ORIGINAL RESEARCH

The effect of moisture on corrosion of concrete structures and solutions to combat it

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Abstract:

With the increase in the world population, especially in developing countries, it has caused an increase in housing density and a decrease in land. Today, construction systems are faced with a shortage of suitable land and have moved towards the banks of rivers and seas in humid provinces, which has caused a problem of moisture in buildings, especially concrete structures. In tidal marine environments, the diffusion of chloride ions into the concrete and the resulting corrosion are usually the main causes of damage and reduced useful life of reinforced concrete structures. In these structures, which are not completely saturated and are constantly affected by the successive wetting and drying processes, the penetration of chlorine ions into the concrete occurs much faster than the net diffusion.In this regard, we have examined many studies on the corrosion of concrete structures with the aim of improving their performance in aqueous environments and observed that the use of microsilica technique is the most effective technique for combating concrete corrosion in wet conditions in concrete structures due to its proper placement in the concrete paste and immobility.

Keywords:
Concrete structures, concrete corrosion, microsilica, reinforced concrete

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1. Introduction

Corrosion is a phenomenon involving a chemical or electrochemical reaction between a material, usually a metal, and its surrounding environment that will lead to a change in the properties of the material, which is a harmful reaction in general. Four environmental factors, reinforcement corrosion, alkaline reaction of aggregates, freezing and sulfate attack, and chloride ion penetration, are factors that cause premature failure in concrete structures. Concrete and the loss of the spontaneous oxide layer around the reinforcement are the factors that initiate reinforcement corrosion in concrete structures implemented in coastal areas. The penetration of this ion depends on factors such as environmental conditions, composition, and quality of concrete implementation.

Reducing the water to cement ratio reduces the penetration of chloride ions in concrete. There are also numerous studies that show that the use of cement additives such as microsilica in concrete is effective in reducing the penetration of chloride ions in concrete (1).

The most important factor in the occurrence of corrosion in coastal areas is various problems such as improper design, poor execution, and corrosive environmental conditions with a maximum temperature of 34 to 36 degrees and a maximum relative humidity of 73 percent.

The prevalence of this phenomenon has presented serious challenges to the useful life of concrete structures constructed in these areas. As a result of these execution problems, which result in poorer quality and more permeable concrete, the penetration of chlorine ions by seawater or soil in the area accelerates the onset of corrosion and ultimately we witness a significant reduction in the useful life of structures in these areas (2).

In recent decades, reinforcement corrosion has been the main cause of premature damage to concrete buildings and bridges. Corrosion of reinforcement in reinforced concrete structures usually occurs under the influence of chloride ions. Carbon dioxide can also be mentioned as another factor that causes damage and corrosion in concrete structures (4,3).

Predicting the performance and strength of concrete structures subjected to carbon dioxide and chlorine attack requires a thorough understanding of the factors that contribute to concrete deterioration, the initiation of corrosion in concrete reinforcement, and corrosion damage. Factors such as the quality of the concrete used, distance from the sea, severe or mild environmental conditions, the amount of concrete cover, water-to-cement ratio, and loading affect the rate and time of corrosion (4, 10). The corrosion process in which reinforcement is rapidly corroded is a complex process that is largely dependent on environmental and external factors such as temperature and humidity. It is important to note that the surface chloride load and the rate of chloride ion penetration will vary depending on the type of exposure to different marine conditions. Figure 1 shows the different marine conditions to which the structure is exposed (7, 9).

The aim of this study is to provide solutions to minimize damage to concrete structures and the efficiency of the structures industry in wet conditions.

2. Description of the proposed method

To achieve the above goal, we collected and studied a set of research conducted in the field of concrete structures. Among the available sources, we further examined the top 20 sources in the field of concrete structure crumbling and the results of our study series will be presented in the next section. We will continue to review the results and provide solutions to deal with the corrosion of concrete structures.

