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Investigation of long-term corrosion resistance of reinforced concrete structures constructed with various types of concretes in marine and various climate environments

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HIGHLIGHTS

- Investigation of long-term corrosion of OC, SSC and LWC.
- Specimens were exposed to varying chloride levels and temperature conditions.
- LWC provided more resistance to corrosion as compared to OC and SSC.
- Models were developed for the prediction of corrosion rates for OC, SSC and LWC.

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ABSTRACT

Corrosion of steel in reinforced concrete is a serious concern for owners and asset managers of various concrete structures and infrastructure. Literature suggests there is limited research on long-term corrosion behaviour of various types of reinforced concretes under similar conditions of chloride and surrounding temperature environments. This paper presents results of a comprehensive experimental program designed to investigate the long term corrosion resistance of various types of reinforced concretes in the coupled effect of varying chloride and temperature conditions. Large size specimens (slabs) made of ordinary concrete (OC), lightweight concrete (LWC) and self-compacting concrete (SCC) were developed. The specimens were subjected to 365 days of corrosion under varying levels of chlorides and three temperature exposures respectively. The test results indicated that the corrosion rates of the rebars in LWC are the lowest compared to those of OC and SCC. Relations were developed for corrosion rates as a function of percentage chloride, temperature and time for different types of concretes. The current research can serve as a benchmark for adequate selection of type of concrete for construction in aggressive environments.

1. Introduction

Corrosion-induced deterioration of structures and infrastructure accounts for 2.5 trillion dollars per annum globally [1]. Significant efforts have been devoted to the development of new materials to enhance the service life of reinforced concrete structures and infrastructure against corrosion. Chloride attacks are the most detrimental to steel/rebar in any type of concrete, including ordinary, self-compacting or lightweight concrete [2–4].

Recently, the use of lightweight concrete in construction has increased in the last 10 to 15 years [5–10]. New techniques have been developed for construction with LWC, which are simple [11–13], cost-effective and environmentally friendly [14,15]. Moreover, several studies on the structural performance of LWC have been undertaken over the last 20 years [16–20]. However, research on the durability of LWC, and specifically on chloride-induced corrosion of the rebars is scarce [4,21]. Furthermore, there are limited comparisons between chloride-induced corrosion of LWC and other types of reinforced concrete. Moreover, long-term chloride attacks, which may prove to be detrimental to the service life of various types of reinforced concrete in hot climatic conditions, have not been adequately investigated.

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The preference of LWC over OC based on durability is debatable. As such, there are conflicting studies on the corrosion behaviour of both OC and LWC in aggressive environments. Some researchers assume that rebar in LWC resembles that in OC when analysing corrosion [22,23]. Other researchers have reported that LWC is more resistant to corrosion than OC [24,25].

Self-compacting concrete (SSC) is another type of concrete that is commonly used in reinforced concrete structures due its workability and durability [26]. However, the research on the long-term comparisons of the corrosion behaviour of SCC with LWC, and OC is very limited in literature.

From the aforementioned studies, it is evident that the long-term corrosion behaviour of structures built from various type of concretes (LWC, SCC and OC), under similar aggressive corrosive conditions have not been investigated previously. Furthermore, no long-term corrosion monitoring data has been reported for structures composed of these types of concrete. Moreover, the long-term coupled effect of corrosion and weather conditions (temperature variations) on these structures has not been investigated by other researchers, which can further cause durability concerns. In this paper, these limitations and gaps are addressed by comparing the durability of three different types of reinforced concrete after long-term exposure to varying chloride levels and climatic conditions. Three levels of chlorides concentrations (1, 3 and 5%) were admixed in OC, SCC and LWC specimens and exposed to three different temperatures of 30, 40 and 50 °C, respectively, to investigate the impact of temperature coupling with chloride. Corrosion monitoring of all specimens was carried out over 365 days. Models were developed for predicting the average corrosion rates under the given testing conditions. These models can aid the development of design guidelines for predicting the service life of existing structures. They can also guide the selection of concrete for the construction of more durable reinforced concrete structures near the sea.

2. Test methodology

2.1. Specimen design

Slab specimens (OC, SCC, LWC) with dimensions of 1000 × 1000 × 150 mm were prepared. These dimensions were selected to resemble existing concrete structures. Each specimen was reinforced with two 10 mm steel bars. Details on the composition of the steel and the specimens' design can be found in [3].

2.2. Test variables

The temperature and chloride concentrations were varied for OC, SCC and LWC specimens. Chloride (Cl) concentrations of 1%, 3% and 5%, and temperatures of 30 °C, 40 °C, 50 °C were selected to resemble different real-world conditions. The test plan is summarised in Table 1, which lists the number of specimens, measurements, the concentration of chlorides and temperature values used in the current research.

2.3. Concrete design

Type 1 ordinary Portland cement (OPC) was used for the preparation of all specimens in accordance with ASTM C150 [27]. The samples were mixed according to the requirements of ASTM C 192 [28]. Constituents of the mix designs are shown in Table 2.

The lightweight coarse and fine aggregates used in this research had water absorption percentages of 5.75 and 5.6, respectively, while their respective densities are 965 and 996 kg/m^3. Further details on the concrete mixtures, and the physical and chemical properties of the aggregates, sands, cement and superplasticisers, can be found elsewhere [3].

Table 1
Test plan.

Type of concrete	Temperature (°C)	Chloride (%)	Number of specimens	Measurements
OC	30, 40, 50	1	3	Corrosion current and mass loss
		3	3	Corrosion current and mass loss
		5	3	Corrosion current and mass loss
SCC	30, 40, 50	1	3	Corrosion current and mass loss
		3	3	Corrosion current and mass loss
		5	3	Corrosion current and mass loss
LWC	30, 40, 50	1	3	Corrosion current and mass loss
		3	3	Corrosion current and mass loss
		5	3	Corrosion current and mass loss

Table 2
Mix design of various concretes.

