations and knowledge concerning concrete behaviour and RA specificities.

The focus of this paper is the analysis of experimental data. However, since this work was part of an experimental programme, findings of other work within its scope are briefly summarised whenever relevant. Studies on the mechanical and durability properties of RAC produced from the same CDW but without SP incorporation are reported in [13,24] and the microstructure and composition of those RAC can be found in [23].

The slump class of all concrete compositions was fixed as within the S3 slump class of EN206 [25], ensuring that we were comparing concrete with the same application range.

6. Experimental campaign

6.1. Materials

The NA were siliceous river sand and natural limestone, and the cement followed EN197's [26] CEM I 42.5 R requirements. Tap water was used. The polycarboxylic-SP is an aqueous solution with density of 1.07 ± 0.02 kg/liter, pH of 5.0 ± 1.0, content of chloride ions below 0.1%, and solid content of 32% ± 2.0%.

The RA were sourced from four different CDW plants chosen based on their geographical location. Two sources (Ambilei and Vimajas) provided FRA and two others (Retria and Valnor) provided CRA. RA from different sources were not mixed in the same composition. Table 1 summarizes the RA production processes of each plant. The RA from each CDW facility were collected once. The variability of the composition and properties of RA sourced from the same plant over time was not analyzed.

The CDW plants were chosen from different regions since the composition of CDW and resulting RA are fairly variable amongst different sources [6]. In three of the production schemes of the plants, the smaller fraction is rejected. This is because this fraction is typically composed of soil and other undesirable materials. Notwithstanding the rejection of the smaller particles during the production of the RA, the commercialized products have them, since storage and transport leads to the desegregation of bigger particles.

Table 1
RA production process of each CDW facility.

Plant	Region	RA production
Ambilei	Leiria	Manual screening of hazardous waste and preliminary separation of concrete from other CDW; hammer mill crushing (maximum diameter of 50 mm), magnetic separation of metals.
Retria	Porto	Separation in three fraction by sieving (0–40 mm; 40–150 mm; above 150 mm); rejection of the smaller fraction; manual removal of undesired materials of the other two fractions; crushing to desired maximum size.
Valnor	Portalegre	Manual removal of undesired materials; crushing to a maximum diameter of 50 mm; magnetic removal of metals; crushing and separation in three fractions: 0–10 mm, 10–50 mm and 50–100 mm. Rejection of the smaller fraction and commercialization of the other two fractions.
Vimajas	Lisboa	Manual separation of metals; removal of fines (below 45 mm) by sieving; impact crushing (maximum diameter 38 mm) and magnetic separation of remaining metals; sieving and separation of aggregate in fractions below and above 8 mm.

Table 2
RA composition (visual inspection, by weight).

Composition (%)	FRA Ambilei	FRA Vimajas	CRA Valnor	CRA Retria
Concrete, mortar and stone	83.7	75.2	70.8	69.1
Clay materials	0.9	11.6	28.6	28.6
Glass	15.4	1.0	0.5	2.1
Bituminous materials	0.0	10.5	0.0	0.0
Others	0.0	1.7	0.1	0.2
Total	100.0	100.0	100.0	100.0

Table 3
Density and water absorption of the RA.

	FRA Ambilei	FRA Vimajas	CRA Valnor	CRA Retria
ρ_a (kg/dm^3)	2906.3	2613.7	2546.6	2608.2
ρ_{rd} (kg/dm^3)	2112.0	2069.7	2090.5	2137.2
ρ_{ssd} (kg/dm^3)	2385.3	2277.9	2269.6	2317.8
24-h water absorption (%)	12.9	10.1	8.6	8.4
Shape index	–	–	23.9	23.6

The composition of the RA was assessed following EN 933-11 [27]: a visual separation of each material was followed by weighing. Table 2 reports these results. All types of RA are mostly composed of concrete, mortar or stone. The CRA have significant amounts of mortar/clay materials and the FRA from Ambilei have a non-negligible glass content.

These results are in agreement with [6], where concrete and related materials are the main constituents of RA from CDW. Considerable dependence of the composition on the source is observed.

FRA have higher 24-h water absorptions than CRA as shown in Table 3. The shape index of the three particle size ranges of the coarse NA was in the range of 14.8–17.8, whilst the shape index of the RCA was above 23.

Table 4
NAC composition with no superplasticizer (m^3/m^3).

Cement			0.115
Fine aggregates	Sieve sizes (mm)	0.063–0.125	0.017
		0.125–0.25	0.044
		0.25–0.5	0.050
		0.5–1	0.058
		1–2	0.066
Coarse aggregates		2–4	0.076
		4–5.6	0.041
		5.6–8	0.047
		8–11.2	0.047
		11.2–16	0.120
		16–22.4	0.122
Water			0.184
Voids			0.015
Total			1.0

6.2. Mix design

The specification [25] of the NAC concrete with no superplasticizer that served as a reference for the experimental campaign was: strength class C30/37, consistency class S3 (slump of 125 ± 15 mm), and exposure class XC3. No strength criterion was imposed for the superplasticizer concrete compositions.

