



Effect of silica fume and steel slag coarse aggregate on the corrosion resistance of steel bars



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HIGHLIGHTS

- The using of steel slag as a full replacement reduces the annual corrosion rate.
- Mixing with 100% steel slag and 20% silica fume enhanced corrosion current density.
- Mixing with 100% steel slag clear resistance the NaCl attack due to low porosity.

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ABSTRACT

This study evaluates the corrosion resistance of concrete cylindrical specimens. The concrete samples were prepared from electric arc furnace steel slag (EAFSS) with percentages equal to 0%, 20%, 40%, 60%, 80% and 100%, and were examined as a partial replacement of ordinary coarse aggregate (dolomite). Silica fume with 20% replacement of the weight of the used cement was utilized in order to study its effect on the corrosion resistance of the embedded steel bars. Twenty cylindrical specimens, with a diameter equal to 50 mm and a height of 200 mm, were prepared and merged in NaCl solution with 3.5% concentration. Subsequently, the electrochemical behavior of the specimens was assessed using linear polarization resistance technique and open circuit voltage. The results indicated that rebar in the concrete specimens which contains steel slag was found to be resisting corrosion efficiently better than the control specimens which incorporates dolomite as coarse aggregate.

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1. Introduction

The materials of reinforced concrete require exact controls, due to reinforced concrete as the most widely used a structural material in construction. The concrete is required to be under control to reduce the deterioration of concrete under severe conditions. The main factor effect on corrosion is chloride-ions which have destroyed the natural passivity of the surface of reinforcing steel.

The durability of concrete is a key concern in civil structures because it depends strongly on the interactions of the material with the environment. There is also a little knowledge about the long-term performance of fly ash concrete, and this is one of the main limitations which facing the adoption of this technology on a large industrial scale [1]. Not only the reduction of pH of the concrete due to carbonation causes corrosion but also the chloride penetration [2]. The chloride diffusivity depends on the concrete

pore structure and all the factors that determine it such as mixing the design parameters (W/C ratio, type, and proportion of mineral admixtures and cement, etc.), compaction, curing, placing and a presence of cracks [3]. The crack width promotes the corrosion of steel reinforcement due to concrete permeability [4].

Marine environments and the extensive use of de-icing salts can cause rupture of the passive layer, which allows the steel surface to act as a coupled anodic and cathodic reaction cell, where corrosion processes can take place [5,6]. Corrosion of bars reinforcement in concrete has been studied in the last decades under severe conditions, mostly in relation to chloride threshold value (CTV) or critical chloride content [7,8]. A number of electrochemical techniques have been used, such as open circuit potential, electrochemical impedance spectroscopy, and cyclic polarization. A wide range of reported CTVs is mainly due to the variability of pH values of the porous network solution of cement-based materials, the chloride binding capacity, and an environmental interaction [8,9].

A Prior detection and monitoring corrosion of steel in reinforced concrete structures have paved the way to evaluate the lifespan of

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civil structures and have taken appropriate rehabilitation aspect. The nondestructive electrochemical corrosion monitoring methods such as galvanic potential measurement [10,11], open circuit potential measurements, linear polarization measurements and electrochemical impedance provide effective information on corrosion status [12,13] of the rebar in concrete. The continuous increase in the steel production since the 19th century has led to an imbalance between waste products generated in steel production processes and their subsequent usage. As a consequence, the mass dumping at the waste disposal sites has caused a significant environmental problem over the years [14,15].

2. Experimental program

2.1. Materials and mix proportions

In the current experimental program, a mixture was produced by using an ordinary Portland cement (CEM I 42.5 N), which was employed for the preparation of the concrete test specimens. With contents equal to 350 kg/m³, 450 kg/m³, and 550 kg/m³ according to 4756/1-2007 of the Egyptian standards [16]. Two types of coarse aggregates were used dolomite and electric arc furnace steel slag EAFSS as a partial replacement of 0%, 20%, 40%, 60%, 80% and 100% of dolomite, with a maximum nominal size of 10 mm, specific gravity of 2.65 and 3.52 and absorption of 2.05% and 1.02% respectively. Silica fume with a percentage of 20% as a replacement of cement, which locally produced in Egypt, has a bulk density and specific gravity of 0.345 t/m³ and 2.15 respectively.

As for Table 1, it showed the mechanical and the physical properties of steel slag coarse aggregate. Table 2 illustrated the chemical compositions of cement, silica fume, and steel slag coarse aggregates. The fine aggregate was river sand with a specific gravity of 2.64 and a bulk density of 1.78 t/m³ and water absorption of 0.8%. Water binder ratios were 0.25 at cement content 350 kg/m³ and 0.38 at cement content 450, 550 kg/m³. Super plasticizer ratio was 4% according to fine materials (cement and silica fume). To induce corrosion through steel bars, a 3.5% of sodium chloride solution was used. Table 3 showed details of mixing proportions for concrete.

