Investigation of the Effectiveness of Repairs and Protection Materials/ Techniques for Alleviating Durability Problems

Amal Al-Far [1], Salam Al-Far [1], Khaled Kahhaleh [2] and Tareq Al-Hadid [2]

[1] Middle East University, Amman, Jordan.
[2] Royal Scientific Society, Amman, Jordan.

ABSTRACT

Chloride-induced corrosion is one of the major forms of premature concrete deterioration in Jordan, particularly in the industrial structures located in the Dead Sea Region, which is one of the most severe corrosive environments in the world. Significant forms of deterioration occurred within (10-15) years of the service life of the structures.

Achieving the desired service life without expending excess funds for maintenance or rehabilitation is the objective of any designer. Proper attention to durability considerations in design can greatly extend the life of a structure. High quality concrete and adequate cover provide the first line of defense against corrosion and should always be specified to assure durability. However, the experience of the research team has shown that relying solely on concrete quality and cover as a corrosion-protection strategy may not assure long-term durability and protection against corrosion-induced damage. Concrete cracking and variations in materials and construction quality can undermine the effectiveness of "concrete only" protection strategies.

This paper presents the outcomes of a 4-year duration research work conducted to evaluate the effectiveness of some selected repair and protection materials/ techniques that are available at the Jordanian market in alleviating the problem of chloride-induced corrosion, hence improving concrete durability.

KEYWORDS: Durability, Chloride-induced corrosion, Severe environments, Epoxy-coated bars, Patch repair, Concrete coating.

INTRODUCTION

People used to believe that reinforced concrete is durable and maintenance-free (Smith et al., 2004). However, while reinforced concrete performs very well in some environments, it may develop problems in others. In particular, if concrete is exposed to moisture (especially in the presence of chloride ions), corrosion of reinforcing steel may lead to damage of the structural elements (Mirsa and Uomoto, 1991).

In Jordan, chloride-induced corrosion is the major form of concrete deterioration for structures located at the shores of the Dead Sea and Red Sea regions. The Dead Sea location is one of the most severely corrosive environments in the world (Charach et al., 1990). It is characterized by elevated temperature and humidity, as well as high ground and ambient salinity with high levels of chlorides in soil and groundwater.

Many on-shore industrial RC structures in Jordan are operating in very harsh environmental conditions. These structures are subjected to chemical seepage, abrasion and vibration during operation. As a result, severe deterioration and damage to some structural elements have occurred as shown in Figure (1), which

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may jeopardize the safety and/or disrupt the continuity of production (Al-Far, 2006). This could eventually lead to very serious consequences in terms of increased maintenance cost, reduction of productivity and a complete halt to production (due to shutdowns necessary for maintenance). Such an unpleasant outcome could have serious consequences on the national economy.

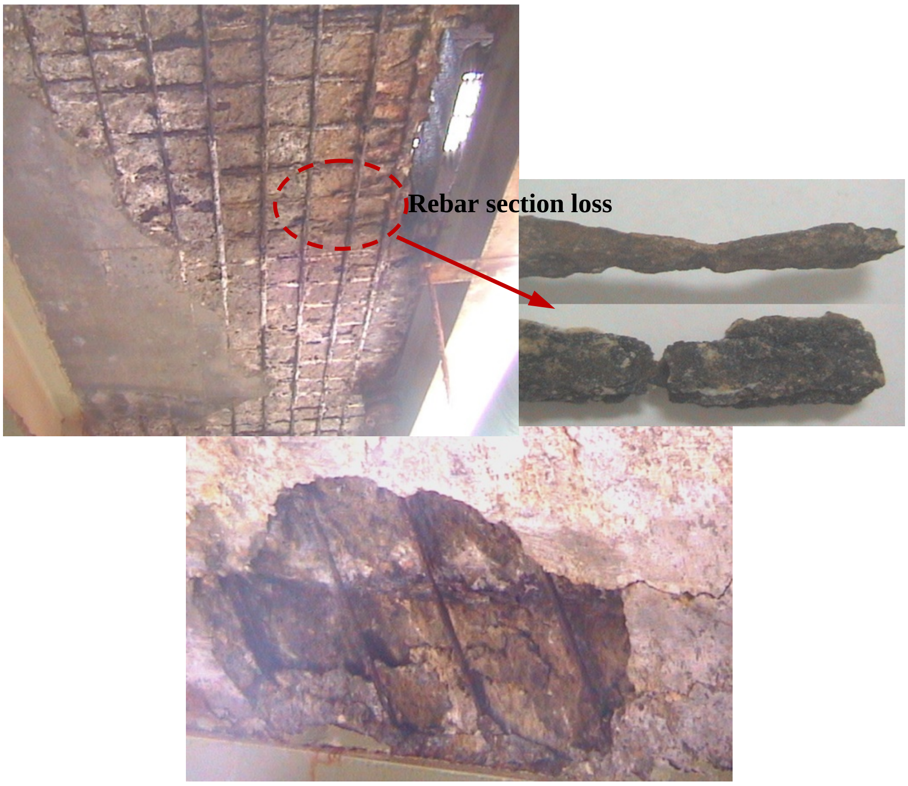

Figure (1): Severe deterioration and damage at the soffit of slabs industrial structures-Dead Sea region