Since concrete mixing lasted 10 min, the 10 min water absorption of the RA – [28] was considered when designing the mixes in order to add compensation water. Distinction between the apparent water content (total water mixed) and the effective water content (free water during mixing) was made and the effective w/c ratio was used for concrete comparisons. The water content of the RA at the time of mixing was estimated the day before each batch by weighing and oven-drying a portion of the aggregates and subtracted from the 10 min water absorption capacity. All aggregates were stored in sealed containers and the aggregates were selected for this test after they were graded.

The mixing process was done by an initial step were RA and 2/3 of the total water, including the compensation water were inserted; after four minutes the NA were added; after two more minutes the cement, the remaining mixing water and the SP were introduced and the mixing lasted four more minutes. The concrete batches were made by weighing. A 75 liter capacity mixer was used, all specimens were produced and vibrated in plastic molds, and cured in a wet chamber under standardized conditions. The cement content was fixed at 350 kg/m^3. All compositions with SP had an SP content of 3.5 kg/m^3.

The only processing of the RA was sieving in order to ensure the same aggregate grading of NA (Table 4), since a comparison between compositions with the same grading was intended. Moreover, it is expected that future production processes lead to RA with similar grading to those of NA. Table 4 shows the composition of the NAC composition with no superplasticizer. The incorporation of RA was made by volume replacement of NA. As shown in Tables 5–6, in some cases RA incorporation caused increases in effective water content and in all cases SP incorporation decreases in water content (thus increases in aggregate volume).

6.3. W/c ratio and workability

Table 5 shows the effective w/c ratios and slumps of all concrete compositions with no superplasticizer. Increases in effective w/c ratios with increasing incorporation ratios are reported for RAC produced with Valnor CRA and RAC produced with Vimajas FRA. Table 6 shows the effective w/c ratios of the concrete compositions with superplasticizer.

By comparing the results of Tables 5 and 6, a decreased influence of SP incorporation on the workability of concrete made with Retria CRA and Vimajas FRA is observed: increasing RA incorporation ratios corresponded to less pronounced SP-related reductions of the effective w/c ratio. These concrete families were also the ones whose effective w/c ratio had to be increased to ensure workability in the concrete batches with no superplasticizer. When the effective w/c ratios of the other concrete families are analyzed, the same reductions due to SP are reported irrespective of RA incorporation ratio. Analysing these findings and the RA properties, the following reasoning is made:

Table 5
Effective w/c ratios of the compositions with no superplasticizer.

	RA replacement ratio (%)														
	0			10			25			50			100		
	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*
CRA Valnor	108	0.53	184.0	105	0.53	184.0	140	0.53	184.0	106	0.53	184.0	110	0.53	184.0
CRA Retria				125	0.53	186.0	116	0.54	188.5	100	0.54	188.5	120	0.55	192.5
FRA Vimajas				100	0.54	188.5	120	0.56	196.0	100	0.59	206.5	133	0.64	224.0
FRA Ambilei				134	0.53	185.5	150	0.53	185.5	150	0.53	185.5	140	0.53	185.5

* (kg/m^3 of concrete).

Table 6
Effective w/c ratios of the compositions with superplasticizer.

	RA replacement ratio (%)														
	0			10			25			50			100		
	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*	Slump (mm)	Eff. w/c	Eff. water*
CRA Valnor	120	0.42	147.0	115	0.42	147.0	120	0.42	147.0	125	0.42	147.0	130	0.42	147.0
CRA Retria				120	0.43	150.5	125	0.45	157.5	100	0.47	164.0	130	0.48	168.5
FRA Vimajas				115	0.43	150.5	110	0.44	155.5	100	0.51	179.0	105	0.53	185.5
FRA Ambilei				100	0.42	147.0	110	0.42	147.0	125	0.42	147.5	140	0.42	147.5

* (kg/m^3 of concrete).

- It seems that the absorption of water with SP is not responsible for the decrease in SP effectiveness, since Retria CRA and Vimajas FRA had lower water absorptions than their respective CRA and FRA counterparts;
- When it comes to CRA comparison, Retria and Valnor CRA had very similar shape indices, hence losses in workability caused by oriented laminated aggregates does not seem to be a cause for losses in SP efficiency on workability;
- Vimajas FRA were composed of 10% less "Concrete, mortar and stone", 10% more "Mortar and clay" and 15% less "Glass" materials than Vimajas FRA. Valor and Retria CRA had very similar compositions but microscopy analyses [23] reported than the "Concrete, mortar and stone" category of Valnor CRA was mostly composed of mortar, whilst Retria CRA had higher stone contents. These compositions strongly suggest that Vimajas FRA and Retria CRA were composed of increasingly rougher materials than Ambilei FRA and Valnor CRA, hence polycarboxylic SP seem to lose efficiency with increasing aggregate specific surface;
- The trends reported on SP efficiency were very consistent for all incorporation ratios of the four RA sources.

