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Performance evaluation of repair systems under varying exposure conditions

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Abstract

This paper reports results of a study conducted to assess the performance of commonly utilized repair systems when exposed to some selected exposure conditions, such as marine, belowground, fire, acid, and sulfur fumes. The performance of the selected repair systems was assessed by exposing large-sized repaired concrete specimens to the selected exposure conditions in addition to thermal variations. After the completion of the exposure, the repaired specimens were visually examined for damage to the surface coating and presence of rust stains, salt scaling, etc. The bond of the coating with the substrate was evaluated and then the specimens were crushed to retrieve reinforcing steel bars that were examined for the extent of corrosion, if any. The data developed in this study were utilized to recommend repair systems suitable for the selected exposure conditions.

Keywords: Repair materials; Repair systems; Thermal variations; Reinforcement corrosion; Adhesion

1. Introduction

Reduction in the useful service-life of reinforced concrete construction is a major problem confronting the construction industry worldwide. Repair and rehabilitation of deteriorated concrete structures are essential not only to utilize them for their intended service-life but also to assure the safety and serviceability of the associated components. A good repair improves the function and performance of the structure, restores and increases its strength and stiffness, enhances the appearance of the concrete surface, provides water tightness, prevents diffusion of chloride, oxygen and carbon dioxide to the reinforcing steel, and improves the overall durability of the structure.

Several repair materials, particularly repair mortars, are marketed for repair of damaged concrete structures. The repair mortars are classified into different types, such as cement, epoxy resins, polyester resins, polymer latexes, and polyvinyl acetates. Cement-based or polymer-based materials are the most widely used repair mortars [1–3].

While several repair materials, both cement- and polymer-based are used in the repair and rehabilitation of deteriorated concrete structures worldwide, their performance in the hot weather environments, dominated by extremes of temperature and aridity, has not been thoroughly investigated. A few studies conducted at King Fahd University of Petroleum and Minerals, Dhahran Saudi Arabia [1,4–6], have evaluated the short-term durability of a limited range of commercially available repair materials. Dehwah et al. [4] and Basunbul et al. [5] evaluated the durability performance of some cement- and epoxy-based repair materials. Al-Gahtani et al. [6] evaluated the performance of epoxy resins. Al-Juraifani et al. [7] evaluated the performance of repair mortars under hot-weather conditions and performance criteria were

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suggested. Similar criteria were proposed by Vaysburd et al. [8]. Al-Dulaijan et al. [9,10] evaluated the performance of several generic types of surface coatings. Maslehuddin et al. [11] evaluated the performance of steel primers and suggested relevant performance criteria.

As discussed earlier, few studies [1,4–7,9–11] were conducted to assess the performance of repair materials, particularly repair mortars, surface coatings, and steel primers. However, the performance of a complete repair system needs to be evaluated.

This paper reports results of a study conducted to assess the performance of complete repair systems, particularly when exposed to conditions that are commonly encountered in the field, especially in industrial environments.

2. Methodology of research

The details of the ten repair systems and seven exposure conditions investigated are summarized in Tables 1 and 2, respectively.

2.1. Casting of reinforced concrete specimens

Reinforced concrete beam specimens, measuring $0.25 \times 0.25 \times 2.5$ m, with two 16 mm diameter steel bars at the top and bottom and 8 mm diameter stirrups spaced at 15 cm, were prepared for marine and below-ground exposures. Reinforced concrete slab specimens, measuring $1 \times 1 \times 0.15$ m, with two steel meshes of 12 mm diameter steel bars at 150 mm center to center and placed at the mid depth, were prepared for other exposures. Figs. 1 and 2 show the dimensions of the beam and slab specimens, respectively.

The concrete mixtures were prepared with a cement content of 370 kg/m^3 and an effective water–cement ratio of 0.40. ASTM C 150 Type I cement was utilized in the preparation of the concrete mixtures.

Prior to casting, wire leads were soldered to the top and bottom mesh of the reinforcing steel bars. These connections were utilized to measure the corrosion potentials. The steel bar-wire interface was coated with cement paste followed by an epoxy coating to avoid localized corrosion of reinforcing steel due to the galvanic effect. Electrode ports were also installed in both the beam and slab specimens prior to casting of concrete to measure corrosion potentials. The electrode ports consisted of 6 mm diameter Teflon tubes of short length that were inserted to the reinforcement level. The reference electrode was fixed in the electrode port to measure the corrosion potential near the steel level; thus minimizing the inaccuracies in the potential measurements due to the high resistivity of concrete, particularly in the

