

# Effect of hydrophobic admixture and recycled aggregate on physical–mechanical properties and durability aspects of no-fines concrete



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## HIGHLIGHTS

- The compression strength, carbonation depth, water absorption and leaching of different no-fine concretes are compared.
- Each mixture is repeated adding a hydrophobic admixture and replacing ordinary aggregates with recycled ones.
- No-fines concrete with compressive strength ranging from 7 to 30 MPa are obtained.
- Recycled aggregate increases capillary water absorption that can be counteracted with a hydrophobic admixture.

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## ABSTRACT

No-fines concrete with a compressive strength in the range 7–30 MPa at 28 days of curing were optimized by changing the water/cement ratio from 0.41 to 0.34 and the aggregate/cement ratio from 8 to 4. Some mixtures were also repeated with the addition of a hydrophobic admixture and prepared by fully replacing the ordinary aggregate with recycled aggregate to evaluate durability effects. High susceptibility to carbonation was observed for all the no-fines mixes studied. The use of recycled aggregate increases capillary water absorption (about 50%); however, the related decrease in durability could be easily counteracted with the use of a hydrophobic admixture.

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## 1. Introduction

No-fines concrete, also known as porous, pervious, permeable and cellular concrete, has little no fines aggregate and has just enough cementitious paste to coat the coarse aggregate particles while preserving the interconnectivity of the voids [1].

The most widespread applications of no-fines concrete include road paving, pavement permeable base, pavement edge drains or shoulders [2–4].

The recent emphasis on sustainability issues in the construction has increased the interest in exploring possible further uses of no-fines concrete. No-fines concrete has a porous structure with

relatively large interconnected voids that confers to it acoustic [5] and thermal insulation characteristics, water permeability, and economy in terms of material cost [6–8]. In addition, no-fines concrete could be also more interesting than an ordinary concrete, considering its environmental impact in terms of reduction of carbon dioxide emission. More than 50% of carbon dioxide emitted during cement production originates from calcinations of limestone. This CO<sub>2</sub> is reabsorbed during the life cycle of the cement-based products in the carbonation process. During a 100 year period, the estimated CO<sub>2</sub> uptake through carbonation of the concrete produced in one year seems to amount to a significant proportion of the CO<sub>2</sub> emitted by calcination of the raw mix used to produce the Portland cement used in the concrete [9]. In order to accelerate the process of CO<sub>2</sub> uptake, low strength porous concrete can be advantageous with respect to ordinary or high strength concrete, at least when structural requirements are not so important. For this reason, no-fines concrete has been proposed by some authors [10,11] with the aim of enhancing CO<sub>2</sub> uptake.

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Since no-fines concrete fulfills many of the properties required to be a sustainable building material, this class of concretes could be particularly useful not only for road paving but also for a wide range of vertical applications which would probably require their use in the form of panels, where a great surface area is exposed to the atmosphere, high structural performance is not required, and acoustic and/or thermal insulation characteristics are desired such as roof tiles, rendering mortars and cladding or acoustic panels.

Moreover, of particular interest to favor the sustainable development of no-fines concrete is the use of recycled aggregate in replacement of those that are natural. Using recycled aggregate in a new no-fines concrete offers several environmental advantages: reduced dumping at landfill sites, gravel mining, and reduced hauling of virgin aggregate there by reducing emissions. Moreover, recycled aggregates are formed through the adhering of mortar and original aggregates and are likely to be made of concrete that is not completely carbonated. This is due to the crushed concrete for producing recycled aggregates, leading to new surfaces that are created, which can be newly in contact with air and would undergo carbonation [12–15]. Such particles are also able to contribute to CO<sub>2</sub> sequestration in addition to the alkali generated by the hydration of a non-hydrated cement. Therefore, the use of aggregates from recycled concrete, instead of natural ones would allow an increase in the amount of CO<sub>2</sub> uptake. Moreover, adhered mortar in recycled aggregate is a very porous material, with a high absorption capacity and high permeability [16].

At present, one of the main limitations to broaden the potential applications of no-fines concretes is their low durability, due to porosity, water and the relative dissolved aggressive substances that can penetrate them and induce degradation processes. Low durability is not “sustainable” friendly, since it increases the long term impact of the structures. In relation to the application of no-fines concrete, the knowledge of the durability has been limited to the study of freezing and thawing, shrinkage, thermal expansion, capacity to percolate water through the cement paste and abrasion resistance [17–20].

The durability problem could be reduced by manufacturing no-fines concretes with a hydrophobizing admixture which may reduce water uptake. Concrete degradation would not occur if water, which acts as the main carrier for aggressive substances and the medium where degradation reactions develop, is permanently prevented from wetting the porous structure. Furthermore, if reinforcements are introduced [21,22], once the corrosion has initiated, the corrosion rate is expected to be related to the moisture content of the thin layer of carbonated cement paste that covers the steel bar. Therefore water uptake in the no-fines concrete becomes the controlling factor.

