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Understanding the influence of properties of fine recycled aggregates on recycled concrete

María Eva Sosa PhD
Professor, National University of Technology, LEMAC, CONICET, UTN-FRLP, Buenos Aires, Argentina (Orcid:0000-0003-2190-0481)
(corresponding author: hormigones@lemit.gov.ar)

Claudio Javier Zega PhD
Professor, La Plata National University, LEMIT, CONICET, Buenos Aires, Argentina (Orcid:0000-0002-9199-9176)

Angel Antonio Di Maio Eng.
Engineer, LEMIT, Buenos Aires, Argentina

Scarcity of fine natural aggregates suitable for concrete, the pollution caused by their mining and the great environmental impact produced by the final disposal of waste concrete, have all motivated several studies about their use as recycled aggregates for concrete, particularly the fine fraction. The use of fine recycled concrete aggregates (FRCAs) is directly linked to the feasibility of obtaining target properties in concrete. Agreement about FRCA's technical viability has not yet been achieved. In this paper, the properties of FRCA associated with different features of the parent concrete and with the performance of recycled aggregate concrete prepared with them were analysed. The results show that the FRCA paste content is not linked to the compressive strength level of the parent concrete. In addition, the total water-to-cement ratio in recycled aggregate concrete seems to have a greater influence on concrete performance compared with quality and composition of FRCA.

1. Introduction

For several years, the use of fine recycled concrete aggregates (FRCAs) to produce concrete has been widely studied on account of the need to find a new environmentally friendly raw material. The scarcity of fine natural aggregates (FNAs), and the pollution caused by their mining, added to the great environmental impact associated with the final disposal of concrete waste, appear to be good enough reasons to justify such studies.

The properties of FRCAs are different from those of FNAs, especially those connected with porosity, such as density, water absorption and soundness. The hardened cement paste in FRCA is responsible for this difference (Li *et al*., 2019; Nixon, 1978; Ravindrarajah *et al*., 1987; Rueda and Alaejos, 2019). Therefore, the use of FRCA is appropriate only if concrete with suitable performance can be achieved. No agreement regarding the technical suitability of concrete prepared with FRCA has been reached in this regard, however.

Controversial results can be found in the literature concerning the properties of fresh and hardened states of concrete prepared with different FRCA contents. Some researchers have reported that several properties of concrete prepared with FRCA are similar to – or even better than – those of pattern concrete in relation to slump (Khatib, 2005; Leite *et al*., 2013), compressive strength (Evangelista and de Brito, 2004; Mardani-Aghabaglou *et al*., 2015; Pereira *et al*., 2012; Sosa *et al*., 2015; Zega and Di Maio, 2006), static modulus of elasticity (Evangelista and de Brito, 2010; Sosa *et al*., 2015; Zega and Di Maio, 2011) and drying shrinkage (Evangelista and de Brito, 2004; Sosa *et al*., 2015). Conversely, other authors have reported the detrimental effect on concrete performance when FRCAs are used as replacement for FNAs, even for small percentages of substitution (Cartuxo *et al*., 2015; Khoshkenari *et al*., 2014; Kim and Yun, 2014; Lima and Leite, 2012; Ravindrarajah *et al*., 1987; Valencia *et al*., 2015).

These mixed results regarding the performance of recycled concrete could be caused by the different features of the parent concretes used to produce FRCA. The main property associated with this hypothesis is the compressive strength level of the parent concrete, which has been considered as the determinant of quality of FRCA (Nixon, 1978). Since features of the parent concrete are difficult to identify, some characteristics of FRCA could provide information in this regard. In this sense, water absorption of FRCA is often used as an indicator of its quality (de Juan and Alaejos, 2009; Sosa *et al*., 2018a), and some relationships between this parameter and compressive strength (of the parent concrete) could therefore be expected. However, based on a literature review, no direct correlation between these parameters can be established (Figure 1).

Studies in the literature about the influence of the characteristics of the parent concrete on the properties of FRCA are not exhaustive, so there is no general knowledge about the impact that different features of the parent concrete may have on the properties and quality of FRCA. Such data could be important for the ready-mix concrete industry, especially as the use of FRCA still requires a much more thorough understanding. The aim of this study is to contribute to the knowledge about the influence of the properties of parent concretes on the quality of FRCA and in what way the properties of FRCA can affect the features of recycled concretes. The influence of the types of coarse natural aggregates and the compressive strength level of the parent concrete on different properties of FRCA was also analysed. In addition, the effect of these variables on the compressive strength, static modulus of elasticity, capillary water absorption and drying shrinkage of concrete prepared with the FRCA was also assessed.

