Materials and Structures (2017) 50:120
DOI 10.1617/s11527-016-0989-z

ORIGINAL ARTICLE

Fracture energy of coarse recycled aggregate concrete using the wedge splitting test method: influence of water-reducing admixtures

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Received: 18 June 2016 / Accepted: 19 December 2016 / Published online: 23 December 2016

Abstract The aim of this study is to evaluate the effect of the replacement levels of coarse natural aggregates with recycled aggregates and water-reducing admixtures on the fracture energy of concrete. Four mixes with 0, 20, 50 and 100% replacement ratios are produced per concrete family: without admixture, with plasticizer and with superplasticizer. The experimental fracture energy is tested using the wedge splitting test method on notched specimens at 28 days. The results prove that the incorporation of up to 20% coarse recycled aggregates led to improved energy absorption capacity of concrete mixes with water-reducing admixtures, reaching 1.5% for concrete with normal plasticizer and 7.0% for concrete with superplasticizer. Furthermore, the compressive strength, slump, and fresh density are tested in order to evaluate the effect of water-reducing admixtures on recycled aggregate concrete with different ratios of coarse natural aggregate replacement, allowing to conclude that the use of plasticizers and superplasticizers improves the behaviour of recycled aggregate concrete for all these properties.

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Keywords Fracture energy · Wedge splitting test · Recycled aggregate concrete · Water-reducing admixtures

1 Introduction

The large amount of construction and demolition waste (CDW) generated worldwide during the last decades leads to the need of an efficient management of these outputs in the construction sector. Consequently, the transformation of this product flow into raw materials used in new construction works is extensively researched in several countries. Previous studies have indicated that recycled materials from CDW could successfully be used as a substitute of natural aggregates [1, 2] or as cement additive since CDW with ceramic content has pozzolanic activity [3, 4], taking into account the economic and environmental benefits.

However, it is recognized that one of the main drawbacks of using recycled aggregates in concrete is the higher water absorption capacity of such aggregates relative to the corresponding natural materials generally used for concrete production [1, 5, 6]. Several techniques have been studied to solve this problem: pre-saturation of recycled aggregates [7, 8], use of water-reducing admixtures [9, 10]; chemical treatment [11, 12], biodeposition [13, 14], two-stage mixing approach [15, 16], among others.

This study deals with the influence of different water-reducing admixtures on recycled concretes with different replacement ratios of coarse natural aggregates with coarse recycled aggregates from concrete waste. Since admixtures are also frequently used in commercial concrete with natural aggregates, it was decided to include control concrete with admixtures, in addition to a control mix without admixture. This paper presents the results for slump, density, compressive strength and fracture resistance behaviour of all concrete mixtures, with main focus on the fracture behaviour of recycled aggregate concrete. In fact most published studies on this phenomenon are focused on fibre-reinforced concrete [17, 18], but there is a knowledge gap about energy absorption capacity in recycled aggregate concrete without reinforcement. Understanding the fracture behaviour of recycled aggregate concrete is necessary to determine the shear and bond strength of concrete structures [19–22].

According to Ishiguro and Stanzl-Tschegg [23], the specific fracture energy of concrete with 100% recycled concrete aggregates (coarse and fine) is only 60% of that of conventional concrete. Sato et al. [24], in spite of different air-entraining and water-reducing agents that were used claim that this ratio achieves 70%. Casuccio et al. [25] state that recycled aggregate concrete presents significant reductions in energy of fracture (27–45%) and lower fracture zone size, when compared with conventional concrete. Bordelon et al. [26] state that, to achieve the same fracture properties as conventional concrete, recycled concrete aggregates must be modified by blending them with coarse natural aggregates or adding discrete structural fibres. Based on the findings of Gesoglu et al. [27], the fracture energy of self-compacting concretes made with recycled aggregates is less than that of those with natural aggregates. Guo et al. [28] investigated the fracture behaviour of a steel fibre reinforced recycled aggregate concrete and pointed out that full replacement of coarse natural aggregate with coarse recycled aggregates results in a decrease in the fracture energy. However, according to these authors [28], the fracture energy represents the energy dissipation capacity of concrete mixes, while the fracture toughness reflects resistance to brittle fracture of concrete mixes, and the replacement of coarse natural aggregates with coarse recycled aggregate leads to a significant increase in the fracture toughness. Arezoumandi et al. [19] obtained higher fracture energy in recycled aggregate concrete with 30% replacement ratio in the presence of air entraining and water-reducing admixtures, but for higher ratios the energy absorption capacity decreased with the increasing coarse recycled aggregate replacement level. However, the samples used in the three-point bending test and the beam specimens were $150 \times 150 \times 600$ mm, i.e. the sample self-weight can play an important role in the results.

Therefore, in spite of the recognized difficulty in finding a suitable method to test fracture energy of concrete [29–32], the wedge splitting test method was chosen in this research paper. It is a complex-step method and there is yet no agreed standard test method for conformity assessment around the world, but this method reduces the effect of sample self-weight on the fracture result, making it less sensitive to the specimen's size, and the required high volume of concrete used in the three-point bending test [29].

2 Materials and methods

2.1 Experimental procedure

The wedge splitting test method was performed to characterize the fracture behaviour of 12 concrete mixes with natural and recycled concrete aggregates, which were included in three different families (without admixture, with a normal plasticizer and with a superplasticizer). Four levels of replacement of coarse natural aggregate with coarse recycled aggregates from a source concrete were used in each family (Table 1).

Slump, fresh density and compressive strength tests were also conducted to check the quality of each batch. Previously, aggregate characterization tests were made in order to know the suitability of recycled aggregates in concrete mixes: size distribution [33] and [34], particle density and water absorption [35], water content [36], shape index [37] and resistance to fragmentation [38].

