Sustainable and Durable No-fines Concrete for Vertical Applications

Francesca Tittarelli, Alessandra Mobili, Chiara Giosuè, and Maria Letizia Ruello

***Abstract*—** No-fines concretes with 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.

***Keywords*—**Hydrophobic Admixture, Leaching, No-fines concrete, Recycled Aggregate, Durability.

I. Introduction

NO-FINES concrete, also known as porous, pervious, permeable and cellular concrete, has little no fine aggregate and has just enough cementitious paste to coat the coarse aggregate particles while preserving the interconnectivity of the voids [1]. No-fines concrete has a porous structure with relatively large interconnected voids that confers to it acoustic and thermal insulation characteristics, water permeability, and economy in terms of material cost [2]-[4]. In addition, more than 50% of carbon dioxide emitted during cement production originates from calcinations of limestone but this CO_2 is reabsorbed during the life cycle of the cement-based products in the carbonation process. In order to accelerate the process of CO_2 uptake, low strength porous concrete can be advantageous with respect to ordinary concrete. For this reason, no-fine concrete has been proposed by some authors [5] with the aim of enhancing CO_2 uptake. Since no-fines concrete fulfils many of the properties required to a sustainable building material they could be particularly useful not only for road paving [6] that is the actual most widespread application, but also for a wide range of vertical applications which could probably require their use in 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 [2]-[4].

At present, one of the main limitations to broaden the potential applications of no-fines concretes is the low durability, since through their porosity, water and the relative dissolved aggressive substances can penetrate them and induce degradation processes. The durability problem could be reduced by manufacturing no-fines concretes with a hydrophobizing admixture [7]-[9] which may reduce water uptake. Moreover, if reinforcements are introduced [10]-[11] once that 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.

In addition, of particular interest to favour a sustainable development of no-fines concrete is the use of recycled aggregate in replacement of those natural. [5].

In this work, no-fines concretes with three different mixtures corresponding to low (~5-10 MPa), medium (~15-20 MPa) and high (~25-30 MPa) compressive strengths were manufactured. The effect of hydrophobic admixture and recycled aggregate on the mechanical performances and durability aspects, such as carbonation rate, capillary water absorption and leaching test in de-ionized water, was investigated.

II. Experimental

A. Materials and Mixes

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. 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

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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 ratios.

Each mixture was cast in cubic molds (10x10x10 cm) in two layers. Each layer was compacted for 5-10 seconds with a drill equipped with a flat square with side equal to that of the formwork. Cubic specimens were de-moulded after 24 hours from casting and cured at R.H. > 95% and T = 22°C until time of testing. Density of no-fines concrete was measured on cubes after de-moulding. Once density is known, the mix proportions of the mix were back calculated and expressed in terms of kg per cubic meter of no-fines concrete. The porosity of each mixture of no-fines concrete was also estimated knowing mass and density of cement, water and aggregate (Table 2).

TABLE I
MIX DESIGN OF NO-FINES CONCRETES

Mixes	w/c	a/c	Water kg/m^3	Cement kg/m^3	Aggregate (kg/m^3)
1	0.41	8.0	76	184	1470
2	0.39	7.0	82	210	1478
2-r	0.39	6.4	82	210	1350
2-1	0.39	7.0	82	210	1478
3	0.38	6.0	99	261	1570
4	0.37	5.1	113	307	1570
4-r	0.37	4.7	113	307	1434
4-1	0.37	5.1	113	307	1570
5	0.34	4.0	129	382	1530
5-r	0.34	3.7	129	382	1397
5-1	0.34	4.0	129	382	1530

Mixes 2, 4 and 5 were repeated by adding the hydrophobic admixture at the dosage of 1% by cement mass. The same mixes were also repeated using recycled aggregate instead of natural ones. In the denomination of mixes the number 1 define the dosage of hydrophobic admixture; the letter r indicates the use of recycled aggregates. Since the specific weight of recycled aggregates (2420 kg/m^3) is lower with respect to that of natural aggregates (2650 kg/m^3), aggregate replacement was calculated by volume (100% of replacement).

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

B. Carbonation

After 28 days of curing, cube specimens of each mixture were exposed to a carbonation chamber at CO_2=(3±0.2)%, T=(21±2)°C and RH=(60±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.

C. Capillary Water Absorption

Capillary water absorption tests have been carried out on cube specimens according to Italian Normative UNI 10859:2000. 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.

D. Leaching Tests

Leaching tests were conducted following Italian regulations for reuse of no-toxic waste materials as by-products (D.M.A. 1998). Examples of similar international standard test 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 of more general applicability since leaching behaviour is strictly related to the durability properties of the material.

III. TEST AND RESULTS

A. Porosity, Density and Mechanical Properties

Table 2 reports the density, porosity and mechanical strength after 7 and 28 days. It can be observed that the density of materials ranged from 1730 kg/m^3 for mix 1 to 2230 kg/m^3 for mix 5-1 The porosity, calculated from density values, ranged from 31% to 9%.

