

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.

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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 ($\text{pH} < 9$) 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 cm²) 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 × 100 × 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 Elazığ 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 ₂ O ₃)	5.62	0.4–1.4	16.72
Iron oxide (Fe ₂ O 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 ₂ O)	–	0.1–0.4	–
Potassium oxide (K ₂ O)	–	0.5–1.0	–
Carbon (C)	–	0.8–1.0	–
Sulphur (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 (%)	4	2	1	0.50	0.25
8	65	48	33	19	7
Specific gravity (g/cm ³)				Water absorption (%)	
2.5				3.1	

Table 4

Details of the concrete mixes (kg/m³).

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/CuSO₄) 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

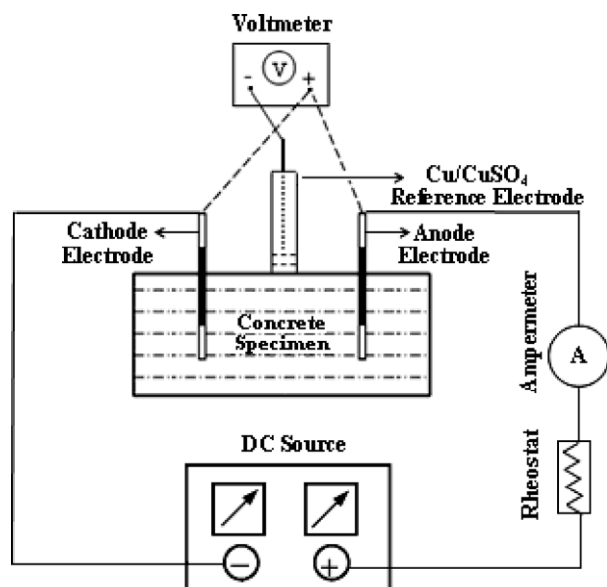


Fig. 1. Schematic representation of the polarization measurement using galvanostatic method.

$$P = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \quad (1)$$

where P stands for vacuum saturation porosity (%); W_{sat} weight in air of saturated specimen; W_{wat} weight in water of saturated specimen and W_{dry} weight of oven-dried specimen.

Three test specimens for sorptivity measurement were prepared for each mixture. The sorptivity measurements were also carried out on 100 mm cube specimens. Measurements of capillary sorption were carried out using specimens pre-conditioned in the oven at about 50 °C until constant mass was achieved. Then, the concrete specimens were cooled down to room temperature. As shown in Fig. 2, test specimens were exposed to the water on one face by placing them on a pan. The water level in the pan was maintained at about 5 mm above the base of the specimens during the experiment. The lower areas on the sides of the specimens were coated with paraffin to achieve unidirectional flow. At certain times, the mass of the

specimens was measured using a balance, then the amount of water absorbed was calculated and normalized with respect to the cross-section area of the specimens exposed to the water at various times such as 0, 5, 10, 20, 30, 60, 180, 360 and 1440 min. The capillary absorption coefficient (k) was obtained by using the following equation;

$$\frac{Q}{A} = k\sqrt{t} \quad (2)$$

where Q stands for the amount of water absorbed in (cm^3); A the cross-section of specimen that was in contact with water (cm^2); t time (s) and k the sorptivity coefficient of the specimen ($\text{cm/s}^{1/2}$). To determine the sorptivity coefficient, Q/A was plotted against the square root of time ($\sqrt{t}$), and then, k was calculated from the slope of the linear relation between Q/A and $\sqrt{t}$. This method for measuring the capillary absorption of the concrete specimens was also used by [8,12,30,33].

3. Results and discussion

3.1. Results of mechanical and physical experiments conducted on hardened concrete

The data obtained from the mechanical and physical experiments conducted on the concrete specimens are presented in Table 6.