2.2 Materials

Type I cement of class 42.5 R was used. The chosen admixtures were Sikament® 400 Plus, as normal plasticizer, and SikaPlast® 898, as superplasticizer, of which technical data are provided in Table 2. Washed sands with particles of quartz, quartzite and feldspar were used as fine aggregates (the washing process is recommended in order to remove silt, clay and other organic impurities present). One fraction with grain size 0–2 mm (FA1) and another one with grain size 0–4 mm (FA2) were used. Three fractions of limestone gravel were used as coarse natural aggregates: CA1 (grain size 4–5.6 mm), CA2 (4–16 mm) and CA3 (4–22.4 mm). Coarse recycled concrete aggregate (RA) was obtained by crushing 28-day old concrete, even though at this age, the mechanical strength of concrete has not been completely developed and its shrinkage has not stabilized yet. Over time, these properties are expected to improve, which has positive repercussions on the mechanical properties and durability of the recycled concrete [39–44], whose properties in accordance with Eurocode 2 [45] are: Strength class C30/37; Cement content 350 kg/m^3; w/c ratio 0.45; Exposure class X0; Slump S2 (80 ± 10 mm); Type of cement CEM I 42.5 R; Maximum size of aggregates 22.4 mm. Previously prepared concrete blocks were at that time crushed by a jaw crusher. These steps were followed instead of employing recycled aggregates directly from a CDW treatment plant, to guarantee the homogeneity of the raw material and know the characteristics of the source concrete. Based on other research studies, it has been shown that the properties of recycled aggregates derived from different source concretes affect deeply the characteristics of concrete manufactured with this kind of material: the water absorption of recycled aggregate decreases with an increase in strength of the source concrete from which the recycled aggregates are derived [46]; the water absorption and density value of recycled aggregates influence the quality of the ITZ and therefore the concrete compressive strength [47]; the properties of the source concrete have a significant influence on the mechanical properties of recycled aggregate concrete—strength, shrinkage, creep—[39–41, 43, 44, 48–54]; controlling the source concrete strength, over 25 MPa, recycled aggregates of good quality for the production of structural concrete can be obtained [55]; or as the aggregate strength increases, the modulus of rupture also increase [56].

Recycled aggregates were separated into different size fractions to obtain an optimum replacement with a maximum aggregate compaction factor.

The physical properties of the aggregates used with the standard limits stipulated in the EN 12620 + A1 [57] standard and the Spanish Code on Structural Concrete, EHE-08 [58] are: oven-dry particles density 2.464 Mg/m^3; water absorption 5% (limit: ≤7%); water content 3.6%; shape index 20.4% (limit:

Table 1 Mix designation

Replacement (%)	Without admixture	With normal plasticizer	With superplasticizer
0	C0	C0-NP	C0-SP
20	C20	C20-NP	C20-SP
50	C50	C50-NP	C50-SP
100	C100	C100-NP	C100-SP

Table 2 Properties of the water-reducing admixtures

Technical data	Type of admixture	
	Sikament® 400 Plus	SikaPlast® 898
Chemical base	Mixture of organic polymers and additives	Aqueous solution of modified polycarboxylate
Density (kg/l)	1.24 ± 0.03	1.07 ± 0.02
pH value	10.5 ± 10	5.0 ± 1.0
Total chloride ion content (%)	<0.10, w/w (chloride free)	
Content (% of cement mass)	0.5–1.5	0.5–1.5
Mixing	It is added to the mixing water or directly into the freshly mixed concrete at the end of the batching cycle	

≤35%); Los Angeles coefficient 43 (limit: ≤50). Their size grading curves in Fig. 1.

2.3 Mix design

Faury's reference curve method was used for mix design, taking into account following parameters: C25/30 strength class, CX3 exposure class and S3 slump. The water-reducing admixtures were incorporated at 1% by cement weight, respecting recommended contents by the manufacturer and standard EN 934-2 [59]. Based on these reference concrete mixes, the different percentages of coarse natural aggregates were replaced with coarse recycled aggregates, keeping in mind density and water absorption of aggregates. Additional water was provided at an amount corresponding to the global water absorption of the recycled aggregates at 24 h minus their existing water content (the water absorption of the recycled concrete aggregate was 5% and the moisture was 3.57%). This amount of extra water is used to solve the water absorption problem of the recycled aggregates and achieve concrete mixes with the same effective water/cement ratio. Since the ability of recycled aggregates to absorb water affects the amount of water available for mixing, a lower water/cement ratio would lead to poorer cement hydration and lower concrete workability in the short-term. In the long-term, the mechanical and durability properties will also be affected by this lower amount of available water [60–65]. The mix proportions are shown in Table 3.

2.4 Experimental test and cast specimens

In the fresh state, workability and density tests were performed, according to standards EN 12350-2 [66] and EN 12350-6 [67].

The compressive strength was studied on hardened concrete using standard EN 12390-3 [68]. Cylindrical specimens (diameter of 150 mm and height of

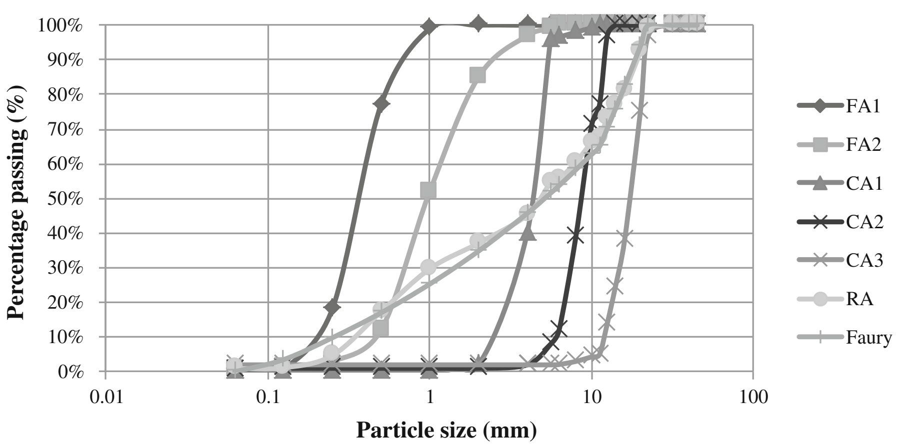


Fig. 1 Particle size distribution of FA1, FA2, CA1, CA2, CA3, RA and Faury's reference curve

