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Assessment of the surface permeation properties of recycled aggregate concrete

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Abstract

The water permeability, air permeability and surface permeability of recycled aggregate concrete (RAC) are compared with those of a control concrete made with natural aggregate. The study shows that the permeation properties of RAC depend on mix-design, conditions of curing and drying of samples. Relationships between permeability and other physical characteristics of concrete such as water absorption capacity and diffusivity are discussed. According to the criteria existing for ordinary concrete made with natural aggregate, RAC could be classified as being of moderate quality rather than poor quality. The testing methodology shows that some of the techniques used to measure the permeability of RAC need to be modified in order with the distinctive characteristics of this material.

Keywords: Building wastes; Recycled aggregates; Concrete; Permeability; Tests; Durability

1. Introduction

The opportunity for using recycled building waste in concrete construction has been a subject of intensive research for many years [1]. Recycled aggregate is primarily used in road construction. The lack of data on the durability of concrete made with recycled aggregates is hindering large-scale use of this economic and "environmentally friendly" material in construction industry [1,2]. The prediction of the RAC durability depends on two problems:

(a) Assessment of the influence on durability induced by the features of recycled aggregate and the overall quality of RAC. Recycled aggregate cannot be considered as inert. They are highly heterogeneous and porous, as well as a high content of impurities. The main drawback of RAC is the difficulty in obtaining a good workability. The water–cement ratio (W/C) must be high, even when using water-reducing admixtures.
(b) Selection of reliable parameters for the characterisation of RAC behaviour, and implementation of adjusted methods for the assessment of these parameters. An approach at a microscopic level is inappropriate due to the heterogeneous nature of this material [2]. The present approach focuses on the assessment of parameters at the macroscopic level, representing the porous structure and the flow properties of the concrete.

The high W/C ratio of RAC results in high values of permeability and porosity. On the other hand, it is currently accepted that these characteristics provide a reliable indication (at least on a qualitative level) of the durability or degradation of this material [3,4].

Experiments have been conducted over a twenty-year period [5] and have shown a consistent increase in permeability and porosity resulting from the degradation of the material. Since the early 1930s, the rate of water flow through concrete has been of particular interest to civil engineers, for example in dams and water retaining

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structures [6,7]; however, interest shifted in the 1960s when permeability and adsorption were used as indicators of the quality of concrete [8,9]. Improved testing methods and new standards are currently available for in-site and laboratory assessments of gas and water permeability of concrete and porous media [10–16]. As a consequence water, air and surface permeability can be considered as being among the most representative parameters in relation with RAC durability. Air diffusing into concrete can cause carbonation, and is thus commonly assumed that an increase in air permeability of the concrete is significant for numerous degradation processes [17].

In order to assess the application of permeability measurements in durability studies, correlation between air and surface permeability and flow parameters such as diffusivity, depth of carbonation, capillarity, and water absorption must be studied.

2. Experimental study

2.1. Materials

Two fractions of recycled aggregates RA were used: fines (0–6 mm), called recycled sand, and coarse (6–20 mm). They are produced by Recyclage des Matériaux du Nord (RMN) 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 concrete, its use requires systematic control. For this reason the recycled aggregate was preliminarily monitored for 12 months [18]. 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. Recycled sand is occasionally coarser. Its fineness modulus is equal to 3.78 ± 0.27;
- The distinctive characteristic of recycled aggregate is that mortar always adheres to original natural aggregate. The weight fraction of old cement paste is $28\% \pm 4.5\%$. For the recycled sand, the fraction is relatively higher than for the coarse;
- Because of the mortar coating, recycled aggregate has lower density and higher porosity than natural aggregate;
- High water absorption is the most significant difference in the physical characteristics;
- Recycled aggregate 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;
- Despite satisfying mechanical characteristics (i.e., Los Angeles abrasion loss percentages 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), recycled aggregate is less durable [3];
- It should be noted that industrially produced recycled aggregates can contain various impurities which influence hydraulic concrete production [1–3]. 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 (0.008%), confirming the efficiency of the different processes for removal used by RMN;
- Because of the plaster content (0.6% calculated as SO_4), recycled aggregate could induce a sulphate reaction [3].

The natural sand (0–4 mm) was used for reference concrete and obtained from the river Seine. The coarse natural aggregate (6–20 mm) was a siliceous crushed rock. 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 superplasticiser Sikament 10 from SIKA Company was used as water-reducing admixture.

