



Performance Evaluation of Seawater-Mixed Mortar under Carbonation Exposure for Sustainable Repair Applications

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Abstract. Corrosion and carbonation pose significant risks to reinforced concrete structures, necessitating timely patch repairs, especially when using seawater-mixed mortar. This study evaluated the influence of binder type, cover thickness, corrosion protection methods, and exposure conditions on the durability of reinforced concrete. Specimens using Portland Pozzolan Cement (PPC) and Portland Composite Cement (PCC) with 3 cm and 5 cm cover depths were tested over 400 days. PCC exhibited superior corrosion resistance due to its higher CaO content, enhancing strength, reducing permeability, and limiting chloride ion ingress. Surface concrete coatings were the most effective in mitigating carbonation, limiting carbonation depth to 0.38 cm, while steel-coated and uncoated specimens showed greater depths of 0.50 cm and 0.55 cm, respectively. Exposure conditions significantly influenced performance, with dry and dry-wet cycles accelerating carbonation, while wet conditions provided better protection. The findings recommend PCC-based mortar combined with surface coatings for patch repair applications to improve long-term durability in marine environments.

Keywords: carbonation-induced corrosion, corrosion, durability, seawater-mixed mortar, patch repair

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1. Introduction

There are two types of the cause of corrosion in concrete structure, chloride and carbonation induced corrosion [1,2]. Both types of reinforced concrete corrosion reduce concrete structure durability worldwide. In the carbonation process, carbon dioxide (CO₂) reacts with calcium hydroxide (Ca(OH)₂) in concrete, resulting in the formation of calcium carbonate (CaCO₃) [3,4]. The concrete pore solution pH decreases due to this chemical reaction, making the environment more acidic. Concrete's strong alkalinity generates a passive oxide layer on steel reinforcing bars, preventing corrosion. When carbonation reduces the pH of the environment to a critical level (around pH 9), the passive layer on

steel reinforcement may degrade [5,6]. Lack of passivity causes electrochemical corrosion of the reinforcement, which may degrade steel, expand corrosion byproducts, and fracture and spall concrete. It results in the progressive deterioration of the concrete and homogenous corrosion over time. Chloride-induced corrosion occurs when chloride ions (originating from seawater, deicing agents, or contaminated aggregates) penetrate the concrete and promptly compromise the protective oxidation layer on the steel [7,8]. Coastal regions and urban environments with high automobile traffic, where deicing compounds and CO₂ are prevalent, are susceptible to carbonation- and chloride-induced corrosion. Both varieties are present in suburban areas and streets in frigid climates as a result of atmospheric CO₂ and winter road sodium [7,9,10].

In some circumstances, the deteriorated concrete structures were remedied by using patching material due to its necessary to replace the degraded material by using new corrosion free material to improve the cross-sectional capacity and durability [11,12]. The new patch material required the higher properties characteristic than the substrate and its effect on the incompatibility on electrochemical properties that increase the macro-cell corrosion initiation [13,14]. Research on patch repair in reinforced concrete has concentrated on improving materials [13,15,16] and techniques to restore structural integrity and reduce additional degradation from corrosion and carbonation. The effectiveness of repairs is influenced by factors such as the compatibility of the repair material with the existing concrete, bond strength, permeability, shrinkage, and thermal characteristics [13,17]. Enhanced performance has been seen using polymer-modified mortars, fiber-reinforced composites, and corrosion-inhibiting additives, which reduce cracking and moisture penetration. As the green material was also developed to achieve sustainable development goals (SDGs) in concrete engineering and construction [18–21]. Recent advancements have explored seawater concrete as a sustainable option for construction in coastal areas [22–24]. Although chlorides in seawater often pose corrosion risks, the use of corrosion-resistant reinforcements such as FRP, stainless steel, or galvanized steel, has made its application more viable. Furthermore, seawater may promote early strength development, particularly when included into dense, low-permeability mixes including other cementitious materials [25–27]. These developments underscore the need of selecting appropriate materials and adapting to climatic conditions to improve the durability of concrete restorations.