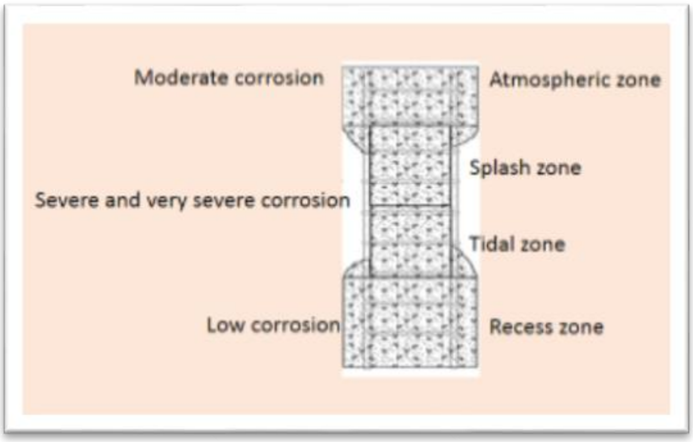

Figure 1: Concrete cross-section under different environmental conditions under corrosion (Shekarchi et al., 2008).

5. Results

Mechanism of concrete degradation in seawater

Based on the location of the structure in seawater, the methods of concrete degradation are divided into three categories; 1. Concretes that are above the tide line and not exposed to water; these concretes are exposed to air currents containing sea salts. The air currents that affect this part of the concrete may cause corrosion of the concrete reinforcement. 2. Concretes that are located in the intertidal zone; can be affected by alternating wetting and drying, corrosion of the reinforcement, chemical reactions that cause the destruction of hydration products, and erosion caused by the impact of waves and sand. 3. The part of the concrete structure that is below the tide line; is fully prepared for chemical reactions but is less damaged by corrosion of steel (8). The stability of concrete in seawater depends on the mineral composition of the cement, and the problem of the stability of concrete in seawater can be solved by using pozzolanic cements. According to studies conducted by researchers, to deal with this problem, the right cement composition is low in alumina and calcium sulfate, and concrete with a low water-cement ratio and high density, this type of cement is called siliceous (1).

In general, the aggressive compounds of seawater against concrete include sulfate, chloride, carbonate, bicarbonate, alkali metals, and magnesium ions, which interact and react more intensely with the warmer the air. Below, we will describe some of these factors:

1. Sulfates

are converted into heavy hydrosulfoaluminates simultaneously with two other processes, namely, C3A solid-liquid interaction through which magnesium hydroxide and possibly gypsum are produced in the pores of the gel that increases the surface energy of the solid phase, and mechanical pressure resulting from the crystallization of salts that occur in pores near the surface of the concrete that are subjected to alternating drying and expansion (1).

2. Carbonate and bicarbonate

Carbonate and bicarbonate ions may participate in the carbonation reaction of Ca^{++} with Ca (OH)، formed during cement hydration. Water-soluble CO_2, such as carbonic acid, causes local softening and decomposition, which causes carbonation-induced shrinkage. The intensity of carbonation depends on the permeability, relative humidity, specific surface area of the cement paste, and CO_2 concentration, but

CO2 itself is relatively unstable in a form capable of interacting with most hydrated cement constituents (1).

3. Chloror

Chlorine ions may act similarly to sulfate ions and produce a product called chloroaluminate. They may also participate in reactions that contribute to the corrosion of reinforcement or other metals in concrete. The role of chlorine in seawater in interactions with concrete is twofold. First, it acts independently and secondly, it slows down or prevents the expansion of concrete by the sulfate solution (1,7).

Mechanism of steel corrosion

Corrosion of steel in concrete is a chemical or, in other words, electrochemical process. Like other chemical and electrochemical processes, this activity is a function of environmental conditions, especially the temperature of the environment and concrete. This activity is intensified in the hot air of the region. Humidity is necessary for corrosion. OH ions play an important role in corrosion and the formation of iron hydroxide, and the water present plays the role of electrolyte and also causes ion mobility. For this reason, the electrical resistance of wet and saturated concrete is much lower than that of air-dried concrete.