Type of concrete	Materials	Kg/m^3
Ordinary Concrete	Cement content	371
	coarse aggregates	1031
	Fine aggregates	756
	Water/Cement	0.45
Self-compacting concrete	Cement content	450
	coarse aggregates	781
	Fine aggregates	659
	Water/Cement	0.45
	Super plasticizer (L)	1.6
Lightweight concrete	Cement content	380
	Silica fume	20
	Light weight coarse aggregates	548
	Light weight Fine aggregates	348.7
	Red silica sand	199.9
	Water/Cement	0.45
	Super plasticizer (L)	3

2.4. Test specimen preparation

The procedure for preparing the concrete slabs is illustrated in Fig. 1 and listed as follows:

- The first step involved the preparation of moulds for the test specimens
- Secondly, the concrete was mixed according to ASTM C 192 [28]. Each sample contained 1%, 3% and 5% chloride. The required quantities of chlorides (NaCl) were first dissolved in water and then added to each type of concrete mixture. The quantities of chlorides were selected based on prior research [3].
- The third step involved the preparation of a concrete bed for each type of concrete slab on which steel rebar was to be placed at a clear cover depth of 15 mm [29]. The slab was then cast with the relevant type of concrete.
- Finally, after 24 h of curing, the specimens were de-moulded and transferred to environmental chambers, which were set at 30, 40 and 50 °C. The samples were cured and monitored for 365 days. The humidity of the chambers was controlled at 80% throughout the duration of the test. Further information can be obtained from [3].

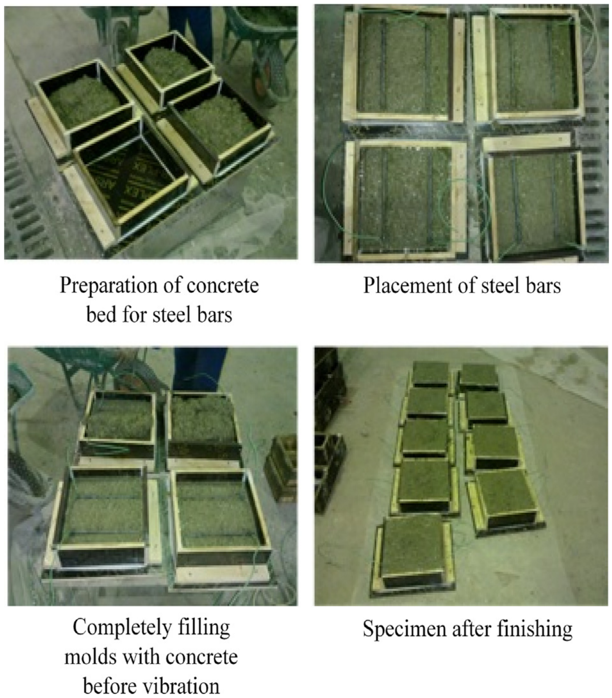


Fig. 1. Methodology of specimen preparation [3].

2.5. Test measurements

The corrosion currents (I_{corr}) in the concrete specimens were measured using GECOR 8 corrosion rate determination system and then converted to corrosion rates. The concept and details related to the measurements, and accuracy of GECOR 8 can be found in [3]. The measurements were taken regularly for two weeks to check the stability of the passive film qualitatively. Subsequent readings were then taken at weekly, quarterly and then monthly intervals. Conventional mass loss measurements according to ASTM G1-03 [30] were also performed to compare the corrosion rates obtained by GECOR 8. ASTM G1-03 [30] provides detailed procedures for carrying out measurements of the mass losses due to the corrosion of steel rebar. Regression models were then developed using SPSS Statistics to predict the corrosion rates.

3. Corrosion rate analysis

The corrosion currents (I_{corr}) in OC, LWC and SCC specimens under various environmental conditions were measured throughout tests by GCORE 8. These measurements were then converted to corrosion rates using ASTM G 102-89 e1 [31] to estimate the sectional loss of the rebar, which is standard industry practice. ASTM G 102-89 e1 [31] uses the following equation, which is based on electrochemical calculations (Faraday's Law) and not the actual mass loss:

$$\text{Corrosion Rate } (CR) = K \times I_{corr} \times EW/(D)) \tag{1}$$

where K = 3.27×10^{-3}mm·g/(μA·cm·yr), EW is the gram equivalent weight (element atomic weight divided by its valency), A is the area in cm^2, T is the time in hours, and D is the density in g/cm^3.

The corrosion rates of LWC, SCC and OC contaminated with 5% chloride at 30 °C were found to be 0.0244 mm/yr, 0.0352 mm/yr and 0.0471 mm/year after 365 days, respectively (Fig. 2a) From this Fig., it can be seen that there is a non-linear increase in corrosion rates of the rebar in OC. In SCC, the rates decline after reaching the peak, which may be attributed to the growth/development of

