

Assessment of Environmental Factors on Corrosion in Reinforced Concrete with Calcium Chloride

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Abstract Corrosion of steel in reinforced concrete causes severe damage in durability as weakness support of reinforced elements. We investigate impacts of cement fraction and curing method on corrosion progression. Corrosion level is evaluated by measuring carbonation penetration and electrical conductivity in concrete plots as indicators of corrosion. Two types of cement were used, Normal and quick setting. For each cement type, two concrete mixes were used (3% and 8% C3A are designed). Six levels of CaCl₂ ranging from 0.5 % to 3% were used to simulate corrosion. Also, two curing methods are compared, liquid water and steam application are used. Chloride ion in low alumina cement mortar progressed faster than high alumina. The results show significant increase in carbonation depth for (less cement) compared to (more cement) mixes. Also, steam curing showed less penetration than normal water setting method. Variation in carbonation penetration for 0.5 and 1 % CaCl₂ is high close to double. Electrical potential of steel in cement mortar is negatively related with increasing calcium chloride content and with increasing cement content. Also, normal setting cement shows better corrosion protection as demonstrated by higher measured EC.

Keywords Corrosion, Calcium Chloride, Carbonation, Electric Potential

1. Introduction

Cement is the most common used construction material worldwide. Concrete is basic building material used in construction, usually with steel in many elements of reinforced concrete. Concrete and steel in structure elements are exposed to corrosive chemicals that penetrate into the concrete elements with water. This effect causes severe damage and weakness in affected elements [1, 2, 3, and 4]. Reinforcement of concrete with steel strengthens the structural element in tension because concrete alone cannot provide it [5, and 6].

The reinforced concrete, has steel bars to give the concrete's its tensile strength capacity [6, 7]. Water is required for hardening the cement and reaching the proper mix consistency. A major factor that determines concrete properties is the water/cement ratio. High water fraction causes an increased number of capillary voids which reduces concrete rigidity.

Calcium chloride is common additive to the concrete mix since it improves rate of resistance in cold temperatures and it shortens setting time. It is typically used in cold climate which increases the heat emission during the initial setting [8, and 9].

Freezing in concrete mix leads to increasing the volume of concrete and reduces the water content usable for chemical reactions which reduces resistance and delay

solidification processes.

In structure repair tasks operators prefer early-rich mixtures with low w/c ratio and calcium chloride. However, a side effect is the oxidation of steel. There is a risk of reducing alkaline environment by chemicals interaction in the presence of calcium chloride in concrete elements [10, 11].

Fresh concrete is highly alkaline, which creates protective environment surrounding steel bars [12, and 13]. Salts dissolved in water, particularly chloride ions in water penetrate in concrete. This hazard impacts highway structures, buildings, and foundations in coastal regions. The salt absorbed in concrete erodes the steel protective layer. If oxygen and moisture come in vicinity of steel bars rusting process is initiated and cracks from corrosion forms with volume expansion in the affected areas. The concrete layer above the reinforcement is pushed away which results in serious concrete damage. The steel embedded in concrete is protected from corrosion by the alkalinity of the cement matrix, which forms a passive film on the steel surface.

Corrosion in concrete is defined as the physical change in material due chemical reaction with its environment. [4, 10, and 14] . Corrosion of steel bars weakens its support function significantly and may cause elements to fail if not treated [14, and 15].

Corrosion is serious problem worldwide, with costly repairs that reach billions of dollars annually. In addition, the numerous intangible losses such as the energy needed to manufacture replacements of corroded objects [16, and 17] .

The produced protective film will erode away when the Cl⁻ content reaches high critical content (threshold level), and corrosion in steel will occur when reaction with oxygen and water [18, 19, and 20].

Reinforced concrete elements may corrode highly in proximity to marine environments through groundwater and droplets in atmosphere. Chloride was detected in marine environments within 300m of ocean transported by wind reaching 500 ppm or greater [21]. The repair cost of corrosion impacted structures is major concern for highway agencies and estimated to be more than \$20 billion and expected to increase by \$500 million per year in united state [22, 23].

Steel when fully covered by concrete it gives high corrosion protection because the cement paste provides an alkaline environment which protects steel bars with a ferric oxide layer that builds up on the surface steel. This protection film is few nanometers thick and it is stable in alkaline environment at pH >11 [24]. The thin film protection can be removed by carbonation of concrete especially in vicinity of chloride ions. The steel becomes unprotected when the pH becomes < 10 [23, 25].

Weakening of concrete in corrosion of steel is due to growth of the oxide that has an increase in volume [11]. Steel corrosion weakens areas when hydrated it swells

and becomes porous which increases the volume to at the steel-concrete interface by two times at least.

This leads to cracking of the concrete protection film as a result of corrosion of steel in concrete and make it rusty with brittle and flaky on the bar which increase risk of cracks in the concrete [10, and 25]. The protection of the alkaline environment can be damaged when chloride ions are present. Steel bars surfaces become exposed and dissolution reaction occurs [11].

Corrosion treatment molecules penetrate the concrete through pores and cracks to restore the thin film surrounding steel to extend life of the concrete structure [26].

Related research evaluated corrosion progress and found that calcium nitrite is good protection agent against corrosion in the presence of chloride [27]. Other research investigated effectiveness of corrosion inhibitors, authors investigated concrete samples containing NaCl and soaked in saturated Ca (NO₂)₂ solutions to simulate strong mortar deterioration [8]. They observed visual deterioration in form of cracks and bulging in concrete without corrosion of reinforcing steel because of using corrosion inhibitors.

In other study, researchers investigated the performance of new types of corrosion inhibitors based on bipolar mechanism and it can penetrate deep in concrete by its high vapor pressure [19]. The inhibitor was applied as an admixture in concrete mix and it is applied as a coating on hardened concrete. Authors measured half cell potential and found a reduction in concrete strength. Authors observed that adding inhibitors did not affect mechanical properties like workability, water absorption, setting time, and compressive strength [19].