In relative terms, the w/c reduction varied between 14% and 21%. Cartuxo et al. [29] studies FRAC with FRA sourced from concrete and reported polycarboxylic-SP efficiencies of roughly 25% and independent of RA incorporation and lignosulfate-SP efficiencies in the range of 16% (NAC) and 9% (FRAC with total FRA incorporation). Similar findings were reported by Pereira et al. [2] – w/c reductions between 11% (total FRA incorporation) and 18% (NAC) for lignosulfate-based SP and analogue w/c reductions of 24% and 31% when polycarboxylic-based SP were used. Both these studies were made with FRA sourced from concrete. Matias et al. [1] reported losses of lignosulfate-SP efficiency when coarse recycled concrete aggregates (CRCA) were used, in comparison with coarse NA. The Garcia-González et al. [30] study on CRA concrete was characterized by fixed effective w/c ratios independent of CRCA incorporation ratios and type of SP used (lignosulfate or polycarboxylic-based) but with losses of slump with increasing CRA incorporations.

Despite our study suggesting that RA sourced from CDW causes decreases in polycarboxylic-SP efficiency on workability when compared to NA and RA sourced from concrete, workability gains were always satisfactory.

The results reported concern concrete compositions determined after achieving the target slump values in trial batches. Only one slump value was taken from each trial batch and only a single slump value was taken from each of the batches of the experimental campaign presented here. The slump values reported here concern the latter.

6.4. Mechanical properties

Compressive strength tests were made on 15 cm standard cube specimens according to EN-12390-3 [31]. 3 cubes were tested at 7 days, 5 at 28 days, and 3 at 56 days. Splitting tensile strength followed EN-12390-6 [32] and three cylinders (diameter of 150 mm; height of 300 mm) were tested at 28 days. Three cylinders (diameter of 150 mm; height of 300 mm) were tested for Young's modulus as specified in LNEC-E397 [33] at 28 days. Due to unforeseen circumstances, the 56-day compressive strength test of the Retria CRA with total RA incorporation was assessed by testing a single specimen.

6.4.1. Compressive strength

Table 7 reports the results on the 28-day compressive strength of the concrete compositions without and with superplasticizer. RA incorporation decreased this property strongly and decrease in compressive strength depended on the RA: for total RA replacement ratios, the strength loss varied between 26.2% (Valnor CRA) and 52.6% (Vimajas FRA). FRA incorporation was more detrimental than CRA. This is justified by the higher content of porous and rough materials of Vimajas FRA, which led to higher effective w/c ratios and to the significant presence of glass on Ambilei FRA, leading to weaker ITZs [23].

Fig. 1 reports the effect of the RA incorporation ratio on the SP efficiency. In this figure and henceforth, SP efficiency on a property is to be understood as the relative difference between a concrete

Table 7
28-day compressive strength ($f_{cm,28}$) – MPa.

		RA incorporation ratio (%)									
		0		10		25		50		100	
		$f_{cm,28}$	St Dev	$f_{cm,28}$	St Dev	$f_{cm,28}$	St Dev	$f_{cm,28}$	St Dev	$f_{cm,28}$	St Dev
No SP	Valnor CRA	53.9	1.8	54.1	2.2	48.9	1.1	46.2	2.7	35.3	1.4
	Retria CRA			48.3	2.3	44.6	0.8	44.9	1.4	40.1	1.1
	Vimajas FRA			49.2	1.1	45.6	1.5	37.6	1.3	30.2	0.5
	Ambilei FRA			51.6	1.0	47.3	1.1	46.8	1.2	40.1	1.1
With SP	Valnor CRA	75.4	1.9	71.0	0.2	69.3	0.8	65.6	2.5	55.6	1.9
	Retria CRA			64.5	0.3	62.6	1.4	62.1	3.8	62.4	0.6
	Vimajas FRA			72.5	1.9	55.5	2.4	44.8	0.4	35.7	0.2
	Ambilei FRA			81.0	1.5	67.2	0.4	63.4	1.5	61.8	0.0

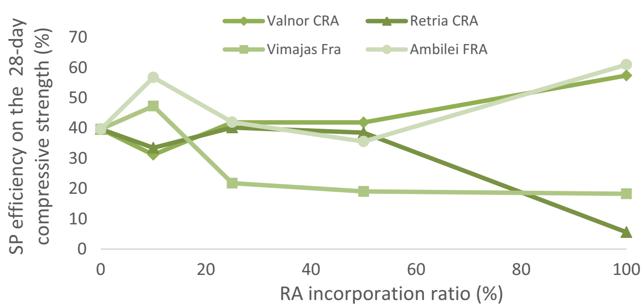

Fig. 1. SP efficiency on the 28-day compressive strength.

property of a SP composition and its analogue concrete composition with no superplasticizer.