The results presented in Table 6 indicate to a systematic reduction in the unit weight as the amount of the mineral admixtures (FGP and SF) in the concretes increase. This is an expected outcome; due to the low specific gravity of FGP and SF, the unit weight of concretes containing FGP or a combination of FGP and SF (double adding) decreases while the percentage of FGP and SF content gets increased. In addition, the highest compressive strength was obtained in the control concrete (C) and the lowest strength was obtained in the concrete with a FGP (P20) at 28 days. Similar relationships have also been reported by the studies appearing in references [6,17]. The compressive strength values of concretes with FGP plus SF (FGPSF) are between the values for C and FGP. It is generally accepted that the pozzolanic reaction in the pozzolan/cement systems becomes dominant at ages greater than 28 days [34,35]. Therefore, the pozzolanic effect of the FGP at 28 days may not be sufficient. A number of scanning electron microscope (SEM) micrographs illustrating various characteristic features of the specimens are shown in Fig. 3. As seen in Fig. 3, the quantity of hydration products derived from the concretes produced by FGP admixtures is low compared to other concrete types, whereas the amount of pores is higher. This is one of the most important factors at the compressive strength reduction.

The fineness of a mineral admixture is an important parameter with respect to filling pores inside the concrete. Since the average particle size of SF is very small compared to that of cement particle, the filler effect of mineral admixture may be as important as its pozzolanic effect according to Goldman and Bentur [36]. Thus, the fineness of a mineral admixture is highly critical for the modification of aggregate/cement interface zone, which is the weakest link of a concrete's structure [8]. The SEM morphologies of the binders (cement, FGP and SF) used in this study are shown in Fig. 4. The SEM micrograph shown in Fig. 4b specifies that FGP mainly consisted of very irregularly shaped particles with a porous

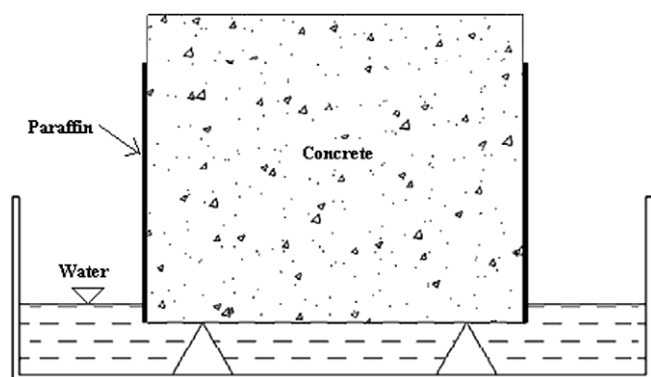


Fig. 2. The measurement of water capillary sorption.

Table 6
Results of mechanical and physical tests of the specimens.

Experiments	Specimens								
	C	P5	P10	P15	P20	PS5	PS10	PS15	PS20
Unit weight (kg/m^3)	2245	2240	2238	2233	2227	2220	2215	2185	2162
Compressive strength (MPa)	49.71	46.72	44.50	43.51	37.92	46.87	45.84	45.75	38.94
Sorptivity coefficient $\times 10^{-3}$ ($\text{cm/s}^{1/2}$)	1.142	1.184	1.195	1.339	1.356	0.618	0.627	0.695	0.761
Porosity (%)	8.442	8.835	9.362	9.720	9.848	5.385	6.038	6.067	6.649
Ultrasonic pulse velocity (km/s)	4.552	4.396	4.355	4.266	4.139	4.409	4.359	4.300	4.237