In other study researchers evaluated corrosion impact on existing reinforced concrete on bridge decks. They used suction to remove excess moisture from concrete elements then injected inhibitor by pressure in the concrete. This method reduces the corrosion by slowing the anodic and cathodic reactions [20].

Steam curing of concrete is advantageous because it provide hardening in short time. Desired effect is increasing compressive strength of the concrete in short time without cracking. The improvement in concrete resistance to chemicals such as Sodium and Magnesium Sulfate Salts can be achieved by steam curing.

Chemical additives are used in concrete in small fraction for several reasons like voids reduction, reduction of water or cement content plasticization, and control of setting time.

The calcium chloride additives for concrete have several benefits on physical properties of concrete.

Calcium chloride (CaCl₂) is a chemical admixture and a secondary product of the sodium carbonate solvay process. Calcium chloride is available as flakes of calcium chloride and as pellets or granules [28, and 29]. Calcium chloride is typically added to concrete mix in cold climate

because it allows gaining strength of concrete at similar extent under normal curing temperatures [30].

The chloride ions level causing corrosion in concrete at soluble chloride ion level of 0.1% and higher. This is equivalent to average of 700 gm of chloride per m³ of concrete [17]. The chloride threshold level for corrosion is expressed as a ratio of chloride / hydroxyl ions. Corrosion begins when chloride concentration exceeds 0.6 of the hydroxyl concentration, corrosion is initiated. This is equivalent to a level of 0.4% chloride by weight of cement cast into concrete [29 and 30].

In normal conditions, calcium chloride is used to accelerate time for proper hardness during initial setting. A major limitation to the wider use of calcium chloride in reinforced concrete is it promotes corrosion of the reinforcement if present in large free amounts [31].

There is a chloride threshold concentration that initiates corrosion in metal embedded in concrete and grout. The chloride threshold values are stated in construction codes in several countries. Design codes specify maximum allowable chloride contents in concrete and grout. The American Concrete Institute (ACI), American Association of State Highway and Transportation (AASHTO) code, and a Post-Tensioning Institute (PTI) code suggest a fraction of (0.06 -0.08) percent by weight of cement [20].

On fresh concrete, calcium chloride shortens time for initial concrete hardening which reduces waiting time to safely remove support frames by 40-50% at least without reducing the final resistance. The positive effect is reducing waiting time for hardening which allows moving to next phases in construction.

The penetration of chloride ions through pores in concrete reaches steel bars which weaken the protection layer and expose the steel bar to be undergo corrosion in the presence of moisture and oxygen [32].

The chemical damage from chloride compounds come from Cl reactions with cementitious matrix which leaches calcium hydroxide due to decalcification of calcium silicate hydrate, and forming of brucite (Mg(OH)₂ and magnesium silicate hydrate [30].

The chloride ion is adsorbed inside porosity voids or join with the hydration process [33]. Chloride binding in concrete elements induces the rate of chloride entrance, which indicates chloride-induced corrosion occurrence. The chloride pore solution controls diffusion process, which is hindered by the binding reaction [34].

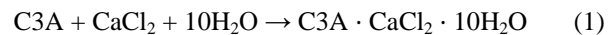
When binding effect of chloride is strong, concentration of free chloride is reduced which means that chloride diffusion decreases simultaneously [35].

Chloride ions react with calcium aluminates and

calcium aluminoferrite in the concrete material to form calcium chloroaluminates and calcium chloroferrites where chloride is bonded in insoluble precipitate [31]. Some active soluble chloride remains free in liquid form in the concrete. While the concrete is not carbonated state, free dissolved chloride remains low about 10% of the total Chloride. However, when active carbonation proceeds, hydrated cement phase breaks and for chloroaluminates, chloride ions are released. Thus carbonated concrete contains more free chloride [36].

The chloride binding chemical reaction occurs between chloride ions and the C4AF, C3A, and the hydration products which are known as formation of Friedel's salt [37].

The chemical reaction between C3A, and chloride ions, leads to the formation of Friedel's salt, is given below:



This study aims to investigate the influence of carbonation on the penetration of chloride in concrete and its degree of corrosion. Chloride ions may be transferred into concrete from external sources such as de-icing salt, seawater and groundwater, and internal sources through contaminants in concrete such as marine aggregate and chemical admixtures containing chloride ions [3].

Carbonation in concrete is associated with CO₂ dissolution in the solution in pores, which reacts with calcium in calcium hydroxide (CaOH) and calcium silicate hydrate (3CaO • 2SiO₂ • 3H₂O) producing calcite (CaCO₃).

The exposed fresh concrete surface will react with CO₂ in air gradually. Corrosion process penetrates deeper into the concrete at a proportional rate to the square root of time [29]. After 1 year penetration may reach 1 mm if concrete is dense or low W/C ratio. If concrete is porous it may reach 5 mm if high porosity cement.

This study aims to investigate the effect of calcium chloride (CaCl₂) as an admixture on the corrosion process in concrete.

2. Materials and Methods

The depth of carbonation is measured as the the average measured carbonation depth for three points in the cube.

In this research, we add calcium chloride to concrete mix by 2% by weight of cement. In this research we consider two types of cement, and 1) Ordinary Portland cement, and 2) Quick-setting Portland cement (QSC) with 2% of gypsum to improve setting time, as shown in table 1.

Table 1. The Composition of Concrete Mix Types used.

Types of cement	Description	Used Cement Types Ingredients (%)		
		3CaO.SiO ₂ (C3S)	2CaO.SiO ₂ (C2S)	3CaO .Al ₂ O ₃ (C3A)
Type 1	Normal Temperature – NTC	21	57	3
Type 2	Quick Setting QSC	70	3	8

Experimental work included preparing concrete samples in cubic frames measuring 15*15*15 cm of mortar with 1:2 ratio of cement: sand (sand is larger than 0.60 mm sieve) (Type1).

The second mix (Type2) was composed of 1:3 (water / sand). The two samples were reinforced with 5 mm diameter steel bars and the percentage of water: cement = 1:2.

