Behavior of Reinforced SCC Short Columns Subjected to Weathering Effects

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Abstract. Bridges & offshore structures are often subjected to fresh and saltwater wet-dry cycles, freeze-thaw cycles in winter, and heating cycles in summer. These environmental effects often cause steel reinforcement corrosion which can be protected using zinc coating. Zinc coating acts as a protective layer for the steel against corrosion. In this paper, the behavior of steel bars with and without zinc coating is investigated. An experimental study is performed on short reinforced concrete columns. Short 50-cm length concrete columns with square 10 × 10-cm cross-section, reinforced by four steel bars of 10-mm diameter are subjected to various weathering effects: accelerated corrosion, cycles of freshwater wet-dry, saltwater wet-dry, Freeze-Thaw (FT) and heating. Self-compacted concrete (SCC) mixes are prepared with 28 MPa average strength. A total of 20 concrete column samples are casted and divided into five groups: 1) salt water-wet-dry-uncoated rebars, 2) salt water-wet-dry-zinc-coated rebars, 3) fresh water-wet-dry-uncoated rebars, 4) heating to 70 °C, and 5) freeze-thaw samples, where 5 samples acted as a control sample and another 5 samples are subjected to accelerated corrosion. The remaining 10 samples are divided among the five groups where each group has 2 samples that are subjected to deterioration cycles. Results indicated that samples subjected to saltwater wet-dry cycles had the least strength among the five groups as expected. However, the diameter and mass losses in accelerated corrosion samples are doubled the values of that of the saltwater dry-wet cycles with the same mean strength.

Keywords: Self-compacted concrete · Accelerated corrosion · Freeze-Thaw · Wet-dry · Zinc coated-rebars

1 Introduction

Sustainable urban cities are one of the main goals that the world is trying hard to achieve nowadays. Today, 55% of the world population is living in urban cities and it is estimated to rise to 68% by 2050 (United Nations 2019). With increasing number of the population in urban areas, the construction of new buildings and structures in addition to maintenance of older structures become an urgent need. The concrete industry has the highest share in the Middle East region due to its relatively cheap cost compared to steel and timber. However, while reinforced concrete is a good thermal insulation material, it

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often fails to resist other deterioration effects mainly due to corrosion of reinforcement steel and chloride effects on the concrete material.

Deterioration of concrete can be likely seen in bridges in reinforced concrete columns subjected to either fresh or saltwater wet-dry cycles or dry columns subjected to cycles of freeze and thaw in cold areas or heating and cooling down in hot regions. Recent research had studied the effect of weathering effects by replacing the weathering cycles with accelerated corrosion to achieve faster results (Sanz et al. 2018; Ye et al. 2018). However, there's a need to investigate the validity of the accelerated corrosion to replace different weathering effects. In this paper, short reinforced concrete columns, cast using self-compacted concrete (SCC), were subjected to various weathering effects and compared with accelerated corrosion results.

SCCs were developed to provide the construction industry with more durable concrete that can resist the weathering effects. This can be obtained through the high workability of this concrete which could help with casting small sections, heavy-reinforced sections, repaired members, or members where it will be critical to use internal vibrators for compaction. Concrete compacted without the aid of vibrators, increases the bond between concrete and the embedded reinforcement, which improves the performance of the cast members, also, the low permeability of this high workable mix will lead to a more durable structure. SCC, due to its high mobility, can fill the formwork without any mechanical help, and with no risk of segregation (Paultre et al. 2005).

Some researchers dealt with SCC through the mix proportioning, and properties of concrete in the fresh and hardened stages (Sharifi 2012). Others studied the structural performance of such concrete. When studying the flexural and shear behavior of SCC reinforced beams versus the normal reinforced concrete beams, Luo and Zheng (2005) found that there is nearly no difference in performance between the two concretes regarding the failure mechanism, the yielding and ultimate moments, and the shear capacity. Therefore, SCC does not affect the structural behavior of members, however, it may have a positive effect on structures' durability.

