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Influence of water-reducing admixtures on the mechanical performance of recycled concrete

Auxi Barbudo [a], Jorge de Brito [b,*], Luís Evangelista [c], Miguel Bravo [b], Francisco Agrela [a]

[a] Area of Construction Engineering, University of Córdoba, Spain
[b] Instituto Superior Técnico (IST), Technical University of Lisbon, Lisbon, Portugal
[c] Lisbon's Polytechnic Engineering Institute (ISEL-IPL), Lisbon, Portugal

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A B S T R A C T

The use of recycled aggregates from construction and demolition waste in concrete is not new. One of the main problems found in this application is the aggregates' high water absorption and, therefore, low workability. Incorporating water-reducing admixtures (plasticizers) can reduce the amount of water required, improving the compactness of concrete. This research aims at determining the suitability of using two types of water-reducing admixtures to improve the characteristics of concrete made with recycled aggregates. Three series of concrete with various replacement ratios (0%, 20%, 50% and 100%) of natural aggregate by coarse recycled concrete aggregate were manufactured for this study and used without admixtures, with a traditional plasticizer and a high-performance plasticizer. The basic properties of the aggregates were considered, and the workability and density of fresh concrete and key mechanical properties of hardened concrete, such as compressive strength, tensile strength, elastic modulus and abrasion resistance, were studied. The results obtained were encouraging to use plasticizers in concrete with recycled aggregates.

1. Introduction

The economic viability of a construction and demolition waste (CDW) recycling plant has been demonstrated by Coelho and de Brito (2013). But research is also focused on the technical issues concerning the use of these materials to replace natural aggregates. So, there are many researches on the application of recycled aggregates from construction and demolition waste in the manufacture of concrete. Although, in theory, they worsen the mechanical behaviour (Khatib, 2005), the workability for the same water/cement (w/c) ratio (Agrela et al., 2011) and the durability (Evangelista and de Brito, 2010) of new concrete, some authors obtained equal or better performance due to the high quality of recycled aggregates (Medina et al., 2013), a careful selection of the replacement aggregate and/or treatment prior to batching (Richardson et al., 2011). Some authors recommend washing the aggregates to eliminate the finer fraction, which is the one with higher soluble sulphate content and greater water absorption (Rodrigues et al., 2013) and it is feasible to produce recycled concrete for structural purposes if a series of appropriate steps are taken like pre-soaking the recycled aggregate (Ferreira et al., 2011), adjusting the content of cement and curing conditions (Wattanasiriwech et al., 2009), or using cement with mineral admixtures (Kou et al., 2011). However, there are few studies on the effect of admixtures on this concrete, hence the importance of this research.

Regarding their definition, authors do not always agree on the differences between plasticizers and superplasticizers. Thus, Matias et al. (2013) told plasticizers and superplasticizers apart according to their origin and capacity as flowing inducers or reducers of mixing water. These authors also mentioned Malhotra (1989) who suggested distinguishing between admixtures by their water-reducing power. Meanwhile, Coutinho and Gonçalves (1997) suggested distinguishing them according to their origin: plasticizers are industrial by-products and superplasticizers are chemicals produced specifically for their intended purpose.

The current definitions and requirements of concrete admixtures are given in standard UNE-EN 934-2:2001 where plasticizer is defined as an admixture which is incorporated in the concrete mix at an amount less than 5% by cement weight. Without modifying the consistency it reduces the water content, or, without modifying

* Corresponding author. Tel.: +351 218419709.
E-mail addresses: abarbudo@uco.es (A. Barbudo), jb@civil.ist.utl.pt (J. de Brito), evangelista@dec.isel.ipl.pt (L. Evangelista), miguelnbravo@gmail.com (M. Bravo), fagrela@uco.es (F. Agrela).

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Table 1
Properties of the aggregates.

	Water absorption 24 h (%)	Density d_{ssd} (Mg/m^3)	Moisture (%)	Shape coefficient (%)	Dry density (Mg/m^3)	Los Angeles coefficient
	EN 1097-6		EN 1097-5	EN 933-4	EN 1097-3	EN 1097-2
FS	0.487	2.710	0.1	–	1.55	–
CS	0.993	2.553	0.1	–	1.56	–
FG	1.760	2.545	0.2	18	1.35	22.68
MG	1.546	2.789	0.1	17	1.51	27.25
CG	1.245	2.581	0.1	15	1.37	24.84
RCA	7.337	2.451	2.7	21	1.36	40.04

NOTE: Fine Sand (FS), Coarse Sand (CS), Fine gravel (FG), Medium Gravel (MG), Coarse Gravel (CG), Recycled Aggregate (RCA).

that, it increases the slump, or both effects are induced. Meanwhile, a superplasticizer is also a water-reducing admixture but one with high activity, i.e. it greatly reduces the water content or/and it considerably increases the slump. This standard further specifies requirements, which are explained in the section on materials.