The routine method of repairing deteriorated reinforced concrete structures involves removal of the deteriorated concrete, sandblasting the surfaces of reinforcing steel and, in some cases, replacing the degraded reinforcing bars. Protective coatings are often applied to the exposed, cleaned reinforcing bars. Thereafter, the area from which the concrete has been removed is patched (filled) with high quality concrete or cement mortar or a specially-modified repair mortar. Finally, protective coatings may be applied to concrete surfaces to guard against the ingress of harmful substances into concrete.

Repetitive repairs (frequently every two years) in the form of patch repairs to some of the structural elements at the Dead Sea industrial facilities were reported. There, the repaired parts or, often, the adjacent areas became severely damaged, perhaps more than the original sections before repair. Thus, cyclic application of remedial and preventive measures to the concrete structures became necessary to ensure continued production. To this end, reducing the rate of deterioration of existing industrial structures in Jordan, avoiding premature failure of patch repairs and the need to improve the effectiveness and durability of repair systems in a cost-effective manner were the main purposes of this investigation.

EXPERIMENTAL PROGRAM

Twenty-four reinforced concrete specimens (representing 12 slabs and 12 columns) with a length of (1000) mm, a width of (450) mm and a thickness of (120) mm, were constructed using low quality concrete with high permeability and a (142) mm slump. Specimen group denoted "S" was cast similar to the conventional *in situ* slabs; whereas, specimen group denoted "C" was cast similar to the conventional columns.

Table 1. Repair materials adopted in the investigation

Type of Repair Material		Abbreviation
Concrete Coatings	Acrylic	AC
	Epoxy	EC
	Silane/ Siloxane	SSC
Concrete Lining		HDPE
Corrosion Inhibitors	Organic	OI
	Calcium Nitrate	CNI
Super Plasticizer		SP
Cement Additives	Microsilica	MS
	Ground Granulated Blast Furnace Slag	GGBFS
Polymer Repair Mortars		PRM
Steel Coating	Zinc Rich Primer	ZRC
	Epoxy	ECR

All specimens were reinforced with (2ϕ16) mm black bars except two specimens that were reinforced with (2ϕ20) mm epoxy-coated bars. Concrete cover to reinforcing steel was kept at (16) mm in all specimens. The reinforcing bars were pickled in (10) % Sulphuric acid for (10) minutes and then rinsed with excess tap water before placement in the moulds as per ASTM Standards (ASTM G109-92 1992).

A total of (30) cubes of (150 x 150 x 150) mm size using the same concrete mix as the slab and column specimens were also cast for carrying out control tests. These cubes were used to determine the characteristics of the concrete used, such as strength, density, permeability,… etc., in addition to measuring chloride penetration into concrete following exposure to salt solution.

A plastic dike in the shape of a rectangular box of (400 x 600) mm dimensions was fixed on the top surface of each specimen. The bottom sides (borders) of the plastic dikes in contact with concrete were sealed properly using silicon-based sealant to prevent any leakage of the confined solution outside the area of exposure when the test started. Furthermore, the reinforcing steel bars for each specimen were connected together by welding their projected ends by a cross tie to enhance macro-cell action.

In the course of this research study, a two-phase experimental program was implemented. The first phase started when the original specimens were prepared and subjected to accelerated dry/wet cycles by ponding their top surfaces with (3)% saline solution (NaCl) for 2 weeks followed by a dry cycle for another 2 weeks. This phase lasted three years and ended just before the specimens were repaired, but after they experienced severe environmental conditions approximating those encountered in splash and tidal zones of marine environments. Ambient temperature extremes are in the range of (17 to 37)ºC and relative humidity is in the range of (11.5 to 70)%. Control cubes were immersed in the same saline solution (3% NaCl solution) under similar accelerated dry/wet cycles. During this phase, total chloride ion content, half-cell potential, corrosion rate, concrete resistivity, in addition to relative humidity and ambient temperature, were determined at the end of each wet cycle in order to assess the corrosion state of reinforcement in each specimen.