The low-cost versatile material, concrete, must withstand the attack of the surrounding deterioration factors to survive in severe environments. These factors include, but not limited to, attack of chlorides, sulphates, carbonation, freezing-thawing, heating to elevated temperatures, drying-wetting cycles in tidal zones, etc. According to Wang and Li (2014), concrete is a heterogeneous material with passageways for water and aggressive ions penetrations. This phenomenon decreases the probability of surviving in severe environments if durability is not taken into consideration when designing concrete members. Current studies are still searching behind the environmental effects on concrete and how to protect concrete mainly from the corrosion of its reinforcement. Attack of saltwater and carbonation may be considered the main factors for reinforcement corrosion. Ghanooni-Bagha et al. (2020) stated that slight adjustments in concrete proportioning, water-cement ratio and cement content, may delay the corrosion initiation and improve concrete durability.

2 Experimental Study

An experimental study is performed on self-compacted short reinforced concrete columns. Short 500 mm length concrete columns with square 100 × 100 mm cross-section, reinforced by four steel bars of 10 mm diameter are subjected to various weathering effects such as cycles of freshwater wet-dry, saltwater wet-dry, Freeze-Thaw (FT) and heating and cooling and compared with accelerated corrosion. A total of 20 concrete column samples are cast and divided into five groups: 1) salt water-wet-dry-uncoated rebars, 2) salt water-wet-dry-zinc-coated rebars, 3) fresh water-wet-dry-uncoated rebars, 4) heating to 70 °C and cooling down to room temperature, and 5) freeze-thaw samples, where 5 samples act as control samples and another 5 samples are subjected to accelerated corrosion as shown in Fig. 1. The remaining 10 samples are divided among the five groups where each group has 2 samples that are subjected to deterioration cycles.

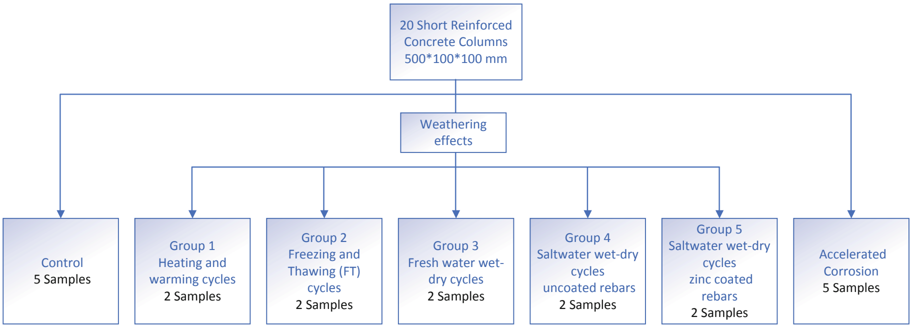

Fig. 1. Experimental program

2.1 Sample Preparation

Self-compacted concrete mix design was chosen as shown in Table 1 to facilitate the casting of the concrete in relatively small samples. Portland cement, sand, coarse aggregate, and water were all mixed in 0.142 m^3 concrete mixer with the addition of superplasticizer to facilitate the concrete workability. Slump test was recorded at 17.3 cm showing good workability of the mix design.

Table 1. Mix design for self-compacted concrete

Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Super plasticizer (kg/m^3)	Water (kg/m^3)
350	945	850	8.8	210

For steel reinforcement, 10 mm diameter deformed steel rebars were cut into three 470 mm long rebars and one 550 mm long rebar. The four rebars are held together using four stirrups of 6 mm diameter where each side is 70 mm width to fit inside the 100 × 100 mm formwork as shown in Fig. 2. Five steel cages were cleaned from dust using a cleaning agent and coated with Sika Zinc Rich® coating using hand brush as shown in Fig. 3 where two sides were coated first then left to dry for two hours, then the other two sides were coated and left to dry. While the most effective way to avoid corrosion is to apply the coating before installing the stirrups, the samples in this study were coated after the installation of the stirrups to simulate actual site conditions.

