Investigation for the impact of nature of coarse aggregate on the passive layer formation and corresponding corrosion of reinforcement bars in high performance concrete

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HIGHLIGHTS

- High performance reinforced concrete from different heavy and normal weight aggregates.
- Chloride induced corrosion of steel rebars.
- Recommended values for corrosion estimation of HPRC based on aggregate types.

ARTICLE INFO

ABSTRACT

This research paper deals with the influence of high performance reinforced concrete (HPRC) produced from different heavy and normal weight aggregates on the corrosion rate of steel rebars. Three normal weight and two heavy weight coarse aggregate sources were used in this research. For each type of coarse aggregate, prismatic specimens of $200 \times 100 \times 100$ mm were cast and cured in water tanks with 5% chloride concentration. Identical specimens were also cast from mixtures having the same mix proportions but containing 2% chloride by mass of binder. Through this investigation, it was observed that it is desirable to determine experimentally the corrosion rate of HPRC when various coarse aggregates are used for a specified HPRC mixture with and without the use of silica fume. Experiments performed in this research demonstrated that the type of aggregate has significant influence on the corrosion of HPRC. It is therefore recommended to use the appropriate values for corrosion rate estimation of HPRC based on varying aggregate types in a particular specific concrete mixture. In the absence of such values, however, the corrosion rates may be calculated using the experimental curves presented in this paper.

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1. Introduction

The corrosion of high performance reinforced concrete (HPRC) is a question of prime importance in the durability of HPRC structures. During the past several years, corrosion of reinforcement induced by chlorides, carbonation, hot weather, acids or low-quality concrete cover has caused a lot of damage to concrete structures all over the world necessitating repairs or replacement. Rebar corrosion has been the subject of numerous investigations in the past by the authors and other researchers [4,3,22,13,27,14,17, 18,20,21,15,16,10,23,6]. In spite of the extensive investigations and findings in the past on the topic of corrosion in HPRC, the research related to the effect of coarse aggregate type on the

corrosion of HPRC has yet to be fully explored. Hussain and Ishida [19] have investigated the effect of volume of coarse aggregate on the corrosion rate of steel in chloride contaminated concrete in the past. However, the effect of nature of coarse aggregate was not investigated and remained as scope for future research. It is an ever demanding requirement for the construction projects to use the locally available aggregates for economic reasons or to use special type of aggregates to attribute certain required properties to HPRC which may not be beneficial in all cases. As the properties of aggregate materials change from one location to another, it would be desirable to experimentally determine the corrosion of high performance reinforced concrete with a specified mix design incorporating different types of aggregates.

This gap in the previous research formed basis for the present research. In this paper, laboratory scale experimental investigations are carried out to find the effect of coarse aggregate type

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on the corrosion of steel reinforcement bars embedded in high performance concrete. This has been done with and without the presence of silica fume in the concrete mixture. Overall, the results generated in this investigation have presented an opportunity to successfully assess the effects of coarse aggregate type on the corrosion of HPRC.

2. Experimentation

2.1. Materials and mix proportions

This section contains the material properties of HPRC ingredients, mix design as per ACI 211.4, rebar characteristics and procedures for corrosion testing of steel reinforced concrete. Type I ordinary Portland cement in compliance with the requirements of ASTM C150 has been used. Table 1 shows the chemical composition and physical characteristics of the cement. Silica fume (micro silica) used in this study as 10% cement replacement complies with the requirement of ASTM C 1240. Chemical composition and physical characteristics of micro silica are listed in Table 2. A super plasticizer made of polycarboxylic ether was employed as chemical admixture. The relative specific gravity of this admixture was almost 1.1.

The water-to-cement ratio (w/c) of 0.30 was held constant throughout the experimental program so that the effect of coarse aggregate with and without silica fume can be revealed. Three types of normal weight coarse aggregate (designated as AB, MK, RY) and two types of heavy weight coarse aggregate (BR and HM) with and without silica fume (designated as 'S') have been investigated in this paper. The three normal weight coarse aggregates were taken from three different cities of Saudi Arabia, namely Abha, Makkah and Riyadh located far apart from each other. Aggregate 'AB' is of meta sediment rock origin composed primarily of Quartz along with some Biotite contamination and Schist layers, especially in the flaws. Aggregate 'MK' is also Quartz but with the additions of Plagioclase and chlorite minerals. It also contains chunks of feldspar here and there in its geometrical formation. The third type of aggregate named 'RY' in this paper is the most commonly used local aggregate in the central region, primarily used in the central region of Saudi Arabia and is composed of limestone.

