EFFECT OF POLYOLEFIN FIBER ON THE ENGINEERED PROPERTIES OF CEMENT-BASED COMPOSITES CONTAINING SILICA FUME

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ABSTRACT: This study is aimed to evaluate the engineered properties of cement-based composites which comprise polyolefin fibers and silica fume in the mixes. Material variables include water-cementitious ratio, dosage of silica fume, polyolefin fiber length and dosage. Compressive strength, splitting tensile strength, direct tensile strength, resistivity, rapid chloride penetration test and microscopic observation were conducted. Test results indicate that the specimens containing silica fume have higher compressive strength than fiber and control specimens. The specimens with polyolefin fiber and silica fume have much higher tensile strength and ductility than the control and silica fume specimens. The specimens containing silica fume and polyolefin fiber demonstrate better resistance in chloride penetration than polyolefin fiber composites or silica fume composites. For a given volume fraction, short polyolefin fiber performs better than long polyolefin fiber in improving concrete properties. The specimen containing silica fume significantly increases in resistivity and decreases in total charge passed. SEM microscopy illustrates that the polyolefin fiber acts as the crack arresters in concrete, which can inhibit internal crack propagation.

Keywords*: Polyolefin Fiber, Direct Tensile Strength, SEM Observation, Resistivity*

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. However, micro or medium cracks always exist in cement-based composites no matter how much efforts have been done. Cracks may lead water, chloride-ion, and carbon dioxide into concrete and finally induce steel corrosion, and cracks may rapidly cause the durability problem of concrete structure. To make the composite less permeable and the paste denser or to inhibit crack propagation should be an effective way to minimize the durability problem [1]. The densification of paste can be achieved by using low water cementitious ratio or supplementary cementitious materials (SCMs) and the crack inhibition can be increased by adding fibers [2, 3]. If the cement-based composite is less permeable and well protected throughout its designed service life, the detrimental substances such as chloride ion, sulfate ion and acid cannot easily penetrate into the composites, and thus the durability of structure is maintained.

According to a report by Al-amoudi et al. [4], 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 [3, 5]. 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 [6-8] 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. Improvement in performances of cement-based composites becomes an important topic for construction materials sector and attracts many researchers focus on this subject. This study evaluates the engineered properties of cement-based composites which comprise polyolefin fibers and silica fume in the mixes. The results of mechanical properties and permeability for cement-based composites are then compared and contrasted.

2. EXPERIMENTAL

2.1 MATERIALS

In this study, 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) are used in the mix design. Table 1 represents the properties of polyolefin fiber and Figure 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 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 PROPERTIES

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; “0” and “5”, to represent the dosages of silica fumes at 0% and 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. The embedded #6 rebar was made of medium carbon steel following the specification of ASTM A615-09.

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 %

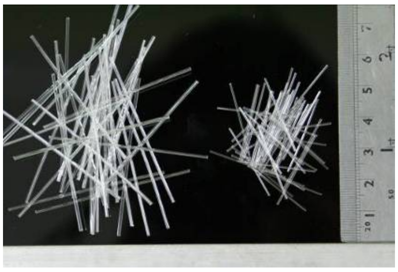


Fig. 1 Appearance of polyolefin fiber

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

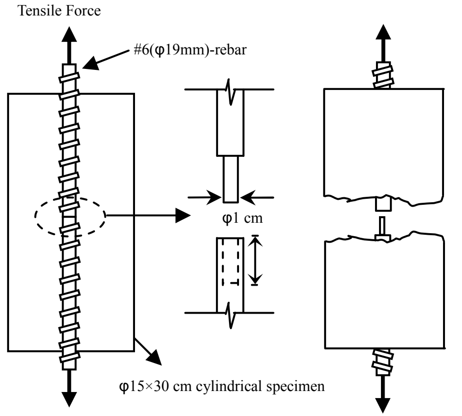
2.3 SPECIMENS

Specimens with a total of twelve different mixes were cast. For each mix, twenty-one ψ100x200 mm cylindrical specimens used for testing compressive strength, splitting tensile strength and resistivity were prepared and cured in saturated limewater until testing. Six ψ150x300 mm cylindrical specimens were cast for testing splitting tensile strength and direct tensile strength test. 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).

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. Splitting tensile strength tests were performed in accordance with ASTM C496-04. The resistivities of the specimens were measured using a four-probe device and the tests were carried out on saturated surface dry specimens. RCPT of those specimens was measured following ASTM C1202-10. In addition, the microstructure of the hardened concrete specimen was assessed by SEM according to ASTM C856-04.

The direct tensile strength test that was designed is a relatively new test, which was modified from those in previous studies [9]. Figure 2 shows the design of the direct tensile strength test. Two rebars (#6) were placed along the longitudinal axis of the ψ150×300 cylindrical specimen. A hole with a diameter of 10 mm and a length of 25 mm was drilled in the center of one rebar while the other rebar was machined into a ψ10 mm cylindrical plug at one end. The outside rebars of the tensile specimen were attached to a load, which was applied at 50 kgf/min until failure occurred. Excluding compressive strength tests, the specimens of other tests kept in a curing room until at the age of 120 days for testing.