Table 3 Concrete mixes

	Concrete mixes											
	C0	C20	C50	C100	C0-NP	C20-NP	C50-NP	C100-NP	C0-SP	C20-SP	C50-SP	C100-SP
Cement (kg)	335.7	335.7	335.7	335.7	335.7	335.7	335.7	335.7	335.7	335.7	335.7	335.7
Admixture (kg)	–	–	–	–	3.357	3.357	3.357	3.357	3.357	3.357	3.357	3.357
Water (kg)	181.3	181.3	181.3	181.3	151.1	151.1	151.1	151.1	134.3	134.3	134.3	134.3
Additional water (kg)	–	3.1	7.7	15.4	–	3.2	8.0	16.1	–	3.3	8.2	16.5
W/C	0.54	0.54	0.54	0.54	0.45	0.45	0.45	0.45	0.40	0.40	0.40	0.40
FA1 (kg)	126.4	126.4	126.4	126.4	131.9	131.9	131.9	131.9	135.0	135.0	135.0	135.0
FA2 (kg)	145.9	145.9	145.9	145.9	152.2	152.2	152.2	152.2	155.8	155.8	155.8	155.8
CA1 (kg)	268.1	214.5	134.1	–	279.8	223.8	139.9	–	286.3	229.0	143.1	–
CA2 (kg)	296.0	236.8	148.0	–	308.9	247.1	154.5	–	316.1	252.9	158.0	–
CA3 (kg)	570.0	456.0	285.0	–	594.8	475.8	297.4	–	608.6	486.8	304.3	–
RA (kg)	0.0	215.6	539.0	1078.0	0.0	225.0	562.4	1124.8	0.0	230.2	575.4	1150.9

300 mm) were cast to determine the compressive strength at 7 and 28 days. After demoulding, the samples were stored in a wet chamber with a relative humidity higher than 95% and a temperature of 20 °C.

To determine fracture energy, the wedge splitting test method was performed, based on standard NT BUILD 511 [69]. Four cubic specimens of each concrete mix were manufactured according to geometry standard recommendations (example 150 × 150 × 150 mm^3); in this study, guide notches were cast in lateral faces and in the bottom face too, to improve the samples' support (Fig. 2).

After demoulding, the specimens were water cured until testing. The notches were sawn with a diamond saw blade at 15 days after casting (Fig. 3).

To perform the wedge splitting test (Fig. 4), a deformation controlled testing machine, a clip gauge and a wedge splitting equipment (two steel plated-loading devices with a roller bearing, a linear support and a wedging device) were required (Fig. 5).

Just before the test, the weight of the specimen was measured. When the specimen was placed on the support, a pre-load of 50 kN was imposed. At this moment, the test started. In order to adjust the rate of the crack mouth opening displacement (CMOD) to standard NT BUILD 511 [69], the loading rate of the wedging device was set at 0.006 mm/s. CMOD was measured continuously by the clip gauge and vertical force (F_v) were registered with a frequency of 10 Hz.

After the test, the depth and the width of the split surface were measured (Fig. 5).

Based on the vertical force (F_v), the splitting force (F_{sp}) is calculated as (Eq. 1):

$$F\mathrm{sp} = \frac{F_V}{2\tan(\propto)} \quad (1)$$

where α is the angle between the wedge and the vertical load line.

The work of fracture (W_f) is calculated as the area under the splitting load-CMOD curve (F_{sp}-CMOD). At a specific CMOD the energy dissipated during fracture ($W_{f.CMOD}$), is normalized with respect to the total split surface (A_{sp}), at complete fracture. This intermediate specific fracture energy is denoted G_f (kN/mm) and is determined from the test result by performing the following calculation (Eq. 2):

$$G_f = \frac{W_{f\cdot CMOD}}{A_{sp}} \quad (2)$$

3 Results and discussion

3.1 Workability

The workability of all the concrete mixes is within the specified limits (S3) (Table 4). As expected, in each family, the slump decreased as the replacement