Previous researches have been done by using several types of binder material on patching material [13,16]. The geopolymer material become one of option on innovation to be the patching material due to its relatively low electrical resistivity, but if the repair strategy is combined by using another electrochemical method, the reliability is unfavorable [28–30]. Some innovative and eco material using by product waste or agriculture waste were reported to be patch repair in the viewpoint of mechanical properties and lack information on electrochemical behavior [15,31]. Also, the information of the patching material using seawater as mixing water and the correlation of the carbonation effect is unknown. The objective of this research is to find the effect of carbonation induced corrosion on the patching material performance by using sea water as mixing water to increase the early strength development.

2. Methods

The research was done by using experimental method after the literature study was conducted and the research procedure was depicted in Figure 1. The cubical specimens (15cmx15cmx15cm) fabrication were prepared after the mix design of the mortar was done. The detail of specimen was presented in Figure 2. The seawater was used as the mixing water and tap water replacement in the mortar production. PCC and PPC were used as the binder material. Two round steel bars were embedded in the specimen with 3 cm and 5 cm cover depth. The corrosion prevention methods were applied to the two conditions, steel bar coating and surface concrete coating, by using bituminous based corrosion inhibitor [32,33]. After mixing the mortar material, the flow table was conducted to measure the workability. After that, the casting on the cubical timber mold was done. After one day, the specimens were demolded and cured in the wet towel condition until 28 days. The exposure condition was started after curing period until 400 days in the three specific conditions, wet condition, dry condition, and dry-wet condition by using

two days wet and followed by five days dry. The 18 type specimens with all variations were listed in Table 1. Each variations contained three specimen replications. All specimens mix proportion using 554,69 kg of binder material (cement), 1694,07 kg of fine aggregates, 225,87 kg of seawater, and 4,24 liters of superplasticizer. The pH of seawater used in this experiment is 8,2.

After 400 days of exposure, the periodical non-destructive test showed the decreasing value of half-cell potential value that less than -350 mV vs CSE indicating the corrosion initiation occurred [34,35]. The scheme of corrosion potential testing by using half-cell potential was expressed in Figure 2. Then, the destructive test was conducted by crushing process to understand the mortar condition. The carbonation test was used to identify the carbonation depth by using 1% pheoptalein solution spray. This method is the easiest way to investigate the carbonation process in concrete or mortar material [3,4,36,37].