Table 1
Repair systems investigated

System	Repair mortar	Bond coat	Steel primer	Surface coating
1	Free flowing micro-concrete	Wetting only (saturated surface dry condition)	Single-component zinc-rich epoxy	Chloride/sulfate barrier
2	Pre-bagged acrylic modified mortar	3-Component epoxy resin and modified cement based slurry	Single component zinc-rich epoxy	Chloride/sulfate barrier
3	Portland cement mortar/concrete (max. w/c ratio = 0.38)	Wetting only	Composite cement epoxy	Chloride/sulfate barrier
4	Portland cement/micro-silica mortar (max. w/c + s = 0.38) (micro-silica = min 5% of total cement)	Portland cement/micro-silica slurry (proportions as mortar)	Composite cement epoxy	Chloride/sulfate barrier
5	Portland cement micro-silica mortar (max. w/c + s = 0.38) (micro-silica = min 5% of total cement)	Portland cement/micro-silica slurry (proportions as mortar)	Composite cement epoxy	Chemical-resistant epoxy
6	Resin mortar	None	Single-component zinc rich epoxy	Chemical-resistant epoxy
7	Shotcrete (dry mix) Portland cement (max. w/c = 0.38)	None	None	Chemical-resistant epoxy
8	Shotcrete (dry mix) Portland cement + micro-silica (max. w/c = 0.38) (micro-silica = min. 10%)	None	None	Chemical-resistant epoxy
9	Resin injection grout	None	None	Chloride/moisture resisting, i.e. polymer modified cement
10	Cement injection grout (max. w/c = 0.38)	None	None	Chloride/moisture resisting, i.e. polymer modified cement

Table 2
Repair systems and exposure conditions

Exposure	Repair systems investigated									
	1	2	3	4	5	6	7	8	9	10
Marine (salt spray; UV)	√	√	√	√			√			
Below ground (chloride–sulfate solution at 40 °C)	√	√	√	√		√				
Acid (2% H_2SO_4)					√	√			√	
Sulfur fumes					√	√		√		
Potable water (water retaining structures)									√	√
Saline water (water retaining structures)									√	√
Fire damage							√	√		

coated specimens. The locations of the electrode ports are shown in Figs. 1 and 2.

2.2. Damage and repair of reinforced concrete specimens

2.2.1. Marine and belowground exposures

Concrete beam specimens for marine and belowground exposures were cast with a chloride content of 1% by weight of cement, and the concrete in an area measuring $0.5 \times 0.5 \times 0.075$ m was damaged in the center of the beam. The damaged area was obtained by inserting Styrofoam boards of required dimensions at the required locations prior to pouring concrete in the forms. After curing, the Styrofoam boards were removed and the empty space in the concrete specimen was repaired with the selected repair material. The damaged area was repaired with repair systems 1, 2, 3, 4, or 7 for the marine exposure, and repair systems 1, 2, 3, 4, or 6 for belowground exposure. Six control specimens that were neither damaged nor repaired, three each for marine and belowground exposures, were also cast.

2.2.2. Fire

Concrete slab specimens, measuring $1 \times 1 \times 0.15$ m, were cast to evaluate the performance of the repair systems selected for repairing fire-damaged concrete. Fire damage was inflicted over an area of 0.5×0.5 m of the slab. This was done by placing the concrete specimen over an oven and heating the exposed concrete surface until the temperature on the unexposed surface was of 300 °C. The temperature on the unexposed surface was monitored by fixing thermocouple wires.

The fire-damaged concrete was removed using a light pneumatic hammer so that an area of $0.5 \times 0.5 \times 0.075$ m was exposed. The exposed area was sand blasted to clean the reinforcing steel of the rust product, if any, and to roughen the exposed concrete surface. The exposed area was then repaired by shortcreting. Two types of cements, namely Type I (System 7) and Type I plus silica fume (System 8) were utilized to repair this group of concrete specimens.

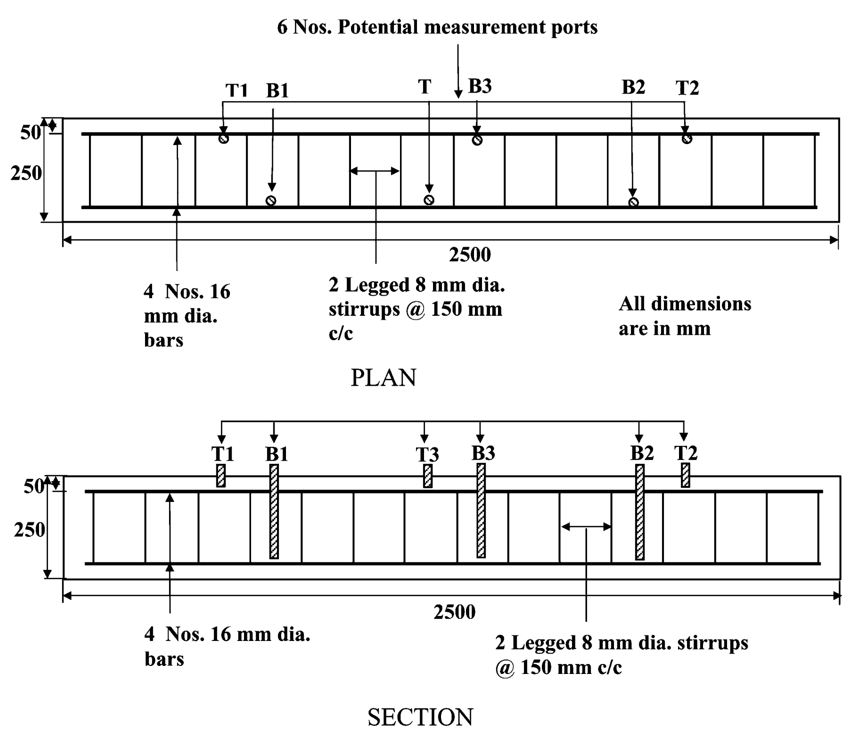

Fig. 1. Dimensions of the beam specimens.

