Computers and Concrete, Vol. 9, No. 6 (2012) 457-467
DOI: http://dx.doi.org/10.12989/cac.2012.9.6.457

Effect of polyolefin fibers on the permeability of cement-based composites

Hui-Mi Hsu[1], Wei-Ting Lin[1,2] and An Cheng*[1]

[1]Dept. of Civil Engineering, National Ilan University, Ilan 26047, Taiwan
[2]Institute of Nuclear Energy Research, Atomic Energy Council, Executive Yuan,
1000 Wenhua Road, Longtan 32546, Taiwan

(Received September 15, 2010, Revised March 9, 2011, Accepted September 30, 2011)

Abstract. This study evaluates the permeability of cement-based composites, which are a mix of polyolefin fibers and silica fume. Test results indicate that permeability increases as the water/cementitious ratio increases. Silica fume in cement-based composites produced hydrated calcium silicate and filled the pores. However, permeability decreased as the addition of silica fume increased. Specimens containing polyolefin fibers also provided higher permeability resistance. The polyolefin fiber length did not have a significant effect on permeability. The decrease in the permeability is mainly due to the addition of silica fume and lower water/cementitious ratio. Addition of fibers marginally decreases the permeability. Incorporating polyolefin fiber and silica fume in composites achieved more significant decreases in permeability. The correlated test results reveal the interrelationship between them.

Keywords: polyolefin fiber; silica fume; diffusion coefficient; ponding depth; corrosion rate.

1. Introduction

Cement-based composites are some of the most widely used construction materials because of their low cost, high compressive strength, high durability, versatility and ease of handling. However, cement-based composites are intrinsically porous and may deteriorate or degrade because of exposure to a harsh environment or poor construction quality. The deterioration effect on concrete structures has led to the realization that the durability of cement-based composites should be improved by adding extra suitable constituent materials to normal concrete. An effective way to minimize the durability problem is to make the composites less permeable and the paste denser or to inhibit crack propagation and provide enough cover thickness for concrete structures (Sahmaran and Lee 2009). Using a low water/cementitious ratio or supplementary cementitious materials (SCMs) achieves paste densification, and adding fibers increases crack inhibition (Chang *et al.* 2001). According to a report by Al-amoudi *et al.* (2007), silica fume is the most effective blending material of the SCMs. Using silica fume in cement-based composites enhances durability due to its extremely fine spherical particles (Lin *et al.* 2009, Lin *et al.* 2008). The highly amorphous silica content densifies the microstructure and improves strength, permeability and other properties.

Polyolefin fibers are new commercial products using synthetic fibers. Polyolefin fibers have the advantage of allowing high composite volumes without fiber balling. Some literatures (Neeley and

---

* Corresponding author, Professor, E-mail: ancheng@niu.edu.tw

O'Neil 1996, Ramakrishnan 1996, Tagnit-Hamou *et al.* 2005) have reported that the toughness of polyolefin fiber reinforced concrete is similar to steel fiber reinforced concrete. A specimen containing polyolefin fibers can increase its flexural strength by up to 13% and reduce the growth or propagation of cracks by up to 70%, compared to control specimens. In addition, the impact resistance of polyolefin fiber reinforced composites is two times greater than that of steel fiber reinforced composites and fourteen times greater than that of the control specimens. While many studies have focused on the mechanical properties of polyolefin fiber-reinforced composites, only a few have addressed their permeability. Therefore, evaluating the permeability of polyolefin fiber-reinforced composites is an important task.

This study evaluates the effects of polyolefin fiber and silica fume additions on the permeability of cement-based composites using two fiber lengths (25 mm and 50 mm), two silica fume contents (0% and 5% by weight of cement), and two water/cementitious ratios (0.35 and 0.55) in the mix design. This research evaluates the permeability of cement-based composites using the penetration of chloride ions, absorption, resistivity and corrosion rate as measures.

2. Experimental

2.1 Materials

Table 1 represents the properties of polyolefin fiber and Fig. 1 shows their appearance. The aspect ratios (*l*/*d*) of the long fiber and the short fiber are 79 ($d = 0.6$ mm) and 66 ($d = 0.4$ mm), respectively. The specific gravity and specific surface area of the silica fume are 2.20 and 22500

Table 1 Properties of polyolefin fiber

Property		Results
Fiber type	Long	50 mm
	Short	25 mm
Specific gravity		0.90
Tensile strength		275 MPa
Young's modulus		2647 MPa
Elongation at break		15 %

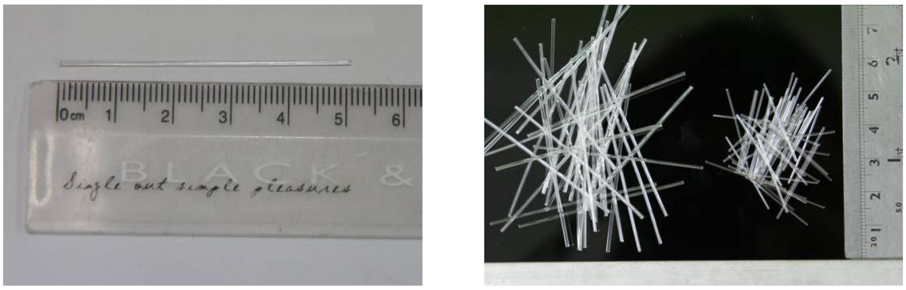

(a) Long polyolefin fiber (b) Long and short polyolefin fiber

Fig. 1 Appearance of polyolefin fiber

Table 2 Mix design (kg/m^3)

