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New Challenges in the Conservation of Fair-Faced Reinforced Concrete with Aesthetic Value: The Lessons from an Italian Brutalist Monument

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Abstract: The conservation of experimental building materials that were introduced during the 20th-century currently represents one of the main challenges in building restoration. Fair-faced concrete is especially affected by durability problems and requires careful assessment to implement effective conservation methods, even more so when the building has artistic and expressive value. In addition, the literature in this field is still limited and case studies are very rare. In this paper, the Partisan Ossuary Monument, a brutalist monument at the Certosa of Bologna, was studied and analysed in order to find the most effective restoration techniques, especially for its concretes, which have a particularly expressive texture. The aim was to combine both the preservation of the aesthetics and functional quality of the building with the use of existing technologies in this field. Firstly, archive research was carried out to discover the original building techniques and the materials used. The literature on the Monument was studied to unveil the expressive role given to the concretes' surface finishing. Then, after an on-site investigation, all the materials used in the Monument and the degradation processes were analysed and mapped out. Significant samples of the Monument were manually collected whilst limiting invasiveness. Then, diagnostic tests were carried out to identify the causes of degradation and to comprehend the nature of certain superficial finishes. Several techniques were used, i.e., X-ray diffraction, optical microscopy, and FT-IR spectrometry. Finally, guidelines were drafted for possible future restoration, merging all the results from the previous phases of this study with compliance with heritage structures' restoration requirements. Many technologies commonly used for the repair of concrete structures could not be applied to this Monument due to its features. Hence, new solutions were studied and proposed. The results obtained may contribute to an increased awareness of the need to restore 20th-century heritage buildings in order to limit degradation and partial reconstruction. Many concrete heritage buildings of this period suffer from the same problems, and this paper could offer an important starting point for future research.

Keywords: reinforced concrete; cultural heritage; conservation; surface treatments; ethyl silicate; cathodic protection; TiO_2

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1. Introduction

Reinforced concrete (RC) was probably the most iconic construction material in the 20th-century. As an experimental material with outstanding mechanical properties and incredible ease of application, it allowed for the creation of new structural shapes and forms of expression. However, until the seventies, RC was also considered to be everlasting, and the problem of durability was not considered at all in the design and construction phases, exposing the structures to environmental threats and decay [1]. In addition, after World War II, reinforced concrete was often left in a fair-faced condition, i.e., it was directly exposed to an outdoor environment, resulting in even more limited durability. Exposed concrete was used as an architectural material, and it became a fundamental part of the language of modernism [2]. The problem of the scarce durability of these concretes is now emerging as a new challenge, especially for those RC structures where concrete was provided with specific surface finishings to pursue some symbolic effect [3]. These RC structures may have strong artistic value, hence belonging to cultural heritage, but this heritage is presently at risk.

The fact that the repair of heritage RC structures is one of the biggest challenges of contemporary research is clearly asserted in the Madrid–New Delhi Document of 2017 [4], which considers new approaches and criteria as necessary, also taking into account possible new challenges deriving from climate change. The repair of heritage RC cannot rely on conventional techniques applied to common RC buildings which are based on the replacement of deteriorated concrete because strict requirements related to the preservation of the original materials and texture must be respected. Despite the growing acknowledgement and appreciation of modern heritage structures, the literature in this field and analysis of case studies are still extremely limited, and the problem of the maintenance and conservation of heritage RC has only recently come into the spotlight [5].

Two recent papers focused on techniques to reconstruct lost concrete. In the first paper, a new method to reconstruct the lost concrete with mortar patches which are designed case-by-case was presented [6]. The aim is to achieve chromatic texture and finishing compatibility between the repair mortar and the concrete surface. The new methodology that the authors describe was applied to Piscina das Mares in Portugal, an iconic construction of exposed concrete designed by Alvaro Siza. The second study investigated various kinds of mortars used to reprofile reinforced concrete slabs, with a focus on effectiveness and compatibility. The concrete floor slab under investigation was in "Casa del Fascio" in Predappio, Italy, a public building built in the 1930s [7]. Furthermore, there are two significant recent studies on treatments to be applied to heritage concretes. In the InnovaConcrete project, the use of impregnation treatments to strengthen concrete was studied [8]. In this project, multifunctional silane-based impregnation treatments that produce C-S-H gel were designed and validated on mock-up specimens from European heritage buildings. Another study tested a method used to protect concrete from rebar corrosion without affecting the shape and surface of a building [9], i.e., through the application of a cathodic protection system with localised anodes in Torre Velasca's façade in Milan.

One of the most fascinating challenges of the conservation of heritage RC structures is identifying which features of concrete are worth preserving, and which repair techniques are suitable and affordable. This challenge is common to many 20th-century buildings constructed with a variety of new materials, whose conservation is not only a matter of technology but also of approach [10]. To this aim, an assessment of the original characteristics and deterioration state of concrete is needed through historic analyses and onsite and laboratory tests. This approach is very common in ancient buildings, but it is seldom used for heritage RC structures, where just a limited range of diagnostic tests that are used for ordinary concrete are applied.

In this paper, the materials of a brutalist concrete monument were studied and characterised by procedures usually adopted for ancient buildings, to identify the most promising conservation strategies. The investigated monument is the Partisan Ossuary Monument at the Certosa cemetery in Bologna, Italy (Figure 1), which was built in 1954–1964 and is entirely made of fair-faced RC. The Monument is a fusion of artistical and technological values, being representative of the interdisciplinary approach followed by its designer, namely Piero Bottoni. Bottoni was an architect, city planner, and member of the Italian group of CIAMs (International Conferences of Modern Architecture). During his professional life, Bottoni designed several constructions in the Bologna area, such as Villa Muggia in Imola and the Riding Club in Bologna, besides the Partisan Ossuary Monument. He also contributed to the development of several City Plans for Bologna [11].