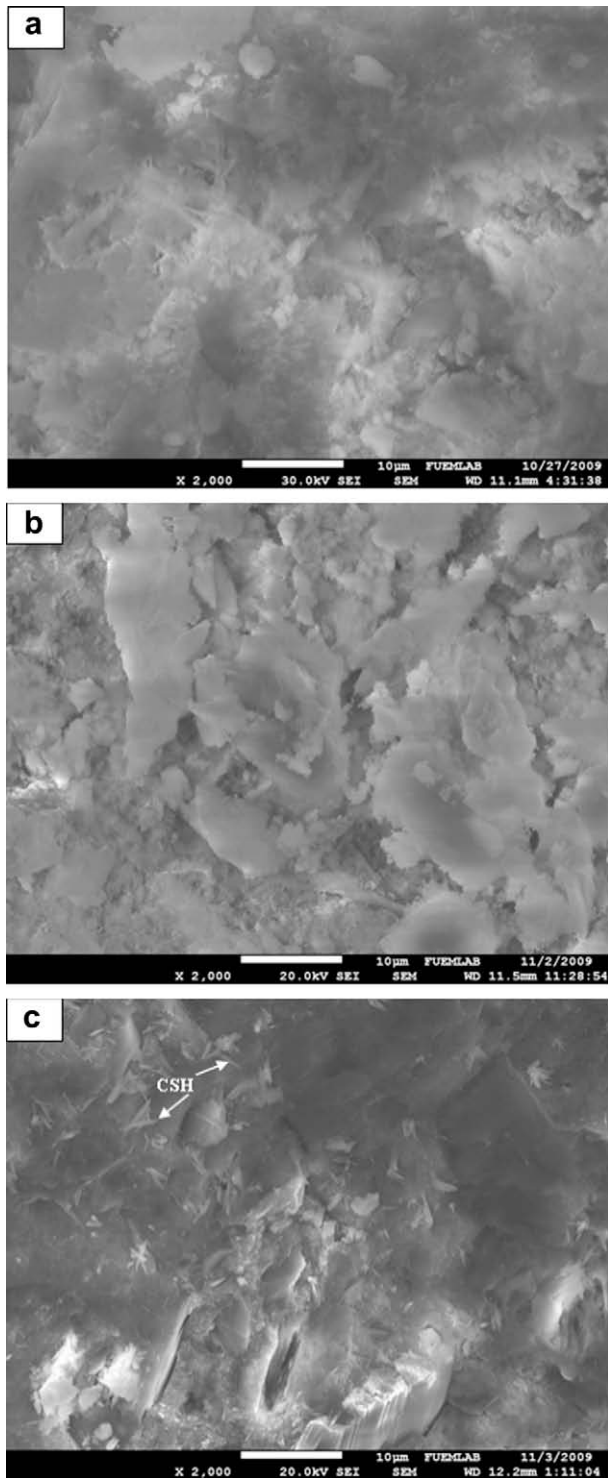


Fig. 3. SEM observation of the concrete specimens: (a) C, (b) P20 and (c) PS20.

cellular surface. The SEM micrograph of SF shown in Fig. 4c has revealed that SF mainly consisted of very small spherical particles.

As seen in Fig. 4 the average particle size of FGP is very large compared to SF and cement, thus its filler effect may not be sufficient. It can be concluded that compressive strength of concretes with FGP is relatively low, because both pozzolanic activity and filler effect of FGP are not as good as those of SF. The SF particles, however, may act as ideal microfiller in the interfaces between aggregate and cement paste or pores in the bulk paste. Therefore,