Fig. 2. Reinforcement steel cage

Fig. 3. Applying zinc coating to steel reinforcement cages

Plywood formworks were prepared to fit reinforced concrete columns with a cross-section of 100 × 100 mm and a length of 500 mm. The concrete cover was 15 mm from each side so that steel cage cross-section including stirrups was 70 × 70 mm. The steel cage was placed first so that it fits inside the formwork except for the 550 mm long rebar which was left out to be used for accelerated corrosion's electrical connections. A 150 × 150 × 150 mm cubic steel formwork was prepared for casting to evaluate the strength of the concrete after 28 days. The concrete was cast five times into 9 formworks of columns and cubes at a time for each group as shown in Fig. 4, however, only 4 samples per patch were used for the current study. After curing for 28 days, the 550 mm rebar and the upper surface of three columns samples out of four samples per each group were cut and ground, respectively. The remaining sample of each group with overhanging rebar was used in the accelerated corrosion process.

Fig. 4. Casted reinforcement concrete (RC) samples

2.2 Accelerated Corrosion

Five concrete columns were placed in a container filled with saltwater up to two-third of the column's height. The salt percentage was set to 3.5% of the total volume of the water to simulate the average seawater salt percentage. A rebar was placed in the water to act as the cathodic element while the reinforcement bars inside the columns act as the anode elements. The external driven voltage was set to 12 V and connected in parallel to all five samples as shown in Fig. 5. The saltwater was changed once throughout the total duration of 17 days and as the dark brown rust started accumulating on the surface as shown in Fig. 6, the accelerated corrosion stopped, and the columns were then cleaned for compressive testing.

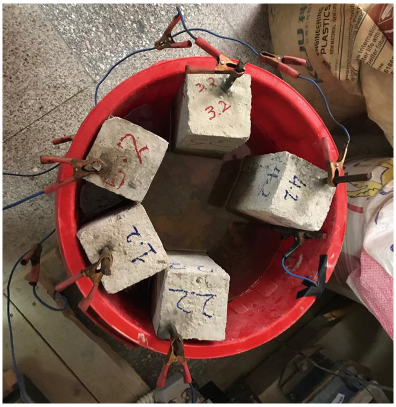

Fig. 5. Connected circuit for accelerated corrosion

Fig. 6. Accumulated rust on the surface of the columns after accelerated corrosion

2.3 Weathering Effects

Two samples of each group were subjected to different conditions to simulate actual weathering cycles. These cycles are divided into five groups as follows: 1) salt water-wet-dry-uncoated rebars, 2) salt water-wet-dry-zinc-coated rebars, 3) fresh water-wet-dry-uncoated rebars, 4) heating to 70 °C and cooling down to room temperature, and 5) freeze-thaw samples.

The first and the second group consisted of reinforced concrete samples without and with Zinc-coated rebars, respectively. The two samples were placed in a large ceramic tiled sink and subjected to saltwater with different water levels. The salt percentage was set to 3.5% which is the same of accelerated corrosion setup for comparison purpose while the water level was set to one-third (1/3) of the column height for 4 days and raised to two-thirds (2/3) of the column height for 3 days to simulate the water tide as shown in Fig. 7. A total of 11 cycles over three months were performed before the samples were left to dry in the open air for a week before testing. A similar procedure was applied to the third group but with fresh tap water.

(a) (b)

Fig. 7. Samples subjected to saltwater wet-dry cycles with water level is set to (a) 2/3 of column height for 3 days and 1/3 of column height for 4 days

The fourth group was subjected to freezing in a deep freezer with the temperature setting of −2 °C for 7 days as shown in Fig. 8 and then left outside the freezer for 4 days for thawing in average laboratory temperature of 20 °C. This cycle was repeated for 6 cycles. The −2 °C temperature was chosen to simulate average low temperature in the Middle East region and specifically Egypt where the low temperature occurs at high altitude mountainous areas. The fifth group was heating up to 70 °C in the oven for 1 day and cooled down to room temperature as shown in Fig. 9. A total of 50 cycles were performed over a total period of 100 days.

Fig. 8. Samples placed on a deep freezer and subjected to −2 °C freezing and thawing cycles

Fig. 9. Samples placed on an oven and subjected to 70 °C heating cycles

3 Test Results and Discussion

Initial material testing was performed to determine the material properties used. Self-compact concrete cubes were tested under compressive testing using ELE compression test machine. The mean value of the compressive strength of the concrete cubes was 28 MPa. In addition to concrete, samples of 10 mm diameter steel bars were tested under tension loading using an Instron universal machine where a typical load-elongation curve is shown in Fig. 10.