The remaining two types of coarse aggregate 'BR' and 'HM' are of heavy weight in nature and were imported from Belgium for the research under consideration. The aggregate 'BR' is a mineral consisting of barium sulfate ($BaSO_4$). The baryte group consists of baryte, celestine, anglesite and anhydrite. Baryte itself is generally white or colorless, and is the main source of barium. The aggregate 'BR' consisted of fragmental samples of clay, light in color in the form of rock as white, pink and gray which indicate quartz and feldspars minerals with clear cleavage (plagioclase and orthoclase). The clay was due to the weathering of feldspars and the mother rock

was an acidic rock (granite). The petrographic studies were carried out by taking a thin section from a hard fraction of aggregate 'BR'. It showed a wavy extinction (Fig. 1a) in more than 70% of the sample with some of quartz seen filling fractures as veins (Fig. 1b). This orientation of quartzite reflects the deformation for the aggregate 'BR'. The second type of heavy weight aggregate 'HM' consisted the mineral form of iron (III) oxide (Fe_2O_3), one of several iron oxides. Hematite crystallizes in the rhombohedral system, and it has the same crystal structure as ilmenite and corundum. Hematite and ilmenite form a complete solid solution at temperatures above 950 °C. The coarse aggregate 'HM' was a mineral colored reddish brown as the main ore of iron composed of friable material with light magnesium tinged and black streaked. The petrographic study indicated oxide minerals seen dark with polarized light by the use of reflected light microscope. Overall the 'HM' aggregate was hematite with very fine grains of quartz, mostly sand stone rich in iron oxides as shown in Fig. 1(c). Most of the materials used in this investigation meet the requirements of ACI 318.

Table 3 contains the material properties of HPC ingredients used in this research. The unit weights refer to the bulk state in the table. The gradation of each type of fine aggregate is shown in Fig. 2(a)–(c). A combination of CR and RN sand with a ratio of 35–65% respectively was used. This was done to give a fineness modulus of 2.74 in compliance with the ASTM C 136 as shown in Table 4 and Fig. 2(c). The gradation of coarse aggregates are shown in Fig. 3(a)–(e) respectively. Table 5 shows concrete mix proportions for HPC used in this research. All mixtures were prepared in a rotary planetary mixer with capacity of 180 L. The coarse and fine aggregate and one third of the water were measured and placed into the mixer and mixed for 1 min. After that the cement, micro silica and super plasticizer and the rest of the water were added and mixed for three minutes followed by a 3 min break and then another 3 min mixing was performed. The slump test was performed as per ASTM C143.

Deformed round carbon steel bars 10 mm in diameter were used as reinforcing steel. The rebar elemental composition (C:0.35, Si:0.48, Mn:0.5, Cr:0.02, S:0.01, Ni:0.03, Cu:0.05) was determined using photo electron spectroscopy. 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 prismatic specimens in plastic molds were stored in the laboratory environment at room temperature for the first 24 h followed by de-molding and then moist cured until the age of testing.

2.2. Specimen preparation and experiment scheme

Schematic diagram and original picture of the prismatic specimens in duplicate (100 × 100 × 200 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 is shown in Fig. 4. 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 of specimen having a clear cover of 15 mm cast in plastic molds (Fig. 4).

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 HPRC 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 (Uomoto [26]. The end corners of rebars were covered with Teflon tape and epoxy coating.

The test consisted of two types of specimens. One type of specimens were cast having a total chloride (Cl) concentration of 2% by mass of cement added to the mixing water of HPRC mixtures. The other type of specimens were cast without any admixed chloride and were then immersed in 5% Cl solution as curing water. A wetting drying cycle of seven days was maintained for all the specimens after a continuous curing of 28 days. Sodium chloride (NaCl) with 99.9% purity was used as source for chloride ions.

The steel rebar corrosion current (Icorr) and corrosion potential (Ecorr) were measured for all specimens using a GECOR device [11] and following the ASTM C-876 [7] standard testing procedure. The GECOR measures the corrosion rate as reflected by the corrosion current density and the half-cell corrosion potential. A true measure of the corrosion rate can be made by the polarization resistance technique. It has been well established by Stern and Geary [24] that the corrosion current is linearly related to the polarization resistance, which gives a direct quantitative measurement of the amount of steel turning into oxide at the time of measurement. By Faraday's equation [9], this can be extrapolated to direct metal sectional loss. The corrosion current values in GECOR are calculated from the polarization resistance Rp using the relation Icorr = B/Rp, where Icorr is given in μA/cm² when Rp is given in kΩ/cm² and B = 26 mV. The Icorr is directly proportional to corrosion rate through the relation, corrosion rate (μm/year) = 11.6 × Icorr. This gives a tool for quantifying the average reduction of rebar diameter over time. The measurement of corrosion rate usually involves applying electrical signal through a con-

Table 1
Chemical composition and physical characteristics of cement (OPC type-I).

Chemical composition	(%)	Physical characteristics	
SiO_2	19.96	Specific gravity	3.15
Al_2O_3	5.99	Consistency	23.7%
Fe_2O_3	3.59	Initial setting time	50 min
CaO	62.75	Final setting time	350 min
MgO	0.59		
SO_3	2.73		
Alkalies	0.2		
C_3S	50.6		
C_2S	19.1		
C_3A	9.8		
C_4AF	10.9		

Table 2
Chemical composition and physical characteristics of micro silica.

Chemical composition	(Mass %)
(SiO_2)	93.2
(Al_2O_3)	<0.01
(Fe_2O_3)	0.05
(CaO)	0.72
(MgO)	0.14
(SO_3)	<0.01
(Cl)	0.03
(Na_2O)	0.07
(K_2O)	0.15
Loss on Ignition @ 950 °C	5.4
Specific gravity	2.27