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Monitoring of a Very-High Performance Concrete Bridge

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ABSTRACT

Long-term durability of reinforced concrete structures is today a major concern for both environmental and economical reasons. The issue of mix design with respect to durability seems particularly relevant to develop lifetime-oriented design that takes into account both service life prediction of RC structures and the long lifetime required. In this context, it is very important in construction practice to introduce new materials improving the poor properties of traditional ones. A high-performance concrete meets special combinations of performance and uniformity requirements that cannot always be routinely achieved using conventional constituents and normal mixing, placing, and curing practices. In the 90s, very high performance steel fiber-reinforced prestressed concrete beams (with microsilica addition) were used for a road bridge (the first application in Italy). In this paper, the results of the inspection of the bridge deck, together with the results of laboratory tests on specimens naturally weathered are presented.

INTRODUCTION

A rising interest on the requirements to design for durability has recently occurred. In this context, the need for minimization of construction deficiencies and life cycle maintenance requirements is a critical issue. A fundamental feature is to take into account the interaction between the structure and its environment, which unequivocally plays a key role in defining the durability of the structure in use. Exposure classes are often defined (e.g. the European Standard EN 206) where restrictive values in the form of minimum concrete strength, maximum water/cement ratio, minimum cement content and so on, are included. A high-performance concrete, capable of improving the poor properties of traditional building materials, can be an optimal choice to minimize the infrastructure maintenance costs that represents significant expenses during the operation stages of an infrastructure [Aitcin 1998, Metha and Montero 2006]. The concrete deterioration requires frequent repair and strengthening, which generate remarkably amplified maintenance costs for bridges. High-performance materials allow to design lighter structures and reduce the volume of concrete produced. They guarantee an enhanced durability reducing the maintenance needs of the concrete construction, and limit the amount of non-renewable special repair materials that need to be used in maintaining the concrete [Naik 2008].

The objective of this paper is to inspect a prestressed reinforced concrete bridge for assessment of its health condition. The concrete used for the prestressed elements was a very high-performance concrete (average compressive strength >130MPa). The focus is to determine the impact of environmental exposures on the durability of the structural components. The bridge under investigation is located in Rezzato (Brescia), Italy over an irrigation channel; it was built in 1999. In order to evaluate the damage conditions of the concrete, compression and bending tests were carried out on aged specimens. Physical analyses were also performed by the use of Mercury Intrusion Porosimetry (MIP) to evaluate the porosity and pore-size distribution. Finally, as additional indicators of damage, ultrasonic pulse velocity (UPV) measurements and carbonation tests were performed and are discussed in this paper.

EXPERIMENTAL INVESTIGATION

Materials

The mix-design used for this application was developed to have good workability (workability class S4, a slump of about 200mm for almost one hour), high strength (average cubic strength of about 130MPa) and good durability performance. According to previous results on frost-durability performance [Biolzi et al. 1999], the optimal microsilica content (about 10% of binder) was chosen. Furthermore, the use of a fiber content of 1% in volume allowed both an improvement of the material properties and a sustainable cost for a practical application [Cattaneo 2001]. The optimized mix design is reported in Table 1.The main components were:

- Portland cement CEM I 52.5 R, according to ENV 197/1 European Standard with a Blaine fineness of 4.590 cm^2/g
- Gray microsilica in the form of a dry, uncompacted powder having a surface area of 20 m^2/g (B.E.T. method)
- Natural river siliceous aggregates
- Acrylic copolymer superplasticizer, 30% solid content
- Carbon steel microfibers, diameter 0.16 mm, length 13 mm

Table 1. Mix-design

Binder (cement+microsilica)	770 kg/m^3
Aggregates 0.06-6mm	1282 kg/m^3
Microsilica/binder	0.1
Water/binder	0.225
Acrylic superplasticizer (dry extract)	13.3 kg/m^3
Fibers (1% - d=0.16mm, l=13mm)	78 kg/m^3

Experimental Program and Testing Apparatus

The experimental program involved both laboratory tests and in-situ inspection.