The high percentage of chlorine ions in the environment around the concrete causes it to leak more into the cement and concrete. Researchers believe that other environmental conditions such as the presence of sulfate can cause more chlorine ions to penetrate, and concrete buried in wet soil containing sulfate and chlorine ions has worse conditions than concrete submerged in salty seawater, which can also be attributed to the presence of oxygen and the concrete not being completely saturated.

Research shows that for corrosion to start and continue, we need a certain amount of chlorine ions in the alkaline environment around the rebar buried in the concrete. This amount of chlorine ions has been mentioned from 0.25 percent of the weight of the concrete cement to 0.5 percent. However, most often, a value of 0.35 to 0.4% is mentioned, which is called the chloride ion threshold for corrosion and is calculated in terms of chloride ions dissolved in water as a percentage of the weight of cement. This value should not be confused with the permissible amounts of chloride ions in primary and fresh concrete. Wind can cause the penetration of chloride ions present in the air of the area, especially on a certain side of the concrete (1).

Frequent wet and dry conditions, such as those in the tidal zone or in a place exposed to seawater spray, severely affect and intensify the corrosion of rebars. Increasing the concentration of salts in the water of the area and the availability of moisture and oxygen can also be factors that intensify it (8,3).

If Fe(OH3) is the main product of round bar corrosion, its volume is 2 to 14 times that of the original round bar, and its expansion exerts a great deal of pressure on the surrounding concrete, which causes cracking of the concrete coating around the reinforcement, leaving the reinforcement exposed to environmental factors without protection. Continued corrosion causes a gradual reduction in the surface area of the reinforcing bar, and if repairs are not made, destruction and breakage occur, and the life of the concrete structure ends (Figure 2).

Important and practical factors in preventing corrosion of concrete structures

1. **Use of microsilica in concrete mix**

Adding microsilica to the concrete mix causes its active SiO2 to combine with the free calcium hydroxide solution Ca(OH2) present in the capillary pores of the concrete, forming insoluble calcium silicate crystals and ultimately causing the cement paste structure to become dense. The cementitious and pozzolanic properties obtained from the microsilica mix produce new C-S-H compounds and provide a stronger texture, which leads to higher strength, and also, due to its high softness, it fills all the microscopic pores of the cement paste and provides a completely solid concrete, which leads to higher durability. Research results show that using microsilica as a substitute for cement has increased the compressive strength of concrete compared to samples without microsilica, such as the following:

- Concrete construction on seashores, piers and bridges
- Construction of concrete with high strength and mechanical properties
- Construction of concrete for dams, canals, tunnels, reservoirs and water sources
- Flooring and facades
- Construction of concrete exposed to corrosion
- Use in all structural elements
- Production of dense and impermeable concrete

In general, the effects of using microsilica in concrete can be summarized as reducing permeability, increasing compressive, flexural and tensile strength, increasing concrete resistance to erosion, preventing the penetration of chloride ions, sulfates and other destructive chemicals into the concrete, reducing the heat of hydration, delaying the alkaline reaction of grains, reducing the effect of the freeze-thaw cycle and increasing the cohesion of concrete. Also, the use of microsilica blocks the capillary channels of concrete perspiration (2,4).

