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Frost resistance of recycled aggregate concrete

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Abstract

The research presented in this paper deals with concrete containing building waste recycled as aggregates. The frost resistance is used as a durability indicator. The characteristics of recycled aggregates (RAs) and their impact on the characteristics of RA concrete are presented. Some basic factors concerning the frost resistance of RA concrete as RA content and degree of water saturation are considered. The RA concrete is compared with a control concrete made with natural aggregates. The pertinence of different criteria for the assessment of the frost resistance is also discussed.

Keywords: Waste management; Aggregate; Concrete; Freezing and thawing; Durability

1. Introduction

Building waste recycled aggregates (RAs) can be used as a substitute to natural aggregate, but they find application mainly in road construction [1–3]. Their use in ordinary concrete manufacturing is hindered by their partial nonconformity to the standards on concrete aggregates and by the lack of data on the durability of recycled aggregate concrete (RAC; [2–6]).

The common practice of RA used for RAC is a partial substitution of natural coarse aggregates by recycled ones [3,11]. The use of fine RA is rarely allowed because it is considered as a main cause of RAC drawbacks [3,4]. The study presented in this paper is a part of a larger work on the durability of RAC, containing both fine and coarse industrially produced RA [8–10].

The frost resistance of these RAC is investigated because there is no common opinion in the scientific literature concerning the frost resistance of RAC. This can be explained by the different characteristics of RA, which vary in a large scale. Another reason can be the use of inappropriate test methods [3,12]. Because aggregates represent about 75% of the total volume of concrete, their influence on the frost resistance of concrete should never be underestimated. For the following three reasons, RA could have been previously considered as frost susceptible: old attached cement mortar, presence of unsound particles, and porous surface. The frost resistance of concrete is also affected by its porosity, the presence of water within it, and the environmental conditions [12–15]. As part of an assessment of different methods of testing the freeze/thaw resistance of RAC, the effect of different conditioning and different degree of water saturation is investigated. The impact of these methods is highlighted.

2. Materials and mix design

2.1. Characterization of used RA

Two fractions of RA have been used: fine 0–6 mm, called recycled sand, and coarse 6–20 mm. They result from the recycling of demolition waste and are industrially produced by the French company RMN [16].

In comparison with natural aggregates, RAs are characterized by heterogeneity, presence of old cement paste, and undesirable impurities [2–9]. They cause:

- angular form and rough surface of grains,
- lower density—for recycled sand, it is equal to 2.16 ± 0.4 t/m^3, as for recycled coarse aggregate, it is equal to 2.25 ± 0.4 t/m^3,

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- porosity, from 11% to 22%,
- high water absorption—the average coefficient is equal to 5.8% for coarse RA and 12.5% for recycled sand.

The high water absorption of RA is the main obstacle to their use in concrete manufacturing—the freshly mixed RAC lose quickly their initial workability, even when superplasticizers are used. To prevent the suction of the mixing water by RA, it is necessary to presoak them. It is established that RAs have satisfactory mechanical characteristics, although lower than those of natural aggregates [3,13,16].

The frost resistance of RA can be assessed as satisfactory by the method based on the change in the Los Angeles coefficient after 25 direct freezing–thawing cycles on saturated sample (according to NF P 18-593 [17]), but they are less resistant than natural aggregates are. Testing sulphate soundness (according to ASTM C88-99a [18]), sometimes used as frost resistance indicator, showed that the threshold of 10% of weight loss was overpassed, even after the first three cycles. That could indicate that coarse RAs are not frost resistant.

2.2. Experimental characterization of RAC

The frost resistance of RAC is compared with the one of a reference natural aggregate concrete called NAC. 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 after the first 5 to 10 min). The choice resulted from industrial and economic considerations [10]. To isolate the effect of the substitution of natural by RAs, no air-entraining admixtures are used. A superplasticizer "Sikament 10" is added.

The mix proportion of NAC enables to resist to 300 freezing–thawing cycles.

Three types of RAC are studied:

- concrete with coarse RA and natural sand (RAC1);
- concrete made entirely of RA, where RA are water presoaked (RAC2); and
- concrete made entirely of RA, where RAs were not presoaked (RAC3).

For producing RAC, previous experience of the laboratory is used [9]. RAs are currently presoaked to improve the placing of fresh concrete. This quantity of presoaking water is calculated as the difference between the water required for the full saturation of aggregates and the water content into the aggregates at the time of mixing. To study the influence of the presoaking, for producing RAC3, the RAs were not presoaked. The mix proportion and the characteristics of fresh and hardened, at 28 days, concrete are presented in Table 1.