Mix no.	w/cm	Water	Cement	Silica fume	Fine aggregate	Coarse aggregate	Fiber	SP
A	0.35	189.4	558.0	0	908.0	700.0	0	5.6
APL	0.35	189.4	558.0	0	887.0	679.0	14.5	5.6
APS	0.35	189.4	558.0	0	887.0	679.0	14.5	5.6
AS5	0.35	189.4	530.1	27.9	908.0	700.0	0	5.6
AS5PL	0.35	189.4	530.1	27.9	887.0	679.0	14.5	5.6
AS5PS	0.35	189.4	530.1	27.9	887.0	679.0	14.5	5.6
B	0.55	217.0	395.0	0	908.0	780.0	0	0
BPL	0.55	217.0	395.0	0	887.0	759.0	14.5	0
BPS	0.55	217.0	395.0	0	887.0	759.0	14.5	0
BS5	0.55	217.0	375.2	19.8	908.0	780.0	0	0
BS5PL	0.55	217.0	375.2	19.8	887.0	759.0	14.5	0
BS5PS	0.55	217.0	355.5	19.8	887.0	759.0	14.5	0

m^2/kg, respectively. The silica fume is in powder form with an average of 91.5% silicon dioxide. Type I Portland cement conforming to ASTM C150-09 was used in all mixes. The maximum size of the coarse aggregates was 13 mm, and the fineness modulus of the fine aggregates was 2.87.

2.2 Mix proportions

Table 2 summarizes the mix proportions and two water/cementitious ratios (w/cm) of 0.35 and 0.55 were chosen. The fiber amount ($V_f = 1.6$ by volume of total cement-based composites) was selected for each mix. The coding used in column one should read: "A" and "B", to represent the w/cm of 0.35 and 0.55; "S5", to represent the dosages of silica fumes at 5%; and "PL" and "PS", to represent the long fiber and short fiber. The target slump was set to around 150 mm, achieved using a high-range water-reducing admixture.

2.3 Specimens

Specimens with a total of twelve different mixes were cast. For each mix, thirty $\phi 100 \times 200$ mm cylindrical specimens used for testing compressive strength, resistivity, absorption, ponding and corrosion were prepared and cured in saturated limewater until testing. Circular plates with a thickness of 50 mm were cut from the center of the cylindrical specimens and used in the rapid chloride penetration test (RCPT) and the rapid migration test (RMT).

2.4 Testing methods

Compressive strength tests in accordance with ASTM C39-09 were performed on specimens at 7, 14, 28, 56, 91 and 120 days. The resistivities of the specimens at 120 days were measured using a four-probe device and the test was carried out on saturated surface dry specimens. Absorption measurements were performed on those specimens following ASTM C642-06 after 120 days.

The ponding test was conducted in accordance with AASHTO T259-80. An acrylic ring was sealed around the perimeter of the specimen, creating a 20 mm high dam to retain the 3.0% NaCl solution. After a salt ponding of 90 days, the specimen was split longitudinally and sprayed with a 0.1 N silver nitrate. The penetration depth was determined by observing the color changes.

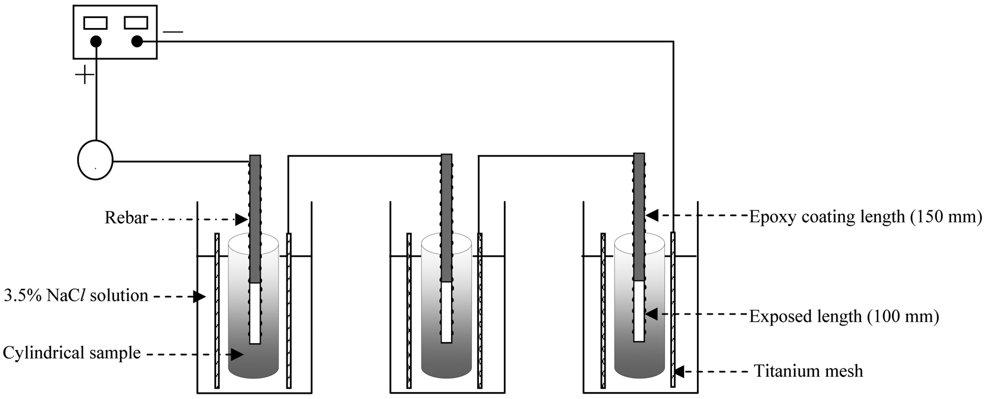
RCPT was performed on specimens after 120 days in accordance with ASTM C1202-10. RMT is a modified version of RCPT, in which the concentration of the chloride ion in the anode cell is obtained using an automatic potentiometric titrator. The chloride ions were transported in cement-based composites under an applied voltage. The concentration of the chloride ion was calculated as follows

$$Cl^- = 3.54NV/W \tag{1}$$

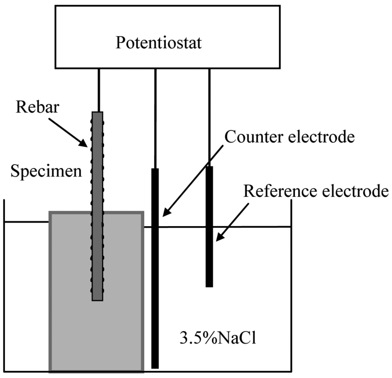
where,

N : concentration of $AgNO_3$
V : a detectable titration point
W : weight of specimen