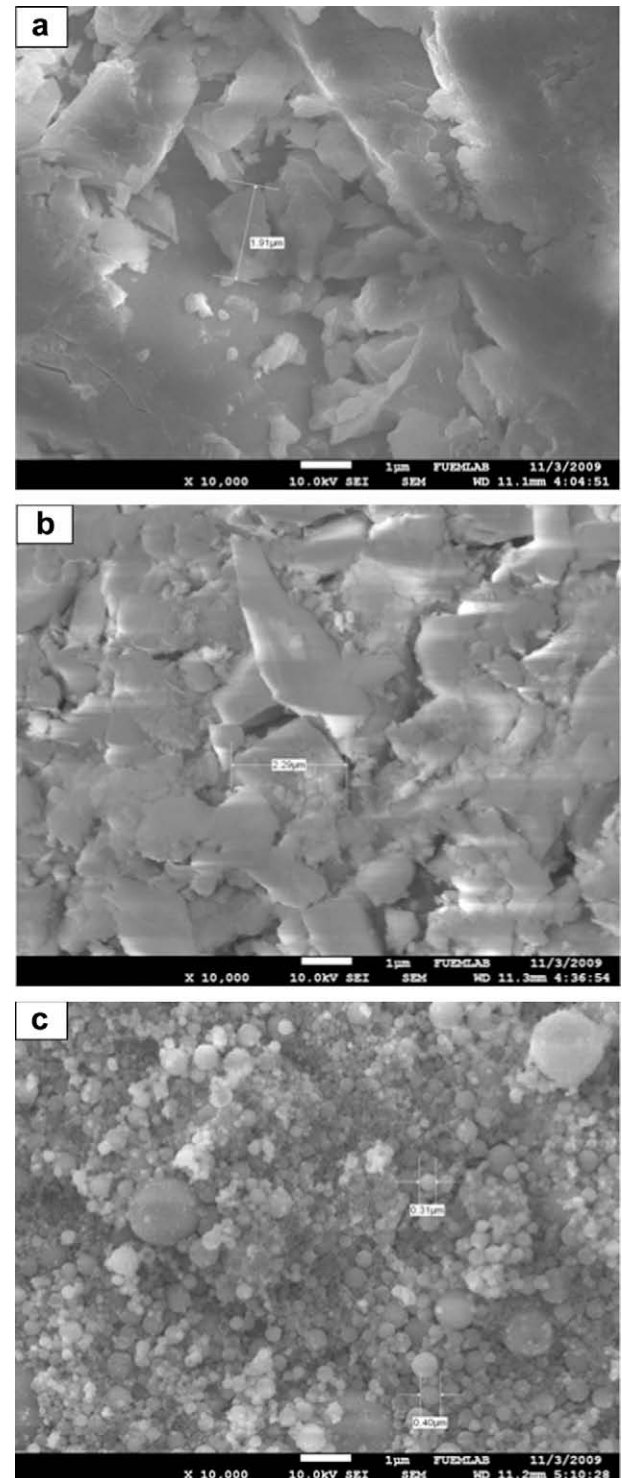


Fig. 4. SEM morphologies of the materials: (a) cement, (b) FGP and (c) SF.

a high level of compressive strength is achieved in concretes with FGPSF compared to that of the FGP concretes. Moreover, the addition of SF into concretes containing FGP has led to an improvement in compressive strength. However, the compressive strength of the SF-mixed concretes has turned out to be lower than that of the C specimen due to the reduction in the quantity of total cement. These observations are in good agreement with earlier findings [6]. It is a well known fact that the pozzolanic effect of the microfiller materials will be significant in the later ages of

the concrete; therefore, it is expected that the differences in the compressive strength might be different beyond 28 days.

As seen in Table 6, the ultrasonic pulse velocity values of concrete specimens with FGP had decreased in accordance with the rise in the percentage of FGP content. This decrease in ultrasonic pulse velocity was more based upon rise of the porous of concrete because of the microstructure of the FGP. Yet, a systematic increase has been observed in the ultrasonic pulse velocity values for the series containing SF as the amount of pores in the concrete has decreased due to filler effect of SF.

The porosity results are illustrated in Table 6. These porosity values indicate the effect of the mineral admixtures (FGP and SF) on the porosity of concrete. When FGP was used as single mineral admixture in concrete, porosity value was higher compared to C concrete and the concrete with FGPSF. However, the porosity of the concrete had improved when both types of mineral admixtures (FGP and SF) were added at the same time (double adding). Our results demonstrate that the porosity of the concrete with double mineral admixtures is less than the C concrete's porosity.

The results of sorptivity tests are also summarized in Table 6. As seen from Table 6, the capillary absorption of concrete specimens with FGP has increased depending on the increase in the volume fraction of FGP. However, this gain was apparently reversed in specimens containing both FGP and SF. Hence, it can be concluded that there is a strong positive relationship between the sorptivity coefficient and porosity. This finding is in agreement with a previous study reported by Gonen and Yazicioglu [30].

In concrete with FGP, the average particle size of the mineral admixture is higher compared to C and double adding concretes, and the pores in bulk paste and interfaces are not filled completely. Thus, the concrete with FGP has larger capillary pores and possesses lower compressive strength, which results in the higher capillary sorption in this concrete. Since SF is very fine, pores in the bulk paste or in the interfaces between aggregate and cement paste are filled by this mineral admixture. Therefore, the capillary pores are reduced. The beneficial role of the mineral admixture (SF) causes an increase in the strength and a reduction in the capillary sorption of the concrete with FGP. Similarly, Song et al. [37] concluded that the diffusivity of concrete can be dramatically reduced when SF replacement ratio is in excess of 8%, and the diffusivity can be lowered further as SF replacement ratio increases from 8% to 12%.

