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Carbon Dioxide Uptake by Recycled-Aggregate No-Fines Concrete

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ABSTRACT

In the present work, four no-fines concrete mixture proportions were prepared, after optimization of the mixture proportions, and tested: two were made of recycled concrete aggregates in which demolished concrete was suitably treated and two were made of virgin aggregates. Two different aggregates to cementitious materials ratios and water to cement ratios were adopted depending on the maximum size of the aggregates. The concrete specimens were evaluated by means of compression tests and also by means of carbonation depth measurements. In particular, resistance to the penetration of carbonation was measured on 25-mm cubes exposed to atmosphere or an environment with 21°C, 60% R. H., and a constant flux of 1% CO_2 (accelerated carbonation). Results obtained show that the porous no-fines concretes, particularly if manufactured with recycled aggregates, were able to absorb higher amount of CO_2 than conventional concretes. A possible application of these materials can be acoustic barriers to be placed along highways and street-traffic roadways.

INTRODUCTION

The building construction sector uses much energy and emits large quantities of carbon dioxide (CO_2) to the atmosphere. Energy is used for extracting, transporting, processing, and assembling materials, and CO_2 is emitted by fossil fuel combustion, land-use practices, and industrial processes reactions, such as chemical reactions in the production and use of portland cement. If the whole life cycle of cement-based products is taken under consideration, there is a positive CO_2 emission from calcinations reaction during cement manufacture but also a negative emission due to carbonation reaction during the building lifecycle, which partially reduce the environmental impact due to cement production.

More than 50% of the carbon dioxide emitted during cement production originates from the calcination of limestone. This CO_2 is reabsorbed during the life cycle of the cement-based products in a process called carbonation. Pade & Guimaraes (2007) showed that the impact of concrete carbonation in the assessment of CO_2 emissions from cement production has not been fully documented. Specifically, they showed a lack of knowledge about the carbonation of demolished and crushed concrete. In fact, the existing models for calculating carbonation do not take into account what takes place after the concrete has been demolished and crushed. Consequently, the contribution of the cement and concrete industry to net CO_2 emissions may be significantly overestimated.

In order to accelerate the process of CO_2 uptake, low-strength porous concrete can be advantageous with respect to high-strength concrete, at least when structural requirements are not so important. For this reason, no-fine concrete has been proposed by several authors [Naik et al. 2005; Park et al., 2005] with the aim of enhancing CO_2 uptake. As its name implies, no-fines concrete does not contain fine aggregates (sand). No-fines concrete has been successfully used in pavement applications, such as pavement surface course, pavement permeable base, pavement edge drains or shoulders [Ghafoori & Dutta, 1995a; Naik et al. 2001]; and non-pavement applications, such as drainage layers, backfill, stabilization of earth surfaces, floors, damp-proof coursing, garden walls, retaining walls, and other similar construction [Ghafoori & Dutta, 1995b]. No-fines concrete has a porous structure with relatively large interconnected voids and exhibits relatively low density and drying shrinkage compared to regular concrete. These unique features of no-fines concrete enhance its use in special applications. Some of the key characteristics of no-fines concrete are lower compressive, tensile, and bond strengths, higher permeability, high thermal insulation, and economy in material cost [Ghafoori & Dutta, 1995b]. Properties of no-fines concrete depend on aggregate to cement ratio; water to cementitious materials ratio; size, shape, gradation, and strength of coarse aggregates; type of compaction and amount of compaction energy; and, curing conditions [Meininger, 1988].

A possible application of no-fine concrete can be acoustic barriers to be placed along highways and street-traffic roadways [Naik 2007]. In fact, traffic noise created by the development of new roads due to the recent rapid increase in vehicle ownership has become a serious environmental challenge. Therefore, to overcome this problem, a new type of concrete needs to be developed that aids in the reduction of environmental loads such as that from noise and emissions from automobiles. From this view point, by using no-fines concretes, the development of porous concrete having water and air permeability, and good sound and CO_2 absorption ability can be achieved, by artificially forming continuous porosity. A similar experience with the same goal was carried out by Park et al. (2005) with encouraging results.

SCOPE OF THE WORK

This work was aimed at evaluating the CO_2 uptake ability of the no-fines concrete for acoustic barriers to be placed along highways and street-traffic roadways. The experimental work was carried out both in laboratory and in field by building a wall (Ancona-wall) with four different no-fines concrete mixtures in order to compare their effectiveness (Figure 1).