Instron universal machine was used to determine the load capacity of the columns by compressive loading of the samples under displacement control. 5 samples were tested as control samples as discussed earlier in Sect. 2 and Fig. 1. Typical compressive testing of concrete columns is shown in Fig. 11(a). First, the upper concrete surface suffered from concrete spalling as shown in Fig. 11(b), then the concrete column held the load until it finally failed showing longitudinal cracks along the reinforcement and concrete spalling at the bottom of the concrete column as shown in Fig. 11(c). Load-contraction curves of the control samples are shown in Fig. 12.

Figure 14(a) shows compression testing of accelerated corroded concrete columns samples. Load-contraction results for the tested samples are displayed in Fig. 13. Spalling of the cover were the typical failure mode of the tested samples as shown in Fig. 14(b). After concrete columns testing, the steel rebars were extracted, cleaned thoroughly using steel wire mesh, cleaning agent and grinding paper to remove any rust then, the diameter and mass losses of the steel bars were measured. A similar process was repeated for all different group to determine the mass, diameter and load capacity losses as shown in Fig. 15.

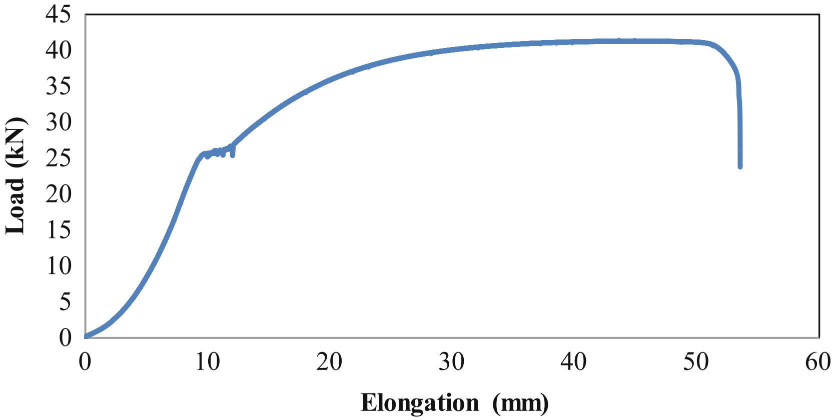

Fig. 10. Typical load-elongation curve for reinforcement steel

(a) (b) (c)

Fig. 11. (a) Compression testing of control RC columns (b) initial failure mode through spalling of the upper surface (c) final failure modes showing longitudinal cracks and lower surface spalling

Figure 15 shows that all weathering effects have limited diameter losses ranges from a mean value of 0.87% for heating and cooling cycles to 2.27% for freezing and thawing cycles. Mass losses were following the same trend for diameter losses however with constant double the value of the diameter losses which indicates that both indicators can lead to the same conclusion. In the other hand, the average load capacity for different samples experienced larger values of losses compared with diameter and mass losses.