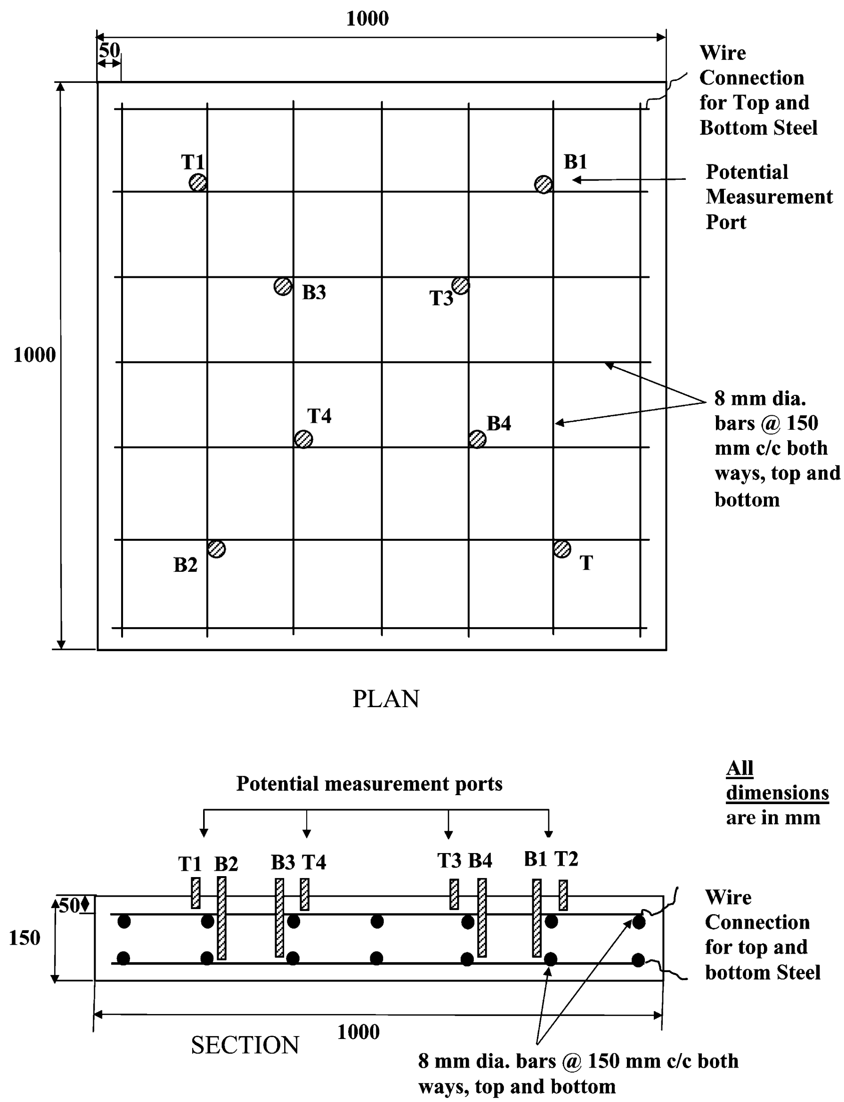

Fig. 2. Dimensions of the slab specimens.

After shortcreting, the concrete specimens were cured for 14 days under wet burlap. They were then cleaned and the selected coating was applied on the concrete surface. The coating was allowed to dry and then the specimens were placed on the racks in the exposure chamber. Three control specimens that were neither damaged nor repaired were also prepared.

2.2.3. Acid and sulfur exposures

Concrete slab specimens, measuring $1 \times 1 \times 0.15$ m, were prepared to evaluate the repair systems most suitable for exposure to the acid and sulfur fumes. After removing the concrete in the central $0.5 \times 0.5 \times 0.075$ m area, the reinforcing steel bars were cleaned by sand blasting such that they became clean and shiny. The bars and the exposed concrete surface were washed with potable water to remove loose rust, dust, etc. The reinforcing steel bars were then dried to remove excess moisture and the appropriate steel primer was applied on the steel bar. After the application of the steel primer, the bond coat was applied on the exposed concrete surface. The damaged area was then repaired with the selected repair material.

The repair material was allowed to cure as required by the manufacturer or to the point at which it was ascertained that sufficient strength has been achieved. The exposed surface was cleaned with a wire brush followed by pressurized air to remove loose dust. After surface preparation, the selected surface coating was applied on the repaired and the unrepaired areas of the slabs. The number of coats and the coverage rate of the surface coating were those recommended by the manufacturer. The surface coating was allowed to dry prior to placing the specimens on the racks in the exposure chamber.

