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Influence of industrially produced recycled aggregates on flow properties of concrete

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ABSTRACT

This research aims at evaluating the main risks for the durability of concrete made of industrially produced recycled aggregates called Recycled Aggregate Concrete (RAC). A characterisation of recycled aggregates is performed and their peculiarities are highlighted. A comparison between the behaviour of RAC and that of ordinary natural aggregate concrete is carried out. The influence of both the composition and the curing conditions is discussed.

The durability study is focused on the assessment of parameters representing the porous structure and concrete characteristics. Because of the high total water/cement ratio of RAC, their flow properties control their durability. It is established that RAC are characterised by significantly higher water absorption and air permeability. The diffusion of the carbon dioxide is faster, too. That leads to a weaker resistance of RAC to environmental attacks.

Since the main durability problems are caused by the fine recycled fraction, its use needs to be restricted. Another way to increase RAC durability seems to be the extended curing in wet environment.

RÉSUMÉ

La recherche présentée dans ce papier a pour objectif d'évaluer la durabilité des bétons à base de granulats recyclés produits industriellement. La caractérisation des granulats recyclés est présentée en insistant sur leurs particularités. Une comparaison des performances des bétons de granulats naturels et recyclés est menée et l'influence de la composition et des conditions de cure est discutée.

L'étude de la durabilité est centrée sur l'évaluation de paramètres représentatifs de la structure poreuse et des caractéristiques du béton. En raison de l'importance du rapport eau totale/ciment, la durabilité est contrôlée par les facteurs de transfert : absorption d'eau et perméabilité à l'air élevées. La carbonatation est également plus rapide. Cela conduit à une faible résistance aux attaques environnementales et chimiques du béton de granulats recyclés.

Les principaux problèmes de durabilité sont dus à la fraction fine, le sable recyclé. Son emploi doit donc être limité. Une autre voie d'amélioration de la durabilité des bétons recyclés est la réalisation d'une cure soignée.

1. INTRODUCTION

The ways of production and the use of Recycled Aggregate - RA issued from building demolition waste are at present well assessed [1]. The use of RA as substitute for natural aggregate to produce concrete offers environmental and economic interest. This interest is greater when the maximum quantity of recycled aggregate is used in concrete manufacturing. However in order to obtain satisfactory concrete performance only coarse recycled aggregate are partially substituting for natural aggregate [2, 3]. Recycled fine aggregate are not used. In addition, the majority of the studies leading to develop RAC have been carried out with RA produced in laboratory conditions.

This study investigates the influence of the use of both fine and coarse industrially produced RA on durability characteristics of RAC for ordinary purposes.

The durability of recycled aggregate concrete depends on RA characteristics, mix proportions, and curing conditions:

– RA issued from building demolition waste presents some distinctive characteristics compared to natural aggregate: despite the increase in the quality of the industrial recycling process, the higher heterogeneity and the presence of impurities and old cement paste

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bonded to original natural aggregates lower the characteristics of RA. In addition, RA are not quite inert and could influence the behaviour of both fresh and hardened concrete [4, 5].
– Mix proportions must take into account the high water absorption of RA. A significantly higher water-concrete (W/C) ratio must be applied to obtain a good workability, even when water-reducing admixture is used [2, 6].
– High water absorption of RA and high Total water/cement ratio of recycled aggregate concrete induce water transfer during and after hydration. Curing conditions therefore have a great effect on the final performance of concrete [7].

This paper purposes to assess the main risks for the durability of industrially produced recycled aggregate concrete. Surface water absorption, air permeability, and carbonation are investigated. There are various relations between these accepted durability indicators and the mechanisms of concrete degradation [8]. The influence of fine recycled aggregate is highlighted.

The described work is a part of a French-Bulgarian research on the development of the use of recycled aggregate concrete [6].

2. EXPERIMENTAL PROGRAM

2.1 Materials

Two fractions of recycled aggregates RA were used: fine (6-0 mm), and coarse (20-6 mm) (Fig. 1). They are produced by the RMN company (Recyclage des Matériaux du Nord) located in Northern France.

For the current study recycled aggregate of only one lot of production was used. However, since recycled aggregate is of heterogeneous origin involving variation of both composition and characteristics of old concrete, its use requires systematic control. For this reason the recycled aggregate production was preliminarily monitored for 12 months [9].