2.2. Mix design

Three types of concrete were produced (Table 2):

(i) Recycled aggregate concrete denoted RAC1, RAC2 and RAC3;

Table 1
Characteristics of aggregates

Type of aggregates	Fine RA	Coarse RA	Fine NA (sand)	Coarse NA
Dry density (t/m^3)	2.16 ± 0.30	2.25 ± 0.40	2.60	2.68 ± 0.02
Porosity (%)	–	12.5 ± 1.5	–	0.3
Water absorption (%)	12.0 ± 1.5	6.0 ± 0.5	2.0	0.2
Frost vulnerability (%)	–	26.7 ± 6.9		5.6
Sulphate soundness (%)	25.7 ± 1.0	26.4 ± 0.5	–	3.8 ± 0.5

Table 2
Mix proportions and properties of fresh concrete

Mix designation	NAC1	NAC2	MAC	RAC1	RAC2	RAC3
Cement (kg/m^3) CEM I 42.5	400	400	400	400	400	400
Superplasticiser Sikament 10 (kg/m^3)	–	4	4	4	4	4
Water of pre-soaking (l)	0	0	0	66	38	0
Water content in the aggregates (l)	20	21	50	63	93	95
Added water (l)	170	147	147	129	129	147
Water in total (l)	190	171	200	260	262	245
Natural sand[a] (kg/m^3)	523	685	787[a]	–	–	–
Recycled sand (kg/m^3)	–	–	–	629	659	675
Recycled coarse aggregates (kg/m^3)	–	–	824	878	846	865
Natural coarse aggregates (kg/m^3)	1219	1140	–	–	–	–
Superplasticiser Sikament 10 (kg/m^3)	–	4	4	4	4	4
(Total water content/cement) W/C	0.48	0.43	0.50	0.65	0.66	0.61
Slump (cm)	6.5	4.5	5.5	5.0	9.0	5.0

[a] Plus coarse aggregates 2.5/8 mm for concrete MAC.

(ii) Mixed aggregate concrete (MAC) made with natural sand and recycled coarse aggregates;
(iii) Normal concrete denoted NAC1 and NAC2 made with ordinary aggregates, and used as reference concrete.

The common parameters of the mixes were: a similar aggregate mix density, an equal cement content, and an equal workability (slump of about 5 cm). The choice resulted from industrial and economic considerations.

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 (W/C) of RAC, regardless of the use of water-reducing admixtures.

The total water content is considered for W/C ratio, because it is impossible to separate the effective water content [19] (water absorbed by recycled aggregate and mixing water) from the total water content in the fresh concrete, especially in the case of recycled sand. In addition, during hardening, part of the water absorbed by the recycled aggregate contributes to the free water content.

For producing RAC, previous experience of the laboratory is used [3,8]. 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 actually 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 and 5.1% for coarse), 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 superplasticiser), then the rest of the superplasticiser. When needed, some additional water was added to obtain the required workability.

2.3. Making, storage and conditioning of samples

Different sizes of samples are used: cylinders (11 cm diameter and 22 cm height) and cylinders (16 cm diameter and 32 cm height), cubes ($15 \times 15 \times 15$ cm^3) and prisms ($7 \times 7 \times 28$ cm^3).

They were stored in an air-conditioned room at 20 ± 3 °C temperatures and 85 ± 5% relative humidity (R.H.). Four curing conditions are adopted:

(1) "Short": 1 day in the mould;
(2) "Extended": 3 days in the mould;
(3) "Favourable": 28 days in the mould;
(4) "Water curing": 1 day in the mould followed by 27 days in water at 20 °C.

After the curing, the cylinders are stored in an air-conditioned room at 20 ± 3 °C temperature and 65 ± 5% relative humidity. Depending on the tests, the samples are made using a water-cooled diamond saw by cutting disks from the 28-days-old cylinders with the following dimensions:

- 11 cm diameter and 4 cm height for air permeability and water absorption test;
- 11 cm diameter and 7 cm height for diffusion test;
- 6.3 cm diameter and 5 cm height for water permeability test.

After the cutting off, the samples used for water permeability test are conserved in water, while the other ones are stored in an air-conditioned room at 20 ± 3 °C and 65 ± 5% R.H. Some samples are tested before and after drying in an oven at 80 °C.

In order to evaluate the influence of pre-treatment temperature on permeation properties of concrete, samples for air permeability test are dried in an oven at 40 or 80 °C.

For surface permeability and water absorption tests the samples are pre-treated in an oven at 40 °C up to reach a constant weight.