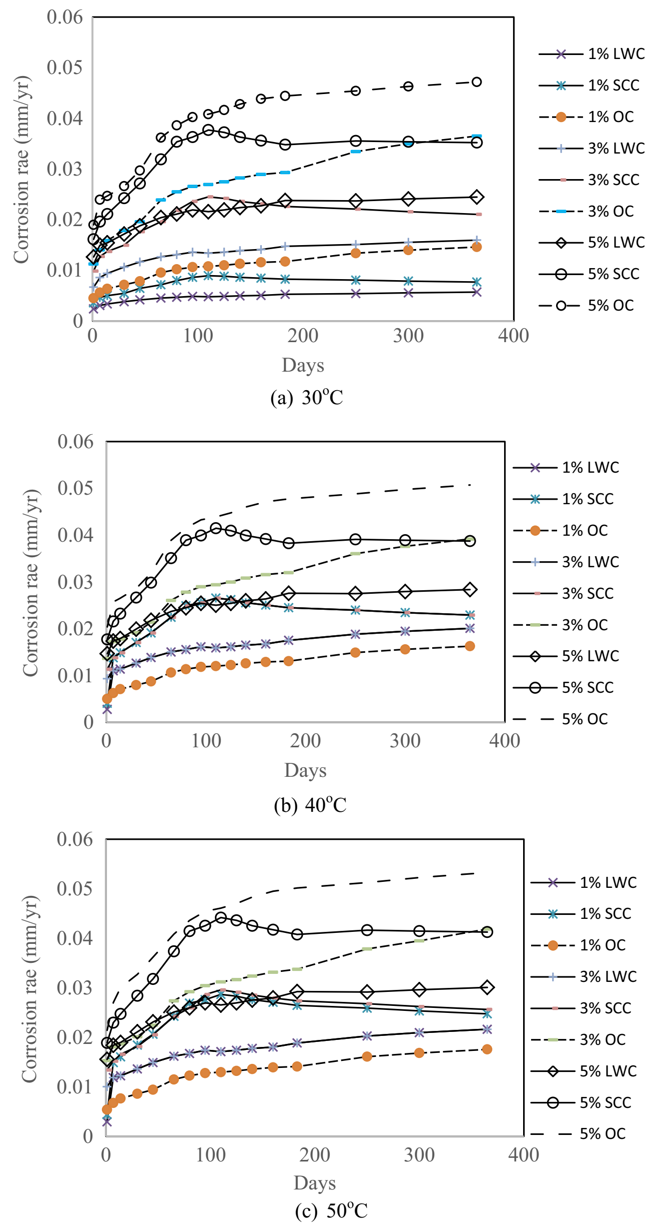


Fig. 2. Corrosion rates (I_{corr}) of OC, SCC, and LWC specimens contaminated with 3% Cl kept.

the passive film. Similar observations were reported by Jiang et al. 2017. In contrast, LWC exhibited corrosion resistance, which was indicated a very slow rise in the corrosion rates with time.

From the above results, the quality and the stability of the passive layer developed on the rebars can be analysed [32]. The passive layer in the rebars of OC was weak and thereby fracture suddenly, which increased the corrosion rates over one year. In contrast, the passive layer on the rebar in LWC was the strongest as the corrosion rates did not increase rapidly for the duration of the test. The strength and stability of the passive layer is probably dependent on the compact or dense microstructure of concrete [33], whereby silica fume [34] and low porosity reduce oxygen diffusion and inhibit chloride from being transported to the steel rebar. Consequently, LWC provided more resistance to corrosion, which may be attributed to its low porosity, higher compactness or fineness of the paste around the steel rebar. These characteristics can prevent aggressive chloride attacks and the diffusion of oxygen [15].

The corrosion rates of the rebars in OC, SCC, and LWC specimens were found to be 0.0507, 0.0387 and 0.0283 mm/year respectively, after 365 days at 40 °C (Fig. 2b), which were higher than their respective rates at 30 °C (Fig. 2a). This behaviour is expected because higher temperatures increase the chemical kinetics of the corrosion reaction [26]. It is also reported that the corrosion rate of steel rebar doubles if the temperature is increased by 10 °C [36]. Furthermore, the chloride-binding capacity of cement is affected by temperature, which results in more free chlorides in the pores [35]. Consequently, the resistivity of concrete to corrosion is reduced when the solubility of chloride ions is increased [26]. Therefore, the corrosion rates of the various types of specimens at 40 °C (Fig. 2b) were higher than those at 30 °C. However, the corrosion rates of LWC were lower than those of OC and SCC possibly due to the same reason as above.

The corrosion rates measured at 50 °C. were 0.0532, 0.0412 and 0.030 in OC, SCC and LWC, respectively, after 365 days (Fig. 2(c)). These rates were found to be higher than those measured at 30 and 40 °C. At 50 °C, the corrosion rates of the rebar in LWC were found to be less than those in OC and SCC possibly due to the same reason as explained above.

Finally, from this long-term corrosion monitoring data, it can be concluded that LWC used in the current research is more resistant to corrosion than normal and self-compacting concretes in chloride-rich hot environments.

OC, SCC and LWC specimens with low Cl content (1%, 3%) were also tested at 30 °C, 40 °C, and 50 °C, respectively, to observe their corrosive behaviour. The corrosion rates of the rebar in the specimens with 1%, 3% Cl at 30 °C (Fig. 2a), 40 °C (Fig. 2b), and 50 °C (Fig. 2c), were all lower than those in the specimens with 5% Cl (Fig. 2). This result indicates that the chloride content directly influences the corrosion rates under the same temperature conditions irrespective of the type of concrete.