Table 1
Mix proportion and characteristics of fresh and of hardened concrete at 28 days

Mix designation	NAC	RAC1	RAC2	RAC3
Cement (kg/m^3)	400	400	400	400
Superplasticizer (22% dry matter, dm^3/m^3)	4	4	4	4
Water content of aggregates before mix (dm^3/m^3)	21	50	93	95
Water of presoaking (dm^3/m^3)	–	–	38	–
Added water (dm^3/m^3)	147	147	129	147
Total water (dm^3/m^3)	171	200	262	245
Calculated free water (dm^3/m^3)	150	135	130	109
Natural sand 5–0 mm [dry] (kg/m^3)	685	787	–	–
Recycled fine aggregates 6–0 mm [dry] (kg/m^3)	–	–	659	675
Recycled coarse aggregates 20–6 mm [dry] (kg/m^3)	–	824	846	865
Natural coarse aggregates [dry] (kg/m^3)	1140	–	–	–
Total W/C	0.43	0.50	0.66	0.61
Free W/C	0.37	0.34	0.33	0.27
Workability (Slump test; cm)	4.5	5.5	9.0	5.0
Density of fresh concrete (kg/m^3)	2410	2220	2190	2200
Density of hardened concrete (kg/m^3)	2380	2300	2160	2190
Water opened porosity of hardened concrete (%)	8.1	14.2	22.8	21.1
Compressive strength (MPa)	47.7	37.8	34.2	38.1
Splitting tensile strength (MPa)	4.1	3.6	2.5	2.7

In case of high water absorption of aggregates as RA (12.5% for fine RA and 5.8% for coarse RA), different water contents can be considered: total water content, which is the addition of mix water, water absorbed by aggregates, water of admixtures, and eventually presoaking water; free water content, which is the water usable for hydration and fresh concrete plasticity, assuming saturated, surface-dry aggregates. But the mechanism of water absorption is complex and irregular, as shown by the comparison between the different W/C values. RAC2 and RAC3 present higher total W/C than NAC and RAC1 do, but lower free W/C.

The comparison between NAC and RAC shows that RAC1 and RAC2 have a lower density, a higher porosity, and lower mechanical characteristics, resulting from the related characteristics of RA and the higher total W/C. The mixed concrete RAC1 takes an intermediate place.

3. Test methods

3.1. Parameters of freezing–thawing cycles

The significant parameters of the experimental methods are the following:

- freezing rate, minimal negative temperature, duration of freezing and thawing periods;
- number of cycles applied; and
- dimension, preconditioning and degree of water saturation of samples.

A lot of experimental methods exist [12,19]. On the basis of previous studies [8,16], a testing procedure close to the one prescribed by NF P 18-424 [20] is adopted: with a temperature from $+6 \pm 3$ to -15 ± 3 °C; a freezing rate of 5 °C/h (from 0 to −15 °C); and a thawing period of 1.5 h (from −15 to +6 °C). Some parameters are, however, modified. The minimal temperature of -15 ± 3 °C is maintained during 2 h, and the maximal temperature of $+6 \pm 3$ °C is maintained during 1 h. The duration of one cycle is equal to 8 h. The samples are in an air environment with relative humidity (RH) = 95 ± 5% during the freezing and thawing periods. Actually, the classical test (in water environment) would not reproduce real conditions of concrete structure environment [12] and would be too severe for RAC. To keep a permanent level of water saturation of samples, they are covered by a waterproof envelop, which prevents the evaporation of water without hindering the free deformation of samples.

3.2. Test samples, conditioning, and type of water saturation

The test samples are prisms 7 × 7 × 28 cm and cylinders with diameter 16 cm and height 32 cm. The conditioning and the way of water saturation are presented in Table 2. The purpose is to implement different degrees of water saturation without damaging the concrete microstructure [12,21–23]. The different types of water saturation are the following:

- The first type, called complete, is the standard water saturation. However, it does not represent the real conditions of the environment.
- The second type of water saturation, called initial, refers to the case when the evaporation of the mixing water in excess is hindered. Therefore, it must allow outlining the difference between NAC and RAC because this quantity of water is higher for RAC.
- The third type of water saturation, called cyclic, reveals the effects of the drying–wetting cycles.
- The fourth type of water saturation, called Hirschwald (by capillary water absorption), could be considered as close to the real exposure conditions of concrete structures, where the capillarity is the main way of water absorption [21].