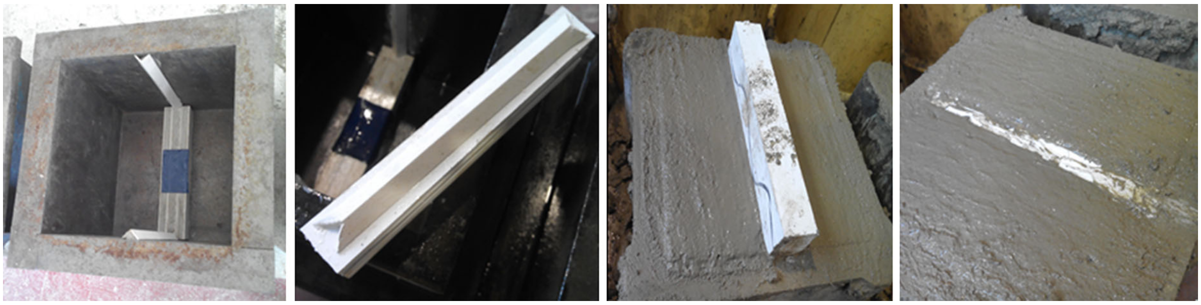
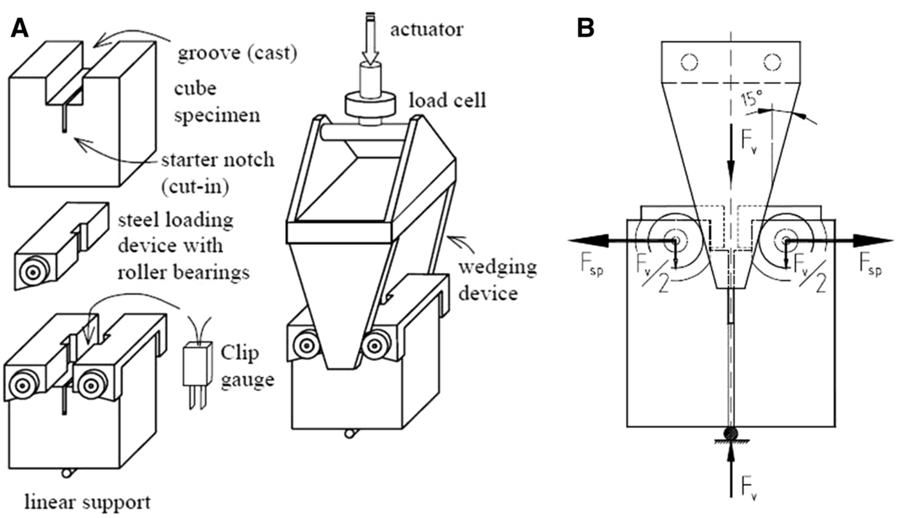


Fig. 2 Formwork setup and concrete casting

Fig. 3 Specimens curing and notches sawing

Fig. 4 **a** Schematic view of the equipment and test setup. **b** Principle of applying the splitting load (NT BUILD 511 [69])



ratio of coarse recycled aggregate increased because of the higher water absorption of the RA [42, 65, 70]. This phenomenon is compensated by the additional water but not completely because of the rougher surface of the RA. It is also shown that the incorporation of water-reducing admixtures enables a reduction of the w/c ratio to keep workability constant [9, 50, 71].

3.2 Fresh density

The density results are shown in Table 4, where it is observed that when the replacement ratio increases concrete density decreases. This can be attributed to the lower density of the recycled aggregates relative to the natural aggregates [42, 72, 73]. Furthermore the results show that the use of water-reducing admixtures

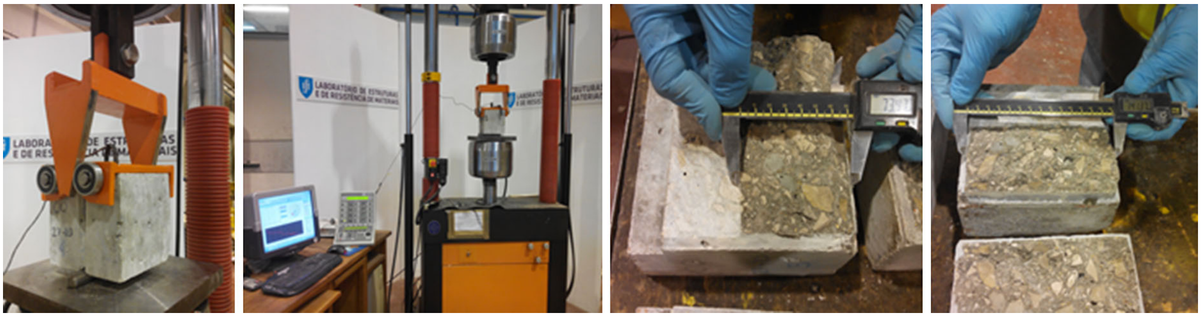


Fig. 5 Wedge splitting test setup and measurement of the split surface

Table 4 Slump, fresh density, compressive strength and fracture energy results

	Slump (mm)	Density (kg/m^3)	$F_{c,\ 7\ days}$ (MPa)	$F_{c,\ 28\ days}$ (MPa)	G_f (N/m)
C0	119	2370	40.8 ± 1.0	51.5 ± 0.7	99.6 ± 8.6
C20	115	2330	40.5 ± 1.4	49.3 ± 0.7	91.3 ± 7.1
C50	113	2310	40.3 ± 0.4	49.0 ± 1.3	89.7 ± 8.4
C100	101	2290	37.3 ± 0.7	47.5 ± 1.3	74.2 ± 4.3
C0-NP	107	2380	57.8 ± 1.6	66.8 ± 1.6	102.0 ± 5.6
C20-NP	104	2380	57.7 ± 0.1	64.8 ± 1.1	103.5 ± 7.6
C50-NP	102	2340	52.1 ± 0.7	63.2 ± 2.9	93.5 ± 9.4
C100-NP	101	2290	49.3 ± 0.9	58.8 ± 1.2	92.9 ± 6.0
C0-SP	106	2390	66.2 ± 0.5	74.9 ± 2.1	177.1 ± 2.8
C20-SP	104	2390	62.4 ± 0.4	73.0 ± 1.5	189.5 ± 12.3
C50-SP	103	2380	59.3 ± 0.5	69.0 ± 1.7	131.1 ± 9.2
C100-SP	100	2290	55.9 ± 0.5	63.1 ± 1.8	120.6 ± 16.8

results in concrete with higher density. The density of the C0-SP mix is higher than that of the C0-NP mix, which is higher than that of the C0 mix. This trend is noticed for all replacement ratios except the mixes with 100% coarse recycled aggregates. Some authors [74] linked this effect to the greater compactness that superplasticizers provide to mixes made with recycled coarse aggregate in comparison with mixes without admixtures.

