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Effect of admixtures in concrete on the corrosion resistance of steel reinforced concrete

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Abstract

The effect of admixtures, namely silica fume, latex, methylcellulose and short carbon fibers (in various combinations), in concrete on the corrosion resistance of steel reinforced concrete was assessed by measuring the corrosion potential and corrosion current density during immersion in $Ca(OH)_2$ and NaCl solutions. Silica fume (15% by weight of cement) was most effective for improving the corrosion resistance, due to decrease of water absorptivity, and not so much due to increase in electrical resistivity. Latex (20% by weight of cement) improved the corrosion resistance because it decreased the water absorptivity and increased the electrical resistivity. Methylcellulose (0.4% by weight of cement) improved corrosion resistance only slightly. Carbon fibers (0.5% by weight of cement) decreased the corrosion resistance due to decrease in electrical resistivity. However, the negative effect could be compensated by adding either silica fume or latex, which reduced the water absorptivity. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Concrete; Steel

1. Introduction

The corrosion of steel reinforcing bars (rebars) in concrete limits the life of concrete structures that are reinforced with steel. Corrosion occurs regardless of the inherent capacity of concrete to protect steel from corrosion; accelerated corrosion results from the loss of alkalinity in the concrete or the penetration of aggressive ions (such as chloride ions). Methods of corrosion control include cathodic protection [1–4], surface treatments of the rebars (e.g., epoxy coating [5])

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and the use of admixtures (e.g., calcium nitrite [6–8]) in the concrete. The use of admixtures is particularly attractive due to its simplicity and relatively low cost.

Admixtures are used in concrete for numerous purposes which include improvement in mechanical properties, bond strength, freeze-thaw durability, impermeability, corrosion control and workability. Admixtures include fine aggregates such as silica fume [9,10], polymers such as latex [11–13] and methylcellulose [14], and short fibers such as carbon fibers [15–23].

The objective of this study was to investigate the effects of silica fume, latex, methylcellulose and carbon fibers on the corrosion resistance of steel reinforced concrete. Although silica fume has been shown to increase the electrical resistivity and decrease the permeability and specific surface area [9,24], the effect of silica fume on the corrosion resistance of steel rebars has not been previously reported. Similarly, latex has been shown to reduce the permeability [11–13] and increase the electrical resistivity [25], but the effect of latex on the corrosion resistance of steel reinforced concrete has not been previously reported. Also, no previous work has been reported on the effect of methylcellulose or carbon fibers on the corrosion resistance of rebars. On the other hand, carbon fibers decrease the electrical resistivity of concrete, [15,19,22,26] and this effect suggests that the corrosion may be accelerated.

This paper compares the effects of silica fume, latex, methylcellulose and carbon fibers in various combinations in concrete on the corrosion resistance of steel rebars. Effects on the corrosion resistance are related to effects on the water absorptivity and volume electrical resistivity of the concretes.

2. Experimental methods

2.1. Materials

Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The admixtures used were (i) latex, a styrene butadiene polymer dispersion (Dow Chemical Co., Midland, MI, Product No. 460NA) with the polymer particles making up about 48% of the dispersion and with styrene and butadiene in the weight ratio 66:34, such that the latex (20% by weight of the cement) was used along with an antifoam (Dow Corning Corp., Midland, MI, Product No. 2210, 0.5% by weight of latex), (ii) methylcellulose (Dow Chemical Corp., A15-LV, 0.4% by weight of cement), which was dissolved in water and used along with a defoamer (Colloids Inc., Marietta, GA, Colloids 1010, 0.14% by weight of cement) and (iii) silica fume (EMS965, Elkem Materials Inc., Pittsburgh, PA, 15% by weight of the cement). The water reducing agent was a sodium salt of a condensed naphthalenesulfonic acid (TAMOL SN, Rohm and Haas Company, Philadelphia, PA) used in weight proportions identified in Table 1 for the various mixes. Table 1 also shows the water/cement ratio for each mix. The proportions in Table 1 were chosen in order to maintain the slump at around

Table 1
The mix design of concretes[a]

	P	P + M	P + M + f	P + M + f + SF	SF	SF + M	L	L + f
Cement	1	1	1	1	1	1	1	1
Water	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5
Coarse aggregate	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49
Sand	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
f	–	–	0.5%[b]	0.5%[b]	–	–	–	0.5%[b]
M	–	0.4%	0.4%	0.4%	–	0.4%	–	–
WR	–	2%	2%	2%	2%	2%	–	–
Colloids 1010	–	0.14%	0.14%	0.14%	–	0.14%	–	–
SF	–	–	–	15%	15%	15%	–	–
L	–	–	–	–	–	–	20%	20%
Antifoam 2410	–	–	–	–	–	–	0.5%	0.5%

[a] Note: P = plain, M = methylcellulose, SF = silica fume, f = carbon fibers, L = latex, WR = water reducing agent.

[b] Corresponds to 0.35 vol% of concrete.

170 mm. The slump was measured in accordance with the ASTM C143-90a method.

The short carbon fibers were isotropic pitch-based and unsized carbon fibers provided by Ashland Petroleum Company (Ashland, Kentucky). The nominal length of carbon fibers and diameter of monofilaments were 5 mm and 15 μm, respectively. The fibers were added as 0.5% by weight of the cement (0.35 vol% of concrete). The physical properties of the carbon fibers are identified in Table 2.