Table 2
Treatment of test samples

Type of water saturation	Curing conditions	Preliminary treatment	Treatment before testing
Complete	27 days in water at 20 °C	In water at 20 °C until constant weight	
Initial	60 days in waterproof envelop at 20 °C	No	No
Cyclic	4 cycles: 15 days in air (at 20 °C and RH = 65%), 15 days in water (at 20 °C)	15 days of drying at 40 °C	15 days in water at 20 °C
Hirschwald	27 days in water at 20 °C, then 3 months at 20 °C and RH = 65%	Drying at 55 °C until constant weight	24 h of water absorption by capillarity, then 24 h under water at 20 °C

3.3. Criteria of assessment of the frost resistance

The classical criteria are the loss of strength and the weight change. They are too rough and characterize only the ultimate period of the degradation of concrete. They need to be completed by other nondestructive tests to assess accurately the beginning of the degradation process and of the internal cracking. In this study, the following criteria are applied:

•Length change (according to NF P 18-424 [20]):

$$\varepsilon_n = \frac{\Delta L_n}{L} \tag{1}$$

Where ε_n is the relative length change after n cycles (μm/m), ΔL_n is the length change of the sample after n cycles (μm), and L is the initial length of the sample before the freeze–thawing test (at 0 cycles; m).

The frost resistance can be expressed by the number of freezing–thawing cycles to which the relative length change ε_n overpasses 500 μm/m [20]. The number of cycles is designated as N_1.

•Ultrasonic pulse velocity and fundamental transverse frequency changes [12,18,24]:

To determine the frost resistance, two criteria have been adopted.

Relative dynamic modulus of elasticity (see Eqs. (2) and (3)):

$$P_{v,n} = \frac{V_n^2}{V_0^2} \times 100 \tag{2}$$

and

$$P_{f,n} = \frac{f_n^2}{f_0^2} \times 100 \tag{3}$$

Where V_n and f_n are, respectively, the ultrasonic pulse velocity and the fundamental transverse frequency after n cycles, and V_0 and f_0 are, respectively, the ultrasonic pulse velocity and the fundamental transverse frequency before the freezing–thawing test (at 0 cycles; [12]).

The frost resistance can be expressed by the number of freezing–thawing cycles to which the relative dynamic modulus of elasticity falls below 60% [24]. The number of cycles is designated as N_2 when the measurements of ultrasonic pulse velocity are used and N_3 when the measurements of fundamental transverse frequency are used.

•Durability factor (Eq. (4)):

$$D = \frac{P_n N}{300} \geq \text{Dcr} \tag{4}$$

where N is the number of freezing–thawing cycles to which the relative dynamic modulus of elasticity ($P_{f,n}$ or $P_{v,n}$) has reached a critical value (threshold, e.g., 60% according to ASTM C 666-97; [24]). N is taken to be 300 when P remains higher than the critical value after the completion of 300 cycles [12]. Dcr is the threshold of the durability factor. According to the value of the threshold [3], the concrete can be divided into the following categories: nonresistant to frost ($D \leq 40\%$), with unproven frost resistance ($D \leq 60\%$), with passable frost resistance ($D \geq 60\%$), and frost resistant ($D \geq 80\%$).

The compressive strength (f_c, MPa) and the splitting tensile strength (f_t, MPa) are measured at the end of the test ($n = 300$). To compare the results between destructive and nondestructive tests, f_c and f_t have also to be measured after N cycles, where N is assumed to be equal to the minimal value of N_1, N_2, and N_3.

4. Results and discussion

The results of the nondestructive measurements are presented in Table 3.

When the criterion of length change is used (N_1), the main role of water saturation degree is confirmed. The complete water saturation type induces a degradation of all types of RAC, far before 300 cycles. Furthermore, concretes containing only RAs (RAC2 and RAC3) are not frost resistant for initial water saturation. This is related to the higher total W/C of these concrete. When RAC containing water-saturated RA (RAC2) is subjected to the cyclic water saturation, it is not frost resistant either. Only the water saturation of Hirschwald type, which is corresponding to a low degree of water saturation, does not cause any important damage on RAC.

Table 3
Frost resistance of concrete, expressed in number N of freezing–thawing cycles, to which $\varepsilon_n = 500$ µm/m (N_1), $P_{f,n} = 60\%$ (N_2), and $P_{v,n} = 60\%$ (N_3)

Type of water saturation	Number of cycles	Type of concrete			
		NAC	RAC1	RAC2	RAC3
Complete	N_1	300	170	70	90
	N_2	300	300	80	165
	N_3	300	300	300	300
Initial	N_1	300	300	150	290
	N_2	300	–	300	300
	N_3	300	–	300	300
Cyclic	N_1	300	300	240	300
	N_2	–	300	300	300
	N_3	–	300	300	300
Hirschwald	N_1	300	300	300	300
	N_2	300	–	300	300
	N_3	300	–	300	300

