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Experimental Durability Analysis of Historical Ferrocement

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Abstract. The paper presents the results of a recent testing campaign carried out on the ferrocement elements built by Pier Luigi Nervi in the structures of Torino Esposizioni. These pavilions, built between 1947-1953, allowed Nervi to apply for the first time in a large structure his advances in the use of ferrocement in civil construction that he had pioneered during the war. The results obtained by Nervi were patented immediately after the end of the construction site and would have characterized Nervi's technique for his whole career. Before Nervi's civil applications, ferrocement was mainly used to build boats. The material is characterized by the multiple layers of mesh or fine rods completely impregnated with cement mortar, which Nervi noted could be applied to build slabs and roofing elements by using a very low amount of material. Considering the historical value of the structures and since the ferrocement elements are extremely thin, to investigate the durability of this material, small-scale ferrocement mockups were built in the laboratory, starting from a small sample collected on-site.

A detailed testing program was developed, which included applying different treatments to the specimens before subjecting the samples to an accelerated weathering procedure to test the effects of each (mixed-in corrosion inhibitor, surface-applied inhibitor, etc.). The analysis of the ferrocement developed by Nervi in his constructions is a mandatory step for evaluating the health state of these elements and will help define the guidelines for their conservation. Moreover, it will help to expand the knowledge of Nervi's system.

Keywords: Ferrocement, Durability, Corrosion, Corrosion Potential, Structural assessment, Cementitious composites.

1 Introduction

As highlighted by the many international organization and experts [1], [2], concrete heritage of the 19th-20th centuries in the world is at risk. It is usually poorly understood and poorly maintained. As a result, it is often left to deteriorate until it is seen as expendable and is demolished.

In its history as a construction material, concrete allowed for the creation of massive civil engineering projects characterized by unprecedented innovative technical and spatial solutions. In the late 19th century concrete was even regarded as an eternal material. However, despite its many wonderful properties, it soon began to show its weaknesses that, in extreme cases, led even to collapses. Its performance over time revealed intrinsic fragilities that, if neglected, can threaten its long term historic, structural, and aesthetic integrity. Therefore, conservation and repair methods for concrete heritage merits specific attention.

Among the different fragilities affecting this heritage, one regards durability issues. Constructions in reinforced concrete have shown a marked vulnerability to aggressive environmental actions, mainly by carbon dioxide in the atmosphere, chlorides, and sulfates in water and soil. These vulnerabilities lead to material degradation often worsened by errors in design of construction details, lack of maintenance of exposed concrete surfaces, and errors in the construction phase. These fragilities were emphasized by the experimental nature of numerous innovative structural and technological configurations adopted by the designers of the time.

Ferrocement was one of the many experimentations in the construction history of the time. Introduced by J. L. Lambot who patented it in France as "*ferciment*" in 1855, it can be considered the first patent on reinforced concrete (Monier patent dates 1867)[3]. It was usually employed to build hulls, silos, tanks, and roofs. Pier Luigi Nervi was one of the first designers to recognize the possible advantages of ferrocement not only for boats but also for civil structures applications [4].

According to the ACI committee 549, ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh [5]–[7]. Ferrocement has a very high tensile strength-to-weight ratio and superior cracking behavior compared to conventional reinforced concrete.

Pier Luigi Nervi started to experiment with the material in 1943. It was during that year that Nervi definitively improved the technical and physical characteristics of ferrocement, as it was used during the 20th century, and removed any

wooden formwork from the manufacturing process [8]. Therefore, by changing the percentage of cement and the amount of reinforcement in the chosen element, Nervi developed a new material that could not only overcome the shortcomings of materials waste, but also enhance the construction field by offering a light, user-friendly, low-cost material. His experiments on boats and small-scale buildings (such as the shed in via della Magliana), culminated with a patent in 1944 (Patent 429331 registered in September 1944)[9]. By using ferrocement it was possible to manufacture very thin slabs of only a few centimeters, which were very ductile, elastic and crack-resistant, and not only possessed an impressive lightness that ensured easy transportation and installation, but also allowed shapes to be made in any desired configuration.

But it was in the Torino Esposizioni pavilions, built between 1947 and 1953, that Nervi had the occasion to apply his advances in the use of ferrocement in civil construction for the first time in a large structure. The pavilions in Torino Esposizioni are better described in [10]–[12], presents a large number of technological innovations and structural solutions. At the time of their construction, they consecrated Nervi as one of the most famous and innovative designers of the world, and his legacy today is still admired and studied.