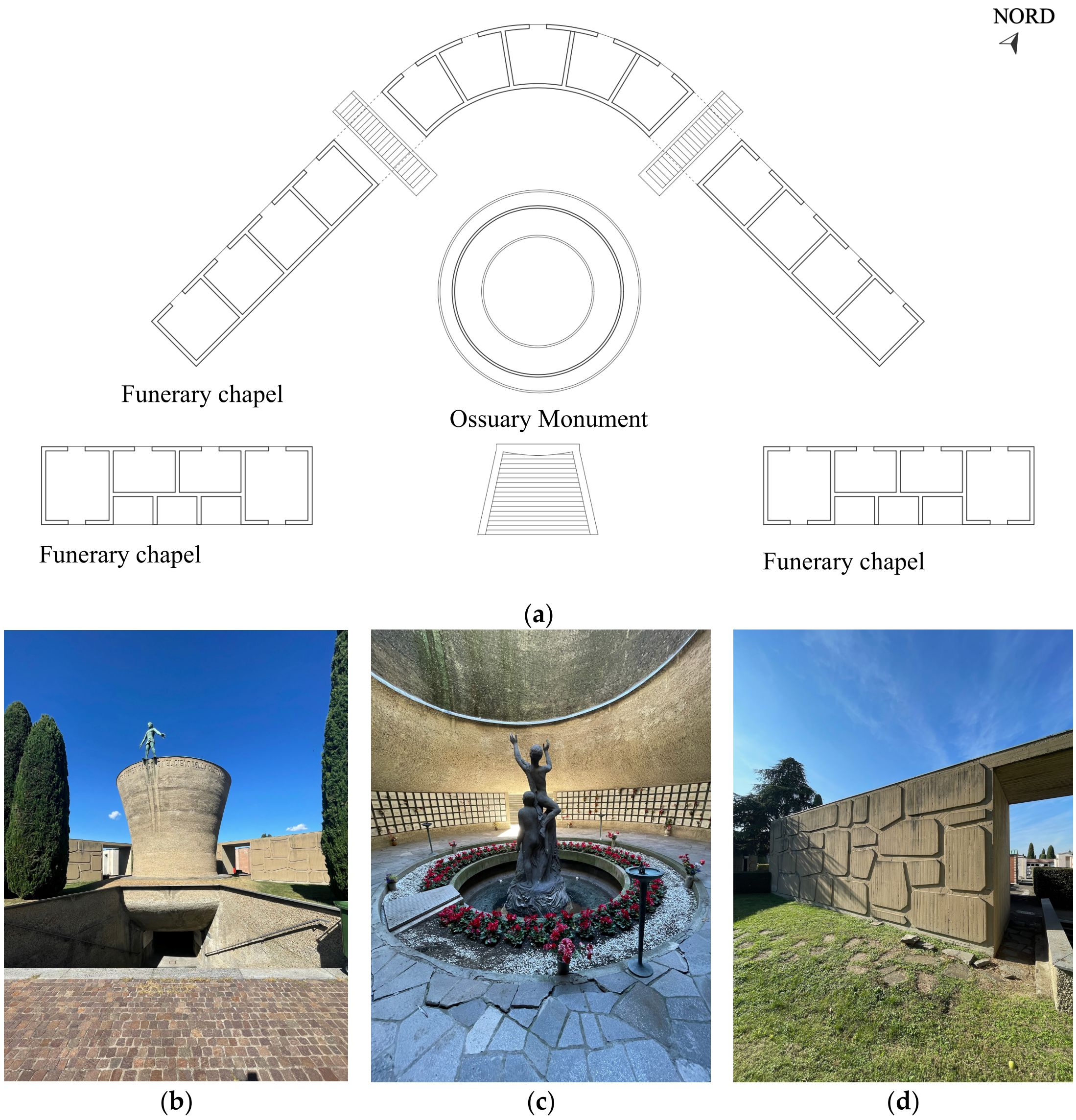


Figure 1. (**a**) Plan of the Partisan Ossuary Monument complex; (**b**) general view of the Monument, showing also the main stairs to the underground crypt (foreground) and the funeral chapels (background); (**c**) the underground crypt of the Ossuary Monument at the basis of the hyperbolic hyperboloid RC structure; (**d**) one of the three funeral chapels surrounding the Ossuary Monument.

The Partisan Ossuary Monument complex is formed by two elements (Figure 1a). The first one is the Ossuary Monument (Figure 1b), a hollow hyperbolic hyperboloid RC structure which contains the underground circular crypt with the ossuary and which is the pivotal point of the complex (Figure 1c). The second element is constituted by three prismatic funeral chapel buildings (Figure 1d), which surround the Monument and have the role of theatrical set. These structures and their brutalist surface somehow isolate the Monument from the surrounding cemetery area and have a strong impact on the visitor.

The Monument has not been listed as a heritage asset yet, as the Italian law D.lgs. n.42/2004 [12] prescribes that a monument can be considered heritage only 70 years after its construction. So, before 2029, it will be not possible to list the Monument as a cultural heritage asset. Nonetheless, the Monument is indeed to be treated as a heritage asset for two main reasons. First, the Monument is located inside the Monumental Cemetery of Certosa, which is listed as cultural heritage and has also been included in the UNESCO World Heritage Site since 2021. Secondly, the cultural, historical, aesthetical and technological values of the Monument (and its prospective listing as a cultural asset) are widely recognised by the local authorities and community, and in fact, the authority in charge imposed very restrictive limits to sampling, i.e., the same limits applied for heritage buildings.

No conservation works have been undertaken since the Monument was built. In 2001, a limited set of analyses was performed in the Monument by Fondazione Cesare Gnudi [13]. The analyses showed that a restoration intervention was already urgent, given the deteriorated state of reinforced concrete. In particular, the phenolphthalein test revealed a carbonation depth equal to 6 cm, involving favourable conditions for the bars' corrosion and the subsequent spalling of concrete, even where this damage was latent.

Given the significance of the Monument as a valuable example of an artistic fair-faced RC structure and the general challenges related to the conservation of heritage RC buildings, this study aims to accomplish the following:

- Assessing the present condition of the reinforced concrete's surfaces and their main degradation mechanisms;
- Suggesting appropriate and low-invasive repair solutions which are compatible with the conservation principles.

However, a solid understanding of the heritage significance of the building is necessary to propose a suitable repair and to conserve the architectural, cultural and symbolic values of the Monument. Hence, a cross-disciplinary approach was adopted and the study of historic records was carried out together with technical analyses.

2. The Monument and Its Deterioration

2.1. Description of the Monument

The Partisan Ossuary Monument is located within the Campo degli Ospedali of the Certosa cemetery in Bologna. The statues of the partisans standing out in the sky are the first items the visitor sees from a distance (Figures 1 and 2). The anchoring of these copper and bronze statues to the Ossuary Monument is ensured by a steel tube structure, which is welded to the statues, and special iron elements placed in concrete during casting. The silhouette of the statues emerges from the Monument, which is a rough, fair-faced, reinforced concrete structure having the shape of a hyperbolic hyperboloid. Along the top border of this structure, an inscription is located: LIBERI SALGONO NEL CIELO DELLA GLORIA (they rise free into the glory sky) (Figure 2a). The Monument is accessible through two narrow stairs leading to the underground sacrarium (Figure 2b). The stairs are characterised by the progressive variation in the ratio between the rise and the tread of the step, transforming, for those who enter, a rapid descent into an almost flat walk, and for those leaving, an easy ascent into a heavy climb. There is also a third stair that was conceived as a large exit to allow the outflow of large masses on festive occasions (Figure 1a). The width of this staircase increases ascending to the surface, thus inviting one to exit. The underground crypt is a circular space, directly surrounded by 500 burial cells with white Carrara marble tombstones. The crypt's ceiling is constituted by rough exposed concrete and has a minimum height of 2 m, ending in a circular opening of 11 m in diameter. Through this opening, those who are inside the crypt can see the sky (Figure 2c). On the crypt's floor, there is a central water pond bordered by a ring of flowerbeds, where a concrete sculpture is present. Inside the crypt, one can see all the statutes of the Monument. Starting from the bottom, these figures are more and more humanised and appear to the visitor lighter and more fluctuating going upwards: from the massive reinforced concrete statues at the bottom to the light feminine figure made with bronze, to the Partisans statues made with copper sheets at the top. The latter ones seem so light that they seem in the act of rising to the sky. In fact, all the statues were conceived as taken by an imaginary sucking whirlpool that starts from the water pond and rises towards the sky (Figure 2d).

(**a**) (**b**) (**c**) (**d**)

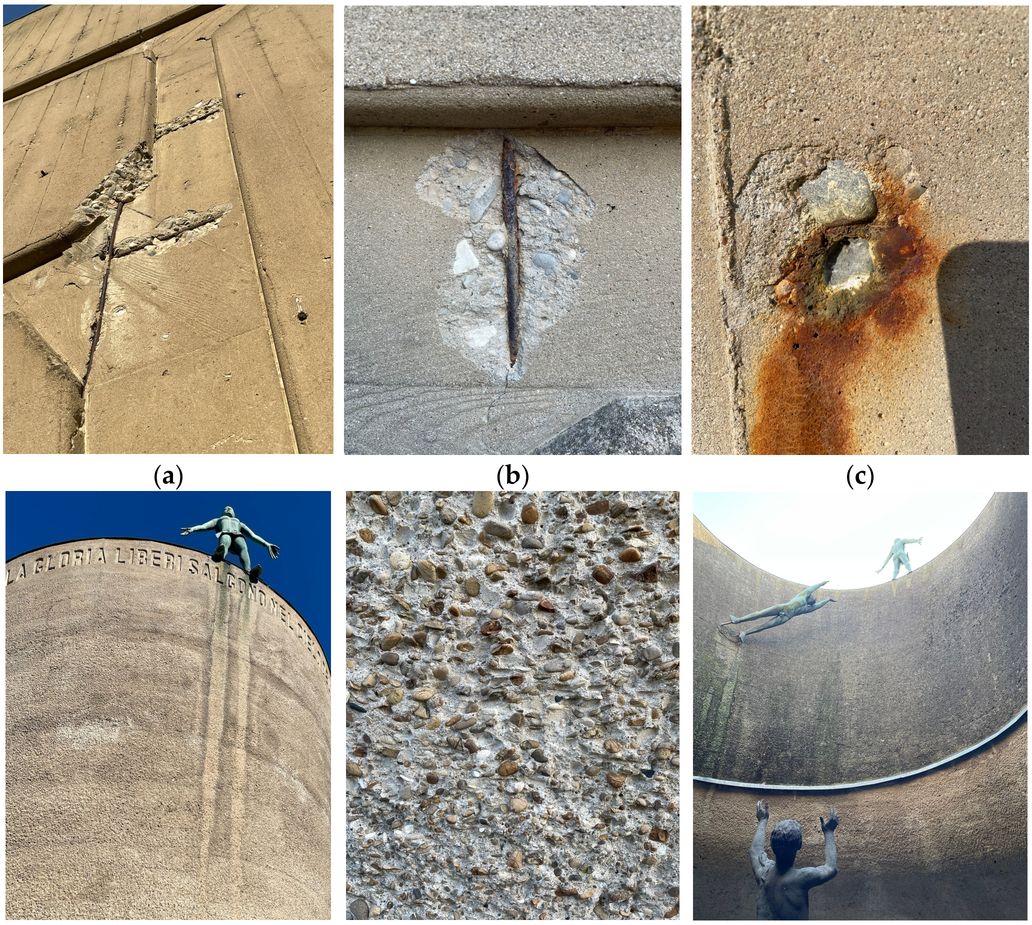
Figure 2. (**a**) The inscription along the top border of the Ossuary Monument; (**b**) one narrow stair to enter the crypt; (**c**) the sucking whirlpool formed by all the statues in the crypt; (**d**) one of the three funerary chapels with its entrances (elevation not facing the Ossuary Monument).