2.2. Concrete sample preparation

The researcher used cylindrical specimens with a diameter of 50 mm and a height of 200 mm for corrosion resistance tests. To perform electrochemical tests on the concrete specimens containing electric arc furnace steel slag (EAFSS) as a partial replacement of ordinary coarse aggregate (dolomite), an electrochemical cell was prepared, this cell contained the steel reinforcement bars to be investigated, the environment in which the tests were performed, as well as all of the implements required to conduct the measurements. Steel rebar with a diameter of 7.0 mm was used in the test. In Figs. 1 and 2, the steel–concrete–atmosphere

interface was protected in each rebar with a 3.0 cm Paraffin wax to prevent possible localized attacks, due to the differences in aeration; the length of the steel in contact with the concrete was 70 mm.

Prior to performing the tests, the steel reinforcement bars surface was prepared so that the initial condition of the measurement could be well-defined and did not vary from test to another. In order to prevent the difference between the distribution of concrete and steel during the measurement, rebars were cut so that they had smooth and flat section areas. In Fig. 3, the steel protection was cleaned by using cleaning machine and washed with distilled water.

The mixture was prepared with a mechanical mixer; the mold was filled in two stages. In the first stage, the first layer of concrete was poured to the height in which the steel rebar should be positioned, subsequently; the steel rebar was placed in position, leaving them embedded along their entire length. More concrete was then poured into the mold in the second stage until it totally full. It was removed from the mold after 24 h and placed in a 3.5% NaCl solution for 28 days.

2.3. Measurement techniques

In most cases, reinforced concrete is exposed to the aqueous medium, where the Steel bars corrosion mechanism is essentially electrochemical in nature. Electrochemical techniques are used to assess, investigate and control the corrosion of steel bars which is caused by a corrosive attack of the chloride ions. In this work, linear polarization resistance (L.P.R) and open circuit voltage (O.C.V) were used to measure the corrosion rate of the rebar, which produced the data on the corrosion rate, the corrosion current density, the corrosion potential and the concrete resistivity in an open circuit.

The electrochemical cell used has a standard three electrodes are the working electrode, the counter electrode, and the reference electrode. The working electrode tested the steel reinforcement bars. The counter electrode provided the applied current and composed of a highly corrosion resistant material (platinum). Fig. 4 showed that a saturated calomel electrode (SCE) was used as a reference electrode, which provided a stable reference for measuring the applied potential to the working electrode accurately.

The measurements were conducted in a 3.5 concentration of NaCl solution at 25 °C by using a potentiostat/galvanostat SP-150 device. The Steel Bars, in which potential was measured, is called the working electrode. The ends of the working electrode and the reference electrode were directly connected to the terminals of one potentiostat in order to measure the corrosion potential. A potentiodynamic polarization technique was used to generate polarization scan for obtaining linear polarization curves and to provide a continuous potential sweep at a constant speed. The electrode potential was properly controlled with the potentiostat, which imposed to the electrode the desired potential, is relative to the reference electrode and records the polarization current as a function of the potential.

As illustrated in Fig. 5, the corrosion of the current density (i_{corr}) of the specimens was calculated from the intersection of the cathodic and anodic Tafel curves by using the Tafel extrapolation method, The Tafel slope, which occurs at open circuit may be obtained from the linear regions of the polarization curve.

3. Results and discussion

3.1. Corrosion resistance

This study investigates the concrete, which is exposed to sulfates environments in order to provide an experimental data for a subsequent specification of the concrete performance. The values of corrosion potential (E_{corr}) of steel reinforcement bars obtained in an open circuit potential measurement (OCP) tests and it also showed the values of corrosion current density (i_{corr}), the corrosion rate (C.R) and the corrosion resistivity obtained in linear polarization tests, were exposed to solution of 3.5% NaCl, as was presented in Table 4. The mentioned data is also shown in Figs. 6 and 7.

The Results of Corrosion resistances were mean values of the three test specimens for each mixture. According to the electrochemical potential monitoring test, the concrete mix M2.6, which has both of steel slag coarse aggregate replacement percentage of 100% and without silica fume, recorded an increase of corrosion resistance (E_{corr}) of steel reinforcement bars about 42% (from about –190 to approximately –110 mV) after 28 days, when the steel slag percentage was used as fully coarse aggregate.

For the evaluation of the results, in terms of the corrosion current density and the corrosion rate, it adopted the criterion proposed by Cristina and Joaquim [17], and González et al. [18]. According to ASTM C876 [19], the potential measurements with

Table 1
Mechanical and physical properties of steel slag coarse aggregate.

Properties	Results	Allowable limits
Specific Weight	3.52	–
Bulk Density (t/m ³)	1.78	–
Crushing Coefficient %	11.54	Not more than 30% ^a
Water Absorption %	1.02	Not more than 2.5% ^b
Abrasion Index (loss Anglos apparatus) %	14.1	Not more than 30% ^b

^a Limits of ESS 1109/2002 [26].

^b Limits of ECCS 203-2008 [27].

Table 2
Chemical compositions of cement, silica fume and steel slag coarse aggregates.

Chemical component	Cement	Silica fume	Steel slag
SiO ₂	21.0	96.0	13.10
Al ₂ O ₃	6.10	1.10	5.51
Fe ₂ O ₃	6.10	1.45	36.80
CaO	61.5	1.20	33.00
MgO	3.80	0.18	5.030
K ₂ O	0.30	1.20	–
Na ₂ O	0.40	0.45	–
So ₃	2.50	0.25	4.180

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