The second phase involved repairing the specimens using selected repair and protection materials listed in Table (1) and exposing them to the same accelerated corrosive cycles for one year. This phase ended when corrosion of reinforcing steel resulted in visible rust spots and cracks on the surfaces of the specimens. The ability of the various repair/protective materials to reduce the progress of corrosion was assessed by visual inspection and electrochemical measurements (half-cell potential and corrosion rate measurements, using the Gecor 6 and GalvaPulse apparatuses), in addition to chloride content determination at the level of the steel.

Repair/Protection Material Application

Patch repairs made of either conventional cement mortar or proprietary repair materials were introduced for reinstatement of the top surfaces of the cut specimens. Wet curing was achieved by using damp burlap for 28 days. Furthermore, steel coatings were applied prior to patching; whereas, concrete coatings were applied after patching. Only the two specimens originally reinforced with epoxy-coated bars did not receive any treatment throughout the period of testing.

The details of repairs along with the labels given for each pair of slab and column specimens after treatment are as follows:

a. Slab 1 & Column 1 (S1SP-EC + C1SP-EC)

- Patch repair: A high performance concrete Super Plasticizer (SP) was added to conventional mortar in the amount of (0.5) liter per (100) kg of cement.
- Concrete coating: a protective high build Epoxy-resin Coating (EC) was applied to the repaired surfaces of the specimens.

b. Slab 2 & Column 2 (S2OI + C2OI)

- Patch repair: Organic corrosion Inhibiting (OI) admixture was added to conventional mortar in the amount of (5) liters/m^3 of concrete.

c. Slab 3 & Column 3 (S3CNI-SSC+ C3CNI-SSC)

- Patch repair: Calcium Nitrite-based corrosion Inhibiting (CNI) admixture was added to conventional mortar in the amount of (10) liters/m^3 of concrete.
- Concrete coating: SilaneSiloxane-based, non-staining water repellent Coating (SSC) was applied to the repaired surfaces of the specimens.

d. Slab 4 & Column 4 (S4CNI-AC + C4CNI-AC)

- Patch repair: Calcium Nitrite-based corrosion Inhibiting (CNI) admixture was added to conventional mortar in the amount of (10) liters/m^3 of concrete.
- Concrete coating: Acrylic reinforced cementitious, flexible waterproof Coating (AC) was applied to the repaired surfaces of the specimens.

e. Slab 5 & Column 5 (S5MS-AC + C5MS-AC)

- Patch repair: Micro-Silica (MS) was added to conventional mortar in the amount of (5) % by weight of Portland cement.
- Concrete coating: Acrylic reinforced cementitious, flexible waterproof Coating (AC) was applied to the repaired surfaces of the specimens.

f. Slab 6 & Column 6 (C6-HDPE)

- Patch repair: Conventional cementitious mortar.
- Concrete coating: Special lining system made of High-Density Poly-Ethylene sheet (HDPE) was applied as a physical barrier to the specimens.
- Slab S6 was excluded from repair, because it was

opened during phase 1 to visually check corrosion of reinforcing bars.

g. Slab 7 & Column 7 (S7MS-SSC + C7MS-SSC)

- Patch repair: Micro-Silica (MS) was added to conventional mortar in the amount of (5)% by weight of Portland cement.
- Concrete coating: SilaneSiloxane-based, non-staining water repellent Coating (SSC) was applied to the repaired surfaces of the specimens.

h. Slab 8 & Column 8 (S8ZRC-PRM-AC+ C8ZRC-PRM-AC)

- Steel coating: Single component Epoxy-based, Zinc Rich primer Coating (ZRC) for steel was applied to the cleaned reinforcement bars.
- Patch repair: Shrinkage compensated, Polymer fiber-reinforced, thixotropic Repair Mortar (PRM) was applied to the specimens.
- Concrete coating: Acrylic reinforced cementitious, flexible waterproof Coating (AC) was applied to the repaired surfaces of the specimens.

i. Slab 9 & Column 9 (S9ZRC-SSC + C9ZRC-SSC)

- Steel coating: Single component Epoxy-based, Zinc Rich primer Coating (ZRC) for steel was applied to the cleaned reinforcement bars.
- Patch repair: Conventional cementitious mortar.
- Concrete coating: SilaneSiloxane-based, non-staining water repellent Coating (SSC) was applied to the repaired surfaces of the specimens.

j. Slab 10 & Column 10 (S10GGBFS-AC + C10GGBFS-AC)