Moreover, the trend of change in corrosion rates for both sets of specimens (1%, 3% and 5% Cl content) were identical at temperatures of 30 °C, 40 °C, and 50 °C for the entire duration of the test

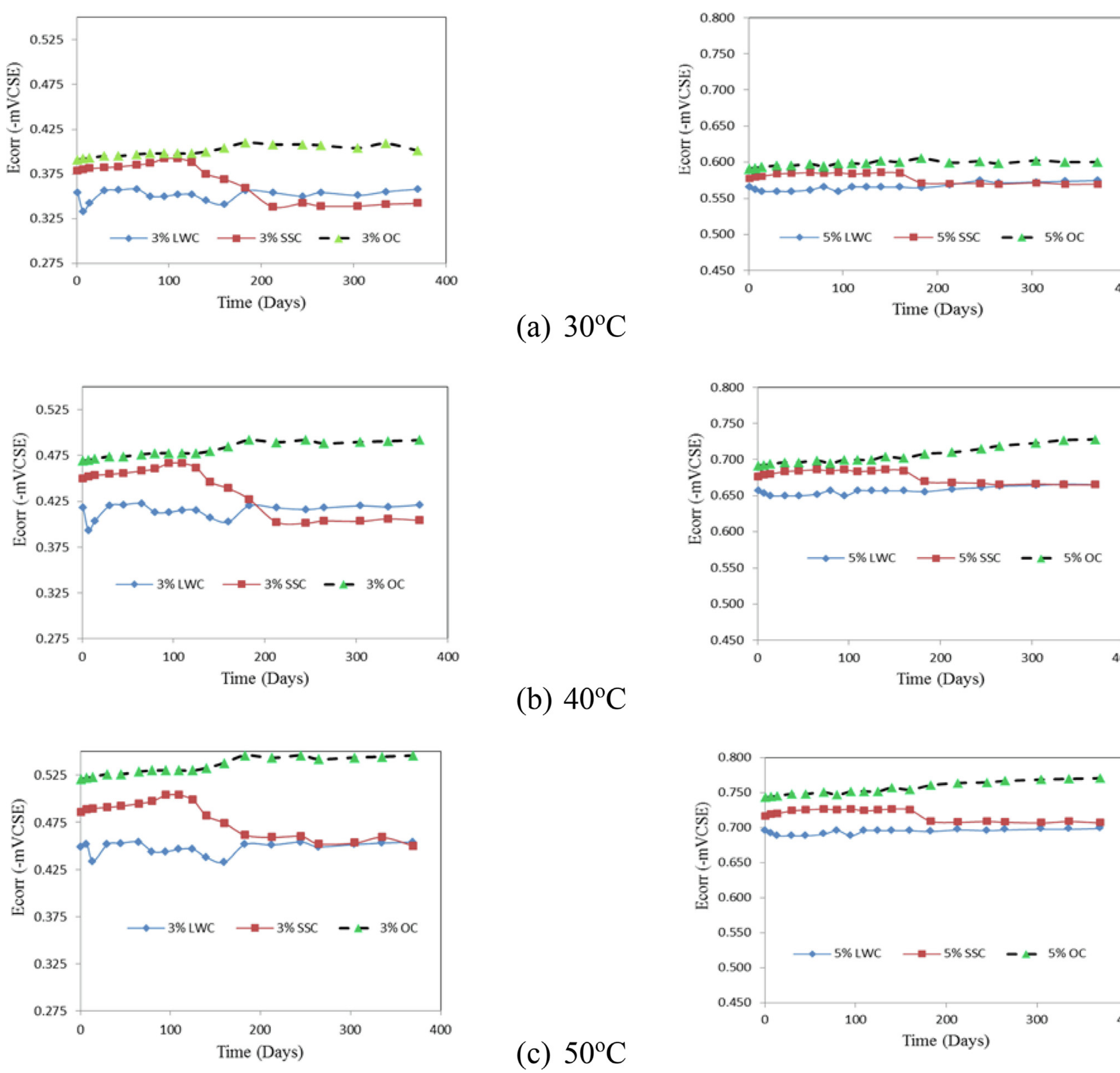
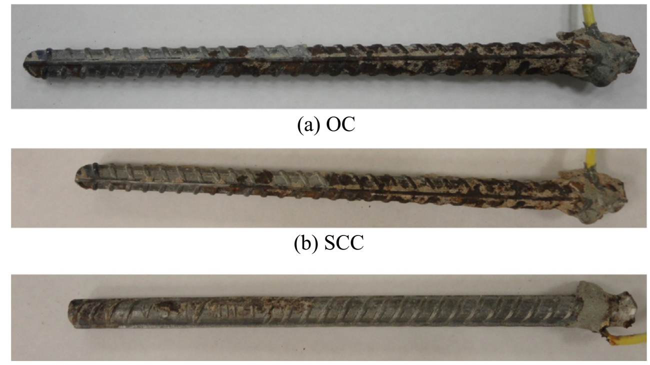


Fig. 3. Ecorr measurement of OC, SCC, and LWC specimens contaminated with 3 and 5% Cl kept at (a) 30 °C (b) 40 °C (c) 50 °C.

(see Fig. 2). This behaviour indicates that temperature is a governing factor that accelerates corrosion in chloride-rich environments.

From the above corrosion monitoring data, it is evident that LWC specimens offered higher resistance to corrosion than OC and SCC under various chloride and temperature conditions. This was attributed to the microstructure of LWC, which reduced the formation of corrosive products [3]. Therefore, the microstructure of LWC will be explored in-depth in future research. SCC specimens all showed a reduction in the corrosion rates after 110 days. This reduction was attributed to the development of corrosion products on the reinforcing steels. In contrast, OC specimens continued to corrode due to the connectivity between their microstructural and capillary pores, which allowed for chloride to be transported freely to the steel surface. Consequently, this behaviour resulted in the development of an initial weak passive layer.



(a) OC

(b) SCC

(c) LWC

Fig. 4. Visual observation of corrosion of steel taken out from various specimens.