Fine aggregate was natural sand, with 100% passing through no. 4 U.S. sieve, 99.91% SiO_2; the particle size analysis in shown in Fig. 1 of Ref. [27]. All of the coarse aggregate passed through 1 in. sieve. Unless stated otherwise, the weight ratio of cement to fine aggregate to coarse aggregate was 1:1.5:2.49.

ASTM Standard no. 3 mild steel rebars used in this work were kindly provided by the Lancaster Steel Co. (Buffalo, NY); the diameter was 0.375 in. (0.953 cm). Unless stated otherwise, all rebars were sand blasted prior to incorporation in concrete. Prior to using, the rebars were blast cleaned in order to (i) provide a uniform metal surface and (ii) remove rust and other impurities from the steel

Table 2
Properties of carbon fibers

Filament diameter	15 ± 3 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	3.0×10^{-3} Ω cm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt%

surface. The blast finishing equipment used was Model S-36-I (Empire Abrasive Equipment Co., Langhorne, PA).

Eight concrete formulations were used to test the effects of different admixtures on the corrosion resistance of rebars in the concrete. The mix design is shown in Table 1. Steps in preparing specimens were: (i) all the ingredients except the coarse aggregate were mixed to form a mortar, (ii) a Hobart mixer with a flat beater was used for mixing, (iii) the coarse aggregate was added and stirred with a 2CM concrete mixer (Stone Construction Equipment, Honeoye, NY), and (iv) the mix was poured into plastic cylindrical molds of diameter 7.8 cm and height 15 cm.

A schematic drawing of a sample containing the rebar is shown in Fig. 1. The rebars were sealed with Teflon tape at both ends to control the exact rebar surface area exposed to concrete. Antifreeze oil was applied to the inner surface of the molds before the concrete mix was poured into the mold, while a steel rebar was positioned vertically and held in place at the center of the bottom inside surface of the mold.

All the samples were demolded after 24 h, and then cured in air with a relative humidity of 40% at room temperature for 28 days before any corrosion test was conducted.

2.2. Testing

The corrosion potential (E_{corr}) and polarization resistance of the rebar in different concretes were measured in both saturated $Ca(OH)_2$ and 0.5 N NaCl solutions to study the effect of different admixtures in concrete on the corrosion resistance of rebar in the concrete. The saturated $Ca(OH)_2$ solution simulated the ordinary concrete environment; the NaCl solution represented a high chloride environment. The common advantage of the two test is that they are both nondestructive methods that are suitable for long-term corrosion monitoring. Concretes have variable and high values of the volume electrical resistivity (of the order of 10^6 Ω cm). This results in a high IR drop which, coupled to other

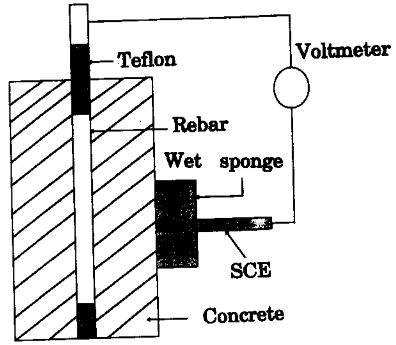


Fig. 1. Schematic of steel reinforced concrete sample under corrosion testing. SCE = saturated calome electrode.

factors, produces ill-defined regions of passivity in practical anodic polarization curves. Therefore, no polarization curve was recorded.

At least three samples of each type were tested. The data scatter among samples of the same type was found to be much smaller than the difference among samples of different types, thus providing statistical validity to the comparative study of different sample types.

A testing method for measuring E_{corr} of concrete is specified in ASTM C876 [28]. The E_{corr} was measured periodically using a high impedance voltmeter and a saturated calomel electrode (SCE). The SCE has a tip diameter of 2 mm and glass casing diameter 1.5 cm. Fig. 1 is a schematic drawing of the test set-up. The SCE was placed on the cylindrical surface of the concrete through a piece of wet sponge of thickness 2 cm before squeezing and 2 mm after squeezing, which occurred by pressure application during the experiment. The area of the sponge in close contact with the concrete surface was 2 cm in diameter. The samples were tested once per week for 44 weeks in saturated $Ca(OH)_2$ and 25 weeks in NaCl solution. According to ASTM C876, an E_{corr} that is more negative than −270 mV suggests 90% probability of active corrosion in concrete.

The corrosion current density (I_{corr}) was determined by measuring the polarization resistance. Because of the high electrical resistance of concrete, a low scan rate (0.167 mV/s) was required. Furthermore, due to the high electrical resistance of concrete, the current involved in the polarization test was low. Thus, a shield made of copper wire mesh was applied to the whole testing apparatus in order to reduce the noise. At least 24 h passed between each successive polarization test in order to allow the sample to become stable electrochemically.

The I_{corr} of rebar in concrete at steady state was calculated from the relationship developed by Stern and Geary [29], of which the following is a simplification:

$$I_{corr} = B/R_p \tag{1}$$

where B is a constant for a given system. A typical value of B for concrete is 26 mV [29].

Water absorption test samples were prepared in the same way as the corrosion samples except that there was no rebar. All the samples were cured in air at a relative humidity of 40% at room temperature for 28 days before testing. All the samples were fully immersed in water after the initial weight had been recorded. At different times, each sample was taken out of the water, wiped to remove the water on the surface, and then weighed. The increase of the weight of each 668 cm^3 sample was considered to be the water absorptivity.