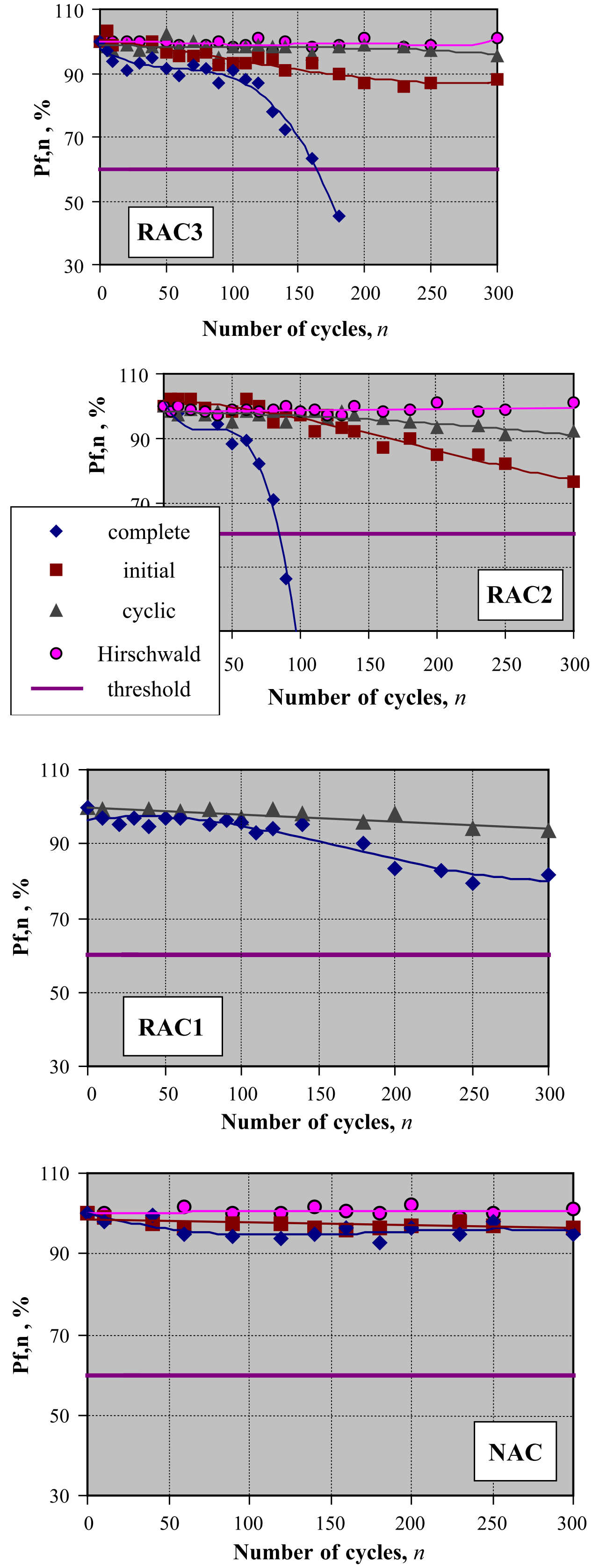

Fig. 1. Effect of water saturation type on the relative dynamic modulus of elasticity (determined from fundamental transverse frequency measurements).

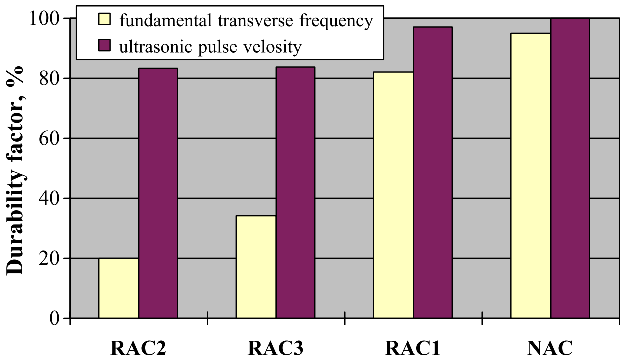

Fig. 2. Durability factor for complete water saturation.

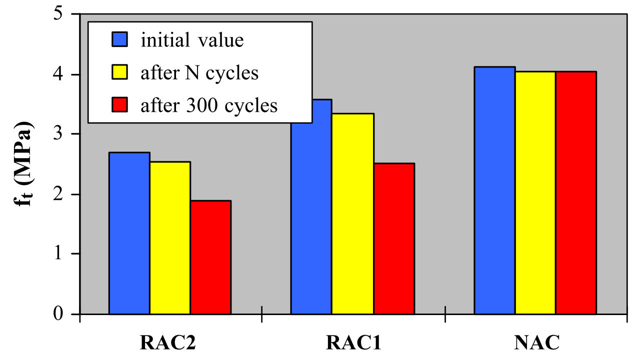

Fig. 4. Splitting tensile strength for complete water saturation.

