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Sonagnon Medjigbodo, Ahmed Bendimerad, Emmanuel Rozière, Ahmed Loukili. How do recycled concrete aggregates modify the shrinkage and self-healing properties?. *Cement and Concrete Composites*, 2018, 86, pp.72-86. <10.1016/j.cemconcomp.2017.11.003>. <hal-04333291>

HAL Id: hal-04333291

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Submitted on 30 Dec 2025

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How do recycled concrete aggregates modify the shrinkage and self-healing properties?

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This paper presents the main results of a research carried out to analyze the mechanical properties, intrinsic permeability, drying shrinkage, carbonation, and the self healing potential of concrete incorporating recycled concrete aggregates. The recycled concrete mixtures were designed by replacing natural aggregates with 0%, 30%, and 100% of recycled concrete gravel (RG) and 30% of recycled concrete sand (RS). The water to equivalent binder ratio was kept constant and recycled concrete aggregates were initially at saturated surface dried (SSD) state. The contribution of the porosity of natural and recycled aggregates to the porosity of concrete was estimated to understand the evolution of the intrinsic permeability and the open porosity. At long term, the maximum variation of drying shrinkage magnitude due to recycled concrete gravels did not exceed 15%. The correlation between drying shrinkage and mass loss through “drying depth” concept showed that recycled concrete aggregates are affected by drying as soon as concrete is exposed to desiccation. A good correlation between 1 day compressive strength and 18 month carbonation depth was observed. The recycled concrete aggregates presented a good potential for self healing as the relative recovery of cracks reached up to 60%.

1. Introduction

Concrete mixtures for general construction are composed on average of 75–80% of coarse and fine aggregates by volume [1]. The concrete industry worldwide, which produces more than 6 billion cubic meters of concrete per year, consumes more than 10 billion tons of sand and rocks annually. This implies a depletion of natural resources and significant CO₂ emissions due to the aggregate manufacturing process [2]. Despite this, the use of concrete will continue to grow in the coming decades, mostly in developing countries. The challenge of the concrete industry in the next decades will be to practice “industrial ecology” in the light of sustainable development. This involves the use of “greener” building materials such as recycled concrete aggregates, obtained from concrete construction and demolition waste [3–6]. This helps reducing the environmental impacts of concrete and promotes conservation of natural raw materials by reducing the need to quarry virgin aggregates.

The study of these aggregates called recycled concrete

aggregates (RCA) is not recent. During and after the Second World War, rubble from buildings destroyed by bombing was already employed in Britain and Germany for the reconstruction of buildings. As shown by Hansen [7] and Nixon [8], between 1945 and 1985, extensive research was conducted on recycled aggregates and recycled aggregates concrete. Similarly, today, many studies regarding these materials can be found in literature [9,10]. These studies show that the physical and chemical properties of RCA are significantly different from natural aggregates. The use of RCA modifies the properties of concrete, namely: strength, porosity, permeability, and shrinkage. However, shrinkage does not systematically result in cracking, and the effects of cracking on concrete permeability can be mitigated by self healing, for instance. Does the influence of RCA on concrete properties necessarily affect the overall performance of concrete and the durability of concrete structures?

Prior to the design of recycled aggregate concrete mixtures, a good characterization of RCA is required. RCA are actually composed of original aggregates and mortar and the crushing procedure is a prime factor influencing their properties [9]. The source of the original aggregates is generally not known and it is not easy to determine the amount and quality of initial mortar bonded to original aggregates, which modifies the properties of the

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new concrete [11]. The proportion of bonded mortar in recycled aggregate has been found to be higher than 30% [7]. This mortar greatly influences the physical properties of RCA (porosity, coefficient of water absorption, absorption rate, shape, specific surface, etc.) [12] and unfavorably the quality of RCA [9,13–15]. According to most of studies, the density of RCA is lower than the density of original aggregate. The relative decrease does not exceed 10%. The water absorption of recycled aggregates is much higher than the water absorption of original aggregates. It is one of the most significant differences between RCA and natural aggregate. As it will be seen later, this considerably affects the long term behavior of recycled aggregate concrete [7,8,14,15]. If the amount of original bonded mortar increases, the density of RCA tends to decrease whereas the absorption capacity tends to increase, regardless of the water to cement ratio of original concrete. All these observations can be explained by the amount of bonded mortar as well as its lower density and higher porosity than natural aggregates [7,8,14,15].

RCA show a higher water demand, which induces a lower workability of fresh concrete especially when the replacement ratio exceeds 50% [7,16,17]. Moreover, the fresh density of recycled aggregate concrete is generally 5%–15% lower than the corresponding natural aggregate concrete [16]. The entrapped air content of the recycled aggregate concrete (RAC) is generally 4–5% (for RCA replacement percentage equal to 100%) higher than the corresponding natural aggregate concrete. This is most likely due to the higher porosity of RCA and the increase in water demand. Consequently, this reduces the strength of the RAC. Some researchers propose to pre treat the RCA in order to prevent excessive water absorption by aggregates during mixing and maintain concrete workability. Several pre treatment methods are suggested in the literature [16,18–20].

Despite the precautions taken during the RAC production, it was often found that the compressive strength of RAC is lower compared to conventional natural aggregate concrete [7–9,14,21–23]. According to McNeil et al. [10] it can be explained by several factors such as aggregate replacement rate, aggregate preparation conditions (saturated or unsaturated), quality of the parent concrete, or water to cement ratio (W/C) of both concretes. However, it is necessary to keep in mind that this is not a general property of RAC. The strength of RAC can be as good as the strength of the original concrete if, for example, the W/C of the RAC is lower or the same as the original concrete, the other factors being otherwise identical [16,24,25]. Moreover, even if the natural concrete often has better compressive strength at 28 days, in the long term (one year), the recycled concrete has the best performance gain. Its strength can even exceed the standard concrete over the very long term (5 years) [26,27]. Concerning the indirect tensile strength of RAC, its value does not seem significantly different from that of conventional concrete. However, a review of the literature shows no consensus about the question [14,28]. Some authors have found an average reduction up to 10% for the tensile strength of RAC, compared to conventional concrete [29]. For others, RAC can sometimes exhibit slightly greater tensile strength [30]. According to Etxeberria et al. [9] et Katz [16], this improvement is due to the good paste aggregate bonding developed by the RCA.

Shrinkage is also likely to affect the RAC performance. Shrinkage of recycled aggregate concretes is found to be higher than conventional concretes [29,31]. This increase depends on the percentage of substitution of RCA, the source of parent aggregate, the water to cement ratio, the mixing and curing procedure, the lower restricted free strain of RCA particles compared to natural aggregate, etc. [14,29–31]. According to Domingo Cabo et al. [31], a limited substitution rate of coarse aggregate (20%) has a negligible effect on shrinkage, compared to natural aggregate concrete.

However, for a period of 6 months, a 50% RCA content was found to cause an increase in shrinkage near 10% and a total replacement of coarse aggregate resulted in a 70% increase compared to natural aggregate concrete. Other results and the main factors influencing the RAC shrinkage are reported in Silva et al. [32].

Considering these properties, studies carried out on RAC showed that these concretes presented a significant sensibility to cracking [33]. Durability of concrete structures is so affected. One of the means of reducing this cracking is self healing, a phenomenon which is well known for conventional concretes. Indeed, many studies and observations showed that, in the presence of water, not only the cracks (even the most visible) lead to close but in some cases, strength was restored as well [34–40]. However, the self healing ability of recycled aggregate concretes has not been studied yet.

This paper presents a research on long term behavior of concretes designed with recycled concrete aggregates produced by crushing concrete blocks from building demolition waste. This work aims particularly to:

- Study the influence of recycled concrete aggregate substitution level on drying shrinkage and durability indicators (permeability, porosity, carbonation) of RAC mixtures designed with the same effective water to equivalent binder content. RAC mixtures with 0%, 30% and 100% of coarse RCA and 30% of fine RCA have been studied.
- Investigate the effects of autogenous healing of cracks in these RAC through permeability measurements and its contribution in the durability enhancement.

2. Experimental program

2.1. Materials and mixtures

Natural aggregates (NA) were crushed dark limestone aggregates. The physical properties of aggregates are summed up in Table 1. Recycled concrete aggregates (RCA) were obtained by crushing unknown waste concrete from the recycling plant of DLB Gonesse (Paris region, France – RECYBETON project). According to Concrete Standard NF EN 206/CN [41], they are classified as aggregates type I, RCU95 which means that they can be considered as good quality RA. The adhered mortar content of these RCA was quantified by Ref. [42]. The old paste of the two fractions 4/10 and 10/20 represent 34.5% and 66% of total mass respectively. Fig. 1 shows the particle size distribution of fine and coarse aggregates.