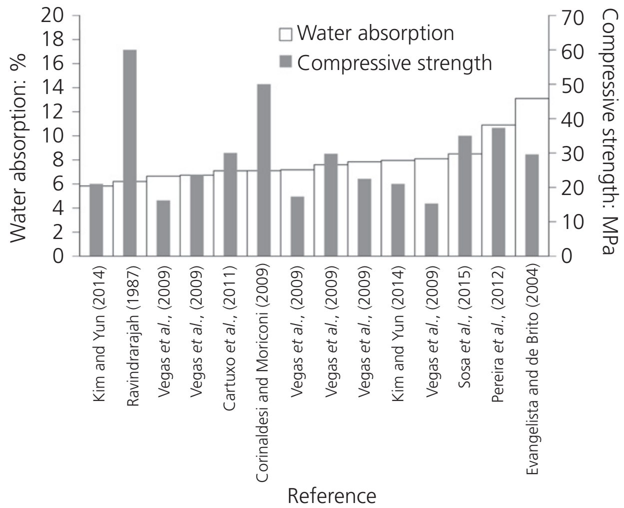

Figure 1. Water absorption of FRCA and compressive strength of the corresponding parent concretes

2. Experimental procedure

2.1 Materials and mixtures

For the concrete production, limestone Portland cement (equivalent to CEM II/A-L 42.5 according to the UNE-EN 197 standard (UNE, 2011)) was used. The FNAs were composed of 70% river siliceous sand and 30% manufactured sand (MS) or FRCA, for parent and recycled concretes, respectively. Coarse natural aggregates and MS with two different types of mineralogy (granite (NG) and quartzite (NQ)) were considered. Both types of rocks are the most used as aggregates in Argentina. Table 1 shows the properties of coarse natural aggregates. Quartzite aggregate presents higher water absorption and lower density and resistance to degradation (Los Angeles abrasion loss test) compared with granite aggregate. These differences result from the mineralogy of each aggregate (Cortelezzi *et al.*, 1988).

Four different FRCAs were used; they were obtained by crushing parent concretes with water-to-cement (w/c) ratios of 0.40 and 0.55. These concretes were prepared with natural aggregates (coarse and MS) of different mineralogy: granite and quartzite. For production of the FRCA, two jaw crushers with different closed size settings were used. Table 2 presents the nomenclature of the FRCAs and properties of the parent concretes. Different physical–mechanical properties of FRCA and MS were evaluated. The procedures (according to American Society for Testing and Materials (ASTM) standards (ASTM, 2005, 2015, 2017a, 2017b, 2018, 2019a, 2019b)) for FNAs were followed in order to determine particle size distribution, density and water absorption, content of particles finer than 75 μm and soundness. In addition, cement paste content was determined by hydrochloric acid dissolution as the complement of the insoluble residue obtained; mercury intrusion porosimetry was also assessed (indicated as porosity test).

Two parent concretes with an effective w/c ($(w/c)_{eff}$) ratio of 0.40, using coarse and MS aggregates with the above-mentioned mineralogy, were prepared. For recycled concrete, MS was totally

Table 1. Coarse aggregates' properties

Mineralogy	Maximum size: mm	Density	Water absorption: %	Abrasion loss: %
Granite	19	2.71	0.2	23
Quartzite	19	2.49	2.7	65

Table 2. Nomenclature of FRCA and properties of parent concretes

FRCA nomenclature	w/c ratio of parent concrete	Aggregates' mineralogy in parent concrete	Compressive strength of parent concrete: MPa	Sorptivity of parent concrete: $g/m^2\ s^{1/2}$	Water absorption of parent concrete: %
RG4	0.40	Granite	45.1	2.32	4.14
RG6	0.55	Granite	36.4	10.09	5.43
RQ4	0.40	Quartzite	28.6	3.55	5.30
RQ6	0.55	Quartzite	25.9	11.89	7.15

Table 3. Concrete mixtures' proportions (kg/m^3)

Materials	CNG	CRG4	CRG6	CNQ	CRQ4	CRQ6
Total water	152	162	164	174	182	184
Cement	381	381	381	381	381	381
River sand	610	610	610	610	610	610
MS	269	—	—	255	—	—
FRCA	—	246	239	—	244	238
Coarse aggregate	981	981	981	901	901	901
Water-reducing admixture	1.14	1.91	2.90	2.63	1.91	1.91
$(w/c)_{tot}$	0.40	0.42	0.43	0.46	0.48	0.48
$(w/c)_{eff}$	0.40	0.40	0.40	0.40	0.40	0.40

replaced by FRCA with the same mineralogy, understanding the latter to be the mineralogy of the aggregates in the parent concretes. With each one of the four FRCAs, concretes of $(w/c)_{eff} = 0.40$ were also prepared. The concrete mixture proportions are presented in Table 3. In order to avoid possible changes in the $(w/c)_{eff}$ ratio, FRCA was used under dry conditions and the mixing water content was corrected according to the American Concrete Institute's 211.1-91 standard (ACI Committee 211, 2009) and the Portland Cement Association design guidelines (Kostmaka *et al*., 2008). However, given the lack of certainty regarding the accurate absorption of aggregates into the fresh mixture (Li *et al*., 2018), literature recommendations were followed and 80% of 24 h water absorption of aggregates (coarse, MS and FRCA) was used (Evangelista and de Brito, 2004; Pereira *et al*., 2012). This percentage relates to the water absorption of aggregates during the first 10 min after immersion. In all concretes, the aggregates content was kept constant. Additional time to allow the FRCA to achieve saturated surface dry condition (SSD) was not provided within the concrete mixing process. The differences in weight of aggregates result from their different densities. In addition, a half-range water-reducing admixture was used to obtain mixtures with plastic consistency.