RAC1 (with coarse RA and natural sand) presents a higher frost resistance related to its higher mechanical characteristics and to its lower porosity. The control concrete, NAC, as it was foreseen at the design of its mix proportion, does not degrade after 300 freezing–thawing cycles, even at complete water saturation.

The conclusions made from the measurement of the length change have to be confirmed by the other tests. The criterion of the relative dynamic modulus of elasticity, however, gives higher frost resistance.

The ultrasonic pulse velocity criterion (N_3) allows for distinguishing the different types of concrete before the freezing–thawing cycles. However, during the test, some degradation of concrete can only be detected for complete water saturation samples. But even in this case, the relative dynamic modulus of elasticity $P_{v,n}$ stays far above the critical value of 60%. Hence, N_3 is always equal to 300 (Table 3).

The fundamental transverse frequency criterion (N_2) is relatively more sensitive (Fig. 1).

The critical value for $P_{f,n}$ of 60% is reached by RAC before the end of the test (300 cycles) only in the case of complete water saturation. Therefore, for the other types of water saturation, the process of crack formation in the concrete can be considered as just started. In terms of the number of cycles for frost resistance assessment, it implies $N_1 < N_2 \leq N_3$ for RAC (Table 3).

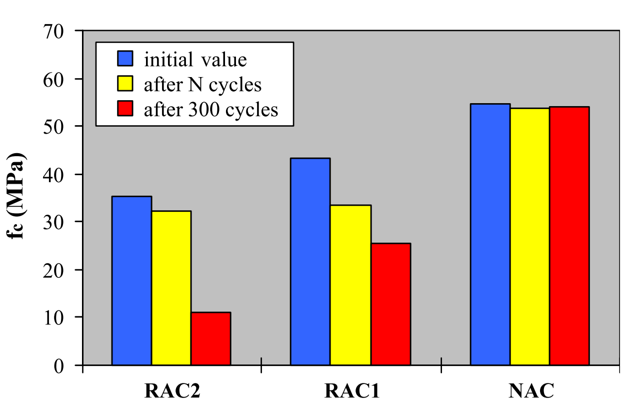

Fig. 3. Compressive strength evolution for complete water saturation.

Fig. 2 illustrates the difference in the assessment of frost resistance in the case of complete water saturation, expressed with the durability factor D. If ultrasonic pulse velocity is used for D estimation, all of the different concrete can be characterized as frost resistant because D>80%. If fundamental transverse frequency is used, RACs containing RA (RAC2 and RAC3) are nonfrost resistant (D < 40%), while the mixed concrete (RAC1) can be defined as frost resistant (D = 82%) and, therefore, could be used even in severe climatic conditions [3].

When the relative length change of RAC in complete saturation reaches its critical value (after $N = N_1$ cycles), compressive and splitting tensile strengths decrease by 10% to 20% (Figs. 3 and 4), while after 300 cycles, the strength of RAC is practically exhausted. The strength of NAC is practically unchanged even after 300 cycles.

5. Conclusions

Generally, the frost resistance of saturated RAC is not satisfying, and their use in structures exposed to severe climate is not recommended. The main reason seems to be the high total W/C, inducing higher porosity and lower mechanical characteristics of RAC [13], as well as the frost resistance of RA themselves: First, they might contain unsound particles, which would be deteriorated by the repeated action of the freezing–thawing cycles, and, second, RA could contribute to the frost damage by expelling water into the surrounding cement paste during the freezing period. Only the mixed concrete (RAC1), with a W/C lower than 0.55 (according to Refs. [13,23]), could be used in moderate cold climate when unsaturated.

The degree of water saturation turns out to be of a great importance. For example, RAC with both coarse and fine RA (RAC2 and RAC3) and Hirschwald water saturation are not damaged after 300 cycles. Frost resistance criteria should be therefore determined with the consideration of the expected exposure conditions.

This problem of choice of reliable methods of frost resistance assessment is particularly significant. Among all the nondestructive methods, the length change of concrete sample is the most accurate index of internal microcracking due to freezing–thawing cycles and seems to represent most adequately the RAC frost resistance. Unfortunately, this is a laboratory test difficult to be conducted in situ. The change of the mechanical characteristics is significant only at an advanced stage of degradation and, therefore, cannot be used as a reliable criterion for frost resistance.

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