The Ossuary Monument is surrounded by three funerary chapels, which form a sort of semi-circular imposing wall around it, protecting the crypt. This wall is continuous, except for two portals which allow one to access the courtyard space and the stairs descending to the underground ossuary. The chapels are private family tombs accessible through doors located in façades that do not face the Ossuary Monument (Figure 2d).

2.2. Preliminary Visual Survey of Materials and Their Deterioration

A careful visual survey highlighted that the RC surfaces are affected by several problems, mostly related to carbonation, causing rust formation on rebars and concrete spalling (Figure 3). The following deterioration patterns were observed:

- Widespread material loss (Figure 3a);
- Corrosion of exposed steel reinforcements (Figure 3b);
- Ferruginous stains coming from the exposed reinforcement or possibly from reactive aggregates contained in concrete (Figure 3c);
- Copper and bronze salt stains on concrete resulting from the leaching of the copper/bronze statues (Figure 3d);
- Surface crumbling of concrete (Figure 3e);
- Biological colonisation of the concrete surface, with patinas' formation (Figure 3f);
- Yellowing of concrete surface in the chapels (Figure 3a).



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 3. (**a**) Material loss due to concrete spalling; (**b**) corrosion of the exposed rebars; (**c**) ferruginous stains; (**d**) copper salt stains. It is worth noting how no biological growth occurs on the concrete surface under the statues due to the biocidal action of these salts; (**e**) concrete crumbling; (**f**) biological colonisation (biological patinas) visible above the drip edge.

Furthermore, the decay was exacerbated by several defects ascribed to the construction phase, such as pieces of wood formworks left into concrete (Figure 4a), honeycombing (Figure 4b), cold joints (visible discontinuity between different concrete batches, as in Figure 4c), and insufficient thickness of the concrete cover, i.e., just 1 cm or even less (Figure 4d). These defects seem related to a low familiarity of workmanship with concrete used for artistic purposes.

(**a**) (**b**) (**c**) (**d**)

Figure 4. (**a**) An insert of wood left in concrete; (**b**) concrete with honeycomb defect; (**c**) cold joint; (**d**) thin concrete cover.

3. Materials and Methods

3.1. Archival Research

Archival research was carried out to collect information on the technologies used in the Monument and the vision and intentions of the architect. Differently from ancient buildings, the 20th-century ones can be often studied also through original photographs. For this Monument, many historical photos of the construction phases were found in the Piero Bottoni Archive (Dpa, Milan's Polytechnique). These photos, most of which were taken by the architect himself, are a significant source of information and were analysed for three main purposes: (I) collecting information about the original colour of the concrete in the funeral chapels [14] to assess if its yellowish colour is original or was due to some alteration; (II) understanding which stains and surface defects were already present at the construction time and which ones are due to deterioration [15–18]; (III) reconstructing the funeral chapels' construction timeline [19–21].

Moreover, original design drawings and specifications by the architect Piero Bottoni, a description of construction methods, and information on the materials used were found in the Bologna Historical Archive.

3.2. Samples

A mapping of materials and decay patterns was prepared through a preliminary visual inspection of the Monument, which allowed to make some first hypotheses on the possible degradation mechanisms. Then, significant samples were collected from the Ossuary Monument's and chapels' surfaces for laboratory characterisation. The sampling was manually performed, limiting the invasiveness and selecting areas where concrete was already partially detached. It is noteworthy that the sampling of concrete usually raises representativity concerns related to the presence of coarse aggregate and the need for large samples (e.g., cores should have a diameter larger than 3 times the maximum aggregate size according to EN 12504-1: 2021 [22]). Given the practical limitations posed by the public authority in charge of the Monument to large sample collection, the sampling of concrete aggregates and cement mortar fractions was carried out in a separate way, according to the purpose of the planned analyses. The samples are numbered and described in Table 1 and Figure 5.

Table 1. Sample description.

Sample Number	Description	Sampling Location
1, 2	fragments of the concrete cover	funeral chapels
3 (a, b)	concrete: (a) aggregates and (b) cement mortar fraction	external surface of the Ossuary Monument
4, 5, 6	white salt efflorescence	different areas of the underground crypt
7	concrete: cement mortar fraction	external surface of the West staircase that leads to the crypt

(**a**) (**b**) (**c**) (**d**)

Figure 5. Locations of samples' collection: (**a**) samples 1 and 2; (**b**) sample 3; (**c**) samples 4, 5, and 6; (**d**) sample 7.

3.3. Characterisation Techniques

Laboratory tests were conducted to address some key questions that are significant for the selection of suitable conservation technique:

- To assess if the rough surface of the Monument (Figure 6a,d) is due to an acid wash or to a chisel treatment, the latter described in the construction's records [23]. The idea that an acid wash was carried out to obtain a rough surface in concrete was suggested by Fondazione Cesare Gnudi [13]. If used, this treatment could have contributed to deterioration by the formation of harmful soluble salts. Therefore, samples 3b and 7 were analysed by ion chromatography in a Dionex ICS 1000 (Thermo Fisher Scientific, Waltham, MA, USA), after grinding, addition to boiling deionised water for 10 min under stirring and filtration.
- To investigate the cause of the ochre-yellow colour of the surface of the funeral chapels (Figure 6b,c), and to assess if it was originally prescribed by Bottoni (hence, possibly worthy of conservation) or is the result of some deterioration (hence, to be cleaned). Therefore, two cross-sections were prepared from samples 1 and 2 and observed in a stereoscopical optical microscope (SOM, SZX10, Olympus Corporation's Scientific Solutions, Center Valley, PA, USA). Samples 1 and 2 were also studied in terms of chemical-mineralogical composition by FT-IR spectrometry in a Nicolet Avatar 360 (Thermo Fisher Scientific, USA) equipped with ATR cells and by X-ray diffraction (XRD) in an Empyrean (Malvern Panalytical, United Kingdom) equipped with a CuKα tube operating at 40 kV and 30 mA, using a 2θ range from 4° to 80° and a step size of 0.026°. Both analyses were performed on dried powder (milled samples). The XRD analysis was chosen because the Monument under study is complex and was conceived by the architect as a work of art. For this reason, the composition of the concrete used was not obvious and needed to be investigated, differently from ordinary concrete structures where other characterisation techniques are currently applied.
- To investigate the nature of salt efflorescence on the surface of the crypt (Figure 6d), and to identify their origin and possible contribution to concrete deterioration. The presence of soluble salts in samples 4, 5 and 6 was investigated by ion chromatography, in a Dionex ICS 1000, after addition to boiling deionised water for 10 min under stirring and filtration.
- To investigate and quantify the porosity of the cement mortar fraction. Porosity is a key parameter used to evaluate the deterioration and vulnerability of concrete and to select compatible conservation solutions. Therefore, the water absorption of samples 1, 2, 3b,

and 7 was determined by the water absorption test (UNI 7699:2018 [24]) measuring the dry and saturated masses of the samples. To evaluate the saturated mass, the samples were immersed in deionised water first for half their volume and then submerged for 72 h.