The recycled aggregate produced by RMN can be characterised as follows:
– The main part of the coarse fraction corresponds to the standard grading of concrete aggregates (*i.e.*, according to the French standard NF P 18-541). Nevertheless recycled sand is coarser (Fig. 2). Its fineness modulus is equal to 3.8 ± 0.3 higher than acceptable fineness modulus for concrete sand (between 1.80 and 3.20).
– The average proportion of old cement paste is 28% ± 5%. The fine fraction presents a higher proportion than the coarse fraction.
– Because of the old mortar coating and the presence of light impurities, RA presents a lower density and a higher porosity than natural aggregate – Table 1;
– High water absorption is the most significant difference in the physical characteristics;
– RA presents a cracked surface which contributes to an increase in water and air flows into the aggregates and between the cement paste and the aggregates;

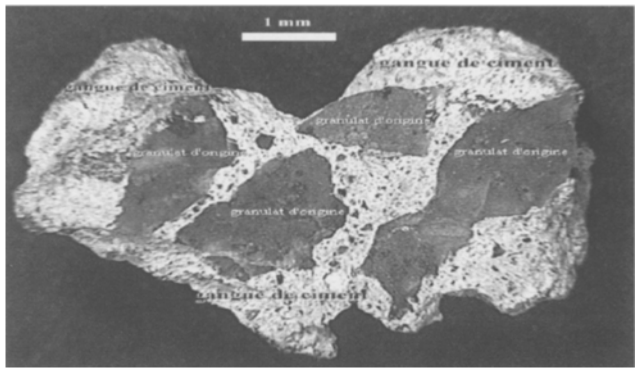

Fig. 1 – Recycled coarse aggregate.

– Despite satisfying mechanical characteristics (*i.e.*, Los Angeles abrasion loss percentage ranged from 27% to 35%), in terms of durability properties such as frost vulnerability (according to NF P 18-593) and sulphate soundness (according to ASTM C88), RA is less durable [10];
– It should be noted that industrially produced recycled aggregate could contain various impurities that influence hydraulic concrete production [5, 10]. The weight fraction of impurities for the recycled aggregate used in the current study is about 10%. The RMN recycling plant separates the major part of light impurities (wood, plastics and paper) through a floating line. For the heavy impurities, bricks (7.1%) and asphalt (3.5%) are commonly observed. Metal appears in very small quantities (0.01%), confirming the efficiency of the different processes for removal used by RMN [9];

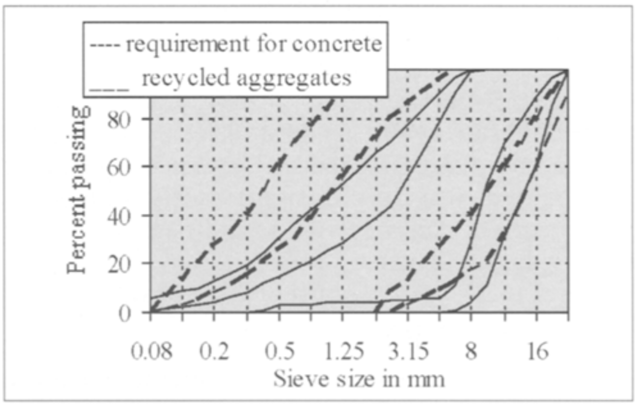

Fig. 2 – Grading curves of aggregates.

– Because of the plaster content (0.6% calculated as SO_4), RA could induce a sulphate reaction [10];
– It is proved that a large part of RA could have potential alkali-aggregate reactivity (according to the Microbar test NF P 18-588) and thus could induce other types of pathological reactions. Therefore some preventive measures must be ordered when using RA in concrete, concerning both the type and the final use of recycled aggregate concrete [5, 10].

The natural sand was used for reference concrete and coming from the river Seine. The coarse natural aggregate (20-6 mm) was a siliceous crushed rock. This type

Table 1 - Characteristics of aggregates				
Type of aggregates	Fine RA	Coarse RA	Natural sand	Coarse NA
Dry Density (kg/m^3)	2160±300	2250±400	2600	2680±200
Porosity (%)	-	12.5±1.5	-	0.3
Water Absorption (%)	12.0±1.5	6.0±0.5	2.0	0.2
Frost sensibility (%)	-	26.7±6.9	-	5.6
Sulphate soundness (%)	25.7±1.0	26.4±0.5	-	3.8±0.5

of aggregate is of current use in North of France. The main characteristics of the aggregates are presented in Table 1. Portland cement (CEM I 42.5), with 9% of C_3A, was used throughout. The superplasticizer Sikament 10 from SIKA Company was used as water-reducing admixture.