- Patch repair: Ground Granulated Blast Furnace Slag (GGBFS) was added to conventional mortar in the amount of (50) % replacement of Portland cement.
- Concrete coating: Acrylic reinforced cementitious, flexible waterproof Coating (AC) was applied to the repaired surfaces of the specimens.

k. Slab 11 & Column 11 (S11GGBFS-SSC + C11GGBFS-SSC)

- Patch repair: Ground Granulated Blast Furnace Slag (GGBFS) was added to conventional mortar in the amount of (50) % replacement of Portland cement.
- Concrete coating: SilaneSiloxane-based, non-staining water repellent Coating (SSC) was applied to the repaired surfaces of the specimens.

l. Slab 12 & Column 12 (S12ECR + C12ECR)

- Epoxy-Coated Reinforcing (ECR) steel bars were originally used in these specimens and no further treatment was carried out throughout the experimental investigation.

TEST RESULTS

Summary of Phase 1 Results

After (31) days of chloride exposure, the values of total chloride ion content by weight of concrete were (1.45)% at (15) mm depth from the top surface and (0.35)% at reinforcement depth for slab specimens. For column specimens, the values were (0.51) % at (15) mm depth from the side surface and (0.10) % at reinforcement depth. The recorded values of $Cu/CuSO_4$ half-cell potential were more negative than (- 350) mV for all specimens, indicating over (90)% probability of corrosion activity in the embedded reinforcing steel according to ASTM Standards (ASTM C876 1991). However, the high measured values of total chloride ion content and electrical potential were inconsistent with the results of corrosion rates, which were small indicating low corrosion activity. In particular, specimens S12ECR and C12ECR, reinforced with Epoxy-coated bars, had very small corrosion rates indicating passive conditions.

After (858) days of chloride exposure, the values of chloride content by weight of concrete increased to high levels reaching (1.78) % at (15) mm depth from the top surface and (1.15)% at steel level for slab specimens. For column specimens, the values became (1.56)% at (15) mm depth from the side surface and (1.20)% at steel level. The half-cell potentials increased to more negative values with a maximum of (-694) mV. In addition, the recorded values of corrosion rate increased to high values with a maximum of (22.6)$\mu A/cm^2$, indicating high corrosion activity. Again, the high values of half-cell potential and corrosion rate were inconsistent with the real condition of the reinforcing steel that was observed after opening the specimens; visual inspection of reinforcing bars revealed low to moderate corrosion-induced degradation.

The results showed that ASTM C876 guidelines to predict the propensity of reinforcement corrosion were not adequate for the test at hand. This could be attributed to particular test conditions that were beyond the limitations of validity of the guidelines. The small cover of (16) mm and high moisture content of concrete while performing the measurements might be the most significant and influential factors in this regard. Consequently, a threshold value for active corrosion potentials more negative than (-600) mV associated with (90)% probability of corrosion occurrence was proposed. Such a limit was found to be more adequate to predict the state of activity of the embedded reinforcement than that of ASTM C876. The usefulness of electrical resistivity measurements was also limited due to the same causes mentioned above. Obviously, electrical resistivity of specimens with very small cover to reinforcement is dominated by the resistivity of that thin layer.

Moreover, the correlation between the corrosion rates and actual corrosion conditions was weak. Therefore, new guidelines for assessment of corrosion risk were proposed as follows:

$I_{corr} \leq 10\ \mu\ A/cm^2$ ► *Prognosis of corrosion risk is "Passive".*

$10\ \mu\ A/cm^2 < I_{corr} \leq 15\ \mu\ A/cm^2$ ► *Prognosis of corrosion risk is "Low".*

$15\ \mu\ A/cm^2 < I_{corr} \leq 20\ \mu\ A/cm^2$ ► *Prognosis of corrosion risk is "Moderate".*

$20\ \mu\ A/cm^2 < I_{corr} \leq 100\ \mu\ A/cm^2$ ► *Prognosis of corrosion risk is "High".*

Summary of Phase 2 Results

After the first cycle of resumed chloride exposure, the measured half-cell potentials for all repaired specimens became more negative with time, but remained less than the proposed threshold of (-600) mV at which (90) % probability of corrosion occurrence may be expected. In addition, the recorded values for specimens S12ECR and C12ECR, originally reinforced with Epoxy-coated bars, were in the range of (-570 - to -587) mV, indicating passive conditions of reinforcing steel. Half-cell potential readings were consistent with the proposed corrosion rate interpretation; corrosion rates increased with time, but remained in the passive range of prognosis of corrosion risk assessment for all specimens. Passivity of the steel was attributed to the effectiveness of the applied repair/protection materials.