The relative volume electrical resistivity was measured on concrete samples that were cylinders of 7.8 cm diameter and 15 cm height. They were cured in air at a relative humidity of 40% for 28 days and measured by the four-probe method, in which all four probes (silver paint) were placed around the whole circumference of the concrete specimen in four parallel planes perpendicular to the cylindrical axis of the specimen. The outer two probes were current probes, 15 cm apart. The inner two probes were voltage probes, 7 cm apart. Due to the large diameter, the current density was not uniform throughout the entire cross section, as shown by the comparison of results obtained on samples of different sizes. Therefore, the resistivity values obtained are only meaningful on a relative scale.

3. Results

3.1. *Effect of silica fume on corrosion*

Two test environments were employed in the corrosion test: (a) saturated $Ca(OH)_2$ solution (normal environment for concrete), and (b) 0.5 N NaCl solution (high chloride condition).

Fig. 2 shows E_{corr} versus time for rebars in plain concrete and in concrete with silica fume in saturated $Ca(OH)_2$ solution. The E_{corr} values were negative, as expected. The E_{corr} of rebar in both the plain concrete and silica fume concrete were less negative than −240 mV versus saturated calomel electrode (SCE) during the entire test period (44 weeks). According to ASTM C876, this indicates that the corrosion was inactive. The E_{corr} of rebar in silica fume concrete stayed at about the same magnitude during the 44 week test, while the E_{corr} of rebar in plain concrete varied by a small amount before week 10 and stabilized after that. On the average, the E_{corr} of rebar in concrete with silica fume was 80 mV less negative than that of rebar in plain concrete. This indicates a greater chance for the rebar in plain concrete to become active than for the rebar in concrete with silica fume.

Fig. 3 shows the curves of I_{corr} versus time for rebars in plain concrete and concrete with silica fume in a saturated $Ca(OH)_2$ solution. A gradually increasing value was obtained for I_{corr} of rebars in both concretes as immersion time increased. The average I_{corr} of rebar in plain concrete was 0.6 μA/cm^2 higher than that of the rebar in concrete with silica fume in it. Both E_{corr} and I_{corr} indicate that silica fume reduced the corrosion rate of rebars in concrete immersed in saturated $Ca(OH)_2$ solution.

Similar results were obtained with the rebars exposed to the high chloride (0.5 N NaCl solution) environment. The E_{corr} of rebar in silica fume concrete in NaCl

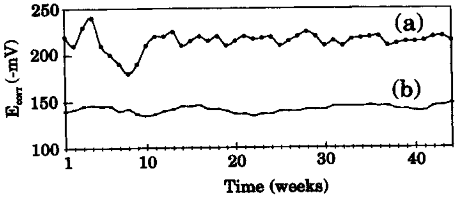


Fig. 2. Effect of silica fume on the corrosion potential of rebar in concrete in saturated $Ca(OH)_2$ solutions. (a) Plain concrete, (b) concrete with silica fume.

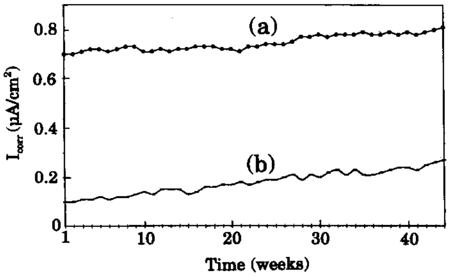


Fig. 3. Effect of silica fume on the corrosion current density of rebar in concrete in saturated $Ca(OH)_2$ solutions. (a) Plain concrete, (b) concrete with silica fume.

solution became more negative by about 100 mV than in saturated $Ca(OH)_2$ solution (Fig. 2); it was near −270 mV, but still slightly less negative than −270 mV, within the 25 week test. This means that the corrosion of rebar in concrete with silica fume in 0.5 N NaCl solution within 25 weeks was not active, although the chloride provided a more aggressive environment than $Ca(OH)_2$ solution. However, the chloride environment caused the E_{corr} of rebar in plain concrete to decrease to −370 mV initially and decreasing with time. This behavior indicates that corrosion developed rapidly for the rebar in plain concrete when exposed to the chloride environment.

The I_{corr} values of rebar in both concretes in the NaCl solution was higher than those for concretes in the saturated $Ca(OH)_2$ solutions (Fig. 3), and the current continued to increase with time. The rate of increase for plain concrete was higher than that for the silica fume concrete. The I_{corr} of rebar in plain concrete was also higher than that in the silica fume concrete in NaCl solution.

Addition of silica fume to concrete improved the corrosion resistance of rebars in concrete in both the ordinary concrete environments (saturated $Ca(OH)_2$ solution) and high chloride environments (0.5 N NaCl solution). Also, addition of silica fume to concrete caused the corrosion of rebar to be minimal even in the chloride environment.

3.2. *Effect of methylcellulose on corrosion*

The effect of methylcellulose addition to concrete on the corrosion behavior of rebar in the concrete is shown in Figs. 4 and 5. Fig. 4 shows the curves of E_{corr}

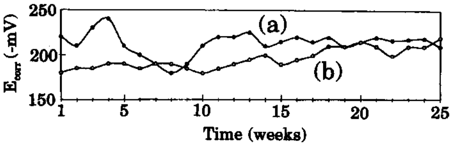


Fig. 4. Effect of methylcellulose on the corrosion potential of rebar in concrete in saturated $Ca(OH)_2$ solutions. (a) Plain concrete, (b) concrete with methylcellulose.

versus time for rebars in plain concrete and concrete with methylcellulose in saturated $Ca(OH)_2$ solutions. The E_{corr} of rebars in both concretes were about the same; they were both about −230 mV, which indicates minimal corrosion in both kinds of concrete. For rebars in both plain concrete and concrete containing methylcellulose in saturated $Ca(OH)_2$ solutions, the two I_{corr} curves crossed, but the I_{corr} of rebar in concrete with methylcellulose, for most of the time, was lower than that of rebar in plain concrete. Hence, methylcellulose alone slightly improved the corrosion resistance of rebar in concrete.