2.2 Mix design

Three types of concrete were produced (Table 2):
– Recycled aggregate concrete called RAC1, RAC2 and RAC3;
– Mixed aggregate concrete (MAC) made with natural sand and recycled coarse aggregate;
– Usual concrete called NAC1 and NAC2 made with natural aggregate, and used as reference concrete.

The common parameters of the mixes were: a similar aggregate mix density, an equal cement content aiming at minimum a compression strength of 25 MPa, and an equal workability (slump of about 50 mm).

The choice resulted from industrial and economic considerations. For non-structural applications, it is usual to design concrete with a low slump.

The coarse surface texture, angularity and high water absorption of recycled aggregate have a considerable influence on RAC workability. The water requirement is increased, resulting in significantly high (total water)/cement ratio of RAC, regardless of the use of water-reducing admixtures – Table 2.

The total water content is considered for water/cement ratio, because it is impossible to separate the effective water content (according to EN 206 'Concrete - Performance, production, placing and compliance criteria' it corresponds to water absorbed by recycled aggregate and mixing water) from the total water content in the fresh concrete, especially when recycled sand is used. In addition, during hardening, part of the water absorbed by RA contributes to the free water content [11].

Mix proportioning and characteristics of fresh concrete are presented in Table 2.

Table 2 - Mix proportioning and characteristics of fresh concrete						
Mix designation	NAC1	NAC2	MAC	RAC1	RAC2	RAC3
Cement (kg/m^3)	400	400	400	400	400	400
Total water (l)	190	171	200	260	262	245
Natural sand* (kg/m^3)	523	685	787*	-	-	-
Fine RA (kg/m^3)	-	-	-	629	659	675
Coarse RA (kg/m^3)	-	-	824	878	846	865
Coarse NA (kg/m^3)	1219	1140	-	-	-	-
Superplasticizer (kg/m^3)	-	4	4	4	4	4
Total water/cement ratio	0.48	0.43	0.50	0.65	0.66	0.61
Workability (Slump test), mm	65	45	55	50	90	50
Density, kg/m^3	2360	2410	2220	2210	2195	2205

* *including coarse aggregates 8-2.5 mm.*

2.3 Manufacturing

For producing RAC, the previous experience of the laboratory is used [9, 10]. Recycled aggregates are pre-soaked to improve the placing of fresh concrete. This quantity of water is calculated as the difference between the water required for full saturation of aggregates and the water absorbed by the aggregates at the time of mixing. For producing RAC3, the recycled aggregates were not pre-soaked because of their high natural water content (7.6% for fine fraction and 5.1% for coarse fraction), hence the reason why the W/C of RAC3 (W/C=0.61) is lower than that of RAC1 (W/C=0.65) and RAC2 (W/C=0.66).

The components are placed into the pan mixer in the following order: aggregates, pre-soaking water, cement, mixing water containing 1/3 of the Sikament 10 superplasticizer), then the rest of the superplasticizer. When needed, some additional water was added to obtain the required workability.

The samples are cylinders (160 mm in diameter and 320 mm in height) and prisms (40x40x160 mm^3). After de-moulding at one day, the samples are stored 27 days in a controlled environment at 20°C and 65% relative humidity (air storage) or in water at 20°C (water storage).

3. CONCRETE CHARACTERISTICS

The performance of concrete is presented Table 3. They are measured after 28 days of storage in water or in air.

Compared to the reference concrete, all the recycled aggregate concrete are characterised by a smaller density, a higher porosity and lower mechanical properties. Mixed aggregate concrete MAC presents intermediate characteristics between natural (NAC1 and NAC2) and recycled aggregate concrete (RAC1, RAC2 and RAC3).