2.2.4. Potable and saline water exposures

Concrete slab specimens, measuring $1 \times 1 \times 0.15$ m, were utilized for assessing the performance of two repair systems, namely 9 and 10, for repairing the cracked concrete. Cracks were induced by applying a three-point load with the use of hydraulic jacks. The load was gradually increased such that well-defined cracks of more than 0.2 mm wide were induced on the lower side of the concrete slab.

The cracked specimens were repaired by using system 9 (epoxy injection material) and system 10 (polyurethane-based injection material). For the purpose of injecting the repair material, several nipples were inserted into the crack and the remaining length of the crack was sealed with putty. The repair material was then injected into the crack, starting from the lower nipple until it oozed out from the upper nipple. This process was continued until the entire crack was filled with the injection material.

After sufficient curing of the crack injection material, the nipples were removed and the surface was ground and sealed with the putty. The putty itself was ground prior to the application of the surface coating. The surface coating was allowed to dry before placing the specimens on the exposure racks.

Figs. 3–5 show the setup utilized for inducing cracks, a close-up view of a cracked specimen and the process of repairing a cracked concrete specimen, respectively.

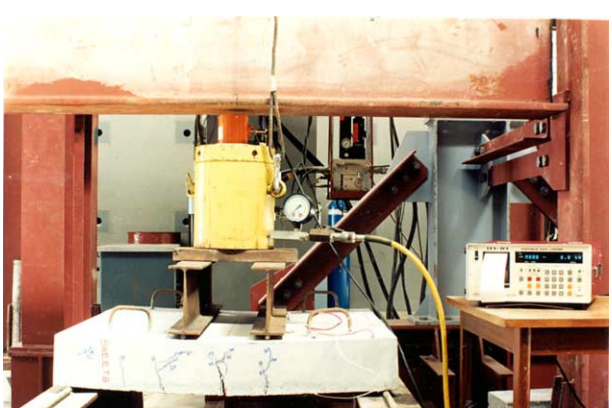

Fig. 3. Experimental setup utilized to induce cracks in the slab specimens.

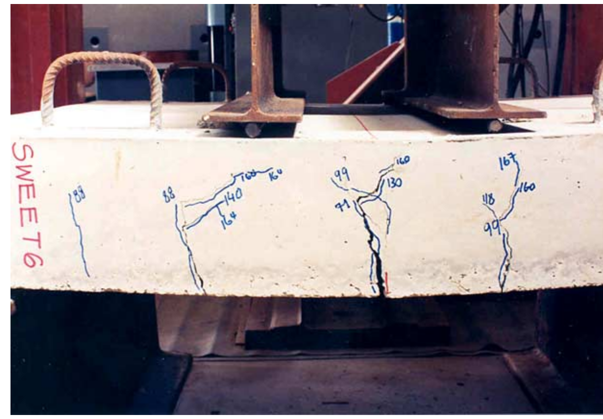

Fig. 4. Close-up view of a cracked concrete specimen.

Fig. 5. Repair of cracks in the slab specimens by epoxy injection.

2.3. Exposure chambers

Two exposure chambers were fabricated to expose the repaired and control specimens to the conditions detailed in Table 2. The first chamber, measuring 16×9 m, was fabricated to expose the concrete specimens to thermal variations in addition to other exposure conditions. The chamber was thermally insulated to maintain the desired temperature. A 12-ton air conditioning unit was installed outside the laboratory and cool air was circulated in the chamber through the ducts. Four heaters each of 10 kW capacity with air blowers were installed at four locations in the exposure chamber. The air conditioning and the heater units were connected to a programmed power supply. This was done to create thermal cycles. The heaters were operated for 3 h, followed by air conditioning unit for the remaining 9 h. The thermostats on the heaters were set at 70 °C. The air-conditioning unit was set to maintain a temperature of 30 °C in the exposure chamber.

The second chamber, measuring 5.5×3.5 m, was fabricated to expose the repaired and control concrete components to belowground conditions. A constant temperature of 40 °C was maintained in this chamber by installing six room heaters of 1.5 kW capacity each. Two wall-mounted fans were fixed to circulate the hot air and maintain a uniform temperature throughout the exposure chamber. The walls and roof of this chamber were insulated to minimize heat losses.

Storage racks were utilized to arrange 89 repaired and control concrete specimens in the two exposure chambers.

Fig. 6. Concrete beam specimens exposed to salt spray and UV light (marine exposure).

Fig. 7. Concrete slab specimens exposed to sulfur fumes.

2.4. Exposure

2.4.1. Marine

In this category, the repaired (systems 1, 2, 3, 4, and 7) and control concrete specimens were placed on three racks and exposed to salt spray, thermal cycling, and UV light. Sodium chloride (5%) solution was sprayed on the concrete specimens through an automated salt spray system. The salt solution was sprayed on the top of the concrete specimens every 2 h for 5 min. Fig. 6 shows the arrangement of the concrete specimens along with the salt spray system and UV lamps.

2.4.2. Acid

The repaired and control concrete slab specimens were exposed to thermal cycling and acid. Twelve concrete slab specimens were placed on the storage racks and the repaired surface was exposed to acid. A Plexiglas frame, measuring $0.5 \times 0.5 \times 0.1$ m, was fixed on the surface of each concrete specimen to hold the acid. A known volume, two liters, of 2% sulfuric acid was placed in the barrier every two weeks. The Plexiglas frame was covered with a plastic sheet to minimize evaporation of acid.