At the time of the test, the concrete was approximately 3 months old for the water permeability and 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.

3. Test set-up

3.1. Water permeability test

The water permeability of concrete is determined by using a triaxial permeability cell, accordingly to [20] – Fig. 1.

As soon as water saturation is achieved, the sample is subjected to a water flow, under controlled pressure conditions. Liquid is injected, at a constant pressure P_i, by a high-pressure pump (Gilson type) from calibrated capillary tubes (3 mm diameter). Such a device has the advantage that the injected flow can be measured with high accuracy and, as soon as a steady state flow is reached, it can be easily recorded. Furthermore, it is a direct measurement of the permeability, under steady conditions, which is carried out and based on the entry flow rate Q measurement. As the flow can be assumed to be laminar and the material fully saturated with water, Darcy's law is applied and leads to:

$$K = \frac{\mu Q}{S}\frac{h}{(P_i - P_0)}, \tag{1}$$

where μ is the viscosity of water at the test temperature (Pa s), Q is the flow rate (m^3/s), S is the cross-sectional area of the specimen (m^2), h is the high of the sample (m), P_i is the driving pressure ($P = 1.5 \pm 0.2$ MPa), and P_0 is the atmospheric pressure.

3.2. Air permeability test

An air permeameter, developed in France by Thénoz (1966) [21] and modified at the Laboratoire Matériaux et Durabilité des Constructions (LMDC) – Toulouse, is used – Fig. 2. The principle of the test is shown in Fig. 3. The vacuum created inside the chamber beneath the

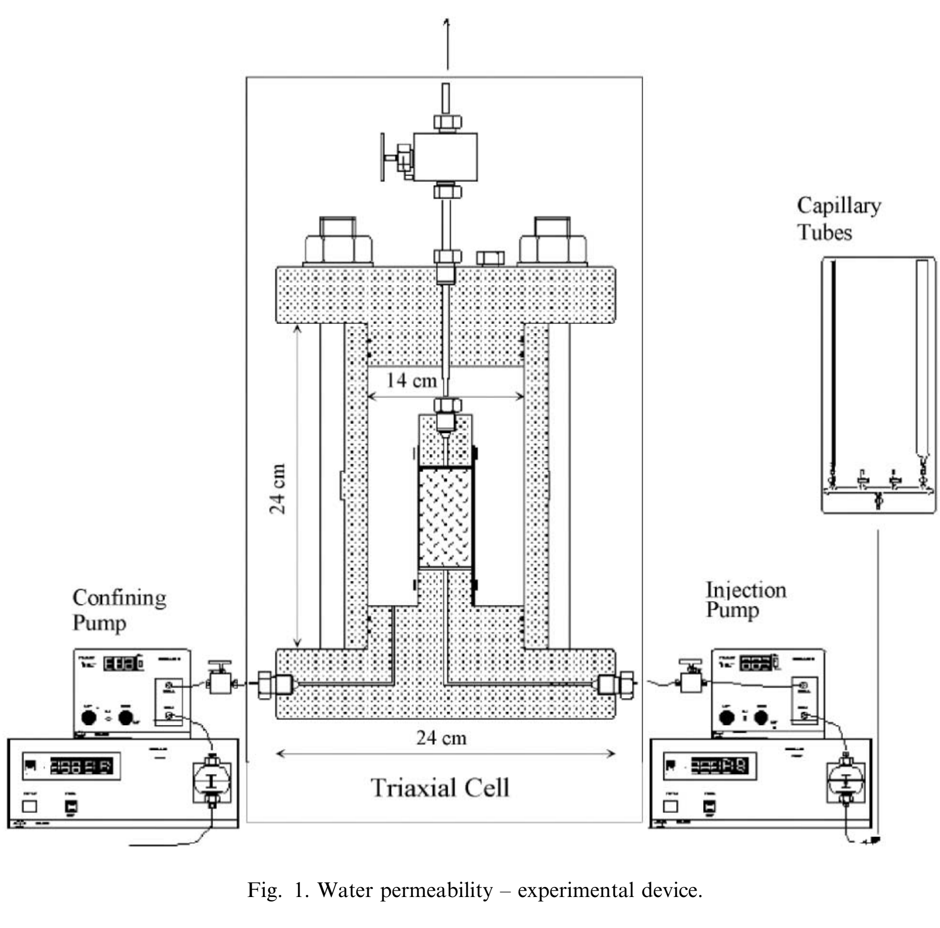

Fig. 1. Water permeability – experimental device.