4. Corrosion potential measurements

The corrosion potential (E_{corr}) of the rebars in concrete specimens was also measured, which is frequently reported for reinforced concrete structures [37]. It can be deduced from Fig. 3 that after 365 days, E_{corr} of LWC, SCC and OC contaminated with 5% chloride at 30 °C is −0.575 V, −0.57 V and −0.6 V, respectively. At 40 °C, E_{corr} in these specimens was measured as −0.665, −0.665, −0.728 V, respectively, after 365 days (Fig. 3b, on the left). At 50 °C, the corresponding E_{corr} values were found to be −0.699, −0.726 and −0.771 V, respectively, after 365 days (Fig. 3c, on the left). It is clear from these results that rebar in LWC was the lowest among the various types of concretes with the highest chloride contamination (5%) at various temperatures. Similarly, E_{corr} of LWC contaminated with 3% chloride was found to be the lowest compared to that of SCC and OC at 30 °C, 40 °C and 50 °C, respectively, (see Fig. 3(a, b, c), on the right). Moreover, the E_{corr} values of rebar obtained from each type of concrete were less than its respective value obtained from 5% chlorides concrete indicating that higher concentration of chloride caused more corrosion. The corrosion potential measurements for 1% Cl contaminated concretes are not presented in this paper.

In summary, the corrosion potential of LWC indicates that it is more resistant to corrosion than SCC and OC. Moreover, the trends of change in E_{corr} with chloride and temperature are in agreement with the corrosion rates measured in the current research.

5. Mass loss measurements

After 365 days, the concrete specimens were broken and rebars were taken out for mass loss measurements. Prior to mass loss measurements, the visual observations of the different steel rebars taken out from OC, SSC and LWC concretes was performed (Fig. 4). From Fig. 4, it can be seen that steel in OC is severely corroded, then in SCC and the least corroded is the one taken out from LWC indicating the corrosion resistance in this type of concrete. After, visual observations, mass loss was performed and converted to corrosion rates using the following equation mentioned in ASTM G1-03 [30]:

$$\text{Corrosion Rate} = K * W/(A * T * D) \tag{2}$$

where K = 8.76 × 10^4, W is the mass loss in grams (original weight minus corroded weight), A is the area in cm^2, T is the time in hours, and D is the density in g/cm^3.

It is important to note that the corrosion rates obtained from the mass loss and electrochemical measurements are different. The corrosion rates from the electrochemical measurements are instantaneous, while the average corrosion rates are obtained from the mass loss. The mass loss was measured to verify the trends of corrosion obtained from I_{corr}.

From the mass loss measurements after 365 days, the corrosion rates of the rebar in the set of specimens with 5% chloride were found to be 0.034, 0.039 and 0.044 mm/yr, respectively, at 30 °C (Fig. 5a). At 40 °C, their respective values were increased to 0.057, 0.06 and 0.071 mm/yr after 365 days (Fig. 5b). At 50 °C, a further increase in the mass loss was observed as the corrosion rates of the rebars were raised to 0.062, 0.066 and 0.076 mm/yr in LWC, SCC and OC, respectively (Fig. 5c).

The mass loss measurements of the specimens admixed with 1 and 3% chlorides in all the three types of concretes were added carried out. From 365 days of corrosion, the corrosion rates of rebar in LWC was found lower than SCC and OC at 30, 40 and 50 °C respectively indicating similar trend of corrosion as obtained from the various specimens admixed with 5% chloride (Fig. 5). Furthermore, the mass loss measurements in both sets of specimens are found to be in agreement with I_{corr} measurements at 30, 40 and 50 °C (Fig. 5).

In summary, the corrosion rates obtained from the mass loss corroborated that LWC provided more resistance to corrosion of steel as compared to SCC and OC in varying chloride and temperature conditions for a duration of 365 days. The results obtained in the current research have practical applications in the field as selected parameters of this research are designed to mimic real-world environments where reinforced concrete structures are commonly exposed to corrosion attacks. For example, structures built in the regions or places of very rich chloride concentrations and extremely hot weather.

6. Models and statistical analysis

Models were also developed for predicting the corrosion rates of rebars in various types of concretes. These models can thereby provide estimates of the service and remaining service life of reinforced concrete structures. Although the determination of corrosion rates using devices such as GECOR 8 is relatively simple, these devices cannot predict the time-dependent service life of structures. To this effect, statistical models for predicting the corrosion rates (converted from I_{corr}) were developed using a reliable statistical software (SPSS statistics version 23) [38,39].

Models for predicting the corrosion rates of steel in OC, SCC and LWC under the same conditions in the tests were developed. The variables for these models were chloride content, temperature and exposure times. After inputting the variables in SPSS and running a standard multiple regression analysis, a report for each model was generated. Using the unstandardised coefficient values