The combined effect of methylcellulose and silica fume was investigated. Fig. 5 shows the curves of E_{corr} versus time for rebars in concrete with silica fume and in concrete with both methylcellulose and silica fume, in saturated $Ca(OH)_2$ solution in both cases. It shows that E_{corr} of the rebar in concrete with both methylcellulose and silica fume was slightly less negative than the E_{corr} of rebar in concrete with only silica fume. I_{corr} versus time for the rebars in concrete with silica fume and in concrete with both methylcellulose and silica fume shows the same trend as in the case of plain concrete compared to concrete with methylcellulose, i.e., the methylcellulose in concrete not only made E_{corr} slightly less negative (Fig. 5), but also made the I_{corr} slightly smaller.

Methylcellulose addition to concrete slightly improved the corrosion resistance of rebar in concrete in $Ca(OH)_2$ solutions, whether the concrete contained silica fume or not. However, this effect is not significant.

3.3. Effect of carbon fibers on corrosion

Tests were also conducted to determine the effects of adding carbon fibers to concrete on the corrosion behavior of rebars in concrete. Fig. 6 shows three plots of E_{corr} versus time in saturated $Ca(OH)_2$ solutions, corresponding to rebar in plain concrete, concrete with carbon fibers (using methylcellulose as the dispersant) and concrete with both carbon fibers (using methylcellulose as dispersant) and silica fume. Corrosion of rebars in all three compositions of concrete was minimal in the 44 week testing period, based on E_{corr} being less negative than −270 mV. As shown in Fig. 6, the addition of carbon fibers and methylcellulose (dispersant) did not alter E_{corr}. In fact, they are all in the range of

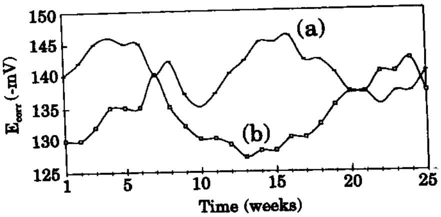


Fig. 5. Effect of methylcellulose and silica fume on the corrosion potential of rebar in concrete in saturated $Ca(OH)_2$ solutions. (a) Concrete with silica fume, (b) concrete with silica fume and methylcellulose.

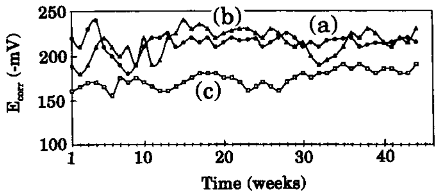


Fig. 6. Effect of carbon fibers on the corrosion potential of rebar in concrete in saturated $Ca(OH)_2$ solutions. (a) Plain concrete, (b) concrete with fibers and methylcellulose, (c) concrete with fibers, methylcellulose and silica fume.

−180 to −220 mV. When silica fume was added in addition to the carbon fibers, E_{corr} became less negative. In this case, the corrosion potentials are in the range of −150 to −170 mV. This means that, in saturated $Ca(OH)_2$ solutions, rebars in concrete containing both carbon fibers and silica fume corroded less than the other two concretes shown in Fig. 6; corrosion of rebars in both plain concrete and concrete with carbon fibers and methylcellulose were about the same. Fig. 7 shows I_{corr} versus time for rebars in the same three compositions of concrete in saturated $Ca(OH)_2$ solutions. The I_{corr} of rebar in plain concrete exceeded that of rebar in concrete containing carbon fibers with methylcellulose as dispersant after week 20; they were about the same before week 20. The I_{corr} of rebars in concrete with methylcellulose, silica fume and carbon fibers was the lowest among the three cases at all immersion times.

We also compared the E_{corr} of rebar in concrete having both carbon fibers (using methylcellulose as dispersant) and silica fume with concrete having only silica fume. The E_{corr} of rebar in concrete with only silica fume was about 20 mV less negative than that of the rebar in concrete with both carbon fibers and silica fume. The E_{corr} of rebar in both concretes were much less negative than −270 mV. This means that the corrosion resistance of rebars in both kinds of concrete was very good, with the rebar in concrete with only silica fume a little better than the rebar in concrete with both silica fume and carbon fibers. In both cases, I_{corr} increased gradually with the immersion time. The average I_{corr} of the rebars in

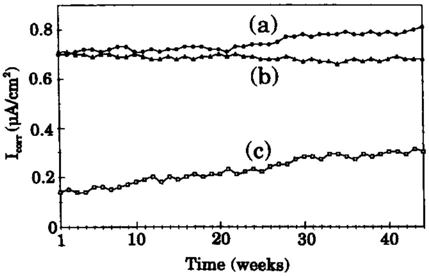


Fig. 7. Effect of carbon fibers on the corrosion current density of rebar in concrete in saturated $Ca(OH)_2$ solutions. (a) Plain concrete, (b) concrete with fibers and methylcellulose, (c) concrete with fibers, methylcellulose and silica fume.

concrete with carbon fibers (using methylcellulose as dispersant) was 0.05 μA/cm^2 higher than that of rebar in concrete with only silica fume. Compared to the 0.6 μA/cm^2 difference in I_{corr} in the case of plain concrete compared with concrete containing silica fume (Fig. 3), the difference here is small.