Plasticizers do not simply improve workability; they also reduce the volume of voids in concrete and so provide better mechanical performance. This improvement is taken into account when using recycled aggregates in new concrete, since it offsets the need to add water which would be absorbed by them, to obtain the same workability.

Other authors have conducted complementary studies where plasticizers are used, as Turu'allo (2007b) which studied the optimum percentage of admixture to optimize the compressive strength. Aruntas et al. (2008) also used plasticizer in recycled concrete but they did not use recycled aggregates from CDW but steel fibres. Other researchers, such as Pereira et al. (2012b) used regular plasticizers but with the incorporation of the fine fraction of recycled aggregates (0–4 mm) instead of coarse recycled aggregates, which are used in this study.

Thus, this work focuses on the effect of using different types of water-reducing admixtures in concrete made with coarse recycled aggregates produced from crushed concrete. This investigation seeks to demonstrate that the worse workability of concrete manufactured with concrete recycled aggregate can be compensated by the addition of plasticizers, even reaching the mechanical properties of the reference concrete.

In this research, the use of plasticizer admixtures is proposed to reduce the amount of water and achieve, thereby, better workability and better mechanical properties of concrete with recycled aggregates.

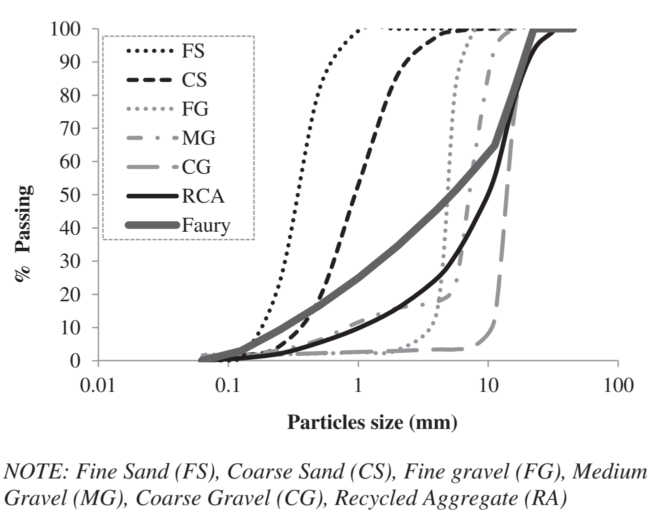


Fig. 1. Particle size distribution.

2. Materials and methods

2.1. Materials

In this research, five natural aggregates and one coarse recycled aggregate from crushed concrete blocks were used to manufacture several concrete mixes, which are described next in more detail. All natural aggregates were extracted from a stone quarry in Zambujal (Sesimbra), except the coarse sand that came from a plant in Seixal (Setúbal), and whose properties are shown in Table 1 and Fig. 1:

- Fine sand (FS): Washed sand, grain size between 0 and 2 mm, and with particles of quartz, quartzite and feldspar;
- Coarse sand (CS): Washed coarse sand of quartz and feldspar, grain size 0–4 mm;
- Fine gravel (FG): Aggregate of grain size 2/6 mm, from compact limestone;
- Medium gravel (MG): Medium size limestone gravel, between 6 mm and 12 mm;
- Coarse gravel (CG): gravel with particles between 12 mm and 20 mm;
- Recycled concrete coarse aggregate (RA): aggregate from crushing concrete approximately 30 days old of 4–22.4 mm size. This was made by Unibetão S.A., a ready mixed concrete company. Its composition is described in Table 2, and the designation is: X0 (P) CL0.40 D_{max} 22 S2 (according to EN 206-1: C30/37). Hardened concrete blocks were crushed in a jaw crusher to obtain the concrete aggregate.

Therefore, this material does not come directly from a CDW treatment plant, but this is intentionally made and crushed to guarantee the homogeneity of the material and know the characteristics of the source concrete from which it comes.