Short-term characteristics of RAC seem to be less related to curing conditions than these of NAC and MAC: the air storage increases the porosity of RAC by only 2% to 7%, while for NAC the increase is about by 13% compared

Table 3 - Performance of concrete (28 days storage)							
Mix designation		NAC1	NAC2	MAC	RAC1	RAC2	RAC3
Density (kg/m^3)	Water storage	2345	2440	2370	2195	2205	2225
	Air storage	2315	2380	2305	2155	2160	2190
Porosity (%)	Water storage	11.2	7.2	12.5	22.6	22.0	19.7
	Air storage	12.6	8.1	14.2	23.1	22.8	21.1
Compress. Strength (MPa)	Water storage	42.6	54.8	43.3	31.5	35.4	39.4
	Air storage	37.7	47.7	37.8	29.5	34.2	38.1
Swelling/Shrinkage (1 year) (μ m/m)	Water storage	-	140	180	-	-	330
	Air storage	-	460	830	-	-	1420

to the porosity of concrete stored in water. This fact could be explained by the role of "water supply" played by fine RA: the water absorbed by fine RA is gradually brought to the cement paste, thus compensating the water loss due to the drying [7].

For the same reason, the compressive strength of RAC decreases by no more than 3% to 6% when the curing conditions change, while the strength of NAC and MAC decreases by three times more.

For air storage curing conditions, the presence of free water in recycled aggregate concrete induces an increase of drying shrinkage by 80% (for MAC) to 3 times (for RAC3) in comparison with natural aggregate concrete (NAC2). The results are similar to these of other studies [2, 5].

For water storage curing conditions, a swelling value of less than 200 μm/m can be caused by the water absorption [12], as observed for NAC2. The higher value of swelling for RAC3 can be explained by the formation of expansive products due to the sulphatic reaction, but this value can not be considered as dangerous [6].

4. DURABILITY STUDY

4.1 Sampling and curing

The concrete used for durability tests are NAC2, MAC, and RAC3. The samples are issued from cylinders (110 mm in diameter and 220 mm in height). Depending on the tests, the disks are made using a water-cooled diamond saw by cutting disks from the 28-day-old cylinders with the following dimensions:

- 110 mm in diameter and 40 mm in height for air permeability and water absorption test;
- 110 mm in diameter and 70 mm in height for diffusion test.

After the cutting off, the disks are stored in a controlled environment at 20°C and 65 % relative humidity.

For water absorption tests the samples are pre-treated at 40°C up to reach a constant weight.

At the time of the test, the concrete was approximately 3 months old for the diffusivity tests and 6 months old for the other tests.

Three samples are tested for each experimental series. The average value of the measurements is presented.

4.2 Water absorption

The lateral surface of the disk is covered with adhesive aluminium sheet. The lower side is put in water. The disk is periodically removed and weighed [13]. Two parameters are calculated:

Initial water absorption (kg/m^2) that is the quantity of water absorbed by a unit of surface for 1 hour after the beginning of the test. According to [14] this parameter is corresponding to the volume of large pores (medium size of 1.25 μm).

Sorptivity ($kg/m^2.h^{0.5}$) which is defined as the slope of the line "quantity of water absorbed by a unit of surface ver-sus square root of the elapsed time" from 1 hour to 24 hours. This parameter features the water absorption of small pores (medium size of 0.04 μm) [14].

The water absorption test shows that RAC would be significantly more vulnerable to attacks than NAC. The initial absorption is nearly 4 times higher - Fig. 3a) and therefore the penetration of liquids would be faster. The sorptivity study leads to the same conclusion - Fig. 3b). The water curing induces a finer porosity and a lower water absorption, but this effect is better observed for MAC and NAC than for RAC. This is highlighting the role of water supply played by fine RA.

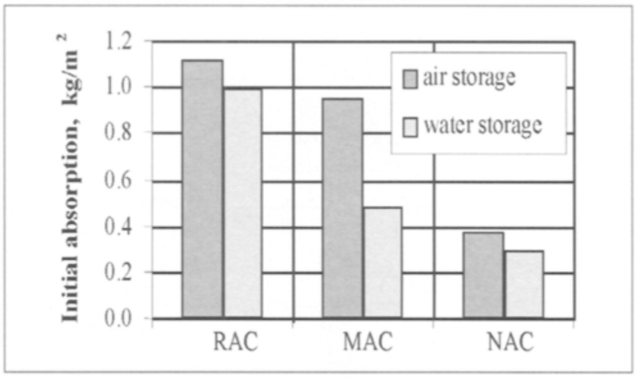

Fig. 3a) – Initial absorption of concrete.