3.2. Results of corrosion tests

The results obtained from corrosion potential measurements of reinforcing steels embedded in the concrete specimens are displayed in Figs. 5 and 6.

In contrast to the literature [14,15,17]; it was surprisingly found out that the electronegative corrosion potential is much higher in all concrete specimens containing any ratio of FGP compared to the C specimen, as seen in Fig. 5. Large increases were observed in electronegative corrosion potential when the FGP amount was increased. Indeed, the reinforcing steels in the C specimen became more passive compared to the specimens with FGP and remained in the passive zone in terms of corrosion during the 90 day period. Then, the corrosion potentials of the steels in C concrete entered the uncertain zone and stabilized afterwards. Unlike the C specimen, the corrosion potentials of the steels embedded in P5 and P10 specimens had reached the uncertain zone after the 2nd week and remained there for the entire duration of the experiment. P15 and P20 specimens, which possess the highest electronegative corrosion potential, had reached the active zone after the 3rd month and remained there until the end of the 160th day. By taking ASTM C876 as a reference, these observations were concluded to indicate that the corrosion still continued in P15 and P20 concretes even at the end of the 160th day. Fig. 5 indicates that the P20 specimen has the lowest corrosion resistance among the FGP specimens. By taking account of the results of corrosion potentials by ASTM C876 standard, it can be stated that the C specimen has higher corrosion resistance than the concrete specimens produced with FGP.

As seen in Fig. 6, SF added to FGP specimens increased the passivation rate of reinforcing steel embedded in the FGP specimens. In addition, the corrosion potentials of the specimens containing SF have rapidly increased as positive further when silica fume was entrained, with the exception of PS20. The corrosion potential of PS5 specimen reached the passive zone after the 20th day, whereas PS10 and PS15 specimens did the same after the 50th day and they have all remained passive for the entire experiment. This situation is an indication of that while the corrosion resistance of a concrete is reduced by adding FGP, it increases again as SF is added to those concretes containing FGP. The addition of SF such that would replace with cement 10% by weight in concretes consisting of FGP up to 15% (P5, P10 and P15), has enhanced the corrosion resistances of the specimens and carried them above that of the C specimen.

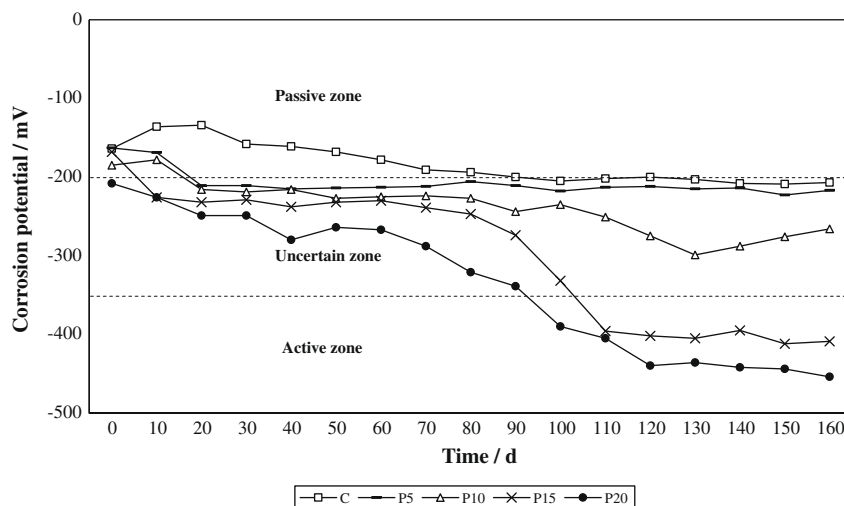


Fig. 5. Change in corrosion potential on the specimens C, P5, P10, P15 and P20.