Four mixtures have been studied: one control concrete (ORS ORG 100SSD) with natural aggregates (NA), three substitutions of 30% (ORS 30RG 100SSD; 3ORS ORG 100SSD) and 100% (ORS 100RG 100SSD) of recycled concrete aggregates. The concrete designation $xRS yRG 100SSD$ means that $x\%$ (in mass) of sand and $y\%$ (in mass) of gravel used is recycled; 100SSD means that the aggregates are at SSD state [42]. Table 2 summarizes the mixture proportions, the fresh concrete properties and the materials used. All the concrete mixtures were designed to reach C25/30. Thus, the water to equivalent binder ratio was maintained close to 0.65 ($W_{eff}/B_{eq} \approx 0.65$) for all the mixtures [41]. The equivalent binder content is determined according to European standard EN 206/CN (Eq. (1)). The same batch of Portland cement CEM II/A L 42.5 N proceeding from the same cement plant were used. Its Blaine fineness and density are of 370 m²/kg and 3.09 kg/m³ respectively. MC Power Flow 3140 was added as superplasticizer (SP).

$$B_{eq} = \text{Cement} + k \times \text{Limestone} \quad (1)$$

where k is the activity coefficient of limestone filler given by NF EN

Table 1
Properties of aggregates [33].

Mineralogy	Natural aggregates			Recycled aggregates		
	Sand 0/4 mm	Gravel 4/10 mm	Gravel 6,3/20 mm	Sand 0/4 mm	Gravel 4/10 mm	Gravel 10/20 mm
	Mixed Alluvial sand	Dark limestone	Dark limestone	Unknown waste concrete	Unknown waste concrete	Unknown waste concrete
Water absorption W_{A24} (%)	1.2	0.56	0.53	10.7	5.3	4.9
Density	2.6	2.73	2.73	2.1	2.34	2.32

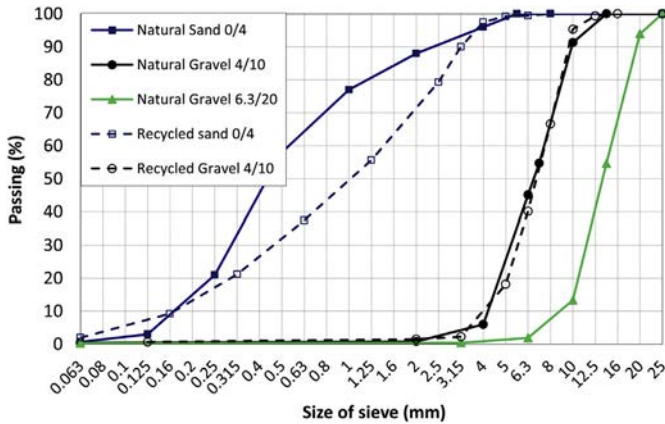


Fig. 1. Particle size distributions of natural and recycled aggregates.

206 standard ($k = 0.25$).

The concrete samples were cast in steel molds following the NF EN 12390 2 standard [43]. For each concrete mixture, eleven 11×22 cm cylindrical specimens and two $7 \times 7 \times 28$ cm prismatic specimens were prepared from a single batch. The specimens were conditioned as described in Fig. 2.

2.2. Testing procedure

The characteristics of all the tests carried out are given in Table 3.

2.2.1. Mechanical properties

Compressive and tensile splitting tests were carried out on 11×22 cm cylinders at 1, 2, and 28 days according to European standards [44,45]. The elastic modulus was also determined with a *Grindosonic* apparatus following Spinner and Tefft Model [46]. The tests were carried on three samples and the given results are average values.

2.2.2. Shrinkage

From the age of one day, total shrinkage, i.e. shrinkage due to drying and cement hydration and mass loss, was measured on $7 \times 7 \times 28$ cm prisms using LVDT sensors, in a room at 20 ± 2 °C and $50 \pm 5\%$ RH [47]. To achieve 2 dimensional drying, the top and bottom surfaces of specimens were covered with an adhesive backed aluminum foil. The specimens used to measure autogenous shrinkage were carefully completely protected by adhesive aluminum against drying from the start of testing. The testing procedure is explained in Ref. [48]. Shrinkage strains and mass were monitored for 3 months.

2.2.3. Carbonation

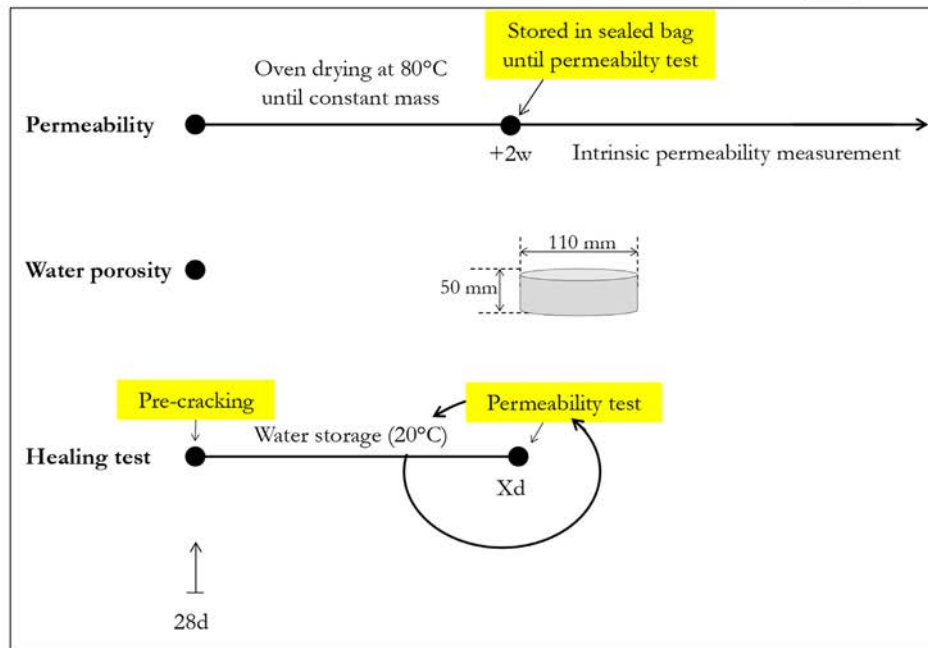
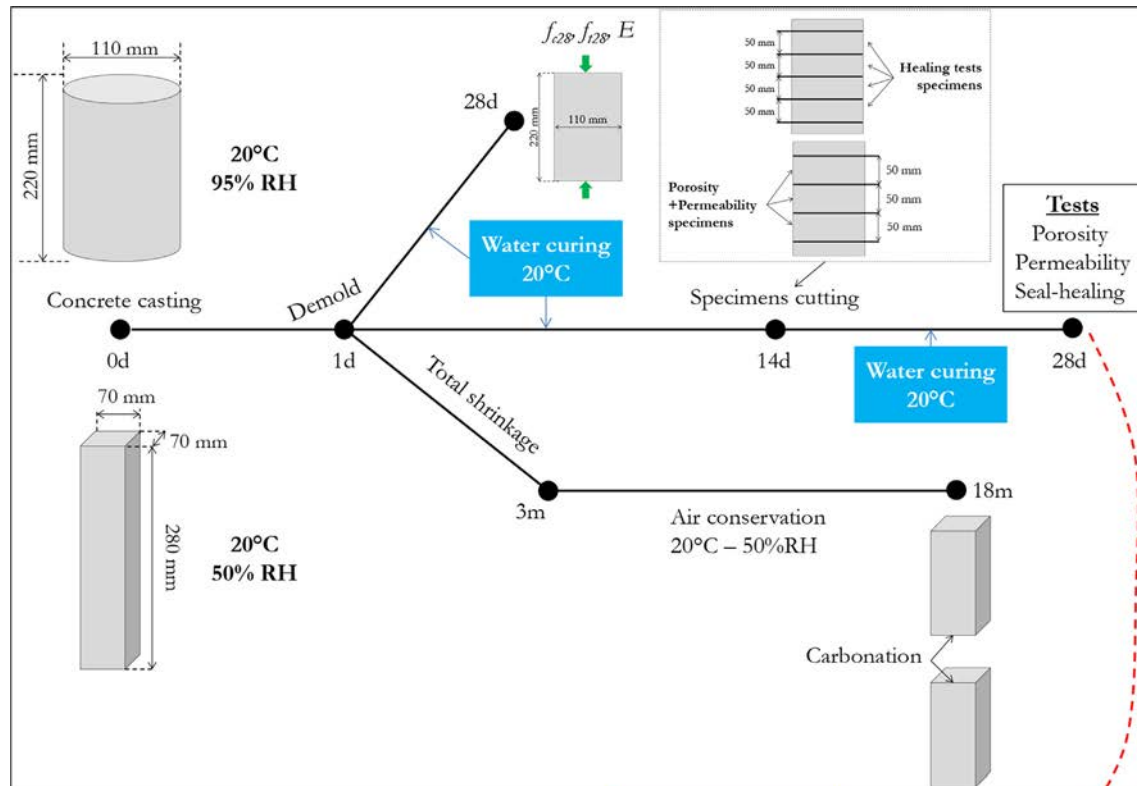
After the shrinkage test, the $7 \times 7 \times 28$ cm prisms were stored

Table 2
Properties and composition of concrete mixtures, with theoretical mixtures composed by dry aggregates and actual mixtures.