For the corrosion test, a 12.7 mm-diameter rebar was embedded in the center of the cylindrical specimen. The exposed surface area of the rebar in 3.5% NaCl solution was approximately 40 cm^2



(a) Corrosion test set-up



(b) Corrosion electrochemical system set-up

Fig. 2 Schematic illustration of acceleration test as demonstrated in Fig. 2. The corrosion cell was connected so that the rebar acted as a working electrode, the saturated calomel electrode as a reference electrode, and the titanium mesh as a counter electrode. A current density of 0.5 mA/cm^2 was applied and the half-cell potentials and linear polarization resistance were measured using a Nichia NP-G100/ED potentiostat at 24-hour intervals. In addition, the corrosion rate of reinforcing steel (r) was computed from the corrosion current density using Faraday's equation $r = i_{corr}a/nF$, where i_{corr} represents current density, n represents the number of equivalents exchanged, a represents the atomic weight, and F represents the Faraday's constant (96500 coulombs/mol).

3. Results and discussion

3.1 Compressive strength

Figs. 3 and 4 show the results of the compressive strength of PFC specimens at 120 days, in which the compressive strength of the specimens with polyolefin fiber increases compared to the control specimens. The specimens with long-polyolefin and short-polyolefin fibers have 3%, 5%, 2% and 2% higher compressive strengths than the control specimens for *w*/cm of 0.55 and 0.35. The effect of composites with short fibers is similar to that of composites with long fibers. In addition, cracks occur in the microstructure of composites and fibers reduce crack formation and development under axial loads.

On the other hand, combining short-polyolefin fibers and silica fume in the composites creates a higher compressive strength than for the other specimens. The specimens with short-polyolefin fiber and 5% silica fume have 17% and 16% higher compressive strengths than the control specimens for *w*/cm of 0.55 and 0.35, respectively. This indicates that adding silica fume to the composites achieves interface densification. From the above-mentioned results, polyolefin fiber does not significantly affect compressive strength compared with silica fume.

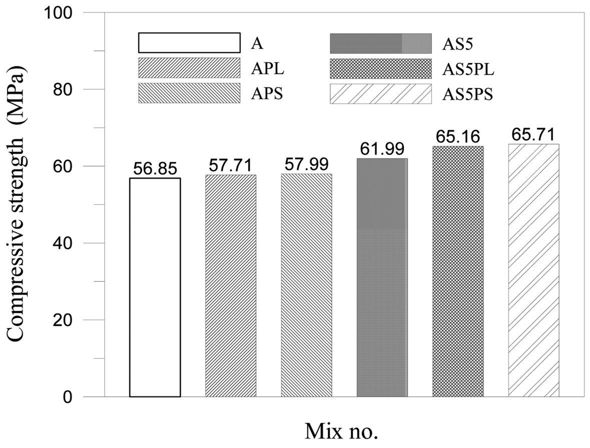


Fig. 3 Compressive strength histogram (*w*/cm=0.35, age=120 days)

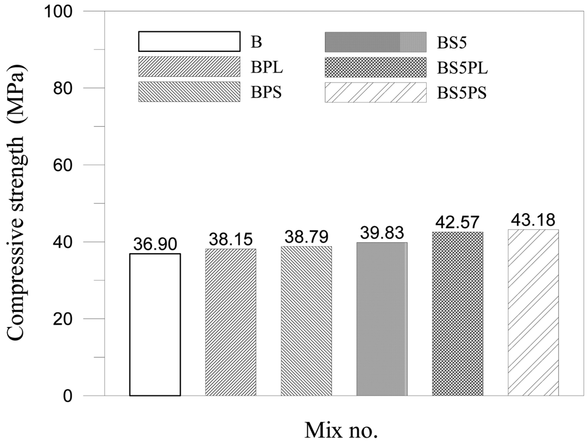


Fig. 4 Compressive strength histogram (*w*/cm=0.55, age=120 days)

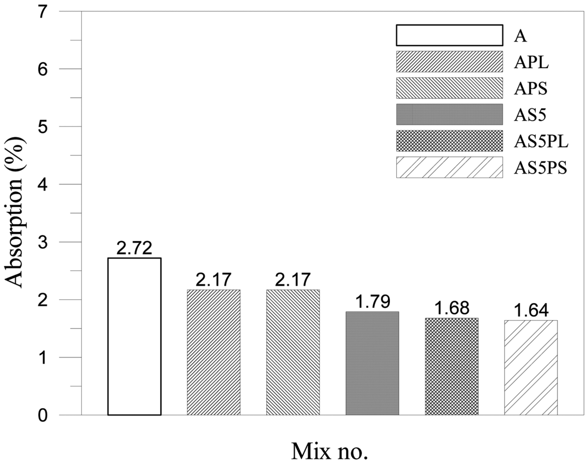


Fig. 5 Absorption histogram (*w*/cm=0.35)