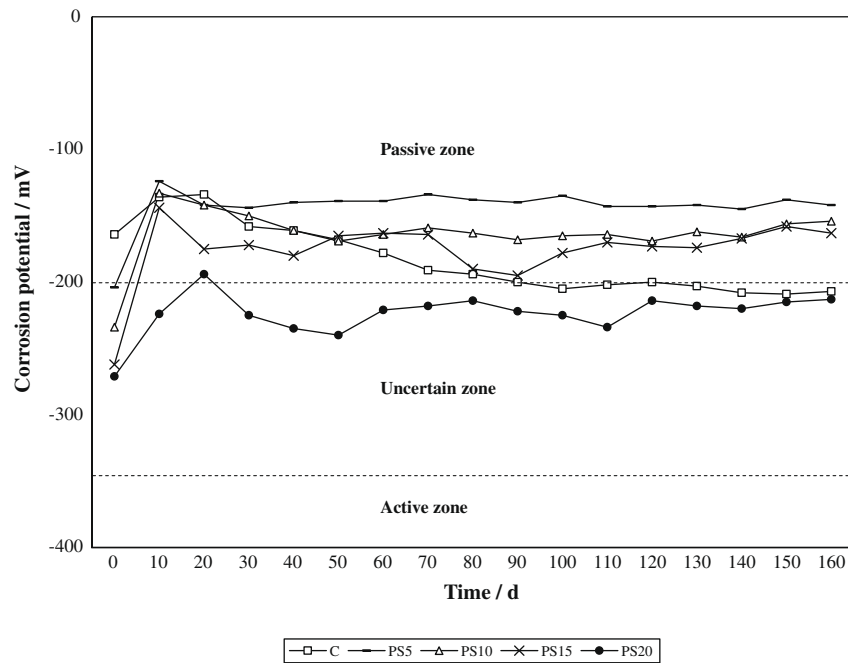


Fig. 6. Change in corrosion potential on the specimens C, PS5, PS10, PS15 and PS20.

The corrosion potential provides qualitative observations and probably points out the corrosion of steel embedded in concrete to a large extent. On the other hand, reliable quantitative data on the corrosion of steel embedded in concrete can be obtained by measuring the steel's resistance or current density [2,24].

Results of corrosion polarization studies on the developed concrete specimens with respect to copper sulfate electrode (CSE) are shown in Fig. 7. The data of corrosion current density (I_{corr}) shown in Fig. 7 have been derived from the experimentally obtained cathodic polarization curves using Tafel's linear extrapolation method.

The corrosion current density values seem to confirm the corrosion potential values. As clearly seen in Fig. 7, the C specimen exhibits the lowest corrosion rate compared to concrete specimens with FGP. In addition, the corrosion rate has increased in parallel to the increase in volume fraction of FGP in the concrete. As already specified, this was attributed to the fact that in the concrete with

FGP, the average particle size of the mineral admixture is higher than the C specimen and the pores in bulk paste and interfaces are not filled completely, which leads to the concrete with FGP exhibiting larger capillary pores. As it is known, oxygen input into the concrete is facilitated at higher porosities. Oxygen and water are definitely required in order to enable the corrosion to continue in a neutral environment [38]. Thus, the corrosion rate of reinforcing steels embedded in concrete specimens with FGP builds up since the oxygen input increases due to the pores emerging after the FGP addition. As seen in Fig. 7, however, the corrosion rate has been reduced as a result of adding SF to concrete specimens with FGP. For instance, the corrosion rate of the steels embedded in concretes with SF is lower than C specimen's rate, with the exception of PS20, thanks to SF possessing a small mean particle size (average 0.3 μm). The fine particles result in a relatively dense structure and relatively more discontinuous pores in the concrete. When SF is mixed with cement in concrete, it reacts with free lime