Six cubic samples (cast dimensions 15 x 15 x 15 cm) were prepared for each cement type. The cement paste was mixed to avoid large voids in the sample. Three concrete samples were treated in a special chamber after casting for six hours under ambient pressure at 80 °C temperature.

Calcium chloride was added at fractions from 0.5 to 3% of the cement weight. Six levels of CaCl₂ are added to concrete samples at 0.5 , 1 , 1.5 ,2 , 2.5 , and 3 percent.

The selected values cover range of expected CaCl₂ levels expected at different operation conditions. For example , 0.3 and 1% fractions are recommended for concrete not protected and well protected from water as suggested by ACI 318-08 (ASCC, 2021). Between 1-3% fractions are selected to produce high corrosion risk and analyze corrosion progress.

A steam curing cycle is followed involves three intervals of curing time, maximum steam temperature and duration at the maximum temperature of 3, 3, 4 hours respectively. Then samples are placed on flame source under ambient humidity and temperature 20 °C. The heating treatment of samples is needed to achieve early resistance that allows handling of concrete production after short time of casting, frames can also be removed in shorter period than typical water treatment, which is beneficial for construction projects. Then the three samples of each type were placed in hardening chamber after removing casts. Steam curing is compared to natural curing, that is in ambient temperature and humidity which takes longer time.

Water steam-curing process consists of 3 stages, 1) heating up impacted area after initial setting, 2) keeping high temperature constant for designated period, and 3) cooling period of impacted area. Water steam curing is conducted at ambient atmospheric pressure inside enclosure especially installed to keep applied moisture on treated area and reduce heat losses. Tarpaulins sheets are typically used in enclosure treatment area.

Injection of water steam in the enclosure cannot start until initial setting is achieved which occurs 3 hours after final placement of concrete. Typically, 3 to 5 hour waiting period before steaming will provide maximum early strength [40]. Steam temperature should be at 60°C in the

enclosure until the desired concrete strength is achieved and temperature should not rise beyond 70°C to avoid heat induced delay expansion and cause reduction in final strength [40].

Carbonation depth is measured by adding phenolphthalein indicator that gives pink color when solution is alkaline with pH > 9 [38]. The indicator test is conducted by spraying on freshly exposed or broken concrete surfaces [39].

The phenolphthalein indicator is added on fresh concrete fracture surface. A fully-carbonated cement mix has a pH of about 8.4. If the indicator turns purple, then pH > 8.6, if surface remain colorless the pH of the concrete is <8.6. A strong, immediate, color change to purple indicates a pH that is >8.6, typically between 9 and 10.

For long term (150 days) a different method was used. Samples were tested for chloride ion using silver nitrate 1%. The reaction produces AgCl and Nitrate.

We measure the intensity of iron bar corrosion using the difference in electrical potential method using electric chemical cell where one pole is immersed in a silver chloride saturated solution and the second electrode is immersed in cement cube.

Concrete temperature should be monitored at the concrete surface. Ambient Air temperatures are not adequate indicator of hydration heat because it causes concrete internal temperature to exceed 70°C. Curing concrete at 60°C temperature is intended to reduce shrinkage and creep relative to curing at 23°C for 28 days [40, 41, and 42].

3. Results

The depth of Carbonation as a function of w/c ratio for the mixes used in this study is shown in Table 1.

Chloride ion is evaluated in cement mortar composed of cement alumina content of (CaCl₂) from 0.5 - 3% of cement per weight analyzed by adding 1% silver nitrate solution. After mortar steam curing, chloride ion was detected at calcium chloride percent of more than 2.5%.

Hydrated calcium aluminate chloride forms when bonding of gypsum present in cement with tri-calcium aluminate. The remaining of the tri-calcium aluminate reacts with calcium chloride.

The resulting compounds of chlorine ion association with ferrous hydroxide are stable.

Mixing water with the dry ingredients hydration reaction is initiated. The extent of the reaction is completed

affecting concrete strength and durability. Typically, fresh concrete contains excess water than amount needed for hydration; however, significant evaporation cause water loss will delay adequate hydration. However, insufficient hydration may occur on the concrete surface since it dries first. Hydration is fast on the initial days and it is important to maintain excess water on concrete. During curing process cement becomes harder, impermeable, and resistant to stress.

There are several types of curing methods, and appropriate method depends on the use of construction and waiting time for hardened concrete. There are several curing chemicals compounds that can be used in covering the fresh concrete with water layer or wet sheet.

During cement hydration the internal water decreases which causes the cement paste to dry out and additional water is needed. Water shortage may affect final concrete properties, especially when internal humidity decreases below 80% during first 7 days. Therefore, curing compounds that builds membrane may not maintain adequate water in the concrete. To secure adequate hydration, fogging and wet curing treatment is used on site [9, and 17]. Moisture fogging after placing concrete protects from cracks especially in low water-cement ratios.

If water decreases to about 80%, hydration curing is stopped and gaining in strength stops. However, if moisture curing is continued, strength increase will continue, but the maximum potential strength will not be obtained.

Curing at warmer or cooler temperature should be avoided to prevent undesired shrinkage. Temperature in the enclosure fitted on concrete surface should be increased and decreased at rate of 33°C per hour based on the

configuration and size of element.

Therefore, continuous initial sufficient hydration curing is essential to reach sufficient strength. Therefore, Concrete surfaces must be hydrated during initial period. Evaporation water loss causes shrinkage in concrete, which creates internal tensile stress within the concrete. If this stress develops before the concrete has reached adequate tensile strength then surface cracks will occur [18].

At low temperature, hydration proceeds at a much slower rate. Cold temperatures below 10°C slows the gaining of early strength [17].

Steam curing is preferred when time is limited and early strength gain in concrete is needed and when additional heat is required for hydration process.

Curing temperature in the installed enclosure should be fixed until concrete area obtains the normal strength. The appropriate curing time depends on the concrete type and water steam temperature inside the enclosure [36 and 40].