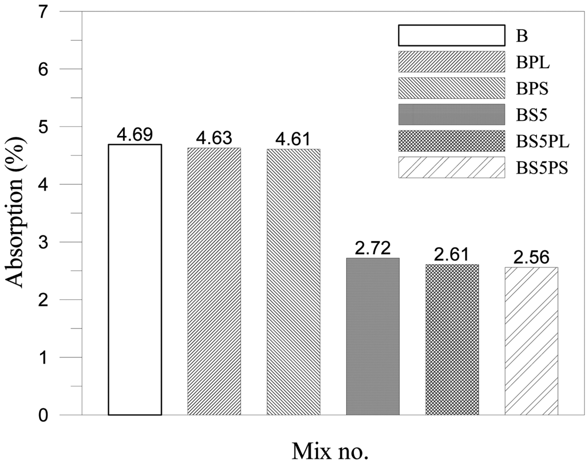


Fig. 6 Absorption histogram (*w*/cm=0.55)

3.2 Absorption

Figs. 5 and 6 show specimen absorption with various polyolefin fibers and silica fume at the *w*/cm of 0.35 and 0.55. At the lower *w*/cm, the absorption of the APS and APL specimens decreases by about 20% compared to the control specimens. At the higher *w*/cm, the absorption of BPS and BPL specimens is similar to that of the control specimens. This indicates that higher compressive strength correlates with less capillary absorption. The specimens with a lower *w*/cm have a more significantly decreased absorption that those at higher *w*/cm.

The absorption of AS5PS, AS5PL, BS5PS and BS5PL specimens decreases by about 45%, 44%, 40% and 38% compared to the control specimens, respectively. The presence of silica fumes obviously reduces absorption because silica fume helps to reduce the sizes of the capillary pores. Adding polyolefin fiber to the composites containing silica fumes helps to reduce absorption. Adding polyolefin fiber further decreases the absorption of silica fume composites by 4~6% and 6~8% at the *w*/cm of 0.55 and 0.35, respectively. The decrease in the absorption is mainly due to the addition of silica fume. Addition of fibers marginally decreases the absorption.

3.3 Chloride ion penetration test

Figs. 7 and 8 illustrate the RCPT results with a potential of 30V for both *w*/cm. The results illustrate that the composites that contain both silica fume and fiber have lower chloride ion permeability than the control composites. The total charge-passed of the APS and APL specimen decreases by up to 8% and 7%, respectively, compared to the control specimens. In addition, the decreasing amount of total charge-passed at a *w*/cm of 0.55 shows the same trend.

In silica fume composites, the six-hour total charge-passed of the short and long fiber shows an additional decrease of about 24%, 14%, 15% and 12% at the *w*/cm of 0.35 and 0.55. The decreasing tendency of the short fiber is more apparent than that of the long fiber. This suggests that fibers dispersed uniformly can cause changes in the matrix and reduced shrinkage cracks may lead to improved permeability.

Figs. 9 and 10 illustrate the chloride diffusion coefficients of both *w*/cm. The chloride diffusion

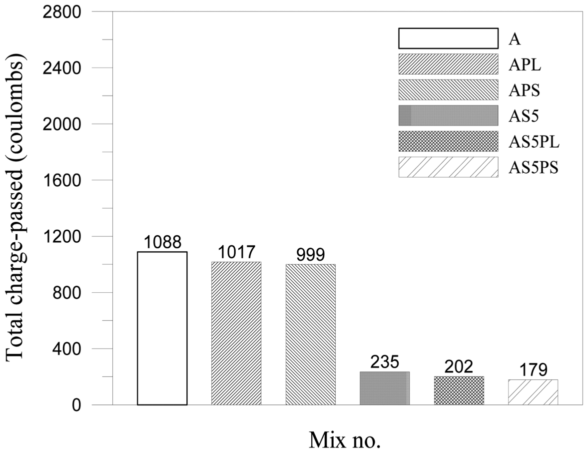


Fig. 7 Total charge-passed histogram (*w*/cm=0.35)

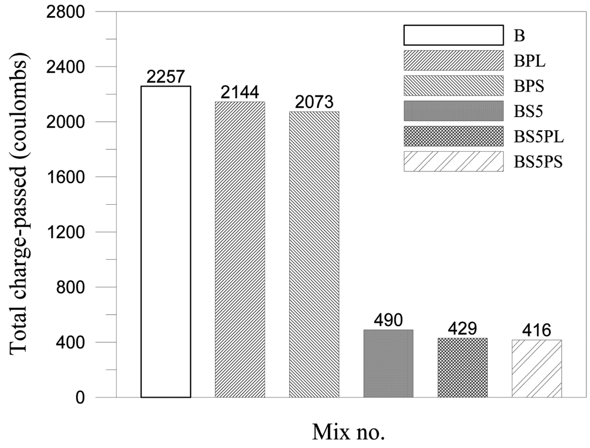


Fig. 8 Total charge-passed histogram (*w*/cm=0.55)