3.3 Compressive strength

Figure 6 displays the 7- and 28-day compressive strength results of all the mixes tested. The use of water-reducing admixtures allows the 7-day compressive strength of the concrete mixes with plasticizer and superplasticizer to pass the 28-day compressive strength of the mix without admixture for all replacement ratios. This behaviour is due to the w/c ratio differences within each mixes family. Authors as Domingo et al. [40], González-Taboada et al. [75] or Tam et al. [44] stated that the effect of the w/c ratio of the new cement paste is more significant than that of the recycled aggregates content.

On the one hand, the 7-day compressive strength decreased as the recycled aggregate content increased and this strength loss was more significant when the w/c ratio was lower (Table 4). The registered loss reaches 8.7% in concrete without admixture, 14.7% in concrete with normal plasticizer and 15.6% in concrete with superplasticizer, in case of 100% aggregate substitution. This is explained by the fact that as the w/c ratio decreases, the effect of the water absorption of the recycled aggregates on cement hydration is greater because less free water is available in the mix. Then as the recycled aggregates content increases, the ability of this material to absorb water increases and produces a more significant strength loss in concrete. Authors as Hansen and Narud [76], Katz [77], Poon et al. [78], Mas et al. [79], Seara-Paz et al. [80] and

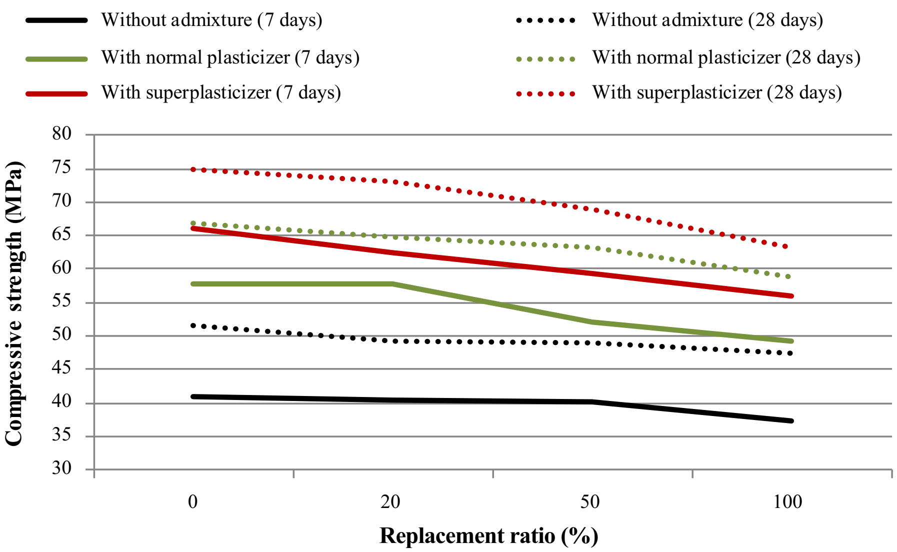


Fig. 6 Compressive strength-recycled aggregate content at 7 and 28 days

González-Taboada et al. [75] have also made this statement. Moreover, these researches have also detected a compressive strength gain between 7 and 28 days, which is due to the reaction of the cement products as curing proceeds.

The 28-day compressive strength has a similar evolution, i.e. the strength loss increased as the replacement ratio increased, with losses of 7.8% in concrete without admixture, 12.0% concrete with normal plasticizer and 15.8% in concrete with superplasticizer. Numerous publications are in agreement with these trend [81–85]. Regarding these findings and to support the important role of controlling recycled aggregates sources' influence on concrete strength, De Juan and Gutiérrez [55] claimed that when the source concrete strength is over 25 MPa, recycled aggregates of good quality for the production of structural concrete are obtained. Ajdukiewiez and Kliszczewicz [39] concluded that, to achieve recycled aggregates concrete with over 80 MPa compressive strength, recycled aggregates from source concrete with around 60 MPa must be used. In some studies [49], where recycled aggregates obtained by crushing unknown waste concrete were used to manufacture concrete, the mixes needed 6–8.3% more cement mass, in 50 and 100% replacement ratio respectively, to achieve the compressive strength of the conventional concrete (100% natural aggregates). Kou et al. [50, 51] stated that the higher the impurities content in recycled aggregates, the greater the compressive strength decrease (up to 35.7% for 16.1% of impurities), obtaining decreases of 12.2% for the case of no impurities (0%). Furthermore, the insignificant changes observed in concrete mixes without admixture for 20 and 50% replacement ratios were similar to those in other studies [84, 86].

On the other hand, Table 4 shows that the compressive strength increases in recycled aggregate concrete when water-reducing admixtures were used and w/c ratio decreased. For concrete with normal plasticizer, the 28-day compressive strength increased 23–31%. For concrete with superplasticizer, 33–48% gains were registered. In both cases, the highest profit was achieved in mixes with 20% coarse recycled aggregate and the lowest gain was measured with total replacement. Authors such as Sagoe-Crentsil et al. [8], Padmini et al. [46] and Matias et al. [74] claim that the use of water-reducing admixtures can avoid strength reductions in concrete with replacement of natural coarse aggregate with coarse aggregate from recycled concrete, even improving strength levels relative to conventional concrete.

3.4 Fracture energy

Figure 7 shows the splitting force-CMOD curves for the tested specimens. The energy dissipated during fracture (G_f) of concrete mixes is calculated from four specimens in a group, except for C0-SP, C20-SP and C50-SP, where some samples cracked in an unexpected way (this phenomenon is explained below) and fracture energy is calculated from two or three specimens (Table 4).

When all the coarse natural aggregates were replaced, it can be seen that recycled aggregate has negative effects on the fracture energy, i.e. this parameter decreases up to 25.5% for concrete without admixture, 8.9% for concrete with normal plasticizer and 31.9% for concrete with superplasticizer.