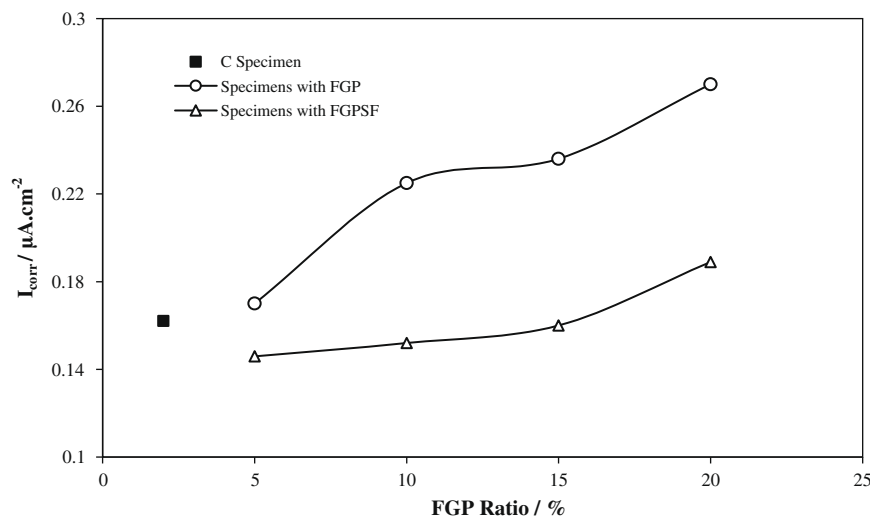


Fig. 7. Changes in the I_{corr} of the specimens.

during the hydration of cement in concrete to form a cementitious compound, namely calcium silicate hydrate (CSH) (as seen in Fig. 3c). It also reduces the volume of large pores and capillaries. The resultant cement matrix is more chemically resistant, has a denser microscopic pore structure and as well as a relatively impermeable concrete structure. Table 6 shows that concretes containing SF demonstrate the lowest water absorption ability and porosity among all the concretes studied in this work. Water normally enters the concrete through capillary action; the fewer and smaller the capillary pores are, the less water enters the concrete and the lower the rates of oxygen diffusion. Due to the high alkalinity in concrete, there are very few H^+ ions to be consumed in the cathodic reaction, so that the oxygen has to be reduced in order to sustain the cathodic reaction. Therefore, when the oxygen reduction rate falls, so does the corrosion rate. Chloride ions tend to eliminate the normal passivation state of reinforcing steel in concrete. Low air void content and low water absorptivity help keep chloride ions from going through the concrete and reaching the surface of the steel. In this manner, a concrete with SF, which has a denser microscopic pore structure, is relatively impermeable to chloride ions [3]. Therefore, in this study, adding SF to concretes with FGP effectively reduced the corrosion rate of reinforcing steels embedded in these concrete specimens which were submerged in chloride solutions.

4. Conclusions

On the basis of the experimental work that has been carried out and presented in this paper, the following conclusions can be drawn;

1. The test results indicated that the unit weight of the concrete decreased as a result of the fact that certain proportions of mineral admixtures (FGP and SF) had been added to the concrete as cement substitutes. This is a desired outcome.
2. The increase in the amount of FGP resulted in a decrease in compressive strength and ultrasonic pulse velocity values of the concrete, but at the same time it lead to an increase in porosity and sorptivity values. This happens due to the fact that in the concrete with FGP, pores in bulk paste and interfaces between aggregate and cement paste are not filled completely.
3. When SF was added to the concrete specimens with FGP, it improved both the strength and other performance parameters (capillary absorption, porosity and ultrasonic pulse velocity). Since SF consist of very fine particles, pores in the bulk paste or in the interfaces is filled by this mineral admixture, therefore, the strength of concrete specimens with FGP increased after the addition of SF.
4. As a result of the experiments conducted for the purpose of determining the corrosion behaviors of reinforcing steels embedded in concretes with FGP, it has been observed that the corrosion rate of the steel increases in line with increasing amounts of FGP. However, SF which was entrained into concretes with FGP at proportion of 10% by weight has significantly reduced the corrosion rate of the steels.
5. The addition of SF, in a way that would replace with the cement 10% by weight, into the concretes consisting of FGP up to 15% (P5, P10 and P15) has reduced the corrosion rate of the reinforcing steels embedded in these concretes to even lower levels than that of the steels in control concrete.
6. In this study, the minimum FGP replacement was selected as 5% and it should be pointed out that further research should be carried out to analyze the effects of lower levels of FGP content on the corrosion of reinforcing steel.

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