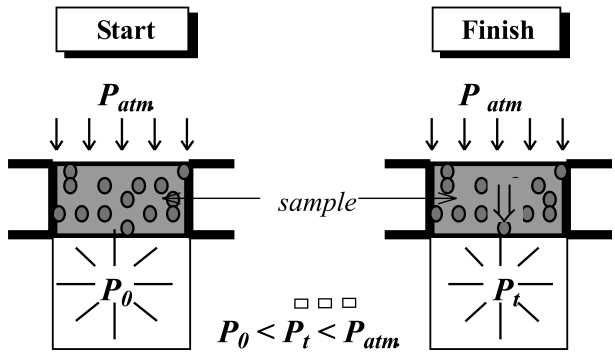

Fig. 2. Air permeability – principle of the experiment.

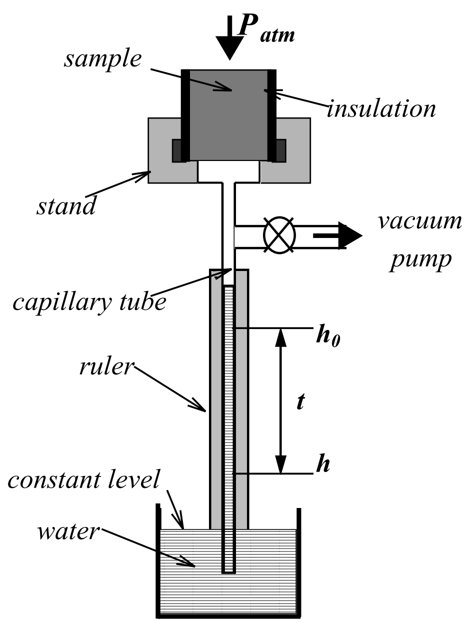

Fig. 3. Air permeability – experimental arrangement.

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:

$$k_a = \frac{\mu s l}{S\rho g t} \ln\left(\frac{h_0}{h}\right), \tag{2}$$

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

3.3. Surface permeability test

The method of Schönlin-Hilsdorf – 1987 is chosen to measure the surface permeability, because this method is non-destructive and easy to perform [22]. The used equipment is developed by Laboratoire Central des Ponts et Chaussées (LCPC), France – Fig. 4. The principle is the following: with a pump, a vacuum $P_{ini} = -1.0$ bar is created in the chamber of volume (V). The vacuum induces a pressure gradient that forces airflow through the concrete with a rate equal to q. The entry of air increases the pressure in the chamber. The time to re-establish the atmospheric pressure (p_a) in the chamber, as shown in Fig. 4, is called the "response time" [23]. Therefore the response time is used as a permeability criterion: the shorter is the time, the more permeable the concrete. The pressure P in the chamber is measured every minute during a period of 15 min.

The value of the pressure in the chamber changes according to an exponential law [22]. The response time T is calculated with the equation:

$$T = -\frac{t}{\ln\left(\frac{P}{P_{ini}}\right)}, \tag{3}$$

where P is the measured pressure, P_{ini} is the vacuum applied pressure, and t is the testing time (s).

The investigated depth of concrete depends on the duration of pumping. Accordingly to the authors of the equipment, a pumping of 30 s permits to characterise at least 30 mm depth of concrete cover [23].

3.4. Water absorption capacity test

The test set-up presented in Fig. 5 evaluates water absorption capacity. The lower side of the sample is placed in water and periodically removed and weighed. Sorptivity ($kg/m^2\ h^{0.5}$) is defined as the slope of the curve "quantity of water absorbed by an unit of surface versus square root of the elapsed time" from 1 to 24 h [24].

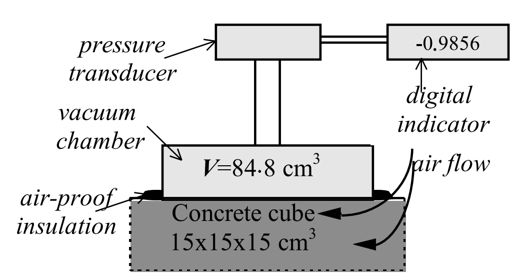

Fig. 4. Surface permeability – experimental arrangement.

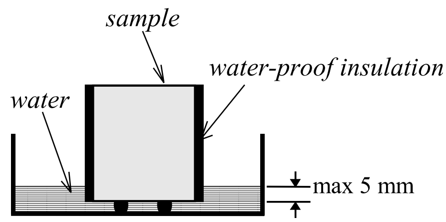

Fig. 5. Water absorption – experimental arrangement.