- To evaluate the quality of the aggregates used in the concrete of the ossuary which are directly exposed to the external environment (Figure 5b) and which exhibit local cracks. Therefore, sample 3a was observed in a stereoscopical optical microscope (SOM) and it was also characterised in terms of chemical–mineralogical composition by X-ray diffraction (XRD) to detect the possible presence of undesirable products. It would be useful to study also the concrete mix, i.e., cement type and cement–aggregate ratio, but it could not be performed in this study because of limitations on sampling. An investigation of this issue could be carried out in the future, as no information on the concrete mix was found in the archival documents.

(**a**) (**b**) (**c**) (**d**)

Figure 6. (**a**) The rough surface of the Ossuary Monument; (**b**) the surface of the funerary chapels; (**c**) the yellow-grey colour of the chapels' surface; (**d**) salt efflorescence in the crypt.

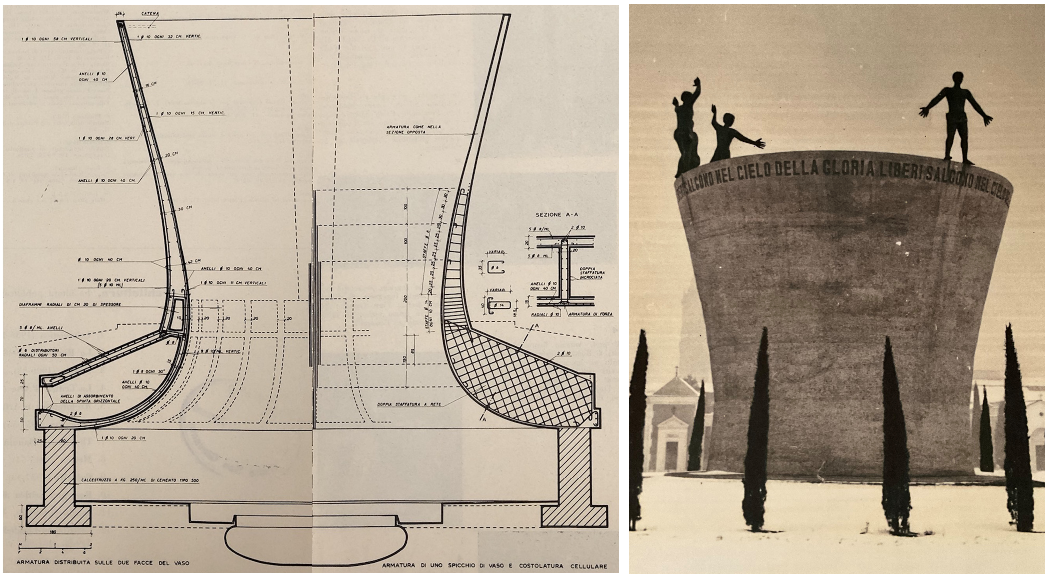
Given the fact that the Monument presently does not exhibit a deterioration pattern suggesting structural issues, and all the damage is owing to the material's deterioration by the environment, analyses on the material's strength were not performed in this study.

At the end of this articulated analysis of the building, conservation techniques were proposed, aiming at finding a compromise between the need to stop degradation and the preservation of the aesthetical value of the Monument's surfaces. The Monument analysed can be considered representative of the RC modern heritage; hence, the findings may contribute to the understanding and conservation of 20th-century RC heritage.

4. Results and Discussion

4.1. The Use of Fair-Faced Reinforced Concrete and the Building Techniques

The Ossuary Monument is a cast-in-place RC bold structure having a total height of 15.20 m, and its construction details are reported in the original executive structural project (Figure 7a) [25]. From this drawing, it is possible to observe that the thin concrete cover was not an error in the casting phase, as it was already reported in the project, demonstrating how low the sensitivity was about the concrete's durability. Moreover, the original documents revealed that after the removal of the formwork, the surfaces were manually chiselled to obtain a rough surface (Figures 6 and 7b) and bring to sight the coloured aggregates specifically required by Bottoni [23].



(**a**) (**b**)

Figure 7. (**a**) The executive project for the Ossuary Monument [25]; (**b**) photograph of the Ossuary Monument soon after its completion (notice the chiselled surface and some already present copper salt stains) [18].

The funerary chapels are cast-in-place RC structures too. The original drawings show how the formworks were manufactured to obtain the big ashlar motif which characterises the surface [26] (Figure 8). After the removal of the formwork, the surface texture was not modified and the prints of the wood veins and knots remained visible (Figure 8b), a feature which was recurrent in brutalist architecture [27]. According to the documents [23], the stylised ashlars of gigantic proportions were designed by Bottoni to make the chapels appear as mighty walls protecting the crypt. From the colour photography of the chapels taken when they had just been completed (Figure 8c) [14], it is not possible to say whether the concrete surfaces already had the yellowish colouring observed today because the original image suffered some chromatic alteration.

(**a**) (**b**) (**c**)

Figure 8. (**a**) Photograph of the funerary chapels during their construction showing the complex formwork [19]; (**b**) the surface texture of the chapels owing to the wooden formwork, as it is today; (**c**) colour photograph of the funerary chapels at the end of their construction [14].

The documents also revealed that the architect wanted the Ossuary Monument to be perceived as a place of experience [28], and indeed it is. The rough surfaces of the crypt constitute a background for the whirlpool of statues, which seem to move upwards and animate the crypt. First, the reinforced concrete group of sculptures at the centre of the crypt, which was designed by Bottoni, represents three bodies that extricate themselves upwards toward the light. Afterwards, the eye is caught by a bronze feminine figure and then by a copper masculine figure protruding upwards. At last, the eyes can free themselves and see the sky, which is the backdrop for a copper group of heroes. As the view goes up towards the sky, the sculptures become more and more humanised, as if emerging from the pit of death to recompose themselves in harmony with the living.