Tests were also conducted to determine the effect of carbon fibers on the corrosion behavior of rebars in the high chloride environment. Fig. 8 shows the E_{corr}, as determined in the 0.5 N NaCl solution, of rebars in plain concrete, concrete with carbon fibers (using methylcellulose as dispersant), concrete with both carbon fibers (using methylcellulose as dispersant) and silica fume, and concrete containing only silica fume. Comparing Fig. 8 with Fig. 6 shows that E_{corr} of rebars in all concretes became more negative in the NaCl solutions relative to the saturated $Ca(OH)_2$ solution. Secondly, in Fig. 8 the E_{corr} of rebars in plain concrete and concrete with carbon fibers is 140 mV more negative than −270 mV, and decreased continuously with increasing immersion time. This means that active corrosion was occurring on the surfaces of the rebars in these two kinds of concrete from the beginning of the test. On the other hand, although the E_{corr} of rebars in the concrete containing only silica fume and concrete with both carbon fibers and silcia fume were more negative in NaCl solutions than in saturated $Ca(OH)_2$ solutions, they survived for ≥ 25 and 10 weeks, respectively, without E_{corr} becoming more negative than −270 mV. After week 10, E_{corr} of rebars in concrete with both carbon fibers and silica fume became slightly more negative than −270 mV. This indicated that rebar in concrete with both carbon fibers and silica fume is less likely to corrode than rebars in plain concrete and concrete with carbon fibers only.

The I_{corr} values of rebar in the four compositions of concrete were higher when immersed in NaCl solutions than in saturated $Ca(OH)_2$ solutions. In NaCl solutions, the I_{corr} of rebars in concrete with carbon fibers (but no silica fume) was much higher than that in plain concrete. The difference of I_{corr} between rebars in plain concrete and concrete with carbon fibers in NaCl was much bigger than that in saturated $Ca(OH)_2$ solutions. The I_{corr} of rebars with carbon fibers and silica fume together was higher than that in concrete with only silica fume.

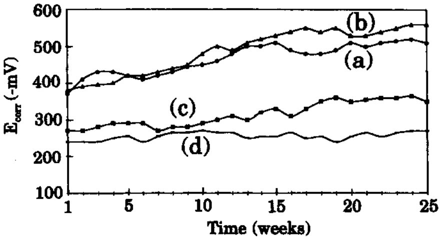


Fig. 8. Effect of carbon fibers, methylcellulose and silica fume on the corrosion potential of concrete in 0.5 N NaCl solution. (a) Plain concrete, (b) concrete with methylcellulose and fibers, (c) concrete with methylcellulose, silica fume and fibers, (d) concrete with silica fume.

3.4. Effect of latex on corrosion

Latex was added to different compositions of concrete to determine the effects of latex on the corrosion resistance of rebars. In contrast to the other concretes studied in this work, a water/cement ratio (water amount excluding that in latex) of 0.4 was used, because the latex used contained 50% water.

E_{corr} versus time for rebars in plain concrete (water/cement ration = 0.5), concrete with latex (water/cement ratio = 0.4), and concrete with both latex and carbon fibers (water/cement ratio = 0.4) are shown in Fig. 9. For the 10 weeks of testing in saturated $Ca(OH)_2$ solutions, E_{corr} of rebars in concrete with only latex and concrete with both latex and carbon fibers remained stable and were less negative than −270 mV. The E_{corr} of rebar in concrete with only latex was a little less negative than that of rebar in concrete with both latex and carbon fibers; both were less negative than that of rebar in plain concrete. The E_{corr} values of rebars in concretes with latex were more stable than those of rebars in plain concrete.

Fig. 10 shows I_{corr} versus time for rebars in plain concrete (water/cement ratio = 0.5), concrete with latex (water/cement ratio = 0.4) and concrete with both latex and carbon fibers (water/cement ratio = 0.4), all tested in saturated $Ca(OH)_2$ solutions. The I_{corr} values of rebars in concrete with latex and in concrete with latex and carbon fibers were more negative than that in plain concrete; I_{corr} was higher in concrete containing both latex and carbon fibers than concrete containing only latex.

In 0.5 N NaCl solutions, the E_{corr} of rebar in concrete with only latex was initially more negative than −270 mV during the first 6 weeks and then gradually became more negative (Fig. 11). The E_{corr} of rebars in concrete with both latex and carbon fibers was about −300 mV initially and became more negative with time. The E_{corr} values of rebars in both latex-containing concretes was less negative than that of rebar in plain concrete.

The I_{corr} of rebars in plain concrete and concrete with both latex and carbon fibers were about the same at about week 12; for most of the test, the I_{corr} of rebars in concrete with both latex and carbon fibers was lower than that of rebars in plain concrete. The I_{corr} of rebars in concrete with only latex was the most negative of the three.

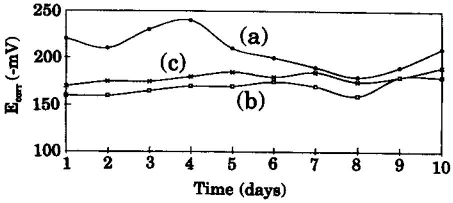


Fig. 9. Effect of latex on the corrosion potential of rebar in concrete in saturated $Ca(OH)_2$ solutions. The water/cement ratio is 0.5 for plain concrete and 0.4 for concretes with latex. (a) Plain concrete, (b) concrete with latex, (c) concrete with latex and fibers.