3.5. Diffusivity test

The accelerated carbonation test is chosen to assess the diffusivity of the concrete and is conducted in a cell filled with a mixture of 50% air and 50% CO_2 with a relative humidity of 65%. The depth of carbonation is measured at 7, 14 and 28 days by the phenolphthalein method. For each sample the average value of three measurements made on different place is presented.

4. Results and discussion

Table 3 shows the basic characteristics of concrete according to the curing conditions in water and in air ("water" and "short" curing). Compared to the NAC, RAC is characterised by a reduction in density, a higher porosity and lower mechanical properties. The mixed aggregate concrete (MAC) displays intermediate characteristics.

It should be noted that unlike natural and mixed concrete, RAC is less affected by a short curing. This fact could be explained by the role of water in the recycled sand: the water absorbed by the sand is gradually transferred to the cement paste, thus correcting the loss of water due to hydration drying.

4.1. Water permeability

According to the values of water permeability of about 10^{-20} m^2, RAC is weakly water permeable. In comparison with NAC, the water permeability of RAC is two times higher. A similar result is obtained by Ujike [2]. The curing conditions have little effect compared with the low accuracy of the results – Table 4.

The permeability of RAC3 is higher than that of RAC1, whereas RAC1 is characterised by a higher porosity resulting from a higher W/C ratio. This can be explained by the higher quantity of recycled sand in RAC3. Other researchers [1,2,18] notice an increase of the permeability with the proportion of recycled sand.

The average duration of test is about three weeks. So the effect of self-healing masks the real influence of the composition and of the curing conditions on the water permeability [16,23]. The high fraction of old mortar bonded to the original aggregate in the recycled aggregate could amplify the self-healing effect for RAC. However, it is possible that self-healing also decreases the water permeability of concrete in real conditions and can be considered as a potential parameter for its durability assessment [23].

The permeability of the conditioned (80 °C) NAC and RAC is between one and two orders (30 for RAC3 and 10 for NAC2) of magnitude above that of naturally conditioned samples. This difference can be explained by the change of the microstructure of the concrete: oven drying induces micro cracking of concrete, supplementary connections of previously disconnected or "dead-

Table 3
Basic physico-mechanical properties of concrete according to the curing conditions

Mix designation		NAC1	NAC2	MAC	RAC1	RAC2	RAC3
Density (kg/m^3)	Water curing	2345	2440	2370	2195	2205	2225
	Short curing	2320	2380	2305	2160	2160	2190
Porosity (%)	Water curing	11.2	7.2	12.5	22.6	22.0	19.7
	Short curing	12.6	8.1	14.2	23.1	22.8	21.1
Compressive strength (MPa)	Water curing	42.6	54.8	43.3	31.5	35.4	39.4
	Short curing	37.7	47.7	37.8	29.5	34.2	38.1

Table 4
Water permeability and porosity of concrete 28 days old

Concrete	RAC1		RAC3		NAC2	
Curing	Water	Short	Water	Water	Water	Water
Oven-drying	No	No	No	Drying at 80 °C	No	Drying at 80 °C
Permeability $k \times 10^{-20}$ (m^2)	1.4 ± 0.3	2.0 ± 0.4	2.4 ± 0.5	77 ± 3	0.8 ± 0.1	8.5 ± 1
Porosity (%)	23.1	22.6	19.7	–	7.2	–

end" pores and mineralogical changes of some cement paste compounds such as ettringite [17,25–28].

4.2. Air permeability

The replacement of coarse natural aggregate by recycled aggregate doubles the air permeability k_a of the concrete – Fig. 6. The replacement of all the natural aggregates by recycled aggregates increases the air permeability by a factor of 11 for RAC2 and 22 for RAC3. However, the value of the air permeability of RAC is within the published range for normal concrete not exposed to strong aggressive environment ($k_a = 10^{-18}$–10^{-17} m^2) [21,29].

The higher air permeability of RAC3 compared to that of RAC2 (short curing conditions) probably results from the lack of pre-soaking of the recycled aggregates: the absorption of water from the cement paste by the aggregates disturbs the process of hydration. Further evidence for this assumption results from the fact that, for water curing conditions, the air permeability of RAC3 is lower than that of RAC2.

The beneficial effect of water curing is also observed for the other concretes. For the extended curing ("extended" and "favourable") smaller effects are noticed on natural and mixed concretes. For RAC an increase from 1 to 3 days of the curing leads to a 50% reduction in the air permeability.