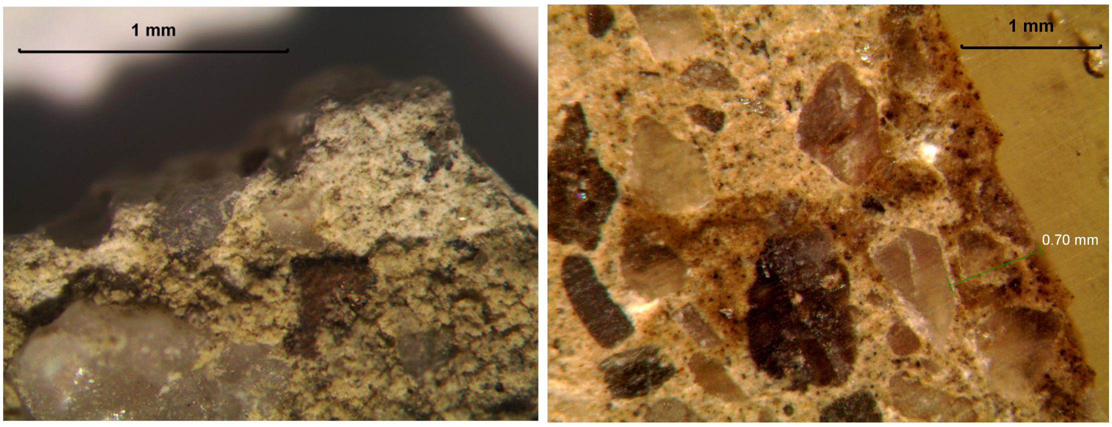
4.2. Laboratory Analyses of Samples

The results of the ion chromatography carried out on the cement mortar fragments from the external surface of the concrete in the Ossuary Monument (samples 3b and 7) are reported in Table 2. As the amounts of sulphate and chloride resulted very low, and that of nitrate negligible, it was concluded that the rough concrete surface was not obtained by acid washing, but rather by hammering with chisel. Hence, the damage to concrete did not derive from residual substances from acid treatment, but from physical–mechanical processes, such as portlandite leaching and frost damage. The amount of chloride ions, despite being low, was not negligible and is likely due to some contamination of the aggregates or water used in concrete manufacturing. The results in Table 2 were compared with the existing standards and available literature to assess if the amounts of ions can be considered non-damaging for concrete. Regarding chlorides, the critical chloride content is considered 0.4–1% of cement mass [29]. Assuming a bulk density of concrete equal to 2400 kg/m^3, a mass of aggregates in the mortar fraction equal to 900 kg/m^3 and a percentage of cement in the mortar fraction equal to 20%, the calculated percentage of chloride with respect to cement mass was 0.19% for sample 3b and 0.31% for sample 7. Hence, the chloride content is below the critical one. Regarding sulphates, the maximum sulphate (SO_3) content accepted for cement is 0.4% [30]. Maintaining the assumptions previously described for chlorides, the calculated percentage of sulphates on cement resulted in 0.2% for sample 3b and 0.23% for sample 7. Hence, the sulphate content is compliant with the standard. In addition, no evidence of sulphate attack, i.e., the presence of ettringite, has emerged through XRD analysis (see the XRD results below) and visual inspections, so the risk of a sulphate attack can be excluded.

Table 2. Results of ion chromatography on samples 3b and 7 (cement mortar fragments).

Samples	Cl^- (%)	NO_3^- (%)	SO_4^- (%)
3b	0.038	0.004	0.049
7	0.062	0.012	0.057

The microscopic observation of the cross-sections of fragments of concrete cover collected from the funerary chapels (samples 1 and 2) revealed a colour difference between the internal concrete and the cortical layer (Figure 9). In fact, there is a surface layer with a thickness between 0.30 mm and 0.70 mm and a yellowish colour responsible for the "warm colour" of the concrete in the chapels. However, the boundary between the two zones is not sharp and the yellowish layer seems to locally extend into the inner grey concrete, as shown in Figure 9b. These observations suggest that the warm colour of the chapels' façades is not due to an intentional surface finishing (e.g., a paint), and an FT-IR analysis was carried out on the surface layer of samples 1 and 2 to further investigate this aspect. The FT-IR spectrum is reported in Figure 10. Besides the bands of calcite at 1420 and 870 cm^{-1} and quartz at 1190 and 1025 cm^{-1}, a band was found at 3350 cm^{-1} which can be ascribed to a disarming product made of vegetable oil [31]. The use of animal, vegetal, and mineral oils are well known as traditionally disarming products. They were used to facilitate the detachment of the concrete casting from the formwork. A study reports that these oils were usually spread on the frameworks with brushes [32]. It is possible that oil was applied in an excessive amount on the wood frameworks used in the chapels for concrete casting, and hence, concrete may have absorbed it, resulting in staining due to the oil's ageing. The yellowing of the grey concrete made with Portland cement after the application of oil-based disarming products on wood frameworks was also observed in a recent study [33]. In conclusion, the surface colour of the concrete in the chapels was probably unintentional, and it was rather caused by the ageing and oxidation of a disarming vegetable oil. This finding is important for conservation, as no need for the preservation of such colour arises.



(**a**) (**b**)

Figure 9. SOM images: (**a**) a fragment of concrete cover collected from a chapel (sample 1). Notice the colour difference between the internal concrete layer (lighter) and the external cortical layer (darker). (**b**) Cross-section of sample 1, where the external darker layer can be noticed, as well as the filtering of this dark part inside the concrete underneath.

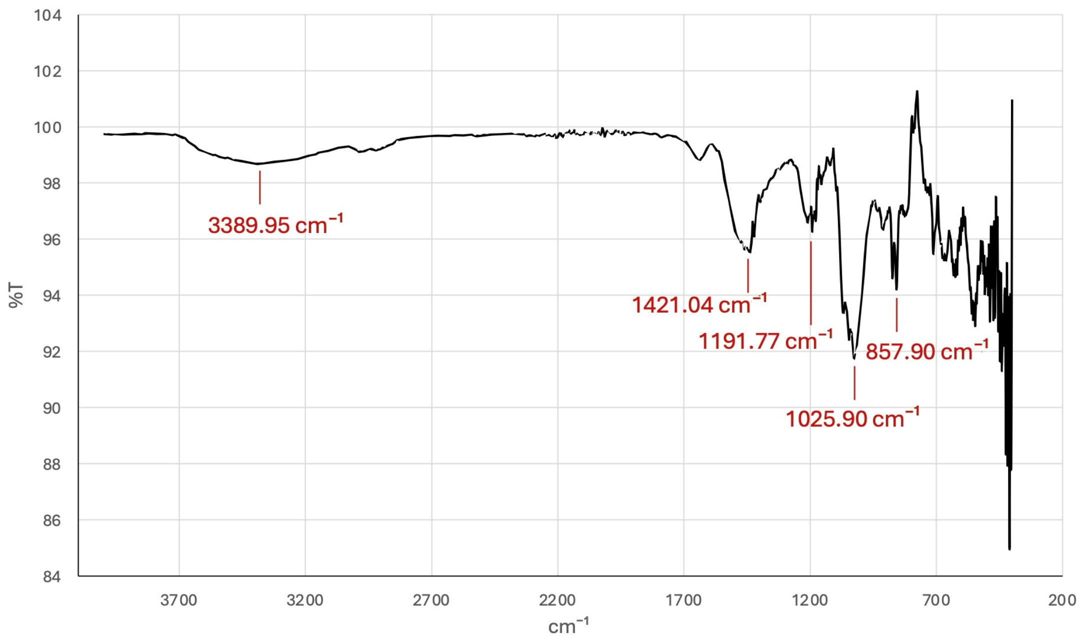


Figure 10. FT-IR spectrum of sample 1 (concrete cover).

The results of the XRD carried out on the samples of concrete cover from the chapels (samples 1 and 2) (Figures S1 and S2) showed the presence of calcite, quartz, albite, microcline and muscovite. Muscovite, belonging to the mica group, seems responsible for the slightly shining appearance of the chapels' surface.

Concerning the salt efflorescence, the results of the ion chromatography (Table 3) showed that they are mainly composed of sulphate. These salts are probably contained in the soil in contact with the concrete walls and were transported by water percolating through the porous concrete. They can have a damaging effect on concrete, causing expansive chemical reactions. Nitrates, which are salts that derive from the transformation of organic matter, are present in almost negligible amounts. Usually, nitrates are abundant in cemeteries, as the soil of burial areas is characterised by high nitrate accumulation due to the decomposition of bodies [34]. The reason for their low amount in the sample may be that the area where the Monument is located, despite being in a cemetery, was not originally a burial ground. In addition to these salts, the remaining fraction of efflorescence can likely be ascribed to limescale from the leaching of the portlandite contained in concrete. The purpose of this analysis was to understand the origin of the efflorescence and not the exact quantity of their components. In conclusion, the efflorescence studied may be mainly ascribed to limescale from the leaching of portlandite and sulphate transported from the ground to the concrete surfaces.

Table 3. Results of ion chromatography on samples 4, 5, and 6 (efflorescence).