Carbonization process initiates from carbon dioxide reaction with hydrated cement in the presence of water. Tables 3 show that the carbonation depth in mortar with a mix design of 1:2 Cement/Sand and a W/C = 0.5 for Mix 1. Similarly, Table 2 shows the carbonation depth in mortar with a mix design of 1:3 Cement/Sand and a W/C = 0.6 for Mix 2.

Table 2. Design Ratio Concrete Mix used.

ID	Cement	Cement Mix Design	Element
		Water : cement : sand ratio	
Type1	NTC	0.5 : 1 : 2	Mortar
Type2	QSC	0.6: 1: 3	Steel Reinforced

Table 3. Depth of Carbonation layer in cement mortar at different C3A content for Type1.

ID	W/C ratio	Cement/ Sand Ratio	Stiffness Conditions	CaCl ₂	Average Carbonation Depth in cement mortar contain % C3A (Xmm)	
					NTC C3A=3%	QSC C3A=8%
					Mix 1	0.5
				1	2.5	4.5
				1.5	2.5	4
				2	1.5	2
				2.5	0.75	2
				3	0.5	1.5
Mix1	0.5	1:2	Stream Curing	0.5	6.5	2
				1	2	1.25
				1.5	2	0.75
				2	1.5	0.75
				2.5	0.75	0.5
				3	0.5	0.25

The excess water due to carbonization process is used in rehydration and calcium carbonate formation and reduces the pores in fresh concrete. However, carbonation and the presence of calcium chloride combine to erode the coating layer on steel bars and starts corrosion process [43, and 44].

4. Discussion

Chloride ion is evaluated in cement mortar composed of cement alumina content of (CaCl_2) from 0.5 - 3% of cement per weight analyzed by adding 1% silver nitrate solution. After mortar steam curing, chloride ion was detected at calcium chloride percent of more than 2.5%.

Hydrated calcium aluminate chloride forms when bonding of gypsum present in cement with tri-calcium aluminate. The remaining of the tri-calcium aluminate reacts with calcium chloride.

The resulting compounds of chlorine ion association with ferrous hydroxide are stable.

Mixing water with the dry ingredients hydration reaction is initiated. The extent of the reaction is completed affects concrete strength and durability. Typically, fresh concrete contains excess water than amount needed for hydration; however, significant evaporation cause water loss will delay adequate hydration. However, insufficient hydration may occur on the concrete surface since it dries first. Hydration is fast on the initial days and it is important to maintain excess water on concrete. During curing process cement becomes harder, impermeable, and resistant to stress.

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If water decreases to about 80%, hydration curing is stopped and gaining in strength stops. However, if moisture curing is continued, strength increase will continue, but the maximum potential strength will not be obtained.

Therefore, continuous initial sufficient hydration curing is essential to reach sufficient strength. Therefore, Concrete surfaces must be hydrated during initial period.

Evaporation water loss causes shrinkage in concrete, which creates internal tensile stress within the concrete. If this stress developing before the concrete has reached adequate tensile strength then surface cracks will occur [18].

At low temperature, hydration proceeds at a much slower rate. Cold temperatures below 10°C slow the gaining of early strength [17].

Steam curing is preferred when time is limited and early strength gain in concrete is needed and when additional heat is required for hydration process.

Water steam-curing process consists of 3 stages, 1) heating up impacted area after initial setting, 2) keeping high temperature constant for designated period, and 3) cooling period of impacted area. Water steam curing is conducted at ambient atmospheric pressure inside enclosure especially installed to keep applied moisture on treated area and reduce heat losses. Tarpaulins sheets are typically used in enclosure treatment area.

Injection of water steam in the enclosure cannot start until initial setting is achieved which occurs 3 hours after final placement of concrete. Typically, 3 to 5 hour waiting period before steaming will provide maximum early strength [36]. Steam temperature should be at 60°C in the enclosure until the desired concrete strength is achieved and temperature should not rise beyond 70°C to avoid heat induced delay expansion and cause reduction in final strength [36].

Concrete temperature should be monitored at the concrete surface. Ambient Air temperatures are not adequate indicator of hydration heat because it causes concrete internal temperature to exceed 70°C . Curing concrete at 60°C temperature is intended to reduce shrinkage and creep relative to curing at 23°C for 28 days [36, 37, and 38]. Curing at warmer or cooler temperature should be avoided to prevent undesired shrinkage. Temperature in the enclosure fitted on concrete surface should be increased and decreased at rate of 33°C per hour based on the configuration and size of element. Curing temperature in the installed enclosure should be fixed until concrete area obtains the normal strength. The appropriate curing time depends on the concrete type and water steam temperature inside the enclosure [33 and 36].

Carbonization process initiates from carbon dioxide reaction with hydrated cement in the presence of water. Tables 3 show that the carbonation depth in mortar with a mix design of 1:2 Cement/Sand and a W/C = 0.5 for Mix 1. Similarly,

Tables 2 show the carbonation depth in mortar with a mix design of 1:3 Cement/Sand and a W/C = 0.6 for Mix 2.

The excess water due to carbonization process is used in rehydration and calcium carbonate formation and reduces the pores in fresh concrete. However, carbonation and the presence of calcium chloride combine to erode the coating layer on steel bars and start corrosion process [39, and 40].