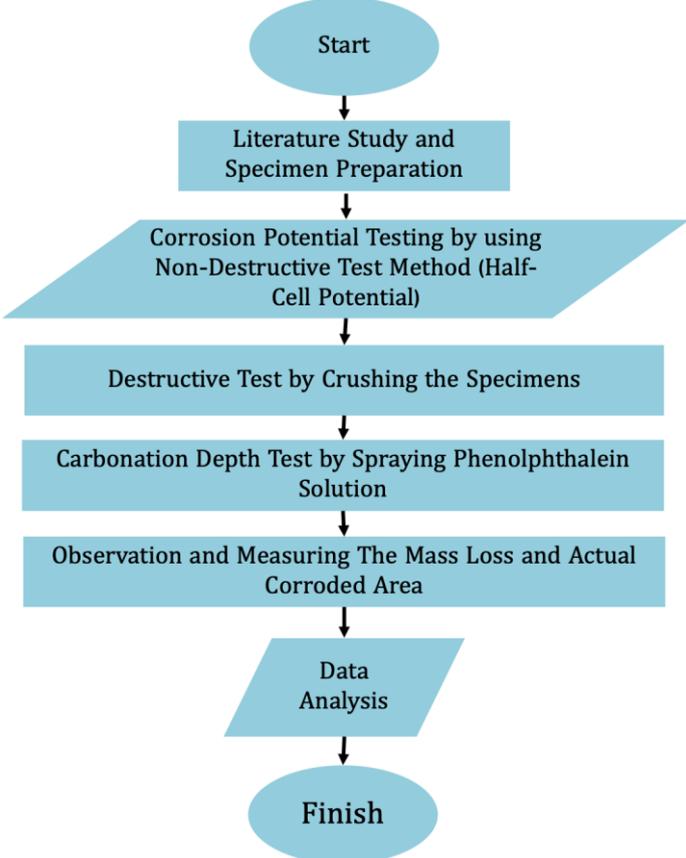


Figure 1. Research programs flow chart

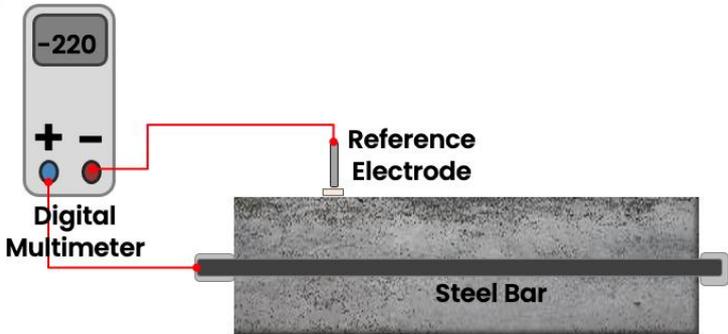


Figure 2. Scheme of corrosion potential testing

Table 1. Detail of specimens

Exposure Condition	Number of Sample	Sample ID	Cement Type	Corrosion Prevention Method
Wet Condition	6	Z1	PPC	Non Coating
		AK1	PCC	
		Z4	PPC	Surface Coating
		AK4	PCC	
		Z7	PPC	Steel Coating
		AK7	PCC	
Dry Condition	6	Z2	PPC	Non Coating
		AK2	PCC	
		Z5	PPC	Surface Coating
		AK5	PCC	
		Z8	PPC	Steel Coating
		AK8	PCC	
Dry-wet Cycle	6	Z3	PPC	Non Coating
		AK3	PCC	
		Z6	PPC	Surface Coating
		AK6	PCC	
		Z9	PPC	Steel Coating
		AK9	PCC	

3. Results and Discussions

3.1. Corrosion Potentials of Steel bar

The corrosion potential of steel bars on all specimens were measured until 400 days and the result were displayed in Figure 2. The measurement method is based on the half-cell potential procedure as stated in ASTM C876 by using Silver/Silver Chloride electrode (SSE) and converted to Calomel Saturated Electrode (CSE) [34]. Several conditions were considered on the half-cell potential test, such as type of binder, cover depth, corrosion prevention method, and exposure condition.

