

**AN EXPERIMENTAL STUDY ON CORROSION OF STEELS  
IN CARBONATED OPC, PPC AND PSC CONCRETE**

by

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## **CERTIFICATE**

This is to certify that the thesis entitled “**An Experimental Study on Corrosion of Steels in Carbonated OPC, PPC and PSC Concrete**”, being submitted by **Mr. Jitu Kujur** to the Indian Institute of Technology Delhi, India, for the award of the degree of “**DOCTOR OF PHILOSOPHY** in Civil Engineering”, is a record of original bonafide research work carried out by him under my guidance and supervision. To the best of my knowledge, the thesis has reached the requisite standard. The material contained in this thesis has not been submitted, in part or full to any other University or Institute for the award of any degree or diploma.

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## ABSTRACT

Corrosion of steel is one of the most important durability problems in RC structures. In addition to presence of chloride, carbonation of concrete is the other major cause responsible for corrosion of rebar in RC structures. In the present research work a comprehensive experimental investigations have been carried out to study the corrosion behavior of steel during depassivation and post depassivation period against carbonation induced corrosion. Carbonation progress in the concrete made with different types of cement and w/c ratio have been also included in the present research work. Potentiodynamic study on the bare steel specimens have been carried out in the carbonated concrete powder solution extracts to obtain the polarization curve and used to calculate corrosion potential and corrosion current of bare steel in concrete powder solution extract.

In order to study change in half cell potential during depassivation stage, test was conducted on the prism specimens made with different types of cement, different types of steel and with varying mix parameters against carbonation induced corrosion. Concrete prism specimens were prepared similar to that specified in ASTM G 109 with little modification. Three types of cement namely ordinary Portland cement (OPC), Portland pozzolana cement (PPC) and Portland slag cement (PSC) were used in the present investigation. Three different types of steel bars of diameter 12mm, namely, TMT Tempcore, TMT Thermex and corrosion resistant steel were used as the steel reinforcement. The specimens were made with three w/c ratio of 0.45, 0.5 and 0.55 and with two clear cover to the top steel bar. Total 84 prism specimens were prepared with three types of cement, three types of steel and three w/c ratios in absence of inhibitor and tested. In addition 27 number of prism specimens were prepared with three types of cement, three w/c ratio and one type of steel i.e., TMT Thermex steel and with

admixed 2% NaNO<sub>2</sub> inhibitor and tested. Further, 27 number of prism specimens were prepared with three types of cement, three w/c ratio and one type of steel i.e., TMT Thermex steel and crack was developed on the same specimens before exposing to the accelerated carbonation environment. 100 mm cube specimens were also prepared from the same mixes mentioned above with twelve replicates to measure carbonation depth parallel with HCP measurement. The all prism and cube specimens were exposed to accelerated carbonation environment. Two types of accelerated exposure environment were adopted. Exposure environment I corresponds CO<sub>2</sub> concentration of 4±0.5% with relative humidity 55±5% and temperature 30-35°C where as exposure environment II contains same carbon dioxide concentration with different relative humidity (RH=69±5%) and temperature (24-29°C). The half-cell potential of top steel bar with reference to saturated calomel electrode (SCE) and the potential difference between top steel bar and the bottom common terminal across 100 Ohm resistor were measured at interval of one week exposure period. Both half cell potential and carbonation depth were measured simultaneously at same ages on concrete specimens made with three types of cement i.e. OPC, PPC and PSC, three w/c ratio i.e. 0.45, 0.5 and 0.55 for three types of steel i.e. TMT Tempcore, TMT Thermex and CRS. Carbonation depth was measured on 100 mm cube specimens and half cell potential was measured on prism specimens made from similar mixes. Both cube and prism specimens were exposed to the identical environment in the same chamber. The exposure period and the potential measurement were continued till the carbonation front reached the reinforcement level. The corrosion rate of the embedded steel reinforcement was determined using two non-destructive methods namely linear polarization resistance (LPR) and AC impedance spectroscopy. In addition corrosion rates determined by LPR technique were compared with those obtained through gravimetric (mass loss) measurement that is performed at the end of the test period. Further the carbonation depth and pH profile on the prism specimens were also measured.

Potentiodynamic study on the bare steel specimens in concrete powder solution extracts were carried out to study the corrosion behavior of steel in carbonated concrete powder solution extracts prepared from three different types of cement, three w/c ratios as stated earlier and two test conditions i.e. with and without deaeration of solution extracts. The total 648 number of bare steel specimens were prepared and tested. In order to confirm the factors affecting on the corrosion potential and corrosion rate significantly, analysis of variance (ANOVA) was carried out.

From the results of carbonation measurement on prism specimens against accelerated carbonation it is observed that concrete cubes made with PPC exhibits higher carbonation depth than those made with OPC and PSC. Concrete cubes made with OPC showed less carbonation depth compared to those made with PSC and PPC. Carbonation rate coefficient obtained is higher in the environment I ( $\text{CO}_2=4\pm0.5\%$ ,  $\text{RH}=55\pm5\%$ , temperature  $30\text{-}33^\circ\text{C}$ ) than the specimen exposed in environment II ( $\text{CO}_2= 4\pm0.5\%$ ,  $\text{RH}= 69\pm5\%$ , temperature  $24\text{-}29^\circ\text{C}$ ) irrespective of types of cement and w/c ratio. The pH value of top 5mm cover concrete was observed to be varying with increase in carbonation depth. The pH value indicated by the phenolphthalein indicator at carbonation front is higher than the pH value 9. Concrete made with OPC showed less negative potential compared to PPC and PSC irrespective of types of steel and w/c ratio. Further it is observed that PPC shows more negative half cell potential value than PSC. Among steel type TMT Tempcore steel shows more negative half-cell potential values than those TMT Thermex and corrosion resistant steel.

.Through corrosion rate measurement on the prism specimens it is observed that percentage reduction in corrosion current density observed in OPC, PPC and PSC in presence of

corrosion inhibitor are 72%, 75% and 77% than that without corrosion inhibitor respectively. Considering for all three type of cement and w/c ratios average reduction in corrosion current density using corrosion inhibitor (sodium nitrite 2% by weight of cement) is obtained 75%.

Through the Potentiodynamic polarization study on uncarbonated concrete with and without corrosion inhibitor various zones of corrosion namely; semi-immune zone, active and passive zone were identified for different types of steel and different types of cement at varying w/c ratios. It is observed that cement content has the significant effect on corrosion potential in absence of corrosion inhibitor irrespective of test conditions. From the ANOVA it was observed that steel type has the strong effect on corrosion potential in presence of corrosion inhibitor irrespective of test conditions. Cement type, w/c ratio and their interaction along with steel type have some effect on corrosion potential in presence of corrosion inhibitor. The w/c ratio seems effective on corrosion current density in absence of corrosion inhibitor whereas cement type becomes effective on corrosion current density in presence of corrosion inhibitor. It is also observed that the steels exhibit perfect Tafel's behavior in carbonated concrete powder solution extract irrespective of cement, steel types or mix proportions with no indication of *passivation* at any stage. However inhibitor when admixed restores the passivation behavior to some extent. Corrosion rate measurement by three methods demonstrate that the rate is low for rebar embedded in carbonated concrete prepared with PPC and PSC compared to that exhibited by concrete prepared with OPC. CRS steel exhibits lowest corrosion rate. Results obtained from three test methods used for corrosion rate measurement corroborate well each other.

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