This was consistent with the results of Casuccio et al. [25], who tested three series of recycled concretes with different compressive strength levels and presented a clear decrease in the energy of fracture in all the cases where natural coarse aggregate is replaced by recycled aggregate. Ishiguro and Stanzl-Tschegg [23] and Sato et al. [24] claim that the fracture energy of concrete decreases between 30 and 40% when recycled aggregate concrete was compared with natural aggregate concrete regardless of the replacement ratio. Similar results are obtained in self-compacting concrete made with recycled aggregates according to Gesoglu et al. [27]. According to Bordelon et al. [26], recycled aggregate mixtures must be modified by blending them with virgin coarse aggregates or adding discrete structural fibres, in order to achieve the same fracture properties as virgin coarse aggregate concrete. Based on the findings of Guo et al. [28] the maximum values of fracture parameters were recorded for natural aggregate, unless steel fibers were added.

However, that trend could be broken when water-reducing admixtures are used and partial replacements are developed in the concrete mixes. This study shows that the fracture energy of concrete with 20% replacement ratio with water-reducing admixtures increases with 1.5% for normal plasticizer and 7.0% for superplasticizer.

The main reason for these results is that, in spite of the crushing strength of recycled aggregate being lower than that of natural aggregates, the better ITZ provided by superplasticizer [87] improves the tensile strength of the recycled concrete. For replacement ratios higher than 20%, a greater decrease of compressive strength is also followed by tensile strength reduction which necessarily causes an energy absorption capacity loss, higher when the recycled aggregate content increases. Then, another advantage of recycled aggregate would be that the incorporation of this kind of aggregate leads to a more ductile mode of failure, i.e. with the same w/c ratio, as recycled aggregates are lower quality aggregates, the compressive strength decreases and the mode of failure is more ductile than that achieved by conventional concrete with the same w/c ratio. The rougher surface of recycled aggregates than natural aggregates can also improve this positive effect, since as the roughness increases, the friction between aggregate and paste also increases, i.e. the fracture is less brittle.

Based on this behaviour, it can be stated that a conventional concrete with the same compressive strength as a recycled aggregates concrete can have a smaller G_f value, since its base under the splitting force-CMOD curve will be smaller than that in recycled aggregates concrete, meaning a more brittle fracture.

When using coarse recycled aggregates from a CDW treatment plant the results can change depending on the quality of these aggregates, i.e. the higher the compressive strength of the recycled aggregates is, the greater the compressive strength of the recycled aggregates concrete will be and, consequently, the higher the G_f value achieved. These fracture findings are in agreement with the data shown by some authors such as Arezoumandi et al. [19], who state that for 30% or less replacement ratios the fracture energy in recycled aggregate concrete with air entraining and water-reducing admixtures was higher than that of conventional concrete made with the same admixtures. Although in their case the w/c ratio increased when replacement ratios increased, the present study displays this effect on concrete families with a constant w/c ratio.

In some cases [62, 63, 88], concrete with aggregates from recycled concrete presents weaker ITZ than conventional concrete and therefore under high stresses the concrete matrix is separated from the surface of recycled aggregates before the aggregates are broken and a less fragile failure is achieved.

During the fracture energy test, some specimens with the highest compressive strength values (C0-SP, C20-SP and C50-SP) presented a brittle fracture (Fig. 8), common in ultra-high-performance concrete [89], this effect has also been observed by Casuccio et al. [25] in concrete using recycled aggregates with improved interface strength. These cases must not be considered to determine G_f, since this failure mechanism in these samples is so fast (crack opening displacement increases too much in a short time) that CMOD cannot be easily measured and G_f values are out of the logical range. Figure 9 shows how the majority of the aggregates in specimens with fragile