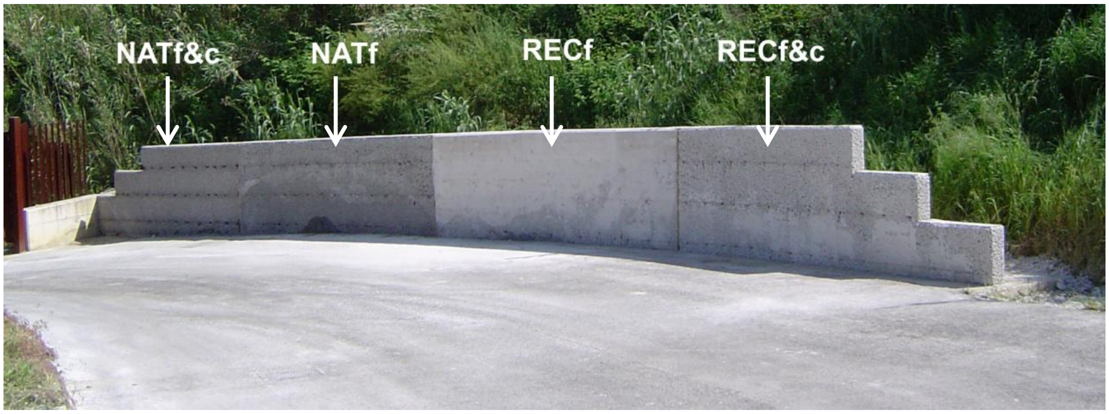

Fig. 1. No-fine Concrete Ancona-Wall

In addition to the ordinary aggregates, recycled concrete aggregates were used to manufacture no-fines concrete. The use of aggregates from recycled concrete, instead of natural, ordinary, limestone aggregates would allow an increase in the amount of CO_2 uptake because aggregate particles from recycled concrete have some coating of cementitious materials, including alkalis. Therefore, such particles are also able to contribute to CO_2 sequestration in addition to the alkali generated by the hydration of cement. In fact, recycled aggregates are likely to be made of concrete not completely carbonated. This is due to the concrete crushed for producing recycled aggregates, leading to new surface that are created, which can now be newly in contact with air and would undergo carbonation.

Moreover, recycled-aggregate no-fines concrete was used with the aim of testing the possibility of producing recyclable acoustic barriers [Naik 2007]. In fact, at the end of the life cycle (that is when CO_2 sequestration ability is already noticeably decreased), such barriers can be totally recycled (by suitably crushing the concrete from barriers) for producing “new” recycled aggregates, which can be mixed with cement and water for rebuilding the barriers. One of the scopes of this experimental work was also to determine the estimation of time required for concrete to achieve full carbonation, in order to evaluate the length of acoustic barrier service life for the purpose of CO_2 sequestration.

EXPERIMENTAL INVESTIGATION

Materials

A commercial portland-limestone blended cement Type CEM II/A-L 42.5 R according to European Standards EN-197/1, fine gravel (6-12 mm), and coarse gravel (11-22 mm) were used in the reference mixtures as solid constituents.

In addition, in order to prepare no-fines recycled aggregates for concrete mixtures, two recycled aggregate fractions were used. These recycled aggregates came from a recycling plant in which concrete from building demolition was selected, crushed, cleaned, and sieved/graded to obtain a fine recycled aggregates fraction (6-12 mm) and a coarse recycled aggregates fraction (11-2 mm).

Grain size distribution curves of virgin/natural and recycled aggregates fractions are shown in Figure 2. Their main physical properties are reported in Table 1.