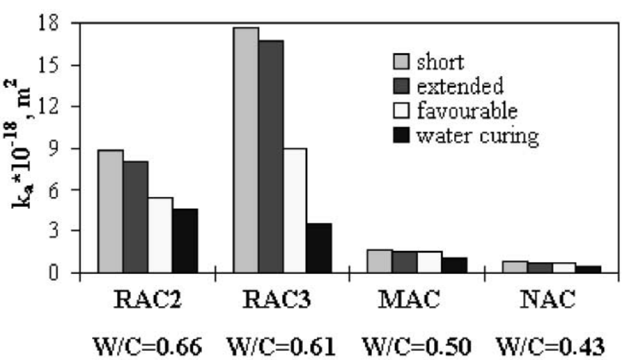

Fig. 6. Air permeability of concrete in accordance with the type of curing.

Results of tests on oven-dried samples confirm the significant influence of the conditioning on the flow properties of concrete. Whatever the concrete and curing conditions, the air permeability increases when the conditioning temperature increases – Fig. 7. The effect of oven drying at 40 °C increases the air permeability by 30–60%. This could be due to partial saturation of the capillary pores. With oven drying at 80 °C, the air permeability of all the concretes increases by a factor of 4 for the RAC and 6 for the NAC. Obviously, the oven drying modifies the microstructure and induces a significant increase of the air permeability, which has been established for NAC by other researchers [25,26].

4.3. Surface permeability

RAC presents a more permeable surface (by a factor of 10 to 25 times) than the reference concrete – Fig. 8. The prime reason is the higher W/C ratio of RAC; the water absorbed by recycled aggregate before and during mixing is gradually transferred to the cement paste. The surface evaporation of the excess water results in an opened porosity in the concrete cover. Nevertheless, based on the criteria proposed in other studies [23,30], RAC could be characterised as being of moderate quality rather than of poor quality. A relationship between surface permeability and W/C ratio may be derived – Fig. 9:

$$T = a(W/C)^b, \quad (4)$$

where T is the response time (s), a and b are the experimental parameters.

The response time T is well correlated with other physical characteristics of concrete: density – Fig. 10 and porosity – Fig. 11. Therefore the surface permeability is

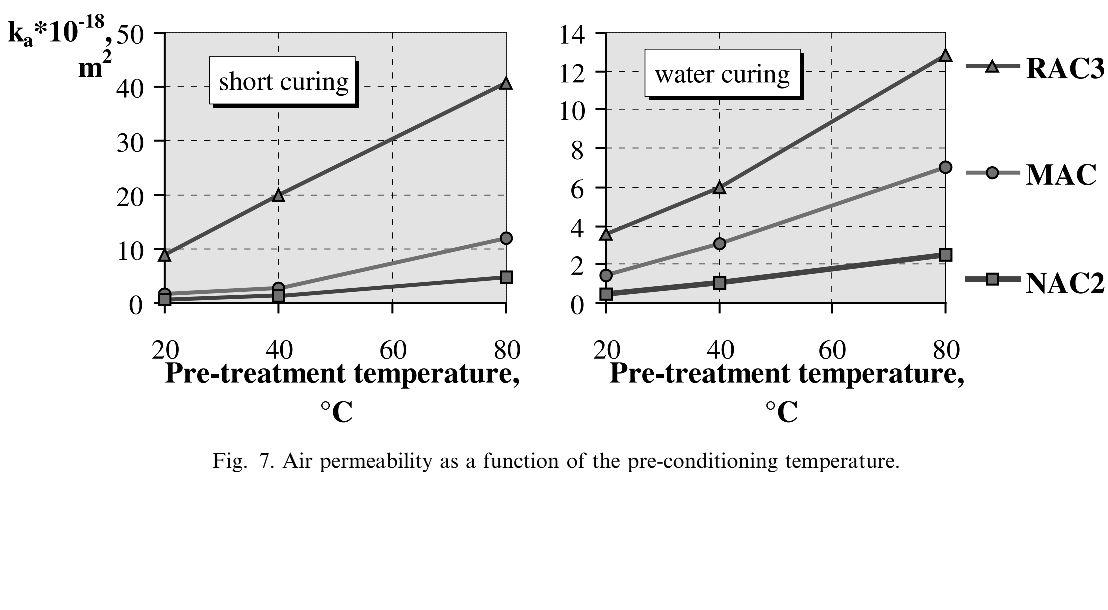

Fig. 7. Air permeability as a function of the pre-conditioning temperature.