Table 4. Depth of Carbonation Layer in cement mortar contain different % C3A for Type2

ID	W/C ratio	Cement/ Sand Ratio	Stiffness Conditions	CaCl ₂	Carbonation Depth in cement mortar contain % C3A in (Xmm)	
					NTC C3A=3%	QSC C3A=8%
Mix2	0.6	1:3	Natural Moisture	0.5	20	6
				1	22	2
				1.5	8	3.5
				2	8	3.5
				2.5	6	3.5
				3	3	3.5
Mix2	0.6	1:3	Stream Curing	0.5	11	2.5
				1	12	3
				1.5	7.5	2.5
				2	6	1.5
				2.5	6	1.5
				3	6	1.5

Table 5. Steel bars electrical potential (EC) for Type1 with W:C ratio = 0.5

ID	W/C ratio	Sand/ Cement Ratio	Stiffness Conditions	CaCl ₂	Steel Bar EC (mv), Oxidation Surface (F %) in cement mortar for % C3A			
					NTC C3A=3%		QSC C3A=8%	
					mv	F%	Mv	F%
Mix 1	0.5	1:2	Natural Moisture	0.5	183	100	114	0
				1	272	100	97	0
				1.5	230	100	41	0
				2	243	100	53	0
				2.5	258	100	24	0
				3	261	100	19	0
Mix 1	0.5	1:2	Stream Curing	0.5	197	100	122	0
				1	278	100	60	0
				1.5	269	100	46	0
				2	282	100	44	0
				2.5	292	100	-2	3
				3	278	100	-1	2

Table 6. Steel bars electrical potential (EC) for Type2 with W: C ratio = 0.6

ID	W:C ratio	Sand: Cement Ratio	Stiffness Conditions	CaCl ₂	Steel Bar electrical potential difference (mv), Oxidation Surface (F %) in cement mortar for % C3A			
					NTC C3A=3%		QSC C3A=8%	
					Mv	F%	mv	F%
Mix 2	0.6	1:3	Natural Moisture	0.5	136	100	37	0
				1	182	100	42	20
				1.5	135	100	21	15
				2	126	100	23	15
				2.5	118	100	7	10
				3	117	100	5	10
Mix2	0.6	1:3	Stream Curing	0.5	22	100	8	0
				1	73	100	34	0
				1.5	275	100	8	7
				2	302	100	23	15
				2.5	282	100	25	15
				3	275	100	25	15

5. Conclusions

In this research, two types of cement were used, Normal and Quick setting. For each cement type, two concrete mixes were used with low and medium Tricalcium aluminate (3% and 8% C3A respectively). Cement plots are designed and prepared in cubic frames (15 x 15 x15 cm3). For each concrete mix, six levels of CaCl₂ ranging from 0.5 % to 3% were used. Also, water setting and steam curing are compared.

Corrosion is measured as carbonation penetration depth in concrete and they correlate positively as shown in Figures 1 and 2. Also, Figures 1 and 2 indicate that QSPC maintain better protection when exposed to high levels of CaCl₂. Natural concrete shows less corrosion resistance. Also, Steam method better inhibits corrosion than normal method consistently. At low CaCl₂ level in concrete mix the curing method and concrete type show explicit variation.

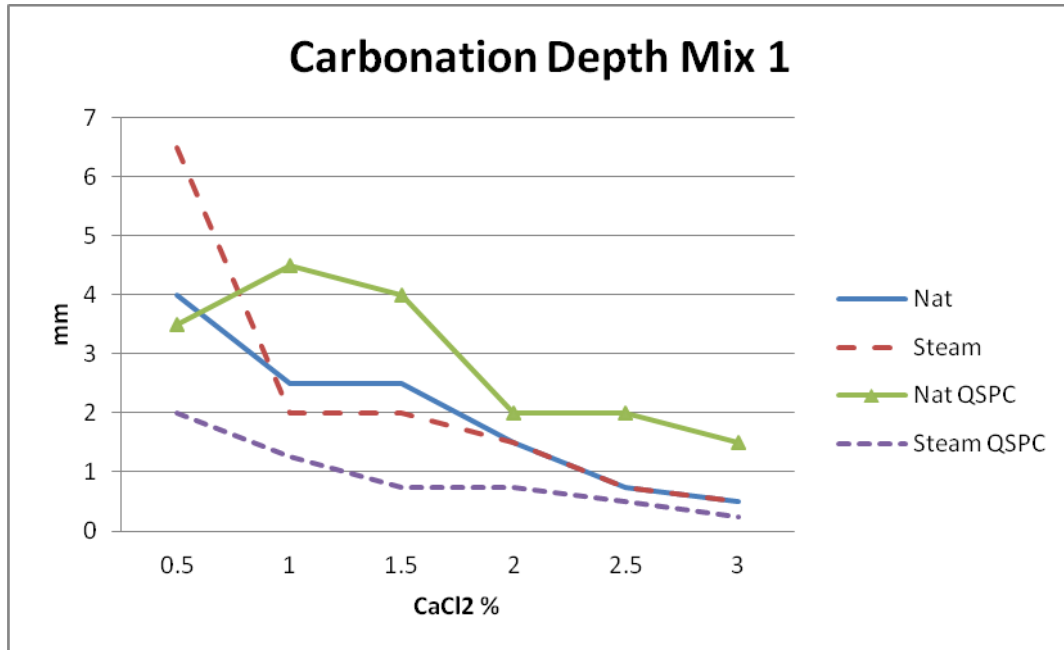


Figure 1. Carbonation Layer depth for Concrete mix with high cement fraction 2:1 using normal and quick setting cement.