Moreover, two admixtures were used in the manufacture of the concrete: a plasticizer (P) and a superplasticizer of high activity (SP), whose technical data are shown in Table 3. These admixtures must comply with the specific requirements stated in the standard UNE-EN 934-2:2001, summarized in Table 4. These were incorporated in the mixes at 1% by cement weight, and their purpose was to reduce the amount of water added, but maintaining the slump.

2.2. Concrete mix proportions

For the same workability, three families of concrete were designed: without admixture, with a normal plasticizer (P), and with a superplasticizer (SP). Within each of them, four different

Table 2
Crushed concrete composition.

Aggregates (kg/m^3)	Cement (kg/m^3)	Type of cement	w/c	Mean strength (MPa)	
				f_{cm} (7 days)	f_{cm} (28 days)
1931	256	CEM IV/B	0.57	30.4	41.4

Table 3
Properties of the water-reducing admixtures.

	Type of admixture	
	Plasticizer (P)	Superplasticizer (SP)
Chemical base	Blend of organic polymers and admixtures	Combination of modified polycarboxylates in aqueous solution
Bulk density	1.22 ± 0.02 kg/dm^3 (23 ± 2 °C)	1.07 ± 0.02 kg/dm^3 (23 ± 2 °C)
pH (23 ± 2 °C)	9.0 ± 1.0	5.0 ± 1.0
Solids content	43.0 ± 2.0%	32.0 ± 2.0%
Chloride content	≤0.1%	≤0.1%

levels of replacement of natural coarse aggregate by their recycled counterparts were studied, as shown in Table 5.

The composition of the reference concrete was determined by Faury's method, using each material according to the reference curve given by this method (Fig. 1). For this, each material was separated into different size fractions and incorporated in the mixes in the proportions indicated by the method, in order to obtain the maximum compacity. The design of the reference concrete mixes took into account the values shown in Table 6, resulting in the final proportions listed in Table 7.

Starting from these reference concrete mixes, natural coarse aggregates were replaced by different percentages by volume of RCA (Table 5). To do this, 4.18% (by weight) of water absorption of recycled aggregate at 10 min was assumed, since this is the estimated mixing time.

The mixes with P and SP incorporated them at 1% by cement weight, less than the maximum recommended by Turu'allo (2007a), and less than given in the definition of admixture in *UNE-EN 934-2:2001.*

2.3. Manufacture of concrete

The mixes were made as follows: first, the mixer was wetted and then drained properly. Then the RCA was introduced into the mixer together with 3/4 of the total water, equal to the mixing water plus the RCA extra absorption water minus the initial water content of RA. The mix was rotated for 10 min. Each of the aggregates was incorporated as rotation continued, from the largest to the smallest particle size. The two types of sand and cement were introduced, as the rotating continued. Rotation proceeded for approximately 1 min for proper mixing (the mixer was tilted for this purpose, when necessary). The admixture (P or SP), previously diluted in ¼ of the mixing water (the water of Table 7 plus 4.18% by weight due to the extra water absorption of recycled aggregates), was then added. Rotation continued for another 5 min, after which it the mixture stood for 2 min. It was rotated again for 1 min (to give enough time for the water-reducing property of the admixture to act). Only then were the properties of the fresh concrete determined and specimens manufactured.

3. Experimental TESTS and results

The various methods used and the results obtained are shown below.

Table 5
Definition of the concrete mixes.

	Without plasticizer	Plasticizer	Superplasticizer
0% replacement	C0	C0-P	C0-SP
20% replacement	C20	C20-P	C20-SP
50% replacement	C50	C50-P	C50-SP
100% replacement	C100	C100-P	C100-SP

Table 6
Reference concretes' characteristics.

Strength	Environmental exposure	Consistency	Binder	Volume of the batch
C25/30	XC3	S3	CEM I/A-L	75 l

3.1. Tests on fresh concrete

The following fresh concrete properties were determined.

3.1.1. Water reduction and effective water-cement (w/c) ratio

The w/c ratio has an important influence on the quality of concrete. A lower w/c ratio leads to higher strength and durability, but may make the mix harder to cast, but these difficulties can be resolved by using water-reducing admixtures. Previous experimental trials were performed to set the effective w/c ratio corresponding to a 125 mm ± 20 mm of slump, in order to get the values shown in Table 8.