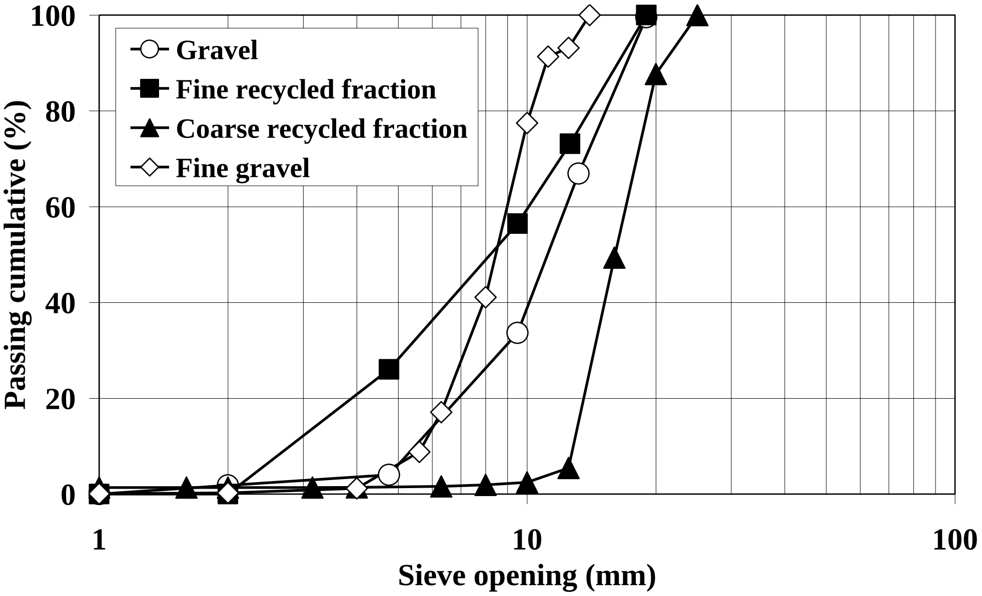

Fig. 2. Particles Size Distribution of Aggregate Fractions

Table 1. Main Physical Properties of Aggregate Fractions

	Fine gravel (6-12 mm)	Gravel (11-22 mm)	Fine recycled fraction (6-12 mm)	Coarse recycled fraction (11-22 mm)
Relative specific gravity	2.58	2.60	2.47	2.48
Water absorption (%)	2.9	2.5	9.0	8.7

Mixture proportions

Four different no-fines concrete mixture proportions were prepared (Table 2). They were the result of a preliminary optimization carried out in a previous experimental work, in which several water to cement ratio and aggregates to cement ratios were tested in order to identify the best mixture in terms of mechanical strength, porosity distribution, and absence of segregation.

Depending on the aggregate maximum size, the optimum aggregates/inert to cement ratio was either 14 or 4.5 and the water to cement ratio either 0.25 or 0.35, the first values corresponding to the higher aggregate size (22 mm instead of 12 mm).

Table 2. No-fines Concrete Mixture Proportions

Mixtures	NATf&c	NATf	RECf	RECf&c
Inert to cement, I/C	14	4.5	4.5	14
Water to cement, W/C	0.25	0.35	0.35	0.25
Water	40	120	120	40
Cement	160	350	350	160
Fine recycled fraction (6-12 mm)	--	--	1600	1086
Coarse recycled fraction (11-22 mm)	--	--	--	1090
Fine gravel (6-12 mm)	1134	1670	--	--
Gravel (11-22 mm)	1143	--	--	--

In the case of the use of recycled aggregate fractions, they were pre-soaked with water up to the condition very close to saturated surface dried (SSD) in order to add the correct dosage of aggregate to the mixture and to better control the right amount of water added to the mixture.

The level of workability was the same for all the concrete mixtures, equal to slump S1.

RESULTS AND DISCUSSIONS

Compression tests

Compressive strength was measured on cube (100x100x100 mm) test specimens at two different curing ages: 3 and 28 days. All test specimens, after demolding (at one day) were covered by plastic sheet to minimize water evaporation. They were then cured at constant temperature of 20°C in water. Results obtained are reported in Figure 3.

On the basis of the results reported in Figure 3, the use of both fine and coarse gravel (natural or recycled) was detrimental in terms of compressive strength with respect to the use of the only fine aggregate fraction, despite the lower w/c used (0.25 instead of 0.35). Surprisingly, recycled aggregate, no-fines concretes were characterized by higher compressive strength with respect to the corresponding ordinary no-fines concretes. The reason probably lies in the better quality of the interface between recycled aggregates and cement paste with respect to that between natural-limestone particles and cement paste [Corinaldesi & Moriconi, 2006; Corinaldesi & Moriconi, 2009]. Also, recycled concrete aggregates have fine particles of cementitious materials that allow greater bond with the surrounding new mortar-fraction of the mixture as well as allow higher value of new C-S-H growth.