In order to analyse the influence of FRCA on the properties of mixtures in the fresh state, the consistency (by Abrams cone), unit weight and entrained-air content were determined in all mixtures according to the ASTM standard (ASTM, 2017b). Specimens with different shapes and sizes were cast for each concrete. These specimens were kept in a fog room (temperature, $T = 23 \pm 2$°C; relative humidity (RH) > 95%) until the age of 28 days. Compressive strength, static modulus of elasticity and capillary water absorption were immediately evaluated after the curing period, while drying shrinkage began at the age of 28 days and was registered for the following 360 days.

3. Results and discussion

3.1 Properties of FRCA

The characteristics of shape and roughness of FRCA and MS were observed visually and by using a stereo microscope (Figure 2). All aggregates exhibited angular shape and rough surface, as a consequence of the crushing process used to obtain them. No clear differences among FRCAs could be visually established from their surface roughness. In addition, recycled quartzite aggregate (RQ) presented greater cubicity compared with NQ, while recycled granite aggregate (RG) exhibited greater angularity and surface roughness compared with NG. These differences may be attributed to the different processes followed in the production of FRCAs and MS, as the latter were obtained from commercial products.

Figure 3 shows the particle size distribution and Table 4 presents the properties of fine aggregates (MS and FRCA), where each reported value is the average of at least three tests. Particle size distributions of the FRCAs were similar when the same mineralogy of natural aggregate in the parent concrete was considered. According to the literature (Khatib, 2005; Sosa *et al*., 2015), this is a consequence of using the same crushing process to obtain different FRCAs. It follows, then, that the crushing process plays an important role in particle size distribution of FRCA, while the mineralogy of natural aggregate in the parent concrete exerts a minor influence. Moreover, no influence of the compressive strength level of the parent concrete on the particle size distribution of FRCA was noted.

Density of FRCA decreased and absorption increased compared with those of MS, as a consequence of the hardened cement paste in the particles of recycled aggregates. The FRCA obtained from concretes with lower compressive strength levels showed higher water absorption. Although this trend was replicated for both types of mineralogy of natural aggregates, this should not be considered conclusive. Such inconclusiveness is related to the uncertainty regarding the measurement of water absorption according to ASTM C 128 (ASTM, 2015; Carrizo *et al*., 2016; Castro *et al*., 2011; Delobel *et al*., 2016). In this regard, in a previous study, the authors reported a variation of 67% when the test was carried out by different operators (Sosa *et al*., 2018b).

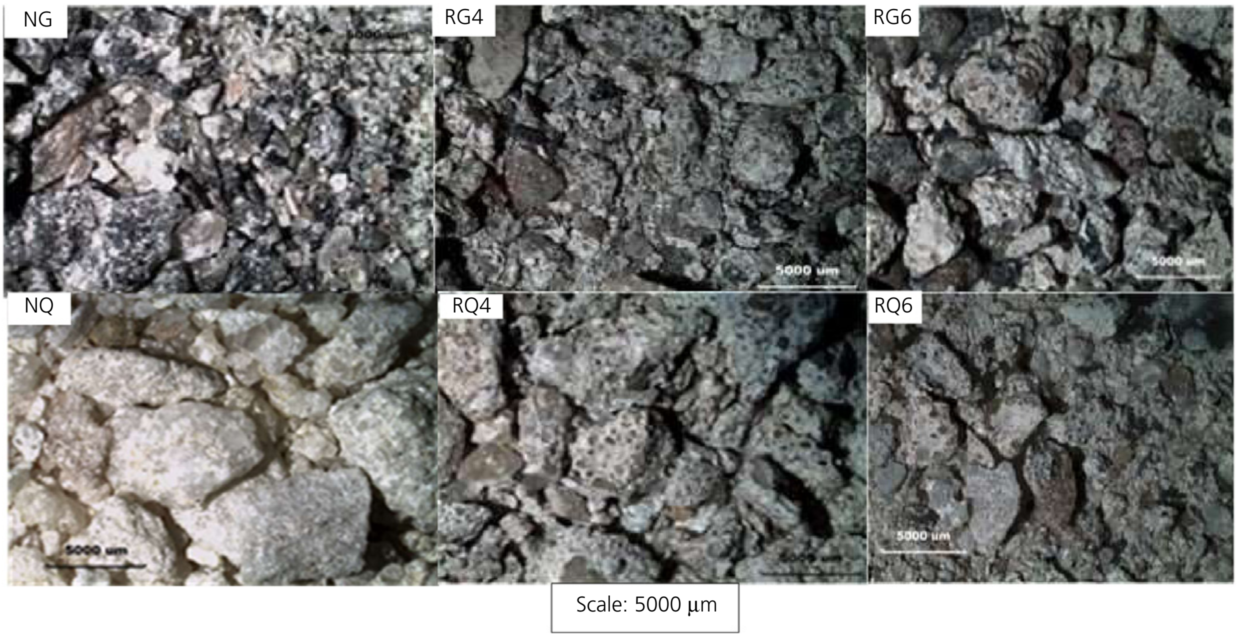

Figure 2. Stereo microscope images of fine aggregates (MS and FRCA)