In this work, no-fines concretes with three different mixtures corresponding to low ( $R_c \sim 5\text{--}10$  MPa), medium ( $R_c \sim 15\text{--}20$  MPa) and high ( $R_c \sim 25\text{--}30$  MPa) compressive strengths were manufactured. The effect of an hydrophobic admixture at two different dosages and recycled aggregate on the mechanical performance(s) and durability aspects (such as carbonation rate, capillary water absorption and leaching test in de-ionized water) are investigated.

## 2. Experimental procedure

### 2.1. Materials and mixes

Several no-fines concrete mixes were made in two different laboratories (a = Ancona or m = Milan).

A commercial Portland-limestone blended cement type CEM II/A-L 42.5 R according to EN-197-1 standard and crushed limestone aggregate with 15 mm maximum size were used. A coarse fraction (15 mm maximum size) was also used to manufacture a no-fines concrete with 100% of recycled aggregate. This fraction

was directly supplied by an industrial crushing plant in Villa Musone, Italy, in which rubble from demolition of buildings are cleaned, crushed and sized. The particle size distribution curves of the aggregates are shown in Fig. 1.

A 45% aqueous emulsion of an alkyl-triethoxy-silane was used as hydrophobic silane-based admixture to manufacture hydrophobized no-fines concrete.

Different mixtures were manufactured with water/cement ratio ( $w/c$ ) and aggregate/cement ratio ( $a/c$ ) ranging respectively from 0.41 to 0.34 and from 8 to 4 (Table 1). Each mix is identified by a number on the basis of  $w/c$  and  $a/c$ , followed by a letter indicating the lab (a = Ancona or m = Milan).

Each mixture was cast in cubic molds ( $10 \times 10 \times 10$  cm) in two layers. Each layer was compacted for 5–10 s with a drill equipped with a flat square with a side equal to that of the formwork (Fig. 2).

Cubic specimens (Fig. 3) were de-molded after 24 h from casting and cured at R.H. > 95% and  $T = 22$  °C until time of testing. Density of no-fines concrete ( $\delta_{no-fine}$ ) was measured on cubes after de-molding. Once the density is known, the mix proportions of the mix are back calculated and expressed in terms of kg per cubic meter of no-fines concrete (Table 1). The porosity ( $p$ ) of each mixture of no-fines concrete (Table 2) was also estimated as:

$$p \equiv \left\{ 1 - \delta_{no-fine} \cdot \left[ \frac{m_c}{\delta_c} + \frac{m_w}{\delta_w} + \frac{m_{agg}}{\delta_{agg}} \right] \right\} \cdot 100$$

where  $m_c$ ,  $m_w$ ,  $m_{agg}$  and  $\delta_c$ ,  $\delta_w$ ,  $\delta_{agg}$  are respectively mass ( $m$ ) and density ( $\delta$ ) of cement ( $c$ ), water ( $w$ ) and aggregate ( $agg$ ).

Mixes 2, 4 and 5 were repeated by adding the hydrophobic admixture at the dosage of 0.5% and 1% by cement mass. The same mixes were also repeated using recycled aggregate instead of natural ones (Table 2). Denomination of mixes have been identified as in Table 1, plus a number that defines the dosage of hydrophobic admixture (0.5% or 1%) or the letter r that indicates the use of recycled aggregates.

Since the specific weight of recycled aggregates ( $2420$  kg/m<sup>3</sup>) is lower with respect to that of natural aggregates ( $2650$  kg/m<sup>3</sup>), aggregate replacement was calculated by volume (100% of replacement). In the mix, the higher water absorption of recycled aggregate (5%) with respect to natural one (0.5%) was considered and the mix proportions were correlated accordingly in order to maintain a constant effective  $w/c$  ratio.

Every material was characterized by compressive test on cube specimens after 7 and/or 28 days of curing (Table 2).

### 2.2. Carbonation

After 28 days of curing, cube specimens of each mixture made in Ancona “a” were exposed to a carbonation chamber at  $CO_2 = (3 \pm 0.2)\%$ ,  $T = (21 \pm 2)$  °C and R.H. =  $(60 \pm 10)\%$ .

The progress of carbonation was evaluated by phenolphthalein tests applied on the fracture surfaces of the specimens (split by indirect tensile test). The percentage of carbonated material was estimated by means of image analysis. After 10 and 30 days of accelerated carbonation, compressive strength was also measured in order to assess possible effects of carbonation on the mechanical properties of the material.

### 2.3. Capillary water absorption

Capillary water absorption tests have been carried out on cube specimens according to Italian Normative UNI 10859:2000 (“Natural and artificial stones, determination of water absorption by capillarity”, in native Italian). Previously dried specimens were placed on a multi-layer absorbent paper saturated with water for 8 days. The water uptake was measured by weighting the specimens at fixed time intervals.

