A-2-1 Bridge concrete maintenance concept

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ABSTRACT: This Bridge in Greece was opened in 2004 and it was designed and built with a service life of more than 100 years. This sort of long service life can of course, only be achieved using appropriate concrete mix designs and placement techniques, followed by a suitable maintenance strategy. This study presents the actions determined for the protection of specific concrete elements of this bridge against future water and chloride-ion ingress. These actions were defined as the structures maintenance management concept, which was developed by the Concessionaire of the Bridge and includes details for the specific requirements of the structure's inspection, testing, assessment and limitations, plus the relevant corrective/preventive actions to be taken. This paper presents the investigation and assessment procedure for the selection of an appropriate concrete protection system within the framework of the European Standards EN 1504. A hydrophobic impregnation and a cementitious flexible waterproofing mortar were both selected as possibly being suitable to prevent further water ingress. In order to investigate the potential of these materials, an evaluation was made, with appropriate testing defined and carried out. The test results highlight the efficiency of the cream consistence hydrophobic impregnation, even when applied on dense concrete substrates. The paper also presentation the results and conclusions from these full scale trail applications which was undertaken starting in 2014.

KEY-WORDS: Bridge maintenance, hydrophobic impregnation, test procedure.

INTRODUCTION

Outline

The ingress of water and chloride ions into concrete elements are the main causes for the degradation of their structural performance in long term basis. The ingress is more pronounced in marine environments where the structures are exposed to extreme weather conditions. Considering the negative impact of such degradations in terms of safety and maintenance cost, preventive actions should be considered.

The paper describes all the actions for the implementation of protection materials against water and chloride ingress in a concrete area which serves as protection cap for prestressing anchorages. The application selection parameters are also presented. From the analysis of the selection parameters, a cementitious waterproofing mortar and a material for hydrophobic impregnation were finally selected. In order to investigate the efficiency of the hydrophobic material a test campaign was launched. The penetration depth of hydrophobic material and the water uptake values were set as the key performance criteria under investigation. Also tests for the characterization of compatibility between the hydrophobic material and the cementitious waterproofing mortar (in case of parallel use) were performed. The results are presented in the application selection paragraph. Ahead of the presentation of actions a brief description for the Rion-Antirion Bridge and its concrete elements and the presentation of the specific maintenance issue are given.

The whole set of action lies in the context of the global maintenance concept of the Concessionaire which is based on the triptych Inspection-Analysis-Maintenance. The Inspection includes all the actions for the collection of data related to the condition survey of the elements while the Analysis includes the actions for the processing of incoming data and the evaluation of their criticality. Maintenance refers to the set of actions for the performance of the decided maintenance actions. Thorough presentation for the applied maintenance strategy are given in [1].

Technical description of the Bridge

The Bridge is a multi-span cabled stayed bridge with total length equal to 2252 m which started operating in 2004 after 7 years for the financing, design and construction stage. Fig.1 depicts the general layout of the Bridge while Fig. 2 presents the terminology of the concrete structural elements of the bridge and gives information for the concrete mix design characteristics. More details for the design characteristics of concrete mixtures are given in [2]. The four piers (M1 to M4) are founded on the sea bed of the Corinthian gulf. The foundation depth varies from 48 to 65 m from the Mean Sea Level.

The diameter of the footings is 90 m (M1, M2, and M3) / 80 m (M4) and the highest point (M3) of the Bridge measures 227 m from the sea bed. The continuous and fully suspended bridge deck is a steel concrete composite structure. As described in detail in technical papers dedicated to the subject [2],[3] the strategy for concrete durability approach to protect the steel reinforcement relied mainly on a proper definition of the exposure zones, selection of appropriate concrete covers for each zone, and a proper characterization and evaluation of the concrete itself. The actual minimum concrete cover is 50 mm for the immersed zone (below Mean Sea Level-5 m) and the airborne zone (MSL+10 m). The higher actual minimum cover is met in the splash zone located in the area -5 m< MSL<+10 m and is equal to 75 mm. Apart from conventional reinforced concrete elements, external and internal prestressing is applied in the Pylon head and Pylon Base region respectively.