The characterization of the material performed in 1999 involved different types of test. Some of them were repeated today on specimens cast in 1999.

In 1999, the specimens were removed from the moulds after 24 h, then cured in water at 20°C for at least 28 days before testing. The specimens not tested in 1999 were naturally weathered for ten years.

Compression tests on cubes (side 100mm) and cylinders (diameter 75mm, height 150mm) and three-point bending tests on prismatic specimens (100mmx100mmx400mm) were performed. The two parts of the broken specimen were subjected to carbonation test.

A standard testing machine was used for the compression tests [according to UNI-EN12390-3] and a closed-loop electromechanical Instron testing machine (maximum capacity 100kN) was used for bending tests [according to UNI-EN12390-5]. The bending tests were displacement controlled and the mid-span deflection was measured by means of an LVDT (± 5mm).

The cumulative porosity was evaluated with a Pascal Fisons (Mod. 240) porosimeter. The samples were previously treated in a vacuum-oven at 40°C for two days before being examined.

The in-situ inspection consisted of a visual inspection of the bridge, carbonation test and ultrasonic pulse velocity tests.
The carbonation tests used phenolphthalein as pH indicator.
The ultrasonic pulse velocity tests were performed according to UNI-EN 12504-4.
The apparatus was a “Controls” model “E46”, with transducers with a 50mm diameter.
The temperature during the tests was of 18°C with a 60% R.H.
The indirect transmission arrangement was applied on the lateral surface of the bridge (Fig.1). The measurements were taken at a distance of 150mm, 300mm and 450mm.

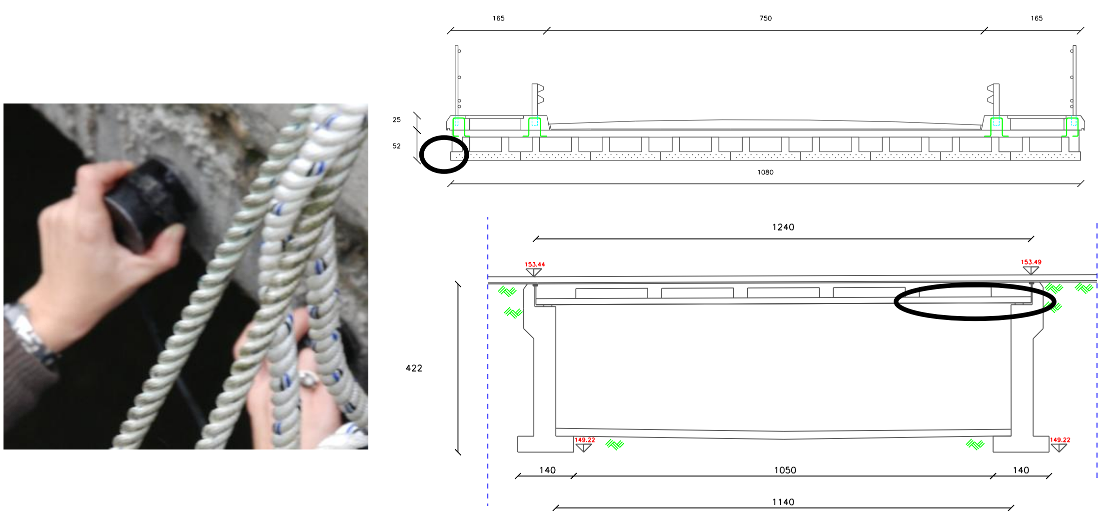

Figure 1. Location of ultrasonic pulse velocity tests

EXPERIMENTAL RESULTS

Laboratory tests

Compression tests were performed on 3 cubes (side 100mm) and on 3 cylinders (diameter 75mm, height 150mm). The bending strength was evaluated on 3 beams (100mm x 100mm x 400mm). The obtained results for each specimen, the average values, the standard deviations and the coefficient of variations (cov) are reported in Table 2.