At the end of phase 2 of the experimental program, the potentials of all repaired areas of the specimens exceeded the proposed threshold value of (-600) mV, indicating a probability of over (90)% of corrosion activity. Again, these readings correlated well with the measured values of corrosion rate. The prognosis of corrosion risk for all specimens was described as low to moderate. When the specimens were opened, significant corrosion deposits were observed on the two far ends of all black bars. This corrosion activity was due to ring anode (incipient anode) formation beyond patching boundaries. Such activity resulted in significant potential shifts and corrosion rate readings at the repaired areas that were initially misinterpreted as being due to corroding steel in the repaired zones. In fact, the process of patching promoted further corrosion around the repaired portions, while little or no corrosion activity was taking place in the repaired areas.

Specimens S12ECR and C12ECR, reinforced with Epoxy-coated bars, also yielded high potential and corrosion rate values after four years of exposure. However, when the Epoxy coating was removed to test its adhesion to the underlying steel, the condition of the steel was good with only superficial rust. The performance of these two specimens was, thus, described as "superior".

Chloride ion contents at the steel level were in the range of (0.25 - 1.24) % by weight of concrete, far exceeding the nominal threshold value of (0.03) % at which chloride-induced corrosion initiates, but less than those values measured at the end of phase 1. This result needs to take into consideration the differences in period of chloride exposure and the source of dust samples; being the companion cubes in phase 1 and the

Table 2. Performance ranking of the repair systems/ slab specimens

	Repair System*	SP-EC	OI	CNI-SSC	CNI-AC	MS-AC	MS-SSC	ZRC-PRM-AC	ZRC-SSC	GGBFS-AC	GGBFS-SSC	ECR
Test	Metal loss (Grams)	1.72 (1)	2.4 (6)	2.61 (8)	3.25 (10)	2.48 (7)	1.86 (3)	2.1 (5)	1.82 (2)	3.33 (11)	2.96 (9)	1.88 (4)
	% Chloride Content	0.25 (1)	0.67 (6)	0.83 (8)	0.99 (10)	0.66 (5)	0.37 (3)	0.65 (4)	0.34 (2)	1.24 (11)	0.86 (9)	0.78 (7)
	Actual Steel Condition	Low (1)	Low (1)	Moderate (2)	Moderate (2)	Low (1)	Low (1)	Low (1)	Low (1)	Moderate (2)	Moderate (2)	Low (1)
Overall Ranking		**1 (1)**	**4.33 (6)**	**6 (7)**	**7.33 (9)**	**4.33 (6)**	**2.33 (3)**	**3.33 (4)**	**1.67 (2)**	**8 (10)**	**6.67 (8)**	**4 (5)**

*: Repair systems are presented in the same order of specimen numbers and labeling.

Table 3. Performance ranking of the repair systems/ column specimens

	Repair System	SP-EC	OI	CNI-SSC	CNI-AC	MS-AC	HDPE	MS-SSC	ZRC-PRM-AC	ZRC-SSC	GGBFS-AC	GGBFS-SSC	ECR
Test	Metal loss (Grams)	3.3 (9)	3.22 (8)	3.0 (6)	2.45 (2)	2.62 (3)	3.3** (9)	3.3 (9)	2.65 (4)	3.14 (7)	3.0 (6)	2.84 (5)	1.92 (1)
	% Chloride Content	1.08 (11)	0.74 (3)	0.94 (8)	0.37 (2)	0.81 (5)	0.28 (1)	1.1 (12)	0.76 (4)	0.97 (10)	0.96 (9)	0.84 (6)	0.9 (7)
	Actual Steel Condition	Moderate (2)	Low (1)	Moderate (2)	Low (1)	Moderate (2)	Moderate (2)	Moderate (2)	Low (1)	Moderate (2)	Moderate (2)	Moderate (2)	Low (1)
Overall Ranking		7.33 **(9)**	4 **(4)**	5.33 **(6)**	1.67 **(1)**	3.33 **(3)**	4 **(4)**	7.67 **(10)**	3 **(2)**	6.33 **(8)**	5.67 **(7)**	4.33 **(5)**	3 **(2)**

*: Repair systems are presented in the same order of specimen numbers and labeling.

**: Amount of metal loss was estimated based on visual inspection evaluation, because no electrochemical measurements were possible to take over the barrier.

test specimens themselves at the end of phase 2. Specimen S10GGBFS-AC, utilizing ground granulated blast furnace slag in the repair mortar and acrylic coating to the outer surface of the repaired area, was an exception, since it exhibited the largest cracks on the top surface at the end of the testing program in phase 2 allowing for direct passage of chloride ions.