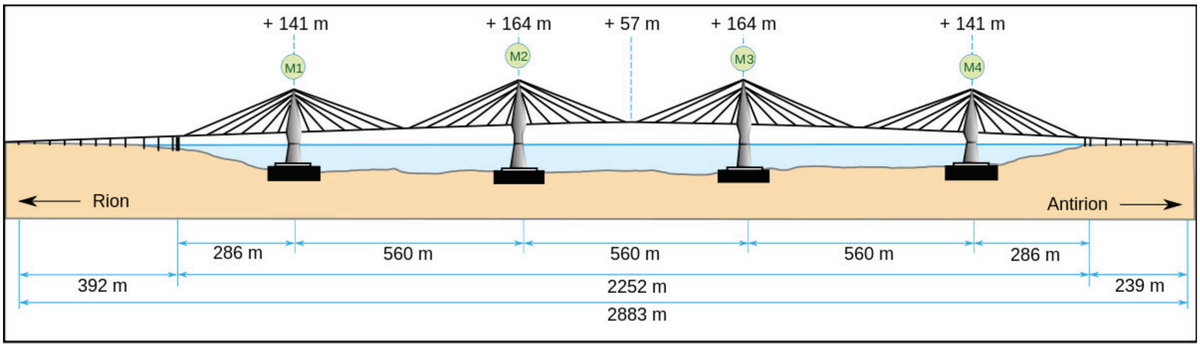


Fig. 1.General Layout of the bridge

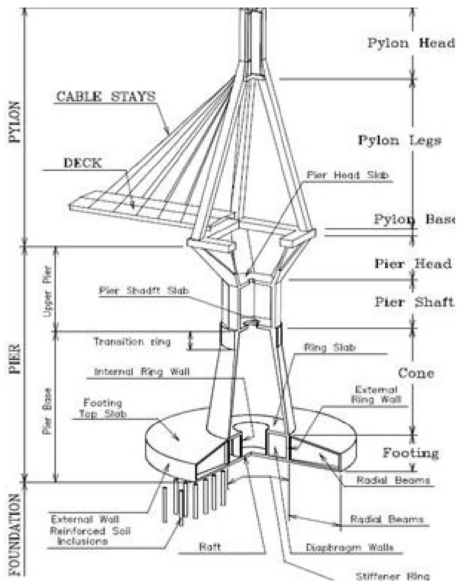


Fig.2. Topology of structural elements of the bridge

Table 1. Concrete mix design characteristics

Element	Exposure Classes	Concrete Classes
Pylon Head	XC4 XS1	C60/75
Pylon Legs	XC4 XS1	C60/75
Concrete deck	XC4 XS1	C60/75
Pylon Base	XC4 XS1	C50/60
Pier Head	XC4 XS3	C45/55
Pier Shaft	XC4 XS3	C45/55
Pier Cone	XC4 XS2	C45/55
Pier Footing	XC4 XS2	C45/55
Cement type: CEM I 52.5; CEM II/B-M (W-P-LL) 32.5 N; CEM III/A 42.5 (60 to 64% slag)		
Water to cement ratio : 0.33-0.40		
Cement content (per m^3):400-490 kg		

POSING THE MAINTENANCE ISSUE

Identification of the issue and analysis of findings

The needs for preventive maintenance were raised in the Pylon Base of all four Pylons which are located nearly 30 m above the sea level. The Pylon Base acts as restraining hoop for the base of Pylon Legs and ensures the transition of forces from the Pylon to the Pier. The restraining action is achieved through prestressing tendons which run along the four sides of the square base, with length 40.5 m. The tendons are anchored at each extremity in a separate anchorage area for each direction, forming eight “anchorage faces” per pylon. In each “anchorage face” 21 tendons are anchored in an orthogonal area measuring 4.89 and 3.50 meters in width and height respectively. The usual construction practice of covering the area with second phase concrete (reinforced with conventional steel reinforcement) was followed also in this case. The design strength class for the concrete cap is C50/60 and the thickness of the cap is 250 mm.