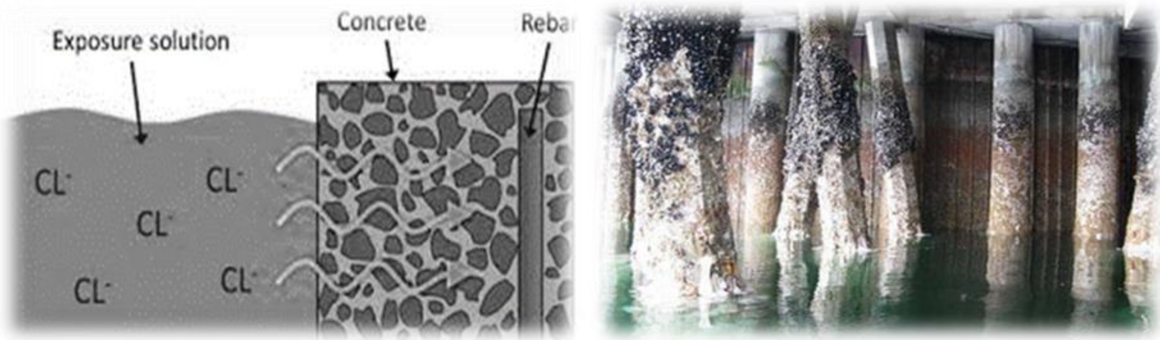

Figure 2: Concrete corrosion in relation to sea humidity and chloride pressure

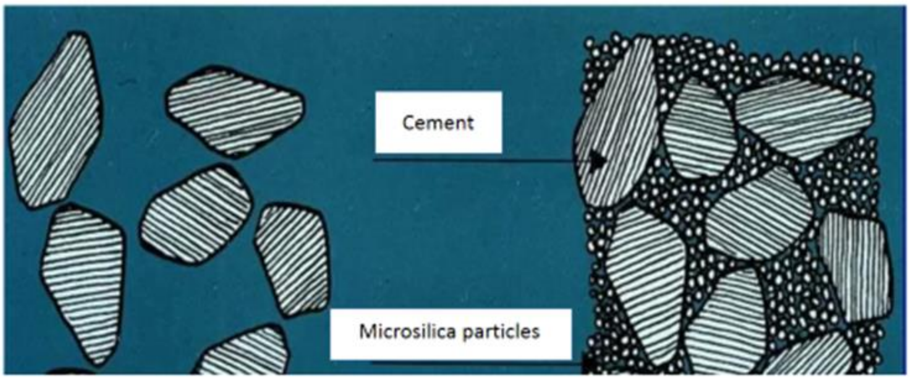

Figure 3: The effect of microsilica on the durability of concrete

2. The effect of using concrete fibers in hydraulic structures and resistance to cavitation

Studies show that the use of fibers also existed in ancient times. The ancient Egyptians used straw to reinforce mud bricks. Fireproof cotton fibers were also used to reinforce clay, and in addition, horsehair was also used for reinforcement. In recent years, the need to design concrete structures with more complex conditions has expanded the use of new materials and methods for reinforcing concrete, and one of the new methods of reinforcement is the use of fibers. The use of fibers in concrete began about 50 years ago and their use in various fields has increased day by day. Adding fibers to the mixing design improves the mechanical properties of concrete and the behavior of the structure after cracking. Fibers also increase the ductility of concrete. In general, fiber-reinforced concrete can be expected to improve parameters related to load-bearing coefficients such as compressive strength, tensile strength, flexural strength, shear strength, as well as resistance to creep, abrasion, cavitation, and erosion.

Cavitation is the process of producing bubbles and voids inside water cycles or turbines, which are created due to pressure differences. When these bubbles reach a high pressure level, they burst and cause shocks and damage to the structure. The use of fiber concrete can control these shocks well. By bridging the cracks, the fibers maintain the integrity of the concrete during high deformations. In fact, the use of fiber concrete can be used in the construction or repair of dams and any hydraulic structure, which can increase the resistance of the structure against cavitation and also against serious corrosion caused by the shocks of the water volume (8).

3. Use of inhibitors

Although numerous inhibitors have been proposed so far, only a few of them have been able to attract the attention of researchers for further studies. According to the classification of the International Society of Engineering, corrosion inhibitors available on the market can be divided into three main groups:

- Anodic inhibitors
- Cathodic inhibitors
- Anodic-cathodic inhibitors

Usually, during the construction of reinforced concrete, an oxide layer forms on the rebars buried in it in the hyperalkaline environment of the concrete. This layer protects the rebars from corrosion even in a chloride environment with a concentration of 3kg/m24. Anodic inhibitors improve and stabilize this natural oxide layer and strengthen the inertness of the rebars in the vicinity of the cement paste.