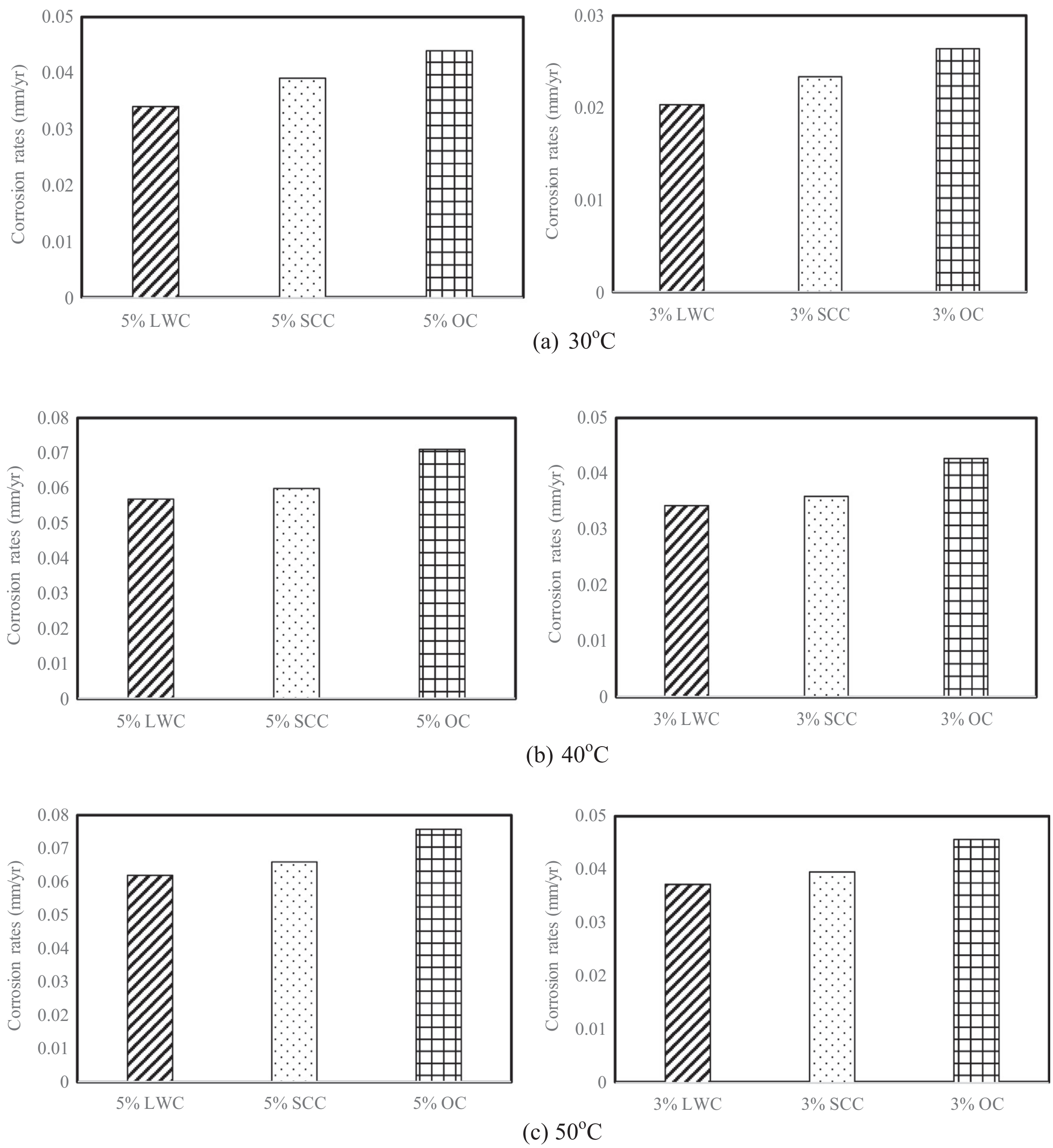


Fig. 5. Corrosion rates (mass loss) of specimens after 365 days in varying chloride ((a)–(c) 3 and 5%, (d)–(f) 1%,) and temperature exposures ((a) 30 °C, (b) 40 °C, (c) 50 °C, (d) 30 °C, (e) 40 °C, (f) 50 °C).

obtained from the outputs of each model, Eqs. (3)–(5) were developed. Although the main focus of the current research is on the corrosion rates, models for predicting I_{corr} were also developed (Eqs. (6)–(8)).

$$LWC(CR) = 0.003 \times Cl + 0.000322 \times T + 0.000033 \times t - 0.009 \quad (3)$$

$$SCC(CR) = 0.004 \times Cl + 0.000202 \times T + 0.000042 \times t - 0.009 \quad (4)$$

$$OC(CR) = 0.006 \times Cl + 0.000215 \times T + 0.000065 \times t - 0.015 \quad (5)$$

$$OC(I_{corr}) = 0.507 \times Cl + 0.019 \times T + 0.007 \times t - 0.9 \quad (6)$$

$$SSC(I_{corr}) = 0.477 \times Cl + 0.023 \times T + 0.005 \times t - 1.07 \quad (7)$$

$$LWC(I_{corr}) = 0.334 \times Cl + 0.017 \times T + 0.003 \times t - 0.87 \quad (8)$$

where, CR is the corrosion rate (mm/yr) obtained from I_{corr} ($\mu A/cm^2$), Cl is the chloride content in %, T is the temperature in degrees celsius, and t is the time in days.

A summary of the corrosion rates obtained from the models for OC, SCC and LWC is provided in Table 3. R^2 coefficients of 0.709, 0.568 and 0.667 were obtained for OC, SCC and LWC, respectively (Table 3), which are within the acceptable range of 57 to 71% [38]. The accuracy of the predictions was also determined by the standard error, which is defined as the square root of the average squared deviation from the mean value. A very low standard error was obtained for each model (Table 3).