The comparison between these results and the strength evaluated in 1999 (28 days) is shown in Fig. 2.

Both compressive (cubes) and bending strengths increased, and the strengths of 1999 were about 81% of current strength. The strength evolution is reported in Fig.3.

Table 2 . Compression and bending test results

	Specimen			Average	St.dev	Cov
	1	2	3	[MPa]	[MPa]	%
Compression - Cylinder (MPa)	147.13	167.95	168.86	161.31	12.29	7.62%
Compression - Cubes (MPa)	159.20	170.40	171.90	167.17	6.94	4.15%
Bending (MPa)	15.96	14.34	14.99	15.10	0.82	5.40%

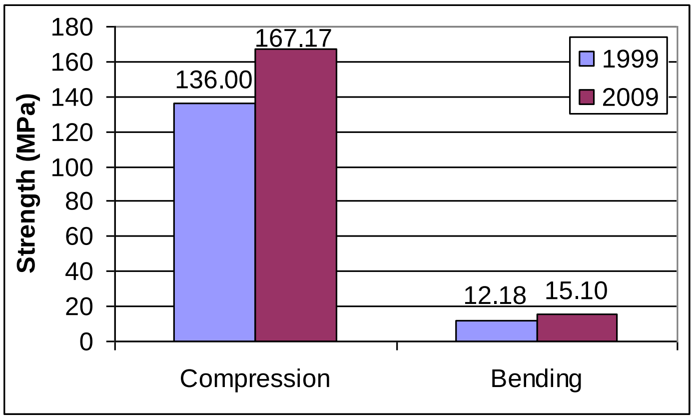

Figure 2. Comparison between 1999 and 2009 test results

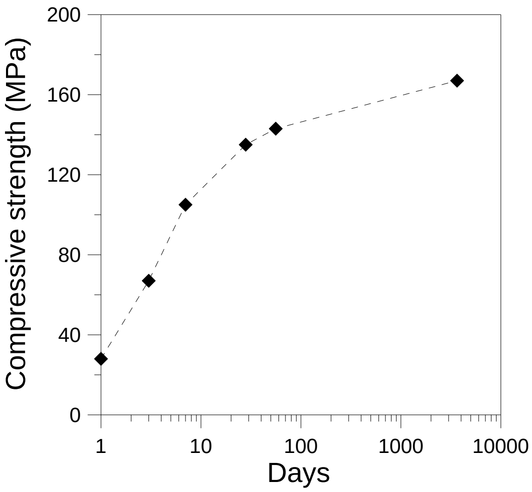

Figure 3. Compressive strength evolution

A comparison between typical stress-displacement (at midspan) curves from bending tests is reported in Fig.4. The aging of the material is beneficial in term of the overall stress-displacement behaviour and therefore an improved structural behaviour is expected.

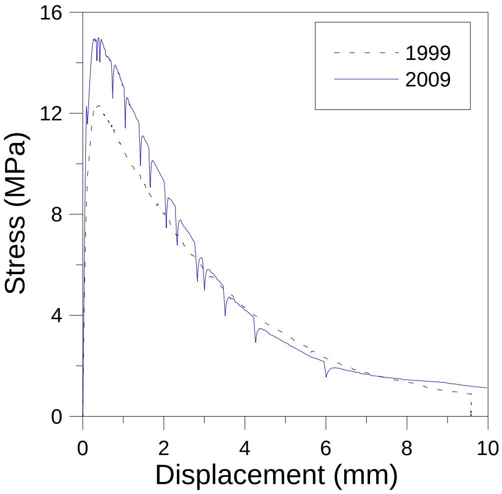

Figure 4. Bending test: Stress-displacement curves at midspan

The tests showed that the carbonation process did not develop inside the specimens. Figure 5 shows specimens before (a) and after testing (b-c).