	ORS-ORG		ORS-30RG		30RS-ORG		ORS-100RG	
	100SSD		100SSD		100SSD		100SSD	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
NG 6,3/20 (kg/m ³)	820	824.3	462	464.4	829	833.4		
RG 10/20 (kg/m ³)			296	310.5			701	735.3
NG 4/10 (kg/m ³)	267	268.5	228	229.3	190	191.1		
RG 4/10 (kg/m ³)							163	171.6
NS 0/4 (kg/m ³)	780	789.4	813	822.8	549	555.6	806	815.7
RS 0/4 (kg/m ³)					235	260.0		
Cement, C (kg/m ³)	270		276		276		282	
Limestone, L (kg/m ³)	45		31		31		31	
Superplasticizer SP (kg/m ³)	0.747		0.861		0.798		0.798	
W_{eff}	180		185		185		189	
W_{tot}	194.6		212.3		221.4		241.0	
W_{SP}	0.6		0.7		0.6		0.6	
W_{sand}	0.0	9.4	0	9.8	0	31.6	0	9.7
W_{gravel}	0.0	5.8	0	18.2	0	5.5	0	42.9
$W_{absorbed}$	15.2		28.0		37.1		52.6	
W_{added}	194.6	179.4	212.3	184.3	221.4	184.4	241.0	188.4
W_{eff}/B_{eq}	0.64		0.65		0.65		0.65	
Entrapped air (%)		1.5		1.9		1.8		2.4
Paste volume (L/m ³)	285		287		287		293	
Gravel/Sand	1.39		1.21		1.30		1.07	
Slump (mm)		195		193		204		195

Nota: NG: natural gravel, NS: natural sand, RS: recycled sand, RG: recycled gravel.

Designation: 30RS-ORG-100SSD means that 30% (in mass) of sand and 0% (in mass) of gravel used is recycled (i.e. there is only natural gravel); 100SSD means that the aggregates are at SSD state [33].



Note: The other prismatic specimen is used for autogenous shrinkage measurement.

Fig. 2. Samples curing and conditioning process.

until 18 months in the same room at $20 \pm 2^\circ\text{C}$ and $50 \pm 5\% \text{RH}$. They were therefore partly carbonated. Then they were cut in half with a diamond saw. Carbonation depth was determined using phenol phthalein spraying test [49]. The calcium hydroxide rich part is colored pink while the carbonated portion remains uncolored.

2.2.4. Porosity, air permeability and self healing evaluations

These tests were performed as shown in Fig. 2. After demolding, the $11 \times 22 \text{ cm}$ cylindrical specimens were cured in water at 20°C for 14 days. Then they were cut using a diamond saw to obtain 5 cm thick discs. Three or four $11 \times 5 \text{ cm}$ discs were sawn from each

Table 3
Summary of experimental tests.

		Size (cm)	Number of specimens	Age (days)	Comments	Standards References
Mechanical properties	Compressive strength	11 × 22	3	1, 2, 28	Loading rate: 5 kN/s	NF EN 12390-3 [43]
	Elastic modulus				Dynamic measurement with Grindosonic	Spinner et al. [45]
	Tensile strength		3		Loading rate: 2 kN/s	NF EN 12390-6 [44]
Long -term shrinkage		7 × 7 × 28	2	Continuous from 1 day to 90 days	2-dimensional drying	Samouh et al. [47]
Carbonation		Half of 7 × 7 × 28	2	18 months	Specimens were stored at 20 °C and 50% RH	RILEM [48]
Water porosity		5 × 11	3	28		NF P18-459 [49]
Intrinsic permeability		5 × 11	3	28	CEMBUREAU Apparatus	Kollek [50]
Healing test		5 × 11	8	From 28 days		

specimen. Then the discs were surfaced using a grinding machine and their thickness was measured with an accuracy of 0.1 mm. They were stored again in water until 28 days. For each concrete mix, fourteen discs were prepared.

- At 28 days, water porosity test was performed on three discs according to the water impregnation method [50].
- Intrinsic permeability was also measured on three other discs. Before proceeding to gas permeability test, these discs were first dried in a ventilated oven at 80 °C until constant mass (mass change not exceeding 0.05% after 24 h). Then, they were stored for 48 h in a desiccator at 20 °C before being tested. Apparent permeability was measured using the Cembureau method with nitrogen as percolating gas [51]. The relative pressure ($P_i - P_{atm}$) applied to the sample ranged between 0.05 MPa and 0.3 MPa [52]. The tests were performed at 20 ± 2 °C. At each pressure level (4 different inlet pressures were applied), when the steady state was established, the nitrogen leakage rate Q (m^3/s) was measured with a gas flow meter at atmospheric pressure. The apparent (or effective) permeability k_a (m^2) was calculated from the Hagen–Poiseuille relationship, assuming the unidirectional laminar flow of a compressible viscous fluid through a porous body:

$$k_a = \frac{Q}{A} \times \frac{2\mu L P_{atm}}{(P_i^2 - P_{atm}^2)} \quad (2)$$

where μ is the dynamic viscosity of nitrogen (Pa.s), L is the thickness of the sample (m), A is the cross section area (m^2), P_i is the inlet pressure (Pa) and P_{atm} is the atmospheric pressure (Pa).

Then the concrete intrinsic permeability k_{int} (m^2) is calculated using the Klinkenberg approach [53].

- To evaluate the self healing potential of RAC, cracks were induced at 28 days on the last eight discs.

2.2.4.1. Pre cracking of specimens. Four levels of crack opening displacement (COD) were assigned to eight discs (110 mm in diameter and 50 mm in thickness): 0 (uncracked), 50, 100 and 150 μm . Each COD level was used twice. Specimens were loaded in compression in the diameter plane with a CMOD rate of 0.02 $\mu m/s$ (Fig. 3). This test presents the advantage of inducing one main crack, whose opening is measured precisely at the center of one side of the specimen using a CMOD sensor as a feedback signal during the test (Fig. 3). On the other side of the specimen, the displacement field is measured by image correlation technique

during loading (Fig. 3b) in order to obtain a crack opening map.

When the required COD level is reached, unloading was performed under force control and the COD, recorded after unloading and called residual displacement δ_{res} , was measured. Typical tensile stress – COD curves are plotted in Fig. 4, and as observed by Gettu et al. [54], the load displacement response exhibits a snap back. It is also shown in Figs. 4 and 5 that at the peak load, the crack widths were approximately 8–10 μm and after unloading, they were reduced by approximately 20–60%. Image correlation technique shows that the crack was really initiated in the center of a specimen (Fig. 6). Some specimens were also examined under an optical microscope with a magnification of 200 \times . The crack patterns in the specimens with different crack widths (located close to the center of the specimen) are shown as an example in Fig. 5.

2.2.4.2. Self healing. The self healing process was achieved by immersing cracked RAC in water. Permeability test was performed on the concrete after each period of immersion ($\Delta P = 1$ bar). By comparing the air permeability coefficient before and after curing in water, the extent of autogenous healing could be investigated.

3. Results and discussion

3.1. Strength, porosity and permeability

Several investigations on the mechanical properties of recycled aggregate concrete (RAC) have been performed. It is essentially shown that they depend on the properties of the original concrete, such as the water to cement ratio of the original concrete [7,8], the RCA replacement percentage [7,9,26,30], the production process [9] and the amount of adhered mortar on the RCA [12]. The compressive strength, the tensile splitting strength, the elastic modulus, porosity, and permeability of studied RAC are given in Table 4. Each value is the average of three measurements.

Despite the same water to equivalent binder ratio, Table 4 shows that compressive strength of RAC decreased with an increase in the replacement with RCA as coarse or fine aggregate, whatever the age of the concrete. For example, the concrete mixtures prepared with 30 and 100% of recycled gravel (RG) showed 9.2 and 12.1% decreases in the 28 day compressive strength compared to NAC. Moreover, the values reported in Table 4 show that the dynamic modulus of elasticity of the RAC was lower, and it decreased with increasing RCA content. At 28 days, when the coarse recycled aggregate replacement percentages were 30 and 100%, the elastic modulus was reduced by 13 and 23% respectively. This is mainly due to the properties of RAC [7,9,55]. Compared to concrete made with natural

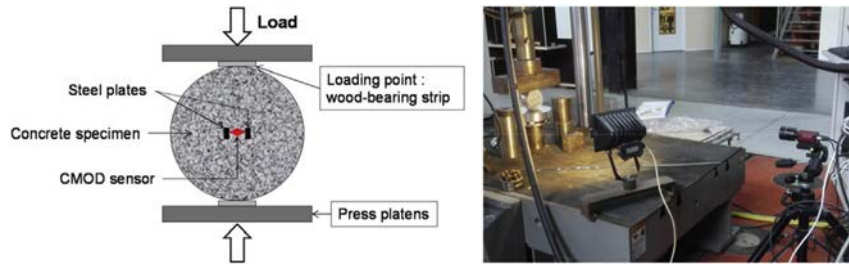


Fig. 3. Lay-out of COD measurement set-up (a) COD and image correlation measurement (b).

