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Research Paper

Parent Concrete Quality of Recycled Concrete Aggregates on Some Engineering Properties of Concrete

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This paper aims to investigate some properties of recycled aggregates concrete (RAC) containing various amount of recycled concrete aggregates (RCA) supplied from different parent concrete strength. Three concretes with different strengths were made. After hardening, they were crushed and the obtained RCA were used to substitute 20%, 40% and 60% of coarse ordinary aggregates (COA) in concrete mix. The properties of these RCA according to their parent concrete strength were analyzed and their effects on the workability, compressive strength and shrinkage were quantified. Concrete workability and final shrinkage seem to be related to the equivalent water absorption of coarse recycled aggregates. An equivalent granular expression can be used in classical model to predict compressive strength according to the RCA content and its parent concrete strength.

List of abbreviations

Abs: water absorption value
COA: coarse ordinary aggregates
CSH: calcium silicate hydrate
EDX: energy Dispersive X-ray
K_{COA} : granular coefficient of COA
NS: natural sand
p: substitution rate of COA by the RCA
Abs_{COA} : equivalent water absorption value of COA
Abs_{eq} : equivalent water absorption value
Abs_{RCA} : equivalent water absorption value of RCA
ITZ: interfacial transition zones
K_{RCA} : granular coefficient of RCA
OAC: ordinary aggregates concrete
S_0: parent concrete compressive strength

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RAC: recycled aggregate concrete
RCA: recycled concrete aggregate
Sc: concrete compressive strength
SEM: scanning electron microscopy
RCA1: recycled concrete aggregate from parent concrete strength of 52 MPa
RCA2: recycled concrete aggregate from parent concrete strength of 44 MPa
RCA3: recycled concrete aggregate from parent concrete strength of 34 MPa

1 Introduction

Construction and demolition activity generate a large amount of waste that creates visual pollution and occupies large landfills. For sustainable development, it is required to think about recycling this waste where RCA can be obtained by simple crushing processes. Most applications of RCA from demolition products are mainly used in the road field, but a better knowledge of concrete behaviour including such aggregates can contribute to the development of this application in the construction field.

The construction and demolition wastes were recycled into aggregates; the latter differs from ordinary aggregates by the old mortar that remains attached to their surfaces. This gives the new aggregates a rough and porous surface with a second interface transition zone. Mortar attached on RCA surface leads it with higher water absorption and weaker strength. The quality and the quantity of this mortar are directly linked to the parent concrete strength. Obviously, the strength and the porosity are related to the composition of the origin concrete thus depending on the sand quality and its w/c ratio [1, 2].

The mortar content attached to RCA might be related to the size of the COA, the parent concrete strength and the degree of prior mechanical crushing received. The content of attached mortar to RCAs is higher for reduced crushing process, small aggregate size and strong parent concrete [3]. The fraction of attached mortar to fine fraction is higher than that to coarse fraction; it was from 33% to 55% for 4/8 mm fraction while it ranges from 23% to 44% for 8/16 mm fraction [4]. Also, Seo and Choi [5] deduced that the amount of attached mortar showed a large reduction at approximately the 10 mm size. As can be seen, some results [4] showed that, 4/8mm RCA particles contained more mortar than the larger RCA particles. This is basically because the weaker parts of RCA that are made predominantly with mortar and can be easily detached during the very first contacts with the jaws of the crusher and fall into the smaller size fractions.

For four concretes mixes made with RCA having various origins concrete, Duan and Poon [3] concluded that RCA with good quality produced mechanical strength concrete comparable to that with only COA. It can be concluded from Duan and Poon [3] results that concrete made with RCA having less than 24.3% of attached mortar content was still able to reach 60 MPa compressive strength. Also, it has been found that RCA containing more attached mortar undergo 10% reduction in compressive strength compared to control concrete. If the attached mortar on the surface aggregate is about 10 percent, the bond quality can be improved. However, over a certain amount of attached mortar, the bond quality improvement is not so effective [5]. It can be noted that only RCA with mortar content lower than 44% could be used for structural concrete [4]. From some experimental results [6], the presence of high content of attached mortar on the RCA surfaces with anhydrate cement particles and high porosity affect activation energy and the maturity of concrete.

The mortar content attached to RCA depends directly to the parent concrete strength. Attached mortar on RCA surface, obtained from high strength concrete, is stronger which cannot be easily removed by crushing. This leads to RCA with higher attached mortar content [7]. Besides, it varies from 40%, 56% and 58% for parent concrete strength of 30 MPa, 60 MPa and 90 MPa respectively. Where concrete containing RCA made from parent concrete strength of 30 and 90 MPa, its compressive strength achieves 42 and 56 MPa respectively [7]. It was obvious that compressive strength concrete made with RCA is always lower than that of parent concrete of these aggregates at all curing ages [8]. Whereas RCA obtained from higher grade concrete leads to concrete with comparable strength grade. The strength concrete drop with recycles aggregates is between 20 and 35% for concrete made with 10 mm maximum size aggregate and 14–35% for 20 mm and 10–25% for 40 mm. This proves that the higher reduction is for concrete composed with smaller size aggregate caused by higher content and weaker parent mortar in smaller size aggregate [9]. In the same way, a decrease of 34.1% and 25.7% in compressive strength is recorded when 100% and 50% of aggregates from crushed field concrete replace natural aggregates respectively [10].

The high-water absorption of RCA is attributed to the presence to old mortar attached to aggregates [11]. The negative effects of this attached mortar on water absorption are proportional to its content and its quality [4]. This characteristic influences in a significant way the effective mixing water and thus implies its eventual compensation [12]. Ait Mohamed et al. [13] concluded that the pre-saturation method of RCA is favourable to compensate the high-water absorption of these aggregates. With its high absorption, concrete with RCA needs more superplasticizer dosage. In Domingo et al. work [14], concrete with RCA needs two times superplasticizer dosage to keep the same workability compared to ordinary concrete. When the dosage of superplasticizer is kept the same the concrete containing RCA exhibits low slump of 50 mm, much lower than the 200 mm slump produced by concrete without RCA [10].

When RCA were subjected to abrasion test, the mortar attached to its surface was easily disintegrated and the Los-Angeles abrasion values increased in proportion to the mortar content. This make RCA more sensitive to abrasion and its Log-Angeles coefficient took a value 50% higher than that of ordinary concrete [15]. From Padmini et al. results [9], it can be noted that abrasion values of RCA decrease for high maximum size aggregates and for weak parent concrete strength. Some results of De Juan and Gutiérrez [4] suggested that RCA with less than 44% attached mortar kept acceptable abrasion values and can be used in concrete formulation.

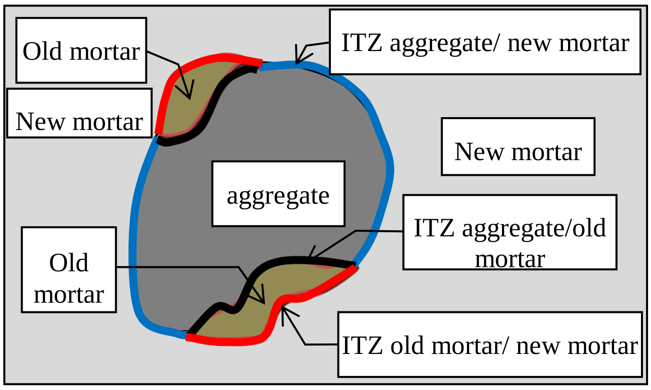

Fig. 1 – Schema of RCA composition with different ITZ types.