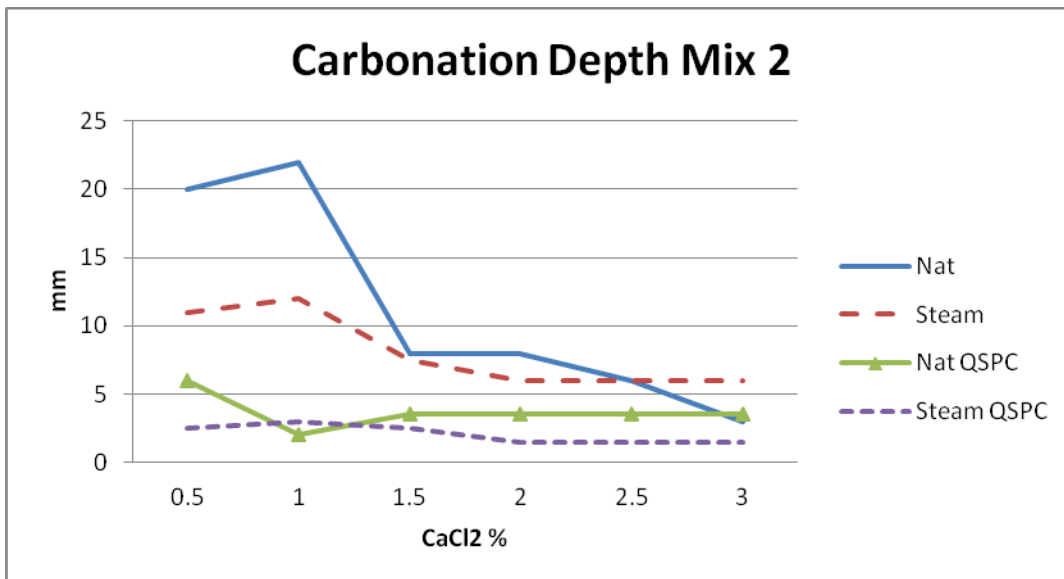


Figure 2. Carbonation Layer depth for Concrete mix with high cement fraction 2:1 using normal and quick setting cement.

Increasing CaCl_2 reduces carbonation layer thickness. natural curing maintain high increasing CaCl_2 fraction inhibits Depth of oxidation layer was measured and it is assessed by measuring electrical potential of mortar samples. Low cement ratio (Mix 2) shows deeper corrosion penetration than higher cement ratio (Mix 1). Also for the normal and quick setting cement types, steam curing produced higher protection than water setting method.

Electrical conductivity of steel in reinforced samples is indicator of protection level surrounding steel bars.

Electrical conductivity of steel bar is inversely related to corrosion.

The results shown in Figures 3.4 indicate that measurement of electrical potential on steel bars depends on content of alumina in cement. The electric potential of steel bars in Type 1 (moderate alumina) is greater than for Type2. Rusting trend in concrete mixes was variable. Corrosion in iron bars is reduced in higher aluminum Cement compared to less alumina level. This trend is attributed to the shortage in chloride ion.

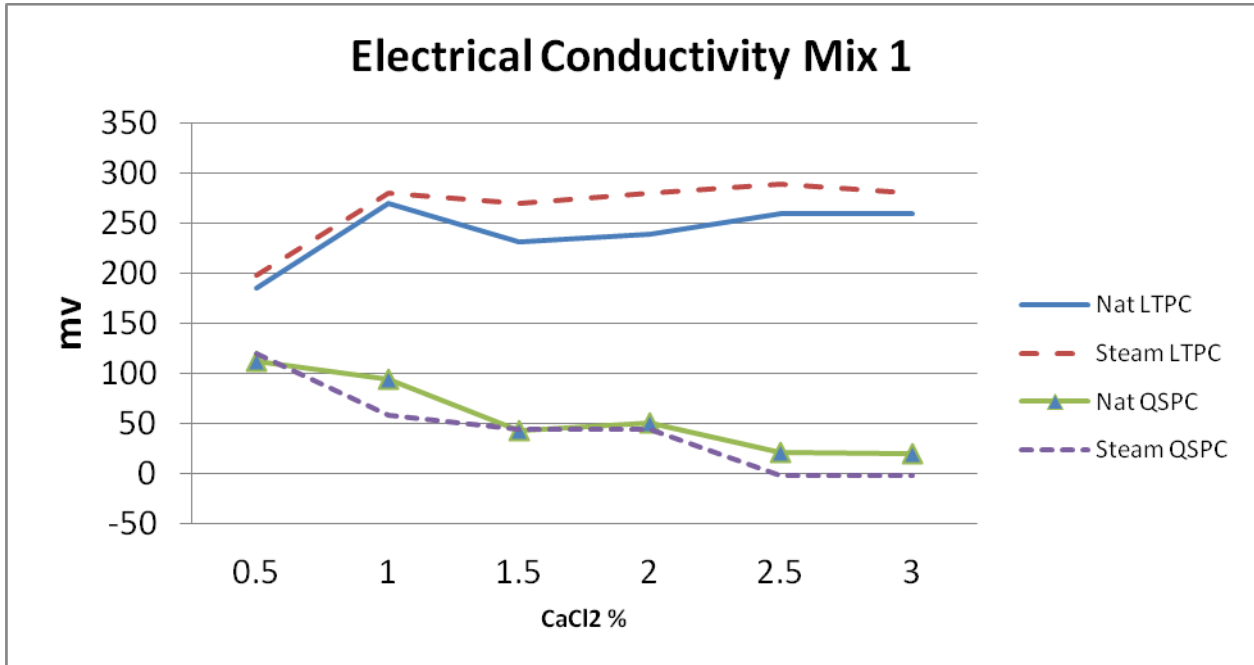


Figure 3. Electrical Conductivity for several levels of CaCl_2 for high cement (2:1) mixture using normal and quick setting cement.

