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COST-EFFECTIVE REPAIRS OF MARINE CORROSION DAMAGE

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ABSTRACT

The selection of materials for corrosion damaged concrete repairs is more difficult than for new construction. The range of materials used is broader than just cementitious materials, because many polymeric compositions can be used effectively for concrete repair. Frequently, the period in which the structure can be brought back into service, the accessibility, and the position of the repair in relation to the level of the tide are also important considerations in the selection of materials and methods for repair.

In the earlier analytical investigation by the first author and collaborators, the time for chloride concentration to reach the threshold value that initiates corrosion in the reinforcement was determined by Fick's law. The structural integrity of the concrete circular pile was compared, before and after repair by finite element modeling beam strength analysis.

The objective of the on-going experimental investigation is the comparison with the analytical values. Six different types of repair are being carried out on sets of three specimens. All the specimens will then be exposed to simulated tidal conditions in seawater tanks to determine their durability. Ultimate strength testing will be carried out to determine the loss of structural integrity.

KEYWORDS

Concrete, corrosion, repair, strength, durability

LITERATURE REVIEW

Corrosion of the reinforcement is one of the major reasons for deterioration of reinforced concrete structures. The corrosion process is very complex, and the modeling is often based on observations, or speculations, rather than a clear understanding of the physical and chemical processes.

Reinforced concrete structures in a marine environment are under constant attack from various elements, which result in the corrosion of the reinforcing steel, thereby weakening the structure and shortening their lifespans. The longer corrosion is left to progress, the more damage it causes; therefore, early detection is essential. Corrosion of reinforcement causes a volume increase of the corroded part of the rebar material, and splitting stresses are induced in the concrete. This often determines the durability of concrete structures. Existing specifications for concrete do not appear to be effective in ensuring long-term performance in the marine environment, and many structures require repairs during their design lives.

The main cause of corrosion of steel in the marine environment is the presence of chloride in the environment. When the percentage of chloride ions at the steel interface exceeds the threshold value, assuming oxygen is present, corrosion initiates. Depending on the effectiveness of the corrosion-protection measures, the penetration of chloride ions into the concrete from seawater, or deicing salts, can result in the corrosion of the reinforcement.

The main form of attack is the penetration and diffusion of chloride ions into the outer layer of the concrete, causing the destruction of the gamma-ferric oxide layer on the reinforcement, and exposing it to corrosion. The selection of materials for concrete repairs is more difficult than for new construction. The range of materials used is broader than just cementitious materials, because many polymeric compositions can be used effectively for concrete repair. Frequently, the period in which the structure can be brought back into service, the accessibility, and the position of the repair in relation to the level of the tide are also important considerations in the selection of materials and methods for repair.

Figure 1: One of the Bryant Patton Bridges Displaying Reinforced Concrete Piles with Significant Corrosion Induced Damage - Florida (reproduced from Concorr, Inc).

Figure 2 illustrates the marine pile zones and their corresponding corrosion susceptibility.

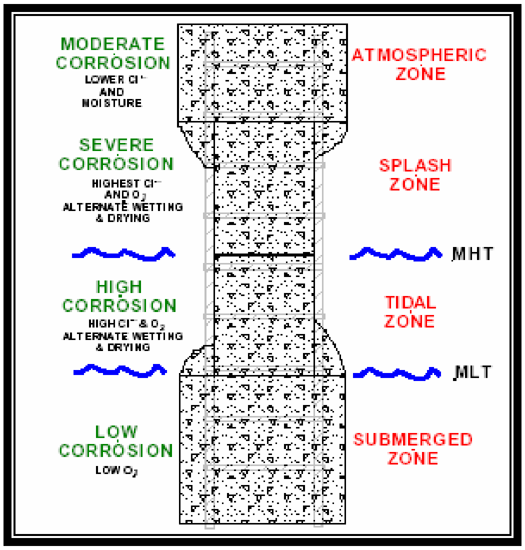

Figure 2: Marine Pile Zones and their Corresponding Corrosion Susceptibility (reproduced from Corrpro Companies, Inc).

Depending on the size, location, and the general function of bridge components, various materials are available for repair. The following influence the selection of materials: a) material compatibility to original concrete, b) environment, including aesthetics, c) cost-effectiveness, d) service life, e) availability, and f) familiarity of the contractors with the product. Therefore, the durability of concrete repair depends both on the careful selection of the repair material, and the method of repairing.