In concrete mixture, interfacial transition zones (ITZ) were connecting elements between COA and mortar. The stronger of such connection allowed the good transfer of the stresses between COA and mortar and the obtaining of high strength concrete [16]. When RCA were introduced into a new concrete mixture, their adherence with the new cement paste was in a different way compared to that of COA as shown in Fig. 1. Several researches [16-18] stated that the interface zones around RCA were poor with negative bond quality compared to that around COA. Furthermore, the attached mortar can produce additional hydration products and thus hardened the interface zone between RCA and the new paste [19]. Several parameters controlled this interface zone, which was generally related to the quality of the new hydrates formed on the RCA surface and their physicochemical bonds [20, 21].

It has been observed in SEM images [22] that concrete containing RCA had some discontinuous voids near the ITZ zones, whereas the concrete with recycled brick aggregates showed some internal voids and visible microcracks that resulted in lower compressive strength, especially for high content. In the same way, it can be seen from Energy Dispersive X-ray (EDX) elemental analysis results [23] that old ITZ had higher amount of hydration products of calcium silicate hydrate (CSH) than the new ITZ, which suggested a relatively stronger old ITZ. If the parent concrete was stronger than the concrete mix, the failure of concrete started in the new ITZ, suggesting that the new ITZ of this mix was weaker than the old ITZ. Unlike the concrete mix was stronger than the parent concrete, the failure started in the old ITZ, suggesting that the new ITZ was stronger than the old ITZ in this mix [23].

The shrinkage phenomenon is the volume reduction caused by the water loss of mixing water by evaporation or cement hydration after concrete mixing. In addition to the well-known factors, which govern this phenomenon, the quality and the quantity of the RCA have a great influence when they are used in concrete mix. Using lower quality of RCA as well as higher replacement ratios leads to higher values of drying shrinkage within the concrete [24]. However, a reduction in the autogenous shrinkage is possible when using higher content of lower RCA quality that can act as internal curing [24, 25]. It has been widely found [26]. that drying shrinkage increased with the increase in the attached mortar content to RCA. According to [27] results, the relationship between the shrinkage values and the recycled brick aggregates content is linear, with an increase between 35 µm/m and 45 µm/m for every 10% of substitution rate. Similar shrinkage was observed when the properties of the parent concrete and the recycled aggregates concrete (RAC) were similar, while varied shrinkage was observed when the properties of the parent concrete and the RAC were different [25]. Several works [23, 26] reported that RCA from higher-strength parent concrete could help to reduce drying shrinkage concrete. RAC with compressive strength of 80 MPa reached

100% increase of 360 days' shrinkage when using RCA of 20 MPa parent concrete strength, but it had only 7% increase when using RCA of 110 MPa parent concrete [28].

The mean objective of this work is to study the quality and quantity of attached mortar to RCA when they are used in concrete formulation. Three concretes with different strengths are crushed to give three types of RCA. These aggregates replace a part of COA in RAC. RCA effects on the properties of workability, compressive strength and shrinkage were studied according to the parent concrete quality.

2 Granular Coefficient

Concrete compressive strength is a property of which most other properties of concrete are connected. For its evaluation, Feret model is used to evaluate this value for concrete containing only ordinary aggregates and a part of RCA [29].

$$S_c = \frac{K_{COA} S_{c28} K_t}{\left[1+\frac{w}{c} d_c (1+y)\right]^2} \tag{1}$$

where K_{COA} is a granular coefficient of COA that depends on its granular skeleton, K_t takes into account the effect of concrete age. Sc28 represents the 28 days' compressive strength of the standardized mortar equal to 42.5 MPa in this case. *c* and *w* are the weights of cement and mixing water used for concrete mix. dc is the cement grains density (dc=3.1) and y is a coefficient depending on the concrete consistency and takes y=0.1 for a plastic concrete [30].

In general case of concrete containing p proportion of RCA with a granular coefficient K_{RCA}, and (1-p) proportion of COA with granular coefficient K_{COA}, the K_{COA} coefficient can be replaced by an equivalent granular coefficient K_{ae} composed of these two parts of aggregates effects expressed as follows:

$$K_{ae} = (1-p)K_{COA} + pK_{RCA} \tag{2}$$

By replacing the expression K_{COA} in Eq. (1) by its equivalent value expressed by Eq. (2), the compressive strength with RCA can be written as:

$$S_{RCA} = \frac{((1-p)K_{COA} + pK_{RCA})}{\left[1+\frac{w}{c} d_c (1+y)\right]^2} S_{c28} K_t \tag{3}$$

From compressive strength of concretes with and without RCA expressed in Eqs (1) and (3), the ratio of the two granular coefficients of COA and RCA is written as follows:

$$\frac{K_{RCA}}{K_{COA}} = \frac{1}{p}\left(\frac{S_{RCA}}{S_{COA}} - (1-p)\right) \tag{4}$$

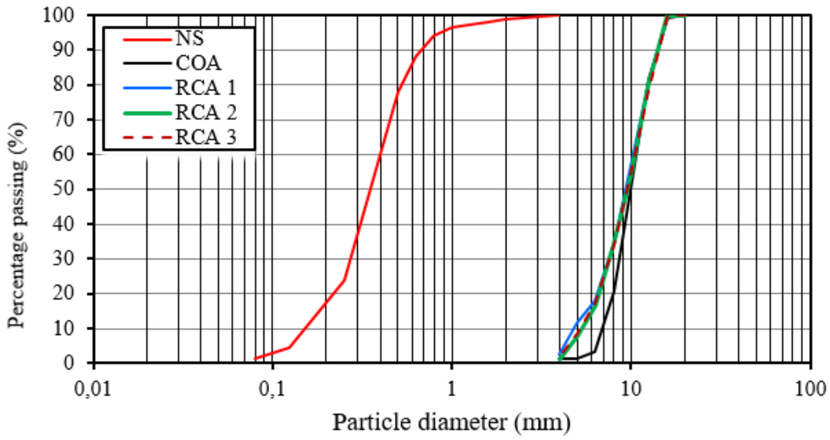

Fig. 2 – Particles size distribution of the aggregates used.

3 Materials and Method

3.1 Materials

Blended cement (CEM II) widely produced and containing 10% of limestone powder, having 28-day compressive strength of 42.5 MPa and specific surface area of 320 m2/kg was used for all mixtures. The COAs used were obtained from the quarry and the natural sand was provided from the river (NS). For practical considerations and to evaluate the quality of mortar attached to RCA on concrete properties, three types of concrete were manufactured with three classes of strength. These concretes were made with COA and mixed with three w/c ratios, namely 0.4, 0.5 and 0.6, which reach 28 days' compressive strengths of 52, 44 and 34 MPa respectively. At this age, the concretes were crushed and sieved to remove undesired particles size less than 4 mm, which gives three types of RCA; RCA1, RCA2 and RCA3. Fig. 2 shows the sieve analysis results of various obtained RCA. Some characteristics of these aggregates are summarized in Table 1. Polycarboxylate superplasticiser was used to maintain the same workability for all tested mixtures.

Table 1 – Physical-mechanical characteristics of aggregates.

	COA	RCA1	RCA2	RCA3	NS
Fineness modulus	-	-	-	-	1.98
Sand equivalent	-	-	-	-	80
Compactness (%)	48,97	47,52	46,93	46,62	55,11
Bulk density (kg/m^3)	1329.7	1188.5	1172.5	1189.4	1473.5
Specific weight (kg/m^3)	2715	2625	2596	2575	2673,8
Los-Angeles (Abrasion) (%)	27	34	37	39	-
Water absorption (%)	0.87	5.12	5.95	6.3	-
Shape index	33	17	19	20	
Parent concrete compressive strength (MPa)	/	52	44	34	/

Table 2 – Mixing proportions of materials used for one m^3 of concrete.