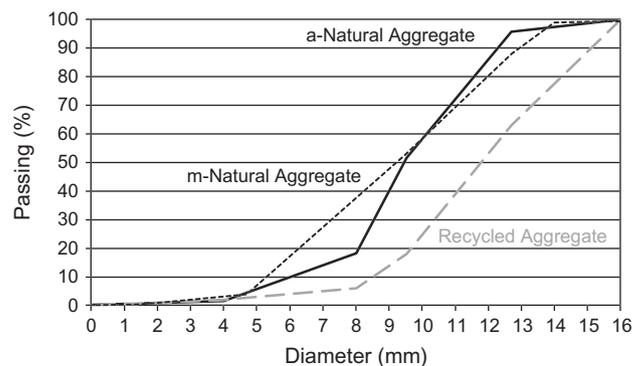


Fig. 1. Particle size distribution of natural and recycled aggregate from different lab (“m” = Milan; “a” = Ancona).

**Table 1**  
Mix design of mixtures.

Mixes	w/c effective	a/c	Water (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	Aggregate (kg/m <sup>3</sup> )
1.a	0.41	8.0	76	184	1470
2.a	0.39	7.0	82	210	1478
2.m	0.39	7.0	83	211	1478
2*.m	0.39	7.0	88	223	1570
3.a	0.38	6.0	99	261	1570
4.a	0.37	5.1	113	307	1570
4.m	0.37	5.1	114	308	1578
5.a	0.34	4.0	129	382	1530
5.m	0.34	4.0	130	384	1536

w/c = water/cement.

a/c = aggregate/cement.

a: Ancona laboratory.

m: Milan laboratory.

\* Repeated mixture.

1 = w/c = 0.41 and a/c = 8.0.

2 = w/c = 0.39 and a/c = 7.0.

3 = w/c = 0.38 and a/c = 6.0.

4 = w/c = 0.37 and a/c = 5.1.

5 = w/c = 0.34 and a/c = 4.0.

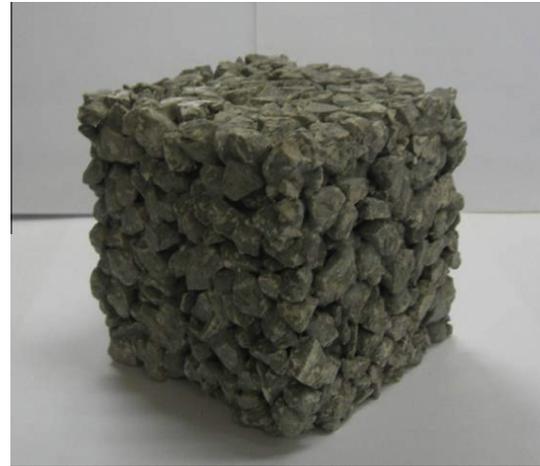


**Fig. 2.** Cast and compaction of no-fines concrete specimens.

#### 2.4. Leaching tests

Leaching tests were conducted following Italian regulations for reuse of non-toxic waste materials as by-products (D.M.A. 1998) [23]. Examples of similar international standard tests include ISO 6961:82 and ASTM C1220:92. Although this method was developed to comply with environmental regulations for re-using waste material in mortars/concretes, it is actually of more general applicability since leaching behavior is strictly related to the durability properties of the material. According to the extraction protocol of the Italian regulations, a sample is placed in contact with a precise amount of de-ionized water (CO<sub>2</sub> free) for a predetermined extent of time, at 20 ± 4 °C. The sample is placed in a polyethylene test vessel, with ample space around it, and leachant water is added and allowed to wet the sample all around (minimum level: at least 2 cm above the specimen). The solid to liquid ratio, expressed as the ratio of volume of solid to volume of the leachant, is 1:5. The test vessel must be hermetically closed to prevent acidification of the water because of CO<sub>2</sub> diffusion. The leachant solution is renewed to drive the leaching process. The renewing sequence is: 2, 8, 24, 48, 72, 102, 168, and 384 h. At each renewing sequence, the fluid is collected for analysis.

In order to follow the release mechanisms, pH and electrical conductivity of the leachant solution were recorded. From the measure of the pH the hydroxyl released was calculated. From the measure of the conductivity the total salts release was



**Fig. 3.** No-fines concrete specimen.

calculated, by applying an average conversion factor of 100 meq L<sup>-1</sup>/mS. In order to follow the release process, both for hydroxyl and salinity the cumulative release related to specific surface of the test specimens was plotted as function of time.

### 3. Results and discussion

#### 3.1. Porosity, density and mechanical properties

Table 2 reports the density, porosity and mechanical strength after 7 and 28 days. The data values reported in Table 2 and in the subsequent tables and figures are average values calculated from the results obtained by three specimens of the same type. It can be observed that the density of materials ranged from 1730 kg/m<sup>3</sup> for mix 1.a to 2230 kg/m<sup>3</sup> for mix 5.a1. The porosity, calculated from density values, ranged from 31% to 9%.