2.4.3. Sulfur fume

The repaired and control concrete specimens in this category were exposed to sulfur fume and thermal cycling. The repaired face, measuring 0.5×0.5 m, was exposed to the sulfur fumes. For this purpose, each of the concrete specimen was placed on a metallic tank filled with sulfur to three quarter of its depth. The bottom of the tank was heated using electric heaters to keep the sulfur in a molten form. Fig. 7 shows the arrangement utilized to expose the concrete specimens to sulfur fumes.

2.4.4. Potable and saline water

This category represents the repair of cracks in the concrete water-retaining structures. The water-retaining structures are exposed to UV light on the outer face and hot water, around 40 °C, in the inner face. In order to simulate these conditions, the unrepaired face of the concrete slab specimens in this group was exposed to a water head of 0.5 m, while the repaired face was exposed to thermal variations and UV light. A total of 18 concrete specimens were exposed to this condition. The concrete specimens were placed on the exposure racks and a cylindrical fiberglass tank, measuring 0.7 m in diameter, was sealed on the unrepaired face. The fiberglass tanks were fitted with two water heaters to maintain water at 40 °C. A water head of 0.5 m was maintained on all the concrete specimens. The level of water in the tanks was monitored through a glass tube installed on the fiberglass tanks. The chemical composition of the potable and saline water is shown in Table 3.

The repaired face was exposed to thermal variations and UV exposure. For UV exposure, two UV lamps were fixed below the unrepaired face of the specimen. Fig. 8 shows the repaired and control concrete specimens exposed to potable and saline water.

Table 3
Chemical composition of potable and saline water

Parameter	Saline water	Potable water
pH	7.5	7.2
Total dissolved solids, mg/l	3338	294
Conductivity, μmhos/cm	5000	480
Turbidity, NTU	4.5	0.8
Alkalinity, bicarbonate as $CaCO_3$, mg/l	180	114
Chloride, mg/l	893	60
Sulfate ($SO_4^=$), mg/l	700	18
Total hardness, mg/l	1187	28
Sodium and potassium, mg/l	449	87

Fig. 8. Repaired and control slab specimens exposed to potable and saline water.

2.4.5. Fire

The repaired face of the concrete specimens, repaired after damage due to fire, was exposed to thermal variations and UV light.

2.4.6. Belowground

This exposure is representative of the belowground conditions in a hot and aggressive climate. In such situations the sub-structural components are exposed to groundwater with high salinity and a temperature of 40 °C. Eighteen reinforced concrete beam specimens were placed on three exposure racks and exposed to a constant temperature of 40 °C, while a mixed chloride (15% Cl^-) and sulfate (2.1% SO_3) solution was ponded on the repaired face. Plexiglas frames were fixed on the concrete specimens in order to retain the chloride–sulfate solution. Air circulating fans were fixed on the bottom of the specimen to force evaporation of the salt solution from below. Fig. 9 shows the concrete specimens exposed to below ground conditions, i.e. chloride–sulfate solution at 40 °C.

Fig. 9. Control and repaired concrete beam specimens exposed to belowground conditions.

3. Results and discussion

The control and repaired concrete specimens were exposed to the selected exposure conditions for eight months. The effect of exposure conditions on the performance of the selected repair systems was assessed by monitoring corrosion potentials and damage to the coating during the exposure period. The corrosion potentials were measured according to ASTM C 876 using a saturated calomel reference electrode (SCE). The corrosion potentials were measured by fixing the reference electrode in the electrode port. This facilitated the measurement of the potential in the vicinity of the reinforcing steel. After terminating the exposure, the concrete specimens were taken out of the exposure chambers and tested to evaluate the performance of the selected repair systems under the selected exposure conditions. After the completion of the exposure, the specimens were tested to evaluate the adhesion of the coating according to ASTM D 4541. The exposed concrete specimens were then broken to remove the reinforcing steel. The reinforcing steel was visually inspected to assess the degree of reinforcement corrosion. The extent of reinforcement corrosion was indicated by a corrosion rating varying from 0 to 5. The interpretation of the corrosion rating is noted below:

Corrosion rating	Condition of reinforcing steel
0	No corrosion
1	Minor discoloration
2	Minor corrosion
3	Moderate corrosion
4	Moderate to severe corrosion
5	Severe corrosion

The data obtained during and after the exposure were analyzed to evaluate the performance of the selected repair systems under the selected exposure conditions with the objective of identifying the repair system/s suitable for the selected exposure conditions.

3.1. Marine exposure

Reinforcement corrosion was not noted on any of the concrete specimens during and after the exposure. Similarly, no damage to the coating, in terms of debonding with the substrate, was noted on any of the concrete specimens.