RA source had a definite influence in the efficiency of the SP on the compressive strength. When Pereira et al. [2] tested lignosulfate-SP, SP efficiencies in the range of 35% (NAC) to 17% (total FRCA incorporation) were reported. Polycarboxylic-based SP lead to efficiencies in the range of 63–65% with no clear RA incorporation effect. The trends of Cartuxo et al. [29] were somewhat in between our results and the findings of Pereira et al. [2]: lignosulfate-SP efficiencies in the range of 8% (total FRCA incorporation) to 35% (NAC); polycarboxylic-SP: efficiencies in the range of 26% (total FRCA incorporation) to 63% (NAC). Garcia-González [30] reported that RA decreased lignosulfate SP efficiency on CRCAC (30% for NAC and a linear decrease to 24% for total CRCA replacement) and on polycarboxylic SP (45% for NAC and 33% for total CRCA replacement). Despite all compositions benefitting from SP incorporations, the SP efficiency for Vimajas FRAC and Retria CRAC was well below all results benchmarked.

These results are in agreement with the findings on the SP effect on workability. The sharp decrease in efficiency for some incorporation ratios (50% for Vimajas FRA and 100% for Retria CRA) suggests that RA strength may have been a limiting factor as well. This hypothesis is further reinforced by analysing the strength development over time of the Retria and Vimajas compositions with and without superplasticizer (Fig. 2). The reduced value of the 56-day compressive strength of the 100% Retria CRA composition was due to a single specimen having been tested.

It is well known that SP compositions usually develop strength at very early stages and then stall their development. However, by analysing the strength development over time of the compositions with no superplasticizer, it is also seen that as RA incorporations increase, strength development over time also tends to decrease. For Retria and Vimajas RA, a marginal strength development between 28 and 56 days for incorporation ratios over 25% is reported. This is probably caused by two different factors: the

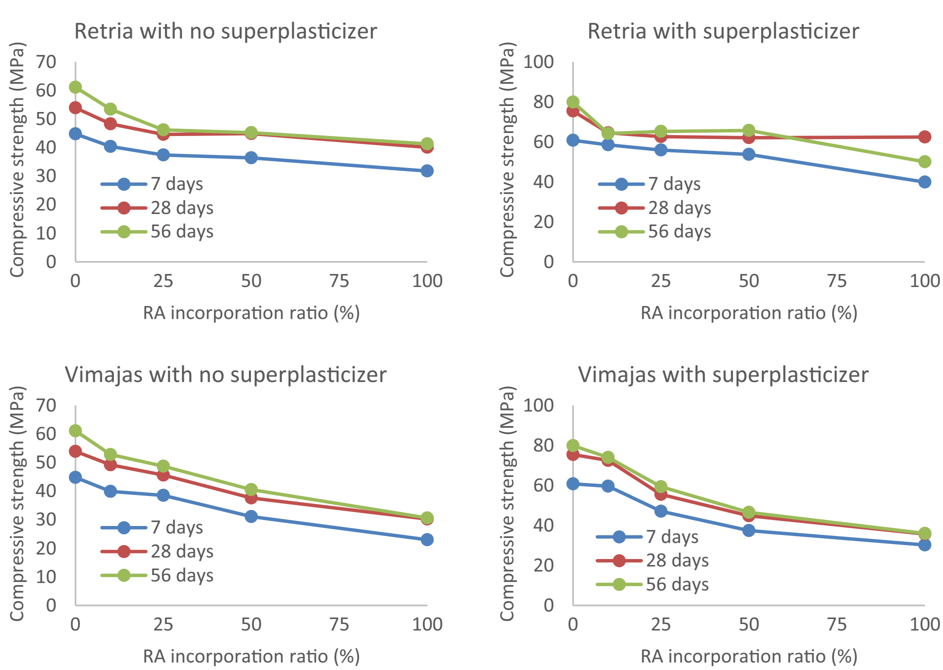

Fig. 2. Compressive strength development over time of the Retria CRAC and Vimajas FRAC.

Table 8
28-day splitting tensile strength ($f_{ct,spl}$) – MPa.