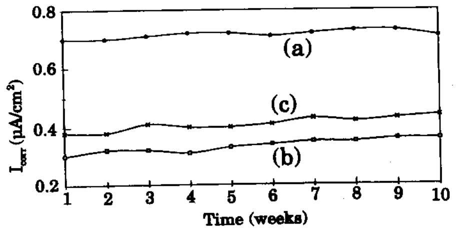


Fig. 10. Effect of latex on the corrosion current density of rebar in concrete in saturated $Ca(OH)_2$ solutions. The water/cement ratio is 0.5 for plain concrete and 0.4 for concretes with latex. (a) Plain concrete, (b) concrete with latex, (c) concrete with latex and fibers.

3.5. Comparison of the effects of latex and silica fume on corrosion

Fig. 12 shows E_{corr} versus time for rebars in concrete containing silica fume (water/cement ratio = 0.5) and in concrete with latex (water/cement ratio = 0.4), both in saturated $Ca(OH)_2$ solutions. The E_{corr} values of rebars in both kinds of concretes were less negative than −270 mV, and the E_{corr} of rebar in concrete with silica fume was less negative than that of rebar in concrete with latex. Fig. 13 shows I_{corr} versus time for rebars in the same concretes in saturated $Ca(OH)_2$ solutions. The I_{corr} of rebars in concrete with silica fume was lower than that of rebar in concrete with latex.

In 0.5 N NaCl solution, the E_{corr} of rebars in concrete with silica fume was less negative than −270 mV in the 25 week test; the E_{corr} of rebar in concrete containing latex was about −270 mV for the first 6 weeks, and then became more negative with time. The I_{corr} of rebar in concrete with silica fume was lower than that of rebar in concrete with latex.

The addition of silica fume was more effective than the addition of latex in improving the corrosion resistance of rebars in concrete, regardless of whether the environment was $Ca(OH)_2$ or NaCl.

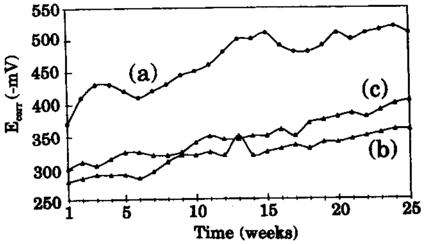


Fig. 11. Effect of latex on the corrosion potential of rebar in concrete in 0.5 N NaCl solution. The water/cement ratio is 0.5 for plain concrete and 0.4 for concretes with latex. (a) Plain concrete, (b) concrete with latex, (c) concrete with latex and fibers.

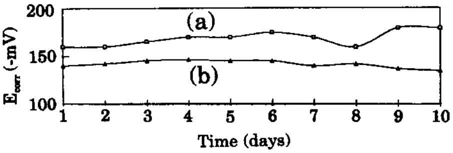


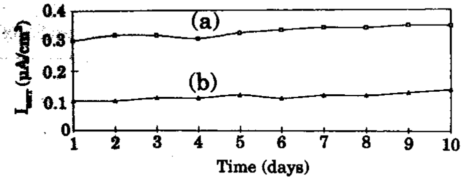
Fig. 12. Effects of latex and silica fume on the corrosion potential of rebar in concrete saturated $Ca(OH)_2$ solutions. (a) Concrete with latex (water/cement ratio = 0.4), (b) concrete with silica fume (water/cement ratio = 0.5).

3.6. Water absorptivity

The absorption of water with time is shown in Fig. 14. For all kinds of concrete studied, the rate of water absorption was higher in the first three days, and reached steady state at about day 5. The weight of water absorbed by day 5 is [illegible] in Table 3. Concretes with silica fume absorbed less water than plain [illegible] whether carbon fibers were present or not. Addition of fibers increased [illegible] absorption of water, regardless of whether silica fume was present. Silica fume [illegible] most effective in decreasing the absorption of water.

[illegible] electrical resistivity

[illegible] covering rebars in a reinforced concrete structure functions as an [illegible] the corrosion of rebars. A higher volume resistivity of the concrete [illegible] with a lower rate of electron transfer in the corrosion process, [illegible] lower corrosion rate. Table 4 lists the relative volume electrical [illegible] of the concretes tested in this work. Concrete with latex and that with [illegible] had the highest volume resistivity; the volume resistivity values were [illegible] that of the plain concrete. Concretes containing carbon fibers had the [illegible] resistivity. Concrete with carbon fibers together with silica fume [illegible] volume resistivity than concrete with carbon fibers together with latex.



[illegible] of latex and silica fume on the corrosion current density of rebar in concrete in [illegible] solutions. (a) Concrete with latex (water/cement ratio = 0.4), (b) concrete with [illegible] ratio = 0.5).

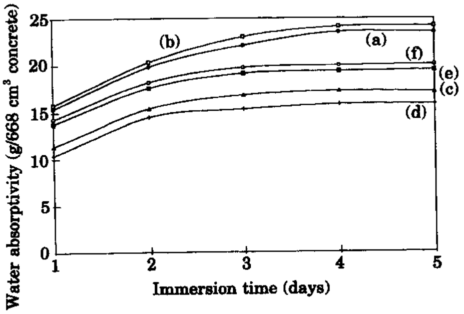


Fig. 14. Water absorptivity as a function of time for six concretes. (a) Plain concrete, (b) concrete with methylcellulose and fibers, (c) concrete with methylcellulose, silica fume and fibers, (d) concrete with silica fume, (e) concrete with latex, (f) concrete with latex and fibers.