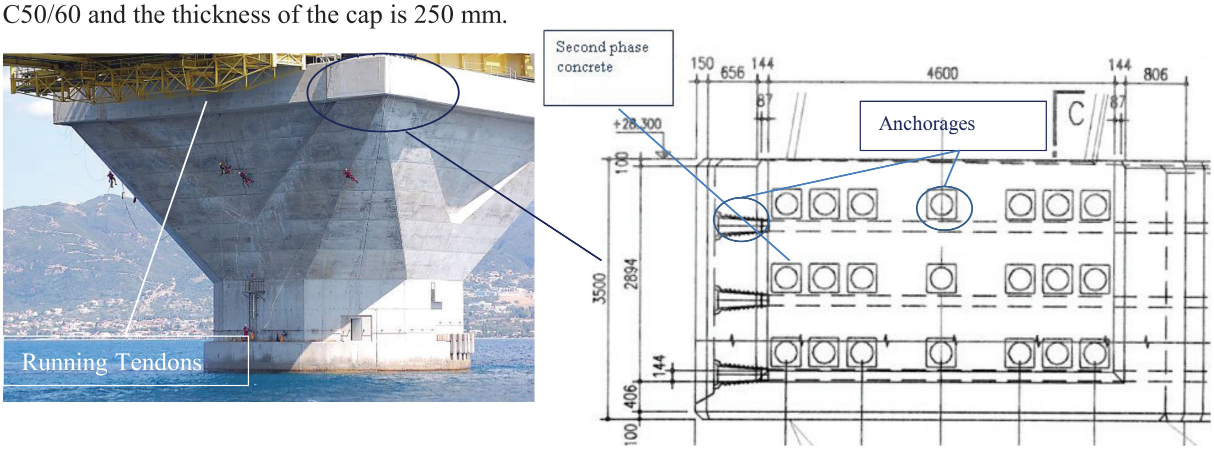
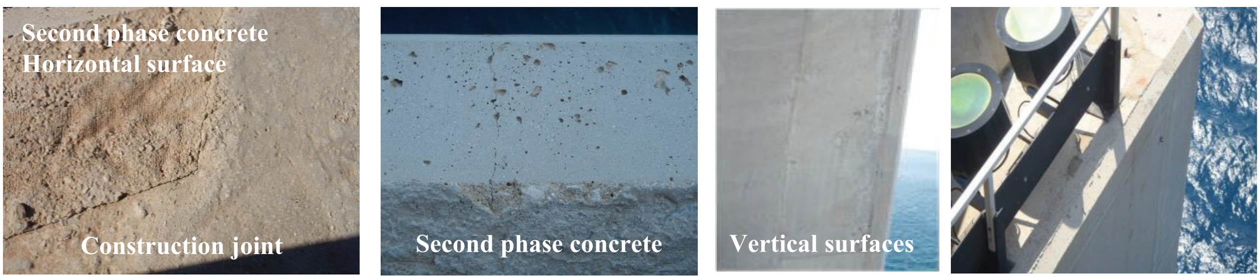


Fig.3. Pylon Base prestressing anchorage area



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

Fig.4. Findings: (a) Construction joint, (b) Cracks over the second phase concrete, (c) Cracks over the vertical surface (d) Aspect of vertical surface and conFig.d chamfer of Pylon Base.

In the course of 2008 visual inspections minor cracks with opening less than 0.2 mm were observed in the construction joint between the two concrete phases but also in the vertical surfaces of the second phase concrete. Defects related to low concrete coverage or exposed reinforcement were not observed in the area. The non-evolutive characteristics of cracks led to the conclusion that these cracks were coming from the construction stage. From the analysis of the findings it was decided to protect the area against water and chloride ingress in all the 32 anchorage faces of the four Pylons. The analysis sets the performance-selection criteria for the appropriate type of application.

APPLICATION SELECTION AND VALIDATION TESTS

Selection parameters for the application

The following Table summarises the parameters for the selection of the appropriate maintenance solution.

Table 2. Selection parameters

No.	Consideration	Analysis
1	Durability I	The main consideration was the technical efficiency of the material which would lead to long term protection. The observed cracks were assessed as not active, this data facilitates the selection of materials since the need for high crack bridging capacity was not so high.
2	Durability II	Durability against UV radiation – from April to September, UV radiation in Greece exceeds 8 and reaches 10 during the summer [4].
3	Aesthetic concern	All the surfaces are visible to the public (from sea and deck pavement).The application of protection materials which modify the aspect of the surfaces was not favourable.
4	Applicability	Nearly the 95% of the surface would be addressed by Rope Access Team which creates a significant cost factor, so special attention should be given to the preparation & application method as well as the overall intervention time and any reapplication interval.
5	Removal cost in case of material failure	The material should be subtracted easily from the surface
6	Environmental consideration	The material should be the least aggressive to the aqueous environment (application over the sea). Also the selected application method should nullify the material loss.
7	Safety of personnel	The material and its application requirements should generate minimum risks to the maintenance staff.