TABLE II
PROPERTIES OF NO-FINES CONCRETES

Mixes	Density (kg/m3)	Porosity (%)	Rc,7dd MPa	Rc, 28dd MPa
1	1730	31	6.1	7.1
2	1770	29	7.0	7.8
2-r	1730	25	-	5.3
2-1	1950	22	-	12.2
3	1930	22	15.7	17.5
4	1990	19	16.0	17.6
4-r	1910	17	-	13.2
4-1	2060	17	-	15.6
5	2040	17	22.0	24.2
5-r	1970	15	-	16.1
5-1	2230	9	-	25.5

Due to high porosity and low content of cement paste, no-fines concrete have low strength performance; compressive strength (Rc) ranged from 6 to 22 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. In order to correlate the mechanical properties of no-fines concrete to its microstructure, both macroscopic voids (which depend on a/c ratio 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, as well as porosity decrease, with the decrease of water/cement and aggregate/cement. 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, are due to the high macroscopic porosity of this material (ranging from 10 to 30%).

Hydrophobic admixture decreases the mechanical performances as observed in traditional concrete [7-9]. However, this behaviour 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 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 natural one [5]. However, since pervious concrete should not have high mechanical performances, the environmental advantage on using recycled aggregates certainly overcome those related to mechanical strength penalization.

B. 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 from the external surface inward. High porosity of no-fines concrete promotes the carbonation penetration also in depth and causes also the partial carbonation of cement paste in contact with inner macro-pores. 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 ones) (Figure 1).

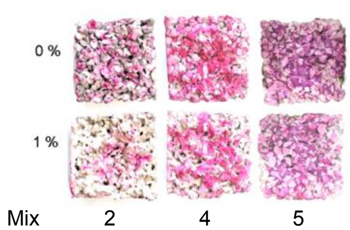

Fig. 1 Phenolphthalein test on no-fines concretes without (up) and with (down) hydrophobic admixture after 30 days of exposure to carbonation chamber

Based on the results obtained from image analysis, a carbonation degree was introduced.

Figure 2 compares carbonation degree calculated after 10 and 30 days of exposure in the accelerated carbonation chamber. After 10 days, more than 50% of the fracture surface of no-fines concrete 2 with w/c ratio 0.39 was carbonated. By increasing the time of exposure, the carbonation degree increased. A lower carbonation degree was observed on mixes 4 and 5 which have lower w/c and a/c (i.e. more cement paste with lower capillary porosity).

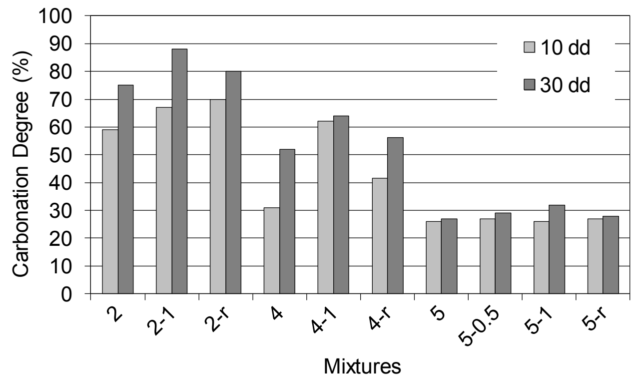

Fig. 2 Carbonation degree after 10 and 30 days of exposure to carbonation chamber

To evaluate the possible effects of the hydrophobic admixture on the carbonation degree, tests were carried out also on hydrophobized no-fines concrete; Figure 1 compares results of phenolphthalein tests carried out on fracture surfaces of no-fines concrete with and without hydrophobic admixture, after 30 days of exposure. The hydrophobic admixture especially at the dosage of 1%, favours the carbonation of no-fines concrete with the highest w/c ratio (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 favouring the diffusion of gases as CO2 [7-9]. The full replacement of natural aggregate with recycled one increases slightly the degree of carbonation in the first 10 days of exposure to CO_2 (especially in no-fines concretes with the highest w/c) confirming that recycled aggregate, differently from natural calcareous aggregate, can contribute to take CO_2 by carbonation [5]. 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. Carbonation increased only slightly the mechanical strength (Figure 3), especially in concretes with the lowest a/c, probably due to the higher content of cement paste susceptible to carbonation and therefore able to improve the mechanical strength of concrete, regardless of the presence of the hydrophobic admixture or recycled aggregate.