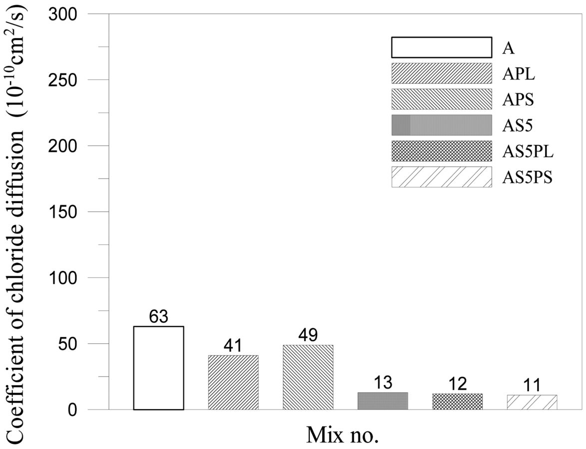


Fig. 9 Coefficient of chloride diffusion histogram (*w*/cm = 0.35)

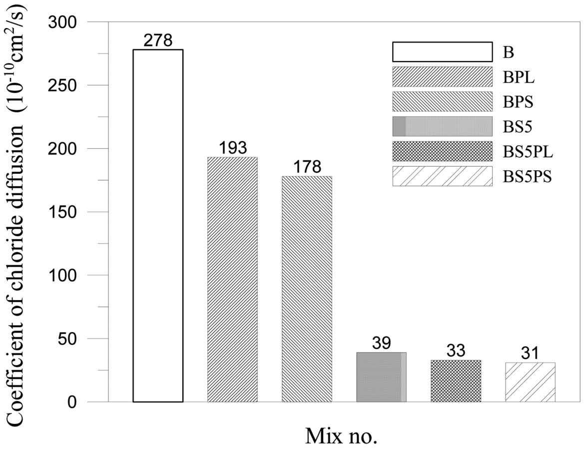


Fig. 10 Coefficient of chloride diffusion histogram (*w*/cm = 0.55)

coefficients on the APS and APL specimens are 49 and 41×10^{-10} cm^2/s, respectively, and the decrease is up to 22% and 35%, respectively, compared to the control specimens. At the *w*/cm of 0.55, the BPS and BPL specimens show a decrease in the chloride diffusion coefficient of about 36% and 31%, respectively, compared to the control specimens. Results of this study are consistent with the findings in previous research (Zhou *et al.* 2010) by assuming that use of polyolefin fiber as a random heterogeneous composite in cement-based composites can decrease the chloride diffusion coefficient. In addition, use of polyolefin fiber decreased pore interconnectivity because the fibers could bridge cracks in the composites (Lin *et al.* 2009).

The beneficial effect of silica fume for each *w*/cm is more profound when the polyolefin fiber is added. When adding the short or long polyolefin fiber to the silica fume composites, the chloride diffusion coefficient in the mix decreases less. Similarly, the chloride resistance is more effective in specimens containing silica fume than in those containing polyolefin fiber.

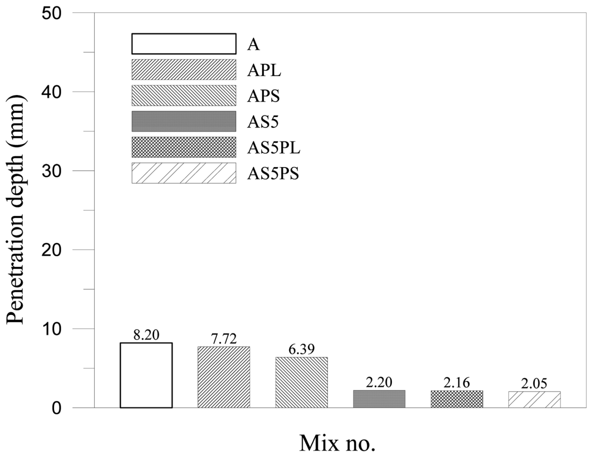


Fig. 11 Penetration depth histogram (*w*/cm=0.35)

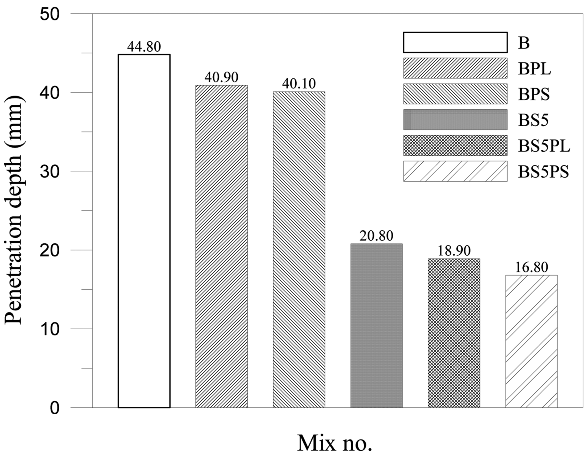


Fig. 12 Penetration depth histogram (*w*/cm=0.55)

3.4 Ponding test

Figs. 11 and 12 illustrate that the penetration depth results agree with the results from the diffusion coefficient. Cement-based composites condense more with increasing silica fume content, resulting in a greatly decreased penetration depth. The composites containing short and long fibers at the *w*/cm of 0.35 decrease in penetration depth by about 22% and 6%, respectively, compared to the control specimens. The BPS and BPL specimens have a lower penetration depth than the control specimens by up to 9~10%. The composites incorporating polyolefin fiber and silica fume have the lowest penetration depth. Using silica fume and polyolefin fiber effectively can improve the chloride resistance of composites covers. Use of silica fume or lower *w*/cm ratio in the cement-based composites effectively decreases the penetration depth.