One of these inhibitors is the inorganic substance calcium nitrite. Calcium nitrite-based inhibitors have been commercially available for over 15 years, and there have been no reports of their effects on reinforced concrete. Two other organic materials introduced in 1991 are butyl esters and marine trace elements, each of which inhibits steel corrosion in concrete. Butyl esters do this by reducing the permeability of concrete and dense mortars. The second mechanism is the formation of a thin-layer barrier on the steel, which has not been evaluated and confirmed by any independent source and requires further study and investigation (8,10).

4. Discussion and Conclusion

In recent years, a large number of concrete structures in different countries of the world and also in Iran have suffered damage or premature failure due to the weakness of concrete. In other words, the useful life of these structures does not match the predicted value and is much less than that. We have conducted many studies and after reviewing many studies, we found that the use of microsilica, due to its better placement in the cement paste and lack of movement, both prevents corrosion and is environmentally friendly.

Considering that one of the main factors of premature failure in reinforced concrete structures is the corrosion of rebars due to chloride penetration in concrete and the most important factor in increasing the speed of this destruction is the permeability of concrete, the use of pozzolanic materials such as microsilica has a positive effect on corrosion, increasing electrical resistance and reducing the permeability of concrete.

Using concrete containing microsilica in the range of 7 to 13 percent of the weight of cement has a significant effect on reducing corrosion compared to concrete without microsilica. Therefore, the use of microsilica affects the onset time and propagation of progress in steel corrosion.

5. References

1. Abedini, M., and Zhang, C. (2021). Dynamic performance of concrete columns retrofitted with FRP using segment pressure technique. *Composite Structures*, *260*, 113473. https://doi.org/10.1016/j.compstruct.2020.113473

2. Zhang, C., Abedini, M., and Mehrmashhadi, J. (2020). Development of pressure-impulse models and residual capacity assessment of RC columns using high fidelity Arbitrary Lagrangian-Eulerian simulation. *Engineering Structures*, *224*, 111219. https://doi.org/10.1016/j.engstruct.2020.111219

3. Ghanei, H. Eskandari-Naddaf, T. Ozbakkaloglu, A. Davoodi, Electrochemical and statistical analyses of the combined effect of air-entraining admixture and micro-silica on corrosion of reinforced concrete, Construction and Building Materials, 262 (2020) 120768. https://doi.org/10.1016/j.conbuildmat.2020.120768

4. L. Li, J. Zhu, Z. Huang, A. Kwan, L. Li, Combined effects of micro-silica and nano-silica on durability of mortar, Construction and Building Materials, 157 (2017) 337-347. https://doi.org/10.1016/j.conbuildmat.2017.09.105

5. W. Wu, R. Wang, C. Zhu, Q. Meng, The effect of fly ash and silica fume on mechanical properties and durability of coral aggregate concrete, Construction and Building Materials, 185 (2018) 69-78. https://doi.org/10.1016/j.conbuildmat.2018.06.097

6. M.I. Khan, M.A.A. Sayyed, M.M.A. Ali, Examination of cement concrete containing micro silica and sugarcane bagasse ash subjected to sulphate and chloride attack, Materials Today: Proceedings, 39 (2021) 558-562. https://doi.org/10.1016/j.matpr.2020.08.468

7. Joshaghani, A., & Moeini, M. A. (2017). Evaluating the effects of sugar cane bagasse ash (SCBA) and nanosilica on the mechanical and durability properties of mortar. *Construction and building materials*, *152*, 818-831. https://doi.org/10.1016/j.conbuildmat.2017.07.041

8. Awoyera, P. O., Adesina, A., Sivakrishna, A., Gobinath, R., Kumar, K. R., & Srinivas, A. J. M. T. P. (2020). Alkali activated binders: Challenges and opportunities. *Materials Today: Proceedings*, *27*, 40-43. https://doi.org/10.1016/j.matpr.2019.08.199

