



Improvement of historic reinforced concrete/mortars by impregnation and electrochemical methods



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ABSTRACT

Old reinforced concrete (RC) structures often exhibit unsatisfactory performances in terms of both residual serviceability and seismic behavior. The durability requirements were not considered at all at the age of design and construction, exposing such structures to severe decay in aggressive urban and/or industrial environment; in the meantime, the use of plain steel bars (with poor bond strength) was common at the age of construction and this jeopardizes the RC performance under cyclic load reversals like those induced by earthquakes.

In this paper, the deep impregnation of cement-based mortars and concrete with a solution of ethyl silicate and with electrochemical treatments by means of a solution of sodium carbonate was investigated, with a twofold aim: (1) increasing the bond strength of the embedded plain steel bars in existing structures without any need for demolition and (2) increasing the durability and safety of the reinforced concrete elements. Both the treatments are already exploited in other fields: ethyl silicate solutions are widely used for stone consolidation (and only recently proposed for concrete surface protection), while migration of sodium carbonate under DC voltage is used for RC realkalization.

In the present study these treatments are expected to penetrate inside mortar and concrete and to modify their microstructure, hence improving their properties. The effects of the treatments are investigated by comparing the characteristics of treated and untreated mortar and concrete samples reinforced with plain bars, in terms of penetration inside the samples, pull-out strength, water absorption, pore size distribution, carbonation resistance and corrosion resistance.

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1. Introduction and research aims

Old reinforced concrete (RC) structures are abundant in the European building stock. In these structures, built approximately between late Nineteenth Century and the Second World War, reinforced concrete was often left in fairfaced condition and exhibited as a symbolic material, firstly due to the excitement for the invention of this new and outstanding material [1] and secondly due to the influence of modern architecture principles [2], such as in the Rationalism current (early – mid XX century). However, fairfaced RC structures built in the first half of the Twentieth century may exhibit two critical issues: (1) an unsatisfactory behavior under seismic actions, due to the presence of plain reinforcing bars and

poor seismic reinforcing details; (2) a scarce performance in terms of durability.

The first issue was discussed in the literature and the vulnerability of these structures to earthquakes was assessed [3–7], with particular reference to the unsatisfactory bond strength between steel reinforcement and concrete. As a matter of fact, the adhesion between reinforcement and concrete is a complex issue and multiple mechanisms were found out to be responsible for the bond strength [8–10]: physical, gear and frictional components were observed by means of pull-out tests. In plain bars, the bond stress is transferred by adhesion between concrete and reinforcing bars before slip occurs and by wedging action of small particles that break free from the concrete upon slip [11] and not by mechanical interlock as in ribbed bars.

The second issue, i.e. the lack of durability affecting old RC structures, is quite understandable, as the mechanisms of degradation of reinforced concrete (corrosion by carbonation, chloride attack, etc.) were still largely unknown at the age of construction and no particular care was given to parameters as the water to

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cement ratio and the thickness of the concrete cover layer, which are now considered basic for the achievement of a satisfactory durability of RC structures [12,13]. Moreover, these structures have often passed through a long exposure to urban or industrial polluted environment, thus losing their integrity and/or ability to further resist to environmental aggressions (*residual serviceability*) [14].

Considering these problems in old RC structures, the development of non-destructive treatments able to jointly improve the concrete/steel adhesion and the residual serviceability of these structures appears of great practical interest. The main purpose of this study is to develop some deep impregnation treatments allowing a twofold improvement of: (1) the bond strength in reinforced concrete structural elements, without any need of partially demolishing the existing structure, (2) the residual serviceability of such structures.

For this purpose, in the present paper, two kinds of treatments borrowed from different fields were applied to reinforced mortar and concrete samples:

(i) Impregnation with ethyl silicate.

Solutions of ethyl silicate in organic solvent are widely used for stone consolidation in cultural heritage conservation [15,16], as they provide a good penetration depth and a good compatibility with stone, as well as the absence of pore blocking effect. Ethyl silicate has been only recently tested for concrete surface protection with encouraging results [17,18], but its penetration depth, its distribution inside concrete pores and its implication on bars bond strength and corrosion resistance were not investigated yet.

(ii) Electrochemical treatments usually proposed for concrete realkalization.

The electrochemical treatment that was applied in this study is based on the migration of sodium carbonate under a controlled DC current application between the bar and an external metallic anode. This is one of the methods used for the realkalization of reinforced concrete [14,19,20].