Samples	Cl^- (%)	NO_3^- (%)	SO_4^- (%)
4	0.072	0.214	7.176
5	0.341	0.135	35.57
6	0.085	0.157	17.82

The water absorption values of the samples collected from the Ossuary Monument and the chapels (fragments of samples 1, 2, 3b, and 7) are reported in Table 4. Water absorption is an important parameter to assess the materials' conservation state and their residual durability because the presence of open porosity on the one side represents the effect of deterioration and on the other side causes further degradation by favouring water ingress into materials. The water absorption values obtained for the concrete cover are very high (8.5–13.3%) if compared to the WA values of concrete considered suitable to ensure good durability (around 4–6%) [35]. The water absorption values obtained for the mortar fragments are very high as well, even if in this case no direct comparison with the values found in the literature can be made, as this is mortar and not concrete. Hence, the concrete used to build the Monument can be considered of low quality due to its high porosity. Moreover, the carbonation of concrete was assessed in the 2001 study [13] by the phenolphthalein indicator method on a concrete core taken from the Ossuary Monument's base. The analysis revealed a high carbonation depth in the Monument's concrete, namely 60 mm, after just 40 years from the construction. The most used analytical model that describes the relationship between carbonation depth and concrete age is as follows:

$$c = K \cdot \sqrt{t}$$

where c is the carbonation depth (mm), K is the carbonation coefficient (mm/year$^{0.5}$), and t is the exposure time to CO_2 (year). The carbonation coefficient K indicates the rate of carbonation penetration depending on environmental conditions and characteristics of concrete [36]. This model was applied to the Monument and the carbonation coefficient was calculated as follows:

$$K = \frac{60}{\sqrt{40}} = 9.49\ \text{mm/year}^{0.5}$$

Table 4. Water absorption (WA%) values of the samples from the Ossuary Monument and the chapels.

Samples		WA (%)
1 (concrete cover)	Fragment 1	12.0
	Fragment 2	9.3
2 (concrete cover)	Fragment 1	11.2
	Fragment 2	10.2
3b (mortar fragment)	Fragment 1	13.3
	Fragment 2	9.0
7 (mortar fragment)	Fragment	8.5

Considering the Monument has a class of exposure XC4 (cyclic dryness and humidity), the value of *K* obtained is slightly higher than the values of *K* calculated in a recent study [36] for other structures in the same class of exposure (5.59–8.95 mm/year$^{0.5}$). The low resistance to carbonation of the concrete in the Ossuary Monument is related to its high porosity and permeability, which is likely a consequence of a high water/cement (w/c) ratio used to enhance its workability at the fresh state and help its casting in formworks having complex shapes.

The result of XRD carried out on the aggregates of the Ossuary Monument's concrete (sample 3a) (Figure 11) showed the presence of quartz and albite. No undesired substances that might suggest the use of unsuitable aggregates were found. Regarding the type of aggregates used in the concrete mix, it can be assumed that they came from local quarries, as this was a common and cheaper practice. In the study carried out in 2001 [13], it was inferred that the aggregates essentially come from the natural disintegration and subsequent transport in a fluvial environment of compact micritic white and grey limestones. However, the SOM observations in this study (Figure 12) showed that the aggregates are (I) often damaged (possibly also due to the chisel treatment); (II) highly porous and likely frost susceptible; (III) potentially reactive. In fact, some aggregates might contain iron sulphides, which oxidise and form sulphate (later ettringite) and iron oxide (Figure 12b). Hence, the concrete aggregates used in the Ossuary Monument appear of low quality and may have contributed to the degradation processes.

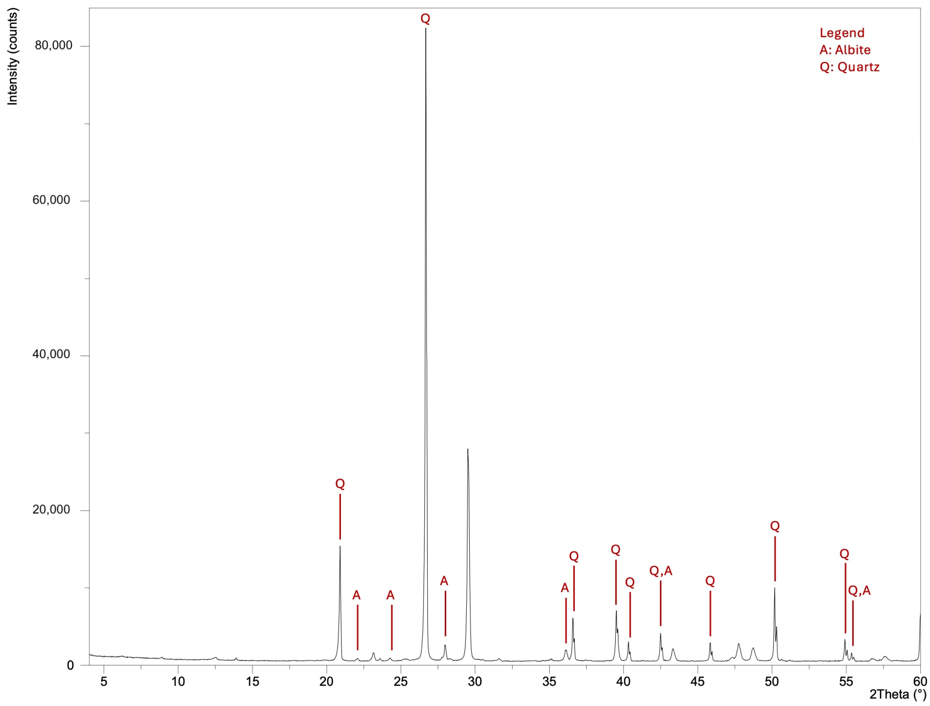
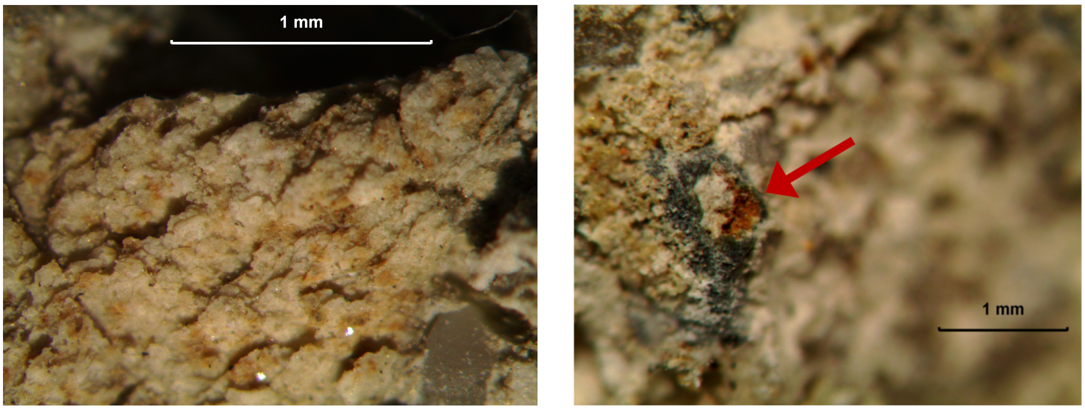


Figure 11. XRD pattern of concrete aggregates of the Ossuary Monument (sample 3a).



(**a**) (**b**)

Figure 12. SOM image of (**a**) a damaged and porous aggregate collected from the Ossuary Monument (sample 3a); (**b**) another aggregate with a small cavity having a rusty colour (sample 3a).

In the 2001 study [13], the particle size distribution of concrete aggregate was determined, and it was found to be largely in agreement with the ideal distribution for concrete, assuming a maximum size of aggregates equal to 30 mm, so the particle size distribution seems adequate.

5. Guidelines for Conservation

According to the laboratory tests conducted, the concrete in the Monument is in bad condition and exhibits deterioration problems, requiring conservation treatments that must also ensure the preservation of its aesthetical value. The following main durability problems were identified:

- Concrete was prepared with poor awareness of durability issues and hence, exhibits high porosity, probably due to a high w/c ratio. This high porosity led to fast and deep carbonation and low resistance to frost. The concrete aggregates seem not particularly durable as well.
- For the same reason, the concrete cover used in the structure is too thin and carbonation has already reached the reinforcement, which is exposed in wide zones. Also based on previous tests, all the reinforcement can be considered not passivated any more even in areas where the concrete cover is still there.
- The roughness of concrete promotes soiling and water accumulation and the formation of biological colonisation, whose growth inside the ossuary is enhanced by the dark and shadowed environment.
- Infiltration of water from the surrounding soil across the concrete structure is occurring, leading to efflorescence (mostly harmful sulphate).