9. Bahurudeen, A., Kanraj, D., Dev, V. G., & Santhanam, M. (2015). Performance evaluation of sugarcane bagasse ash blended cement in concrete. *Cement and Concrete Composites*, *59*, 77-88.

https://doi.org/10.1016/j.cemconcomp.2015.03.004

10. Fairbairn, E. M., Americano, B. B., Cordeiro, G. C., Paula, T. P., Toledo Filho, R. D., & Silvoso, M. M. (2010). Cement replacement by sugar cane bagasse ash: CO2 emissions reduction and potential for carbon credits. *Journal of environmental management*, *91*(9), 1864-1871. https://doi.org/10.1016/j.jenvman.2010.04.008

11. Arenas-Piedrahita, J. C., Montes-García, P., Mendoza-Rangel, J. M., Calvo, H. L., Valdez-Tamez, P. L., & Martínez-Reyes, J. (2016). Mechanical and durability properties of mortars prepared with untreated sugarcane bagasse ash and untreated fly ash. *Construction and building materials*, *105*, 69-81. https://doi.org/10.1016/j.conbuildmat.2015.12.047

12. Lin, X., Li, W., Guo, Y., Dong, W., Castel, A., & Wang, K. (2023). Biochar-cement concrete toward decarbonisation and sustainability for construction: characteristic, performance and perspective. *Journal of Cleaner Production*, *419*, 138219. https://doi.org/10.1016/j.jclepro.2023.138219

13. Li, Y., Chai, J., Wang, R., Zhang, X., & Si, Z. (2022). Utilization of sugarcane bagasse ash (SCBA) in construction technology: A state-of-the-art review. *Journal of Building Engineering*, *56*, 104774. https://doi.org/10.1016/j.jobe.2022.104774

14. Agwa, I. S., Zeyad, A. M., Tayeh, B. A., Adesina, A., de Azevedo, A. R., Amin, M., & Hadzima-Nyarko, M. (2022). A comprehensive review on the use of sugarcane bagasse ash as a supplementary cementitious material to produce eco-friendly concretes. *Materials today: proceedings*, *65*, 688-696. https://doi.org/10.1016/j.matpr.2022.03.264

15. Bheel, N., Ali, M. O. A., Kirgiz, M. S., de Sousa Galdino, A. G., & Kumar, A. (2021). Fresh and mechanical properties of concrete made of binary substitution of millet husk ash and wheat straw ash for cement and fine aggregate. *Journal of Materials Research and Technology*, *13*, 872-893. https://doi.org/10.1016/j.jmrt.2021.04.095

16. Quedou, P. G., Wirquin, E., & Bokhoree, C. (2021). Sustainable concrete: Potency of sugarcane bagasse ash as a cementitious material in the construction industry. *Case studies in construction materials*, *14*, e00545. https://doi.org/10.1016/j.cscm.2021.e00545

17. Saad, T., & Fu, C. C. (2015). Determining remaining strength capacity of deteriorating RC bridge substructures. *Journal of Performance of Constructed Facilities*, *29*(5), 04014122. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000467

18. Shao, W., Nie, Y., Liang, F., & Shi, D. (2020). A novel comprehensive evaluation method for the corrosion initiation life of RC hollow piles in chloride environments. *Construction and Building Materials*, *249*, 118801. https://doi.org/10.1016/j.conbuildmat.2020.118801

19. Shayanfar, M. A., Barkhordari, M. A., & Ghanooni-Bagha, M. (2015). Probability calculation of rebars corrosion in reinforced concrete using css algorithms. *Journal of Central South University*, *22*, 3141-3150.

20. GhanooniBagha, M., Shayanfar, M. A., & Yekkefallah, M. R. (2017). The effect of changes in carbon-dioxide concentrations on corrosion initiation of reinforced concrete structures. *Amirkabir Journal of Civil Engineering*, *50*, 697-706. DOI: 10.22060/ceej.2017.12385.5199