Experience shows that many repairs fail through debonding of the repair material from stresses at the interface caused by drying shrinkage, differential thermal strain, and elastic mismatch (Mehta, 1991). Fig. 3 illustrates a severely deteriorated pile, which had previously been repaired with a fiberglass jacket. High-performance concrete may be differentiated from high strength concrete as that designed for environmental exposure. A well-engineered high-performance repair concrete will typically involve water/binder (cementitious mix) - w/b ratios of 0.40 or lower. In fact, concretes with w/b ratios as low as 0.24 have been investigated in the past, with compressive strengths as high as 140 Mpa (20,000 psi) realized, with associated higher tensile strengths.

Figure 3: Deteriorated Pile – Previously Repaired by Fiberglass Jacketing (reproduced from Concorr, Inc).

A calcium nitrite inhibitor is readily available through W.R. Grace under the trade name “Darey Corrosion Inhibitor” (DCI), or through Degussa Construction Chemicals as Rheocrete CNI (Calcium Nitrite Inhibitor). The calcium nitrite serves to change the ferrous ions produced when reinforcing steel is placed in the alkaline concrete environment into a stable passive layer on the steel which blocks active corrosion.

A new type of fiber reinforced concrete, Slurry Infiltrated Fibrous Concrete (SIFCON), high performance material containing a relatively higher volume of fibrous concrete, has already been used for construction of structures subjected to impact, blast, and dynamic loading, and also for refractory applications, overlays, and repair of structural components because of its high tensile strength and ductility.

For over twenty years, polymers in various forms have played an important part in the protection and repair of piles in the marine environment. The long-term performance and cost effectiveness of styrene-butadiene latex-modified concrete as a repair material for concrete has been evidenced by several case histories. Polymer liquid additives have been shown to increase performance in adhesion, thermal compatibility, water-repellent properties, and freeze-thaw resistance.

Composites offer potential replacements for conventional materials, such as steel and concrete, in infrastructure facilities. FRP (Fiber Reinforced Polymer Composite) is a composite in which strong fibers (glass, aramid, carbon, etc.) are embedded in a matrix of plastic (resin). The advantages are high tensile strength, low density, high-energy absorption, impact resistance, and corrosion- property.

GFRP (Glass Fiber Reinforced Plastic) bars have high resistance to acids, but can deteriorate in an alkaline environment. In a recently completed study for GFRP bars in concrete applications, a particular type of GFRP with some special matrix resins showed excellent durability under high alkaline environment (ACI Committee 440, 1995).

A limited number of tests for tensile strength, moduli of elasticity, and development lengths were carried out for GFRP (E-glass) and Aramid Fiber Plastic (AFRP Kevlar) rods by Pleiman (1987). All bars were deformed by helical wrapping with strands on the outer surface. The GFRP rods indicated lower tensile strength and modulus of elasticity, but better bond strength than the AARP (Kevlar 49) ones.

Even though CFRP (Carbon Fiber Reinforced Plastic) bars also have high resistance to severe environment and higher longitudinal modulus of elasticity than GFRP bars, direct connection to the steel reinforcement or stirrups will cause galvanic corrosion damage on the surface of steel that can cause catastrophic failure of the structure. Splicing of CFRP bars to the steel reinforcement or tendons should be avoided unless proper insulation is provided between the two materials.

In the mid-nineteen eighties, Ohbayashi Co. and Mitsubishi Kasei Co. of Japan developed the concepts of strengthening and retrofitting existing concrete structures using carbon fiber strands and tapes. Three types of structures were targeted: building columns, bridge columns, and chimneys (ACI Committee 440, 1995). These types of composite strengthening repairs and retrofits typically involve layers of structural epoxy and carbon fiber adhered to external surfaces of concrete structural components.

Glass fiber woven roving can be used to repair concrete structures in a similar manner to carbon fiber UD tape wrapping. Mehta (1991) suggested the use of alkali resistant glass fiber reinforcement wrapping on repaired concrete surfaces, with acrylic rubber emulsion film coating, to strengthen the structure. This would also, improve the resistance to ingress of water, chloride, and oxygen for marine concrete structures.