3.5 Corrosion test

According to ASTM C876-09, when OCP ranges from 0 to -127 mV (SCE), the probability that the reinforcing may corrode is less than 10%. If the potential ranges from -127 mV to -276 mV (SCE), the corrosion probability is uncertain. The corrosion probability may be higher than 90% when OCP is higher than -276 mV (SCE). Figs. 13 and 14 show the OPC indicating that the control specimens (specimens A and B) significantly increase their exposure time to severe corrosion. The result shows that within 4 days of the accelerated corrosion, the open circuit potential of the rebar drops below -276 mV (SCE) at a lower *w*/cm ratio. At a higher *w*/cm ratio, the open circuit potential of rebar drops rapidly below -276 mV (SCE) after 1 day immersion. When the specimens immerse up to 7 days at a lower *w*/cm ratio, only the open circuit potential of AS5 and AS5PS specimens are higher than -450 mV (SCE). The results indicate that use of silica fume or lower *w*/cm ratio effectively decreases the rebar corrosion. The silica fume replacement for cement refined the pore structure and reduced the corrosion probability of reinforcing steel, consistent with the comparative results of penetration depth and absorption. In addition, including silica fume in the polyolefin fiber composites reduced the corrosion probability significantly for the two mixes. Composites containing short polyolefin fibers had lower OCP than those containing long polyolefin fibers.

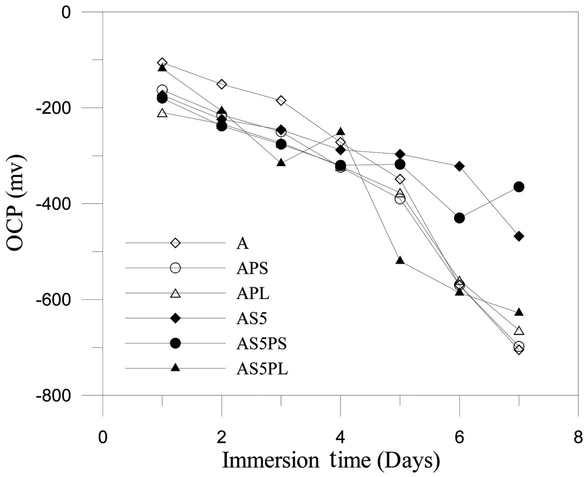


Fig. 13 Relationship between OCP and immersion time (*w*/cm=0.35)

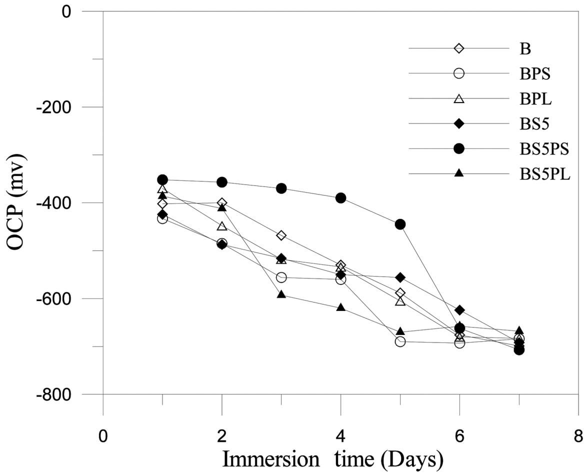


Fig. 14 Relationship between OCP and immersion time (*w*/cm=0.55)

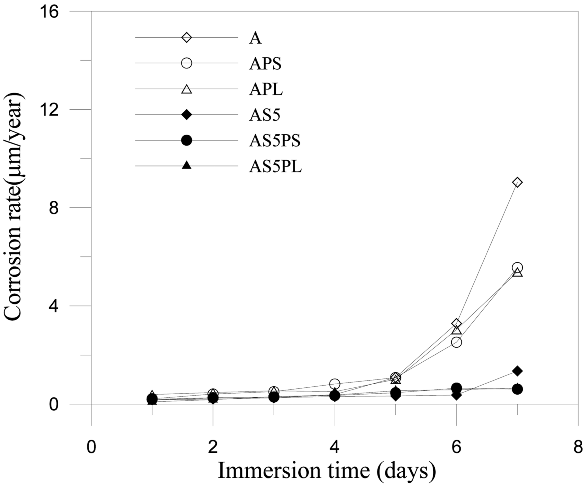


Fig. 15 Relationship between corrosion rate and immersion time (*w*/cm = 0.35)