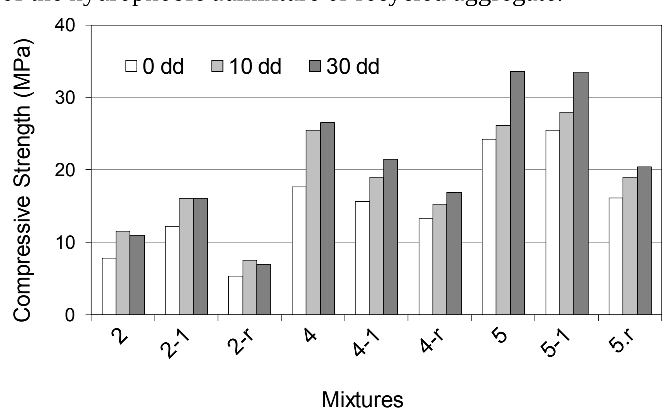

Fig. 3 Effect of carbonation days (dd) on the mechanical strength of no-fine concretes.

C. Capillary Water Absorption

Figure 4 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 reference; 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 ordinary one. The elaborated results show that the hydrophobic admixture is able to reduce water absorption of about 70% both for short periods of contact with water represented by CArel (ratio 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 not carbonated 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. Moreover, only a slight 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 ones. 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.

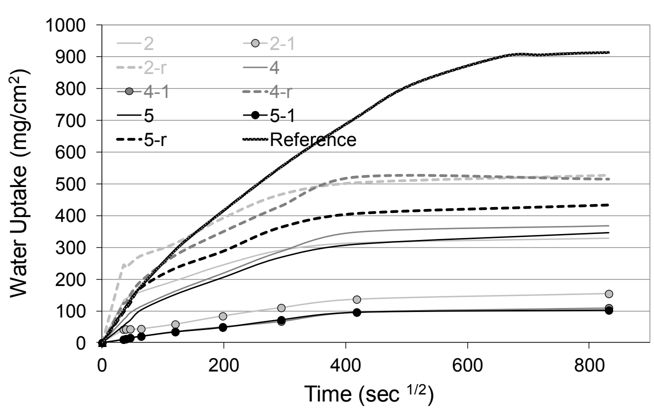

Fig. 4 Capillary water absorbtion test.

TABLE III
RELATIVE CAPILLARY ABSORPTION COEFFICIENT AND RELATIVE CAPILLARY ABSORPTION INDEX OF NO-FINES CONCRETES

Mixes	CArel	ICrel
2-1	0.31	0.41
2-r	1.70	1.63
4-1	0.15	0.27
4-r	1.60	1.48
5-1	0.21	0.29
5-r	1.76	1.32

D. Leaching Tests

Figure 5 show the results obtained with dynamic leaching test comparing the leaching obtained by no-fines concretes and that obtained by an ordinary concrete as reference [12].

The trend in time of the release of salts is the same for no-fines concrete and the reference one. Despite the difficulty of comparing the amounts of release from specimens at so 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 determined by diffusion [13]. 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 not so easily predictable. For example, in a previous study on leaching behaviour of specimens manufactured with aggregates of different size and submitted to increasing mechanical stress [14], 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 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.

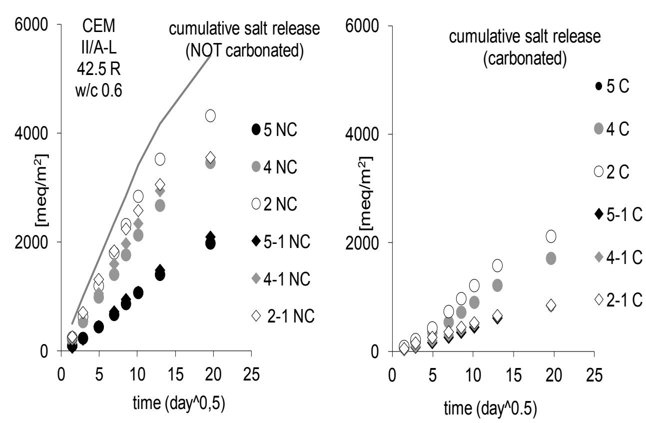

Fig. 5 Release of salt constituent by no-fines concretes before and after carbonation

Focusing on the differences among no-fines concrete specimens, the leaching test demonstrates that the higher the w/c the higher the amount of salts released, because the rates 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 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 constituents 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 (Figure 2): at the dosage of 1% of hydrophobic admixture all the carbonated specimens show the lower release amounting (about 850 meq/m^2). After carbonation this lower amount of release is achievable even without hydrophobic admixture but providing that the mixture has higher 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.

IV. Conclusion

No-fine 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.

On one hand, the hydrophobic admixture decreases slightly the strength of no-fines concretes, but on the other hand, it improves considerably the durability performance by decreasing the capillary water absorption of about 70%, regardless the concrete strength class, and by giving to the specimens with lower strength class the same rate of ions 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%. However, the related decrease in durability could be easily counteracted with the use of a hydrophobic admixture.

The total replacement of natural aggregate with recycled one, at the same mix-design, penalizes the mechanical performance by about 30%. However, since pervious concrete should not have high mechanical performances, the environmental advantage on using recycled aggregates certainly overcome those related to mechanical strength penalization.

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