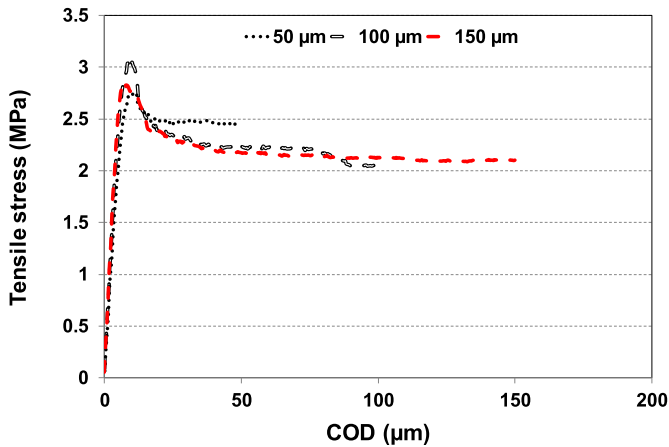


Fig. 4. Typical splitting tensile test stress-COD curves.

coarse aggregate a 20–35% drop in tensile strength was observed in RAC at 1 day and 10% drop at 2 days (Table 4). However, at 28 days, no significant difference in tensile strength has been found between conventional concretes and RAC using 30% of RA (3%) while

the 100% recycled aggregate concrete showed a slight increase. This can be explained by a good bond between aggregates and the mortar matrix.

From these observations, it is important to note that in RAC, controlling the water to equivalent binder ratio is not enough to achieve the desired properties. As shown by many authors such as Ravindrarajah et al. [56], Tabsh et al. [57], Duan et al. [22], Topçu et al. [17], Yamato et al. [58] and Poon et al. [59], the strength reduction in RAC depends also on various factors such as the source of RCA, the mixing procedure and the initial water saturation of RCA.

Porosity and permeability are often used as durability indicators of hardened concrete [60–62]. Water porosity was assessed at 28 days. Permeability was evaluated using Klinkenberg approach. The mean value of open porosity, intrinsic permeability and the Klinkenberg coefficient are given in appendix 1 (Table A1 and A2).

The concrete mixtures prepared with 30 and 100% replacement of coarse RCA present an increase of 16 and 40% in the open porosity compared to natural aggregate concrete (Table A1). Similar results were obtained in literature [28,63–65]. However, in all cases, the higher porosity of RAC seems to be mainly due to the higher porosity of the recycled concrete aggregate. As the coefficient of water absorption can be related to the porosity of a material, it can be shown why the RCA porosity was higher than

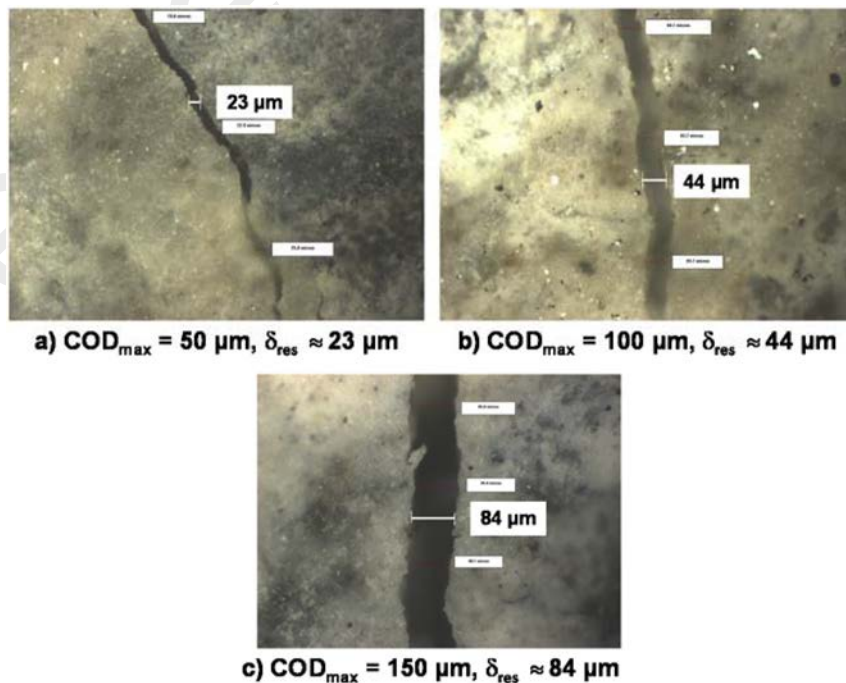


Fig. 5. Observation of the main crack after unloading (ORS-100RG).

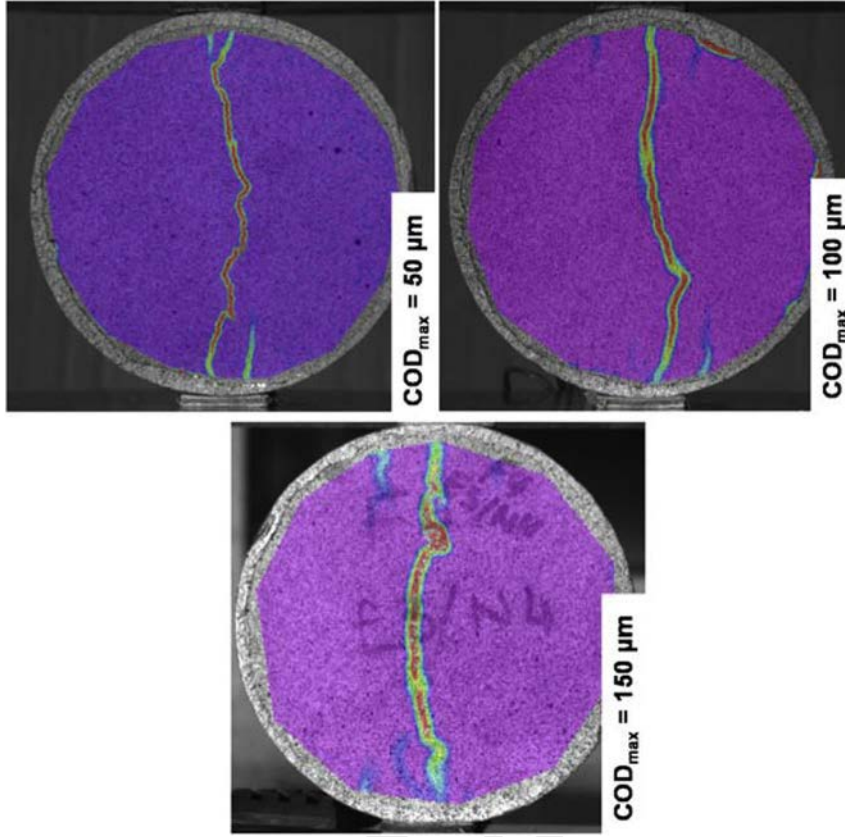


Fig. 6. Crack position.

Table 4
Strength, elastic modulus, porosity and permeability at 28 days.

	ORS-ORG	ORS-30RG	3ORS-ORG	ORS-100RG
f_c (MPa)				
1 day	6.4	5.8	4.2	4.1
2 days	10.3	11.7	10.0	9.5
28 days	31.4	28.5	29.0	27.6
f_t (MPa)^a				
1 day	1.41	1.14	1.02	0.92
2 days	1.64	1.47	1.50	1.46
28 days	2.57	2.50	2.45	2.69
E (GPa)				
1 day	25.5	21.3	18.3	18.7
2 days	32.0	27.2	24.8	24.2
28 days	43.8	38.3	35.6	33.7
Porosity (%)				
28 days	13.5	15.7	15.5	18.8
Permeability, K_v (m²) * 10¹⁷				
28 days	3.5	5.7	5.9	7.0

^a Splitting tensile test.

natural aggregates porosity (Table 1). The contribution of the porosity of the aggregates (natural and recycled) to the porosity of the concrete was assessed from porosity p and water absorption WA_{24} of each aggregate are defined as follows:

$$p_{\text{aggregate}} = \frac{V_v}{V_t} \quad (3)$$

$$WA_{24} = \frac{M_w}{M_d} \frac{\rho_w \times V_w}{M_d} \quad (4)$$

where V_v is the volume of void space, V_t is the bulk volume, M_w , V_w and ρ_w are the mass, volume, and density of absorbed water. M_d is the mass of oven dried aggregates.