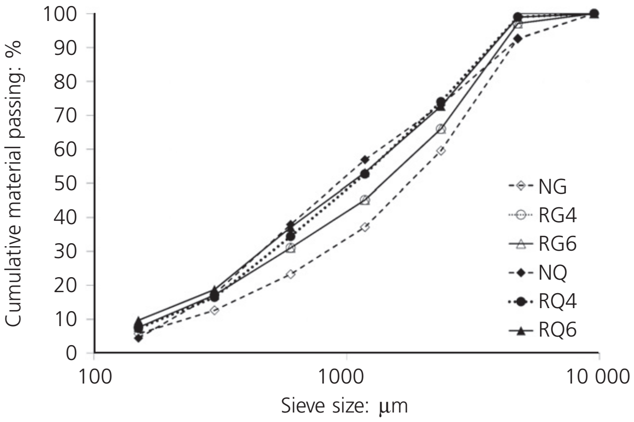

Figure 3. Particle size distribution of fine aggregates (MS and FRCA)

The content of particles finer than 75 μm was higher in FRCA than in MS. This property is affected by the attached cement paste that breaks up during the crushing process. In addition, the content of particles finer than 75 μm was higher for FRCA obtained from concretes with lower compressive strength (43% for granite and 14% for quartzite FRCA), in comparison with those from higher compressive strength level.

Paste content was similar for all FRCAs in spite of the different compressive strengths of parent concretes. This finding must be attributed to the methodology used in the determination of paste content that is most used in the literature (Angulo *et al.*, 2009; Zhao *et al.*, 2013). Thus, a fixed content (by weight) of hydration products involves a larger relative volume of paste as the w/c ratio of the parent concrete increases. Consequently, similar paste contents reported in Table 4 for all FRCAs correspond to different relative volumes of cement paste. Taking into account the differences in densities of FRCAs, the paste content by volume can be estimated. Thus, the volume of paste for RG6 and RQ6 was 7 and 12% higher than that for RG4 and RQ4, respectively. However, these differences are not directly connected with the properties of FRCA, and these do not show a direct connection with cement paste content (by weight or by volume). This lack of connection is probably a consequence of a combination of content and quality of cement paste that determines the properties of FRCA. In this respect, the soundness and porosity of FRCA were linked to the compressive strength level of the parent concrete, but they were not linked with cement paste content. This fact is expected because the porosity of cement paste is connected with the compressive strength level of the parent concrete, while paste content (by weight) was not sensitive to the quality of FRCA.

Figure 4 presents the relationship between different properties of FRCA and (a) paste content and (b) compressive strength of parent concrete. Soundness and porosity seem to be better linked with compressive strength in parent concrete compared

Table 4. Fine aggregates' properties (MS and FRCA)

Properties	NG	RG4	RG6	NQ	RQ4	RQ6
Fineness modulus	3.59	3.36	3.32	3.18	3.16	3.10
Density	2.70	2.48	2.41	2.58	2.46	2.40
Water absorption: %[a]	0.6	5.2	6.2	1.3	5.6	6.9
Content of particles finer than 75 μm: %	2.8	5.0	7.2	1.5	5.2	6.0
Soundness: %	2.1	19.9	23.9	n/d	21.6	28.1
Porosity[b]: %	n/d	22.9	56.6	n/d	30.7	64.2
Paste content: %	—	31.0	30.5	—	26.6	27.7

[a]Determined according to ASTM C 128 (ASTM, 2015)
[b]Determined by mercury intrusion porosimetry
Note: n/d, not determined.

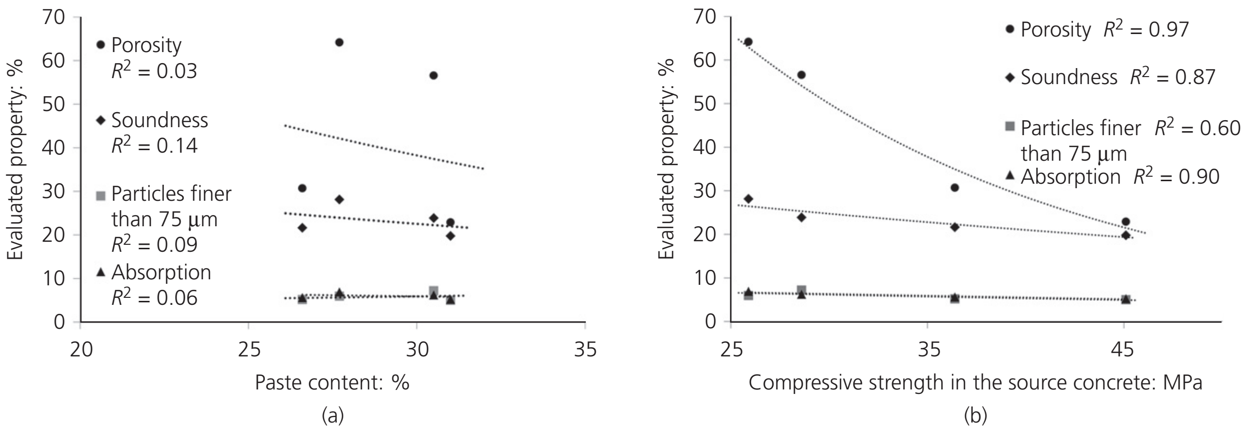

Figure 4. Relationship between the properties of FRCA and (a) paste content, (b) compressive strength of parent concrete