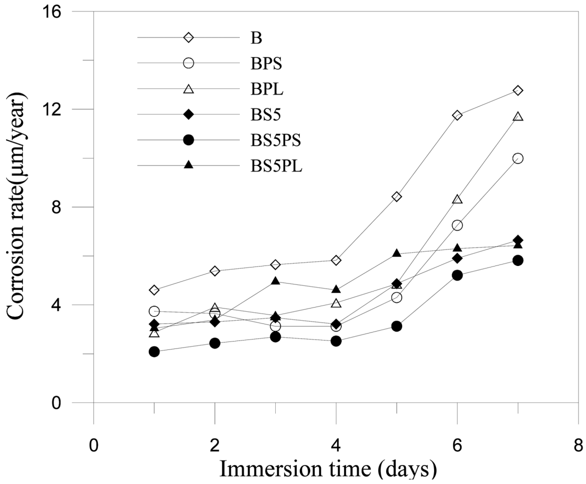


Fig. 16 Relationship between corrosion rate and immersion time (*w*/cm = 0.55)

Figs. 15 and 16 show the corrosion rates of the specimens. The corrosion rate decreased significantly as the silica fume or polyolefin fiber increased. Compared with the control specimens, the corrosion rates of the specimens with 5% silica fumes at *w*/cm ratios of 0.35 and 0.55 decreased by about 85% and 48%, respectively. The corrosion rates in specimens AS5PS, AS5PL, BS5PS and BS5PL also significantly decreased by up to 93%, 93%, 54% and 50%, respectively, after adding polyolefin fiber. Silica fumes in the mixes likely transformed quickly into dense calcium silicate hydrate, filling up the interstitial spaces between the matrix and aggregates and forming a dense, strong and relatively impermeable composite. Adding polyolefin fiber to composites has inhibiting effects on crack initiation and propagation, which may cause improvements (reductions) in permeability. The corrosion products result from rebar corrosion, increasing the volume at the rebar/composite interface by a factor of two to seven. Introducing fibers attenuated the internal stress in composites resulting from rebar corrosion, which evidently reduced the corrosion rate by inhibiting corrosion product expansion.

3.6 Resistivity measurement

Figs. 17 and 18 show specimen resistivity with various polyolefin fiber and silica fume at the *w*/cm of 0.35 and 0.55, respectively. The resistivity increases as the amount of silica fume and fiber added increases. Composites containing short and long fibers exhibit resistivity between 7~8 and 4~5 KΩ-cm at the *w*/cm of 0.35 and 0.55, respectively. The resistivity of AS5PS, AS5PL, BS5PS and BS5PL specimens, increases by about 8%, 7%, 21% and 15%, respectively, compared to the silica fume specimens. The trend in resistivity is evident at the higher *w*/cm and combining fiber and silica fume produced the highest resistivity in the composites. Such a combination is more likely to improve composite resistivity. The absorption is correlated with the penetration depth in

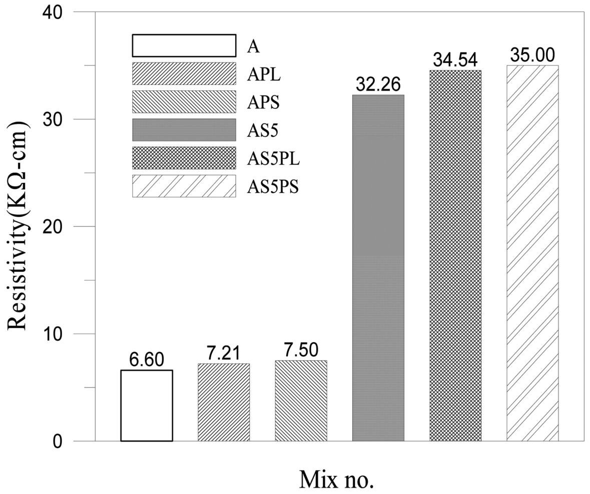


Fig. 17 Resistivity histogram (*w*/cm=0.35)

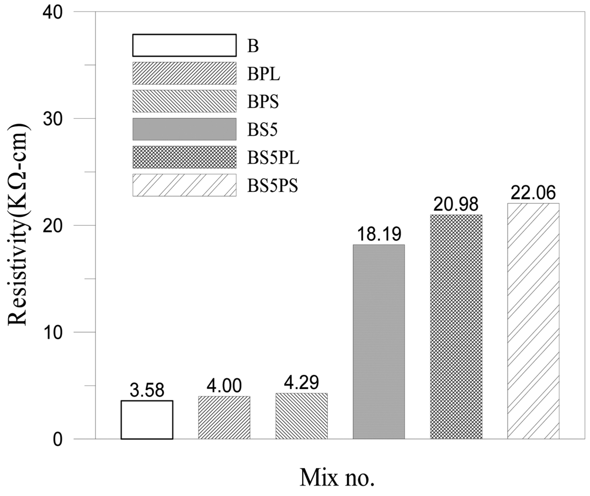


Fig. 18 Resistivity histogram (*w*/cm=0.55)