The use of admixtures decreases the amount of water needed in the mix, and therefore lowers the w/c ratio, as expected. So, the effective w/c ratio decreased by approximately 17% with the addition of P, and by 26% with the addition of SP, compared with the reference concrete, in both cases more than the requirements of the *EN 934-2:2001*, summarized in Table 4.

Since the extra water required by the incorporation of RCA is not taken into account in the effective w/c ratios, the various replacement ratios did not change this parameter.

3.1.2. Workability

The consistency of fresh concrete was measured by the Abrams slump test (EN 12350-2), leading to the values shown in Table 8.

In this research, the water that would be absorbed by the RCA after 10 min immersion was added to the mix, in order to keep the workability constant (slump 125 mm ± 20 mm) when increasing the replacement ratio of natural aggregates by RCA. In this way, each family of concrete had the same effective w/c ratio, as discussed above and very similar consistency.

3.1.3. Density

The method used in this test is set out in *EN 12350-6*. The results introduced in Table 8 showed very similar values, because the replacement of NA was made by RCA in volume, not weight. Furthermore, the incorporation of admixtures, and the subsequent decrease of water do not appear to affect the average values of density.

Table 4
Specific requirements for water-reducing admixtures (same slump) EN 934-2:2001.

	Plasticizer		Superplasticizer	
Water reduction	≥5% compared with reference concrete		≥12% compared with reference concrete	
Compressive strength	7 days	≥110% of the strength of reference concrete	1 day	≥140% of the strength of reference concrete
	28 days	≥110% of the strength of reference concrete	28 days	≥115% of the strength of reference concrete

Table 7
Composition of the reference concretes.

		Mass (kg) in 1 m^3 of concrete		
		Without plasticizer	Plasticizer	Superplasticizer
FS		196.1	204.1	209.1
CS		548.4	570.7	584.7
FG	5.6–8 mm	27.6	28.8	29.5
	4–5.6 mm	131.2	136.5	139.9
MG	11.2–16 mm	8.6	8.9	9.1
	8–11.2 mm	43.5	45.2	46.3
	5.6–8 mm	58.2	60.6	62.1
	4–5.6 mm	32.7	34.1	34.9
CG	16–22.4 mm	190.3	198.1	202.9
	11.2–16 mm	485.8	505.6	518.0
	8–11.2 mm	61.1	63.6	65.2
	5.6–8 mm	10.1	10.5	10.7
Cement		350	350	350
Water		189	157.5	140
Plasticizer		–	3.5	3.5

3.2. Tests on hardened concrete

3.2.1. Compressive strength

EN 12390-3 specifies a test method for determining the compression strength of test specimens of hardened concrete. The average results of this test are shown in Fig. 2, which shows how the compressive strength of the mixes without admixture increases with concrete age. Furthermore, C20 and C0 exhibit similar behaviour, which agrees with Etxeberria et al. (2007) who report that, for replacement ratios below 25%, the strength of concrete produced with RCA is similar to that of the reference concrete. These results prove that low replacement ratios of natural aggregates by RCA do not change the strength.

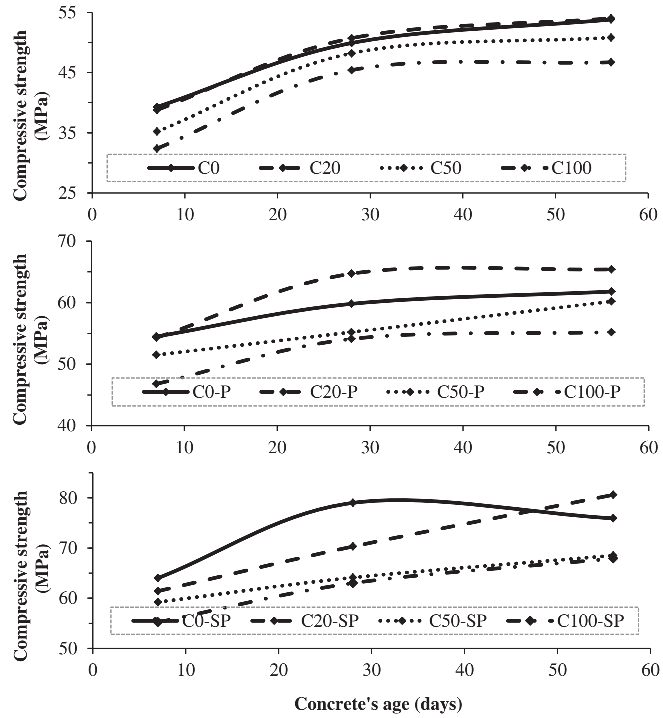
As expected, C100 has the lowest strength, and C50 has a value between that and C0. Also, the obtained values are higher for all ages and all replacement ratios than those obtained by Pereira et al. (2012a), since our work only used coarse recycled aggregates, and no fines. As in this case, there is an increase in compressive strength as the water reducing power of the admixtures increases.