with paste content. This trend contradicts that reported in the literature (Angulo *et al.*, 2009; de Juan and Alaejos, 2009; Zhao *et al.*, 2013), where paste content was mentioned as a useful indicator of the quality of FRCA. Particles finer than 75 μm do not show any relationship with the paste content or compressive strength of parent concretes. This lack of relationship is in agreement with the literature (Florea and Brouwers, 2012), where it is stated that the crushing process affects the content of particles finer than 75 μm. Although only one operator performed the tests in this study, the subjectivity involved in this method for crushed aggregates, which is pointed out by several authors (Carrizo *et al.*, 2016; Castro *et al.*, 2011; Sosa *et al.*, 2018b; Zhao *et al.*, 2013), does not allow the trend between water absorption and compressive strength of parent concrete to be considered as conclusive.

Taking the aforementioned into account, a commonly used test such as paste content was not sensitive to the variables considered in order to know or estimate the quality of FRCA. In addition, the poor influence of the mineralogy of natural aggregates in parent concrete on the properties of FRCA was evidenced. This indicates that, the way in which the quality of FRCA is usually assessed should be rethought.

3.2 Fresh concrete properties

The properties of concrete in the fresh state are shown in Table 5. For quartzite FRCA concretes, slumps were higher than that in the parent concrete, despite the fact that lower amounts of water-reducing admixture were used. For granite FRCA concretes, higher amounts of water-reducing admixture (Table 3) were needed to obtain slump values similar to that in the parent concrete. This fact is in agreement with the differences observed in visual analysis between natural and recycled aggregates, in which more angular shape and roughness were observed in granite FRCA in comparison with NG. In contrast, quartzite FRCA showed more cubicity compared with NQ aggregates, which is in agreement with the higher slump for quartzite recycled concretes. In this sense, FRCA shape could have a great influence on concrete consistency, as the literature suggests (Butler *et al.*, 2014; Leite *et al.*, 2013). However, it is possible that a certain content of water, used to

Table 5. Fresh state properties of concretes

	CNG	CRG4	CRG6	CNQ	CRQ4	CRQ6
Slump: cm	5.5	4.5	4.5	6.0	9.0	8.0
Unit weight: kg/m^3	2465	2394	2423	2323	2323	2323
Entrained air: %	2.7	3.0	3.0	3.5	3.2	3.2

Table 6. Mechanical properties of concretes

Concrete	CNG	CRG4	CRG6	CNQ	CRQ4	CRQ6
Compressive strength: MPa	45.1 (0.5)	39.1 (0.7)	35.2 (1.1)	36.4 (1.8)	34.4 (2.6)	33.4 (2.8)
Flexural strength: MPa	4.2 (0.1)	3.7 (0.1)	2.9 (0.2)	5.2 (0.3)	5.1 (0.3)	4.7 (0.2)

Note: standard deviation is given in parentheses.

compensate for water absorption of aggregates, remains as free water, increasing slump. Moreover, as the content of free water becomes higher, the content of fresh cement paste increases, and the influence of the shape and roughness of fine aggregates on mixture slump becomes lower. Then, as quartzite aggregates (natural and recycled, fine and coarse) have higher water absorption compared with granite ones, the total water content in quartzite concretes increases significantly compared with granite concretes (see Tables 1 and 4).

A higher amount of water-reducing admixture was needed in CRG6 concrete in order to obtain an equal slump value to that of CRG4 concrete. Conversely, in concretes with quartzite FRCA, similar slump values were obtained for concrete with recycled quartzite (CRQ)4 and CRQ6 concretes with the same amounts of admixture. Thus, the compressive strength level in the parent concrete appears to have trivial or no influence on the slump value obtained.

No clear trend was noticeable regarding the influence of quality and type of FRCA on unit weight or entrained-air content of the recycled mixtures. The similarities of entrained-air contents could be due to the similar content of particles finer than 150 μm of fine aggregates that are responsible for occluded air (Bascoy, 1992).

3.3 Hardened concrete properties

3.3.1 Mechanical properties

The compressive and flexural strengths of concretes are presented in Table 6, where each reported value is the average of at least three tests. The corresponding standard deviation (values in parentheses) is also reported.

Concretes prepared with FRCA exhibited lower compressive strength compared with the parent concrete, for both types of mineralogy of natural aggregates. However, this reduction seems to be connected with the quality of FRCA (expressed by compressive strength of the parent concrete) and the mineralogy of natural aggregate. The decrease in compressive strength was between 10 and 20% for granite recycled concretes and close to 10% for quartzite recycled ones.