4. Discussion

The effects of silica fume, methylcellulose, latex and carbon fibers on the corrosion resistance of steel reinforcing bars in concrete were studied and are summarized in Table 5. It was found that silica fume improved the corrosion resistance of rebars in concrete in both saturated $Ca(OH)_2$ and NaCl solutions more effectively than any of the other admixtures, although latex was effective. Methylcellulose improved slightly the corrosion resistance of rebar in concrete in $Ca(OH)_2$ solution. Carbon fibers decreased the corrosion resistance of rebars in concrete, mainly because they decreased the electrical resistivity of concrete. The negative effect of fibers could be compensated by either silica fume or latex. The origins of these effects are discussed below.

4.1. *Effect of silica fume*

Silica fume has a small mean particle size (0.1–0.2 μm). The fine particles result in a relatively dense structure and relatively more discontinuous pores in the concrete. When silica fume is mixed with cement in concrete, it combines with free lime during the hydration of cement in concrete to form a cementitious compound, namely calcium silicate hydrate (CSH). It also reduces the volume of

Table 3
Water absorptivity (weight of water absorbed, in gram) for different concretes (of 668 cm^3 volume)[a]

P	23.5 ± 0.1
M + f	24.2 ± 0.1
M + SF + f	17.1 ± 0.1
SF	15.8 ± 0.1
L	19.4 ± 0.1
L + f	20.0 ± 0.1

[a] Note: P = plain, M = methylcellulose, f = carbon fibers, SF = silica fume, L = latex.

Table 4
Relative volume electrical resistivity of concrete[a]

P	1.00
M + f	0.40 ± 0.05
M + f + SF	0.44 ± 0.05
SF	2.29 ± 0.05
L	2.25 ± 0.05
L + f	0.79 ± 0.05

[a] Note: P = plain, M = methylcellulose, f = carbon fibers, SF = silica fume, L = latex.

large pores and capillaries. The resultant cement matrix is more chemically resistant, has a denser microscopic pore structure, and yields high strength and relatively impermeable concrete. Fig. 14 and Table 3 show that concrete with silica fume has the lowest water absorption ability among all the concretes studied in this work. Water normally enters concrete by capillary action; the fewer and smaller the capillary pores are, the less water enters the concrete and the lower the rates of oxygen diffusion and carbonation. Due to the high alkalinity in concrete, there are very few H^+ ions to be consumed in the cathodic reaction. Thus, oxygen has to be reduced to sustain the cathodic reaction. Therefore, when the oxygen reduction rate is reduced, the corrosion rate is reduced. Carbonation of concrete will substantially reduce the alkalinity of the concrete environment, and eventually break the passivity of embedded steel. The corrosion cell circuit is completed by the diffusion of ions through moist concrete, which functions as an electrolyte. Increasing the electrical resistivity of the concrete slows down the ion transfer and therefore increases the corrosion resistance of rebar in concrete. In addition to a low water absorptivity, concrete with silica fume has more than double the resistivity of plain concrete (Table 4). Chloride ions tend to destroy the normal

Table 5
Effect of carbon fibers (f), methylcellulose (M), silica fume (SF) and latex (L) on the corrosion resistance of rebar in concrete

	In saturated $Ca(OH)_2$ solution		In 0.5 N NaCl solution	
	E_{corr}[b] (−mV, ±5)	I_{corr}[b] (μA/cm^2, ±0.03)	E_{corr}[b] (−mV, ±5)	I_{corr}[a] (μA/cm^2, ±0.03)
P	210	0.74	510	1.50
+M	220	0.73	–	–
+M + f	220	0.68	560	2.50
+M + SF	137	0.17	–	–
+M + f + SF	170	0.22	350	1.15
+SF	140	0.19	270	0.88
+L	180	0.36	360	1.05
+L + f	190	0.44	405	1.28

[a] Note: P = plain, M = methylcellulose, f = carbon fibers, SF = silica fume, L = latex.
[b] Value at 25 weeks of corrosion testing.

passivation state of rebar in concrete. Low air void content and low water absorptivity help keep choloride ions from going through the concrete and reaching the surface of the rebar. Concrete with silica fume, which has a denser microscopic pore structure, is relatively impermeable to chloride ions. Therefore, adding silica fume to concrete effectively reduces the corrosion rate in concrete in chloride solutions.

Carbon fibers decrease the corrosion resistance of rebar in concrete, especially in NaCl solutions, but the negative effect can be overcome by adding silica fume. The corrosion resistance of rebar in concrete with both silica fume and carbon fibers was better than that of the rebar in plain concrete in both kinds of test solutions. Silica fume can be the solution to the corrosion problem associated with using carbon fibers in steel reinforced concrete structures. The passivity effect of silica fume on the corrosion resistance of rebar in concrete was due to the decrease of the water absorptivity, as the electrical resistivity of carbon fiber concrete was essentially not affected by the addition of silica fume (Table 4). On the other hand, the negative effect of carbon fibers on the corrosion resistance of rebar in concrete was mainly due to the decrease of the electrical resistivity of the concrete, as the water absorptivity was only slightly affected by the fiber addition.