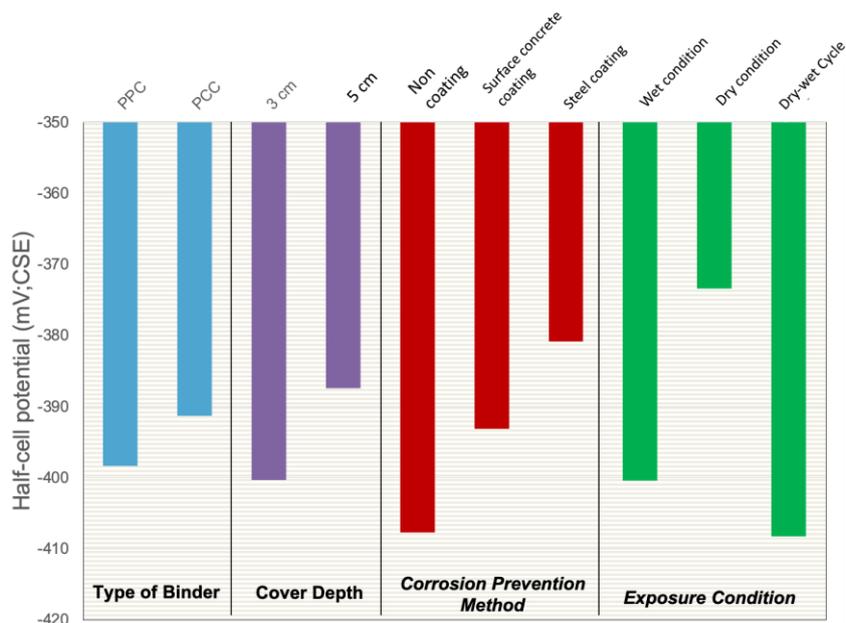


Figure 3. Half-cell potential value of steel bars in varied condition

After 400 days of curing and exposure period, the potential value of all steel bars were less than -350 mV vs CSE. Two types of binder were compared and it resulted PCC binder showed the less corrosion risk than PPC. This phenomenon was in a good agreement with the result of previous research due to higher content of CaO compound in PCC than PPC [38]. The CaO compound contributed to the improvement on strength and low permeability. The cover depth was also presented better in 5 cm than 3 cm due to the higher cover depth, the corrosion probability decreased. The chloride ions intrusion in cement paste is dependent on the material quality and cover depth [39,40]. But, the seawater as mixing water in this research make the worse condition in the view point of corrosion potential measurement result. The effect of corrosion prevention method by using bituminous based coating on the steel and surface concrete coating were also presented. It resulted that the steel coating application presented the best method indicated by the highest corrosion potential value even though the indication was in corrosion condition until 400 day of exposure due to the present of seawater during the mixing steps. The dry condition was the best exposure type on the use seawater as mixing water due to less interaction to the water that will increase corrosion probability as reported on the specimens exposed to wet and dry-wet cycle condition.

3.2. Carbonation Depth

The carbonation evaluation was checked by using 1% phenoptalein solution spraying to the crushed specimens. The purple colour indicated that the mortar condition were in no carbonation. The carbonated condition indicated by no colour change of the sprayed mortar or concrete. The sprayed mortar specimens in this research were presented in Figure 4 and the detail of the difference between the carbonated and non-carbonated part of specimens were displayed in Figure 5.

The quantitative data of the carbonation depth after 400 days of exposure was summarize in Table 2. Based on the type of binder, PCC presented the lower carbonation depth (0,44 cm) than PPC (0,51 cm). The chemical compound of PCC containing CaO higher than PPC is effective to prevent the carbonation phenomena better than PPC due to its base characteristic.