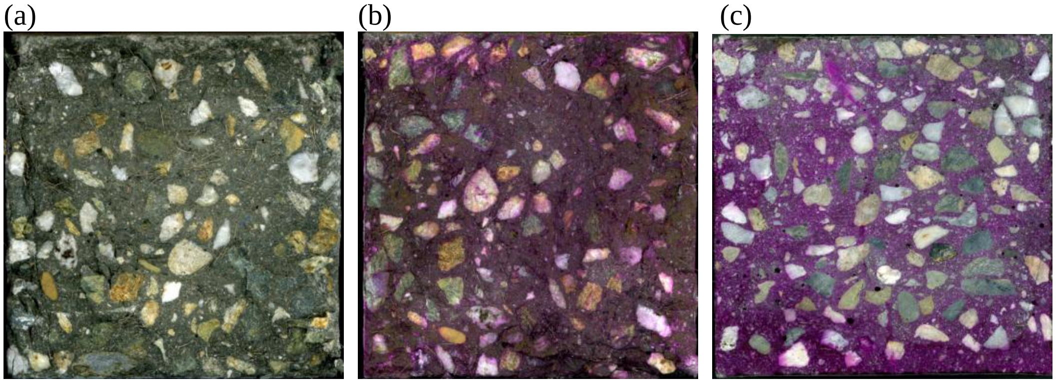

Figure 5. Carbonation tests: before (a) and after testing(b-c)

The total porosity (Mercury intrusion porosimetry) was 4874 mm^3/g, the cumulative and the relative volume are reported in Fig.6 and 7 respectively.

It can be observed that the pores are uniformly distributed and that the most of them has a very small size (radius less than 10nm). Therefore, as determined through porosimetry an insignificant effect on porosity and pore size distribution of concrete was noticed in the aged concrete.

The porosity measured in 1999 was about 9.25%. and for the aged concrete 11.85 %. Therefore the porosity variation is not significant and could be attributed to drying phenomena and hydration developed in the last 10 years in the naturally weathered specimens.

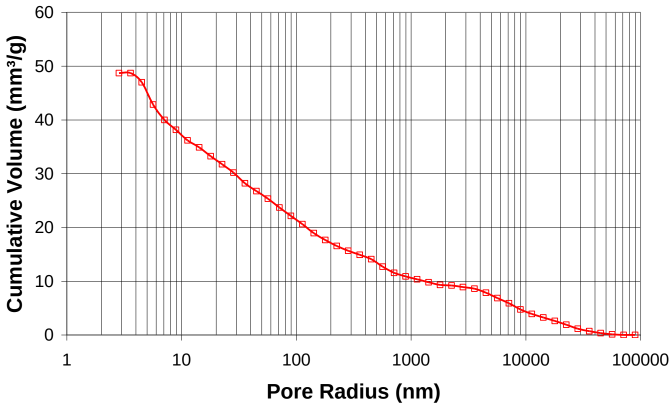

Figure 6. Cumulative volume

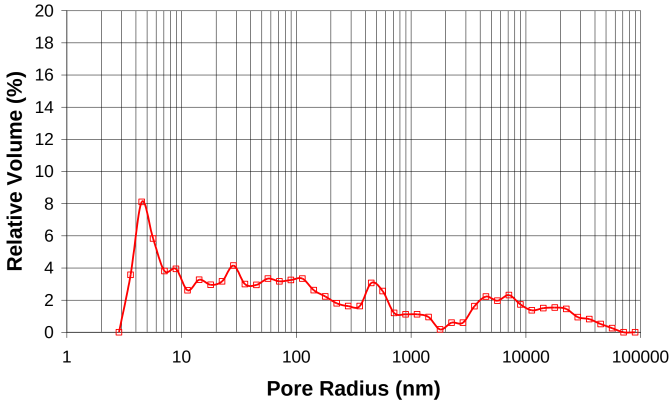

Figure 7. Relative volume

In situ inspection

The in situ inspection involved visual survey, ultrasonic pulse velocity method and the carbonation tests. The visual inspection of the bottom of the bridge revealed the total absence of visible cracks, spalling, reinforcement corrosion or defects of the concrete surface. The bridge deck appears as it was placed (Fig.8).