COMPARISON OF CORROSION PERFORMANCE

To compare the performance of the different repair and protective systems, a ranking system based on metal loss, chloride ion content and actual steel condition was formulated. The results of the individual tests are summarized in Tables (2) and (3) along with their respective ranking in parenthesis underneath each result. Table (2) displays the ranking of repair systems adopted for slab specimens, whereas Table (3) displays the ranking of repair systems adopted for column specimens.

For example, the first field test listed in Table (2) is the metal loss at the end of the experimental program. For this particular test, repair system GGBFS-AC had the largest amount of metal loss; a value of (3.33) grams and scored a performance rank of (11); worst performance. In contrast, repair system SP-EC, utilizing super plasticizer in mortar and Epoxy coating to the repaired surface, had the lowest amount of metal loss; a value of (1.72) grams, and thus scored a performance rank of (1); best performance.

The overall performance ranking of any repair system was taken as the arithmetic average of the ranks of the individual tests of the same system. The repair system that had the lowest overall number was considered to be the most effective. Only the best five systems were marked as shaded cells in Tables (2) and (3).

For slab specimens, the results demonstrated that repair system SP-EC had the best overall performance with a score of (1), followed by ZRC-SSC with a score of (1.67), then systems MS-SSC, ZRC-PRM-AC and ECR, with scores of (2.3), (3.33) and (3.75), respectively. The least effective system was GGBFS-AC whose specimen exhibited the largest cracks on the top surface and had the highest recorded value of chloride ion content. It must be borne in mind that ECR specimens had an extended period of exposure over the whole experimental program unlike the other repaired specimens. Therefore, the readings belonging to Epoxy-coated bars' specimens were adjusted by proportion to enable a reasonable comparison.

For column specimens on the other hand, the results indicated that the repair system CNI-AC had the best overall performance with a score of (1.67), followed by ZRC-PRM-AC and ECR with a score of (3) for each, then systems MS-AC, OI and HDPE, and GGBFS-SSC, with scores of (3.33), (4), (4), and (4.33), respectively. The least effective system was MS-SSC with a score of (7.67).

There is no consistency in the performance ranking of the repair systems, as the relative performance of a given system varied substantially from one test to another and from slab to column specimens. Despite such inconsistency of the relative and overall performance, the following conclusions can be drawn from Tables (2) to (7).

Concrete Surface Protection

a. Slab Specimens

Epoxy Coating had the best performance with a score of (1), followed by SilaneSiloxane Coating with a score of (3.5), then Acrylic Coating with a score of (4.75), as shown in Table (4).

b. Column Specimens

Acrylic Coating had the best performance with a score of (2.75), followed by High Density Polyethylene Sheets with a score of (3.3), then SilaneSiloxane Coating and Epoxy Coating with scores of (4.92) and (6), as shown in Table (5).

Therefore, Epoxy Coating (EC) to concrete is favorable to protect slabs and horizontal concrete applications; whereas, Acrylic Coating (AC) to concrete is favorable to protect columns and vertical concrete surfaces.

Table 4. Performance ranking of the concrete surface protection/slab specimens

Concrete Surface Protection

	SSC				**AC**				**EC**
	CNI-SSC	**MS-SSC**	**ZRC-SSC**	**GGBFS-SSC**	**CNI-AC**	**MS-AC**	**ZRC-PRM-AC**	**GGBFS-Ac**	**SP-EC**
Metal Loss (Grams)	2.61 (6)	1.86 (3)	1.82 (2)	2.96 (7)	3.25 (8)	2.48 (5)	2.1 (4)	3.33 (9)	1.72 (1)
% Chloride Content	0.83 (6)	0.37 (3)	0.34 (2)	0.86 (7)	0.99 (8)	0.66 (5)	0.65 (4)	1.24 (9)	0.25 (1)
Actual Steel Condition	Moderate (2)	Low (1)	Low (1)	Moderate (2)	Moderate (2)	Low (1)	Low (1)	Moderate (1)	Low (1)
Overall Score	4.67	2.33	1.67	5.33	6	3.67	3	6.33	1
Average Score	3.5				4.75				1
Ranking	**2**				**3**				**1**