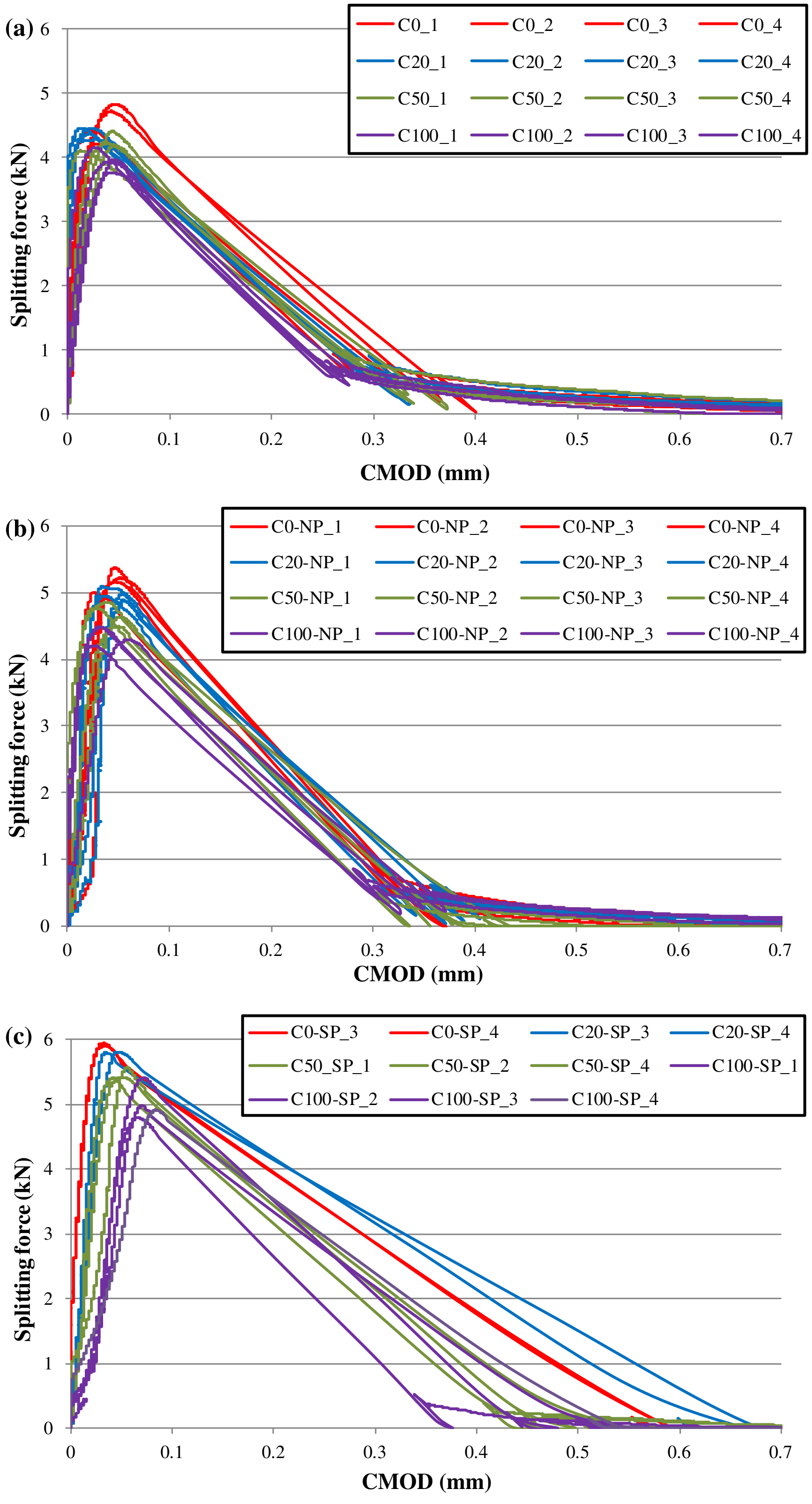


Fig. 7 Splitting force—CMOD curves for concretes **a** without admixture, **b** with normal plasticizer, and **c** with superplasticizer

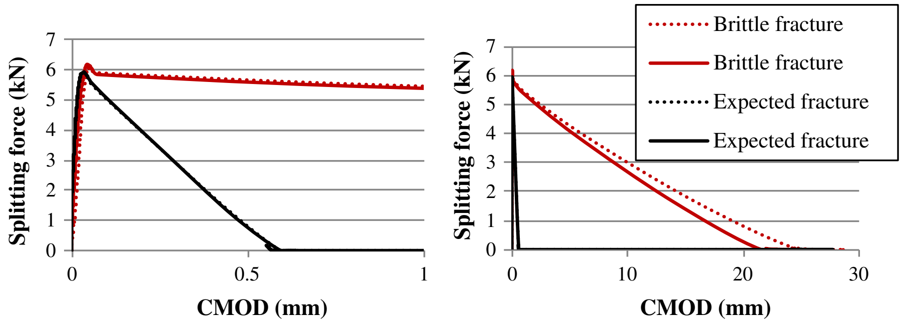


Fig. 8 Splitting force-CMOD curves for C0-SP_1 and C0-SP_2 samples with brittle fracture (the failure mechanism is so fast that CMOD reading cannot follow properly, *red curves*) and C0-SP_3 and C0-SP_4 samples with expected fracture (*black curves*). (Color figure online)

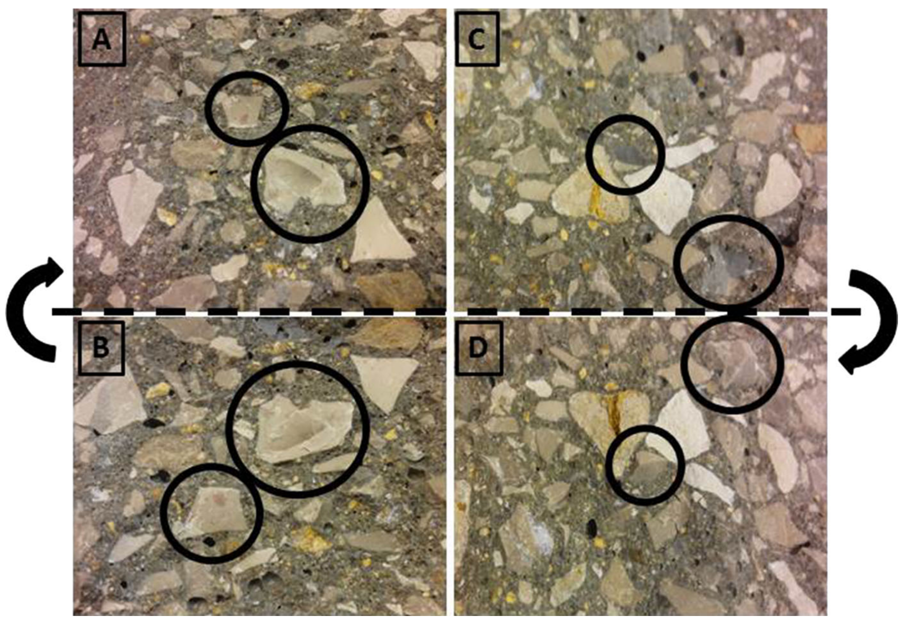


Fig. 9 Specimens with brittle fracture (**a**, **b** symmetric ones) and expected fracture (**c**, **d** symmetric ones)

fracture presented aggregate failure, but for specimens with less fragile fracture some aggregates were separated from the matrix through their ITZ.