As stated earlier, the corrosion potentials were measured during the exposure period. Due to paucity of space these data are not presented. However, the findings of the data are briefly discussed. The corrosion potentials were generally more negative than −270 mV SCE, the threshold value recommended by ASTM C 876 for 90% probability of corrosion in all the concrete specimens. The higher negative values, however, do not necessarily indicate that reinforcement corrosion has been initiated. It is possible that the higher negative values are the result of the saturated condition of the specimen under which the potential values tend to be more negative than −270 mV SCE. Such a situation is commonly encountered in the structural components submerged in water. Under submerged or water-saturated conditions, the lack of oxygen does not permit the formation of γ-Fe_2O_3, giving the impression that the passive layer is not formed. However, the rate of reinforcement corrosion will be very low.

The corrosion potentials in the concrete specimens repaired with repair systems 1 and 2 were generally more positive than the control concrete specimens and those repaired with other repair systems, namely 3, 4 and 7.

The adhesion strength of the coatings utilized to repair the concrete specimens exposed to marine conditions was in the range of 1.0–2.4 MPa.

Information on the condition of the reinforcing steel, after exposure to marine conditions, is summarized in Table 4. A minor discoloration of the steel bars (severity rating of 1) was noted in the control concrete specimens while minor discoloration to minor corrosion (severity rating of 1–2) of the steel bars was noted in the concrete specimens repaired with repair systems 1, 2 and 7. Minor to moderate corrosion of the steel bars (severity rating between 2 and 3) was noted in the concrete specimens repaired with repair systems 3 and 4.

The performance of the selected repair systems exposed to marine environment is listed in descending order in Table 5.

3.2. Belowground exposure

Signs of reinforcement corrosion or sulfate attack were not noted on any of the specimens during the exposure period. Similarly, no damage to the coating, in terms of debonding with the substrate, was noted on any of the specimens. The corrosion potentials were also more negative than −270 mV SCE.

The adhesion strength of the coatings was in the range of 0.9–3.5 MPa. The highest adhesion value was noted in the concrete specimens repaired with repair system 6.

The information on the condition of steel bars after exposure to the belowground conditions is summarized in Table 6. These data show localized corrosion of he steel bars in the repaired concrete specimens, probably due to the formation of incipient anodes at the interface between the repair material and the parent concrete. Further, the corrosion was concentrated on the top steel bars.

The performance the selected repair systems exposed to belowground conditions is shown in Table 7.

Table 4
Condition of reinforcing steel in the beam specimens exposed to marine environment

Repair system	Position	Reinforcement condition	Rating
Control	Top	No sign of corrosion, minor discoloration seen at places	1
	Bottom	General corrosion in unrepaired area	1–2
1	Top	Corrosion noticed in unrepaired section especially near the ends	1–2
	Bottom	General corrosion in unrepaired area	0–1
2	Top	Corrosion at the interface of the repaired and unrepaired area	2
	Bottom	Corrosion at scattered places	1–2
3	Top	General corrosion in the unrepaired area and at the ends	2–3
	Bottom	General corrosion noticed at the ends	1–2
4	Top	Corrosion concentrated on bottom of the rebars in the repaired area with minor corrosion in unrepaired area	2–3
	Bottom	General corrosion in unrepaired area	1–2
7	Top	General corrosion in unrepaired area. Sign of corrosion seen in the repaired area	1–2
	Bottom	General corrosion in unrepaired area	1–2

Table 5
Performance rating of the selected repair systems under marine conditions

Repair system	Performance rating
7	1
1	2
2	3
3	4
4	5

3.3. Sulfur exposure

The corrosion potentials in both the control and repaired concrete specimens were more positive than −270 mV SCE. This was noted on the reinforcing steel, both near and away from the surface exposed to the sulfur fumes. This indicates that the sulfur fumes have not

Table 6
Condition of reinforcing steel in the beam specimens exposed to below ground conditions

Repair system	Position	Reinforcement condition	Rating
Control	Top	Corrosion on the under side of rebar at one location	1–2
	Bottom	No signs of visible corrosion	0
1	Top	General corrosion concentrated in repaired area mostly underneath the rebar	2–3
	Bottom	No signs of corrosion noticed	0
2	Top	General corrosion in the repaired and unrepaired area	2–3
	Bottom	General corrosion noticed at the ends	0–1
3	Top	General corrosion concentrated in repaired area mostly underneath the rebar	3–4
	Bottom	No signs of corrosion noticed	0
4	Top	General corrosion at the interface extending into repaired and unrepaired area	3
	Bottom	Slight corrosion seen at scattered places	1–2
6	Top	General corrosion at the interface extending into repaired and unrepaired area	2–3
	Bottom	No signs of corrosion	0

Table 7
Performance rating of selected repair systems exposed to belowground conditions

Repair system	Performance rating
6	1
1	2
2	3
4	4
3	5

affected the passivity of steel within the exposure duration of eight months. The passive conditions noted on the steel bars in the concrete specimens exposed to sulfur fumes may also be attributed to the lack of moisture in the specimens. It should be noted that moisture and oxygen are essential for the corrosion process.

Damage to the concrete or the coating was not noted on any of the concrete specimens. This is apparently due to the lack of moisture at the face of the specimen exposed to sulfur fumes. The combined presence of moisture and sulfur fumes leads to the formation of sulfuric acid, which is very detrimental to concrete. The adhesion values were in the range of 1.4–3.5 MPa.