Although these results are satisfactory, they cannot be generalized because the strength of manufactured concrete depends on the kind of recycled aggregate used and more specifically, its strength (Bolouri Bazaz and Khayati, 2012).

On the other hand, the compressive strength of the mixes made with SP was higher than that of those made with P, and this in turn was higher than for those without admixtures. This shows that the hydration process in a concrete with water-reducing admixtures (P or SP) is faster than in a normal concrete, as reported by Turu'allo (2007b).

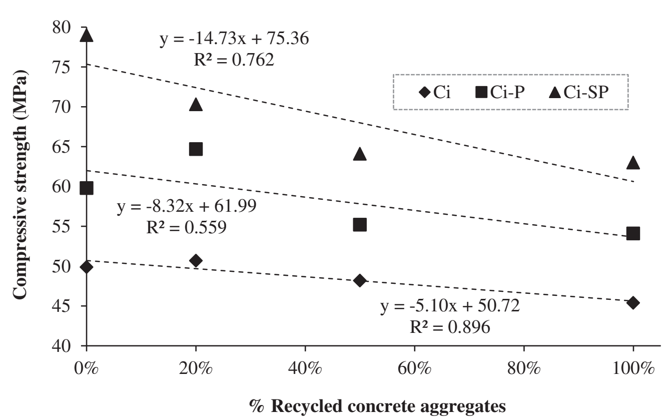
So, the use of P led to 139% compressive strength at 7 days, relative to the reference concrete, and the use of SP to 158% of compressive strength at 28 days, satisfying the requirements of Table 4 (≥110% and ≥115%). Similarly, all the different replacements of coarse natural aggregate by RCA also met the standard requirements.

In addition, Fig. 3 shows the correlation between the replacement percentage of natural aggregates by RCA and the compressive strength obtained when each admixture is used. This figure shows that when no admixture is used the fall in compressive strength is closely related to the replacement ratio of natural aggregates ($R^2 = 0.896$). The scatter of the results is shown in Table 9. The correlation between the replacement ratio and compressive strength is worse when using the two admixtures, especially for the traditional plasticizer ($R^2 = 0.562$).



NOTE: Acronyms in Table 5

Fig. 2. Evolution of concrete compressive strength.



NOTE: Acronyms in Table 5

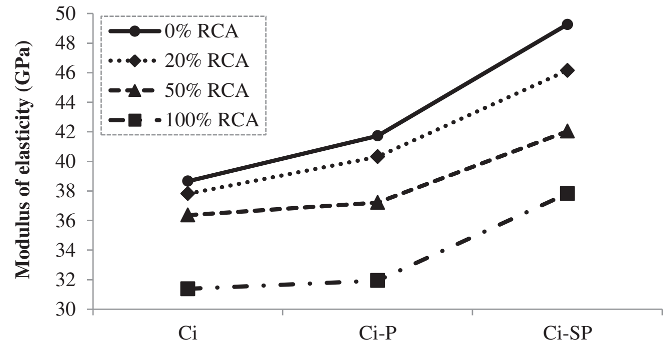
Fig. 3. Correlation between ratio of replacement and 28-day compressive strength.

Table 8
Properties of fresh concrete.

	w/c	Slump (mm)	Density (kg/m^3)
C0	0.54	110	2192
C20	0.54	121	2326
C50	0.54	116	2352
C100	0.54	124	2275
C0-P	0.45	111	2050
C20-P	0.45	109	2390
C50-P	0.45	108	2352
C100-P	0.45	107	2322
C0-SP	0.40	115	2436
C20-SP	0.40	141	2398
C50-SP	0.40	127	2400
C100-SP	0.40	135	2300

Table 9
Standard deviation (σ) of tests of hardened concrete.