		RA incorporation ratio (%)									
		0		10		25		50		100	
		$f_{ctspl,28}$	St Dev	$f_{ctspl,28}$	St Dev	$f_{ctspl,28}$	St Dev	$f_{ctspl,28}$	St Dev	$f_{ctspl,28}$	St Dev
No SP	Valnor CRA	4.0	–	3.7	0.3	3.0	0.1	3.2	–	3.1	0.1
	Retria CRA			4.0	0.4	3.4	0.1	3.2	0.3	2.7	0.2
	Vimajas FRA			3.7	0.1	3.2	0.2	3.0	0.2	2.6	–
	Ambilei FRA			3.4	0.1	3.5	0.2	3.4	0.3	3.2	0.1
With SP	Valnor CRA	4.8	0.3	4.8	0.7	4.3	0.1	4.2	–	3.8	0.1
	Retria CRA			4.3	0.3	4.3	–	4.3	0.1	3.7	0.1
	Vimajas FRA			5.0	0.1	4.2	0.4	3.4	0.0	2.9	0.2
	Ambilei FRA			5.0	0.1	4.5	0.2	3.9	0.1	3.6	0.2

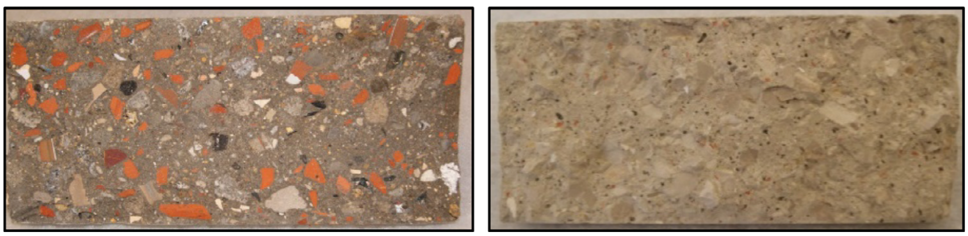

Fig. 3. Failure surface of splitting tensile strength tests. Left: Retria CRA; right: Vimajas FRA.

internal curing effect of the RA, that contribute to early hydration, and the reduced mechanical strength of RA in comparison with NA. As hydration develops, the cement paste increases its strength and RA strength starts limiting concrete performance with a trend towards fracture surfaces that break the RA. This effect is more pronounced with increasing RA ratios since concrete strength is limited by fracture surfaces and as RA ratios increase, the number of RA that are involved in the failure mechanism also increases. For SP mixes, this effects is more noticeable and limits SP efficiency, since the cementitious paste is stronger than the RA, hence weak RA have higher preponderance in concrete strength. From Fig. 2, it is also concluded that RA incorporation caused a linear decrease in compressive strength for compositions with and without superplasticizer.

6.4.2. Splitting tensile strength

The splitting tensile strength test results are summarised in Table 8. The same trends of the compressive strength are reported: RA incorporation decreases the splitting tensile strength linearly. The maximum decrease of the splitting tensile strength was of 34.6% (concrete without SP) and 39.0% (concrete with SP) when 100% of Vimajas FRA were used. The other RA source with the highest RA effect was Retria CRA – relative differences of 32% (concrete without SP) and 23% (concrete with SP) to the NAC compositions were found. These results clearly show that RA composition influenced the splitting tensile strength of the concrete. The same findings were reported for the compressive strength, and the tensile strength is characterised by a brisker type of failure, more dependent on aggregate strength, and with less dependence on the

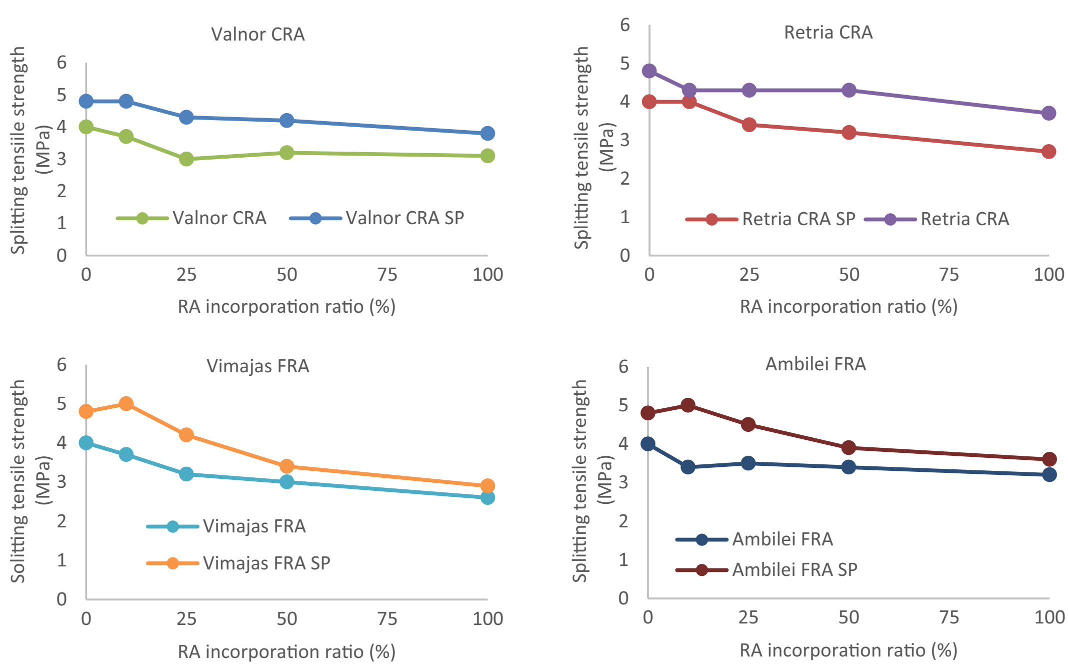

Fig. 4. 28-day splitting tensile strength.