4.2. *Effect of methylcellulose*

The water absorptivity of concrete with carbon fibers using methylcellulose as dispersant was 2.8% higher than that of plain concrete (Table 3). The effect on the corrosion resistance of adding methylcellulose to concrete with silica fume seems to be larger than that in plain concrete, suggesting that methylcellulose tends to close small pores better than it does to bigger holes, since concrete with silica fume has smaller pores than plain concrete.

4.3. *Effect of latex*

Latex in concrete is known to fill tiny pores and flaws, increase the density, improve the cement-aggregate bonding and reduce the stress concentrations. With latex present, the water absorptivity was lower than that on plain concrete (Table 3). The corrosion resistance of rebar in concrete was improved by adding latex, due to the decrease in water absorptivity and increase in electrical resistivity (Table 4).

According to Table 4, the electrical resistivity of concrete with latex and carbon fibers was lower than that of plain concrete. Yet, when carbon fibers were used together with latex, the corrosion resistance of rebar was decreased, compared to rebar in plain concrete, both in $Ca(OH)_2$ and NaCl solutions, particularly in the latter. The low resistivity tends to degrade the corrosion resistance of rebar in concrete, but the addition of latex reduces the water absorptivity (Table 3) and thus improves the corrosion resistance.

4.4. Comparison of the effects of latex and silica fume

Table 5 shows that silica fume prevented the rebar corrosion more than latex did in both $Ca(OH)_2$ and NaCl solutions. This is because silica fume decreased the water absorptivity more than latex (Table 3). The electrical resistivity was similar for concrete with silica fume and concrete with latex (Table 4).

4.5. Effect of carbon fibers

Adding carbon fibers (using methylcellulose as dispersant) had little effect on the corrosion resistance of rebar in concrete in $Ca(OH)_2$ solution, but decreased the corrosion resistance of rebar in concrete in NaCl solution. Even though concrete with carbon fibers had lower electrical resistivity than concrete without the fibers, the effect of the fibers on the corrosion resistance is not significant in $Ca(OH)_2$ solution, where the passivity environment of concrete kept the corrosion of rebar from becoming active. Moreover, methylcellulose helped keep the water absorptivity of concrete with carbon fibers at the same level as that of plain concrete (Table 3), thus reducing the oxygen diffusion and carbonation. The effect helped maintain the corrosion resistance of rebar in concrete with carbon fibers in the same level as that of the rebar in plain concrete. When both concretes were immersed in NaCl solution, the passivation state of concrete was quickly destroyed by the chloride ions. When the passivation was destroyed and active corrosion began, the ion transfer rate became the dominant factor affecting the corrosion resistance of rebar in concrete, and the corrosion resistance of rebar in concrete with carbon fibers, which had a low electrical resistivity, became lower than that of the rebar in plain concrete.

This work shows that adding carbon fibers to concrete decreased the corrosion resistance of rebar in concrete, especially in aggressive environments such as a high chloride content solution. However, Figs. 6–8 show that silica fume overcomes the disadvantage of carbon fibers on the corrosion resistance of rebar in concrete. From Table 3 and Figs. 2 and 4, one can see that concrete with both silica fume and carbon fibers had much lower water absorptivity than plain concrete, and had about the same water absorptivity as concrete with only silica fume. Even though the electrical resistivity of concrete with both silica fume and carbon fibers was lower than that of plain concrete, silica fume in the concrete helped keep the corrosion reaction of rebar from accelerating, and thus made concrete with silica fume and carbon fibers a better protecting environment from corrosion of rebar than plain concrete.

The corrosion resistance of rebar in concrete with both silica fume and carbon fibers was still not as good as that of rebar in concrete with only silica fume. The large difference in volume resistivity between the two compositions of concrete is the main reason for the lower corrosion resistance of rebar in concrete with both silica fume and carbon fibers.

5. Conclusions

1. Silica fume improved the corrosion resistance of rebar in concrete in both saturated $Ca(OH)_2$ and NaCl solutions. The effectiveness of silica fume for improving the corrosion resistance of rebar in concrete is mainly due to the decrease of the water absorptivity, though it is partly due to the increase in electrical resistivity. Corrosion of rebar in silica fume concrete was inactive even in NaCl solution.
2. Methylcellulose slightly improved the corrosion resistance of rebar in concrete in $Ca(OH)_2$ solution, probably because methylcellulose filled some of the small pores.
3. Carbon fibers decreased the corrosion resistance of rebar in concrete, mainly due to the decrease in the volume electrical resistivity of concrete. However, the negative effect could be compensated by adding either silica fume or latex. Silica fume was more effective than latex for improving the corrosion resistance of carbon fiber concrete. This is mainly because silica fume reduced the water absorptivity. The small increases in electrical resistivity of carbon fiber concrete after adding either silica fume or latex contribute only slightly to the effect on corrosion. Corrosion of rebar in concrete with silica fume and carbon fibers was inactive in $Ca(OH)_2$ solution, but active in NaCl solution. However, the corrosion resistance in NaCl was better than rebar in plain concrete and similar to that of rebar in latex concrete without fibers.
4. Latex improved the corrosion resistance in concrete, because it decreased the water absorptivity and increased the electrical resistivity of the concrete. Latex was less effective than silica fume for improving the corrosion resistance, because latex addition decreased the water absorptivity less significantly than silica fume addition. Corrosion of rebar was inactive in latex concrete in $Ca(OH)_2$ solution, but active in latex concrete in NaCl solution.

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