In both pavilions, ferrocement is used in different forms and solutions, that were also patented in those years: such as the waved ashlars (Patent n. 445781 registered in August 1948), and curved and undulated slabs, called “tavelloni” (Patent n. 465636 registered on 19 May 1950).

Recently both halls, which have been abandoned for a long period, apart sporadic and temporary use, have been the object of a thorough investigation campaign in order to outline the best conservation strategies [13], [14].

Today, the ferrocement at Turin Exhibition Halls has reached an age where professionals are faced with preservation issues and questions regarding its conservation: How to conserve ferrocement? Given its lightweight and fragile nature, ferrocement elements pose difficult questions to its conservation. Replacement in kind is not the first-choice professionals should take. Ferrocement elements are primarily affected by its thin section which provides limited cover to the metal layers within the element. Corrosion induced by carbonation is the most common deterioration mechanism that affects ferrocement element as observed during the field work at the Turin Exhibition halls.

Considering the historical value of the structures and since the ferrocement elements are extremely thin, to investigate the durability of this material, small-scale ferrocement mock-ups were built in the laboratory, starting from a small sample collected on-site. Then, the specimens were subjected to an accelerated corrosion procedure to test the effects of different treatments solution for protecting the material from corrosion (mixed-in corrosion inhibitor, surface-applied inhibitor).

The objective of this paper is to show the experimentation campaign carried out on ferrocement mock-ups replicating Nervi's ferrocement, evaluating the health state of these elements and develop guidelines and conservation protocols to preserve these unique elements.

2 Sample Construction Methodology

2.1 Material Analyses

To replicate Nervi’s ferrocement it was fundamental to study the patents and the writings authored by the designer [15], as well as identifying all the ferrocement elements in the halls and their differences. After these steps, a sample of ferrocement, of about 12x6 cm, was extracted from an undulated beam situated in the west area of Hall C (Fig. 1). The sample was used to determine the concrete composition and analyze the actual number of layers employed by Nervi, and the wire characteristics.

Cement matrix. For characterization purposes, the sample was grounded in a jaw crusher down to 2 mm and metallic fibers were manually removed. Chemical analysis was carried on using an X-ray fluorescence spectrometer (XRF Panalytical Axios Cement), allowing to obtain a semi-quantitative composition in terms of metallic oxides.

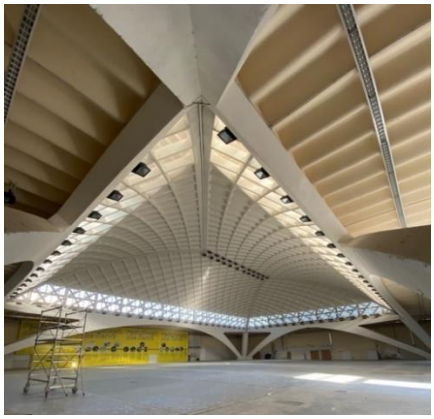
(a)  (b)  (c) 

Fig. 1. (a) View of the structures of Hall C. (b) scarification of the ferrocement element. (c) extracted ferrocement sample.

Mineralogical phases were evaluated by means of X-ray diffraction (XRD) using a Bruker D4 Endeavor instrument. Data treatment was performed using the TOPAS software based on the Rietveld method. For both XRF and XRD, the sample was milled and pressed in pellet using an automatic pelletizer. Chemical composition is summarized in Table 1: silicon, calcium, iron, and aluminum accounts for more than 75% of the overall composition of the sample.

Table 1. Chemical composition of the original material (*weight loss is determined calcining the sample at 950°C).

Element (oxide)	Amount (%)	Element (oxide)	Amount (%)
Weight loss*	17.72	TiO2	0.32
SiO2	41.28	P2O5	0.12
CaO	22.73	MnO	0.11
Fe2O3	6.30	BaO	0.09
Al2O3	6.14	SrO	0.06
MgO	2.23	Cr2O3	0.03
K2O	1.41	Cl	0.02
SO3	0.73	NiO	0.02
Na2O	0.66	CuO	0.02

Mineralogical analysis by X-ray diffraction is carried out, results are shown in Table 2.