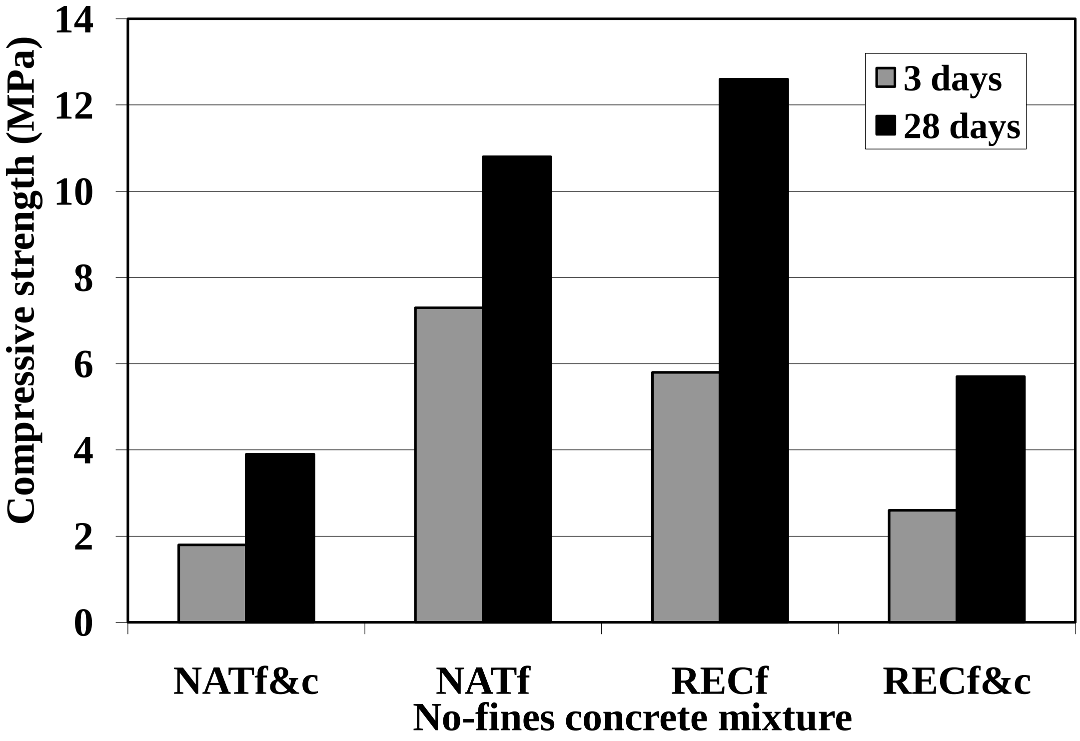

Fig. 3. No-fines Concrete Compressive Strength vs. Curing Time

Evaluation of carbon dioxide uptake

Carbon dioxide uptake was evaluated both on concrete cube test specimens exposed to either atmosphere or accelerated conditions in a climatic chamber and on concrete cores extracted from the Ancona-wall subjected to the natural climatic conditions of the wall site.
Resistance to the penetration of carbonation was measured on cubes exposed to either atmosphere, or an accelerated environment, with 21±1°C, 60±10% R.H., or a constant flux of 1% CO_2 (accelerated carbonation), according to UNI EN 13295 (2005). The percentage of CO_2 was chosen equal to 1%, according to the Italian standard practice.
After either 90 days of exposure to atmosphere or three days of exposure to accelerated carbonation, 100-mm test specimens were split in two parts and carbonation depth was measured by the phenolphthalein test, according to prEN 14629 (2003). Results obtained for the 'RECf&c' mixture are shown in Figures 4 and 5.

By visually comparing the specimen appearances shown in Figure 4 and Figure 5, it can be seen that three days in climatic chamber correspond to a period longer than 90 days at open air. However, carbonation depth of 'RECf&c' concrete (as well as of the other three no-fines concretes) was very high. The reason most likely is the high rate of continuous porosity of no-fines concrete.

Fig. 4. Carbonation Depth of 'RECf&c' No-Fine Concrete after 90 Days in Atmosphere.

Fig. 5. Carbonation Depth of 'RECf&c' No-Fine Concrete after 3 Days in Climatic Chamber.

In order to evaluate not only qualitatively the CO_2 penetration but also the amount of $CaCO_3$ formation due to CO_2 reaction with $Ca(OH)_2$, several concrete cores (200-mm long, equal to the wall thickness) were extracted from the Ancona-wall and divided into four portions (about 50-mm long). Each portion of the core was ground and the resulting powder was analysed by means of Thermogravimetry (TG) and Differential Thermal Analysis (DTA) in order to quantitatively evaluate the content of $CaCO_3$. The amount of calcium carbonate formed depends on the initial concrete composition and on the carbonation reaction progress from the outside of the Ancona-wall to the inside. Such reaction will presumably be faster for external (labelled 'A' and 'D') rather than for internal (labelled 'B' and 'C') portions of the cores from the Ancona-wall. Results obtained on cores taken after one month after wall was constructed, and exposure to the atmosphere started, (expressed in % of $CaCO_3$ content) are reported in Table 3.