3.5 Relationship between fracture energy and compressive strength of recycled aggregate concrete

According to NT Build 511 [69], the specific fracture energy (G_f) may be determined taking into account the work of fracture (area under the splitting force-CMOD curve) and the area of the split surface. For this reason, it is reasonable to assume that higher compressive strength mixes present a higher peak of the splitting force-CMOD curve, and as a result higher energy fracture is expected. Then, fracture energy and compressive strength of recycled concrete correlate with a reasonable quadratic fit and a R^2 of 0.856 (Fig. 10). Based on the study of the relationship between fracture energy and compressive strength of each family (Fig. 11), it can be stated that in recycled aggregates concrete without admixture an increase of the replacement ratio causes a decrease of fracture energy, which is almost proportional with the compressive strength decrease (R^2 of 0.999). However, in recycled aggregates concrete with admixtures, the increase of replacement ratio produces a fracture energy decrease lower than the corresponding compressive strength

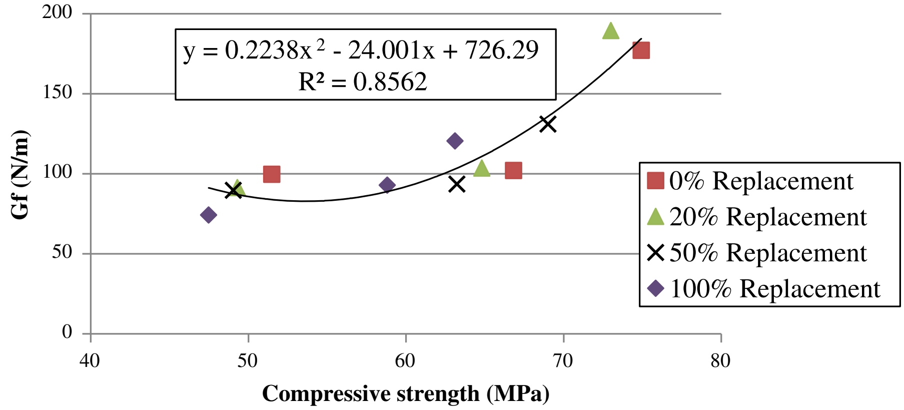


Fig. 10 Relationship between compressive strength and fracture energy

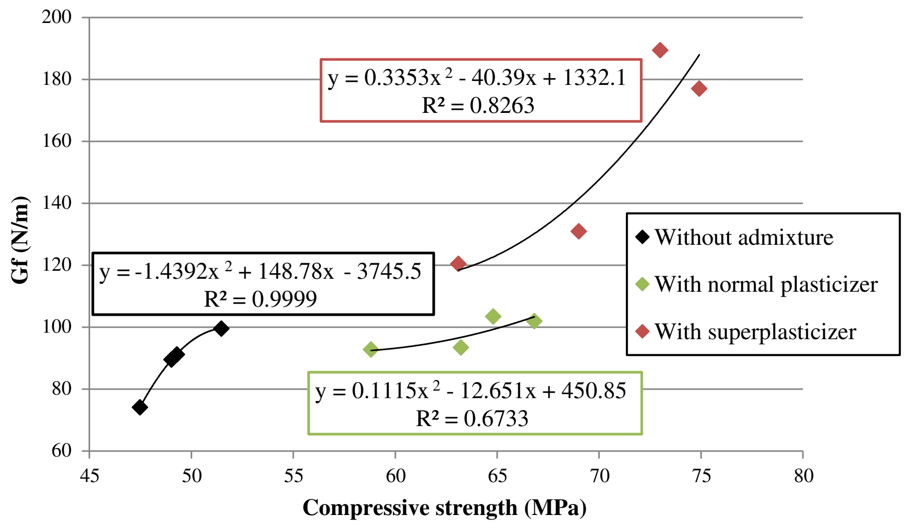


Fig. 11 Relationships between compressive strength and fracture energy per concrete families

decrease (R^2 of 0.673 in the normal plasticizer family and R^2 of 0.826 for mixes with superplasticizer).

Compressive strength plays an important role on the absorption of energy during concrete fracture. However, some properties of the aggregate also can affect the value of G_f, such as the roughness of the recycled aggregates and its appropriate integration in the new paste.

4 Conclusions

Compressive strength gains of 23–31% (normal plasticizer) or 33–48% (superplasticizer) were achieved in concrete with water-reducing admixtures. On the other hand, a lower variation due to the increase of recycled aggregate content was registered for concrete without admixture than for concrete with admixtures: in case of 100% aggregated replacement, the strength loss at 7 days amounted to 8.7% for concrete without admixture, whereas it reached 14.7 and 15.6% for concrete with normal plasticizer and with superplasticizer respectively.

The incorporation of up to 20% coarse recycled aggregates led to similar or improved energy absorption capacity of concrete mixes with water-reducing admixtures, reaching 7.0% for concrete with superplasticizer, because the failure of recycled aggregate concrete is more ductile than that of natural aggregate concrete. For higher replacement ratios, the strength loss causes a decrease in fracture energy, because the effect of strength is more prevalent than that of the ductility.

In comparison with previous studies, higher fracture parameters of recycled aggregate concrete than conventional concrete have been obtained by simply adding superplasticizers, without reinforcing fiber, air entraining agents or changes in w/c ratio. A direct relationship exists between compressive strength and fracture energy of recycled aggregate concrete, when the samples do not present brittle failure.

Although the use of recycled aggregates contents above 20% reduced the fracture energy, the very brittle behaviour occurring especially in mixes with water-reducing admixtures and lower w/c ratio was avoided.

The wedge splitting test method may be a suitable way to evaluate the energy absorption capacity of recycled aggregate concrete under fracture, reducing the effect of the sample self-weight on the fracture result, but this method presented some limitation for the higher strength and more brittle concrete mixes, because the clip gauge may have problems in registering an overly fast fracture development.

Acknowledgements This research was made possible by the Research Staff Training Grant (FPI BES-2011-047159) associated with Project BIA2010-21194-C03-02, the Training Grant for Mobility (EEBB-I-15-10379) and the Project BIA2013-48876-C3-3-R (funded by the Spanish Ministry of Economy and Competitiveness and FEDER program). The support of the CERIS-ICIST Research Institute, IST, University of Lisbon and of the FCT (Foundation for Science and Technology) is also acknowledged.

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