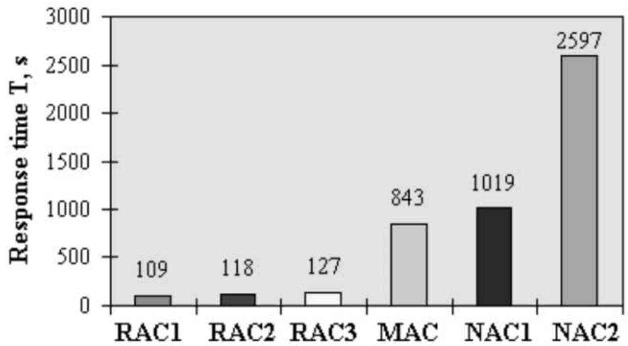

Fig. 8. Surface permeability of concrete (short curing; oven drying at 40 °C).

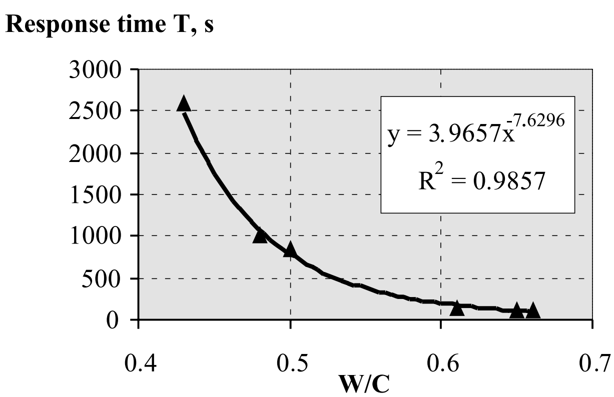

Fig. 9. Dependence of surface permeability on W/C ratio.

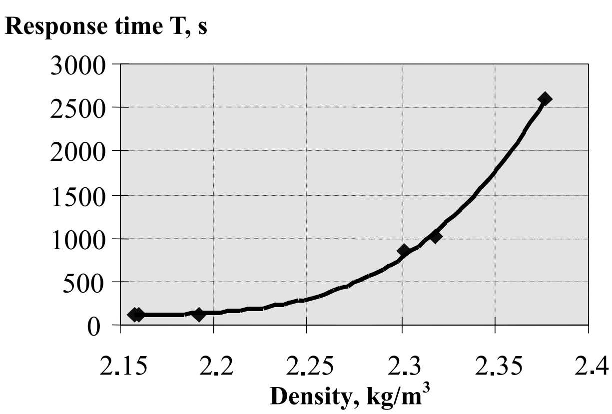

Fig. 10. Relationship between surface permeability and density of concrete.

a good indicator of the effects of the replacement of natural aggregates by recycled aggregates on concrete properties.

It is difficult to relate the response time to the intrinsic permeability, but the surface permeability is well correlated with other durability parameters such as sorptivity and diffusivity.

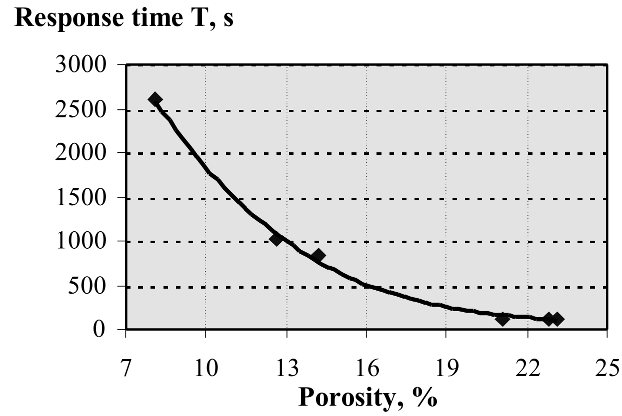

Fig. 11. Relationship between surface permeability and porosity of concrete.

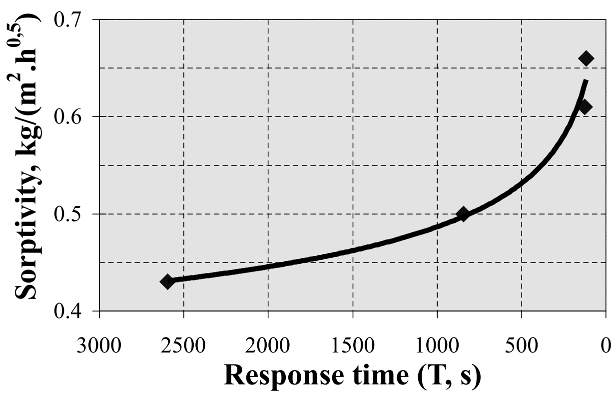

Fig. 12. Relationship between surface permeability and water sorptivity of concrete.