ANOVA analysis was conducted on each of the proposed models, which indicates high statistical significance (Sig. = 0.0000; significantly less than $p < 0.05$). The results from the ANOVA analysis obtained from SPSS statistics are listed in Table 4. Several statistical variables such as df (degree of freedom), residuals, the sum of

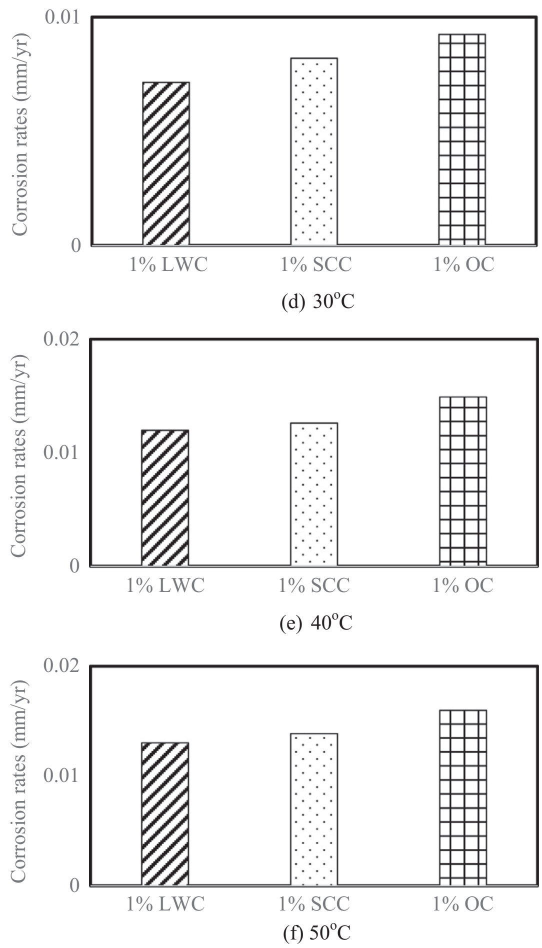


Fig. 5 (*continued*)

Table 3
Models summary.

Model	R	R Square	Std. error of the estimate
OC	0.891[a]	0.794	0.0071421
SCC	0.754[a]	0.568	0.0074749
LWC	0.817[a]	0.667	0.0041770

squares, mean squares and F distribution are also shown. An explanation of these statistical terms can be found in [39].

Moreover, the outliers, normality, linearity, homoscedasticity and the independence of residuals in each model were checked. The dependent variables were found to be normally distributed as shown in Fig. 6. The linearity of the model developed in SPSS

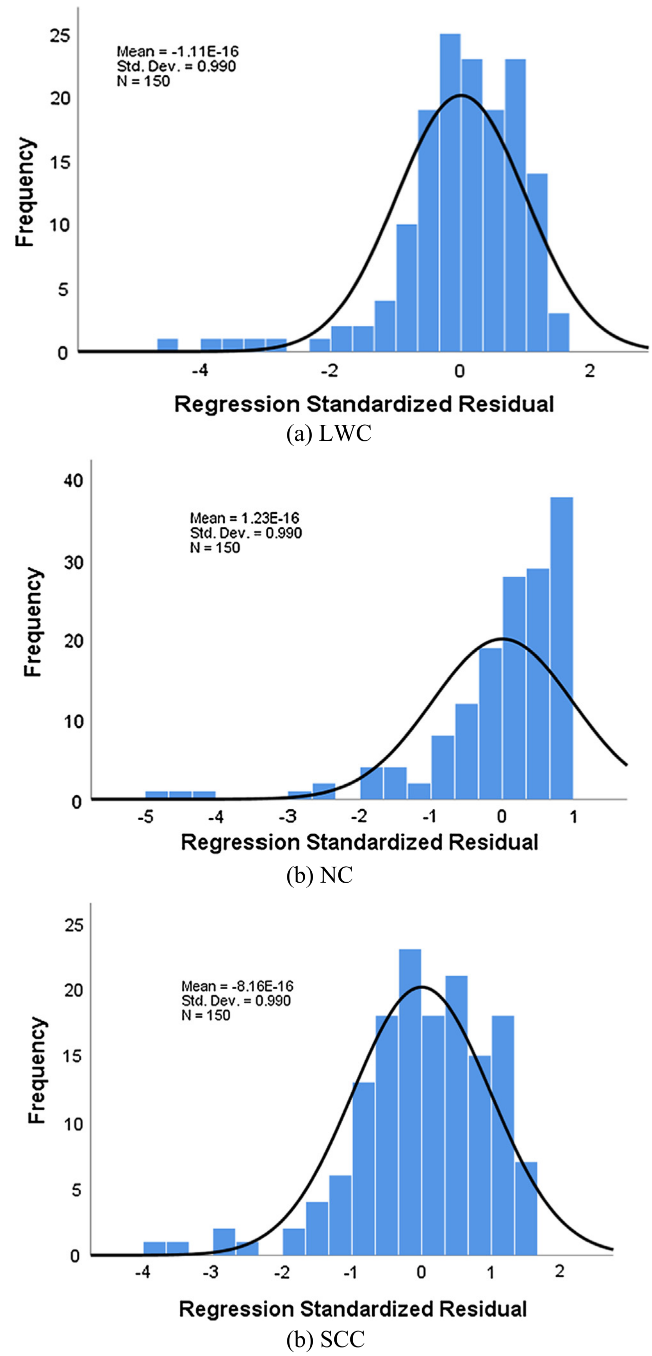
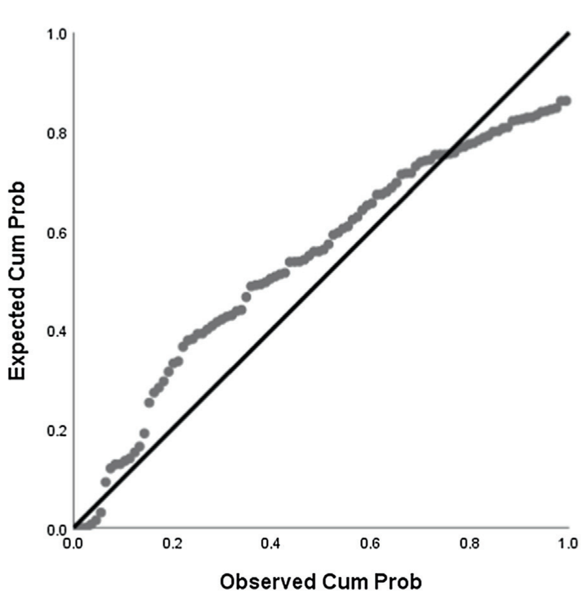