Proposed solutions

According to EN 1504[5], the candidate applications were the coating and the hydrophobic impregnation of surfaces. The different surface type (mainly their slope), the different access conditions and the significant difference in the magnitude of application area imposed the different approach in the maintenance issue. For this reason the application was decomposed in two parts: vertical and horizontal.

Specifically for the vertical surfaces there were two options. The first was the coating with a polyurethane waterproofing membrane and the second one, which was finally selected, was the hydrophobic impregnation with a silane based material. The efficiency of properly applied hydrophobic impregnation in order to prevent chloride penetration in the presence of cracks is well proven in [6], [7]. Additionally the Swiss Bridge Authorities [8] indicate that hydrophobic impregnation can treat cracks up to 0.750 mm providing a certain penetration depth linked to the crack width. Except from its technical efficiency, a great advantage of hydrophobic impregnation against coating is the limited aesthetic impact and its applicability.

For the horizontal surfaces three options were available (a) Covering the area with polyurethane membrane, (b) covering with a cement based flexible waterproofing mortar (c) covering the area by combining hydrophobic impregnation and the cement based coating. The third approach was assessed as conservative but further investigation was performed in order to assess the effect of hydrophobic impregnation in the bonding conditions between the concrete substrate and the cement based coating. Table 3 presents the response in the considerations which were posed in Table 2. The responses refer to the finally selected applications.

Table 3. Response on the posed application considerations.

No.	Vertical surfaces Selected application-Hydrophobic impregnation	Horizontal surfaces Selected application-Coating with a cement based flexible water proofing mortar.
1	In [6-7], [9-12], the efficiency of this solution is presented. Up to 20 years durability from field experiments with regards to chloride penetration in marine environment is referred. Numerous tests have also shown the benefit to treat concrete surface in presence of cracks to prevent chloride migration.	Cement based system complying with EN 1504-2. Crack bridging capacity: A3
2	The major success factor of this application is related to the migration ability of the material within the concrete. Although silicone networks are known to be highly resistant to UV, this is of little concern as the product is supposed to migrate in the concrete; hence it will be protected against UV radiation.	Many references of the proposed product applied externally show little effect of the UV radiation as the matrix material is mainly cement based.
3	"Invisible" protection as the product does not form a film at the surface of the concrete.	Mineral look of the harden surface – initially some differences may be noticeable; differences will decrease over time.
4	The creamy consistence of the product will allow to the Rope Access Team a fast and relatively easy application – with reduced number of passes.	1-component product, easy to apply.
5	Only potential negative point as once applied at the surface of the concrete, it will be impossible to remove the product.	If required; the applied coating can be removed by mechanical means.
6	Water based product in cream form. Limited wastage and dripping of the material is expected.	Cement based product to be mixed with water.
7	Water based product. Only cleaning of the tools requires solvent. This operation can be done in safe environment.	Necessary safety protection tools need to be worn by the application team.

Experimental campaign

Regarding hydrophobic impregnation, the main queries raised from the Concessionaire part were:

(i) the penetration efficiency of the material in dense concrete mixes – Wittman[13] indicates in his paper the need of at least 5 to 6 mm penetration of hydrophobic impregnation in marine structure to be efficient.

(ii) the waterproofing performance against water for the specific concrete mix of the structural element.

(iii) Finally, of major concern was the application mean of the material. For this reason an experimental program which is presented in the next paragraph was deployed.

(iv) Concerning the horizontal surfaces the effect of hydrophobic impregnation in the bonding characteristics of the substrate concrete and cement based materials was examined by pull of tests mainly for academic purposes; previously indirectly investigated by Baillemont [14] and directly tested by Sika using different cement resurfacing materials [15].