	OAC	RCA1-20%	RCA1-40%	RCA1-60%	RCA2-20%	RCA2-40%	RCA2-60%	RCA3-20%	RCA3-40%	RCA3-60%
Natural sand (kg)	713	713	713	713	713	713	713	713	713	713
Coarse ordinary aggregates (kg)	1287	1029	772	514	1029	772	514	1029	772	514
RCA1 (kg)	0	257	515	772	0	0	0	0	0	0
RCA2 (kg)	0	0	0	0	257	515	772	0	0	0
RCA3 (kg)	0	0	0	0	0	0	0	257	515	772
Cement (kg)	430	430	430	430	430	430	430	430	430	430
Mixing water (Kg)	215	215	215	215	215	215	215	215	215	215
superplasticizer (%)	0.55	0.55	0.65	0.7	0.65	0.75	0.8	0.75	0.85	1
Slump (mm)	155	160	150	120	170	160	160	160	140	150

3.2 Mix Proportions

The effect of parent concrete strength of RCA was studied by comparison concrete properties mixed with various RCA. Dreux-Gorisse method is used to determine the best proportion of each aggregates used to obtain a compact mixture. Ordinary aggregate concrete (OAC) was made with fine and COA and w/c ratio of 0.5 which represent the reference concrete. In ordinary concrete, the COA were partially substituted by 20; 40 and 60% by weight for each type of RCA in its dry state. The tested concretes with various compositions are summarized in Table 2.

3.3 Sample Preparation and Testing Procedure

Cement, COA and RCA were first mixed dry for 2 minutes, then 2/3 part of mixing water was added and mixing was continued for 2 minutes. Finally, the remaining mixing water and the superplasticizer were added and another additional minute of mixing was performed. Concrete workability was evaluated using the Abrams cone slump test according to European standard 12350-2 [31]. To measure compressive strength concrete, 100x100x100 mm cubic specimens were made according to European standard 12390-4 [32]. The samples were cast in steel molds with vibrating table compaction. One day later, the samples were remolded and stored in water at a temperature of 20 ± 2 °C until the testing day. Each value obtained represents the average of three tests whose coefficients of variation for the results were less than 5%. From the age of one day, total shrinkage was measured on 70x70x280 mm prisms conserved in laboratory conditions (20± 2 °C and of 50± 5% RH) by using LVDT sensors. To avoid the edges effect, the top and bottom surfaces of specimens were covered with a waterproof layer. Shrinkage strains were measured up to 1 year with accuracy less than 0.001 mm.

4 Results and Discussion

4.1 Recycled Concrete Aggregates Properties

Mechanical and physical tests were performed on COA and RCA obtained from various parent concrete strength which allow to distinguish some properties presented in Table 1. The parent concrete strength is critical to control the RCA quality. The Los-Angeles abrasion values and the water absorption became lower if this aggregate is from high strength concrete as is the case of RCA1. COA present weak absorption value and meets the required conditions for concrete manufacture. The obtained RCA presents high water absorption value according to the attached mortar content as well as its quality. It is obvious that if RCA is from high parent concrete strength, the lower the mortar porosity and the lower the mortar absorption. RCA reach water absorption values of 5.12%, 5.95% and 6.3% for parent concrete strength of 52 MPa, 44 MPa and 34 MPa respectively which is in concordance with others researches results [11-13]. This found is in conformity with Liu et al. [33] results in which RCA from parent concrete of 34.9 47.2 and 57.3 MPa reach coefficient absorption of 6.4, 5.6 and 4.6% respectively

4.2 Workability

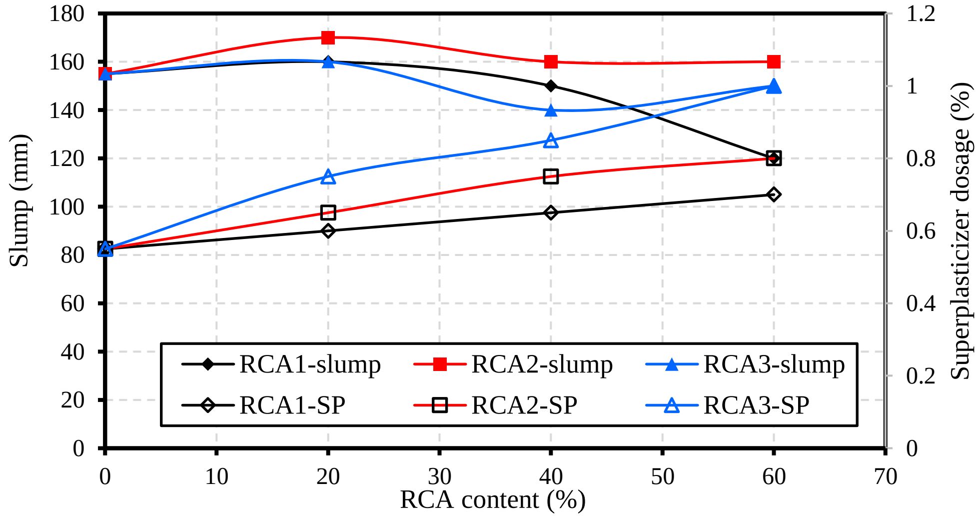

Fig. 3 – Variation of slump and superplasticizer requirement according to RCA content.

To maintain the same workability for all concretes, suitable dosages of polycarboxylate superplasticizer were added for each mixture. The concrete workability was about 160±10 mm measured by Abrams cone which represents a convenient concrete for casting. The required dosage of superplasticizer found for each concrete was illustrated in Fig. 3. It is shown that when RCA content increases, the workability gives a strong decrease and concrete needed more superplasticizer dosage to keep the same workability as is presented in Fig. 3. For concrete containing 60% of RCA, it must be added more than 0.15, 0.25 and 0.45% of superplasticizer to have the same workability for RCA1; RCA2 and RCA3 aggregates respectively. In the same way Braymand et al. [34] used a large quantity of admixture (3%) for RAC to take into account a large amount of mixing water absorbed by the RCA.

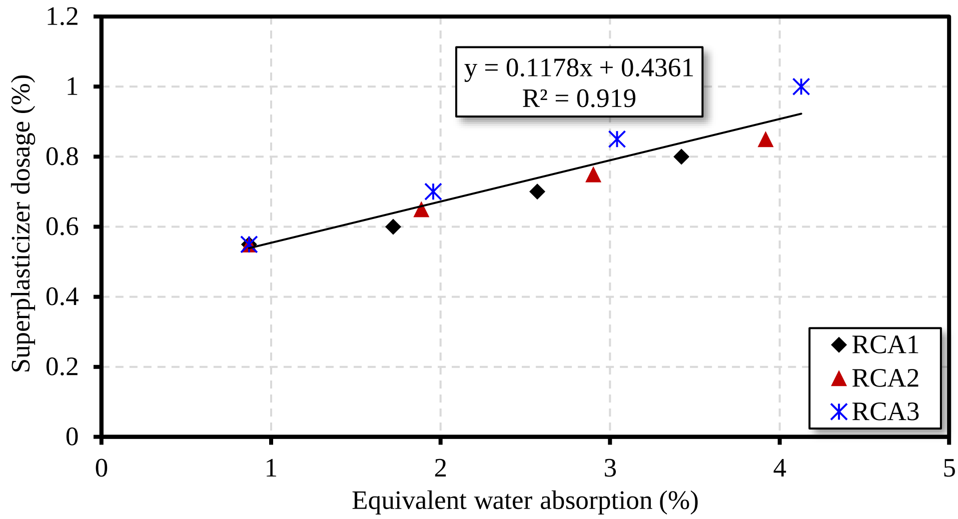

Fig. 4 – Superplasticizer dosage for RAC according to the equivalent water absorption of RCA.