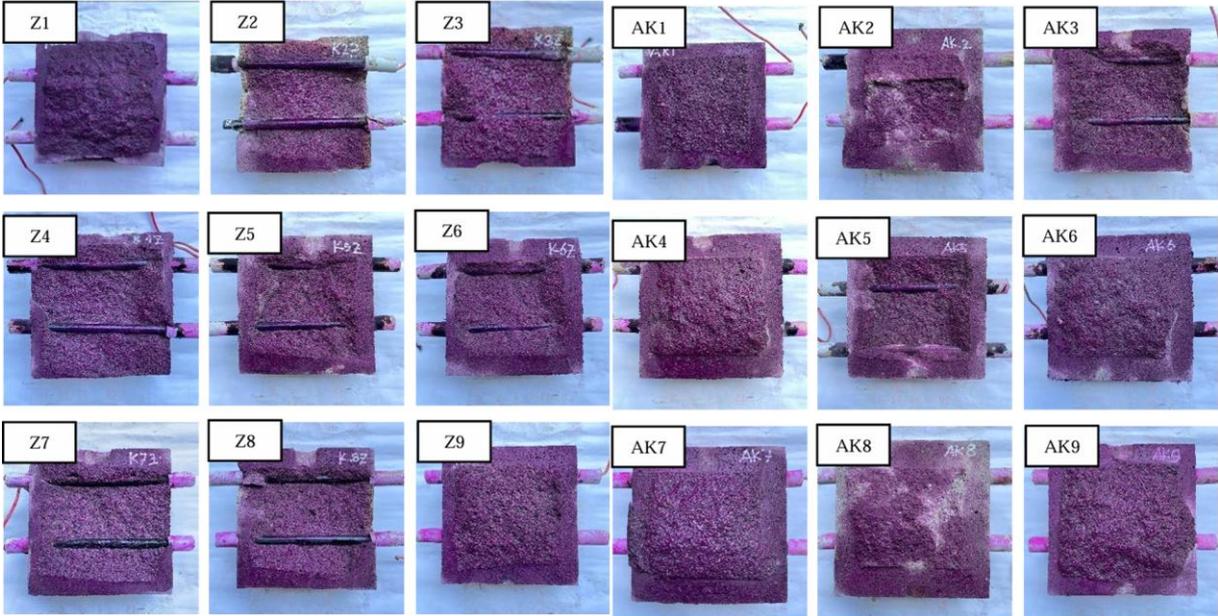


Figure 4. The sprayed mortar specimen conditions during carbonation test

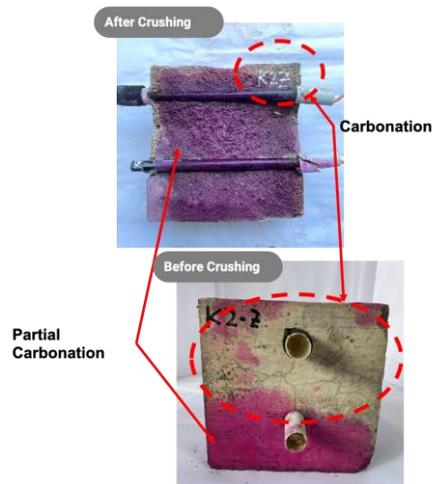


Figure 5. The difference of carbonated and non-carbonated part of specimen

Table 2. Carbonation Depth

Type of Binder	Carbonation Depth (cm)
PPC	0,51
PCC	0,44
Prevention Method	Carbonation Depth (cm)
Non Coating	0,55
Surface Concrete Coating	0,38
Steel Coating	0,50
Exposure Condition	Carbonation Depth (cm)
Wet Condition	0,23
Dry Condition	0,60
Dry-Wet Cycle	0,60

The effect of corrosion prevention method by using surface concrete coating and steel coating is evaluated. Based on the carbonation depth test data, surface concrete coating is the most effective method to prevent carbonation process due to it was applied on the surface of specimen and filled the pore so it prevented the air and water intrusion. The carbonation depth of specimen with surface concrete coating is 0,38 cm, and there is almost similar result of carbonation depth in the steel coating (0,50 cm) and no coating method (0,55 cm). The exposure condition also affects the carbonation condition, the wet condition presented the best condition due to the immersed water prevents the carbon dioxide intrusion to the specimen surface. The dry condition and dry-wet condition presented the same result, 0,60 cm.

PCC (Portland Composite Cement) often provides better corrosion protection compared to PPC (Portland Pozzolan Cement) due to its composition and hydration characteristics based on the result of corrosion potential and carbonation test indicated by the higher potential value and smaller carbonation depth, respectively. PCC is made by blending Ordinary Portland Cement (OPC) with a variety of materials such as fly ash, slag, or limestone, but in carefully controlled amounts to enhance strength and durability without significantly lowering the alkalinity [38,41]. This composition allows PCC to maintain a high pH environment, which is critical for the formation of a passive protective layer on steel reinforcement, reducing the risk of corrosion. In contrast, PPC, which contains a higher percentage of pozzolanic material like fly ash, consumes more free calcium hydroxide ($\text{Ca}(\text{OH})_2$) during pozzolanic reactions [16,42,43]. Although this improves the long-term density and chemical resistance of the concrete, it slightly reduces the immediate alkalinity, which can weaken the early corrosion protection for embedded steel. Therefore, PCC, with its balanced composition, offers stronger early corrosion

protection while still improving durability, whereas PPC, despite being excellent for long-term performance, may initially be less effective against corrosion due to reduced free lime content.

The performance of steel coating, surface concrete coating, and no coating varies chemically and physically under different exposure regimes. In the corrosion potential test, the steel coating performed the best because it provided direct chemical protection to the reinforcement by forming a new inhibitor layer, preventing oxidation and corrosion through stabilization of the steel surface and isolation from aggressive ions. Physically, this coating acted as a barrier against moisture and chlorides [44–46]. In contrast, during the carbonation test, the surface concrete coating showed superior performance by physically blocking the intrusion of carbon dioxide into the concrete, which in turn prevented the chemical reaction that lowers the concrete's pH and leads to steel depassivation. By maintaining high alkalinity, the surface coating chemically protected the steel indirectly. Specimens without any coating performed the worst in both tests, as they were fully exposed to environmental effects without any chemical or physical barriers. Overall, the steel coating is most effective against direct corrosion processes, while the surface concrete coating is more effective against carbonation by limiting gas penetration.