In addition, concretes prepared with quartzite aggregates showed lower compressive strength compared with those prepared with granite aggregates. These differences could be due to the quantity of water added to compensate for the absorption of quartzite (Q) aggregates (natural and recycled, coarse and fine), which could be higher than their water uptake during the mixing (Neville, 1995; Newman, 1969). Then, the $(w/c)_{eff}$ ratio would be higher in concretes with Q aggregates compared with concretes with granite (G) aggregates.

To verify this hypothesis, relationships between compressive strength and (*a*) total w/c ($(w/c)_{tot}$) and (*b*) $(w/c)_{eff}$ ratios are presented in Figure 5. Data from concretes under study (where 80% of aggregate water absorption was added as an additional amount of water) and from the literature are included. For each series, the coefficient of determination (R^2) for the exponential adjustment is reported. The compressive strength of concretes seems to be more strongly related to the $(w/c)_{tot}$ ratio than to the $(w/c)_{eff}$ ratio. From Figure 5(a)), as the $(w/c)_{tot}$ ratio increases, compressive strength decreases, despite the fact that R^2 is not high enough in some cases. When the $(w/c)_{eff}$ ratio is considered (Figure 5(b)), compressive strength to $(w/c)_{eff}$ ratio relationships do not follow the trend most widely known in the field, for any of the considered cases, but conversely compressive strength increases as the $(w/c)_{eff}$ ratio increases. This finding could be due to the overestimation of the quantity of water uptake by FRCA. If aggregates do not achieve their full absorption capacity during mixing, as recent literature suggests (Khoury *et al.*, 2018; Li *et al.*, 2018; Velay-Lizancos *et al.*, 2015), the additional amount of water added to compensate for the water absorption of aggregates remains free, increasing the $(w/c)_{eff}$ ratio.

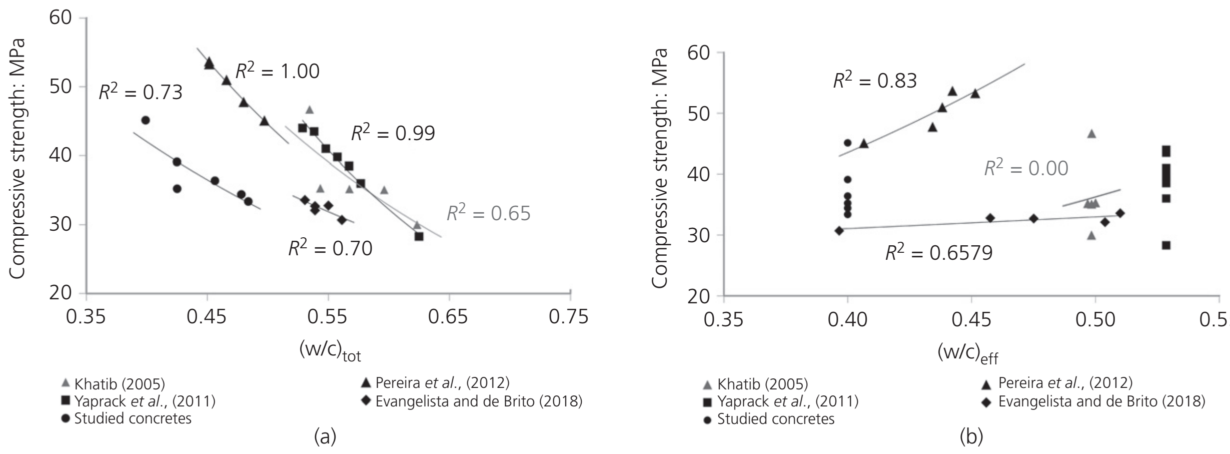

Figure 5. Compressive strength plotted against (a) $(w/c)_{tot}$ ratio, (b) $(w/c)_{eff}$ ratio

Therefore, considering full (or even 80%) absorption in mixture proportioning would not be the right practice to compensate for mixing water (to obtain the target $(w/c)_{eff}$ ratio), particularly in the case of recycled aggregates. Higher absorption of FRCA could lead to serious errors in the $(w/c)_{eff}$ ratio of the concretes produced. Thus, in this study, the higher slump values of Q concretes, compared with G concretes, could be a consequence of the overestimation of the water uptake by the aggregates during mixing (natural and recycled).

Regarding flexural strength, the trend is similar to that described for compressive strength – that is, the use of FRCA decreases flexural strength, less so for Q FRCA but more so for lower quality of parent concrete in both cases. In addition, concretes with Q aggregates showed higher flexural strength compared with concretes with G aggregates, for parent and recycled concretes. This is due to the greater surface roughness of coarse Q aggregates, compared with G ones that improve the quality of the interfacial transition zone (ITZ) (Giaccio and Zerbino, 1998). In this sense, flexural strength was close to 10% of the compressive strength for concretes with G aggregates, whereas it was approximately 15% for those prepared with Q aggregates.