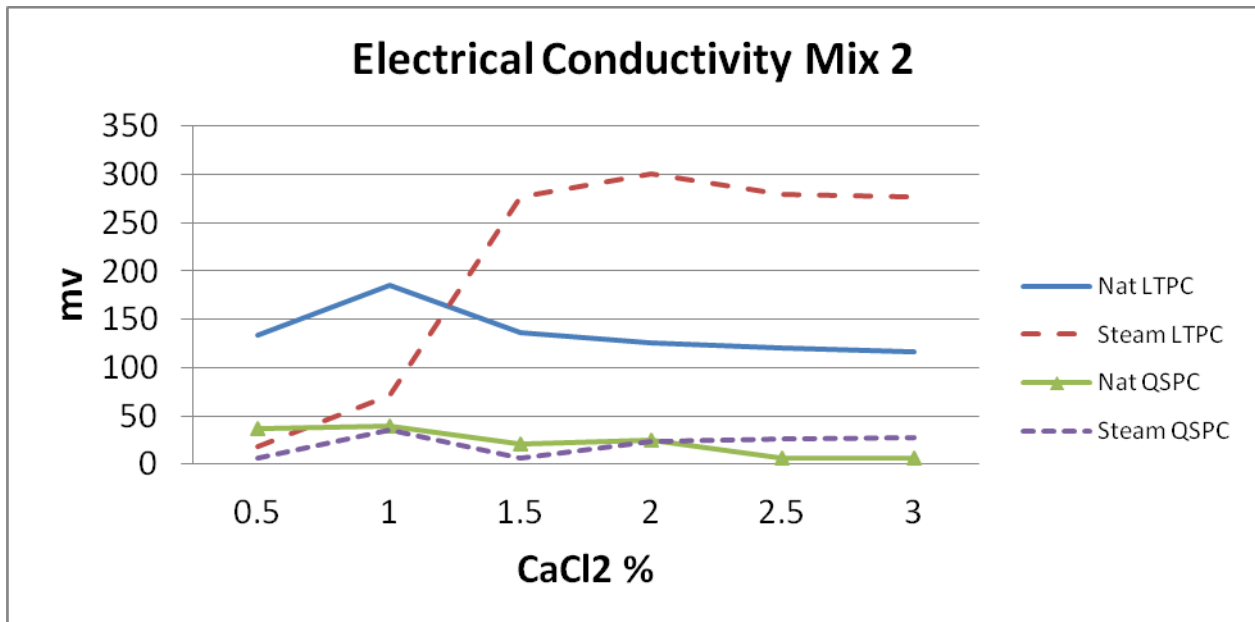


Figure 4. Electrical Conductivity for several levels of CaCl_2 for medium cement (3:1) mixture using normal and quick setting cement.

High cement ratio (Mix 1) shown in Figure 3 indicates significantly higher conductivity compared to lower cement ratio (Mix 2) for the two types of cement used (Figure 4). High EC in mv means higher protection from corrosion. While quick setting type had lower EC and less corrosion resistance.

In summary, the results show significant corrosion of steel iron bars in cement with low alumina (Mix2). The minimum corrosion is observed in the moderate alumina cement mortar (Mix 1) and where the corrosion of iron with a calcium chloride content of 3%.

Also, additional benefit of adding calcium chloride is increasing final strength resistance of the concrete. The gain in concrete strength and corrosion protection due to use of calcium chloride is comparable to wet burlap for three days. Steam curing provided higher protection as shown in higher EC. A CaCl_2 level of 1 % show highest level of protection.

REFERENCES

- [1] ACI Committee 222 R -96, "Corrosion of Metals in Concrete", ACI Manual. 2002, ISBN: 9780870310607
- [2] ACI Committee 201 2R-92, "Guide to Durable Concrete", Chapter 4, ACI Manual, chapter four, November, 2016, p.16-20, ISBN: 978-1-945487-39-2
- [3] American Concrete Institute (ASCC), 2021. Acceptable use of Calcium Chloride in Concrete. ASCC Position Statement #31.
<https://www.asconline.org/Portals/0/docs/POSITION-STATEMENTS/PS-31-acceptable-use-calcium-chloride-concrete.pdf>
- [4] American Society for Testing and Materials (ASTM), C496-86, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", Annual Book of ASTM Standards, Vol. 04.02, 1989, PP. 259-262.
- [5] ASTM Special Technical Publication 908, 1984. "Corrosion Monitoring in Industrial Plants Using Nondestructive Testing and Electrochemical Methods", Canada, 22-24 May 1984.
- [6] British Standard Institution (BSI), "Method for Determination of Flexural Strength, B.S. 1881, Part 118, 1989a, PP. 3.
- [7] British Standard Institution (BSI), "Method for Determination of Compressive Strength of Concrete Cubes", B.S. 1881: Part 116, 1989b, PP.4.
- [8] Hope B.B. and S.V. Thompson, "Damage to Concrete Induced by Calcium Nitrite", ACI Materials Journal, Sep-Oct. 1995, PP. 529-531.
- [9] Jamil H.E., Shri A., Boulif R., Bastos C., Montemor M.F. and M.G.S. Ferreira, "Electrochemical Behavior of Amino Alcohol- Based Inhibitors Used to Control Corrosion of Reinforcing Steel", Science @ Direct, Electrochemical Acta, 2004, 2753-2760.
- [10] John P. B. "Corrosion of Steel in Concrete", Understanding, Investigation and Repair, 1997, E & FN Spon an Imprint of Rutledge London & New York.
- [11] Kepler J.L., Darwin D. and C.E Locke. "Evaluation of Corrosion Protection Methods for Reinforced Concrete High way Structures. SM Report No. 58, University of Kansas Center for Research, Inc., Lawrence, Kansas, May 2000, 221 pp.
- [12] Fontana M.G., "Corrosion Engineering", McGRAW-HILL international book company, 1978.
- [13] Mahmoodian, M. Reliability and Maintainability of In-Service Pipelines, Elsevier, United Kingdom, 2018, DOI:10.1016/c2016-0-05259-2.
- [14] Berke N. S. "Review of Corrosion Inhibitors in Concrete", Materials Performance, Vol.28, No.10, Oct. 1989, PP.41-44.
- [15] Bertolini, L., B. Elsener, P. Pedferri and R. Polder, "Corrosion of Steel in Concrete", 2004, Germany.
- [16] Quraishi MA, DK Nayak, R Kumar and V Kumar, "Corrosion of Reinforced Steel in Concrete and Its Control: An overview," Journal of Steel Structures & Construction, Vol. 3, Issue 1, pages 1-6, 2017, DOI: 10.4172/2472-0437.1000124
- [17] Bavarian B., "Corrosion Protection of Steel Rebar in Concrete Using Corrosion Inhibitors MCI 2021 and MCI 2022", College of Engineering and Computer Science, California State University, Northridge, March 2002.
- [18] Landroum R.J., "Fundamentals of Designing for Corrosion Control: A Corrosion Aid for The Designer", National Association of Corrosion Engineers, Houston, Texas, 1989, PP.352
- [19] Limaye R.G., R.D Angal and A.S. Radke, "Experiment Studies on Penetrating - type Corrosion inhibitor in reinforced concrete", Indian Concrete Journal, Jan. 2000, PP. 22 - 26.
- [20] Virmani P. Y., and H. Ghasemi, "Literature Review of Chloride Threshold Values for Grouted Post-Tensioned Tendons." FHWA Publication No.: FHWA-HRT-12-067, 2012. Online: <http://www.fhwa.dot.gov/research>.
- [21] Virman Y. P., "Effectiveness of Calcium Nitrite Admixture as a Corrosion Inhibitors", Public Roads, Vol. 54, No. 1, 1990, PP. 171-182.
- [22] California Department of Transportation, Division of Engineering Services, Materials Engineering and Testing Services (CDT), Corrosion Technology Branch "Corrosion Guidelines", Version 1.0, September 2003.
- [23] Paul T. T., "Materials and Methods for Corrosion Control of Reinforced and Prestressed concrete structures in New Construction", U.S. Dep. Of Transportation, Federal Highway Administration. August, 2000.
- [24] Kwon S. J., "Current Trends of Durability Design and Government Support in South Korea: Chloride Attack", Sustainability, 9, 417; 2017, doi:10.3390/su9030417
- [25] Perez N., "Electrochemistry and Corrosion Science", Department of Mechanical Engineering, University of Puerto Rico, Kluwer Academic Publishers, 2004.