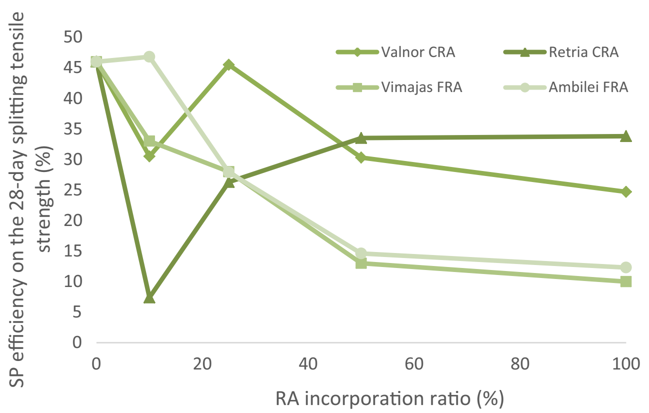

Fig. 5. SP efficiency on the 28-day splitting tensile strength.

cementitious matrix than the compressive strength. Fig. 3 backs this claim by showing that the failure surface of the Retria CRAC with no superplasticizer involves CRA fracture. In FRAC and NAC compositions, no coarse NA fractures were observed. In the SP concrete compositions, trans-aggregate fractures were common.

The comparison of analogue concrete compositions with and without superplasticizer is shown in Fig. 4. No significant absolute differences in the SP efficiency of the splitting tensile strength of CRAC compositions is reported. Relative differences were also scattered, with no perceived RA incorporation trend when coarse CRA were incorporated (Fig. 5). However the SP had a reduced effect in FRAC compositions when the FRA incorporation ratio was of 50% or above, as also shown in Fig. 5. This significant decrease in SP efficiency in FRAC compositions is probably caused by the considerable clay and glass contents of the FRA, which contributed to a worse mortar phase of the FRAC, a fundamental property for tensile strength [34], limiting potential gains in strength caused by higher compactness due to SP incorporation.

Pereira et al. [16] reported lignosulfate-SP efficiencies in the range of 35% (NAC) to 17% (FRAC with total incorporation), with clear trends towards RA incorporation decreasing the SP efficiency on the splitting tensile strength. However, when polycarboxylic-SP were used, the efficiency was between 62% and 69% with no clear FRA incorporation effect. From our study, it seems that RA sourced from worse quality materials (as CDW are) limit polycarboxylic-SP's efficiency. This claim is in agreement with the meta-analysis on the tensile strength vs. compressive strength relationships for RAC presented in [35]. This study concluded that the incorporation of RA sourced from concrete has clearly less detrimental effects than when RA sourced from CDW are used, due to higher porosity and reduced strength of the latter.

6.4.3. Young's modulus

Young's modulus decreased linearly with RA incorporation (Table 9 and Fig. 6). Of all properties, Young's modulus was the property that benefitted the least from SP incorporation. This is due to the considerable dependence of this property on aggregate

Table 9
28-day Young's modulus (E_{cm}) - GPa.

		RA incorporation ratio (%)									
		0		10		25		50		100	
		$E_{cm,28}$	St Dev	$E_{cm,28}$	St Dev	$E_{cm,28}$	St Dev	$E_{cm,28}$	St Dev	$E_{cm,28}$	St Dev
No SP	Valnor CRA	40.5	0.2	39.1	0.4	34.6	0	29.2	0.9	21.1	0.5
	Retria CRA			37.7	0	35.5	0.4	31.5	0.2	**26.3**	0
	Vimajas FRA			38.6	0.9	34.9	0.5	31.9	0.2	23.3	0.6
	Ambilei FRA			40.3	0.3	38	0.2	37.4	0.4	**32.5**	0.6
With SP	Valnor CRA	44.6	0.5	46.5	1	40.7	1.1	39	0.1	29.2	0.4
	Retria CRA			42	0.3	40.9	0.4	37.2	0	28.3	0.8
	Vimajas FRA			43.8	0.1	38.4	0.4	32.5	0.1	26.8	0.3
	Ambilei FRA			49.1	0.1	47.6	0.1	42.9	0.6	38.1	0.2