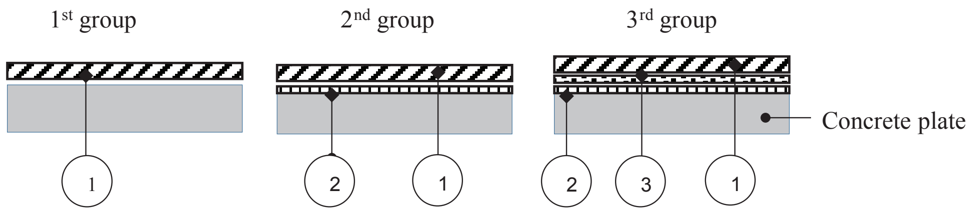
Hydrophobic impregnation

Two concrete surfaces located in the Pylon Base measuring 0.75 m^2, were treated with hydrophobic impregnation material. These surfaces were constructed by the same concrete mix formula as of the actual application area. Material quantity equal to 500 g/m^2 and 700 g/m^2 was applied respectively in each surface. Before the application of the material the surface was prepared by low pressure water jetting (≈120 bars) in presence of the supplier. The application of the material started when it was ensured by humidity measurements that the substrate was dry enough. The upper limit for water content level in the substrate was equal to 6 %. The material was applied in two coats by brush and spatula. Both application means were assessed as non-productive. During the application limited dripping of material was observed. The maximum material wastage was observed to the application by brush. The second coat was applied three hours after the application of the first coat.

Five weeks after the application, four cores (Ø 50 mm, depth: 50 mm) were extracted from the application surfaces and two from non-treated surfaces. The cores were stored in sealed bags to the premises of the supplier where the conduction of the penetration depth and capillary absorption tests were held. The tests were planned to be performed 90 days, 1, 2, 3, 4, 5, 8 & 10 years after treatment.

Adhesion tests

In these tests the impact of hydrophobic impregnation in the bond behaviour between the concrete substrate and the cement based coating was investigated. Pull-off tests were conducted according to EN 1542 at the supplier facilities using concrete plates. Fig. 4 depicts the test program while Table 4 presents further test details. In the third group of tests a bonding agent was also used.



1. Cement based coating; 2. Hydrophobic impregnation; 3. Acrylic bonding agent

Fig.4. Schematic lay-out of test program and test set-up.

Table 4. Compatibility test details

Substrates:	Concrete plate 40x40 M 0.40 according to EN 1766 - Light sand blasted surface
Hydrophobic Impregnation:	~80% cream silane based hydrophobic impregnation applied at 700 g/m^2
Primer:	Water based acrylic primer (typically used as primer underneath water based coating) applied at 120 g/m^2
Cement based topping:	1-comp. cementitious elastic waterproofing mortar. Mixing ratio: 6.5 l per 22 kg bag Applied by brush at 2 kg/m^2 (~1 mm thick)
Hydrophobic impregnation to mortar/acrylic primer waiting time:	7 days after hydrophobic treatment – by then, the water beading effect will be maximum
Acrylic primer to mortar waiting time:	Application by brush – Mortar applied 2 hours later
Curing after application:	28 days at room temperature

TEST PROCEDURE OF PRODUCTS

Penetration depth

Two cores from both zones were split across its longitudinal axis and water was sprayed onto the fracture surface. Areas where the hydrophobic impregnation has penetrated did not absorb the water hence the surface remained dry after water spraying. The differentiation between the water absorptive and dry areas was clearly visible. The distance between the top of the specimen and the extremity of the water beading area was recorded. In total 6 measurements (3 in each face) were taken. The average value was calculated and presented in Table 5. Measurements were conducted with electronic length meter with accuracy on two decimals.

Table 5. Penetration depth results

Consumption	Penetration depth
500 g/m^2	7.8 mm ± 0.46 mm
700 g/m^2	10.2 mm ± 0.59 mm

Capillary uptake

In order to evaluate the cream silane performances on reducing water absorptivity of the concrete, capillary absorption test was conducted according to EN 1062-3[16]. Two cores from each area (treated ones and non-treated) were sealed with epoxy resin, leaving the exposed surface unsealed. After 7 days of curing of epoxy, the specimens were subjected to 3 cycles of wet/drying regime – 1 week each. Finally, the samples were immersed in water tank, with the coated surface under test facing downwards so that this face was 5 mm to 10 mm below the surface of the water and also at least 10 mm above the base of the container. Measurements of the water uptake (change in weight of the cores) were conducted during the first day (24 hours) with a weight scale with accuracy on 0,01 g.

As water uptake phenomenon shows a rising tendency, the measurements continued for two weeks, in order to evaluate the performance of the capillary absorption. Fig. 7 depicts the evolution of water uptake in relation with time.