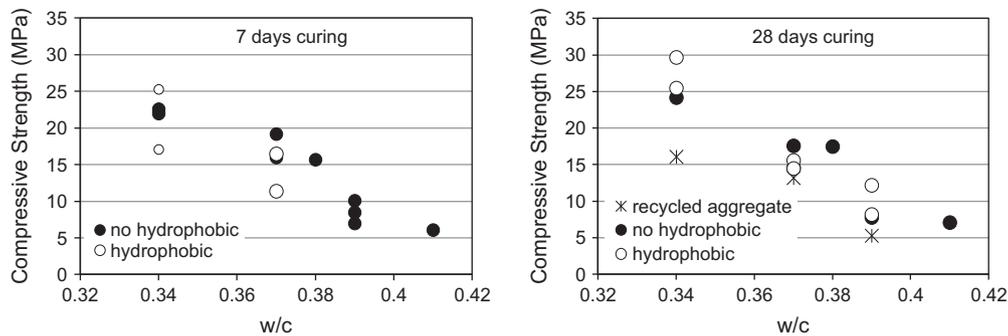
Due to high porosity and low content of cement paste, no-fines concrete have low strength performance; compressive strength (Rc) ranged from 6 to 25 MPa after 7 days of curing. Moreover, for, every w/c ratio, after 7 days of curing, no-fines concrete already reach the 80–90% of the compressive strength observed after 28 days of curing. No-fines concrete with the same mix proportions (for example, a w/c ratio of 0.34) made in different laboratories can show values of compressive strength significantly variable (from 17 to 25 MPa, Fig. 4). The variability depends on porosity that for given mix proportions is strongly affected by the compaction effort during placement (variable also in the same laboratory when the vibration amplitude or the operator changes) [3,24,25].

In order to correlate the mechanical properties of no-fines concrete (with and without admixture and recycled aggregate) to its microstructure, both macroscopic voids (which depend on a/c and compaction) and capillary pores in the hydrated cement paste (which depend on w/c ratio, curing time) should be considered. In fact, compressive strength and density increase, while porosity decreases, as a function of decreasing of w/c and a/c ratios. The conventional compressive strength versus w/c relationship for normal concrete does not apply to no-fines concrete both at 7 and 28 days of curing (Fig. 4). In traditional concretes, according to Powers' theory, the value of compressive strength (Rc) can be assessed as a function of the w/c and the degree of hydration  $\alpha$  as:  $Rc = K (0.6790\alpha / (0.3185\alpha + w/c))^3$  where K is a constant [26]. The low values of compressive strength, particularly when compared with those expected for ordinary concrete with the same type of cement and w/c ratio (ordinary concrete manufactured with the same type of cement after 28 dd of curing, with a w/c = 0.34 a Rc = 75 MPa can be obtained; with a w/c = 0.4 a

**Table 2**  
Main properties of no-fines concrete.

Mixes	Hydrophobic admixture (%)	Density (kg/m <sup>3</sup> )	Porosity (%)	Rc, 7 days (MPa)	Rc, 28 days (MPa)
1.a	0	1730	31	6.1	7.1
2.a	0	1770	29	7.0	7.8
2.a.r	0	1730	25	–	5.3
2.a0.5	0.5	1810	27	–	8.2
2.a1	1	1950	22	–	12.2
2.m	0	1770	29	8.5	–
2.m	0	1880	25	10.1	–
2.m1	1	1940	22	9.6	–
3.a	0	1930	22	15.7	17.5
4.a	0	1990	19	16.0	17.6
4.a.r	0	1910	17	–	13.2
4.a0.5	0.5	2040	17	–	14.6
4.a1	1	2060	17	–	15.6
4.m	0	2000	19	19.2	–
4.m1	1	2060	17	16.5	–
4.m1	1	1980	20	11.4	14.5
5.a	0	2040	17	22.0	24.2
5.a.r	0	1970	15	–	16.1
5.a0.5	0.5	2200	10	–	29.7
5.a1	1	2230	9	–	25.5
5.m	0	2050	17	22.6	–
5.m1	1	2160	12	25.3	–
5.m1	1	2070	16	17.1	–

r = concrete with recycled aggregate.



**Fig. 4.** Compressive strength as a function of w/c for different mixtures after 7 days and 28 days of curing.

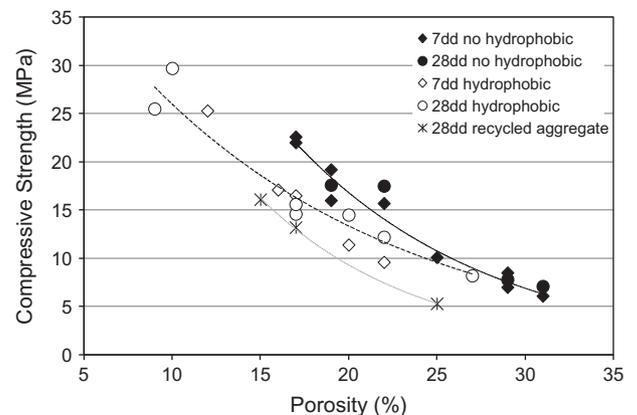
Rc = 65 MPa can be obtained [26]), are due to the high macroscopic porosity of this material (ranging from 10% to 30%).