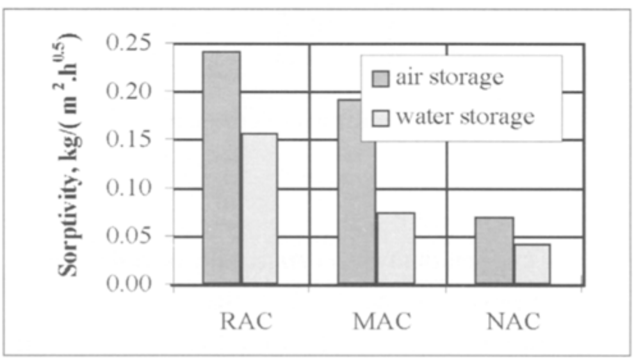

Fig. 3b) – Sorptivity of concrete.

4.3 Air permeability

An air permeameter, developed in France by Thénoz (1966) [15] and modified at the Laboratoire Matériaux et Durabilité des Constructions (LMDC) – Toulouse, is used. The principle of the test is shown Fig. 4. The vacuum created inside the chamber beneath the sample induces a pressure gradient that forces airflow through the concrete sample. The entry of air increases the pressure in the chamber and is measured by a glass tube filled with water. The time for the level in the tube to move from the starting level h_0 (corresponding to pressure P_0) to the final level h (corresponding to pressure P) is measured. The coefficient of apparent air permeability k_a (m^2) is calculated by the following equation:

$$k_a = \frac{\mu \times s \times l}{S \times \rho \times g \times t} \times \ln\left(\frac{h_o}{h}\right)$$

where: μ = viscosity of air at the test temperature (Pa.s); ρ = density of water (kg/m^3), g = gravity (m/s^2); S = cross-sectional area of the specimen (m^2); s = cross-sectional area of glass tube (m^2); l = length of the sample (m); t = time for water to pass from level h_0 to h (s).

The substitution from coarse natural aggregate by recycled aggregate doubles the air permeability k_a of the concrete – Table 4.

When both fine and coarse RA is used (for RAC), the permeability increases 6.5 times compared to that of MAC and 13 times compared to that of NAC. However, the value of the air permeability of RAC is within the published range for normal concrete not exposed to strong aggressive environment ($k_a = 10^{-18}\ m^2 - 10^{-17}\ m^2$) [15, 16].

The beneficial effect of curing is observed for all the concretes but is more noticeable for RAC.

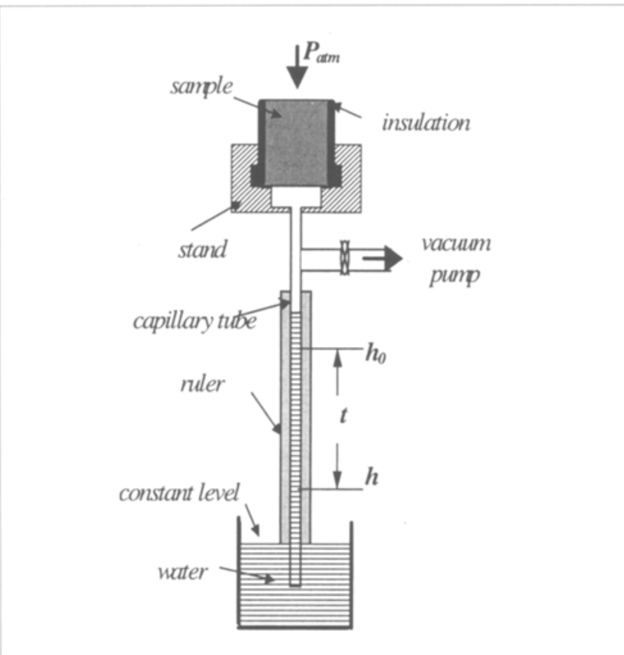

Fig. 4 – Principle of measurement of air permeability.

Table 4 - Coefficient of air permeability vs. curing type						
Type of Concrete	RAC		MAC		NAC	
Type of Curing	air	water	air	water	air	water
k_a, $10^{-18}\ m^2$	20.0	6.0	3.1	2.8	1.45	1.04

4.4 Carbonation

The accelerated carbonation test is chosen to assess the diffusivity of the concrete [8] and is conducted in a cell filled with a mixture of 50% air and 50% CO_2 at 20°C and 65% relative humidity [17]. The depth of carbonation is measured at 7, 14 and 28 days by application of phenolphthalein to a free surface obtained by splitting. The test results show that the process of CO_2 diffusion in recycled aggregate concrete complies to the parabolic rate law established with classic concrete. So a model of the recycled aggregate concrete carbonation kinetics can be designed accordingly to the basic law of diffusion (Fig. 5):

$$x = C \times \sqrt{t}$$

where: x, C and T are depth, rate and time of carbonation.

