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Corrosion behavior of reinforcing steel embedded in concrete produced with finely ground pumice and silica fume

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ABSTRACT

In this study, the mechanical and physical properties of concrete specimens obtained by substituting cement with finely ground pumice (FGP) at proportions of 5%, 10%, 15% and 20% by weight has been investigated, in addition to analyzing the corrosion behavior of reinforcing steels embedded in these specimens. Besides, with the purpose of determining the effect of silica fume (SF) additive over the corrosion of reinforcing steels embedded in concrete with FGP, SF has been entrained to all series with the exception of the control specimen, such that it would replace with cement 10% by weight. Corrosion experiments were conducted in two stages. In the first stage, the corrosion potential of reinforcing steels embedded in the concrete specimens was measured every day for a period of 160 days based on the ASTM C 876 standard. In the second stage, the anodic and cathodic polarization values of the steels were obtained and subsequently the corrosion currents were determined with the aid of cathodic polarization curves. In the study, it was observed that a decrease in the mechanical strength of the specimens and an increase in the corrosion rate of the reinforcing steel had taken place as a result of the FGP addition. However, it was determined that with the addition of SF into concretes supplemented with FGP, the corrosion rate of the reinforcing steel has significantly decreased.

1. Introduction

Reinforcing steel in concrete is normally protected from corrosion by the passive film formed at the steel/concrete interface inside the alkaline cementitious matrix [1]. However, this passivation can be eliminated either by a decrease in the pH value ($pH < 9$) due to carbonation, or by the presence of chloride salts, which initiates an expansive corrosion of the reinforcing steel and eventually damages the surrounding concrete. Concrete structures such as bridges, buildings, sanitary and water facilities, and other reinforced concrete structures might suffer severe damages due to corrosion of the reinforcing steel. Damages caused by the consequent cracking and spalling of the concrete cost billions of dollars each year. In addition to the economic losses incurred, public safety is also jeopardized, even culminating in loss of lives due to incidents like collapsing of bridges and structures [2]. Methods of corrosion control for reinforcing steel include cathodic protection [3,4], surface treatments of the rebars (e.g., epoxy coating) [3], usage of a surface coating on the concrete [4] and the usage of mineral admixtures (e.g., silica fume) [2] in the concrete. Utilization of mineral admixtures is a particularly appealing alternative due to its simplicity and relatively low cost [3].

Mineral admixtures such as silica fume, fly ash and slag are added into concrete for numerous purposes, including the improvement of mechanical properties, bond strength, freeze–thaw durability, impermeability, corrosion control and workability [3].

The objective of this study is to analyze the effects of using FGP as a mineral admixture in combination with SF over the corrosion of reinforcing steel embedded in concrete. The properties of the mineral admixtures used in this study, FGP and SF, have been investigated in prior studies [5–13]. However, even though some studies have been conducted for analyzing the effects of FGP additive over the corrosion of reinforcing steel embedded in concrete, they have not adequately clarified the subject [14–17]. On the other hand, although SF has been shown to increase the corrosion resistance [3,4,18–21], the effect of its addition over corrosion resistance of reinforcing steel embedded in concrete which has been produced with FGP has not been reported to date.

This experimental study has investigated the effect of adding SF (10% by weight of cement) over corrosion behavior of reinforcing steel embedded in concrete that was obtained by substituting cement with FGP at proportions of 5%, 10%, 15% and 20% by weight. Effects on the corrosion resistance exhibit correlation with the effects on the mechanical and physical properties of the concretes.

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2. Materials and methods

A total of nine series of concrete specimens including the control specimen were prepared in order to examine the effect of adding SF (10% by weight of cement) on corrosion behavior of reinforcing steel embedded in a concrete obtained by substituting cement with FGP at proportions of 5%, 10%, 15% and 20% by weight. A total of forty-five pieces of concrete specimens were obtained, with five specimens being taken from each series.

2.1. Preparing electrodes

As an electrode, the SAE1010 steel bar produced by Ereğli Iron and Steel Factories in Turkey, which is the fundamental construction material of the construction industry, was selected for the study. The as-received material was in the form of a hot-rolled bar 12 mm in diameter. The chemical composition of SAE1010 steel is presented in Table 1.

Ninety pieces of steel bars in 120 mm length were cut out from the as-received material and their surfaces were mechanically cleaned. Then, sample surfaces were polished with 1200 mesh sandpaper. Polished surfaces were cleaned with ethyl alcohol. Surface areas (10 cm^2) were kept open in the tips of electrodes which would be embedded in the concrete. Screw thread was machined in the other ends of steel electrodes and cables were connected to these ends in order to make measurements during the experiment in an easier way. Remaining sections of the electrodes were protected against external effects by covering them with epoxy resin at first and then with polyethylene.

2.2. Preparing concrete specimens for the corrosion experiments

$100 \times 100 \times 200$ mm concrete specimens were prepared for the corrosion experiments, in which the steel electrodes prepared in advance were embedded.