The proposed restoration methods are described below and summarised in Figure 13. Great consideration was given to both identifying the elements of value that need to be preserved and selecting the least invasive methods for the preservation of these elements. The elements of value emerged during the study of historical documents and the analyses previously described and are the following: the two different surface textures (hammered rough surface of the Ossuary Monument and brutalist surface of the chapels with visible wood prints from the formworks) and the colour of the Ossuary Monument's surface given by the aggregates. It seems there is no need to preserve the ochre colour of the chapels' surface because no indication of surface treatment was found in historical documents and it appears to be unintentional. However, deeper archival research on the funerary chapels could be carried out in future studies. Given the heritage value of the Monument, the main criterion for selecting the most suitable conservation strategies was to search for treatments that involve minimal destructive action while protecting the surfaces and slowing down the degradation process. In general, the Monument would need to be protected from aggressive environmental conditions, but it is not possible to modify the site without distorting the Monument itself, as it was designed like it appears today, i.e., directly exposed to the atmosphere. Also, the statues contained in the Monument should be investigated, as they need a dedicated restoration project, but this is beyond the scope of this paper.

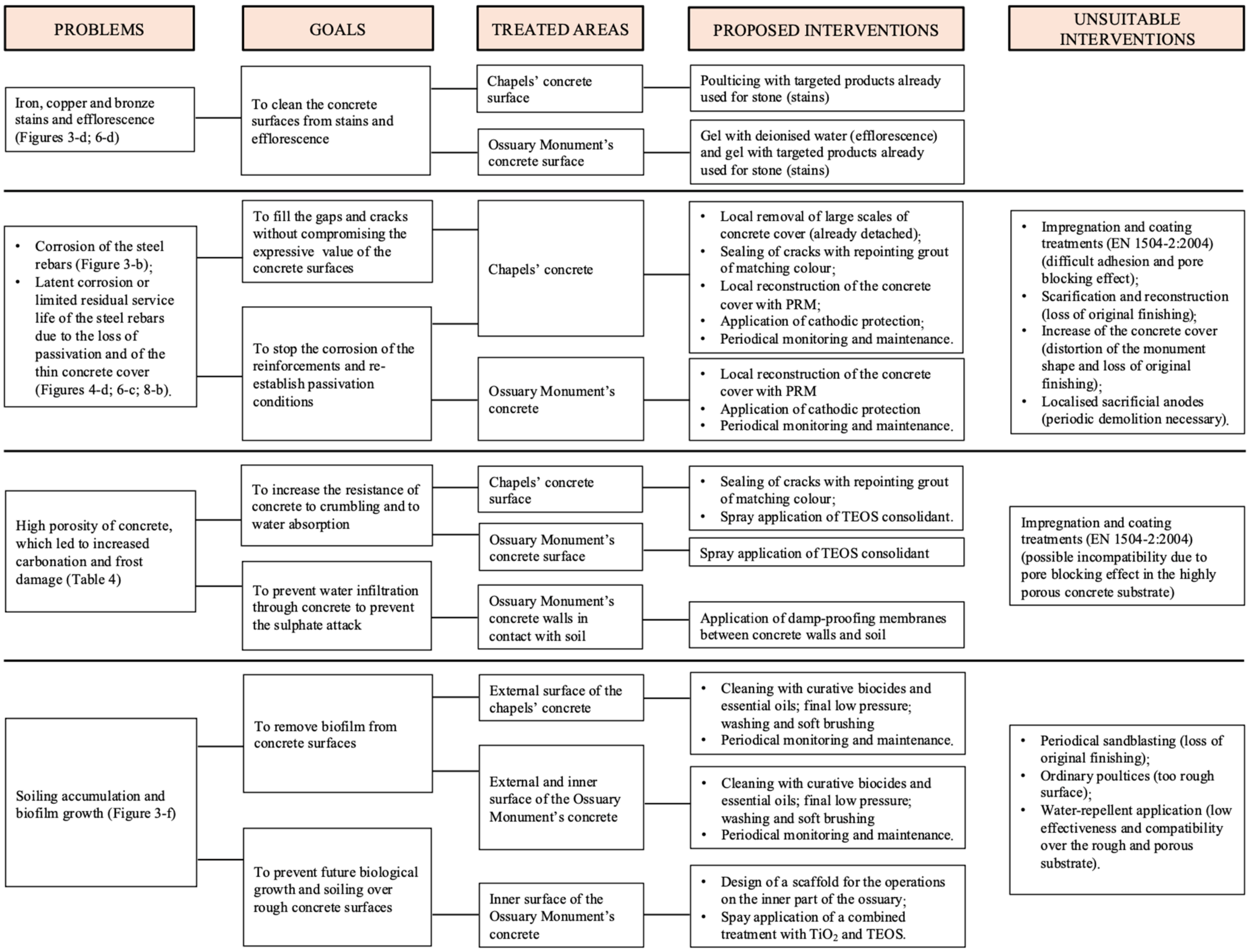


Figure 13. Framework of the restoration proposal.

Firstly, the concrete surfaces should be cleaned from biological colonisation, soiling, stains, and efflorescence. Given the deteriorated concrete surfaces, cleaning methods with low aggressiveness must be used, preserving the surface texture, such as low-pressure washing followed by soft brushing. The water washing is not expected to create any complications, i.e., increasing the dissolution of soluble salts, as the structure is already exposed directly and permanently to rain. The removal of biological growth can be performed with essential oils [37], curative biocide, and soft brushing [38]. The main challenges of biofilm removal from the Ossuary Monument are the surface roughness and the high sorptivity of concrete, requiring techniques and materials that do not leave potentially harmful residues in the substrate. Copper and bronze salt stains and iron stains can be cleaned with targeted cleaning products identical to those used in old buildings with poulticing and gel (for rough surfaces) [39], while efflorescence can be removed by dry brushing or poulticing followed by soft brushing for the removal of the poultice residues.

The condition of the steel reinforcements in the Monument is critical, and their corrosion is already in progress (Figures 3 and 4) due to thin concrete cover and passivation loss. Three main stages of degradation were detected: completely uncovered rebars with corrosion in progress (Figure 3b); areas where the concrete cover is almost detached and is about to fall off (Figure 6c); and areas where the concrete cover is starting to show the first hair cracks or the corrosion is latent (Figure 8b). To stop the steel bar corrosion, the application of cathodic protection is recommended. This technique is commonly used for the protection of big infrastructures but has been recently proposed for the protection of heritage concrete [9,40]. Alternative methods to cathodic protection, which are used in contemporary RC structures or buildings without heritage value, are considered inapplicable for the Monument. For example, the complete scarification of the external layer of concrete and its reconstruction, possibly with an increase in the concrete cover thickness, is to be avoided because it would lead to the total loss of the concrete's expressive value, which lies in its surface layer. Another method could be the application of a surface impregnation or coating with a waterproof layer. This is impractical because the substrate of the Monument was found to be very porous, and this treatment might cause an excessive pore-blocking effect and subsequent defects. In addition, problems may arise when applying a surface layer on a substrate as rough as the Ossuary Monument's one. Moreover, this intervention does not guarantee sufficient protection of the steel reinforcements from the corrosion which is already in progress. Conversely, cathodic protection can be considered a non-invasive technique that does not affect the appearance of the surface (texture and colour), as it allows to preserve already carbonated concrete that has not been damaged by corrosion yet. The cathodic protection system requires a proper design that takes into account the geometry of the reinforcements' cage provided by the original drawings (Figure 7a). However, the main idea is that anodes can be easily inserted in the ground around the Monument (where the lawn is present) and connected to the steel rebars in the underground "sails", which constitute the base of the structure (Figure 7a). The steel rebars, because of the way the structure was designed, appear all electrically connected, allowing their cathodic protection. The underground location of the anodes, which could be either inert or galvanic, ensures that the protection system is invisible to the visitor. Inert anodes are connected to a voltage source and are usually considered highly reliable, but they require continuous monitoring and are more expensive. On the other hand, galvanic anodes do not need any generator and could be used in a relatively small structure like the Monument, but the consumption of the anode material should be properly considered in the design stage and its substitution timely planned [9] to avoid irreversible damage to the structures. An alternative system could be the direct insertion of galvanic anodes in the concrete near the rebars and their covering with mortar patches (localised sacrificial anodes) [9], but this is not recommended in this case, as it would compromise the aesthetic value of the Monument's concrete surfaces and moreover, periodic demolition would be necessary to replace the anodes once consumed.