Fig. 5 reports compressive strength, measured after 7 and 28 days of curing, as a function of the porosity, mainly affected by macroscopic voids rather than capillary pores, which depends on curing time. It can be observed that a better correlation than that of Fig. 4 can be found. Moreover, Fig. 5 shows a different correlation for hydrophobized no-fines concrete, suggesting that the hydrophobic admixture seems to decrease the mechanical performances as observed in traditional concrete [27–29]. However, this behavior is more evident for low porosity no-fines concrete. Probably, in no-fines concrete with higher porosity, i.e. with lower cement paste content, the negative effect of silane addition on capillary porosity of cement paste [30] is partially compensated by the positive effect on macro-porosity due to a certain plasticizing effect of silane that improves the compactibility of the fresh material.

The full replacement of natural aggregate with recycled one slightly decreased the compressive strength (30%) of no-fines concrete due to the lower specific weight and strength of recycled aggregate with respect to the natural one, confirming results that have been already reported in the literature [12]. However, since pervious concrete should not have high mechanical performances, the environmental advantage on using recycled aggregates certainly overcomes those related to mechanical strength penalization.

### 3.2. Carbonation resistance

Initially, the hydrated cement paste of no-fines concrete is alkaline as for conventional concrete. Differently from conventional concrete, carbonation of no-fines concrete does not only occur inward from the external surface. The high porosity of no-fines



**Fig. 5.** Compressive strength after 7 and 28 days of curing as a function of porosity for different mixtures.

concrete promotes carbonation penetration in depth and also causes the partial carbonation of cement paste in contact with inner macro-pores. Thus each single thin layer of cement paste that covers the coarse aggregates is subjected to carbonation. For this reason, the resistance to carbonation could not be evaluated by carbonation depth measurements, as for traditional concrete, but an image processing software was used to estimate the percentage of carbonated surface (counting the pink pixels corresponding to not carbonated concrete with respect to the total number) (Fig. 6). Based on the results obtained from the image analysis, a “degree of carbonation” was introduced; Fig. 7 compares carbonation degree calculated after 10 and 30 days of exposure in the accelerated carbonation chamber. After 10 days in accelerated conditions, more than 50% of the fracture surface of no-fines concrete 2.a with  $w/c$  ratio 0.39 was carbonated. By increasing the time of exposure, the carbonation degree was to increase. A lower carbonation degree was observed on mixes 4.a and 5.a which have lower  $w/c$  and  $a/c$  (i.e. more cement paste with lower capillary porosity).

To evaluate the possible effects of the hydrophobic admixture on carbonation degree, tests were carried out also on hydrophobized no-fines concrete; Fig. 6 compares results of phenolphthalein tests carried out on fracture surfaces of no-fines concrete with (bottom of Fig. 6) and without (top of Fig. 6) hydrophobic admixture, after 30 days of exposure. The phenolphthalein test showed that the hydrophobic admixture (especially at the dosage of 1%, Fig. 7) favors the carbonation of no-fines concrete, especially in more porous concrete with the highest  $w/c$  (0.39). These results are in agreement with the expected effect of hydrophobic admixture that hinders penetration of liquid water, keeping the cement paste dry and favoring the diffusion of gases like  $\text{CO}_2$  [30–32].

The full replacement of natural aggregate with a recycled one (Fig. 7) increases the degree of carbonation in the first 10 days of exposure to  $\text{CO}_2$  slightly (especially in no-fines concretes with the highest  $w/c$ ) confirming that recycled aggregate, differently from natural calcareous aggregate, can contribute to take  $\text{CO}_2$  by carbonation [10,11,14,15]. However, at longer curing times the difference is not evident any more.

To evaluate the effect of carbonation on mechanical properties, compressive strength has been measured also on specimens of no-fines concrete exposed to accelerated carbonation. The results were compared with those obtained in uncarbonated specimens

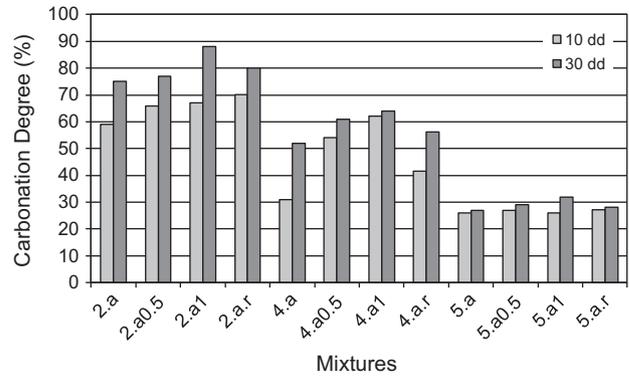


Fig. 7. Carbonation degree in no-fines concretes after 10 and 30 days of exposure to carbonation chamber.

and these showed that, after 30 days of exposure to  $\text{CO}_2$ , the carbonation process does not significantly increase the density and the dynamic elastic modulus of no-fines concrete (data are not reported for brevity). Carbonation increased slightly only the mechanical strength (Fig. 8), especially in concretes with the lowest  $a/c$ , probably due to the higher content of cement paste susceptible to carbonation and therefore improving the mechanical strength of concrete, regardless of the presence of the hydrophobic admixture or recycled aggregate.