	% RCA	Compression strength			Splitting tensile strength	Modulus of elasticity
		7 days	28 days	56 days		
C_i	0	1.48	1.52	1.21	0.52	0.06
	20	1.01	3.44	3.79	1.15	0.59
	50	2.24	1.19	0.49	0.80	0.91
	100	0.23	0.87	2.23	4.02	0.34
C_i-P	0	2.26	1.30	3.15	1.07	0.02
	20	2.23	1.40	3.66	1.57	1.20
	50	1.38	2.93	0.03	0.49	1.41
	100	2.08	2.24	3.60	0.10	0.54
C_i-SP	0	7.01	2.88	0.60	0.76	0.31
	20	0.03	4.25	2.68	0.00	1.15
	50	1.99	1.95	1.37	0.57	0.99
	100	2.72	4.09	1.73	3.21	0.01



NOTE: Acronyms in Table 5

Fig. 5. Modulus of elasticity *versus* use of water-reducing admixtures.

3.2.2. Splitting tensile strength

In this test, based on *EN 12390-6*, three specimens were subjected to a compressive force applied to a narrow strip along its length. The determination of the splitting tensile strength of a concrete specimen is generally associated with high scatter in the results. This is a property which depends not only on the strength of the aggregates, but also on the quality and quantity of the connections established between them, together with the cement matrix micro cracking and imperfections and the test sample (Neville, 2011).

No clear trends are observed in Fig. 4, although there was not much scatter as shown in Table 9. Results obtained showed no correlation with the replacement percentage of NA by RCA or the use of admixture.

However, in the series C_i, there was a 12% decrease in the splitting tensile strength for a total replacement of NA by RCA. This is close to the results of Hansen (1992), who stated that the use of 100% recycled concrete aggregate causes a decrease of 20% in this property. The main reason is that the bond between the cement paste and recycled aggregates is weaker.

3.2.3. Modulus of elasticity

This test was performed according to the method proposed by the Portuguese standard *LNEC E397*, which characterizes the stiffness of a concrete, or deformability, through the stress/strain ratio (σ/ε). However, this σ/ε ratio is not linear. For this reason, in this research the modulus of elasticity (E) was defined as the secant between two known points on the same curve, after a series of loading and unloading cycles: initial point with null stress-strain and 1/3 the ultimate stress (f_{cm}).

The modulus of elasticity (E) values that are shown in Fig. 5 (with the scatter shown in Table 9) increased with the use of admixtures and decreased with the percentage of replacement ratio of NA by RA. However, 20% of replacement did not cause such a significant difference as in the study of recycled sand by Dapena et al. (2011).

Furthermore, looking at the correlations in Fig. 6, it can be stated that the modulus of elasticity is inversely proportional to the replacement of natural aggregates, both without superplasticizer ($R^2 = 0.962$) and with the two types of admixture ($R^2 = 0.996$ and $R^2 = 0.979$, for P and SP). This may be due to the greater deformability of cement paste and the fine stone adhering to the RCA.

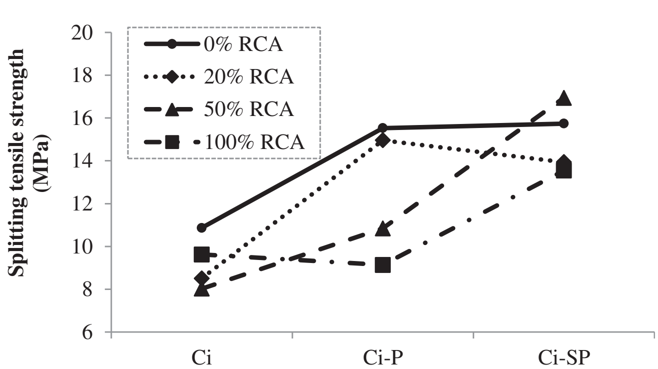
For C100 a 19% reduction of the modulus of elasticity was obtained, slightly higher than the 15% obtained by Gerardu and Hendriks (1985), but lower than that obtained by Katz (2003), 25%. As stated by Hansen (1992), this reduction is due primarily to the fact that the recycled aggregates contain mortar whose modulus of elasticity is lower than that of natural aggregates.

On the other hand, the replacement of 100% natural aggregates in concrete with P or SP caused a fall in the modulus of elasticity of approximately 23%.

There is a high correlation between compressive strength and modulus of elasticity, as shown in Fig. 7, and in agreement with Khatib (2005), except for concrete made with P, with a $R^2 = 0.591$. This may be due to the higher value rarely obtained in the compressive strength test at 28 days of C20-P.