Table 2. Mineralogical composition of the original material.

Phase name	Amount (%)
Portlandite	0.6
Calcite	18.4
Quartz	44.2
Anorthite	8.8
Albite	5.5
Microcline	7.8
Biotite	3.9
Montmorillonite	3.0
Chlorite	3.5
Kaolinite	4.3

Portlandite and, partially, calcite, can be ascribed to the binder component of the mortar, they are phases typically developed during the hydration of Portland cement. Quartz and feldspar (anorthite, albite and microcline) comes from the aggregates, namely sand and gravel. The presence of clay minerals (montmorillonite, chlorite, and kaolinite) suggests the addition of clay to the mortars to make it slightly sticky. As a matter of fact, according to the patent 429331, Nervi used to add fossil minerals or bentonite to the mortar to adjust its consistency.

The material suitable for the realization of mock-ups was prepared in the Buzzi Unicem mixing plant in Trino (VC). The product, chosen on the basis of the investigation above described, is a premixed mortar based on pozzolanic cement. The pozzolanic component (in replacement of bentonite) confers to the mortar a thixotropic consistence, making it suitable to be set and modelled around the metallic net, with 60 minutes of workability time. Typical performances are compressive strength higher than 10 MPa, 35 MPa and 45 MPa after 1, 7 and 28 days respectively; flexural strength higher than 4 MPa, 6 MPa and 8 MPa after 1, 7 and 28 days respectively; elastic module higher than 2 MPa after 28 days.

Metal Mesh. A visual analysis of the original metal wire mesh was the carried out. The sample was extracted at the roof of Hall C to verify the metal mesh configuration and type used by Nervi. The thickness of the ferrocement element was determined to be approximately 25 mm, in line with the original design. Each layer of metal mesh was carefully removed from the cement matrix by using a hammer, chisel and an electric abrasive (Fig 2a-b). After removal, all layers extracted were documented and catalogued as shown in Fig. 2c. The resulting steel meshes consist of interwoven steel wires spaced 1 cm apart. From this analysis the reinforcements for the mock-ups are chosen, smooth steel bars and woven meshes with 1mm diameter and 10x10 mm spacing are selected.

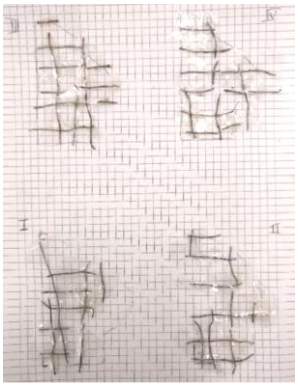
(a)  (b)  (c) 

Fig. 2. (a) Ferrocement sample. (b) Exposition of the wire layers from the ferrocement sample. (c) Ferrocement steel nets layers.

2.2 Construction of the Samples

The ferrocement samples have been realized following Pier Luigi Nervi's design and in accordance with ACI Standard PRC-549-18 [5][4]. In the end, a total of thirty samples were prepared to be treated and aged to study the durability and their performance (30x7.5x3 cm), each sample included seven layers of metal mesh 270x55 mm.

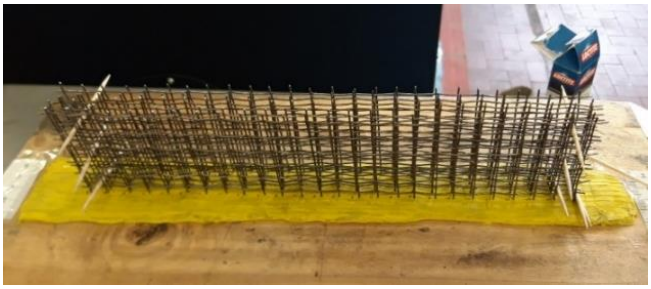
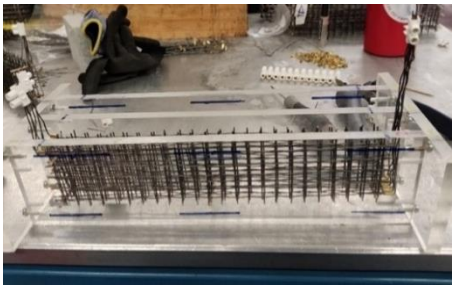
(a)  (b) 

Fig. 3. (a) Steel net positioning. (b) Plexiglass formwork and layered wires.