Since the laboratory tests on specimens did not show carbonation, the test was repeated on the bridge. A very small piece (thickness of about 2mm) of concrete was removed from a lateral member of the deck. In addition to this, a larger piece (thickness of about 5mm) of concrete was removed from the concrete jersey barrier (installed just after the bridge deck). Both parts were treated with a phenolphthalein indicator. The HPC bridge did not show any carbonation since a purple-red coloration appeared after few seconds (Fig.9 left), while the concrete jersey barrier (made with normal concrete) carbonated, since no coloration appeared (Fig. 9 right).

Finally, the ultrasonic pulse velocity method was applied to evaluate the presence of voids, cracks or other imperfections and changes in the material which may have occurred in time due to freze-thaw or chemical attacks. The velocity measured on different path lengths remained always almost constant denoting uniformity of the concrete. The obtained results were similar to the 1999's measurements. This suggests that the mechanical properties were unaffected.

Figure 8. Bridge

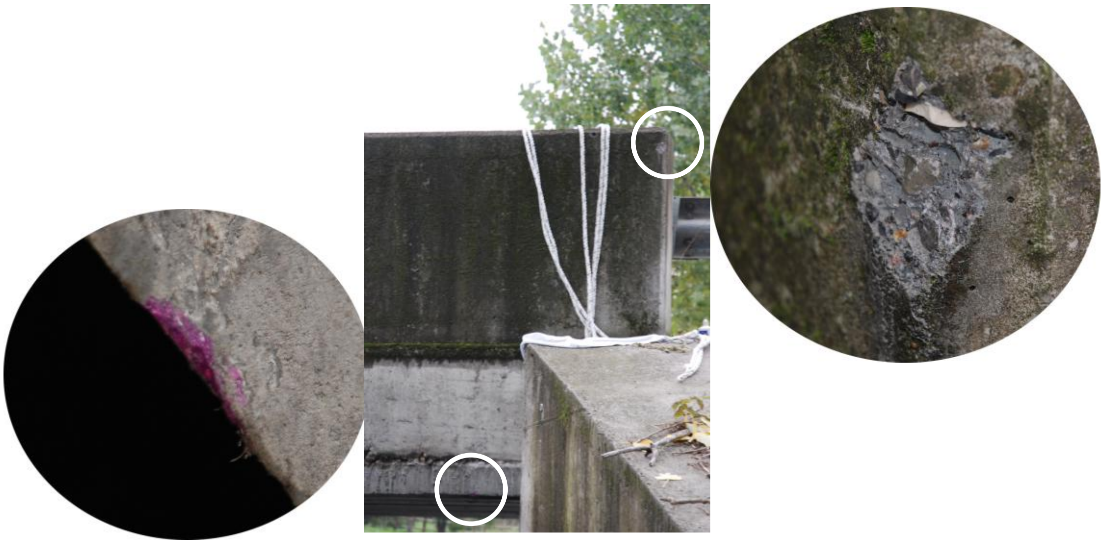

Figure 9. Carbonation tests

DISCUSSION

A significant improvement of the mechanical properties of the aged concrete has been observed.

A compressive and a bending strength increase of about 20% was observed. In terms of post-failure behavior, an increase of the specific fracture energy was also detected, revealing the less brittle nature of the material.

Regarding the durability issues, the porosity and the carbonation tests revealed a positive aging effect on the microstructure of the material. The porosity slightly increased and the pore structure was characterized by a uniform distribution with very small pore diameter.
The carbonation did not take place, neither on the specimens nor on the bridge deck. The direct comparison of carbonation between normal concrete (of the jersey barrier) and HPC, of the same age and subjected to identical weathering conditions was very significant. In fact, the first one revealed carbonation, while the second one appeared unaffected by this phenomenon.