Commercial grade ASTM Type I Portland cement, which is produced in Turkey as CEM I Portland cement, was used in the preparation of all concrete specimens that were employed in the experiments within the scope of the study. The pumice used in this investigation was collected from the volcano called Mount Meryem, located in Elazig province of Turkey. The pumice was very finely ground for the hydration reactions and was then passed through 0.075 mm sieves to be used in the concrete preparation. The SF was obtained from Antalya Electro–Ferrocrome Plant in Turkey. A comparison of the chemical and physical properties of the FGP and SF with those of the cement is given in Table 2.

In our study, high quality river gravel and sand were used as the aggregate, which are widely employed in concrete production (max. grain size of aggregate = 8 mm). Grading, density and water absorption values of the aggregate are shown in Table 3. Besides, tap water was used as the mixing water during the preparation of the concrete specimens.

The mixture design properties of all the concrete groups were prepared in compliance with ACI 211.1 [22], and are presented in Table 4. Neither plasticizers nor any other chemical admixtures were used.

The concrete specimens were kept in molds for duration of 24 h. Then the specimens were cured for seven days at 25 °C in 100% relative humidity, before getting partially submerged in a 3% NaCl solution to induce a corrosive environment.

Table 1
Chemical composition of the steel (wt.%).

C	Mn	Si	P	S	Fe
0.17	0.250	0.050	0.005	0.050	Balance

Table 2
Chemical compositions of the cement, silica fume and finely ground pumice.

Oxide compounds (mass %)	CEM I 42.5 N	SF	FGP
Silica (SiO_2)	21.12	93.0–95.0	49.52
Alumina (Al_2O_3)	5.62	0.4–1.4	16.72
Iron oxide (Fe_2O_3)	3.24	0.4–1.0	11.26
Calcium oxide (CaO)	62.94	0.6–1.0	8.26
Magnesia (MgO)	2.73	1.0–1.5	4.54
Sulphur trioxide (SO_3)	2.30	–	–
Sodium oxide (Na_2O)	–	0.1–0.4	–
Potassium oxide (K_2O)	–	0.5–1.0	–
Carbon (C)	–	0.8–1.0	–
Sülphur (S)	–	0.1–0.3	–
Loss on ignition	1.78	0.5–1.0	1.68
Density (gr/cm^3)	3.10	2.20	2.8

Table 3
Grading, density and water absorption values of the aggregate.

Sieve size (mm)					
Passing (%)					
8	4	2	1	0.50	0.25
100	65	48	33	19	7
Specific gravity (g/cm^3)				Water absorption (%)	
2.5				3.1	

Table 4
Details of the concrete mixes (kg/m^3).

Specimens	Water	Fine aggregate (0–4 mm)	Coarse aggregate (4–8 mm)	Cement	FGP	SF
C	200	1043	560	400	–	–
P5	200	1043	560	380	20	–
P10	200	1043	560	360	40	–
P15	200	1043	560	340	60	–
P20	200	1043	560	320	80	–
PS5	200	1043	560	340	20	40
PS10	200	1043	560	320	40	40
PS15	200	1043	560	300	60	40
PS20	200	1043	560	280	80	40

2.3. Corrosion tests

Corrosion experiments were conducted in two stages. In the first stage, the corrosion potential of steels embedded in concrete was measured every day for a period of 160 days in accordance with ASTM C876 method [23]. Saturated copper/copper sulfate ($Cu/CuSO_4$) was used as the reference electrode, and a high impedance voltmeter was used as the measurement device in corrosion potential measurements. Changes in corrosion potentials versus time were indicated in graphs in order to determine whether the steel was active or passive. Recommendations on evaluation of potential measurement results in ASTM C876 experiment method are stated in Table 5 [2,24–26].

In the second stage, the anodic and cathodic polarization values of steel embedded in the concrete were obtained by using the galvanostatic method and then the corrosion currents were determined with the aid of cathodic polarization curves.

Experimental setup used for the application of Galvanostatic method is schematically displayed in Fig. 1.

Black areas on the electrodes displayed in Fig. 1 indicate the areas kept under protection. In this circuit, the electrode that is connected to the positive terminal is the anode and the other that is connected to the negative terminal of the power source, which supplied a fixed voltage of 20 V DC to the system, is the cathode. The same material (reinforcing steel, SAE1010) has been used for anode and cathode electrodes.

2.4. Hardened concrete experiments

The corrosion behaviors of the concrete specimens consisting of FGP at various proportions and SF at 10% by weight of cement, as well as their mechanical and physical properties like unit weight, compressive strength and ultrasonic pulse velocity were investigated in accordance with ASTM C138 [27], ASTM C39 [28] and ASTM C597 [29], respectively. Moreover, porosity and sorptivity measurements were also conducted on the concrete specimens. The data were interpreted together with the corrosion rate of steels embedded in these concrete specimens.

The porosity measurements were carried out on 100 mm cube specimens. Three test specimens for porosity measurement were prepared for each mixture. The specimens were dried in the oven at about 50 °C until constant mass was achieved and were then placed for at least 3 h in desiccators under vacuum. Finally, they were filled with de-aired, distilled water. The porosity was calculated through Eq. (1). This method for measuring the porosity has previously been reported [12,30–32]

Table 5
Estimation of corrosion probability as determined by half-cell potential test.

Potential (mV) (CSE)	Probability of the presence of active corrosion
>−200	The probability for corrosion is very low
−200 to −350	Uncertain
<−350	The probability for corrosion is very high