After placing the mesh layers, the electrical connections for the corrosion potential testing were prepared using a fasten terminal, allowing a stable electrical connection between each mesh layer to perform the electrochemical tests. A fasten is placed on each mesh from which a steel wire was connected on both short sides of the steel mesh package, bottom and top. Once the electrical connections are completed, the samples were then placed in a plexiglass formwork in preparation for casting.

The samples are poured in December 2021. Two different water/cement (w/c) ratios had been previously tested to achieve the best consistency for this application: WC 0.15 and 0.18.

All the samples were cast using w/c ratio equal to 0.18, which provided the best workability for this application. The following steps were taken for the pouring:

- The plexiglass formwork is assembled, and an Oil-Based Release Agents was applied to all the surface to prevent concrete to stick to the sides of the formwork.
- 1.458 kg of concrete mix powder is weighted and placed in the kneader machine's jar.
- 0.292 kg of water is added into the jar.
- The kneader machine is switched on at speed one (low speed) for 60 seconds, then at speed two (high speed) for other 30 seconds.
- When the concrete mix is ready to pour, half of the mix is placed in the formwork and compacted by handshaking and a hand electric vibration tool.
- The steel mesh package is inserted in the formwork and placed in position.
- The remaining part of the concrete mix is then poured in the formwork.
- The mix is again compacted by handshaking and a hand electric vibration tool.
- The samples are then covered with a plastic polyethylene covering and left for 24 h in a humidity-controlled room.
- The samples are left to cure for 28 days underwater, in a humidity-controlled environment for 28 days.

(a)  (b) 

Fig. 4. (a) Oil spreading operation on the formwork. (b) Samples underwater curing.

2.3 Treatments for Corrosion Inhibition

The samples are divided into seven series, each sample is identified in a unique way with the following code system, e.g., S1-SA-PA- 01, where:

- S1 is referred to the series number (S1, S2, S3, S4, S5, S6).
- SA is referred to the application of corrosion inhibitor on the sample (SA for surface applied, MI for mixed-in inhibitors).
- PA is referred to the application of painting on the sample (if written VF refers to the application of glass-based compound).
- 01 is referred to the sample number, the number 01 is always the control one.

A synthetic description of the treatments of each sample is provided in the following table.

Table 3. Samples treatments description.

Series	Sample ID	Treatment Type	Series	Sample ID	Treatment Type
S1	S1-MI-01	Aged with no treatment applied	S4	S4-SA-VF-01	Aged with no treatment applied
	S1-MI-02	Inhibitor Mixed-in (Aged)		S4-SA-VF-02	S.A. Inhibitor + Glass based comp. after 2H (Aged)
	S1-MI-03	Inhibitor Mixed-in (Aged)		S4-SA-VF-03	S.A. Inhibitor+ Glass based comp. after 2H (Aged)
	S1-MI-04	Inhibitor Mixed-in (Aged)	S5	S5-VF-01	Aged with no treatment applied
	S1-MI-05	Inhibitor Mixed-in (Aged)		S5-VF-02	Glass-based compound (Aged)
	S1-MI-06	Inhibitor Mixed-in (Aged)		S5-VF-03	Glass-based compound (Aged)
	S1-MI-07	Inhibitor Mixed-in (Aged)	S6	S6-M-01	No treatment and No ageing applied
S2	S2-SA-01	Aged with no treatment applied		S6-M-02	No treatment and No ageing applied
	S2-SA-02	S. A. Inhibitor (Aged) [2-layer application by brush]		S6-M-03	No treatment and No ageing applied
	S2-SA-03	S. A. Inhibitor (Aged) [2-layer application by brush]		S6-M-04	No treatment and No ageing applied
	S2-SA-04	S. A. Inhibitor (Aged) [2-layer application by brush]		S6-M-05	No treatment and No ageing applied
	S2-SA-05	S. A. Inhibitor (Aged) [3-layer application by brush]		S6-M-06	No treatment and No ageing applied
	S2-SA-06	S. A. Inhibitor (Aged) [2-layer application 1 by brush + 1 sprayed]			
	S2-SA-07	S. A. Inhibitor (Aged) [3 layer application by spray]			
S3	S3-PA-SA-01	Painted (Aged)			
	S3-PA-SA-02	Painted+S.A. Inhibitor (Aged)			
	S3-PA-SA-03	Painted+S.A. Inhibitor (Aged)			
	S3-PA-SA-04	Painted+S.A. Inhibitor (Aged)			