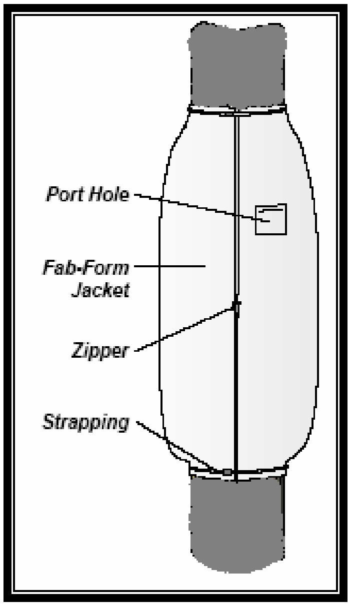

Figure 4: Fab-Form Concrete Pile Jacking (reproduced from Denso North America Inc).

The use of High Density PolyEthylene (HDPE) corrugated exterior/smooth interior pipe jacketing, together with high performance fiber reinforced concrete, is an innovative repair method proposed by Reddy (1995). Many repair processes similar to those reviewed in "Cost-Effective Repairs of Marine Concrete Piles," by Reddy and Ahn (1999), have been carried out in the past. However, most laboratory and field investigations focused mainly on the elimination or deceleration of the corrosion process in repaired marine piles, without addressing durability characteristics. Of course, corrosion in prestressing and reinforcing steel directly affects the durability of the concrete structure, although little research seems to exist on the strength of actual patch material and bonding agents.

Corrosion of steel reinforcement limits the service life of concrete exposed to sea water. Because of the expansion of the steel due to corrosion, concrete piles are extremely susceptible to cracking and spalling. Although steel reinforcing bars are initially protected by the alkaline nature of the surrounding concrete, chloride ions from sea water can slowly infiltrate through the concrete cover and into the reinforcement. All chloride contaminated concrete must be removed and replaced with low shrinkage, low modulus, high creep, high tensile strength patch material having the same thermal expansion and oxygen permeability (Vaysbund and Emmons 2000). Such repairs can barely be carried out under wet conditions and are unrealistic for piles corroding in tidal waters (Mullin et al., 2005).

Surface treatments have been tested by Sagues (1994) at the University of South Florida to determine if the corrosion process can be reduced or eliminated. This process was tested on exposed marine piles above the water line. The two types of surface treatments used included an alkyl alkoxy silane and an alkyl alkoxy siloxene. After a three-year testing period, both the silane and silxane were beneficial in preventing water ingress, but did not cause water to be retained to the extent that unwanted enhancement of corrosion macrocell action would have taken place. Although the Sagues (1994) test was not for an actual concrete repair procedure, it offers valuable insight on surface treatments that can aid in decelerating the corrosion process.

In the past, replacing damaged concrete piles was considered more cost- effective and efficient than repairing. However, new technologies, along with the need for increased infrastructure cost optimization, have focused attention on different repair techniques. The Allen Creek Bridge located in tidal waters in Clearwater Florida has recently undergone repair on its prestressed piles (Mullin et al., 2005). Carbon and glass fiber-reinforced polymer material were wrapped underwater to repair damaged concrete. The underwater wrap consisted of a water-cured polyurethane resin system that can be used with woven glass fabric, unidirectional glass fabric, woven carbon fabric, or unidirectional carbon fabric. This system eliminated the need for cofferdam construction, which is required for dewatering of a site that may adversely cause restrictions to the cross-section of the water body. Linear polarization measurements, taken before and after the wrapping, showed the corrosion in the wrapped section to be consistently lower than that of the unwrapped sections. The findings of Mullins et al. (2005) are encouraging, and suggest that underwater wrapping, without cofferdam construction, may provide a cost-effective solution for pile repair.

Sen and Mullins (2005) of the University of South Florida also conducted a research program using fiber-reinforced polymers to reduce the post-repair corrosion rate in prestressed piles. Their experiments addressed four objectives: (1) The effect of the fiber type and number of FRP layers on the corrosion rate, (2) The effect of exposure on the FRP-concrete bond, (3) The role of surface preparation on FRP performance, and (4) Strengthening the effectiveness of underwater wrap using a newly developed water-actuated resin. Both ambient and accelerated conditions results showed that the FRP wrap was successful in slowing down the rate of corrosion.