Table 3. Content of $CaCO_3$ (in %) of the Cores Extracted from the No-Fines Concrete Ancona-wall, after One Month after Exposure, depending on the Portion of the Core.

Core portion	NATf&c	NATf	RECf	RECf&c
External 'A' (0-5 mm depth)	86.4	74.1	68.2	74.9
Internal 'B' (5-10 mm depth)	83.5	76.4	58.4	74.5
Internal 'C' (10-15 mm depth)	86.1	72.5	62.9	75.2
External 'D' (15-20 mm depth)	83.7	72.9	65.6	75.4

As expected, higher content of $CaCO_3$ (due to the initial concrete composition) was detected for the no-fines concretes prepared with ordinary (carbonic, limestone) aggregates rather than for the no-fines concretes prepared with recycled-concrete aggregates. In addition, higher content of $CaCO_3$ was detected for the no-fines concretes prepared with both fine and coarse aggregate fractions, due to a higher amount of aggregates added to Mixture RECf&c (Table 2).

Concerning the evolution of carbonation reaction, evidence was not detected after one month of exposure; in fact significant differences in the $CaCO_3$ content between external and internal portions of the concrete cores were not detected, except for Mixture RECf.

CONCLUSIONS

The following general conclusions can be drawn from the study reported in the paper:

- In terms of mechanical strength, the best results for the production of no-fines concretes can be obtained by using only the fine recycled-concrete aggregates;
- In terms of CO_2 uptake, all the tested no-fines concrete mixtures performed very well due the high rate of continuous porosity of such type of concrete;
- In particular, preliminary results obtained in from the Ancona-wall showed that the evolution of carbonation reaction seems faster for the mixture prepared with the only fine recycled-concrete aggregate, but this result needs further, long-term exposure and study.
- Future development of this experimental work is to monitor the evolution in time of CO_2 uptake for the Ancona-wall, in order to estimate the time necessary for the carbonation reaction depletion and, consequently, the wall service life before its recycling.

REFERENCES

Corinaldesi, V., Moriconi, G. (2006). "Behaviour of Beam-Column Joints Made of Sustainable Concrete under Cyclic Loading.", *Journal of Materials in Civil Engineering,* 18(5), 650-658.

Corinaldesi, V., Moriconi, G. (2009). "Influence of mineral additions on the performance of 100% recycled aggregate concrete.", *Construction and Building Materials,* 23(8), 2869-2876.

Ghafoori, N. and Dutta, S. (1995a). "Development of No-Fines Concrete Pavement Applications.", *ASCE Journal of Transportation Engineering,* Reston, VA, U.S.A., 121(3), 283-288.

Ghafoori, N. and Dutta, S. (1995b). "Building and Non-Pavement Applications of No-Fines Concrete.", *ASCE Journal of Materials in Civil Engineering,* Reston, VA, U.S.A., 7(4), 286-289.

Meininger, R.C. (1988). "No-Fines Pervious Concrete for Paving.", *Concrete International,* American Concrete Institute, Farmington Hills, MI., 20-27.

Naik, T.R., Chun, Y.M., Kraus, R.N., Singh, S.S., Pennock, L.C., Ramme, B.W. (2001). "Strength and Durability of Roller-Compacted HVFA Concrete Pavements.", *ASCE Practice Periodical on Structural Design and Construction,* Reston, VA, U.S.A., 6(4), 154-165.

Naik, T.R., Shah, T.C., Kraus, R.N., Canpolat, F. and Chun, Y. (2005). "CO_2 sequestration in no-fines concrete.", *Center for By-Products Utilization, Report No. CBU-2005-15 REP-586,* 1-35.

Naik, T.R.(2007). "Use of Concrete to Reduce Greenhouse Gases: Opportunities for the Future.", *A seminar presented at the UNIVPM, Ancona, Marche, ITALY, June 2007*.

Pade, C. & Guimaraes, M. (2007). "The CO_2 uptake of concrete in a 100 year perspective.", *Cement and Concrete Research,* 37, 1348–1356.

Park, S.B., Seo, D.S., Lee J. (2005). "Studies on the sound absorption characteristics of porous concrete based on the content of recycled aggregate and target void ratio.", *Cement and Concrete Research,* 35, 1846– 1854.

prEN 14629 (2003). "Products and system for the protection and repair of concrete structures – Test methods – Determinations of carbonation depth in hardened concrete by phenolphthalein method.".

UNI EN 13295 (2005). "Prodotti e sistemi per la protezione e la riparazione delle strutture di calcestruzzo - Metodi di prova - Determinazione della resistenza alla carbonatazione."