As the aggregates are saturated at SSD state to determine WA_{24} , it is assumed that all the void spaces are filled with water, so $V_w = V_v$. By combining this equality and equations (3) and (4), the porosity of aggregate is given by:

$$WA_{24} = \frac{M_w}{M_d} \frac{\rho_w \times V_w}{M_d} \quad (5)$$

Fig. 7 summarizes the contribution of the porosity of sand and gravel (natural and recycled) to the porosity of concrete. The porosity of cement paste was deduced from the porosities of concrete and aggregates. In the concrete made with 30% replacement of fine recycled aggregate, the increase in porosity is strongly linked to the high porosity of recycled sand (2.55%). As the volume of paste was kept constant in (3ORS ORG) and (ORS – 30RG) concretes, it can be shown that both 30% replacements (by fine and coarse RCA) had not the same effect in terms of water porosity of cement paste. This can be explained by the possible filler effect of the very fine broken particles from fine recycled aggregate generated during the mixing process. The released particles contributed to improve the density of the cement paste in 3ORS ORG concrete. However, a more significant substitution rate of fine recycled aggregate in concrete would lead, on the contrary, to a significant increase in the porosity and other parameters (compressive strength, etc.) compared to coarse recycled aggregate concrete [66].

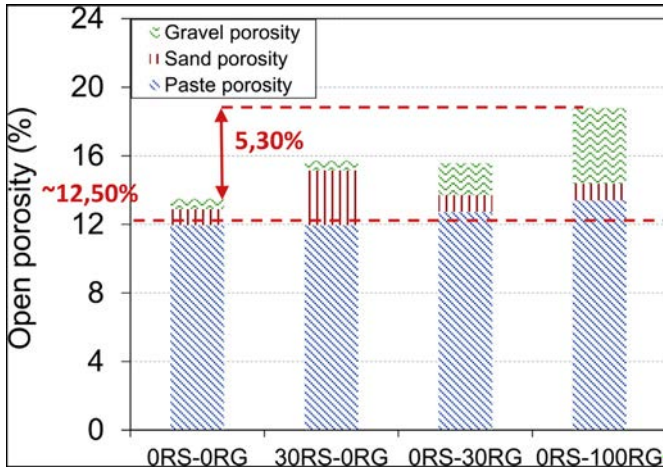


Fig. 7. Open porosity of each component of concrete for various recycled aggregate ratios.

A good correlation between intrinsic permeability and water porosity was observed (Table 4). As expected, the permeability increased with RCA substitution. The same trend was reported by Thomas et al. [28]. This is explained by the high porosity of the adhered mortar of RCA compared to new mortar, which causes higher overall permeability of a concrete with RCA. Micro cracks formed in RCA during processing are also a cause of lower potential durability. The 100% replacement of natural coarse aggregate by RCA resulted in doubled intrinsic permeability of concrete. The same result was found by Zaharieva et al. [67]. However, other studies suggest that permeability of RAC can be reduced by increasing the cement content or by reducing the effective water/cement ratio [28,68]. Gonçalves et al. [69] stated that a 100 kg/m³ increase in cement content is necessary to get the same permeability for RAC and NAC.

3.2. Long term shrinkage

The total shrinkage of hardened concrete mainly includes autogenous shrinkage, drying shrinkage, and carbonation shrinkage. Drying shrinkage is the most significant strain of normal strength concretes. It generally accounts for about 80–90 percent of the total shrinkage deformation from drying time [70].

Fig. 8 shows the evolution of autogenous shrinkage deformations. They remained relatively low, which is consistent with the high W/C ratio (>0.65) of the concrete mixtures. The highest magnitude (25 $\mu\text{m}/\text{m}$) was observed for concrete made with natural aggregate. The autogenous shrinkage of recycled aggregate concrete was approximately 40–50% lower than for the conventional concrete, and finally negligible for the concrete with 100% coarse RCA. This can be attributed to the influence of initial water content of the recycled concrete aggregate. Maruyama et al. [71] also reported 40% lower autogenous shrinkage for high strength concrete with recycled aggregate compared to corresponding control concretes made with conventional aggregates. The recycled concrete aggregates provide water that mitigates self desiccation. The water content of aggregates is a well known parameter in reducing the autogenous shrinkage. The permeability and absorption capacity of RCA allow them to store and release more water per volume unit. This water is absorbed by cement paste, as its porosity becomes finer due to hydration. Kohno et al. [72], Zhutovsky et al. [73] and Henkensiefken et al. [74] also reported the same behavior on artificial lightweight aggregates.

Subsequently, the contribution of autogenous shrinkage to long

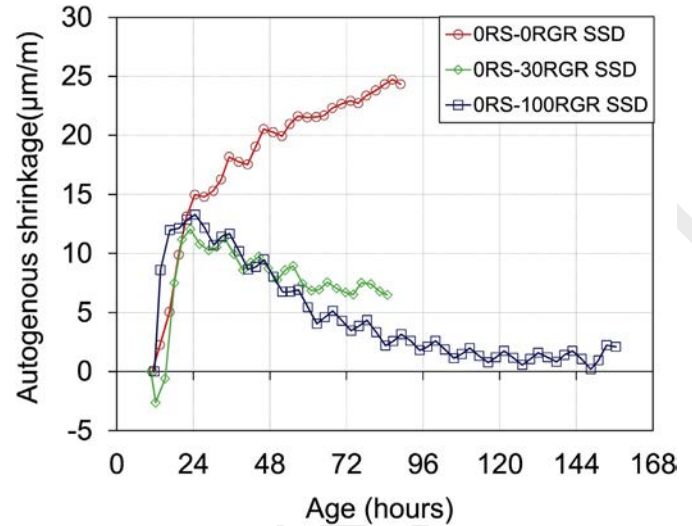


Fig. 8. Autogenous shrinkage vs. concrete age.

term behavior is assumed to be negligible. The total shrinkage measured during testing is thus considered as the drying shrinkage. The drying shrinkage of the four concrete specimens is plotted in Fig. 9. The addition of RCA increased the drying shrinkage deformation of RAC. This result is consistent with previous studies on RAC [14,31,75–78]. Drying shrinkage depends on the water to cement ratio, paste content, and the restraining effect of aggregates on cement paste shrinkage. The use of coarse RCA results in excess water in the pores of the RCA as well as an increase in paste content. The increase in drying shrinkage of RAC can be explained by the presence of a higher amount of cement paste (old paste + new paste), as well as the content, interconnection and distribution of pore sizes [79,80]. This causes a higher RAC porosity (Fig. 7) resulting in a relatively higher free shrinkage rate than normal concrete. Moreover, the elastic modulus of RCA is generally lower than natural aggregates (Table 4). This results in a lower restraint of the drying shrinkage of cement paste and higher shrinkage of concrete. Thus, the replacement of coarse NA by coarse RCA typically results in an increase in drying shrinkage.

Drying shrinkage is a long term deformation of concrete. The

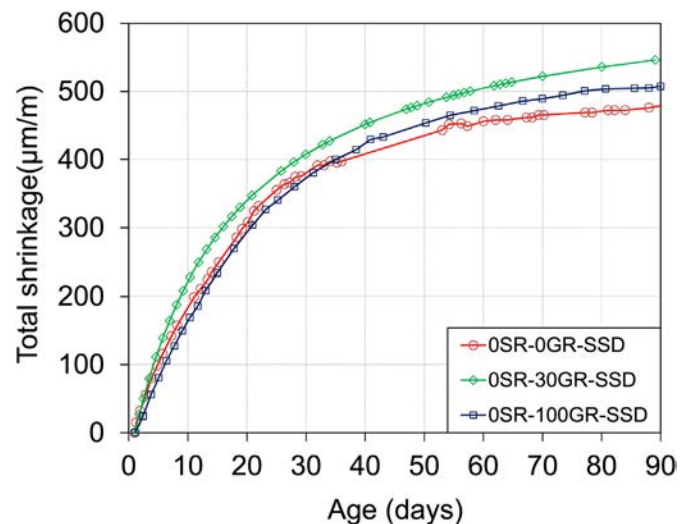


Fig. 9. Total shrinkage deformation vs. concrete age.

shrinkage magnitude at a given time is not a reliable indicator of long term deformation, as the studied parameter is likely to influence the kinetics of drying. Thus, to characterize the long term behavior of the concrete, it is sometimes necessary to extrapolate the experimental measurements. Existing models from the literature can be used to predict the long term shrinkage [81,82]. By using Torben's model [81], the two characteristic parameters ϵ_∞ and N_s were determined from experimental data (Fig. 9), and the following equation:

$$\epsilon(t) = \frac{t}{N_s + t} \epsilon_\infty \quad (6)$$

where ϵ_∞ is the ultimate shrinkage and N_s the time to reach half of the long term drying shrinkage, or shrinkage half time.