Whiting et al. (2001) simulated marine conditions to test conventional repairs, such as patches, sealers and coatings. Their study included a survey of twelve prestressed bridges with evidence of deterioration due to corrosion, as well as an extensive laboratory examination of the repairs. Tests included visual examinations, cover, survey, delamination surveys, half cell potential measurements, corrosion rate (linear polarization) measurements, chloride sampling, and petrographic analysis. All specimens were located in the United States, and had been previously exposed to either the marine environment or inland exposure areas. Materials evaluated in the laboratory repairs included conventional Portland cement concrete, latex-modified fiber reinforced patching mortar, and silica fume concrete containing either organic or inorganic corrosion inhibitors. Specimens were exposed to seawater for approximately 200 weeks. The beams and slabs were subjected to wet and dry cycles, and the piles were exposed to a 24-hr immersion cycle. After testing, Whiting et al. (2001) concluded that there was more deterioration and corrosion in the steel where latex- modified mortar had been used as repair material than where conventional concrete or silica fume concretes were used. Results also showed that the inorganic corrosion inhibitors succeeded in decelerating corrosion rate more so than the organic inhibitors. Although these materials slowed the process of corrosion, they did not appear to ensure long-term protection and should only be considered for temporary repairs.

The method of choice for repairing one of the longest bridges, the Lake Pontchartrain Causeway located in New Orleans, consisted of using an all-polymer encapsulation process. A report written by Trader of the MADCON Corporation described the procedures and findings. Engineers picked the all-polymer or advanced encapsulation process (A-P-E), over other repair processes, such as epoxy paste, crack injection, and several wrap methods, because they believed the A-P-E would not only seal the cracks, but provide a composite barrier that would completely surround the affected length of the pile and eliminate any further deterioration. The basic features of the repair procedure included using translucent FRP jackets and pumping aggregate filled polymer grout into the jackets from the bottom up. In 1998, 21 piles were encapsulated for a length of ten feet in the splash zone. After service for seven years, tests were performed by taking several cores through the old encapsulations. The cores revealed that a tightly bonded composite barrier was still in place. The piles showed no evidence of further deterioration. Tensile tests were also performed on the specimens to determine the bond strength of the encapsulated materials. The test method chosen was an in-situ direct bond test using the Modified Electrometer Method. When the specimens were tested to failure the tensile strength exceeded that of 8,500 psi concrete. The results of the all polymer encapsulation process were cinvincing enough for the engineers to want to use the same process on other damaged piles of the Lake Pontchartrain Causeway Bridge.

While the engineers of the Lake Pontchartrain Causeway claim to have positive results using jackets, Sohanghpurwala and Scannel (1994) indicate that there is no real benefit against corrosion. Two of the reasons are as follows: (1) Capillary action allows water from the submerged section of the pile to rise up the pile, and (2) High levels of chloride ions remain in un-repaired areas. Corrosion may actually be accelerated within these repair zones, because the concrete is never allowed to dry out and there is always a strong presence of oxygen. One example of jackets having a detrimental effect was found in the pilings at the Bryant Patton Bridges in Florida. The Florida Department of Transportation found that over 50% of the piles that had been repaired previously using fiberglass jackets were now deficient. This caused FDOT to start a new rehabilitation project that required the addition of supplementary piles for each and every pile that had been jacketed.

ANALYTICAL PROCEDURES FOR DETERMINING CHLORIDE DIFFUSION IN CONCRETE AND EFFECTIVENESS OF MARINE CONCRETE PILE REPAIRS

Funahashi (1990) developed a finite difference method by which the future chloride concentration could be calculated from the present chloride ion concentrations. As an example, a detailed investigation was conducted on a selected area, where high chloride ion contents were found. To estimate the remaining life of the deck system of an existing parking garage, cored concrete powder specimens at different depths were used to find the initial chloride concentrations, for use in predicting future chloride concentrations.

To develop a finite difference approximation, a grid pattern with time (in years) and concrete depth was produced. Using the known interior and boundary grid points obtained by the present chloride concentration profile, future chloride concentrations at each grid point were calculated. If it is assumed that a threshold chloride concentration to initiate corrosion exists, it is possible to calculate the time when the chloride ion concentration will be exceeded at any given depth.

Funahashi (1990) evaluated the chloride diffusion coefficient from the specimens taken from the aforementioned parking garage to be 0.54 cm^2/year. The threshold chloride concentration of 250 parts per million (ppm) was used and the future chloride concentrations plotted. The surface chloride concentration for the diffusion problem was assumed to be a linear function of the square root of the age of the structure. From the diffusion coefficients obtained from experiments on actual structures and the time dependent constant coefficient mentioned above, the chloride concentration and initiation time of corrosion were predicted.