3 Aging and Monitoring

3.1 Aging Methodology

The S1, S2, S3, S4 and S5 samples were subjected to an accelerated weathering cycle of six months, to verify the effectiveness of the treatments in their durability. A solution with 3.5% NaCl solved in water is used to accelerate the corrosion process. The aging cycles run for a six-month period alternating wet and dry cycles as follows:

- Wet day: One day of salt spray, where the samples are sprayed continuously for a period of three hours.
- Dry day: the samples are drying in natural conditions.

The accelerated weathering was conducted in a chamber of 150x100x100 cm containing eight nozzles uniformly spaced located at the top. The platform, where the samples are displayed, is a steel plate placed at an angle of 15°. To prevent direct contact between the samples and the water running off, each sample will be lifted by using a 20 mm clay layer. The solution is sprayed from the eight nozzles, the solution is then collected by a water tank located underneath the table. The solution is then recirculated by using an electric surface pump with a 2-bar pressure.

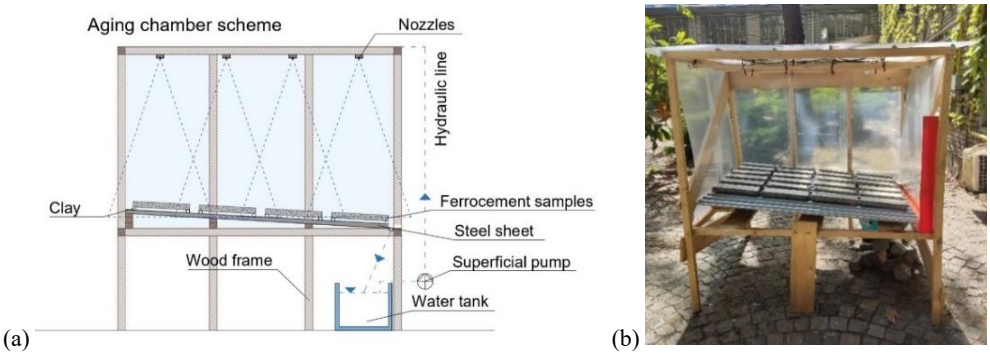


Fig. 5. (a) Aging chamber scheme. (b) Aging chamber with ferrocement samples.

3.2 Monitoring Corrosion Potential

Half-cell corrosion potential measurements are carried out with a Cu/Cu SO4 reference electrode (Fig. 6). Half-cell Corrosion potential is measured before starting the aging cycle, and every two weeks, during the aging process.

All the data collected are evaluated in accordance ASTM C876 Guidelines [16] for corrosion potential of reinforcement steel without cover in concrete.

The values are evaluated as follows:

- If corrosion potential is higher than -200 mV (with reference to Cu/CuSO4), the probability of corrosion activity of the steel reinforcement is less than 10%.
- If corrosion potential is between -200 and -350 mV (with reference to Cu/CuSO4), there is uncertain probability of the probability of corrosion activity of the steel reinforcement in the tested area.
- If corrosion potential is lower than -350 mV (with reference to Cu/CuSO4), the probability of corrosion activity of the steel reinforcement is higher than 90%.

Twenty-two measurements are collected based on a 25 mm equally spaced grid on the treated surface of the sample (Fig. 6b). Before performing the measurements, the treated surface is wetted by spraying water. It is important to highlight that since the aim of the study was to monitor changes in the corrosion potential, these values were taken as a mere qualitative indication, while more importance was given to the trends of the measurements.