The performance of coatings also depends heavily on the exposure conditions, which include dry, wet, and dry-wet cycle environments. In the corrosion potential test, specimens under dry conditions performed best because the lack of moisture limited the electrochemical reactions necessary for corrosion. Chemically, corrosion of steel reinforcement requires the presence of water and oxygen to drive the oxidation-reduction process; thus, a dry environment physically reduces the availability of electrolytes and slows down corrosion initiation [47–51]. In contrast, the wet condition and dry-wet cycle promoted higher corrosion risk due to continuous or periodic moisture presence, which facilitated ionic movement and electrochemical reactions. However, in the carbonation test, the wet condition surprisingly offered the best performance. Continuous immersion in water physically blocked carbon dioxide from penetrating into the concrete pores, preventing the chemical reaction between CO₂ and calcium hydroxide that leads to carbonation. Chemically, since carbonation requires the diffusion of carbon dioxide gas into the concrete and its dissolution in pore water, the saturation of pores with water under wet conditions reduced the gas diffusion rate dramatically [4,52–54]. In comparison, dry conditions allowed faster CO₂ penetration due to open pores, and dry-wet cycles further accelerated carbonation due to alternating drying (increasing CO₂ access) and wetting (providing moisture for the reaction). Thus, exposure conditions affect the performance of coatings by controlling the availability of moisture, oxygen, and carbon dioxide, critical factors in both corrosion and carbonation processes.

Portland Composite Cement (PCC) has proven to be highly effective in enhancing the durability of concrete structures, demonstrating superior resistance to corrosion due to its higher CaO content, improved strength, and reduced permeability compared to Portland Pozzolan Cement (PPC). Among the protective methods evaluated, steel coatings were most effective in directly protecting the reinforcement against corrosion, while surface concrete coatings provided the best defense against carbonation by limiting the ingress of carbon dioxide and moisture. Exposure conditions significantly influenced performance, with wet environments offering the greatest protection by restricting carbon dioxide penetration, whereas dry and dry-wet cycles accelerated deterioration. Considering the combined effects of binder type, coating strategy, and environmental exposure, PCC-based mortar, particularly when paired with a surface concrete coating, is identified as the most suitable material for patch repair applications. This combination effectively addresses both corrosion and carbonation risks, making it an optimal choice for extending the service life of repaired concrete structures as patch repair material even using seawater as mixing water.

4. Conclusions

This study evaluated the performance of different cementitious materials, protective coatings, and exposure regimes in enhancing the durability of reinforced concrete, with a focus on their applicability for patch repair applications. The findings indicate that Portland Composite Cement (PCC) exhibits superior resistance to corrosion compared to Portland Pozzolan Cement (PPC), attributable to its higher

calcium oxide (CaO) content, which improves mechanical strength, reduces permeability, and limits chloride ion ingress. Among the corrosion mitigation techniques, steel coatings were found to provide the most effective protection against corrosion of embedded reinforcement, while surface concrete coatings demonstrated the highest efficacy in mitigating carbonation by reducing the penetration of carbon dioxide and moisture into the concrete matrix. Exposure conditions were also found to significantly influence durability, with wet conditions offering enhanced resistance to carbonation due to the restriction of CO₂ diffusion, whereas dry and dry-wet cycles resulted in increased carbonation depths. Based on these results, PCC-based mortars, when used in combination with surface concrete coatings and optimized exposure conditions, particularly under wet environments, are recommended as the most effective materials for patch repair applications. This combination provides comprehensive protection against both corrosion and carbonation even using seawater as mixing water, thereby significantly extending the service life and durability of repaired concrete structures.

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