Table 5. Performance ranking of the concrete surface protection/column specimens

Concrete Surface Protection

SSC				**AC**				**EC**	**HDPE**
CNI-SSC	**MS-SSC**	**ZRC-SSC**	**GGBFS-SSC**	**CNI-AC**	**MS-AC**	**ZRC-PRM-AC**	**GGBFS-Ac**	**SP-EC**	**-**
3.0 (5)	3.3 (7)	3.14 (6)	2.84 (4)	2.45 (1)	2.62 (2)	2.65 (3)	3.0 (5)	3.3 (7)	3.3 (7)
0.94 (6)	1.1 (10)	0.97 (8)	0.84 (5)	0.37 (2)	0.81 (4)	0.76 (3)	0.96 (7)	1.08 (9)	0.28 (1)
Moderate (2)	Moderate (2)	Moderate (2)	Moderate (2)	Low (1)	Moderate (2)	Low (1)	Moderate (2)	Moderate (2)	Moderate (2)
4.33	6.33	5.33	3.67	1.33	2.67	2.33	4.67	6	3.33
4.92				2.75				6	3.33
3				**1**				**4**	**2**

Repair Materials

a. Slab Specimens

- For all slab specimens protected by SilaneSiloxane Coating, the corrosion performance of the different repair materials varied in the following descending order: Super-Plasticized mortar, Zink-Rich Epoxy-Coated steel in normal mortar, Micro-Silica mortar, Calcium Nitrite Inhibitor in mortar, Organic Inhibitor in mortar and Ground Granulated Blast Furnace Slag in mortar. These materials had the following scores, respectively: (1, 1.67, 2.33, 2.67, 3.33 and 5.33) as shown in Table (6).

Table 6. Performance ranking of the repair materials/slab specimens

	*SSC				**No surface protection			***AC				**No surface protection		
	CNI-SSC	MS-SSC	ZRC-SSC	GGBFS-SSC	SP	OI	ECR	CNI-AC	MS-AC	ZRC-PRM-AC	GGBFS-AC	SP	OI	ECR
Metal Loss (Grams)	2.61 (6)	1.86 (3)	1.82 (2)	2.96 (7)	1.72 (1)	2.4 (5)	1.88 (4)	3.25 (6)	2.48 (5)	2.1 (3)	3.33 (7)	1.72 (1)	2.4 (4)	1.88 (2)
% Chloride Content	0.83 (6)	0.37 (3)	0.34 (2)	0.86 (7)	0.25 (1)	0.67 (4)	0.78 (5)	0.99 (6)	0.66 (3)	0.65 (2)	1.24 (7)	0.25 (1)	0.67 (4)	0.78 (5)
Actual Steel Condition	Moderate (2)	Low (1)	Low (1)	Moderate (2)	Low (1)	Low (1)	Low (1)	Moderate (2)	Low (1)	Low (1)	Moderate (2)	Low (1)	Low (1)	Low (1)
Overall Score	2.67	2.33	1.67	5.33	1	3.33	3.33	4.67	3	2	5.33	1	3	2.67
Ranking	**4**	**3**	**2**	**6**	**1**	**5**	**5**	**5**	**4**	**2**	**6**	**1**	**4**	**3**

*: Performance of (CNI, MS, ZRC and GGBFS) repair materials under SSC concrete coating.

**: Performance of (SP, OI and ECR) repair materials with no concrete surface protection.

***: Performance of (CNI, MS, ZRC and GGBFS) repair materials under AC concrete coating.

- For the slab specimens protected by Acrylic Coating, the corrosion performance of the different repair materials varied in the following descending order: Super-Plasticized mortar, Zink-Rich Epoxy-Coated steel in Polymer Repair Mortar, Micro-Silica mortar, Organic Inhibitor in mortar, Calcium Nitrite Inhibitor in mortar and Ground Granulated Blast Furnace Slag in mortar. These materials had the following scores, respectively: (1, 2, 3, 3, 4.67 and 5.33) as shown in Table (6).

Apparently, a repair system consisting of Super-Plasticized mortar patching with either Epoxy or Acrylic Coating to repaired surfaces is a preferred solution for slab treatment.

b. Column Specimens

- For all column specimens protected by SilaneSiloxane Coating, the corrosion performance of the different repair materials varied in the following descending order: Ground Granulated Blast Furnace Slag in mortar, Organic Inhibitor in mortar, Calcium Nitrite Inhibitor in mortars, Zink-Rich Epoxy-Coated steel in normal concrete patch, Super-

Plasticized mortar and Micro-Silica mortar. These materials had the following scores, respectively: (2, 2.33, 3, 3.67, 4.67 and 5), as shown in Table (7).