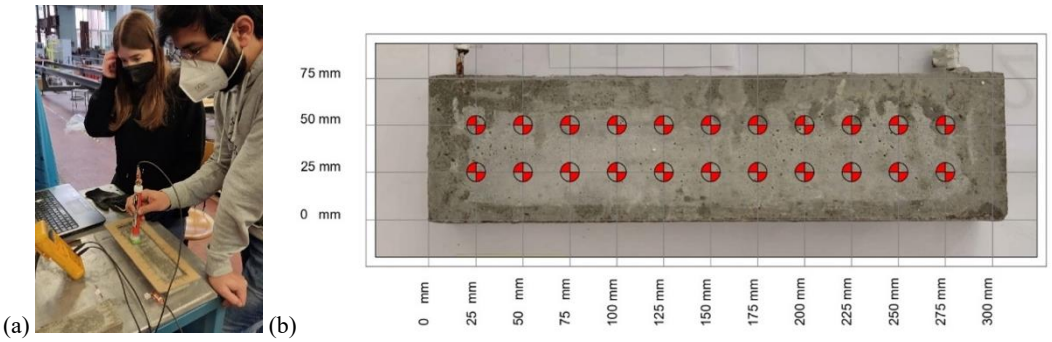


Fig. 6. (a) Corrosion potential measurement. (b) Corrosion potential measurements scheme.

4 Discussion of the Results

After six months of aging, all samples show evident deterioration on the surface (Table 4). For the analysis, it is important to notice that the focus must be pointed at the central part of the samples, as it is the more uniform area considering the aging conditions, the samples construction method, and the treatments applied to the samples. Some samples are considered more representative samples of the series among the thirty samples available (Table 4).

Sample S1_MI_02, presents some spots that show higher spreading of corrosion, and a large part of the sample surface results not largely corroded. In S2 SA 01, the untreated sample, corrosion spreads from some point by an important distribution. The upper part of the sample seen in the photo is better conserved. Sample S2_SA_02 is quite uniformly conserved, spots of corrosion are found is areas with higher porosity. In sample S2_SA_05, the corrosion is regularly distributed along the sample surface. Corrosion defects develops in area both with and without high porosity. In sample S3_SA_PA_02, a good conservation state is noticed. Corrosion effects are visible due to the contrast between rust color

and white painting, but defects are only limited to some of the local defects of the surface, even if the surface shows large pores. S4_SA_PA_02 sample, shows a reaction between the glass-based compound and the surface applied corrosion inhibitor, after this reaction on the sample surface a white layer has developed. The white layer was not washed out from the chloride solution sprayed on the sample during the aging. Corrosion in the sample is uniformly developed in different spots. Sample S5_VF_03 shows corrosion only on a lateral area of the sample, not in correspondence of superficial pores.

Table 4. Pictures of the samples before and after aging.

S1 MI 02	S2 SA 01	S2 SA 02	S2 SA 05	S3 SA PA 02	S4 SA PA 02	S5 VF 03
						
						

Fig. 6 shows the measurements of corrosion potential on the selected samples. In the first two weeks, a high shift of the corrosion potential is notices in the negative direction. The higher shift is noticed in samples with surface treatments applied on them.

The negative shift of the corrosion potential appears to remain stable showing results with less negative values (from June to end of the aging cycle). Sample S2_SA_02, shows low negativity values, compared to other samples. The most negative values of the corrosion potential are found in S1 MI 02, and S2 SA 01 sample, which are the samples without superficial treatments. Sample S2_SA_05, shows the most negative value only in one point of the monitoring, for the rest is just standing in the middle between superficially untreated samples and the S2_SA_02 one.

Samples S3_SA_PA_02, S4_SA_PA_02, and S5_VF_03 shows values of corrosion potential shifting from the second week (around -300 mv) up to the end of aging (-420 mv). The accelerated weathering process was concluded on 08/12/2022. After completing the aging cycles it can be noticed a general shift in all the series from values around -450 mv of the corrosion potential up to less negative values, between -420 mv and -300 mv.