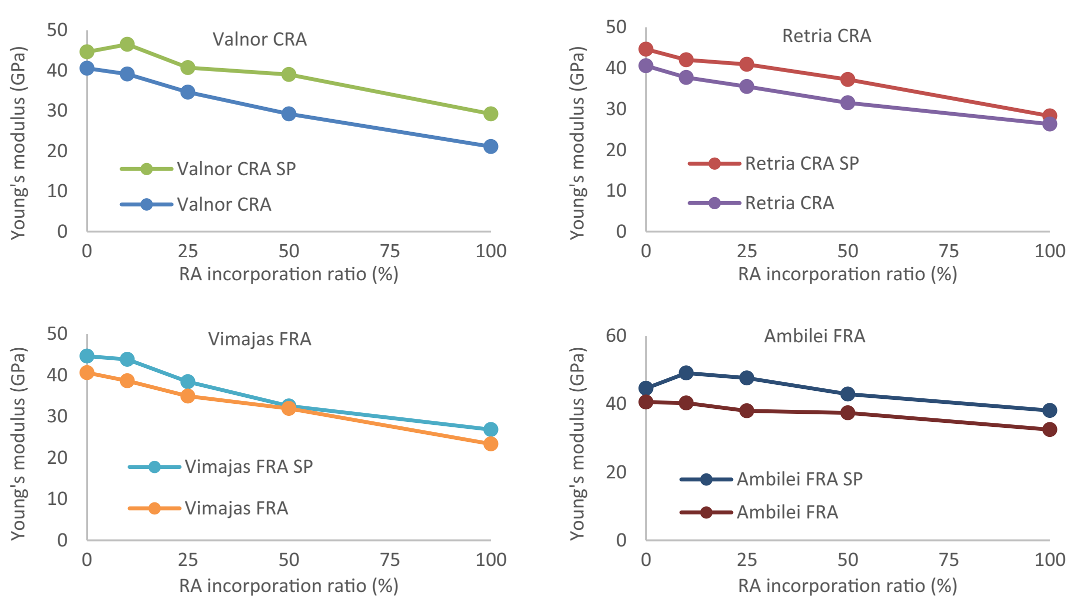

Fig. 6. 28-day Youngs' modulus.

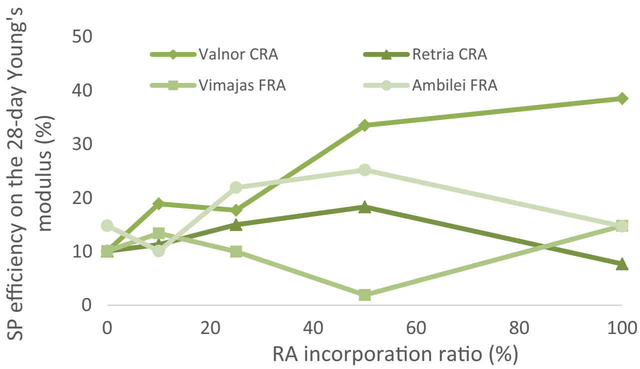

Fig. 7. SP efficiency on the 28-day Young's modulus.

stiffness. CRA incorporation was more detrimental than FRA incorporation. This was expected since coarse aggregate stiffness has a key role in restricting concrete strains.

RA composition greatly influenced the Young's modulus of each concrete family. Ambilei FRA had a relatively reduced effect on this property: not only the composition of this aggregate favoured similar w/c ratios in relation to the reference concrete, but also its glass content contributed to mitigate the lower stiffness of the other FRA that compose Ambilei FRA. Valnor CRA incorporation had the highest effect on Young's modulus because of its lower content of stiffer materials: the "Concrete, mortar and stone" content of these RA was mostly composed of mortar and concrete materials instead of stone [23].

Concerning SP efficiency (Fig. 7), varying trends were reported:

- The SP increased its efficiency with increasing Valnor CRA ratios. This is probably caused by the lower stiffness of these CRA, implying that increases in the stiffness of the cement paste have a considerable influence for the CRAC;
- The results of the other three concrete families are somewhat similar: SP efficiency between 9% and 20% for all RA incorporation ratios, except when 50% RA were incorporated. No physical reason justifies the peaks for this incorporation ratio, which were probably caused by test scatter.

Pereira et al. [16] reported SP efficiencies between 8% (RFAC) and 20% (NAC) when lignosulfate-based SP were used. A clear trend towards FRA incorporation decreasing SP efficiency was not reported, despite the results suggesting it. When polycarboxylic-SP were used the SP efficiency was in the range of 24–33% with no influence of FRA incorporation.

Tables 10 and 11 summarize the effect of the polycarboxylic-SP on the 28-day mechanical properties in absolute and relative terms.

7. Conclusions

There is evidence that the beneficial effects of sulfonated superplasticizers on concrete properties is reduced when recycled concrete aggregates are used. Conversely, when polycarboxylic-based superplasticizers and recycled concrete aggregates are used, there is no consensus on such reduction. This investigation assessed whether when recycled aggregates are sourced from construction and demolition waste plants with limited screening, the beneficial effects of polycarboxylic superplasticizers on the mechanical properties of concrete decrease. Four different recycled aggregates sources were tested and the influence of the superplasticizer on the workability and mechanical properties of concrete compositions was analyzed considering the composition of each aggregate source.