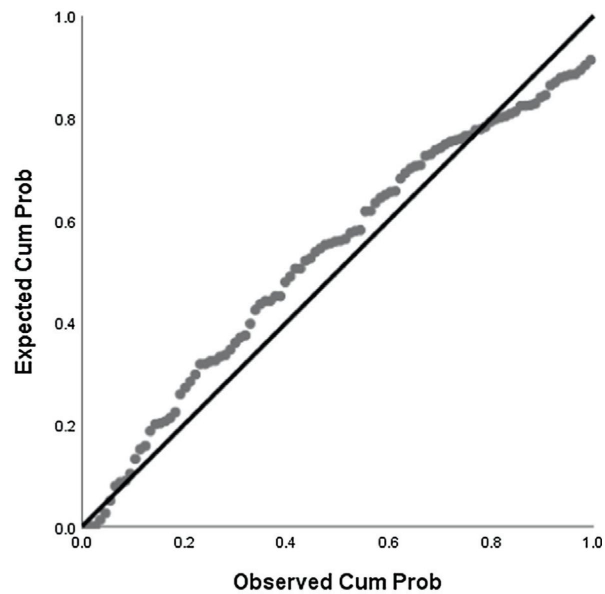
Fig. 6. Probability distributions for the corrosion rates (I_{corr}) of various types of concrete.

Table 4
ANOVA analysis for OC, SCC and LWC.

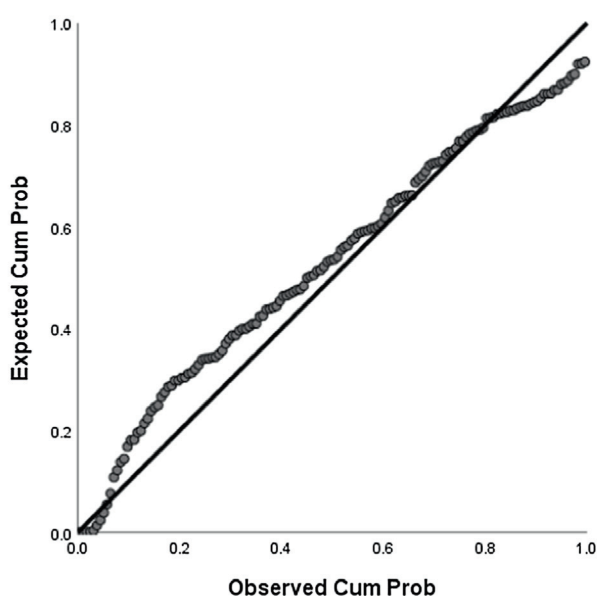
	Model	Sum of squares	df	Mean square	F	Sig.
OC	Regression	0.012	3	0.004	79.754	0.000[b]
	Residual	0.005	98	0.000		
	Total	0.017	101			
SCC	Regression	0.007	3	0.002	42.962	0.000[b]
	Residual	0.005	98	0.000		
	Total	0.012	101			
LWC	Regression	0.003	3	0.001	42.962	0.000[b]
	Residual	0.002	98	0.000		
	Total	0.005	101			



(a) OC



(b) SCC



(c) LWC

Fig. 7. Normal P-P plots of the corrosion rates (I_{corr}) of various reinforced concretes.

was also verified by plotting the expected Vs. observed probability (P-P) of the regression standardised residual, and the scatter plot. Statistically, in a normal P-P plot, it is expected that the points lie along the diagonal line (from the bottom left to the top right), and there are no significant deviations from normality and linearity. The generated P-P plot of each model was found to be linear as shown in Fig. 7. The scatter plot (Fig. 8) of the regression also shows very few outliers in all models, which further indicates a strong degree of linearity. It is to be noted that in the current research, only key statistical analyses are demonstrated in this paper. Other measures that are performed by The developed models in this research have some limitations in terms of their applications for predicting corrosion rates due to: many levels of chlorides ranging from below zero to up to 10%; and varying levels of water content in the mixtures used in the experiment. In future research, the proposed models will be enhanced by considering concrete mixtures with a wider range of chloride and varying water content. The enhanced models then can be used as tools to alert owners and asset managers of reinforced concrete structures for the time to carry on repairs.

7. Conclusions

This paper presented a comprehensive analysis of the long-term corrosion of rebars in various types of concretes that are commonly used in modern construction. Slabs made of ordinary (OC), self-compacting (SCC) and lightweight (LWC) concretes were exposed to highly corrosive environments with varying chloride levels and temperature conditions for a duration of one year. Electrochemical monitoring and weight loss measurements of OC, SCC, and LWC admixed with 5%, 3% and 1% chlorides at temperatures of 30, 40 and 50 °C were performed, respectively. It was found that rebars in LWC are more resistant to corrosion than those in OC and SCC when exposed to extreme chloride concentrations and high temperatures. This behaviour may be attributed to the compact and dense microstructure of LWC (silica fume and paste near the steel surface). Models for predicting the corrosion rates of steel in OC, SSC and LWC under the given conditions were also developed and a detailed statistical analysis was performed to check their reliability. The authors believe that the findings presented in this paper can be used as a benchmark for constructing a durable reinforced concrete structure in extremely corrosive environments near the sea. Furthermore, the current research will be extended by investigating various LWC mixtures with a different water/cement ratio and chloride levels, to accelerate the adoption of the developed tools for practical applications in the construction industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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