The water transmissibility w, in kilograms per square meters per square root of hours, is determined by the mass increase (in kilograms) divided by the area of the test specimens (in square meters) and by the square root of time (√24h).

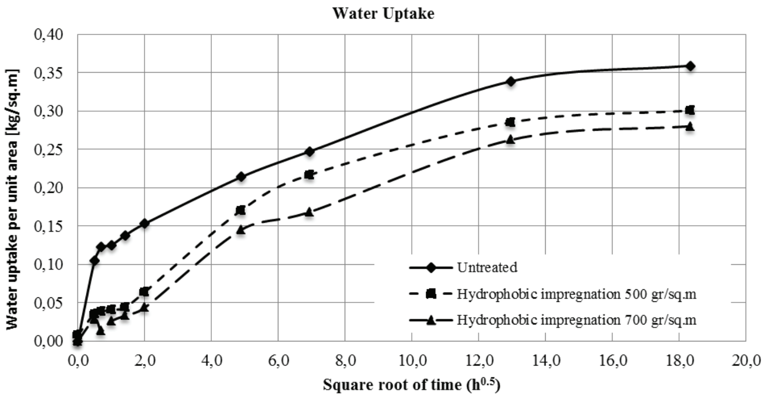


Fig. 7. Water uptake as a function of time

Bonding strength
Table 6 presents the failure stress and the failure mode which resulted from the pull off tests. For all the specimens a cohesion fracture in the cementitious mortar layer was observed. The tests were performed according to EN 1542.

Table 6. Bonding Strength Results

	1st group		2nd group		3rd group	
	Strength [MPa]	Failure mode	Strength [MPa]	Failure mode	Strength [MPa]	Failure mode
Average	1.91	100% Mortar	1.80	100% Mortar	1.97	100% Mortar
Standard deviation	0.04		0.17		0.02	
% of 1st group	100%		94%		103%	

DISCUSSION OF RESULTS

Regarding hydrophobic impregnation, the tests exhibited the high performance of the material in terms of material penetration and water absorption resistance. From the results referring to the penetration depth the increase of applied quantity by 40 % led to increase of the average penetration depth by 31%. The same image is not met in the investigation for water uptake where the respective positive influence of the material is increased by 7 %. This can be attributed to the fact that the extra quantity is diffused in depth. The achieved penetration depth over 5 mm ensures the durability of the solution. Although the higher quantity the more durable solution is achieved, for the sake of economic optimization it was decided to apply to the field application quantity equal to 600 gr/m^2.The achieved sorption coefficient values are lower than 0.1 kg/(m^{2}h$^{0.5}$) which was considered as performance criterion. Also the low water absorption of the untreated concrete has to be noted. This indicates the high construction standards of the structure.

From the results which refer to the bonding properties we conclude that the presence of hydrophobic impregnation and bonding agent do not change the failure mode which is expressed with failure in the coating. The minor differentiation in the failure strength can be attributed mainly to the effect of the extra applied materials on the stress distribution over the interface between the mortar and the concrete substrate.

FULL SCALE APPLICATION

After the full examination of test data, the Concessionaire decided to proceed to the application of material. Regarding the application means, although an airless spray would allow the highest material economy, it was rejected since the presence of high wind would not allow controlled application. Also, comparing with the application by brush, the application with roller was assessed as more productive. Carefully weighed doses corresponding to application area dimensions were applied by rope access team. The total application area was equal to 476 m^2.

Additional care was addressed to the sequence of faces to respect the maximum substrate temperature (depending on sun exposure). The result is aesthetically and technically compliant with the objectives.

CONCLUSIONS

The presented paper highlights:

1. The importance of selecting the preventive application according to EN 1504 recommendations. The proposed terminology from EN 1504 acted as a common language for the manufacturer and the client and also facilitated the proper selection of interventions.

2. The high level of cooperation between the client and the supplier which ensured the success of maintenance actions, through extensive dialogue, technical support and laboratory studies.

3. The thorough validation process prior to application.

4. The high performance of material despite the dense concrete.

5. The compatibility between cement based coating and surface treated with hydrophobic impregnation.

6. The definition of application parameters related to applicability and quality control.

The presented maintenance actions minimized the risk for development of defects of high severity and high maintenance cost through a durable and aesthetically acceptable prevention of chloride ingress in the concrete.

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