



## Coupled effect of ambient high relative humidity and varying temperature marine environment on corrosion of reinforced concrete

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### ABSTRACT

Chloride induced corrosion under coupled environmental effects of high humidity and high temperature often found in gulf marine environment is a very serious threat for durability of reinforced concrete structures. There exist different schools of thought between various researchers and the data in high relative humidity and high temperature range is also limited. This has been investigated by laboratory controlled experimentation under three different temperature conditions (30, 40 and 50 °C) and 85% R.H. A non-uniform and non-linear corrosion reaction was observed even after the breaking of passive layer. Furthermore, a decrease in corrosion potential and corrosion mass loss at 50 °C in comparison to 40 °C temperature conditions was seen. This may be due to the reduction of oxygen solubility in the pore solution at high temperature and blockage of concrete pores at high relative humidity. Thus, producing a reversing trend in corrosion mass loss as a function of chloride concentration at high temperature condition of 50 °C and high relative humidity of 85%. It is expected that a stable oxide layer may have developed under limiting oxygen controlled corrosion reaction. This can form basis for the development of a new technique to passivate steel bar embedded in chloride contaminated concrete. The paper also presents qualitative analysis of the microstructure of corrosion products under coupled varying temperature-chloride conditions and identifies the dividing line and turning point chloride concentration.

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### 1. Introduction

The deterioration of reinforced concrete (RC) structures due to the corrosion of reinforcement has been widely investigated, experimented, modeled and reported in the past [1–4]. In various parts of the world many divergent techniques have been used to prevent corrosion of steel reinforcement bars which include use of admixtures, epoxy coating of steel bars etc. Alongside with the precautionary measures many other techniques are also being used in practice to keep a check on the extent and rate of steel bars corrosion so that the service life of reinforced concrete structures can be extended. This corrosion induced deterioration of reinforced concrete is significant under chloride attack [5,6]. Since the chloride induced corrosion is investigated as an electrochemical thermodynamic process, its rate is influenced by temperature [6,7] and humidity [8] which may vary from one place to another due to the difference in seasonal conditions. In a good quality concrete high alkalinity of environment helps in formation of passive film which protects steel reinforcement bars from further corrosion. But the presence of high chloride content aided by the severe tem-

perature and high humidity coupled conditions not only break this passive film but also accelerate the corrosion of reinforcement steel bars even in repaired RC structures [9]. Therefore, it is necessary to conduct in-depth investigations in order to further understand the mechanisms of chloride induced corrosion in reinforced concrete influenced by the coupled effects of high ambient relative humidity (R.H.) and temperature.

Investigations have also been conducted in the previous research on the corrosion of steel in RC structures including under water submerged corrosion measurements [10], the effect of carbonation on corrosion [11] with silica fume [12], effect of inhibitors on chloride induced corrosion [13], significance of the ambient temperature and the steel material on corrosion [14], atmospheric corrosion [15] etc. But, the magnitude of chloride activated corrosion for the effect of ambient relative humidity as high as 85% under varying temperature conditions relevant to the harsh environment found in the coastal gulf regions has not been investigated in the past which leads to the objectives and research methodology adopted in this paper.

### 2. Experimentation

#### 2.1. Materials, mix proportions, casting and curing

Type I cement in compliance with the requirements of ASTM C150 has been used. Coarse aggregates were a blend of 20 mm and 10 mm crushed limestone obtained from quarries around Riyadh, Saudi Arabia. The fine aggregates were a blend

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of natural red sand and manufactured sand obtained from the crushed limestone. Deformed round carbon steel bars 10 mm in diameter were used as reinforcing steel (C:0.35, Si:0.48, Mn:0.5, Cr:0.02, S:0.01, Ni:0.03, Cu:0.05). The surface of steel bar was polished by sand paper No.200. Finally, steel bar was degreased by acetone just prior to being placed in the mold. The mix proportions used in this investigation are shown in Table 1. The water-to-cement ratio (w/c) of 0.50 was held constant throughout the experimental program. Tap water available in Civil Engineering Department of King Saud University was used. Standard laboratory curing conditions were used where the standard prism specimens in the plastic molds were stored in the laboratory environment at standard room temperature for the first 24 h followed by demoulding and then moist curing under standard conditions until the age of testing.