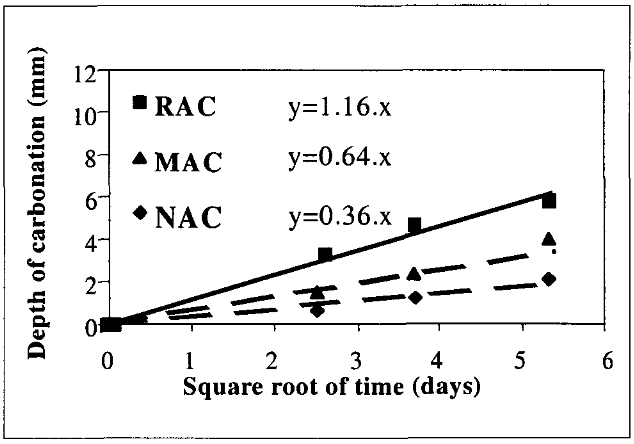

Fig. 5 – Relationship between depth of carbonation and square root of time.

However, according to various studies [5] recycled aggregate concrete is carbonated faster than natural aggregate concrete - the rate of carbonation of RAC is about 4 times greater than that of NAC. Therefore, reinforced recycled aggregate concrete would require a larger concrete cover.

The depth of carbonation of RAC, as well as this of NAC, is almost two times smaller when concrete are cured in water - Fig. 6. It should be noted that the depth of carbonation decrease might be partially due to the higher internal humidity content of these concrete. This influence would be however less pronounced for RAC because of its higher porosity allowing a faster water evaporation after curing. Therefore, extended cure seems

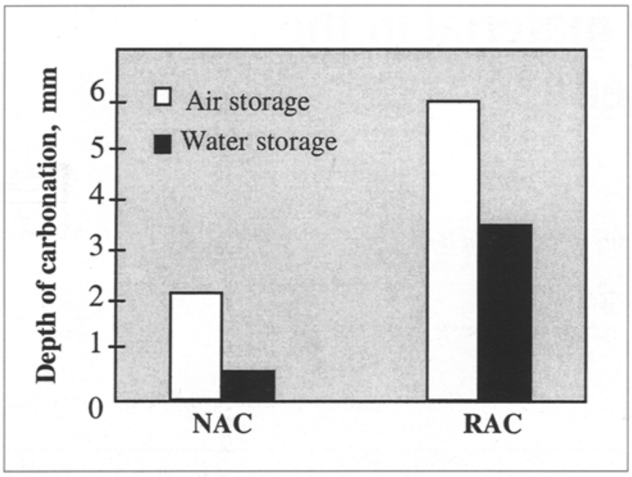

Fig. 6 – Influence of curing on depth of carbonation after 28 days of accelerated carbonation.

to be one of the more practical methods to decrease the carbonation rate of recycled aggregate concrete

5. CONCLUSIONS

The performed characterisation of industrially produced RA shows that they could induce some pathological reactions such as alkali-aggregate reaction or sulphate reaction. Therefore, some precautions must be taken when using RA for concrete making.

The mix proportioning of recycled aggregate concrete must be suited, particularly when both fine and coarse aggregates are totally substituted for natural aggregate. The comparison of performance shows that their decrease is related to the increase of total water/cement ratio required by the preservation of workability.

About durability study, recycled aggregate concrete is characterised by significantly higher water absorption and air permeability, mainly due to the higher porosity of cement paste. The own porosity of RA and their cracked surface, as well as the presence of some impurities (*i.e.* brick particles), contributes to an increase in water and air flows into the aggregates and between the cement paste and the aggregates.

The carbonation rate of recycled aggregate concrete is also higher. That leads to a weaker resistance of recycled aggre-gate concrete to environmental attacks.

The mixed aggregate concrete (coarse RA and natural sand) presents intermediate performance between recycled aggregate concrete and natural aggregate concrete. It can be concluded that the use of fine recycled aggregate substituted for natural sand is the main cause of weakening of performance, even if sometimes the water supply effect of fine recycled aggregate can be interesting. Therefore their use needs to be restricted, sometimes prohibited.

Another way to increase recycled aggregate concrete performance is to make an extended cure in a wet environment.

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