These material properties turned out in an excellent structural behavior. Indeed, the visual survey revealed a total absence of cracks or surface defects, according to UPV results.
These performance could be explained, among others reasons, by the presence of microsilica in the mix [ACI 2006].

This component is a highly reactive pozzolan. In hydrating the cement paste, silica fume will react with CH to form calcium-silicate hydrate (CSH). Several studies [Ono et al. 1985, Malotra 1987] have shown that the dosage of silica fume has a significant effect on the amount of CH present after various periods of hydration. The results show that for low water/cement ratios (about 0.23) a 10% of silica fume in the cement paste reduced CH by 50% at 28 days. No further data for older concretes are available.

Regarding the compressive strength issue, controversial results can be found in literature [ACI 2006]. The obtained results are in line with ACI Committee's view of the strength non-regression of silica fume concrete. However, evidence of a significant increase in strength is not reported in literature, probably because of the young age of the tested materials. The time horizon of this research suggests that microsilica could be crucial for the development of materials with very high performance both in terms of strength and durability.

CONCLUSIONS

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

1. The laboratory tests and the visual survey showed that the investigated material is characterized by excellent durability.
2. The porosity and pore system characteristics of the concrete obtained through MIP results did not show any degradation that could have an effect on the mechanical properties. Porosity, as measured by mercury intrusion, varied from 9.25 to 11.85 %.
3. Cracks, spalling, varying colour or texture and visible surface damage, were not identified from the visual survey of the structure.
4. The UPV results confirmed always an excellent homogeneity of the concrete, and absence of cracks or other imperfections.
5. The carbonation tests with phenolphthalein indicator showed that the concrete of the bridge beams was not carbonated; conversely, concrete jersey barriers, made of normal concrete, were clearly carbonated.
6. A noteworthy increase of the bending and compressive strengths in the aged concrete has been observed. An increase of about 20% was assessed. In term of post-failure behavior, an increase of the specific fracture energy was also detected, revealing a less brittle nature of the material.

REFERENCES

ACI 234R-06 (2006). “Guide for the use of silica-fume in concrete”, *American Concrete Institute*, 63 pages.

Aitcin, P. C. (1998). “High Performance Concrete”, F & FN Spon, New York.

Biolzi L., Guerrini G.L., Rosati G. (1999). “Frost durability of very high performance cement-based materials”, *ASCE J of Materials in Civil Engineering*, 11 (2), 167-170.

Cattaneo S. (2000). “Ultra high-performance concrete: constitutive behavior and structural applications”, *Ph.D. Thesis, Politecnico di Milano*, 185 pages.

EN 12390-3 (2003). “Testing hardened concrete - Compressive strength of test specimens”, 19 pages.

EN 12390-5 (2002). “Testing hardened concrete - Flexural strength of test specimens”, 12 pages.

EN 12504-4 (2005). “Testing concrete Part 4: Determination of ultrasonic pulse velocity”, 16 pages.

EN 206-1 (2006). “Concrete - Part 1: Specification, performance, production and conformity”,71 pages.

Malhotra, V. M., Painter, K. M., and Bilodeau, A. (1987), “Mechanical Properties and Freezing and Thawing Resistance of High-Strength Concrete Incorporating Silica Fume.”, *Cement, Concrete, and Aggregates*, 9(2), 65-79.

Mehta, P. K., and Monteiro P. J. M. (2006). “Concrete: Microstructure, Properties, and Materials,” 3rd edition, McGraw-Hill.

Naik, T. R. (2008). “Sustainability of Concrete Construction” *ASCE Practice Periodical on Structural Design and Construction*, 13(2), 98-103.

Ono, K., Asaga, K., and Daimon, M. (1985). “Hydration in the System of Cement and Silica Fume.”, *Cement Association of Japan, Review of the 39th General Meeting—Technical Session*, Tokyo, 40-43.