### 3.3. Capillary water absorption

Fig. 9 shows the results of capillary absorption tests on different mixes of no-fines concrete. The water uptake of a reference concrete ( $w/c = 0.6$  and  $a/c = 6.6$ ) has been also reported as comparison; for long periods of contact all no-fines concrete absorb much less water (about 50%) than ordinary concrete since no-fines concrete has less cement paste with capillary pores than the ordinary one.

The elaborated results (Table 3) show that the hydrophobic admixture is able to reduce water absorption of about 70% both for short periods of contact with water represented by CAr<sub>el</sub> (ratio

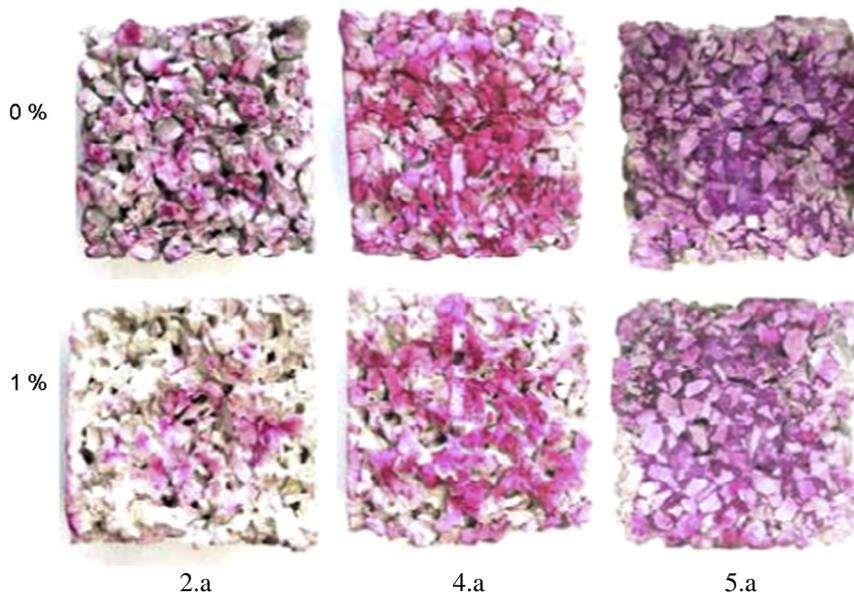


Fig. 6. Phenolphthalein test on no-fines concretes without (up) and with (down) hydrophobic admixture after 30 days of exposure to carbonation chamber.

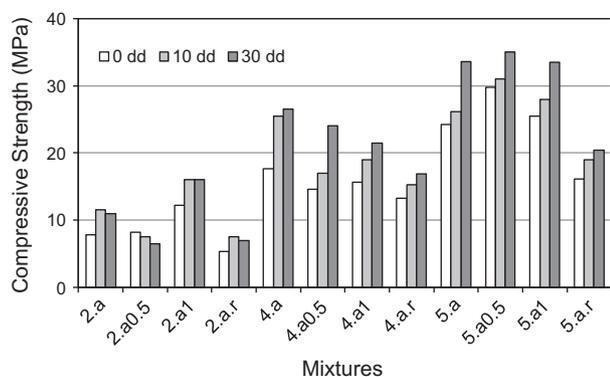


Fig. 8. Effect of days of carbonation (dd) on the mechanical strength of no-fine concretes.

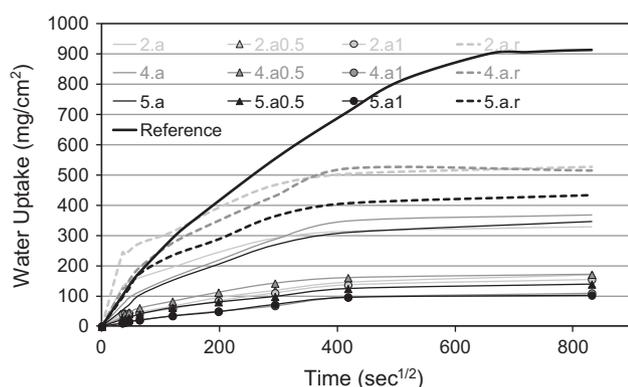


Fig. 9. Capillary water absorbed by no-fines concretes.

between the slope of the initial part of the water absorption curve of hydrophobic concretes with respect to that obtained by the same strength class concrete but without hydrophobization) and of about 60% for longer periods of contact represented by ICrel (ratio between the area subtended by the water absorption curve of hydrophobic specimens with respect to that of the same strength class concrete but without hydrophobization).