The calculated chloride profiles related closely to the experimental values. Hence, it was concluded that it was safer to estimate chloride content distribution by assuming that the surface chloride content changes with time, than by assuming it to be constant.

The two following approaches have been recently developed for modeling the behavior of chloride into cracked concrete media:

1) A smeared approach presented by the Japanese Society of Concrete Engineers (1999), where diffusivity and permeability increase according to the extent of damage in the cracked area as measured by a damage variable.

2) A discrete approach by Tsukahara and Uomoto (2000), where the crack geometry is explicitly represented by two surfaces between which flow occurs, and an exchange of moisture and chloride ions is allowed between the crack and the surrounding concrete.

Reddy et al. (2004), carried out an analytical investigation to compare the performance characteristics of marine piles corroded by chloride diffusion, and to determine their structural integrity after repair by several different methods, for both uncracked and cracked concrete. The long-term objective is the comparison of the analytical values with those from the on-going experimental evaluation. The time for chloride concentration to reach the threshold value that initiates corrosion in the reinforcement was determined by Frick's, law, extended to 2-D and 3-D chloride diffusion, for a) uncracked concrete, and b) for cracked concrete with the Simplified Smeared Approach (SSA). The structural integrity of the concrete circular pile was compared, before and after repair, by a) finite element modeling using ANSYS software with the maximum deflection, and b) beam strength analysis to find the moment capacity for cracked and ultimate conditions.

OVERVIEW OF PROPOSED REPAIRS

ONGOING EXPERIMENTAL INVESTIGATION

Six different types of repair, reviewed by Reddy and Ahn (1999), are being carried out on sets of three specimens. All the specimens are exposed to simulated tidal conditions in seawater tanks. Ultimate strength testing will be carried out to determine the loss of structural integrity. Each of six individual mixes was used to repair three piles making a total of 18 specimens. Prior to patching, the reinforcing steel in each specimen was coated with zincrich rebar primer to protect against corrosion during the wet and dry cycles. Forms were then attached to all the 18 concrete piles. The mix designs had been previously calculated; however, adjustments to the water/binder ratio were necessary to increase the lateral flow of the concrete mixtures. This was done to ensure the volume of voids was kept as small as possible. A concrete mixer was used to mix all the concrete and all pouring was done by hand without the use of pumping or shotcrete. Tamping and vibration of the concrete was carried out during the pouring to ensure a minimal void volume. For mixes requiring surface treatments, a time period of 3-4 days after repair were be required for curing times of patch material. The procedures and final mix designs are as follows:

Repair 1: Patch Repair with Slurry-Infiltrated Fiber Concrete, SIFCON, and spliced FRP (glass/aramid) reinforcement

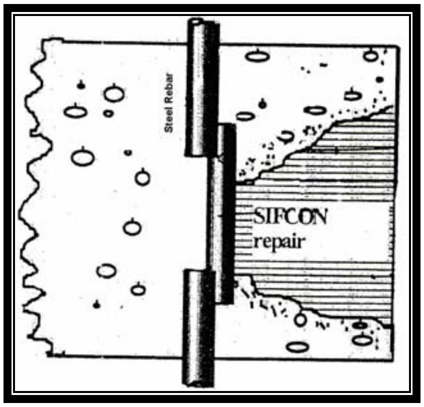

Figure 5: SIFCON Repair

After the steel reinforcement was coated, it was spliced with the FRP reinforcement, Fig. 6. This was achieved by simply cutting the FRP bars to an equal length of the exposed steel reinforcement, and attaching the FRP reinforcement to the steel using wire ties. The ties were also coated with the zincrich rebar primer, Fig 7.

Figure 6: Reinforcement coating with rebar primer

Figure 7: FRP Splicing of cylinders

The forms were then mounted and the concrete mix poured. The mix comprised Type I and Type II Portland cement, sand, fly ash, water, Florida Pearock aggregate, and Polyolefin fibers. The proportions were as follows: 1:2 water to binder, 1:1.25:1.25 (binder:sand:aggregate). The polyolefin fibers consisted of 5.85% by volume in the SIFCON mix. The amounts used for the repair per cylinder are presented in Table 1:

Table 1: Repair 1 – Material Quantities

Material	Quantity (lb)
Cement	9.60
Sand	15.00
Fly Ash	2.40
Aggregate	15.00
Water	6.10