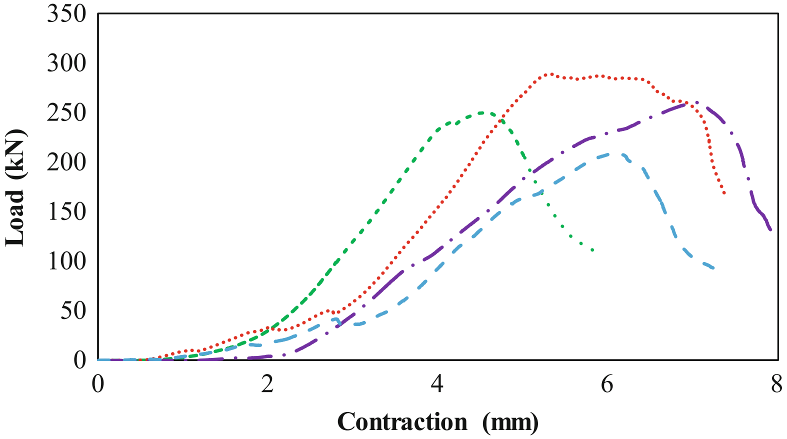

Fig. 12. Load-contraction curves for control RC columns

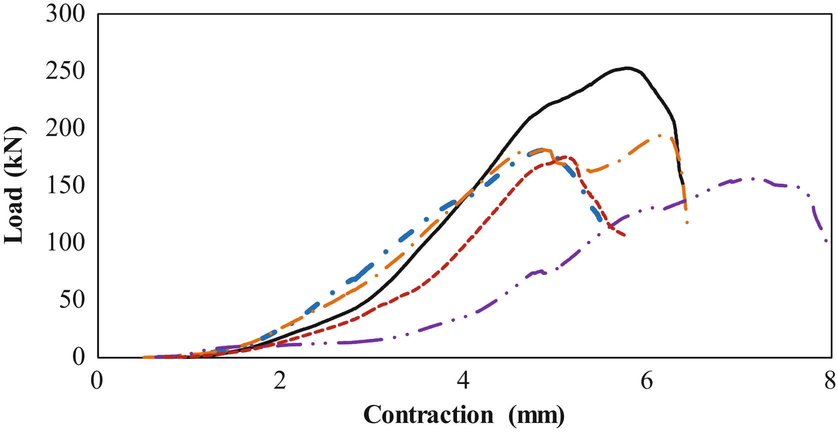

Fig. 13. Load-contraction curve for RC columns subjected to accelerated corrosion

The lowest average load capacity was 13% for samples subjected to heating and cooling cycles, followed by 17% for samples subjected to freezing and thawing cycles, then, 25% for samples subjected to fresh/tap water dry-wet cycles. The highest average load capacity loss was 33% for samples subjected to saltwater wet-dry cycles with coated and uncoated rebars. This can indicate that wet-dry cycles have a limited effect on the corrosion of the steel rebars.


(a) (b)

Fig. 14. (a) Compression testing of accelerated corroded RC columns (b) close caption showing spalling of the concrete cover

Figure 15 can also show a clear comparison between the effects of samples subjected to accelerated corrosion and saltwater wet-dry cycles. Samples with uncoated rebars experienced a close value for both accelerated corrosion and salt wet-dry cycles of an average load capacity loss of 30% and 33%, respectively. However, the diameter and mass losses values for the accelerated corrosion were almost three times that of the saltwater wet-dry cycles raising from 1.9% and 3.7% to 6% and 13% for mass and diameter losses, respectively. That indicates that saltwater wet-dry cycles affect the concrete properties more than the corrosion of the reinforcement steel.

The effect of the zinc coating can be observed through the low losses of load capacity of 13% for coated samples compared to 30% for uncoated samples when subjected to accelerated corrosion. However, the zinc coating has a limited effect when the samples subjected to saltwater wet-dry effect.