No effect of carbonation (water absorption curves of carbonated concretes are similar to uncarbonated ones and are not reported for brevity) or mechanical performance on water uptake of no-fines concrete was observed. As a matter of fact, capillary water absorption occurs just through capillary porosity that, at the same curing time, depends only by  $w/c$ , which is quite similar in all specimens.

Table 3

Absorption Coefficient (CA), Relative Absorption Coefficient (CArel) and Relative Adsorption Index ((ICrel).

Mixtures	CA (mg/cm <sup>2</sup> s <sup>-1/2</sup> )	CArel	ICrel
2.a	3.28	1.00	–
2.a0.5	0.86	0.26	0.45
2.a1	1.00	0.31	0.41
2.a.r	5.57	1.70	1.63
4.a	1.87	1.00	–
4.a0.5	0.97	0.52	0.47
4.a.1	0.27	0.15	0.27
4.a.r	2.99	1.60	1.48
5.a	1.42	1.00	–
5.a0.5	0.56	0.39	0.39
5.a.1	0.29	0.21	0.29
5.a.r	2.50	1.76	1.32

Moreover, only a slightly beneficial effect in reducing capillary water absorption was observed when silane addition increased from 0.5% to 1% by mass of cement.

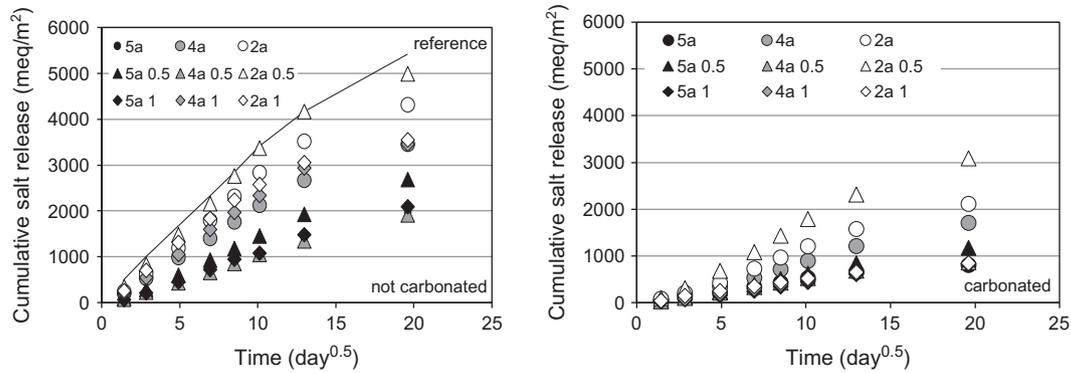
The full replacing of natural aggregate with recycled one induces higher capillary water absorption both for short (+70%) and for longer (+60%) periods of contact with water, regardless the strength class. This is due to the high capillary porosity of recycled aggregate, mainly constituted by cement paste, with respect to natural aggregate confirming what is already reported in the literature for traditional recycled concretes [11,14,16].

The use of recycled aggregates could probably weaken the strength and durability of no-fines concrete; however, this negative effect might be easily counteracted by using a hydrophobic admixture.