RCA are well-known for their high specific surface area and their high absorbent mortar attached on their surfaces. This makes the mixing water insufficient to provide a workable concrete from which a suitable dosage of superplasticizer is desirable. This fall in workability is also concluded in the Hansen and Narud results [35]. In the same way, when the amount of absorbed water by RCA was added with the mixing water, there was no effect on concrete workability and the superplasticizer dosage [36, 37]. This attached mortar leads to rougher texture of the surface and creates an angularity of the RCA which leads to a drop-in workability. For the same reason, the small density of the concrete with RCA leads to a higher demand for mixing water [7, 13, 38].

The quantity and quality of attached mortar to RCA generate high water absorption which reduces concrete workability and leads to an increase of superplasticizer dosage. The substitution of COA by RCA with different water absorption rates requires an evaluation of equivalent water absorption of the mixture using Eq. (2).

$$Abs_{eq} = (1-p)Abs_{COA} + pAbs_{RCA} \tag{5}$$

To give a concrete with a slump of 160 mm, Fig. 4 illustrates the variation of the needed superplasticizer dosage found for each RCA used according to the equivalent water absorption coefficient. The correlation is almost perfect and its correlation coefficient is very close to unity. We can conclude that 1% increase in equivalent water absorption leads to adding 0.12% of superplasticizer to the mixture to reach the same workability.

4.3 Compressive Strength

The obtained results of compressive strength represent the average of three values for each test. For concrete containing RCA, the strength increases over time in the same way as ordinary concrete, as presented in Figs. 5, 6 and 7. These results show a positive effect of RCA which remain linked to their rate used and the quality of their parent concrete. RCA1 obtained from parent concrete strength of 52 MPa lead to a linear improvement as a function of its substitution rate. This gain reaches its maximum values at early age when concrete containing 20, 40 and 60% of RCA1 reaches compressive strengths of 31, 84 and 115% higher than that of the concrete without RCA respectively. At 90 days, this improvement is only 3.4, 8.1 and 12.9% for the same rates respectively. The same result is observed for RCA2 aggregates obtained from parent concrete strength of 44 MPa with a weak improvement. On the other hand, the RCA3 aggregates obtained from parent concrete strength of 34 MPa have a positive effect only at early age. After 28 days, its presence induces a negative effect where there is a drop in compressive strength compared to ordinary concrete of 8.2, 8.6 and 9.4% for replacement rates of 20, 40, and 60% respectively. At 90 days, this fall is negligible and no exceeds 2% for all concrete made.

From the obtained results, it is clear that RCA causes a quick development of compressive strength at early age. This kinetic variation is caused by RCA content as well as their quality specially the water absorption and their parent concrete strength. At early age, a part of mixing water takes refuge in RCA pores, thus causing a drop in water cement ratio, which improves the compressive strength. In addition, the rough shape of the RCAs promotes adhesion with the new paste and makes the ITZ stronger. In the long term, it was observed that the ultimate compressive strength decreases for low quality of RCA aggregates. RCAs are porous and less strong than natural aggregates as evidenced by the high values of water absorption and Los-Angeles abrasion values found. This means that recycled aggregate concrete have an earlier initial strength gain and a lower ultimate strength.

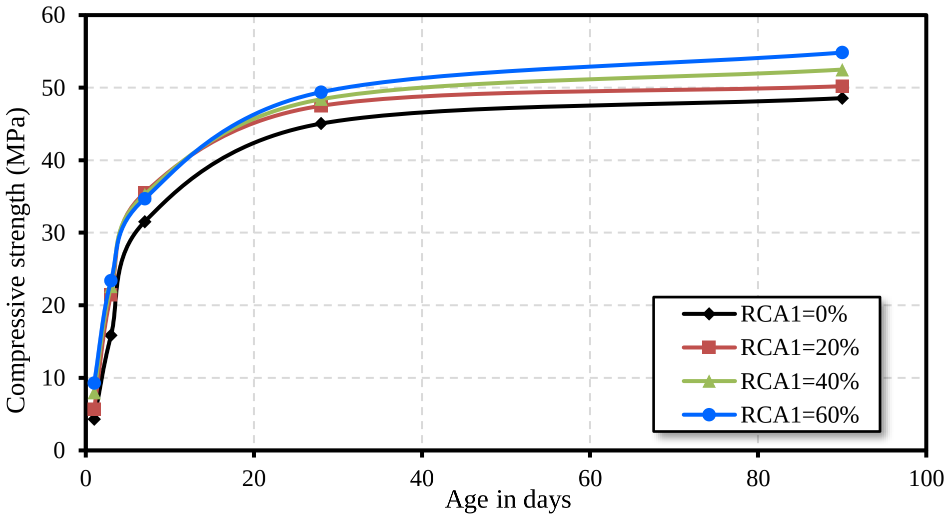

Fig. 5 – Variation of concrete compressive strengths versus age for various RCA1 aggregates content.

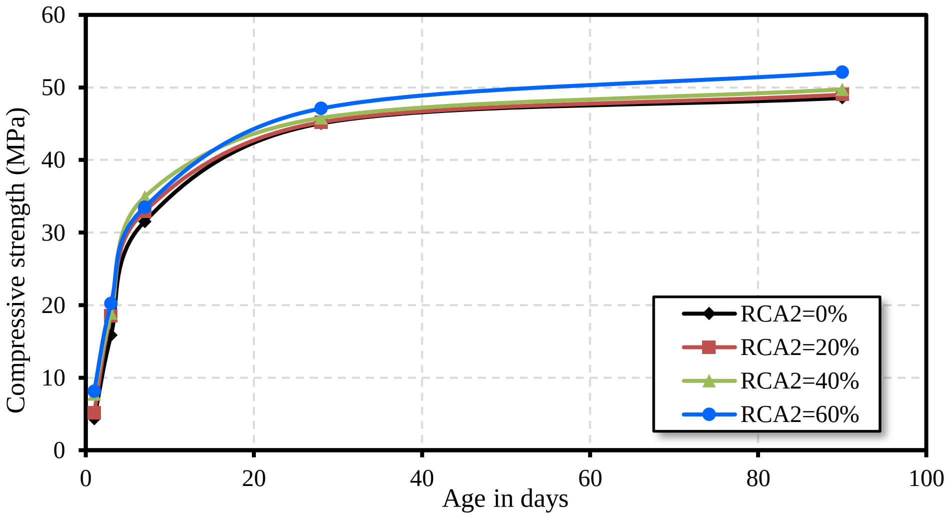

Fig. 6 – Variation of concrete compressive strengths versus age for various RCA2 aggregates content.

According to Etxeberria et al. results [39], this increase in compressive strength is caused by the rougher surface texture of RCA compared to COA, which generates an increase in adhesion between the new paste and the aggregate surface that creates a stronger ITZ and improves the mechanical strength. It is obvious that the quality of the parent concrete promotes this adhesion and makes the new structure more compact with stronger bonds. This is manifested by improvements in early age strength as shown in Figs. 5, 6 and 7. However, Sagoe-Crentsil et al. [40] concluded that compressive strength at 28 days was the same as for the control concrete containing only COA. Also, it was concluded that the use of 30% RCA did not adversely affects the mechanical properties of concrete [41]. The results found in this work were in line with this conclusion, where the compressive strength after 28 days differs only by 10% depending on the parent concrete strength. Also, Cantero et al. [42] reported that in concretes manufactured with RCA, there is a uniform distribution of aggregates types in the cement matrix with no significant differences between the ITZ thicknesses.