Repair 2: Styrene-butadiene latex polymer grout patching followed by prewet glass fabric wrapping

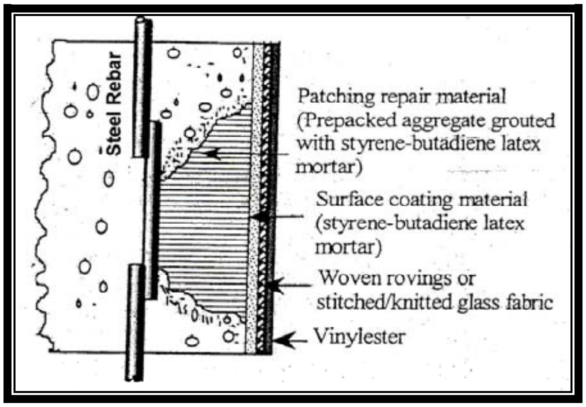

Figure 8: Prewet Glass for Fabric Wrapping

Sika 211, which consists of prepacked aggregate and cement, was used in this mix, along with sand, water, and lime. The proportions were as follows: 1:2.65 water to binder and 1:1.25 binder to sand, with the binder including the aggregate. Lime was added at 10% by volume of Sika 211. Fig. 9 shows the pouring process for the specimens.

Figure 9: Mix Pouring for Repair 2

After the mix was cured, surface treatments consisting of incorporating a styrene-butadiene latex mortar, Sika Latex R, and a vinylester surface coating, Sika 670W, will be used to provide effective salt-damage protection. The amounts used in the repair for each cylinder are given in Table 2.

Table 2: Repair 2 – Material Quantities

Material	Quantity (lb)
Sika 211	10.00
Sand	12.50
Water	3.75
Lime	3.33

Repair 3: Silica fume concrete patching followed by carbon tape and carbon fiber strand wrapping

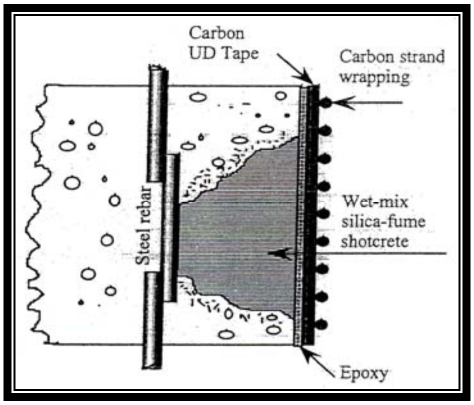

Figure 10: Carbon Wrapping

This mix consisted of Type I and Type II Portland cement, sand, Florida Pearock Aggregate, water, and silica fume with proportions of 1:1.6 water to binder, 1:2.2:2.5 (binder:sand:aggregate). Silica fume was added as replacement of 8.5% by weight of cement, as shown in Fig 11.

Figure 11: Repair 3 – Mix Preparation

The surface of the repair was then wrapped with carbon strand, and it was then covered with a layer of Sikadur 301 mix, in order to glue the wrapping to the specimens. The amounts used in repairs for each cylinder are shown in table 3.

Table 3: Repair 3 - Material Quantities

Material	Quantity (lb)
Cement	8.00
Sand	17.60
Aggregate	20.26
Water	5.00
Silica fume	0.66

Repair 4: Conventional normal concrete patch repair with spliced FRP (glass/aramid) reinforcement.

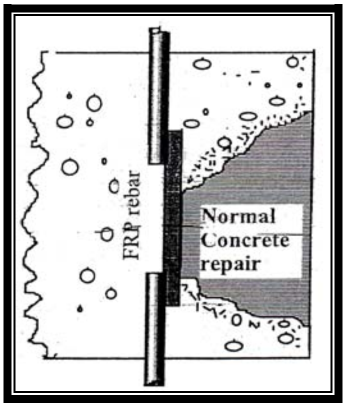

Figure 12: FRP splicing

FRP reinforcement was spliced with the steel reinforcement with the same procedure as Repair 1 before placement of the forms. The concrete mix consisted of Type I and Type II Portland Cement, sand, Florida Pearock aggregate, water, and gypsum, Fig. 13.