2.2. Specimen preparation and experiment scheme

The specimen was derived from a previous research [5,16] with necessary modifications to take care of the factors that have been overlooked in the past research works and thus making the present research work original. Schematic diagram and original picture of the prismatic specimens in duplicate (100 × 100 × 250 mm) with two 10 mm diameter deformed mild steel bars with appropriate spacers to hold the bars in required position firmly in each of the two paired specimens. The bar diameter was kept constant for all the specimens to reduce the number of unknown variables. One bar was completely embedded in one specimen and other coming out from both faces in the other pair specimen having a clear cover of 15 mm cast in steel molds (Fig. 1).

The reason for using two steel bars separately in paired specimens with one bar in each specimen was to make it possible to measure corrosion potential and corrosion mass loss using the same mix cast and cured under exactly same environmental conditions. The specimen with bar emerging out from the two sides was used for the corrosion potential measurement. Since the two edges of the bar were not embedded into the concrete and were not under chloride attack, therefore, in order to find the mass loss using the similar specimen a separate paired specimen with steel bar embedded completely into the concrete was used. This was done to obtain more reliable and accurate results. The clear cover was kept 15 mm because measured half-cell potential values at specimen surface could be considered as actual value at steel surface, if cover depth is within 20 mm [17].

Table 1  
Mix proportions.

Materials	Proportions (kg/m <sup>3</sup> )
Cement content	350
20 mm aggregates	735
10 mm aggregates	315
Crushed sand	195
Silica sand (red sand)	585

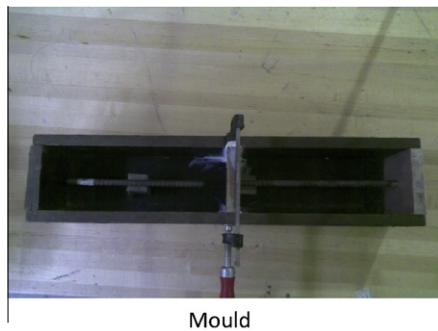


Fig. 2. Half-cell potential measurement assembly.

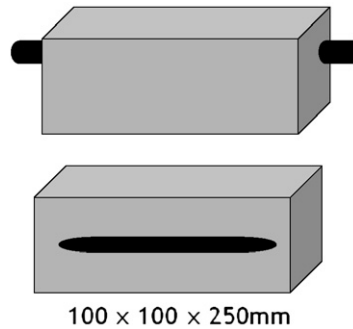
Precautions were observed to avoid the formation of crevice corrosion. Crevice corrosion is a type of localized corrosion that can be developed within crevices or at shielded surfaces at concrete-steel interface where a stagnant pore solution is present. It is one of the most frequently encountered forms of localized corrosion and at the same time one of the most harmful ones. Crevices make a chemical environment in reinforced concrete which is different from that of freely exposed surfaces and therefore accelerate corrosion. This environment keeps moisture, traps pollutants, concentrates corrosion products and meanwhile excludes oxygen at the steel-concrete interface. It was prevented by reducing crevices in the concrete-rebar interface. Where it was not possible to get rid of crevices, precaution was taken to improve drainage and seal edges keeping crevices as open as possible and therefore preventing encapsulation of moisture.

The test consists of 30 specimens having a total chloride concentration varying from 0–5% in mixing water consisting of three sets in duplicate for 30, 40 and 50 °C temperature conditions and 85% relative humidity in environment control chambers. Sodium chloride (NaCl) with 99.9% purity was used as source for chloride ions. All the specimens were allowed to set and harden in mold for 1 day in controlled sealed curing conditions at 20 °C before being de-molded. Half-cell potentials were measured with four days interval for all specimens using copper-copper sulfate reference electrode (CSE) in accordance with standard specifications which can be found elsewhere [18]. For further illustration of the measurement procedure adopted in this research consider Fig. 2. A standard Voltmeter with 0.0001 V accuracy was connected with the RC specimens and the standard electrode through the specified wire in order to make a half-cell potential measuring circuit.

Special care was given in wetting the concrete surface of the specimens before taking half-cell potential measurements because it is one of the most important points in the measurement of half-cell potential so that the resistivity of the con-



Mould



100 × 100 × 250mm



Fig. 1. Schematic and actual diagram of the specimens.

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