Information on the condition of the steel bars after eight months of exposure to sulfur fumes is summarized in Table 8. Signs of reinforcement corrosion were not noted on any of the steel bars in both the control and the repaired concrete specimens, except minor corrosion that was noted at the interface of the repair material and the parent concrete in the specimens repaired with repair system 6. This may be due to the variation of the pH values of the repair material and the parent concrete that leads to the formation of incipient anodes.

The performance of repair system 6 was relatively better than that of repair systems 8 and 5.

3.4. Acid exposure

Deterioration of coating was noted as early as seven days of exposure in the control concrete specimens and those repaired with repair system 5. Deterioration was not noted on the concrete specimens repaired with repair systems 6 and 8. However, after about one month of exposure, coating deterioration was noted on the concrete specimens repaired with repair system 8 while deterioration was not noted on the concrete specimens repaired with repair system 6. After eight months of

Table 8
Condition of reinforcing steel in the slab specimens exposed to sulfur fumes

Repair system	Position	Reinforcement condition	Rating
Control	Top	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0
5	Top	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0
6	Top	No visible sign of reinforcement corrosion	0
	Bottom	Minor corrosion noted on two rebars between 3 and 10 cm in length at the interface of repaired and unrepaired area	1–2
8	Top	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0

exposure, minimal damage was noted on the concrete specimens repaired with repair system 6, while all the other concrete specimens exhibited deterioration of varying intensity.

The corrosion potentials on the steel bars in the control and repaired concrete specimens were generally more positive than −270 mV SCE. However, corrosion potentials more negative than −270 mV SCE were noted at some locations, particularly on the top reinforcement, in some of the concrete specimens repaired with repair systems 6 and 8.

Figs. 10–13 show the control and repaired concrete specimens after exposure to sulfuric acid for eight months. Significant concrete deterioration was noted in the control concrete specimens while enhanced deterioration of the coating and the repair material was noted in the concrete specimens repaired with repair system 5. Only coating deterioration was noted on the concrete specimens repaired with repair system 8. Minimal deterioration was noted on the concrete specimens repaired with repair system 6. The adhesion values were in the range of 1.6–2.3 MPa.

Fig. 10. Control concrete specimens exposed to sulfuric acid.

Fig. 11. Concrete specimens repaired with system 5 and exposed to sulfuric acid.

Fig. 12. Concrete specimens repaired with system 8 and exposed to sulfuric acid.

Fig. 13. Concrete specimens repaired with system 6 and exposed to sulfuric acid.

Information on the condition of steel bars after exposure of the control and repaired concrete specimens to acid is summarized in Table 9. Reinforcement corrosion was not noted in the control specimens, while minor to localized corrosion was noted in the repaired concrete specimens. Corrosion was mostly noted on the top bars. This could be attributed to the variation in the pH of the concrete and the repair material that leads to the formation of incipient anodes.

The performance rating of the selected repair systems exposed to acid is shown in Table 10.

3.5. Exposure to potable water

Corrosion stains or cracking were not noted on any of the specimens during the exposure period. Similarly, damage to the coating, in terms of debonding with the substrate, was not noted on any of the concrete specimens.

The corrosion potentials were generally more positive than −270 mV SCE. The adhesion values were in the range of 0.55–0.60 MPa. These low adhesion values

Table 9
Condition of reinforcing steel in the slab specimens exposed to sulfuric acid

Repair system	Specimen	Position	Reinforcement condition	Rating
Control	1	Top	No sign of reinforcement corrosion	0
		Bottom	No sign of reinforcement corrosion	0
	2	Top	No sign of reinforcement corrosion	0
		Bottom	No sign of reinforcement corrosion	0
5	1	Top	Reinforcement corrosion seen on the outer edge bar in unrepaired section while no visible corrosion seen in the repaired area	1–2
		Bottom	General corrosion of reinforcement steel in unrepaired area	0–1
	2	Top	Pitting corrosion seen on one bar (small length) in the repaired section	0–1
		Bottom	No sign of visible corrosion of reinforcement	0
6	1	Top	General corrosion noticed at the interface of repaired and unrepaired area	1–2
		Bottom	General corrosion of reinforcement steel in unrepaired area	0–1
	2	Top	Corrosion of mesh in repaired area extending slightly into unrepaired area. General corrosion in about 50% of mesh in repaired area	1–2
		Bottom	Visible sign of general corrosion of reinforcement in unrepaired area	1
8	1	Top	No visible sign of reinforcement corrosion	
		Bottom	General corrosion of reinforcement steel in unrepaired area	1
	2	Top	Signs of corrosion seen in two bars approximately 3 cm length at the interface of repaired and unrepaired area	0–1
		Bottom	No visible sign of reinforcement corrosion	0

Table 10
Performance rating of the selected repair systems exposed to acid

Repair system	Performance rating
6	1
8	2
5	3

Table 11
Condition of reinforcing steel in the slab specimens exposed to sweet water

Repair system	Position	Reinforcement condition	Rating
Control	Top[a]	Minor signs of reinforcement corrosion	0–1
	Bottom	No visible sign of reinforcement corrosion	0
9	Top	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0
10	Top	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0

[a] Top steel is near the exposed surface.

are expected, as the coating is cement-based. Further, the adhesive strength of the coating in both the repaired and unrepaired areas is similar, indicating that the exposure conditions, namely UV light and thermal variations, did not affect the adhesion of the selected coating.