Figure 13: Specimen Spliced with FRP


Figure 14. Repair 4 – Mix Preparation

The proportions were as follows: 1:1.25 water to binder, 1:1.4:1.28 (binder:sand:aggregate). Gypsum was added at 10% by weight of cement to facilitate the build-up of thick layers. The amounts used in repairs for each cylinder are shown in Table 4.

Table 4: Repair 4 – Material Quantities

Material	Quantity (lb)
Cement	8.00
Sand	11.20
Aggregate	10.27
Water	6.4
Gypsum	0.8

Repair 5: High performance fiber reinforced concrete patching with HDPE jacket

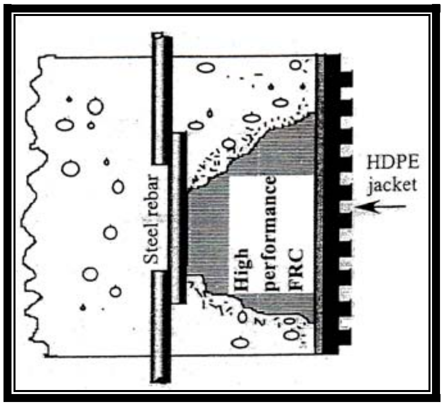

Figure 15: HDPE Jacketing

Repair 5 included using Type I Portland Cement, superplasticizers, Florida Pearock aggregate, sand, silica fume, fly ash, water, and polyolefin fibers. The water to binder ratio was 1:2.88, with silica fume and fly ash each contributing 6.5% to the binder (cementitious mix). The remaining proportions were as follows: 1:1.22:1.09 (binder:sand:aggregate). Polyolefin fibers were added at 1.5% by volume and the superplasticizer at 2% by weight of cement.

Figure 16: Repair 5 Mix Preparation

Figure 17: Repair 5 – Mix Pouring

The patched region sets were wrapped with two semi-cylindrical pieces of corrugated HDPE pipe and sealed together with special polyurethane resin. The amounts used in repairs for each cylinder are shown in Table 5.

Table 5: Repair 5 – Material Quantities

Material	Quantity (lb)
Cement	8.00
Water	3.20
Aggregate	10.00
Sand	11.20
Silica Fume	0.66
Fly Ash	0.66
Superplasticizer	0.16

Repair 6: Modified ASANO refresh method

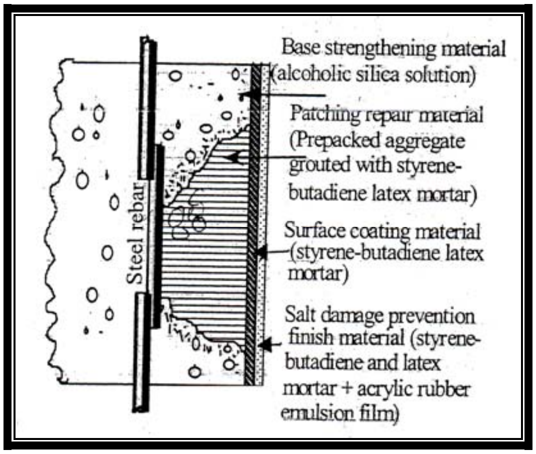

Figure 18. Modified ASANO Process

This mix consists of using Sika 211 with prepacked aggregate and the Sika Latex R as the styrene-butadiene latex mortar. Water, Sand, and Lime were also included in the mix. The water to Sika 211 ratio was 1:2.27, and the Sika 211 to sand ratio 1:1.25 (binder:sand, with the binder including the aggregate). The Sika Latex R was mixed at 10% by weight of Sika 211. Lime was added at only 5% by volume of Sika 211.

Figure 19: Repair 6 – Mix Appearance

Figure 20: Repair 6 – Mix Pouring

Surface coatings of the material, including salt damage prevention finish material, consisting of organic paint, and Sika 670 W (vinylester) were used for the final processing. The amounts used in repairs per cylinder are shown in Table 6.

Table 6: Repair 6 – Material Quantities

Material	Quantity (lb)
Sika 211	10.00
Water	4.40
Lime	0.20
Sika Latex R	1.00
Sand	12.50

CONCLUSIONS

The repair procedures proved to be satisfactory and adequate to continue further testing with seawater exposure. The results, chloride diffusion measurements, and structural integrity, when compared with the earlier investigation of Reddy et al. (2004), will not only enable the evaluation of the cost-effectiveness of the repair procedures used, but also contribute to the development of adequate design methodologies for repair and rehabilitation of concrete marine piles.

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