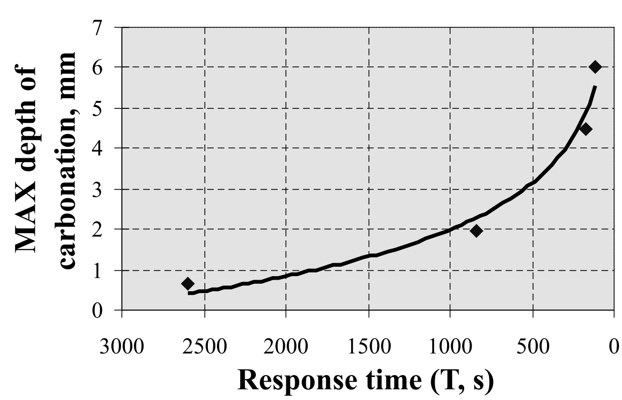

Fig. 13. Relationship between surface permeability and carbonation of concrete.

– The water sorptivity is significant when the response time is low – Fig. 12.
– The carbonation study gives a similar conclusion: a more permeable concrete presents a higher depth of carbonation – Fig. 13.

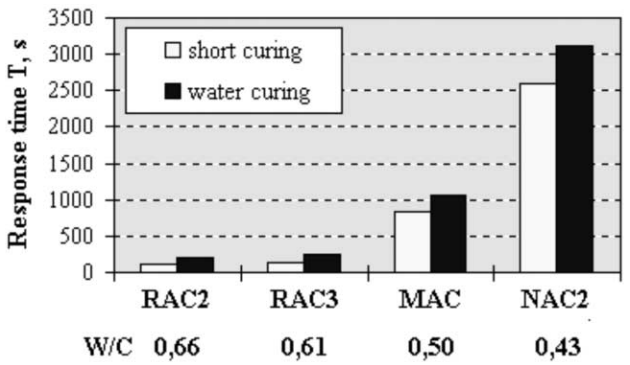

Fig. 14. Surface permeability of concrete in accordance to the type of curing.

The measurement of the surface permeability can be used to assess the ability of the concrete to resist to chemical attacks directed by the processes of absorption and diffusion.

Water curing creates a lower and finer porosity and thus decreases the surface permeability of concrete – Fig. 14. This positive effect is better observed with RAC (RAC2 and RAC3) than with mixed (MAC) and natural (NAC2) concrete.

5. Conclusions

In terms of the testing methodologies employed, the results of this study can be summarised as follows:

1. The air permeability test is relatively simple and quick. The measured coefficient of air permeability allows distinguishing the permeation properties of RAC and those of NAC. The main disadvantage of this method is the sensitivity of the measurements to the moisture content of the concrete. Conditioning of the samples by oven drying is required. The temperature of drying needs to be adjusted in relation with the strength and the porosity of the concrete.
2. The surface permeability test appears to be a very sensitive method in the study of RAC and similar concretes. It is able to detect the effects of both the mix-design and the curing conditions. A good relation between surface permeability and porosity, diffusivity and water absorption capacity is assessed. Tests are conducted in laboratory but it could be used on site with different devices similar to the Autoclam permeability system [31]. Therefore surface permeability measurements can be used as a concrete durability criterion.
3. Water permeability tests are not readily applicable in the study of RAC and similar concretes because of the self-healing phenomenon.

In terms of durability of RAC, the study shows that RAC is significantly more permeable than NAC. Thus their long-term performance is questionable. The replacement of natural aggregates by recycled aggregates affects the quality of the concrete cover. The carbonation of RAC is faster. This effect limits the use of recycled aggregate in the production of reinforced concrete elements. Nevertheless, based on the criteria proposed in other studies, RAC can be characterised as being of moderate quality rather than of poor quality. A possible use of admixtures such as fly ash or silica fume could decrease significantly porosity and permeability of RAC.

The study shows that the permeability is more dependent than other parameters to mix-proportions and curing conditions.

Mixed aggregate concrete is intermediate between RAC and NAC. It can be concluded that the main problems of durability are caused by the use of recycled sand. Therefore, the use of fine recycled aggregate needs to be restricted. Another way of increasing the durability of RAC is to use extended curing using a moist environment.

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