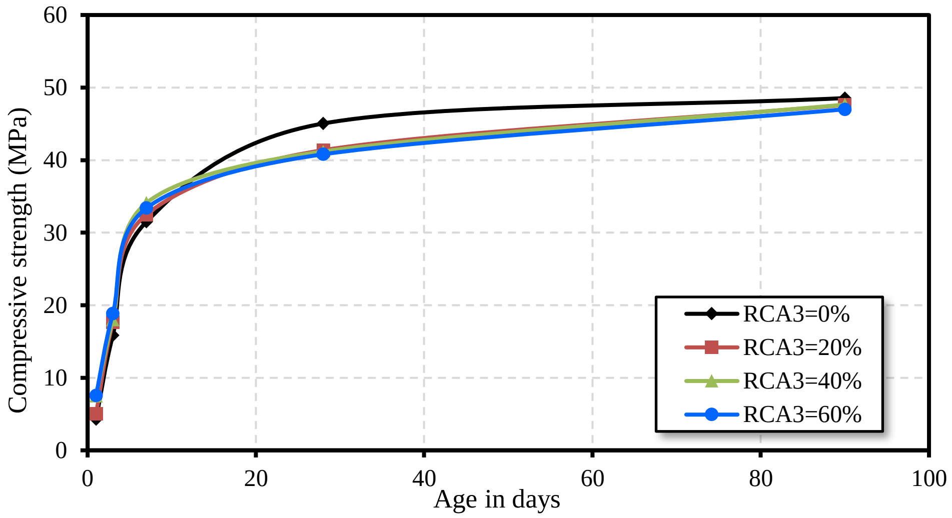

Fig. 7 – Variation of concrete compressive strengths versus age for various RCA3 aggregates content.

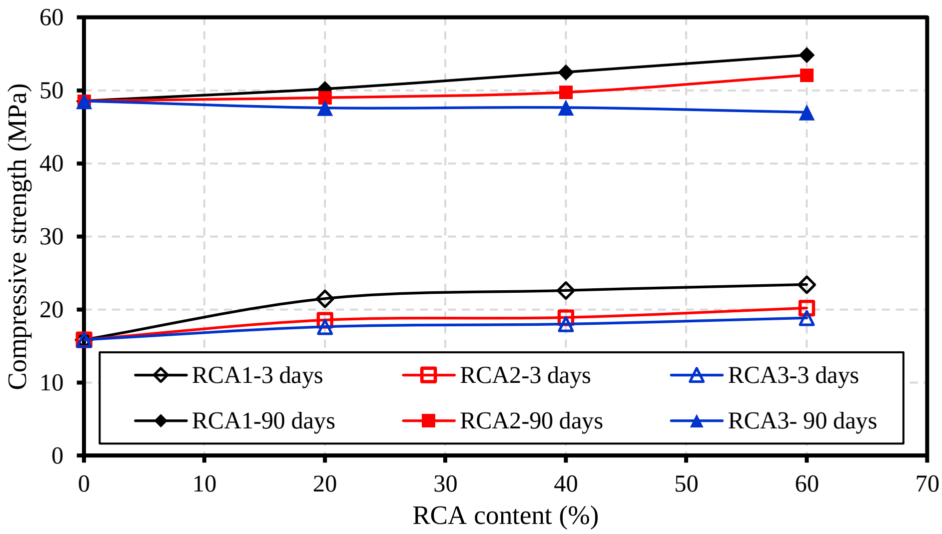

Fig. 8 – Effect of RCA content on concrete compressive strength at early and later age.

The quality of the attached mortar to RCA plays a key role in the development of mechanical strength. Fig. 8 illustrates the variation in compressive strength at 3 and 90 days for concrete containing three kinds of RCA. It is well observed that concretes containing RCA have higher strengths at 3 days. This gain is proportional to the RCA content present in concrete mix as well as to the parent concrete class of recycled aggregates. At later age, RCA of weak quality generate lower strengths depending on their substitution rate in concrete. Parent concrete strength of RCA plays a fundamental role in compressive strength development of RAC. With lower water absorption and a lower Los-Angeles abrasion value, RCA1 adhere better to the new paste and contribute positively to develop high strength.

The strength gain may also be caused by the presence of the RCA which improve the microstructure of the ITZ and increase the bond strength between the new cement paste and the old aggregates. According to bond results Kou and Poon [27] quality, an improvement in bond strength would induce a higher increase in tensile strength than in compressive strength. However, an increase of the mortar content in RCA did not significantly affect the compressive strength of the RCA concretes. In this case, the negative impact of the increase of the mortar content is partially offset by the positive impact of an increase in strength and density as well as the better bond between natural aggregates and mortar present in stronger concretes [43].

One may intuitively expect that for stronger parent concrete of 90 MPa, the mortar is stronger with better bond on the COA that should result in some improvements in RAC proprieties [7].

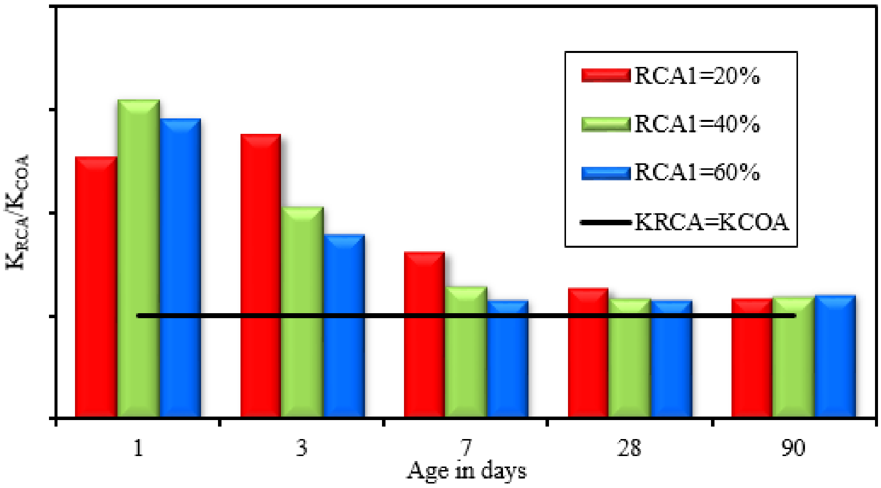

Fig. 9 – Variation of granular coefficients ratio versus age for various RCA1 aggregates content.

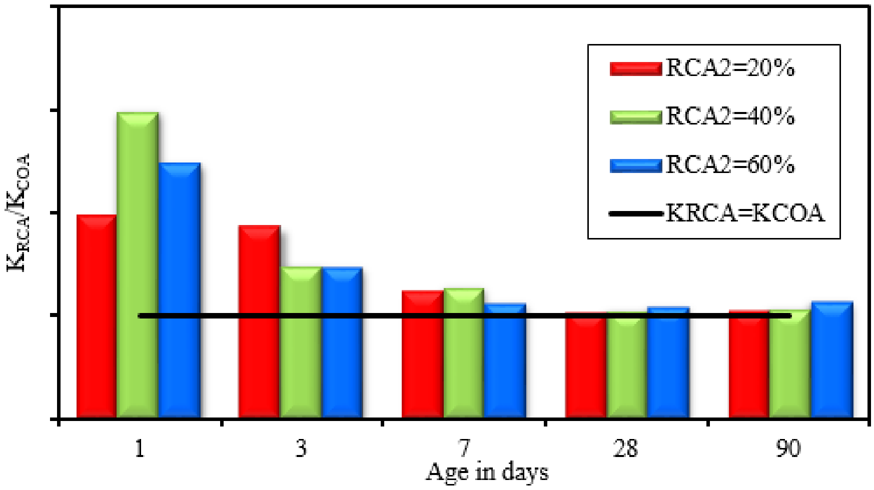

Fig. 10 – Variation of granular coefficients ratio versus age for various RCA2 aggregates content.