Information on the condition of the steel after exposure to potable water is summarized in Table 11. Minor corrosion was noted on the steel bars in the control specimens while corrosion was not noted in the repaired concrete specimens.

3.6. Exposure to saline water

The repaired concrete specimens were monitored to note any crack movement and signs of reinforcement corrosion or other damage during the exposure period. Reinforcement corrosion or cracks were not noted during the exposure period. Similarly, no damage to the coating, in terms of debonding with the substrate, was noted on any of the concrete specimens.

The corrosion potentials on steel in the repaired concrete specimens were generally more positive than −270 mV SCE. No apparent damage, due to reinforcement corrosion or cracks, were noted on the concrete specimens. The adhesion values were in the range of 0.5–0.6 MPa.

Information on the condition of steel bars after exposure to saline water is summarized in Table 12. These data indicate no visible corrosion in the specimens exposed to saline water, except minor corrosion of a severity ranging from 0 to 1 that was noted on one of the top steel bars in a concrete specimen repaired with repair system 9.

Table 12
Condition of reinforcing steel in the slab specimens exposed to saline water

Repair system	Position	Reinforcement condition	Rating
Control	Top*	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0
9	Top	Pitting corrosion noticed on one bar	0–1
	Bottom	No visible sign of reinforcement corrosion	0
10	Top	No visible sign of reinforcement corrosion	0
	Bottom	No visible sign of reinforcement corrosion	0

* Top steel is near the exposed surface.

3.7. Fire damage

The corrosion potentials were more positive than −270 mV SCE, in both the control and the repaired concrete specimens. No apparent damage was noted on any of the concrete specimens. The adhesion values were in the range of 1.0–2.2 MPa.

Concrete cores obtained from the repaired and control slabs were tested to evaluate the depth of carbonation by spraying phenolphthalein solution. Carbonation was not noted in any of the concrete specimens.

Information on the condition of steel bars is summarized in Table 13. These data indicate no visible corrosion of the steel bars in both the control and repaired concrete specimens, except that signs of minor corrosion with a severity of 0–1 were noted on one of the top bars in the concrete specimen repaired with repair system 8.

4. Recommendations

Since the results of tests conducted on the repaired concrete specimens have not provided a clear indication of the relative performance of the selected repair systems, more than one repair system is suggested for each of the exposure conditions. This will provide flexibility with regard to the choice of appropriate repair system, depending on the size of the repair.

The recommended repair systems for the exposure conditions investigated in this study are as follows:

4.1. Repair systems for repair of marine structures

Two repair systems, namely system 7 and system 1, are recommended for repairing concrete structures exposed to marine conditions. Repair system 7 is more appropriate for large repairs while system 1 may be used for medium to small repairs.

4.2. Repair systems for repair of belowground structures

The performance of repair system 6 was better than that of other repair systems evaluated for belowground conditions. Therefore, this repair system may be utilized if small areas are to be repaired. However, repair system 1 may be used for the repair of large areas.

4.3. Structures exposed to sulfur fumes

The performance of repair system 6 was relatively better than that of repair systems 5 and 8. However, in situations where the resin-based repair mortar (system 6) cannot be used, such as structures requiring large repairs, either system 5 or system 8 may be utilized.

4.4. Structures exposed to acid

The performance of repair system 6 was better than that of repair systems 5 and 8 in the specimens exposed to acid. However, in situations where resin-based repair mortar (system 6) cannot be used, such as structures requiring large repairs, either system 5 or system 8 may be utilized.

4.5. Repair systems for potable water retaining structures

The performance of repair systems 9 and 10 was not significantly different from each other. Therefore, either

Table 13
Condition of reinforcing steel in the fire damaged slab specimens exposed to ultraviolet light

Repair system	Specimen #	Steel	Reinforcement condition	Rating
Control	1	Top	No visible sign of reinforcement corrosion	0
		Bottom	No visible sign of reinforcement corrosion	0
7	1	Top	No visible sign of reinforcement corrosion	0
		Bottom	No visible sign of reinforcement corrosion	0
8	1	Top	Signs of minor corrosion on bars at interface of repaired and unrepaired area	0–1
		Bottom	No visible sign of reinforcement corrosion	0

of these two repair systems could be utilized for the repair of potable water retaining structures.

4.6. Repair systems for saline water retaining structures

The performance of repair systems 9 and 10 was not significantly different from each other. Therefore, either of these two repair systems could be utilized for the repair of saline water retaining structures.

4.7. Repair systems for fire-damaged structures

The performance of repair systems 7 and 8 was not significantly different from each other. Therefore, either of these two repair systems could be utilized for the repair of structures damaged by fire.

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