The influence of the RCA percentage on ultimate shrinkage magnitude and shrinkage halftime are shown on Fig. 10a and b respectively. The long term shrinkage of concretes made with natural aggregates is about 15% lower than that of recycled aggregates concretes. The same trend was found by other researchers. For example, for a period of 6 months, Domingo Cabo et al. [31,78] reported that the shrinkage of RAC made with a substitution level of 20% was 4% higher. Moreover, they found that in the case of a substitution level of 50%, the shrinkage was 12% higher than that of the conventional concrete. In other studies, the long term shrinkage of concretes made with 100% of coarse RCA ranged from 20% to 70% more than reference concrete [7,31]. Thus, the influence on RCA on long term shrinkage cannot be generalized, and the RCA proportion is not the only influencing parameter. The influence of RCA quality [6,7,12], modulus, water to cement ratio, initial water saturation of aggregates, test conditions, age of concrete and test time, etc. [1,32] should also be considered. The two parameter analysis performed here allows showing the influence of RCA on the kinetics of drying shrinkage (Fig. 10b). Shrinkage half time increased with coarse RCA content. The porosity of RCA can be assumed to be finer than cement paste because of longer curing time of original concrete. Thus, its water permeability is lower. The water permeability of new concrete can be influenced as well because of internal curing effects, probably at the paste aggregate interface, as suggested by the improvement of mechanical properties with hydration time.

Despite all these effects, the mechanisms involved in drying shrinkage are the same. They are triggered by the relative humidity drop in the pores of cement paste and RCA. The relative humidity gradient in the concrete sample affects the distribution of water saturation in the specimen and cause structural effects. The outer part dries first, thus tensile stresses are generated close to the

surface, whereas the core of the sample is in compression. These effects must be considered to understand the drying behavior. They can be highlighted on drying shrinkage vs. mass loss curves.

Fig. 11 shows drying shrinkage versus relative mass loss curves. The mass loss is expressed as a percentage of initial mass of specimens when exposed to drying. Three stages can be distinguished on these curves. The first stage corresponds to water loss without significant shrinkage. At this stage, the mass loss increased with the recycled aggregates substitution rate. As explained by Samouh et al. [48], this stage depends mainly on the free water content of concrete mixture and phenomena occurring in the outer part of the specimen [83]. The second stage corresponds to a linear relation between shrinkage and mass loss. This stage is characterized by a decreasing internal relative humidity, resulting in the increase of capillary stress (according to Kelvin equation). Therefore, shrinkage increases too. The third phase that is not explicit in Fig. 11 is assumed to extend over a long period, with a stabilization of mass loss and a continuous decrease in drying shrinkage rate.

The analysis of the graph in Fig. 11 leads to the conclusion that the outer layer of RAC would be more affected by drying than NA concrete in the same conditions. However, a higher mass loss in terms of mass loss to initial mass ratio does not necessarily mean a larger extent of drying, as the total water content of RA concretes was higher than the total water content of NA concretes (Table 2). Thus, as the effective water to cement ratio was the same, the free water content was higher in RA concretes.

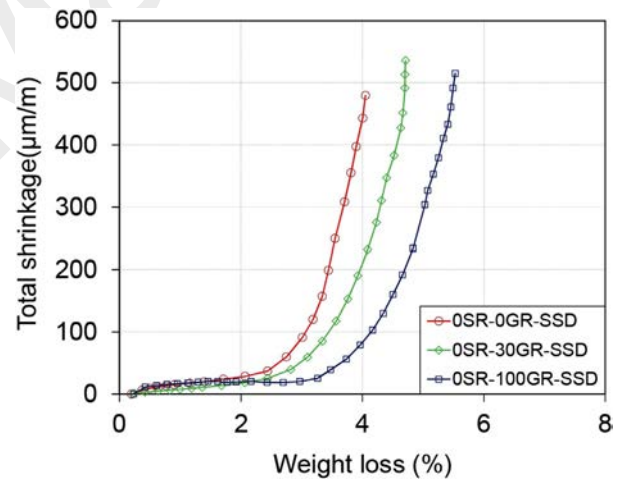
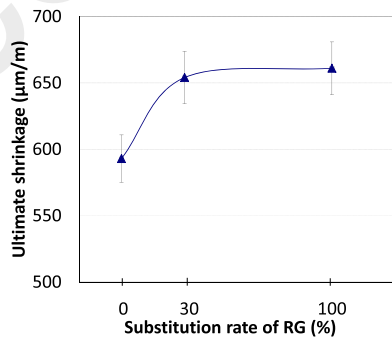
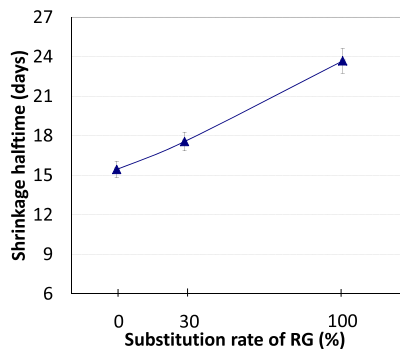


Fig. 11. Total shrinkage vs. Mass-loss of recycled aggregate concrete.



a)



b)

Fig. 10. Effects of RCA replacement on the drying shrinkage characteristics of RAC.

In order to understand the behavior of the samples as a function of RCA content, the mass loss was transformed to an equivalent distance by the following equation [48]:

$$d = \frac{\Delta m / S_d}{m_f} \quad (7)$$

where Δm is the mass loss (kg), S_d the drying surface (m^2) and m_f the free water content in concrete in $1 m^3$ of concrete (kg/m^3), calculated from the following equation:

$$m_f = W_{eff} \alpha W_{\infty} C \quad (8)$$

where W_{eff} is the effective water content (kg/m^3), α the hydration degree when concrete is exposed to drying (from isothermal calorimetry), W_{∞} the ultimate value of the chemically bound water to cement content ratio (kg/kg) and C the cement content (kg/m^3).

A drying depth δ which represents the depth in concrete for which water loss is observed without generating shrinkage was estimated from shrinkage versus d curves. It is defined as the intersection between the linear extrapolation of the second stage (Fig. 11) and the d axis [48], as shown in Fig. 12. The results are presented in Table 5. The values of the drying depth are close to half of maximum aggregate size $D_{max}/2$ for all concretes tested. This could correspond to wall effect. Several phenomena can lead to this behavior: wall effect, micro cracking, and coupling between hydration and drying. As the hydration process is incomplete at this stage, this behavior affects the durability of concrete.

A given drying depth may correspond to two different configurations (Fig. 13). The three concrete mixtures have the same water to equivalent binder ratio thus the same initial quality of cement paste. In the case of recycled aggregates, paste and aggregates dry at the same time (Fig. 13b), while in the case of natural aggregates, the drying depth represents only the cement paste drying (Fig. 13c). This could explain why the drying depths of the three specimens were approximately the same, whereas the mass loss at the end of the first stage (in %) were different. The drying depth was higher for 100% RCA than other concretes. It can be explained by the higher free water and permeability and the drying of both cement paste and aggregates unlike the case of natural aggregate concrete.

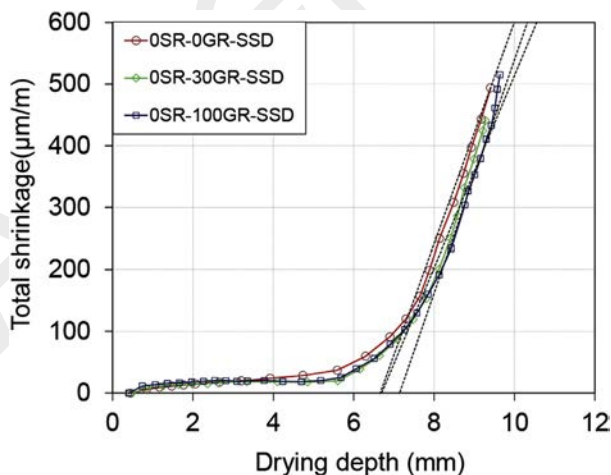


Fig. 12. Total shrinkage vs. Drying depth of recycled aggregate concrete.

Table 5
Drying depth of RAC.

	Drying depth (mm)
ORS-ORG-100SSD	6.7
ORS-30RG-100SSD	6.7
ORS-100RG-100SSD	7.1

3.3. Carbonation

Table 6 summarizes the results of the influence of the substitution rate of recycled aggregates on the carbonation depth. This increased with the percentage of recycled aggregates. The same observation has been done by others studies [7,14,28,84–86]. This result can be expected since both permeability and porosity exhibited the same trend. Carbonation depth followed the same trend as drying depth of ORS ORG and ORS 30RG showed approximately the same values, whereas ORS 100RG showed significantly higher value. These results highlight the influence of drying on carbonation resistance, as the diffusion of carbon dioxide through the porous network closely depends on the water saturation of concrete [87]. The variation of carbonation depth with the replacement ratio of coarse recycled aggregate was not linear. However, Evangelista et al. [86] observed that carbonation depth increases almost linearly with the fine recycled aggregate replacement ratio. This increase can reach 110% at 21 days for concrete made only with fine recycled aggregate while 16% is expected for concrete made only with coarse recycled aggregate. This important difference can be explained by a significant increase in the porosity and other parameters (permeability, connectivity, etc.) for significant substitution rate of fine recycled concrete aggregates [66].