3.3.2 Static modulus of elasticity

Figure 6 presents the average values of static modulus of elasticity determined on three specimens for each concrete. Concretes prepared with both types of aggregates (G and Q) showed differences in static modulus values. Concretes with Q aggregates presented a lower static modulus compared with concretes with G aggregates. This difference results from the mineralogy of each natural rock from which the aggregates were obtained. Compared with the parent concrete, the static modulus was lower for all recycled ones, particularly when FRCA of lower quality were used (RG6 and RQ6). This trend was replicated for both types of aggregates (G and Q). This difference should not be attributed only to the quality of FRCA, since static modulus is also correlated with compressive strength. Thus, lower compressive strength involves a decrease in the static modulus of elasticity. In addition, the difference in the static modulus for concretes prepared with RG4 and RQ4, compared with parent concretes, was close to 5%, which in practical terms is not significant. For concretes prepared with RG6 and RQ6, recycled concretes exhibited a static modulus around 15% lower than that of parent concretes.

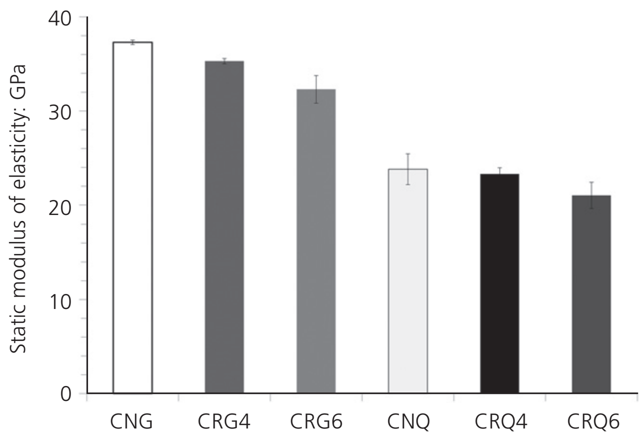

Figure 6. Static modulus of elasticity

A similar behaviour regarding static modulus in parent and recycled concretes is reported in the literature (Kim and Yun, 2014; Pereira *et al.*, 2012; Zega and Di Maio, 2006). Therefore, the influence of FRCA on the static modulus of recycled concrete will depend on the net consequence of the favourable effect of a better quality of the ITZ and the detrimental effect of the lower modulus of FRCA compared with natural aggregates.

3.3.3 Sorptivity

Figure 7 shows the sorptivity values determined according to the IRAM 1871 standard (IRAM, 2004) as a function of compressive strength, where each value was obtained as the average of five specimens for each concrete. The test technique consists of recording, at fixed intervals, the mass increment by capillary suction of a specimen having one face in contact with water, up to a constant weight (the difference between two consecutive weighings when this is less than 0.1%). Sorptivity is then calculated as the slope of the straight line obtained by linear regression that defines the absorption per unit area against square root of time.

Parent concrete prepared with Q aggregates presented higher sorptivity values than that obtained with G aggregates, which is in accordance with the type of natural aggregate used and the lower compressive strength level in Q concrete. Recycled concretes performed differently depending on the type of natural aggregate used (G or Q). For concretes with G aggregates, sorptivity increased 18% for RG4 and 86% for RG6, compared with the parent concrete. For concretes with Q aggregates, sorptivity of recycled concretes was similar to or even lower than that of the parent concrete. Regarding the quality of the parent concrete, its influence on sorptivity value was noted for RG concretes, but not for RQ concretes. What is more, although the compressive strength of RG6 concrete was similar to that of RQ concretes, the sorptivity values were lower for these RQ concretes. Attached mortar in recycled aggregates, the type of natural aggregate in the parent concrete and the ITZ quality are variables that have varying significance and they can modify transport properties. Thus, the ITZ plays an important role in the transport properties of the parent concrete (Leemann *et al.*, 2006), and recycled concretes are not an exception to this rule.

3.3.4 Drying shrinkage

Drying shrinkage in recycled concretes could be strongly influenced by FRCAs, since they have a higher content of particles finer than 75 μm compared with natural aggregates and provide additional quantities of cement paste. Figure 8 shows the drying shrinkage of concretes evaluated up to the age of 365 days on four $75 \times 100 \times 430$ mm^3 prismatic specimens for each concrete. The greatest difference was noted between the concrete groups prepared with each type of natural aggregate, granite or quartzite. This behaviour can be attributed to the different modulus of elasticity of coarse natural aggregates (Giaccio and Zerbino, 1998).

The main differences in drying shrinkage between the parent concretes and recycled ones, for each type of natural aggregate used, were produced at the early stages. Shrinkage of recycled concretes increased quickly until the age of 90 days and then the values remain nearly constant until 360 days, whereas for parent concretes, shrinkage increased slowly until 180 days. Then, for each type of natural aggregate, the ultimate shrinkage values were similar for recycled and parent concretes.