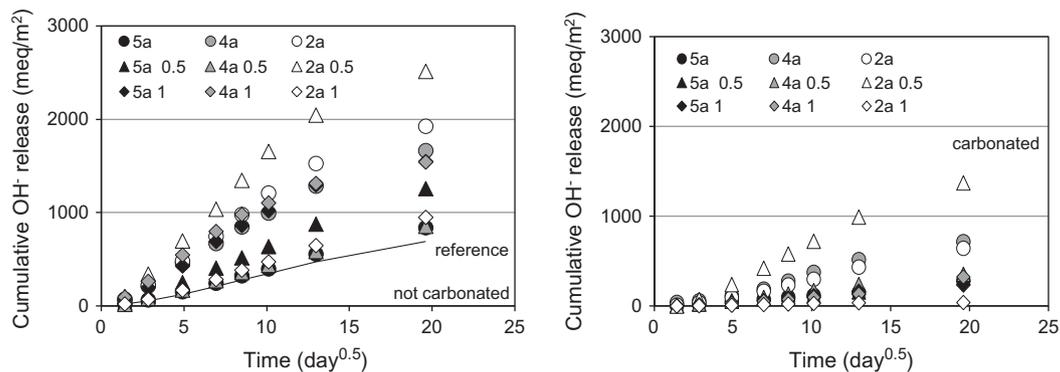
#### 3.4. Leaching tests

Figs. 10 and 11 show the results obtained with dynamic leaching test comparing also the leaching obtained by no-fines concretes and that obtained by an ordinary concrete as a reference [33]. The trends in time of the release of salts and hydroxyls are the same for no-fines concrete and the reference one. Despite the difficulty of comparing the amounts of release from specimens at such different weights and surface effectively exposed to the contact with de-ionized water, it is clear that the mechanism of release is the same and can in fact be identified as diffusion [34]. Different volume mass, porosity, specific surface area, micro-pore ratio, and particle bulk density can lead to greater or lower release with a complex interaction of opposed effects, but the curve shapes point to a diffusion-like process as the prevailing leaching mechanism. This observation is particularly interesting because it is not so easily predictable. For example, in a previous study on leaching behavior of specimens manufactured with aggregates of different size and submitted to increasing mechanical stress [35], the authors observed that the specimen with cracks showed a rate of release more consistent with dissolution from the disintegrated concrete matrix rather than with diffusion of its constituents through the intact matrix. The obtained results point to the fact that in no-fines concrete, despite the presence of large open porosity, the release of ions is determined only by the properties of the thin coating of paste surrounding the coarse aggregates particles.

Focusing on the differences among the no-fines concrete specimens, the leaching test demonstrates that a higher  $w/c$  ratio releases a higher amount of salt, because the rate of diffusion is determined by the porosity of the paste (Table 2). The reduction in porosity caused by the addition of hydrophobic admixture slightly influences the ionic release in the non-carbonated specimen. The effects of hydrophobic admixture are quite clearly evident after carbonation. The reductions in porosity resulting from larger molar volume of calcite, with respect to the portlandite initially present in the cement paste before carbonation, reduces considerably the release of the constituent ions. The effect of carbonation is most pronounced with 1% of hydrophobic admixture, mostly for the mixture with low and medium compressive strength, coherently with the observation that these mixtures are more carbonated than the others (Fig. 7): at a dosage of 1% of hydrophobic admixture all the carbonated specimens show lower release amounts (around 850 meq/m<sup>2</sup>). After carbonation this lower amount of release is achievable even without hydrophobic admixture but providing that the mixture has higher compressive strength (or with only 0.5% of hydrophobic admixture in a mixture with medium compressive strength). In conclusion, the addition of hydrophobic admixture at the dosage of 1% confers to the specimens with lower mechanical strength the same durability of those with greater mechanical performance.



**Fig. 10.** Release of salt constituent by no-fines concretes before (left) and after (right) carbonation. In the left graph, the black line shows the release trend of an ordinary concrete as reference (CEM II/A-L 42.5 R  $w/c = 0.6$ ).



**Fig. 11.** Release of hydroxyl ions by no-fines concretes before (left) and after (right) carbonation. In the left graph, the black line shows the release trend of an ordinary concrete as reference (CEM II/A-L 42.5 R  $w/c = 0.6$ ).

Regarding the values of pH measured during the leaching test, the leachate remained always basic even for carbonated specimens, the pH ranging from 9.26 to 11.75. Analogously to what was seen for the release of constituent salts, the effect of the hydrophobic admixture (1%) is significant only on the specimen with low mechanical strength. On the one hand, carbonation is the main cause of matrix modification and, on the other, hydrophobic admixtures actually promotes the carbonation itself.

However, in current real applications of pervious concrete, what impacts the durability is also that the open pores are easily blocked by dust or muds in water penetrating the concrete. This fact cannot be fully inhibited by hydrophobic admixtures. Investigations on how to reduce the blockage of pervious concrete are also meaningful for enhancing the durability of these materials.

#### 4. Conclusions

No-fines concretes with three different mix design were manufactured. The effect of hydrophobic admixture, at two different dosages, and recycled aggregate on the performances of no-fines concrete was investigated in terms of physical–mechanical characterization, carbonation rate, and durability aspects (such as capillary water absorption and leaching tests).

The results obtained show that:

- no-fines concretes with compressive strength ranging from 7 to 30 MPa were obtained by changing the  $w/c$  from 0.41 to 0.34 and the  $a/c$  ratio from 8 to 4;
- due to macro-voids of the material, high susceptibility to carbonation in the depth of the material was observed for all the

no-fines mixes studied in this work, even when exposed to an indoor environment;

- on one hand, the hydrophobic admixture decreases slightly the strength of no-fines concretes, but on the other hand, it improves the durability performance considerably by decreasing the capillary water absorption from its original value of about 70%, regardless the concrete strength class, by giving to the specimens with lower strength class the same rate of ionic release of the specimens with higher strength class;
- the total replacement of natural aggregate with recycled one, at the same mix-design, increases capillary water absorption of about 50%;
- the total replacement of natural aggregate with recycled one, at the same mix-design, penalizes the mechanical performance by about 30%. However, as pervious concrete should not have high mechanical performance, the environmental advantage of using recycled aggregates certainly overcomes the disadvantage related to mechanical strength penalization.

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