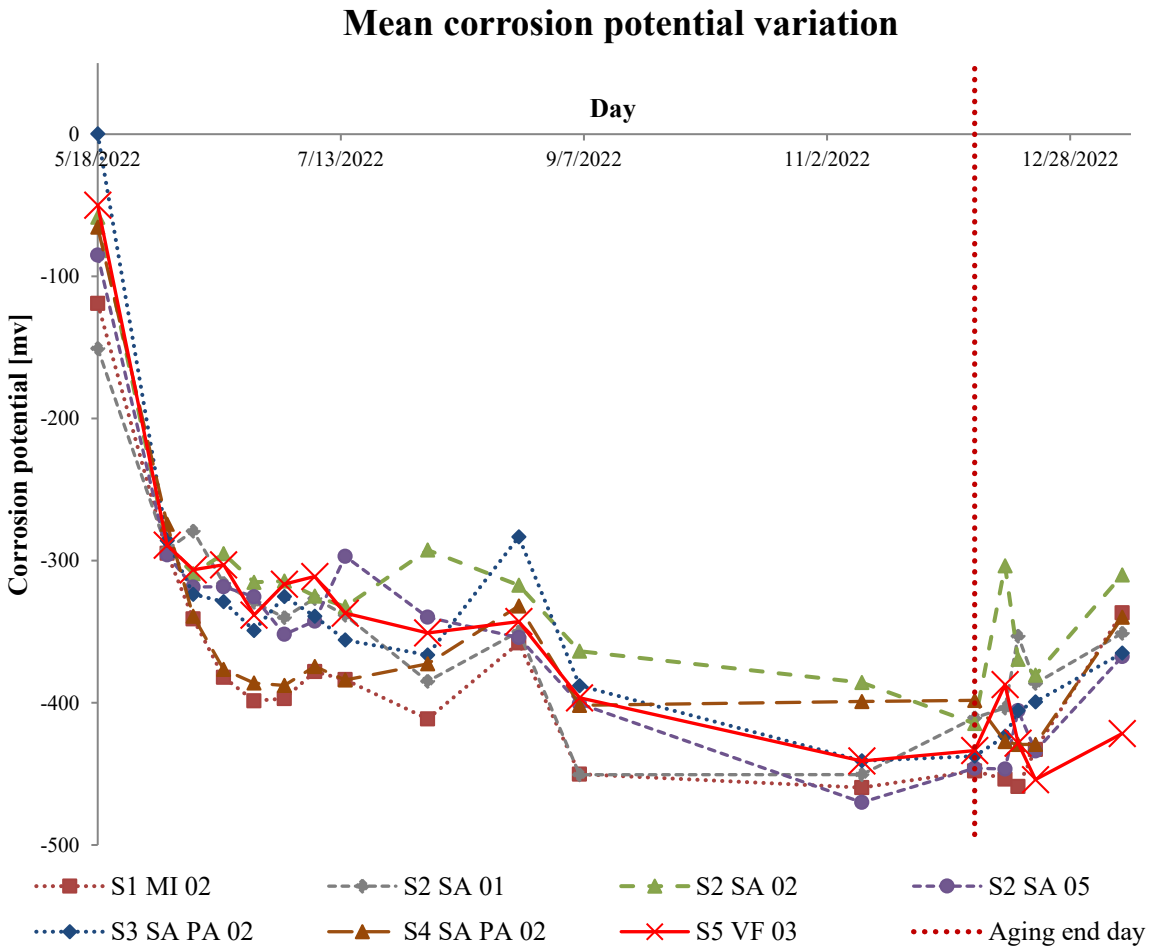


Fig. 7. Mean corrosion potential variation of the selected samples.

5 Conclusions

Samples shown high negative values of corrosion potential, especially after the beginning of the accelerated weathering process. The samples that showed more visible sign of corrosion where the samples that did not receive any treatment. Mixed-in corrosion inhibitors samples showed various types behavior in regards to corrosion: half of them has conserved in a quite good condition, while the other half showed sign of corrosion.

Surface applied corrosion inhibitor samples (S2) showed a good protection condition amongst all the samples of this series, except for one sample (S2_03). S3 (painted+surface applied inhibitor) samples generally showed the best behavior in terms of conservation of the concrete surface original conditions. Reactions between surface applied corrosion inhibitor and glass-based compound in the S4 treated samples generated an unspecified reaction, compromising the surface of these samples. Corrosion traces are clearly visible on samples surface. The series S5 (with a glass-based comp.) showed clear traces of corrosion on the surface at the end of the aging.

In all the cases corrosion in samples has not caused concrete disaggregation, but only superficial evidence of corrosion. Is important to consider that the monitored values concern only the most superficial part of the samples, deeper analysis can be developed by inspecting the samples sections.

After this initial research phase, migrating corrosion inhibitor, combined with painting, have the potential of being a viable solution for the conservation and preservation of ferrocement, a unique material that has become a character defining feature of Nervi's masterpieces. Further testing and research will be completed including in-situ testing. of the treatments will be the next step in this research. In addition, future work will explore the effects of the corrosion on the mechanical properties of ferrocement. After the ageing cycle, mock-ups will be tested by means of 4-point bending test to compare their performances.

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