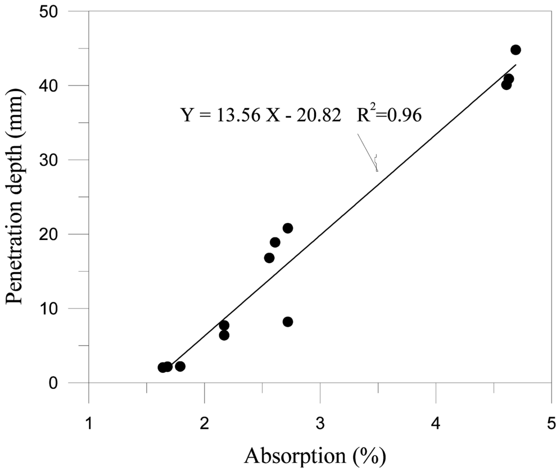


Fig. 19 Relationship between penetration depth and absorption

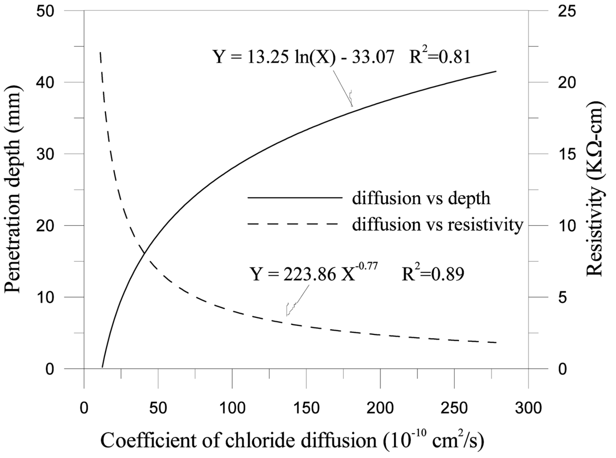


Fig. 20 Relationship among penetration depth, coefficient of chloride diffusion and resistivity

the ponding test in Fig. 19, indicating that penetration depth is positively correlated with absorption.

Fig. 20 also shows good regression curves of penetration depth and resistivity vs. the chloride diffusion coefficient for specimens. Results clearly show that an increased chloride diffusion coefficient of cement-based composites leads to a decreased resistivity and increased penetration depth. The pore system modified by polyolefin fiber or silica fume inclusion strongly influences water and ion penetration through capillary pores from the cement-based composite surface.

4. Conclusions

1. In this study, including 1.6% volume fraction of polyolefin fiber in composites improves absorption (-2 ~ -20%), resistivity (14~20%), the diffusion coefficient (-35 ~ -36%), penetration depth (-10 ~ -22%) and the corrosion rate (-8 ~ -40%) because of decreased capillary porosity.
2. Including silica fume in polyolefin fiber-reinforced composites significantly reduces permeability. This is because silica fume in fiber composites narrows the size of large capillary pores, densifying the pore structure, and enhancing the bonding strength between fiber and paste.
3. The polyolefin fiber length does not significantly affect permeability.
4. Composites combined with polyolefin fibers and silica fumes exhibit better compressive strength, absorption, diffusion coefficient, penetration depth, resistivity, and corrosion rate.
5. Adding polyolefin fibers to composites greatly influences the corrosion rate. Polyolefin fibers may have inhibiting effects on crack initiation and propagation, which may cause improvements (reductions) in permeability.
6. By regression analysis, this study found a good correlation between penetration depth and absorption, the diffusion coefficient and penetration depth, the diffusion coefficient and resistivity.

References

Al-Amoudi, O.S.B., Maslehuddin, M., Shameem, M. and Ibrahim, M. (2007), “Shrinkage of plain and silica fume cement concrete under hot weather”, *Cement Concrete Comp.*, **29**(9), 690-699.

Chang, P.K., Peng, Y.N. and Hwang, C.L. (2001), “A design consideration for durability of high-performance concrete”, *Cement Concrete Comp.*, **23**(4-5), 375-380.

Lin, W.T., Huang, R., Chang, J.J. and Lee, C.L. (2009), “Effect of fiber on the permeability of cement-based composites containing silica fume”, *J. Chin. Inst. Eng.*, **32**(4), 531-541.

Lin, W.T., Huang, R., Lee, C.L. and Hsu, H.M. (2008), “Effect of steel fiber on the mechanical properties of cement-based composites containing silica fume”, *J. Mar. Sci. Technol.*, **16**(3), 214-221.

Neeley, B.D. and O'Neil, E.F. (1996), “Polyolefin fiber reinforced concrete”, *Proceedings of the Materials Engineering Conference: Materials for the New Millennium*, **1**, 113-122.

Ramakrishnan, V. (1996), “Performance characteristics of polyolefin fiber reinforced concrete”, *Proceedings of the Materials Engineering Conference: Materials for the New Millennium*, **1**, 93-102.

Sahmaran, M. and Li, V.C. (2009), “Influence of microcracking on water absorption and sorptivity of ECC”, *Mater. Struct.*, **42**(5), 593-603.

Tagnit-Hamou, A., Vanhove, Y. and Petrov, N. (2005), “Microstructural analysis of the bond mechanism between polyolefin fibers and cement pastes”, *Cement Concrete Res.*, **35**(2), 364-370.

Zhou, C.S. and Li, K.F. (2010), “Numerical and statistical analysis of permeability of concrete as a random heterogeneous composite’, *Comput. Concrete,* **7**(5), 469-482.

CC