Both treatments are expected to penetrate inside the samples and to cause the deposition of solid materials inside the pores, thus causing a partial pore filling, beneficial for both bond strength and durability. The effects of these treatments in reinforced mortar and concrete samples were evaluated in terms of distribution of the impregnating materials inside the samples, modification in microstructure, pull-out test behavior, carbonation and corrosion resistance.

2. Materials and methods

2.1. Materials and samples preparation

Three different series were prepared: two mortars (“Mortar 1” and “Mortar 2”) and one concrete (“Concrete 1”), whose mix proportions are reported in Table 1.

As the aim of the paper is investigating the effects of the proposed treatments on old reinforced concrete, Mortar 1 was prepared in order to somehow simulate the characteristics of

cement-based materials in the first half of XX Cent. After an initial phase when ‘early cements’, differently named in European countries (e.g. Roman cements, slow-setting and quick-setting natural cements, etc. [21–23]), were used mainly for façade decorations and architectural details, structural concrete was usually manufactured with Portland cement with moderate compressive strength and with no particular care to water to cement ratio. For this reason, an ordinary Portland cement CEM I 32.5, a high w/c ratio (0.65) and EN 196-1 quartz sand ($\Phi < 2$ mm) [24] were selected for Mortar 1 manufacturing. Conversely, Mortar 2 was prepared with CEM I 42.5, quartz sand ($\Phi < 2$ mm) and tap water (w/c ratio 0.65) and is expected to represent a material with higher strength and more difficult to treat by impregnation (also due to a lower cement paste fraction). Concrete 1 was prepared with CEM I 42.5, quartz sand ($\Phi < 4$ mm), gravel (4–16 mm) and tap water (w/c ratio 0.55).

Mortars 1 and 2 were prepared in a Hobart mixer, according to the procedure in EN 196-1, and Concrete 1 in a 250 l concrete mixer. After mixing, they were immediately poured into molds as shown in Fig. 1, where Φ 10 mm hot-rolled plain steel bars (yield strength 420 N/mm², ultimate strength 500 N/mm²) had been positioned. Compaction was performed with a steel bar repeatedly dipped into the fresh mixtures. No demolding agent was used, to avoid altering the external surface of hardened samples in view of the treatments.

The sizes of the samples (see Fig. 1) were selected to both allow the pull-out test and to simulate the typical cover thickness of historical reinforced concrete structures. A slightly larger mold was used for Mortar 2 and Concrete 1 (48 mm in diameter instead of 43 mm) respectively to simulate a thicker cover zone and to allow the concrete to better fill the molds. The samples were demolded after 24 h and cured under room conditions up to 28 days.

Prismatic samples of mortars ($4 \times 4 \times 16$ cm³) and cubic samples of concrete ($15 \times 15 \times 15$ cm³) were also casted with the same mixtures, for the compressive strength tests.

2.2. Treatments

2.2.1. Ethyl silicate

After curing, the samples were treated with ethyl silicate (Estel 1000, CTS, Italy; 75 wt.% ethyl silicate with dibutyltin dilaurate as catalyst, 25 wt.% white spirit) by brushing and by immersion. Brushing application was prolonged up to apparent refusal. Immersion in ethyl silicate lasted 6 h, the upper 5 mm of the samples being left not immersed to allow air to exit from the samples.

2.2.2. Electrochemical treatment with sodium carbonate solution

Electrochemical treatment was carried out according to the scheme presented in Fig. 2, by an Amel Instrument Model 7050 Potentiostat/Galvanostat and an Autolab PGSTAT10 Potentiostat/Galvanostat (controlled by the GPES software, EcoChemie, Netherland). A 1 M Na₂CO₃ (sodium carbonate) aqueous solution was used for the treatments, applying different current densities and testing times, as reported in Table 2. The samples had been left partially immersed in the sodium carbonate solution, as shown in Fig. 2, for 3 h before the application of the current.

Table 1
Mix proportions of the mortars and concrete.

Mix	Cement type	Cement	Sand	Gravel	Water	w/c ratio
Mortar 1	CEM I 32.5	500 g	1370 g	–	325 g	0.65
Mortar 2	CEM I 42.5	500 g	1540 g	–	325 g	0.65
Concrete 1	CEM I 42.5	360 kg/m ³	1260 kg/m ³	660 kg/m ³	198 kg/m ³	0.55

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