- [26] Qian S. and D. Cusson, "Electrochemical Evaluation of The Performance of Corrosion Inhibiting System in Concrete Bridges " , Journal of Cement and Concrete Composites, Vol.26, No. 4, May -2004, P.P. 217-233, 2004 (NRC) National Research Council Canada , Ottawa , Ontario, Canada.
- [27] Berke, N.S., "Corrosion inhibitors in concrete", Concrete International, 1991, Vol. 13 No. 7, p. 24,.
- [28] Badogiannisa E., Kakalia G., Dimopoulou G. , Chaniotakis E., S. Tsivilis , "Effect of calcium chloride on the hydration characteristics of ground clay bricks cement pastes." Cement and Concrete Composites, 2012. , Volume 27, Issue 2, February 2005, Pages 197-203
- [29] Tritthart, J. "Chloride binding in cement II. The influence of the hydroxide concentration in the pore solution of hardened cement paste on chloride binding", Cem. Concr. Res., 1989, vol 19, 683–691.
- [30] Ann, K.Y.; J.H. Ahn.; J.S. Ryou, "The importance of chloride content at the concrete surface in assessing the time to corrosion of steel in concrete structures.", Constr. Build. Mater. 2009, vol. 23, pp. 239–245.
- [31] Florea, M.V.A.; H.J.H Brouwers,. "Chloride binding related to hydration products part I: Ordinary Portland cement." , Cem. Concr. Res., 2012, vol. 42, pp. 282–290.
- [32] Ortolan V. K. , Mancio M., B. F. Tutikian "Evaluation of the influence of the pH of concrete pore solution on the corrosion resistance of steel reinforcement", J Build Rehabil, 2016, 1:10. , DOI 10.1007/s41024-016-0011-8
- [33] Al-Kutti W. A. S., Simulation of chloride transport in concrete with stress induced damage [Ph.D. thesis], King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, 2011.
- [34] Glass G. K. and N. R. Buenfeld, "The influence of chloride binding on the chloride induced corrosion risk in reinforced concrete," Corrosion Science, vol. 42, no. 2, pp. 329–344, 2000.
- [35] Shi X., N. Xie, K. Fortune, and J. Gong, "Durability of steel reinforced concrete in chloride environments: an overview," Construction and Building Materials, vol. 30, pp. 125–138, 2012.
- [36] American Concrete Institute (ACI), "Accelerated Curing of Concrete at Atmospheric Pressure" , 1992,
- [37] Han S.-H., "Influence of diffusion coefficient on chloride ion penetration of concrete structure," Construction and Building Materials, vol. 21, no. 2, pp. 370–378, 2007.
- [38] Ho J L, D G Kim, Jang Hwa Lee, M S Cho, "A Study for Carbonation Degree on Concrete using a Phenolphthalein Indicator and Fourier-Transform Infrared Spectroscopy", World Academy of Science, Engineering and Technology 62 2012
- [39] Kim TK, SJ Choi , JH J. Kim, YS Chu , and E. Yu, "Performance Based Evaluation of Carbonation Resistance of Concrete According to Various Curing Conditions from Climate Change Effect", International Journal of Concrete Structures and Materials, 2017, Vol. 11 , pp. 687-700, DOI 10.1007/s40069-017-0206-7 ISSN 1976-0485 / eISSN 2234-1315
- [40] Tang Y., Hui Su, S Huang, Chunlai Qu, and J Yang, "Effect of Curing Temperature on the Durability of Concrete under Highly Geothermal Environment", Advances in Materials Science and Engineering , 2017, Volume 2017, Article ID 7587853, 9 pages <https://doi.org/10.1155/2017/7587853>
- [41] Idowu, O and L Black, "The Effect of Improper Curing on Properties That May Affect Concrete Durability" Magazine of Concrete Research, 2018, Vol. 70 (12), pp. 633-647. ISSN 0024-983.
- [42] Siddiqui M. S., Nyberg W. , Smith W., Blackwell B. , and K. A. Riding , " Effect of Curing Water Availability and Composition on Cement Hydration". ACI Materials Journal/May-June 2013, TECHNICAL PAPER, TITLE no. 110-M27 , PP. 315-322.
- [43] Stephen R.S., "Evaluation of Two Corrosion Inhibitors Using Two Surface Application Methods For Reinforced Concrete Structures " , Virginia Dep. of Transportation, University of Virginia, Des. 2004.
- [44] Paul V Y and G.G. Clemena , "Corrosion Protection Concrete Bridges", Report No.FHWA-RD-98-088,Federal Highway Administration , Washington , D.C.1998.