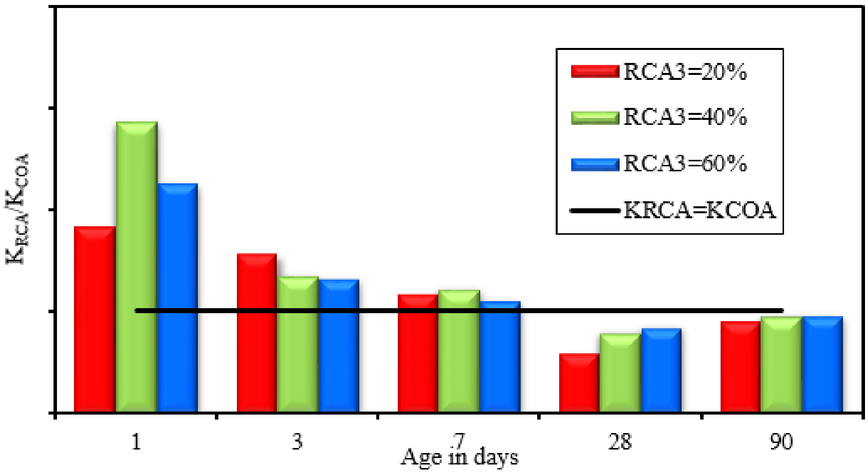

Fig. 11 – Variation of granular coefficients ratio versus age for various RCA3 aggregates content.

The added of superplasticizer is an effective way to compensate water absorbed and strength loss caused by RCA as their contents increase. These mixtures may be less effective for concretes containing high levels of dry RCA, which absorb some of the mixing water. To reduce this effect, it is necessary that RCA will be used in a saturated state to ensure that superplasticizer is properly adsorbed and that it can develop its positive effect [13, 43]. The quality of attached mortar to aggregates is effective only if it comes from a concrete with w/c ratio less than 0.4 or for advanced ages. Fig. 8 illustrates this effect for several ages of concrete.

4.4 Granular Coefficient Evaluation

From compressive strengths results of different concretes tested and by applying Eq. (4) giving the ratio between the granular coefficient of RCA and COA, we obtain the results mentioned in Figs. 9, 10 and 11. The presence of RCA in the manufacture of concrete is more effective at early age. At one day, 40% of RCA leads to optimal values of compressive strength when the granular coefficient is three times greater than that of COA. After 3 days, the quality of the RCA remains important where 20% of RCA1, RCA2 and RCA3 make the granular coefficient 2.7, 1.8 and 1.5 times higher than that of the COA respectively. Whereas beyond this rate this effect takes a weak trend despite the RCA effect still remains positive.

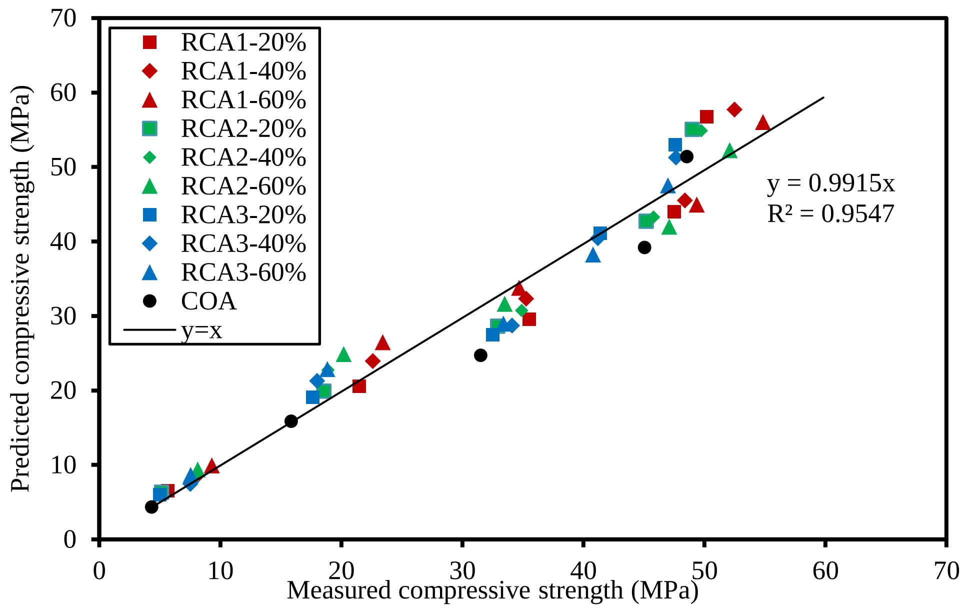

Fig. 12 – Relationship between predicted and measured compressive strength for concretes with various type of RCA.

At later age, only granular coefficient of RCA1 remains slightly higher whereas that of RCA3 aggregates is 10% lower. The superiority of the granular coefficient of RCA is associated with its attached mortar quality which promotes its adhesion with the new mortar. This quality is more pronounced at early age and for RCA obtained from high parent concrete strength like the case of the RCA1 where its parent concrete reaches compressive strength of 52 MPa. At later age, the concretes converge towards similar strength and the granular coefficients decrease to approach more to that of COA. When RCA is derived from a low strength concrete, its contribution is reduced and its granular coefficient tends to a value lower than that of COA as the case of the RCA3.

By applying Eqs. (1) and (3) to compression strength results, the granular coefficients of COA and RCA can be obtained. With linear regression using the least squares method, it is possible to deduce the parameters defining the hardening of the all concretes as a function of time, the RCA content and the parent concrete strength. Several relationships were tested to give the highest correlation coefficient and to minimize the mean squared error at its lowest possible value. Eq. (6) summarized the results found to express Eq. (7). Fig. 12 illustrates a comparison between measured and predicted values where the correlation coefficient reaches a value close to unity of 0.95 corresponding to a mean squared error of 3.4 MPa.

This justifies the reliability of the results found and the presented relationships correlates very well the experimental results. The factors defined in Eq. (3) and found by this operation are summarized as follows:

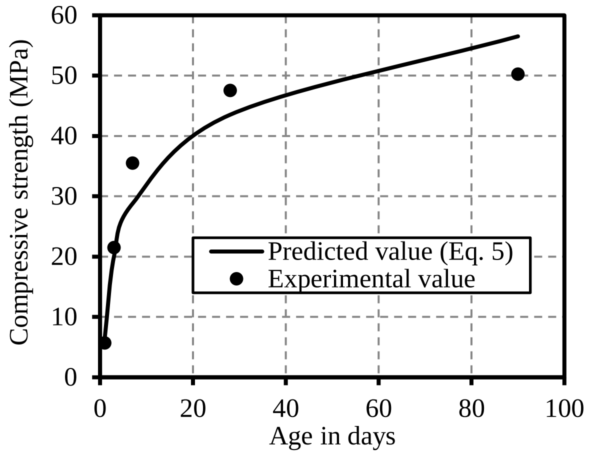

Fig. 13 – Strength-age data best-fit curves for Concrete containing 20% of RCA1.