Table 7. Performance ranking of the repair materials/column specimens

	*SSC				**No surface protection			***AC				**No surface protection		
	CNI SSC	MS SSC	ZRCSS *C*	GGBFS SSC	SP	OI	ECR	CNI AC	MS AC	ZRC PRM AC	GGBFS AC	SP	OI	ECR
Metal Loss (Grams)	3.0 (3)	3.3 (6)	3.14 (4)	2.84 (2)	3.3 (6)	3.22 (5)	1.92 (1)	2.45 (2)	2.62 (3)	2.65 (4)	3.0 (5)	3.3 (7)	3.22 (6)	1.92 (1)
% Chloride Content	0.94 (4)	1.1 (7)	0.97 (5)	0.84 (2)	1.08 (6)	0.74 (1)	0.9 (3)	0.37 (1)	0.81 (4)	0.76 (3)	0.96 (6)	1.08 (7)	0.74 (2)	0.9 (5)
Actual Steel Condition	Moderate (2)	Moderate (2)	Moderate (2)	Moderate (2)	Moderate (2)	Low (1)	Low (1)	Low (1)	Moderate (2)	Low (1)	Moderate (2)	Moderate (2)	Low (1)	Low (1)
Overall Score	3	5	3.67	2	4.67	2.33	1.67	1.33	3	2.67	4.33	5.33	3	2.33
Ranking	**4**	**7**	**5**	**2**	**6**	**3**	**1**	**1**	**4**	**3**	**5**	**6**	**4**	**2**

*: Performance of (CNI, MS, ZRC and GGBFS) repair materials under SSC concrete coating.

**: Performance of (SP, OI and ECR) repair materials with no concrete coating.

***: Performance of (CNI, MS, ZRC and GGBFS) repair materials under AC concrete coating.

- For the column specimens protected by Acrylic Coating, the corrosion performance of the different repair materials varied in the following descending order: Calcium Nitrite Inhibitor in mortar, Zink-Rich Epoxy-Coated steel in Polymer Repair Mortar, Organic Inhibitor in mortar, Micro-Silica mortar, Ground Granulated Blast Furnace Slag in mortar and Super-Plasticized mortar. These materials had the following scores, respectively: (1.33, 2.67, 3, 3, 4.33 and 5.33), as shown in Table (7).

Apparently, a repair system consisting of Calcium Nitrite Inhibitor in concrete patch with Acrylic Concrete to concrete surfaces is a preferred solution for column treatment.

CONCLUSIONS

The conclusions of this two-phase experimental program are the following:

- Adequate evaluation of the state of reinforcement corrosion in concrete structures by nondestructive testing methods is complex. It requires extensive experience and simultaneous consideration of several interrelated factors, such as corrosion rate, half-cell potential, concrete resistivity, chloride ion content and environmental conditions.
- A threshold value for the corrosion potential of (-600) mV *vs.* $Cu/CuSO_4$, at which (90)% probability of corrosion may exist, could be used in lieu of ASTM C876 guidelines. The proposed limit was found to better predict the state of reinforcement corrosion in the test specimens.
- Assessment of corrosion risk can be based on the following criteria in relation to measured corrosion rates:

$I_{corr} \leq 10\ \mu\ A/cm^2$ ► *Risk is "Passive".*

$10\ \mu\ A/cm^2 < I_{corr} \leq 15\ \mu\ A/cm^2$ ► *Risk is "Low".*

$15\ \mu\ A/cm^2 < I_{corr} \leq 20\ \mu\ A/cm^2$ ► *Risk is "Moderate".*

$20\ \mu\ A/cm^2 < I_{corr} \leq 100\ \mu\ A/cm^2$ ► *Risk is "High".*

- The repair/protection materials used in this investigation were effective in extending the lifespan of the test specimens by almost “0.85” times the original lifespan to reach equal conditions; assuming that the lifespans of the original specimens and repaired specimens were (858) and (725) days, respectively. The principal mode of failure associated with patching was ring anode formation in the vicinity of patched areas.
- Super Plasticizer additive to concrete and Epoxy resin concrete Coating (SP-EC) showed the best performance for slab specimens. For column specimens, Calcium Nitrite-based corrosion Inhibiting admixture and Acrylic concrete Coating (CNI-AC) gave the best performance. However, as the test duration was relatively short, the performance of the different repair/protection materials may be expected to change with time. Further monitoring and field studies are needed to corroborate these initial findings.

RECOMMENDATIONS FOR FUTURE RESEARCH

- Further laboratory work to evaluate the performance of the selected repair/protection systems is recommended. The research program needs to consider different levels of concrete quality, especially permeability, various thicknesses of concrete cover, replicate specimens and a wider selection of products from different sources.
- Field exposure of specimens made of the materials/techniques that demonstrate favorable performance is also recommended. This step is important to ensure that promising systems can be put to actual test in harsh environments.

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