A similar or slightly higher drying shrinkage level in FRCA concretes, compared with those prepared with FNAs, has been reported by other authors. Two hypotheses have been proposed to explain this: lower autogenous shrinkage of recycled concretes (Evangelista and de Brito, 2004) and a lower $(w/c)_{eff}$

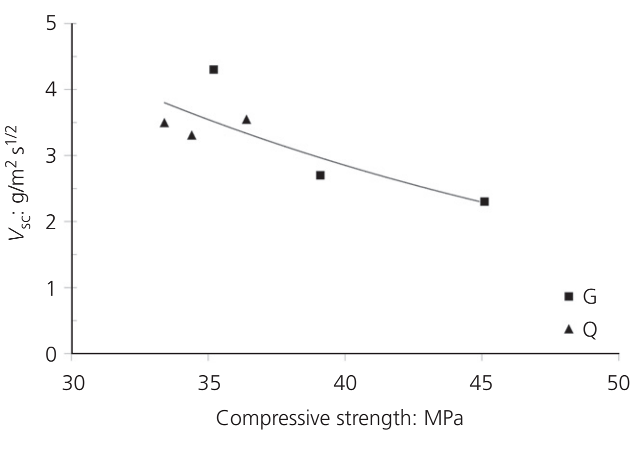

Figure 7. Sorptivity value for concretes

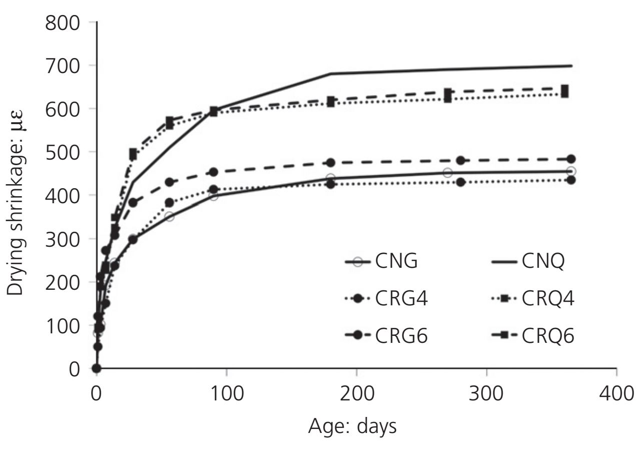

Figure 8. Drying shrinkage as a function of the age

ratio of recycled concretes due to water absorption of FRCA (Zega and Di Maio, 2006). Although these hypotheses can remain valid for those research studies, none of them could explain the results presented in this study. The first hypothesis cannot do so, because the w/c ratios of concretes were higher than those necessary to produce autogenous shrinkage (Bentz and Jensen, 2004). The second hypothesis is not plausible either, because an additional amount of water was added during mixing to compensate for the water absorption of FRCA. A third hypothesis that could explain a similar drying shrinkage between the parent and FRCA concretes is that FRCA retains some water inside (de Juan and Alaejos, 2009; Sosa *et al.*, 2015) that is afterwards released to the matrix. This delay in water transfer would cause recycled concretes to develop higher compressive strength compared with parent concretes. As a consequence, drying shrinkage would stop earlier.

Differences lower than 5% were obtained for ultimate drying shrinkage between the parent and recycled concretes prepared with granite aggregates. In concretes with quartzite FRCA, the ultimate drying shrinkage was 10% lower than that in the parent concrete.

As a consequence, and taking into account that the aim of this study was not to focus exclusively on the drying shrinkage of concretes, but on the influence of the properties of FRCA on different properties of recycled concretes prepared with them, specific tests should be carried out in future studies to understand the real influence of FRCA on drying shrinkage.

4. Conclusions

Different properties of FRCA are linked with some features of the parent concrete. FRCAs were obtained from concretes with two $(w/c)_{eff}$ ratios (0.40 and 0.55) and prepared with two types of natural aggregates (granite and quartzite). The influence of the properties of FRCA on the performance of the recycled concrete is also considered. From the analysis, the following conclusions can be drawn.

- The quality of the parent concrete, expressed by its compressive strength level, shows a great influence on porosity and soundness of FRCA, but this influence is not replicate for other test such as water absorption.
- Paste content in recycled aggregates is not a suitable indicator of the quality of FRCA. Other tests, such as porosity and/or soundness, are needed to determine the quality of FRCA.
- Compressive and flexural strengths, as well as static modulus of elasticity, decrease when FRCAs are used. These two properties also reflect the influence exerted by the compressive strength level of the parent concrete of FRCA.
- Compressive strength is better connected with the $(w/c)_{tot}$ ratio than with the effective ratio, not only based on the authors' own results, but also when those from the literature were considered. This trend could be an indicator that the additional amount of water added to compensate for water absorption of FRCA is not completely taken up by the aggregates, and consequently part of it remains as free water.
- The type of natural aggregate considerably modifies sorptivity values, both for recycled and parent concretes. While the use of granite FRCA increases sorptivity of recycled concretes, similar behaviour between recycled and parent concretes is produced for quartzite FRCA.
- Drying shrinkage of recycled concretes is more influenced by the type of natural aggregate than by the use of FRCA. The small differences between the parent and recycled concretes show minimal influence exerted by the quality of FRCA.
- Features of parent concrete such as the mineralogy and compressive strength of aggregates determine the quality of FRCA. Its influence on the properties of concrete varies according to the property considered. However, it is possible to produce concrete with mechanical and durability performance similar to those of parent concretes using FRCA.

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