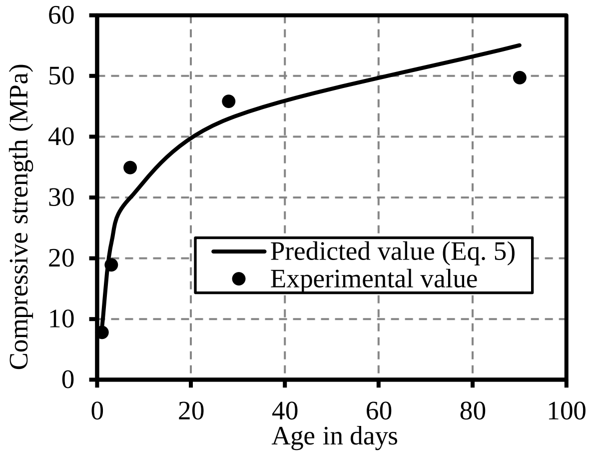

Fig. 14 – Strength-age data best-fit curves for Concrete containing 40% of RCA2.

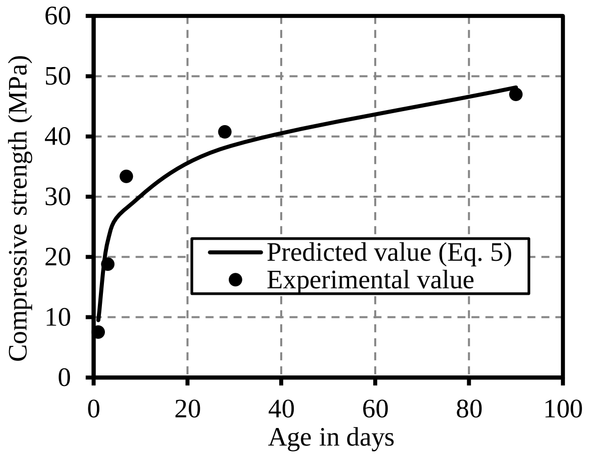

Fig. 15 – Strength-age data best-fit curves for Concrete containing 60% of RCA3.

$$\left.\begin{array}{ll} Classe\ of\ cement: & S_{c28} = 42.5\ MPa \\ ge\ evolution\ effect: & AK_t(t) = 0.3 + 0.72\,ln(t) \\ ranular\ coefficient\ \ (COA): & G\ K_{COA}\ =\ 2.5 \\ Granular\ coefficient\ (RCA): & K_{RCA} = \frac{1.3+0.06\,S_0}{1+p} + \frac{7+0.06\,S_0}{1+t} \end{array}\right\} \tag{6}$$

Eq. (3) takes the following expression:

$$S_c(p,t) = \frac{\left(2.5\,(1-p)+p\left(\frac{1.3+0.06\,S_0}{1+p}+\frac{7+0.06\,S_0}{1+t}\right)\right)}{\left[1+\frac{w}{c}d_c(1+y)\right]^2}\ \ 42.5\,(0.3\ +\ 0.72\,ln(t)) \tag{7}$$

With t is the concrete age expressed in days, p is the substitution rate of COA by the RCA and S_0 is the parent concrete compressive strength. To better illustrate the results found, Figs. 13, 14 and 15 give a presentation of some tested concretes where the comparison of the experimental compressive strength results converges perfectly with those given by Eq. (7) by using the parameters of Eq. (6). Thus their evolution over time makes it possible to deduce a logarithmic equation corresponding to the hardening of the concrete.

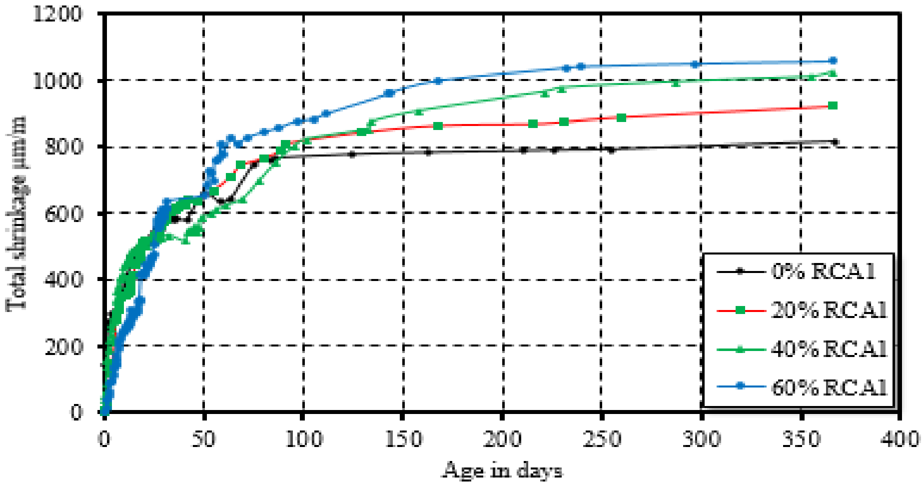

Fig. 16 – Total shrinkage evolution of RAC with various substitution rates of RCA.

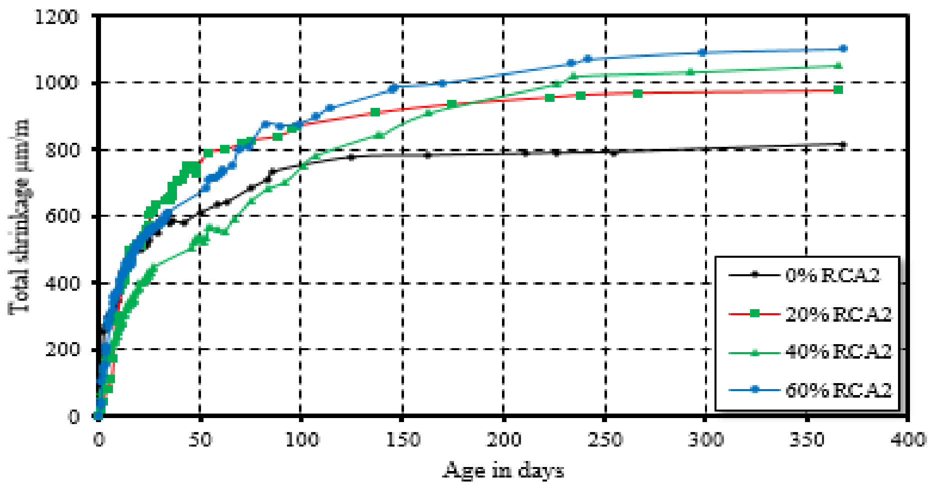

Fig. 17 – Total shrinkage evolution of RCA with various substitution rates of RCA2.

4.5 Total shrinkage

In recycled concrete aggregates, the presence of the attached mortar from a parent concrete gives the aggregates high porosity which acts as a cavern for mixing water. When the concrete hardens, the drying of this water leaves voids and leads to increased shrinkage. This shrinkage is as much higher as the quality of the attached mortar is weak and the RCA content is high. The total shrinkage results illustrated in Figs. 16, 17 and 18 show the change in strains for concretes containing 0%, 20%, 40% and 60% RCA derived from three parent concretes. Before 28 days, all concretes show a similar shrinkage regardless of the quality and quantity of recycled aggregates used in concrete mix. After one year, the shrinkage for concrete containing 20%, 40% and 60% of RCA3 aggregates is 13%, 30% and 40% higher than the shrinkage of concrete without recycled aggregates. The increase in drying shrinkage of RAC can be explained by the presence of higher amount of cement paste composed of old and new paste, which creates high porosity and causes higher shrinkage than normal concrete. This increase in shrinkage is higher and delayed when RCA originates from low-strength concrete. The water initially evaporated through the pores of the cement matrix will be compensated by the reserve stored in the attached mortar porosity and thus delays the shrinkage deformations. Also, the attached mortar to recycled aggregates affects their modulus of elasticity which makes them more deformable, causing more stress in the cement paste and thus more shrinkage. In addition, the week elastic modulus of RCA leads of lower restraint of drying shrinkage as concluded by Gayarre et al. [27]. This is in accordance with the results presented by Domingo-Cabo et al. [44] where the shrinkage of concretes containing 20% of recycled aggregates presents similar shrinkage at 28 days on the other hand after six months it is 4% higher.