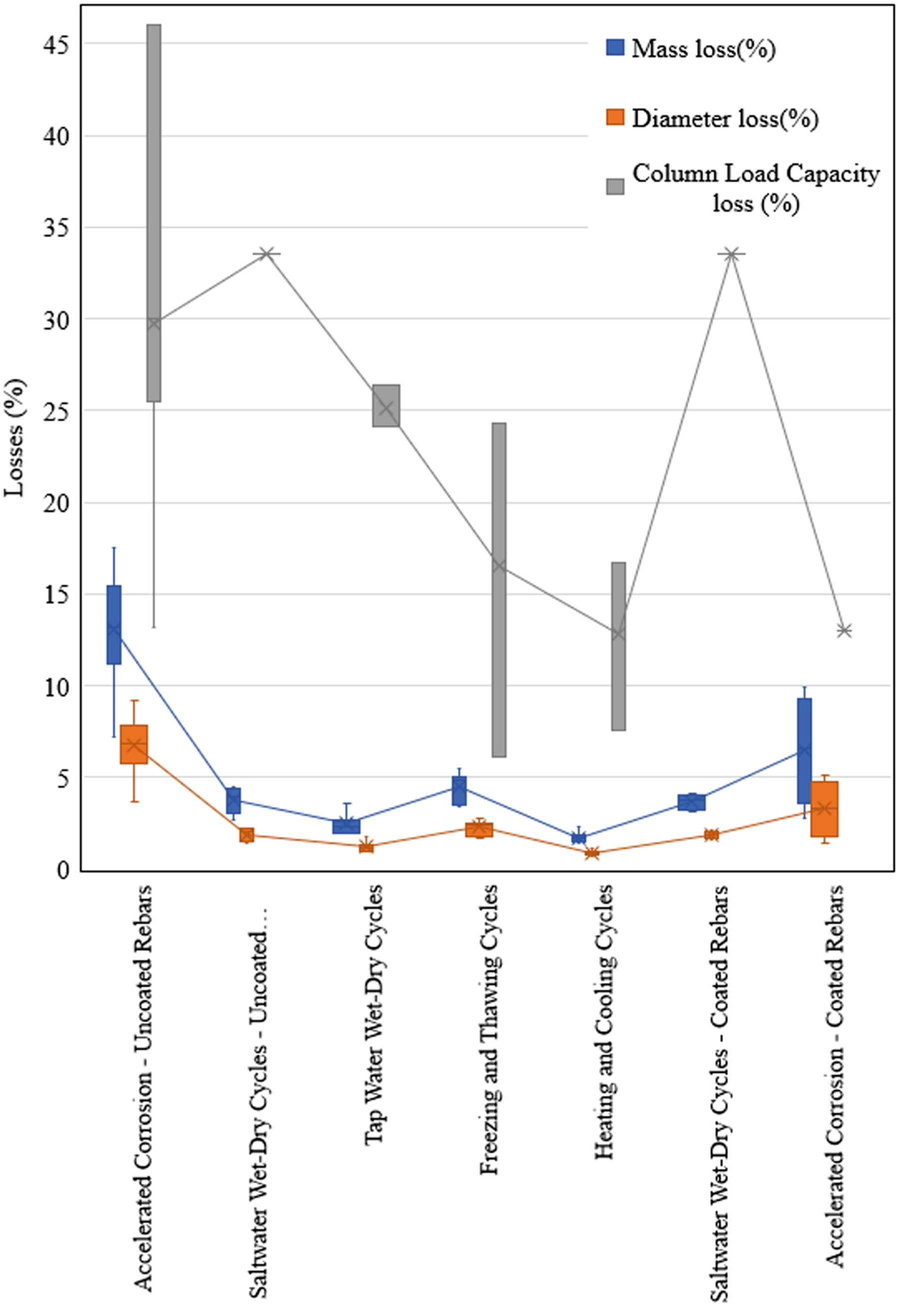

Fig. 15. Losses for samples subjected to different effects

4 Conclusions and Future Recommendation

Steel reinforced concrete-short columns are subjected to different weathering conditions such as saltwater and fresh wet-dry cycles, freezing and thawing, and heating and cooling. The results were compared to control samples and samples subjected to accelerated corrosion samples. Through this study, several conclusions can be noticed as follows:

1. All weathering effects have limited diameter losses ranges from a mean value of 0.87% for heating and cooling cycles to 2.27% for freezing and thawing cycles.
2. Mass losses were following the same trend for diameter losses however with constant double the value of the diameter losses ranging from 1.73% for heating and cooling cycles to 4.52% for freezing and thawing cycles.
3. The average load capacity for different samples experienced larger values of losses compared with diameter and mass losses ranging from 13% for heating and thawing cycles to 33% for samples subjected to saltwater wet-dry cycles with coated and uncoated rebars.
4. Uncoated rebar columns subjected to saltwater wet-dry cycles have similar performance to similar samples subjected to accelerated corrosion regarding load capacity, however, the diameter and mass losses values for the accelerated corrosion were almost three times that of the saltwater wet-dry cycles raising from 1.9% and 3.7% to 6% and 13% for mass and diameter losses, respectively. That indicated that saltwater wet-dry cycles affect the concrete properties more than the corrosion of the reinforcement steel.
5. Zinc coating of rebars has a limited effect when the samples subjected to saltwater wet-dry effect while it effective when samples subjected to accelerated corrosion.

Therefore, we can conclude that accelerated corrosion can only simulate the corrosion without the overall degradation induced from the wet-dry cycles. Ongoing research is currently carried by the authors to investigate the effect of wet-dry cycles on concrete without steel corrosion.

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