All recycled aggregates sources required the addition of compensation water to account for their water absorption and the recycled aggregates sourced from Retria and Vimajas needed increases in their effective w/c ratios as their recycled aggregates incorporation ratios increased, both in compositions with and without superplasticizer. This was caused by the rougher surface textures and subsequent higher specific surfaces of these aggregates.

All recycled aggregates sources caused linear decreases in the mechanical properties of the concrete compositions. The incorporation of polycarboxylic-based superplasticizers was beneficial in all cases, but the extent of its effect was dependent on the aggregate composition and on the property tested:

- The 28-day compressive strength decreased with recycled aggregate incorporation and the composition of the recycled aggregates defined the extent of this decrease. Higher Retria and Vimajas recycled aggregate incorporation ratios resulted in lower superplasticizer efficiency. This was most probably caused by the weak aggregate strength of clay aggregates

Table 10
Absolute difference between 28-day concrete properties, with and without superplasticizer.

Property	NAC	Valnor CRAC				Vimajas FRAC				Ambilei FRAC				Retria CRAC			
	RA incorporation ratio (%)																
	0	10	25	50	100	10	25	50	100	10	25	50	100	10	25	50	100
Compressive strength (MPa)	21.5	16.9	20.4	19.4	20.3	23.3	9.9	7.2	5.5	29.4	19.9	16.6	23.4	16.2	18.0	17.2	2.3
Splitting tensile strength (MPa)	0.8	1.1	1.3	1.0	0.7	1.3	1.0	0.4	0.3	1.6	1.0	0.5	0.4	0.3	0.9	1.1	1.0
Young's modulus (GPa)	4.1	7.4	6.1	9.8	8.1	5.2	3.5	0.6	3.5	8.8	9.6	5.5	5.6	4.3	5.4	5.7	2.0

Table 11
SP efficiency on 28-day concrete properties.

Property	NAC	Valnor CRAC				Vimajas FRAC				Ambilei FRAC				Retria CRAC			
	RA incorporation ratio (%)																
	0	10	25	50	100	10	25	50	100	10	25	50	100	10	25	50	100
Compressive strength (%)	40	31	42	42	57	47	22	19	18	57	42	36	61	34	40	39	6
Splitting tensile strength(%)	18	31	46	30	25	33	28	13	10	47	28	15	12	7	26	34	34
Young's modulus (%)	10	19	18	34	39	13	10	2	15	22	25	15	18	11	15	18	8

(Vimajas) and of porous materials in general (Retria, with bituminous and mortar materials). Recycled aggregate incorporation did not affect the SP efficiency when the other two recycled aggregate sources were used;
- The 28-day splitting tensile strength was considerably affected by recycled aggregate incorporation. Superplasticizer's efficiency was reduced when fine recycled aggregates were used. The gains caused by superplasticizer's incorporation in Vimajas concrete were probably limited by the clay content of its fine recycled aggregates. The weak interfacial transition zones of the glass materials of Ambilei fine recycled aggregates also limited the superplasticizer efficiency;
- Young's modulus was the property that benefitted the least from superplasticizer's incorporation. Coarse recycled aggregates incorporation was more detrimental than fine recycled aggregates incorporation and superplasticizer efficiency was dependent on coarse aggregate properties: the reduced stiffness of the Valnor recycled aggregates meant that the relative increases in the stiffness of the mortar paste had a noticeable effect on the Young's modulus as the recycled aggregates incorporation ratio increased, whilst for all other recycled aggregates the effect of the superplasticizer was independent on the recycled aggregate's incorporation ratios.

All results were benchmarked with tests on recycled aggregates concrete whose aggregates were sourced from concrete waste and with the incorporation of the same commercially available polycarboxylic superplasticizer. Analogue compositions made with a lignosulfate-based superplasticizer were also referred for comparison. While recycled concrete aggregate incorporation has reduced effects on the efficiency of polycarboxylic superplasticizers, when recycled aggregates sourced from construction and demolition waste are used, this may not be the case. Significant dependence on the aggregate composition was found.

The efficiency of polycarboxylic superplasticizers on concrete made with these aggregates was satisfactory and was not as affected as when lignosulfate-based superplasticizers are used in concrete with recycled aggregates sourced from concrete. This implies that lignosulfate-based superplasticizers may not be suitable to concrete with aggregates sourced from construction and demolition waste.

Future research in this area should follow, namely in what concerns the efficiency of superplasticizers on the durability and long-term behaviour of recycled aggregates concrete.

Acknowledgements

The authors gratefully acknowledge the support of the ICIST-CERIS Research Centre, of IST, University of Lisbon, FCT (Portuguese Foundation for Science and Technology), SECIL and Sika.

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