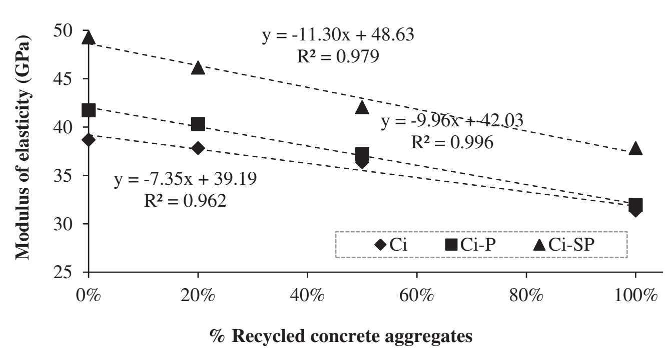
3.2.4. Abrasion resistance

The test produces wear through friction between the specimen's surface and that of a cast iron ring coated with abrasive material.



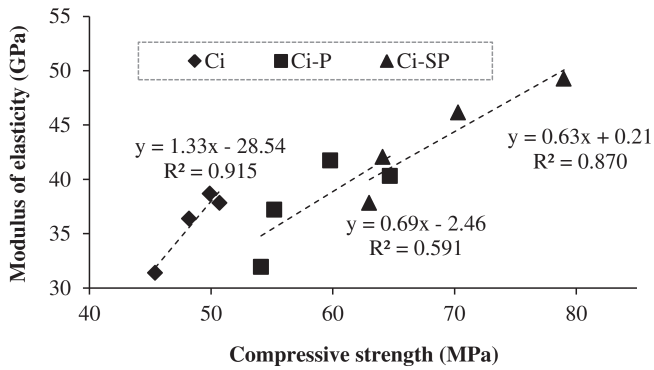
NOTE: Acronyms in Table 5

Fig. 4. Splitting tensile strength *versus* use of water-reducing admixtures.



NOTE: Acronyms in Table 5

Fig. 6. Correlation between the replacement ratio and modulus of elasticity.



NOTE: Acronyms in Table 5

Fig. 7. Correlation between compressive strength and modulus of elasticity.

Table 10
Height loss by abrasion at 91 days.

	Height loss (%)	σ (%)
C0	7.5	38.9
C20	7.3	30.7
C50	7.4	23.4
C100	6.8	4.2
C0-P	5.5	38.1
C20-P	5.6	42.8
C50-P	5.1	20.4
C100-P	4.8	13.8
C0-SP	4.6	19.7
C20-SP	5	3.5
C50-SP	5.2	35.2
C100-SP	5.4	47.2

The method used in this test is described in the German standard *DIN 52108* "Testing of inorganic non-metallic materials: Wear test with grinding wheel according to Böhme", and results are shown in Table 10.

There is no clear influence of the replacement ratio on the height loss by abrasion, as indicated by De Brito (2010). Nevertheless, it can be stated that the use of P or SP decreases the amount of water required, increasing the concrete compactness, and therefore, reducing its loss by abrasion.

4. Conclusions

Regarding the use of recycled coarse aggregates in new concrete, it is concluded that increasing replacement ratio of natural aggregates by recycled concrete aggregates does not interfere with the effective w/c ratio or concrete slump, provided that the additional water absorption of the recycled concrete aggregates during mixing (in this study, 10 min) is compensated in the mix. Also, the conclusions drawn by other authors who report similar compressive strength in concrete made with a 20% replacement of natural aggregates by coarse recycled concrete aggregates, compared to a reference concrete without the use of plasticizers, have been confirmed. However our research shows that a substitution of 100% natural aggregate is possible without affecting the major mechanical properties, as long as a water-reducing admixture, not necessarily of high performance, is used. This is a great boost to promoting the incorporation of recycled concrete aggregates in new concrete.

This is so because water reducing admixtures decrease the need of adding water for the same slump, thereby decreasing the effective w/c ratio and improving the workability of concrete; furthermore, the greater the water-reducing power of the admixture, the greater the differences of these properties compared with those of the original concrete. As a direct consequence of this, it can be stated that the use of water reducing admixtures can even improve the mechanical properties of concrete made with them and recycled aggregates.

As suggestions for future work, higher plasticizer contents may be tested to attempt to obtain greater strength in concrete with recycled aggregates, and other kinds of recycled aggregates could be studied. Furthermore, the effects of these admixtures on the durability of concrete with recycled aggregates must be studied.

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