It is important to note that apart the RCA content level, water to cement ratio, quality and hydrated level of the recycled aggregate and binder content also influence the carbonation depth of recycled aggregate concrete [84,85]. Otsuki et al. [88] and Xiao et al. [84] evaluated the influence of water to cement ratio on the carbonation of RAC. They found that the carbonation depth of RAC was reduced with the decrease in w/c ratio because of the reduction of porosity of concrete [89]. The influence of the original concrete on the carbonation depth of recycled aggregate concrete has been studied by Xiao et al. [84] keeping the water to equivalent binder ratio constant. Their results show that the carbonation depth of RAC decreases with the increase in the strength grade of the original concrete. This trend was also observed by Werle et al. [90]. Xiao et al. [84] also demonstrated that in the long term, the carbonation risk of recycled aggregate concrete using a higher amount of cement (more than $400 kg/m^3$) of concrete mix was larger than in conventional concretes. However, the carbonation depth in recycled aggregate concrete and conventional concrete was similar when the amount of cement employed in the mix is between $300 kg/m^3$ and $400 kg/m^3$. In ordinary concrete, using less than $300 kg/m^3$ of cement, the carbonation depth was similar in both concretes.

3.4. Autogenous healing of recycled aggregates concretes

Cracks in concrete are a common phenomenon due to the relatively low tensile strength and the variety of phenomena inducing tensile stresses: loading, shrinkage, expansion, etc. Cracks significantly reduce the durability of concrete. However, compared to other engineering materials, concrete has an autogenous healing capacity as partially hydrated cement particle can be found in its matrix. Thus, cracks should be repaired by this phenomenon. The process of autogenous healing has been studied by many

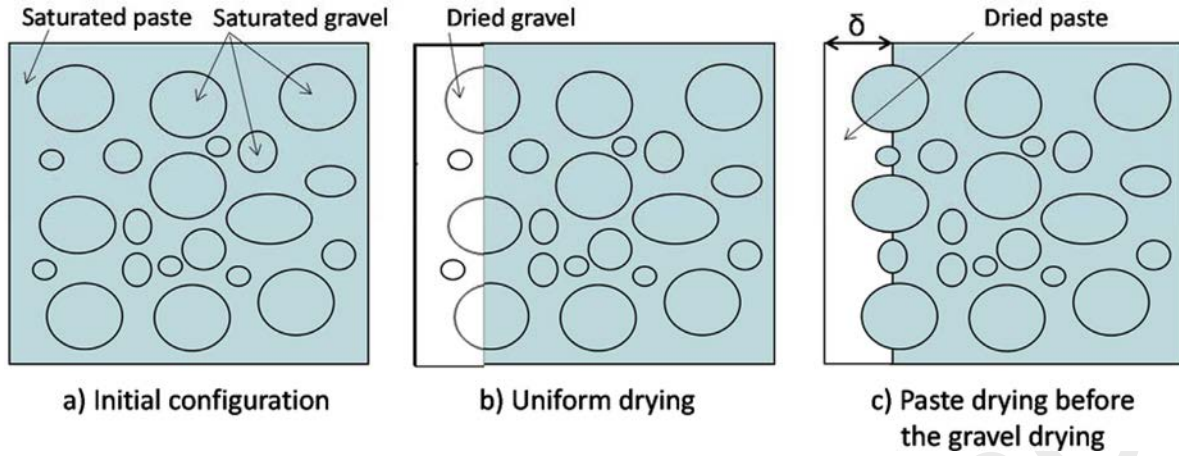


Fig. 13. Drying of concrete samples configuration.

Table 6
Carbonation depth of RAC.

	Carbonation depth at 18 months (mm)	f_{C1d} (MPa)
ORS-ORG-100SSD	12.2	6.4
3ORS-ORG-100SSD	13.7	4.2
ORS-3ORG-100SSD	13.0	5.8
ORS-100RG-100SSD	14.2	4.1

researchers [34,35,40,91–100]. It is reported in these studies that autogenous healing of cracks leads to mechanical properties regains [34,35,96] and the improvement of the durability of concrete [40,92]. However, most of the studies have been performed on normal or high strength concrete. Studies quantifying autogenous healing of recycled aggregate concrete are scarce. However, as shown in Fig. 10, the presence of recycled aggregates in concrete increases its drying shrinkage, and therefore the cracking sensitivity of RAC. It is thus interesting to know if using recycled aggregates influences the autogenous healing ability of concrete.

To contribute to answering this question, the autogenous healing potential of recycled aggregate concrete mixes with different coarse replacement ratio is investigated using air flow measurements through a crack created by splitting tensile test. Table 7 gives the average residual crack opening generated in all concrete samples.

In Fig. 14, the relationship between residual crack opening and air flow under a pressure gradient of 1 bar is presented for all concrete just after tensile loading (Table 7). The three concretes exhibited comparable trends. Thus, the RCA content did not significantly influence the relationship between crack opening and air flow. The data points seem to line up on a single curve (Eq. (9)) with a determination coefficient 0.97:

$$Q = 0.0003W_{ef}^3 + 0.0586W_{ef}^2 + 3.9613W_{ef} - 63.414 \quad (9)$$

Table 7
Average cracks opening after unloading (μm).

	Average COD under loading (μm)		
	50 \pm	100 \pm	150 \pm
ORS - ORG	22	51	120
ORS - 3ORG	21	56	87
ORS - 100RG	23	44	84

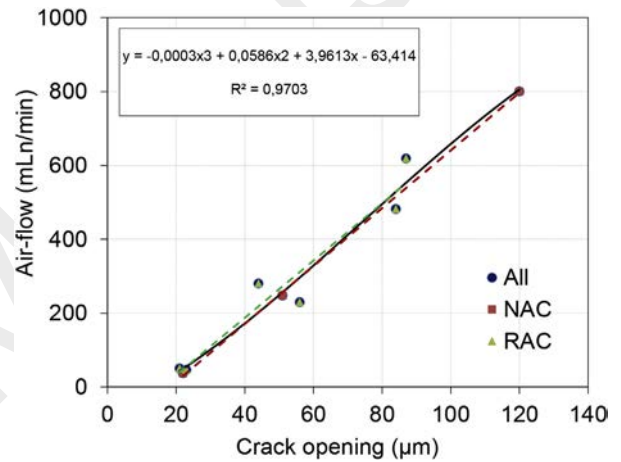


Fig. 14. Relationship between air flow and crack opening (pressure gradient of 1 bar).

where Q is the air flow (mL/n/min) and W_{ef} (μm) the crack opening.

This equation is considered valid only in the case of the specific experimental conditions used for this test. It can be used to estimate indirectly the **effective crack opening** of the concrete during the expected self healing process.

Fig. 15 plots the effective crack opening of each concrete specimen as a function of water re curing time. Initially, the effective crack opening estimated from Eq. (9) is slightly different from residual crack opening (Table 7) but the error is small enough to consider that our method is reliable.

The decrease in the effective crack opening shows that all tested samples underwent self healing after a period in water. This phenomenon occurred regardless of recycled aggregate substitution ratio. It was faster during the first months of water curing and becomes very after (Fig. 15). For both natural and recycled aggregates concretes, analysis of Fig. 15 shows that during the first months (0–100 days), the kinetic of self healing depends on the initial crack opening. It increases with the initial crack opening. Gagné et al. [101] reported the same conclusion on mortar specimens. The slow kinetic of self healing for fine cracks ($<60 \mu\text{m}$) is explained by the limitation of available space for self healing products formation and also by the slow diffusion of water and external CO_2 along the crack path [52,101,102]. On the contrary, large cracks allow easy diffusion of water and they have a larger space where self healing products can be formed.