Concerning the chapels, the gaps caused by reinforcement corrosion and concrete spalling greatly compromise the aesthetic value of the surfaces. The best solution seems applying the "Patch Restoration Method" (PRM) [6,41]. The PRM was specifically developed for fair-faced heritage concretes and allows to achieve chromatic, texture, and finishing compatibility between repair mortar and concrete surface. The PRM was already successfully applied to 'Piscina das Mares' (Leça da Palmeira, Portugal, designed by Alvaro Siza) [6], where brutalist concrete surfaces similar to the Monument's ones are present. The PRM should be applied in the gaps that are already present in those that will be produced by removing the large scales of concrete cover that are almost detached, and to the cracks that need to be sealed with repointing grout of matching colour. An important aspect to be considered is the nature of the repair mortars that are used in the PRM. The mortars should be compatible with the substrate, but they should not replicate the characteristics of the substrate that cause its poor durability, i.e., high porosity, or at least they should be complemented by additional protection measures. Moreover, the high durability of the repairs can be assured by the application of cathodic protection because it has a direct effect on the cause of the concrete cover detachment.

The concrete surfaces of the Ossuary Monument and the chapels are at risk because of their crumbling (Figure 3e) and microcracking (Figure 8b), which facilitate water ingress. The suggested operation is to consolidate concrete and to increase its resistance to water absorption by the spray application of ethyl silicate (TEOS). Ethyl silicate is widely used for stone consolidation in cultural heritage conservation but has been only recently tested for concrete surface protection with promising results [3,42,43]. The application of ethyl silicate to the Monument is expected to provide the following: (I) a consolidating effect for concrete aggregates and paste, also due to the pozzolanic behaviour of silica produced by ethyl silicate's curing and the subsequent C-S-H formation [43]; (II) a good compatibility with porous concrete [42]; (III) a good adhesion to concrete, which is rich of silica (silica is contained in aggregates and cement paste) due to the fact that TEOS gives silica gel as a final reaction product [42]; (IV) an excellent stability in outdoor environment (UV radiation, pollution, etc.) due to its inorganic nature [42]; (V) the absence of pore-blocking effect which is very important for a satisfactory durability of the surface treatment, because the possible presence of water trapped behind the consolidated layer might lead to its detachment [43]; (VI) the aesthetical suitability for architectural concrete, as it causes very low brightness and colour changes soon after the treatment, which further decrease over time [43]; (VII) a reduction in water absorption by slightly reducing the pores means radius. Hence, TEOS application can reduce the susceptibility to carbonation (the high porosity of the Monument and chapel substrates should ensure the effectiveness of the treatment) and improve the corrosion resistance of the steel bars [3]. The proposed application method of TEOS, which is a solution in an organic solvent, is nebulisation onto the cleaned concrete surface until apparent refusal, as currently performed in stone conservation. The spray application is particularly suitable for the Monument for the following reasons: (I) the solution has low viscosity and can easily penetrate the uneven substrate; (II) the porous substrate can absorb the solution fast; (III) the released solvent vapour is not a problem as the Monument is located away from the urban centre. The high porosity of concrete is the reason why impregnation and coating treatments, as defined in EN 1504-2: 2004 [44], are not considered suitable for this application. These surface treatments usually employ organic polymers aimed at creating a physical barrier against the ingress of water, with a partial or total pore-blocking effect [43]. However, the highly porous substrate could easily contain water, leading to the detachment of the protective layer when the transport of the water vapour and hence, water evaporation are inhibited.

Furthermore, in areas of the crypt where efflorescence was found, the application of damp-proofing membranes between concrete and the surrounding soil (e.g., in the staircase walls) is suggested in addition to the TEOS treatment. This intervention is expected to prevent water infiltration through concrete and the damages caused by sulphate attack.

As shown by the analyses, the crypt's concrete walls are covered with moss and dark biological colonisation (Figure 3f) because the rough substrate favours their adhesion, and the humidity and darkness favour their growth. For these reasons, concrete is almost perpetually wet, which is detrimental also because it greatly speeds up carbonation. A possible solution to remove the biological growth could be periodical cleaning with sandblasting or poultices; however, it would be not only extremely expensive and laborious, but also very damaging for the incohesive and fragile substrate. Therefore, to prevent biological growth and soiling accumulation, the inner surface of the Ossuary Monument could be treated with a self-cleaning coating containing TiO_2: a water-based sol of TiO_2 nanoparticles should be sprayed on the concrete surface, possibly combined with the TEOS treatment. The application of these coatings on heritage concrete is still confined to scientific research [45,46]. However, studies have shown their potential in keeping the surface clean under the action of sunlight (photocatalytic effect) and in preventing the adhesion of organic contaminants and dust by flattening water droplets on the surface of the materials (photo-induced hydrophilicity) [45]. Moreover, aqueous TiO_2 sols are considered aesthetically compatible with historic substrates and cause only minor colour variations [45]. The application of the same treatment on the outer surface of the Ossuary Monument is considered unnecessary because its peculiar shape prevents biological growth, which in fact was not detected during the visual inspections.

In addition to all the interventions previously proposed, periodical monitoring and maintenance should be carried out. These actions are essential for several reasons: to extend the effectiveness of the treatments and repairs; to safeguard the original concrete and to possibly minimise the need for future large-scale interventions; and to determine if the expectations of service life of the repairs are met [47]. It is important to specify that any material and method of conservation previously proposed must be tested before the application in the Monument. The tests can consist of the application of the treatment in limited and non-visible areas of the buildings and in the monitoring of the results over time.

6. Conclusions

As the awareness of the cultural significance of 20th-century fair-faced reinforced concrete constructions arises, the growing necessity of their preservation makes the development of specific conservation strategies imperative. In this paper, an experimental study on the texturised reinforced concretes of the Partisan Ossuary Monument in Bologna was carried out, allowing to derive the following conclusions:

- According to the original archive documents, the different surface textures of the concrete in the Monument and the surrounding chapels were designed by Piero Bottoni himself and were identified as original features characterising this structure. Hence, they constitute the main element of value to be preserved in any restoration work.
- The original materials' manufacturing was affected by a poor awareness of reinforced concrete's durability issue and a low familiarity of workmanship with concrete used for artistic purposes, resulting in a generalised low quality of constructive details and materials and in the presence of defects.
- The onsite inspections and laboratory analyses revealed that the concrete is heavily deteriorated by the following: carbonation and reinforcement corrosion; physical-mechanical decay due to high porosity of concrete; staining due to copper and iron salts leaching and deterioration of disarming oils used in the concrete's frameworks; extensive and severe biological deterioration and colonisation, exacerbated by the high concrete roughness; and water infiltration.

Considering the elements to be preserved, the general requirements for the conservation of heritage structures, and the outcomes of the tests carried out in this study, guidelines for the restoration of the Monument were developed. It is noteworthy that many materials and technologies commonly used for the repair of reinforced concrete structures cannot be applied to this Monument due to their incompatibility. To comprehensively restore this Monument a multidisciplinary effort will be necessary. The collaboration among experts on the conservation of metal statues, corrosion experts, and structural engineers for an overall structural assessment and concrete preservation experts can lead to optimal results. Finally, the protection of monuments against aggressive environmental conditions may be the object of future studies.

The present study confirms that a tailored approach must be used in reinforced concrete structures having an artistic value, as suggested by the Madrid–New Delhi Document.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/heritage8050152/s1, Figure S1: XRD pattern for the funerary chapels concrete cover (sample 1); Figure S2: XRD pattern for the funerary chapels concrete cover (sample 2).

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