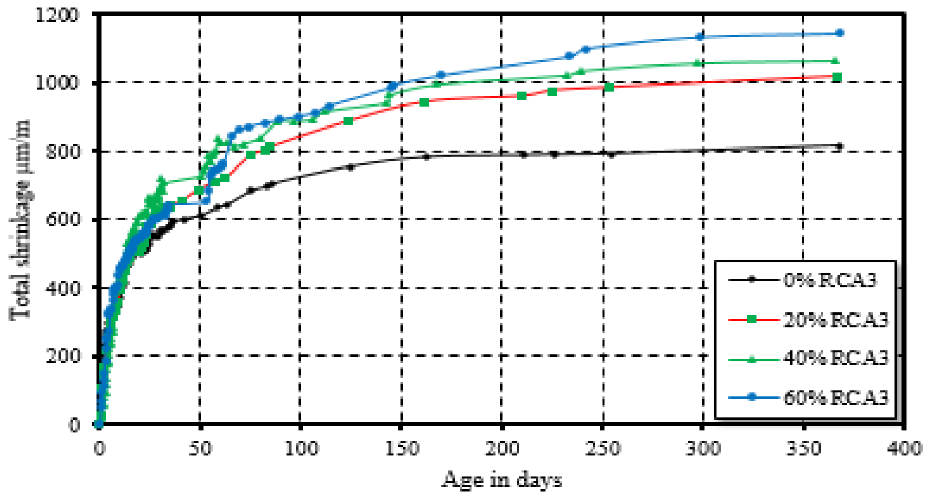

Fig. 18 – Total shrinkage evolution of RAC with various substitution rates of RCA3.

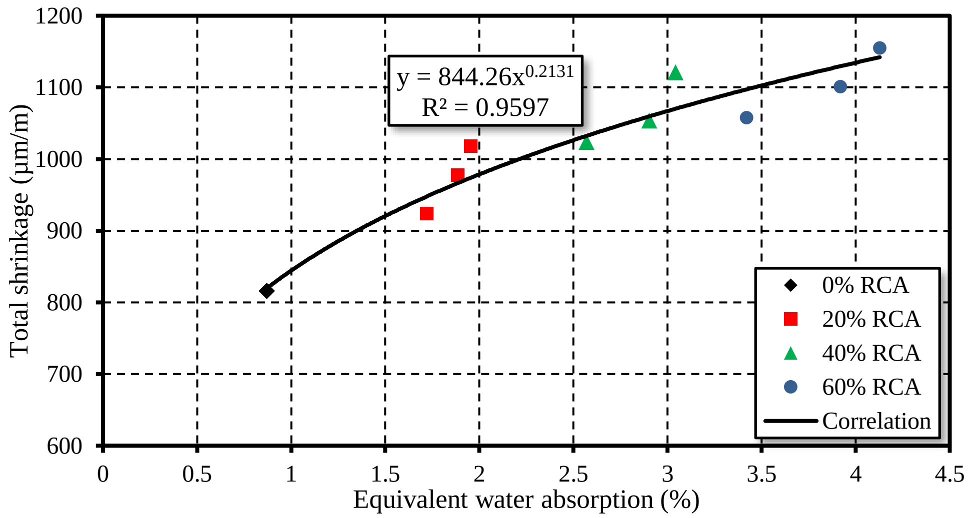

Fig. 19 – Final shrinkage as a function of equivalent water absorption of coarse aggregates.

To well analyzes the effect of the quality and quantity of RCA used in the concrete mix; the final shrinkage values measured at one year were compared with the water absorption value of aggregate. Eq. (5) was used to evaluate an equivalent water absorption values for each composition that represent an intrinsic quality of all the coarse aggregates.

$$Abs_{eq} = (1-p)Abs_{COA} + pAbs_{RCA} \quad (8)$$

Since all concretes keep the same composition, the equivalent water absorption of coarse aggregates seems to have the greatest effect. Fig. 19 illustrates the variation in shrinkage produced after one year of drying as a function of the equivalent water absorption of all coarse aggregates. The power relationship is very adequate and its correlation coefficient closer to unity. Several researchers have confirmed the fundamental role of the water absorption of recycled aggregates and their content used on some properties of concrete. According to Chinzorigt et al. [45], the shrinkage increases by 12% when coarse aggregates with water absorption of 0.48% were substituted by RCA with water absorption of 3.84%. In addition, the shrinkage of RAC can be reduced if recycled aggregates are treated and their water absorption is decreased.

5 Conclusion

This study has highlighted the role and RCA effect on the characteristics of concrete. The results found include the following remarks:

The strength of the parent concrete is critical to control the RCA quality. The Los-Angeles abrasion value, the water absorption became lower if this aggregate is from high strength concrete as is the case of RCA1. When RCA is from high strength parent concrete, the mortar porosity and the mortar absorption are lower. RCA reach water absorption values of 5.12%, 5.95% and 6.3% for parent concrete strength of 52 MPa, 44 MPa and 34 MPa respectively. The quantity and quality of attached mortar to RCA generate high water absorption which reduces concrete workability and leads to an increased need of superplasticizer dosage. For concrete containing 60% of RCA, it must be added more than 0.15%, 0.25% and 0.45% of superplasticizer to have the same workability for RCA1; RCA2 and RCA3 aggregates respectively. The substitution of COA by RCA with different water absorption rates requires an evaluation of equivalent water absorption of the mixture. To keep the same workability, it can conclude that 1% increase in equivalent water absorption for coarse aggregates leads to adding 0.12% of superplasticizer to the mixture.

RCA1 aggregates obtained from parent concrete strength of 52 MPa lead to a linear strength improvement as a function of its substitution rate. This gain reaches its maximum values at early age when concrete containing 20%, 40% and 60% of RCA1 aggregates the compressive strength is 31%, 84% and 115% higher than that of the concrete without RCA respectively. RCA3 aggregates obtained from parent concrete strength of 34 MPa have a positive effect only at early age. After 28 days, they induce a negative effect where there is a drop in compressive strength compared to the reference concrete of 8.2%, 8.6% and 9.4% for replacement rates of 20%, 40%, and 60% respectively. RCA is more effective at one day when 40% of RCA leads to optimal values of compressive strength and the granular coefficient is three times greater than that of COA. After 3 days, the quality of the RCA becomes important where 20% of the RCA1, RCA2 and RCA3 aggregates make the granular coefficient 2.7, 1.8 and 1.5 times higher than that of the COA respectively.

Before 28 days, the shrinkage values are identic despites of the quality and quantity of RCA used in the concrete mix. After one year, the shrinkage strains increase with recycled aggregates content and even more so for recycled aggregates derived from a parent concrete of low strength. Therefore, the shrinkage for concrete containing 20%, 40% and 60% of RCA3 aggregates is 13%, 30% and 40% higher than the shrinkage of concrete without recycled aggregates. The final shrinkage is proportional to the equivalent coefficient of water absorption of all coarse aggregates. A power relation correlates well the results and remains consistent with the conclusions on this area.

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