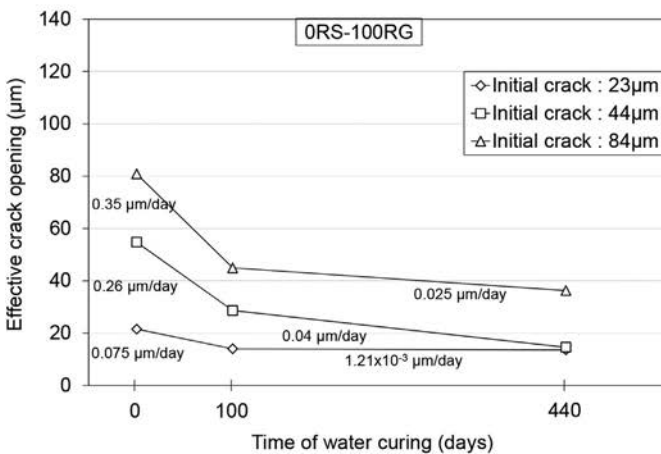
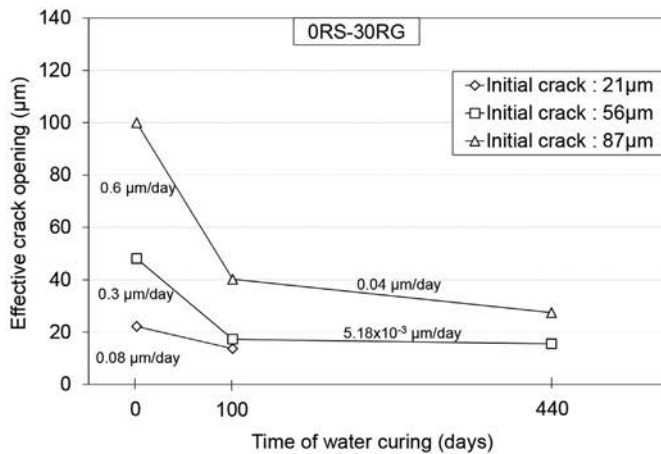
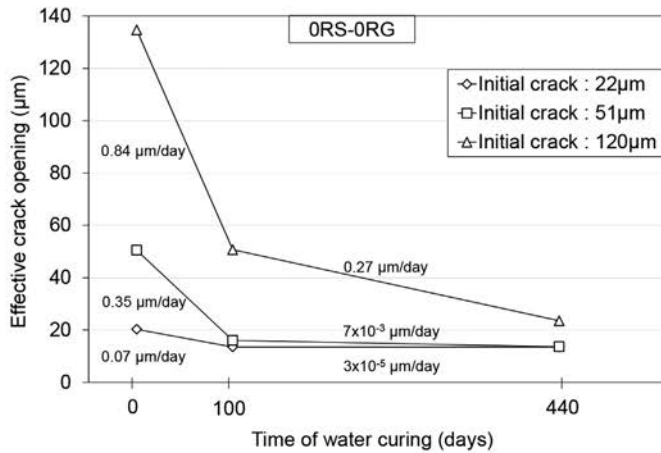


Fig. 15. Evolution of effective crack opening as a function of time of RA substitution ratio.

During the first 100 days of water curing, the kinetics of self healing decreased when the recycled aggregate substitution rate increased (Fig. 15). Moreover, Fig. 16 shows that the recovery of crack opening after 100 days of water curing decreased with the percentage of recycled aggregate substitution. This effect was more pronounced for large cracks openings while it was negligible for small openings cracks. What are the causes of both behaviors? First,

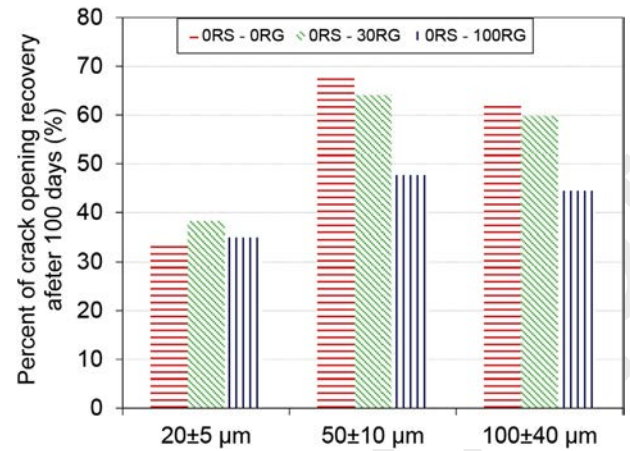


Fig. 16. Crack recovery after 100-day water immersion.

one can think on the residual hydration. However, at 28 days (age of cracking), all of concrete seem to have the same degree of hydration (87%). The explanation can be found in the failure mechanisms of concrete under tensile loading. Contrary to natural aggregates concrete where the crack goes through the ITZ, in recycled aggregates concrete, some recycled concrete aggregates are split. Consequently, surface area where unhydrated cement could react with water is potentially lower for RAC.

After 100 day water curing, no trend is observed on the kinetic self healing of all concrete tested. However, Fig. 15 clearly shows that the concrete continues to self heal with a low speed, and this whatever the percentage of the recycled aggregate substitution.

The self healing of the RAC under water curing is proven. However, due to the presence of a reserve of water in recycled aggregates, one might wonder if the self healing can take place in RAC in ambient environment.

4. Conclusions

The experimental data presented in this research deals with the effect of the proportion of the recycled concrete aggregates on concrete properties and how the overall durability of recycled aggregate concrete can be modified. Based on the research and results presented in this paper, the following conclusions can be drawn:

- The mechanical properties of concretes containing recycled concrete aggregates were lower than the conventional one. At 30% of recycled gravel, the decrease was lower than 10% in compressive strength and elastic modulus and lower than 3% concerning tensile splitting strength for a common water to equivalent binder ratio. Similar trend was found for the open porosity. A 40% increase was observed for the concrete with 100% of recycled gravel. The variations of water porosity could be explained by the porosity of the recycled concrete aggregates (gravel and sand). The intrinsic permeability followed the same evolution. The carbonation depths followed the same trend as porosity, permeability, but the relative variations were much lower. A linear correlation has been found between the 1 day compressive strength and the 18 month carbonation depth.
- The influence of recycled concrete aggregate content on ultimate shrinkage was significant but relatively low. Moreover, shrinkage halftime increased, which allows better relaxation of

stresses with time in case of restrained shrinkage. Higher mass loss during the first days was due to higher free water content but it did not result in higher drying depth.

- The autogenous healing was investigated in this study; the samples were pre cracked by splitting tensile test at 28 days and tested just after to draw a reference curve and correlate the effective crack opening and gas flow. Throughout the water curing period, both series of samples (natural and recycled concrete) presented a self healing potential.
 - i. During the first months of water curing and for crack opening higher than $20 \pm 5 \mu\text{m}$, self healing kinetics decreases with the recycled aggregates substitution rate. However, for small cracks (crack opening lower than $20 \pm 5 \mu\text{m}$), no influence of type of aggregate on self healing kinetics has been observed. After 100 days, the phenomenon of self healing is stopped for initial crack opening equal to $20 \pm 5 \mu\text{m}$. For initial crack opening equal to $50 \mu\text{m} \pm 10$, only concrete made with 100% of recycled gravel develops self healing ability.
 - ii. The recovery of crack opening was more marked for large cracks ($\geq 50 \mu\text{m}$). In this case, the influence of recycled concrete aggregates became significant. The crack recovery decreases when substitution rate of RCA increases. For small cracks, concretes made with 30% of recycled concrete aggregates show a good potential for self healing, which presents a positive effect on the durability behavior of RAC.

- iii. The self healing phenomenon was evaluated by measuring the air permeability. Even if this technique allows to highlight the phenomenon in RAC, it does not allow to explain the mechanisms involved. Therefore, this work should be completed by study the microstructure of concrete (SEM observation for example) during healing process.

Acknowledgments

Support from the *Agence Nationale de la Recherche* (National Research Agency, France) within *ECOREB* project and *Projet National* (National Project, France) *RECYBETON* are acknowledged.

Appendix 1. Repeatability of the open porosity and the intrinsic permeability measurement

The evaluation of the coefficient of variation of open porosity (Table A1) and permeability (Table A2) shows a good homogeneity of the material (very low coefficient of variation). From a statistical point of view, it can be assumed that each of the three samples of each type of concrete is representative of the same population, at 99% confidence level. Only ORS-100RG samples show a significant dispersion in the permeability measurements. This could be explained by an artifact during testing.

Table A1
Open porosity.

		Porosity (%)	Mean value (%)	Measure of statistical dispersion	
				Standard deviation (%)	Coefficient of variation
ORS-ORG	Top	14.51	13.5	0.81	6.03
	Center	13.43			
	Bottom	12.52			
3ORS-ORG	Top	16.81	15.7	0.96	6.08
	Center	15.85			
	Bottom	14.48			
ORS-30RG	Top	15.77	15.6	0.95	6.09
	Center	16.63			
	Bottom	14.33			
ORS-100RG	Top	18.99	18.8	0.46	2.45
	Center	19.22			
	Bottom	18.15			

Table A2
Intrinsic permeability and Klinkenberg coefficient.

		Mean value				Measure of statistical dispersion			
						Standard deviation		Coefficient of variation	
		$k_v \times 10^{-17} \text{m}^2$	β (MPa)	$k_v \times 10^{-17} \text{m}^2$	β (MPa)	$k_v \times 10^{-17} \text{m}^2$	β (MPa)	k_v	β (MPa)
ORS-ORG	Top	3.85	0.085	3.54	0.13	0.29	0.04	0.08	0.32
	Center	3.28	0.14						
	Bottom	3.5	0.17						
3ORS-ORG	Top	5.78	0.18	5.70	0.22	0.08	0.11	0.01	0.52
	Center	5.63	0.13						
	Bottom	5.70	0.35						
ORS-30RG	Top	5.99	0.18	5.85	0.16	0.12	0.02	0.02	0.12
	Center	5.75	0.14						
	Bottom	5.81	0.16						
ORS-100RG	Top	7.97	0.10	7.01	0.12	0.98	0.015	0.14	0.13
	Center	7.06	0.12						
	Bottom	6.01	0.13						

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