(a) specimen (b) failure model

Fig. 2 Schematic description of direct tensile testing

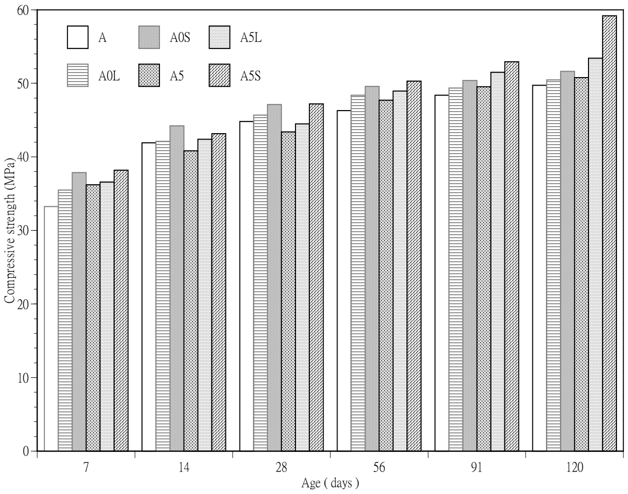


Fig. 3 Compressive strength histogram (w/cm=0.35)

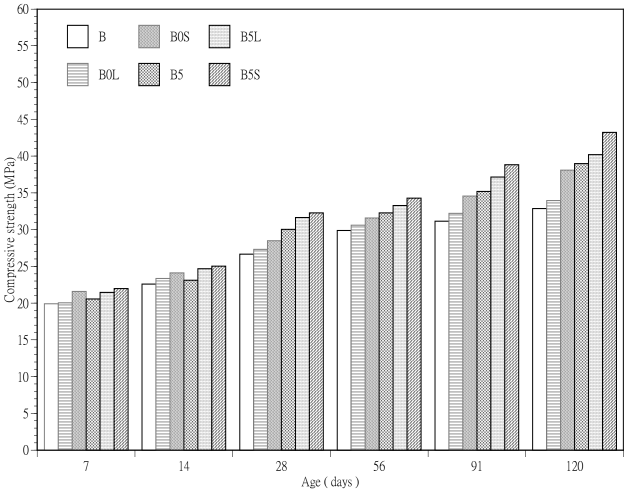


Fig. 4 Compressive strength histogram (w/cm=0.55)

3. RESULTS AND DISCUSSION

3.1 Compressive strength

The compressive strength developments of polyolefin fiber cement-based composites (PFCC) specimens are shown in Figures 3 and 4. The compressive strength increases with the ages. The compressive strength of the specimens with polyolefin fibers increases and those with silica fumes increases compared to the control specimens. The specimens with long-polyolefin and short-polyolefin fibers have 2 %, 4 %, 3 % and 16 % higher compressive strengths than the control specimens at 120 days for w/cm of 0.35 and 0.55. At the lower w/cm, the effect of composites with short fibers is similar to that of composites with long fibers. At the higher w/cm, the effect of composites with short fibers is marginally higher than that of composites with long fibers. It may be due to that polyolefin fibers reduce crack formation and development under axial load.

Combining short-polyolefin fibers and silica fume in PFCC creates a higher compressive strength than for the other specimens. The A5S, A5L, B5S and B5L specimens have 19 %, 7 %, 32 % and 22 % higher compressive strengths than the control specimens at 120 days, respectively. The presence of silica fume would help dispersing fibers in the mix and strengthen the bond between the fiber and matrix. Obviously, the filling effect and pozzolanic activity of silica fume improve strength and strengthen the pore-structure of PFCC, which is consistent to the previous findings [3].

3.2 SPLITTING TENSILE STRENGTH

The splitting tensile strengths of PFCC are plotted in Figures 5 and 6. The splitting tensile strength of the specimens increases with polyolefin fibers addition compared to the control specimens. The A0S, A0L, B0S and B0L specimens have 20 %, 13 %, 34 % and 15 % higher splitting tensile strengths than the control specimens at 120 days, respectively. It indicates that short fiber performs better than long polyolefin fiber in improving tensile strength. In addition, addition of silica fumes in cement-based composites marginally increases the tensile strength compared to specimens containing polyolefin fibers. The inclusion of polyolefin fibers in the composites plays an important role on splitting tensile strength. The fibers increase the ability of crack arresting greatly.

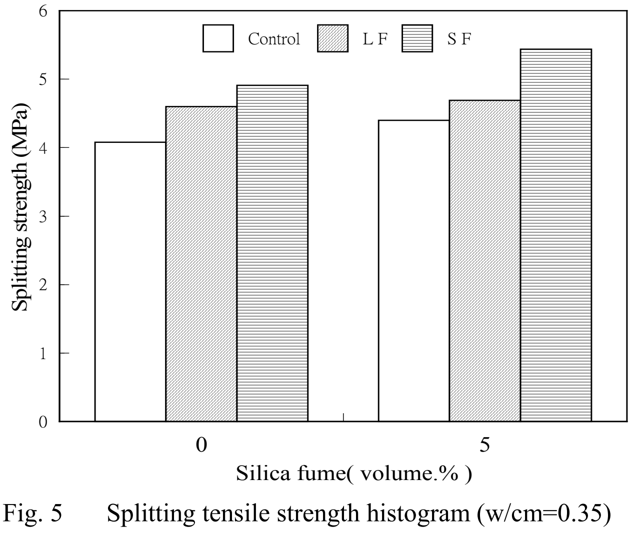


Fig. 5 Splitting tensile strength histogram (w/cm=0.35)

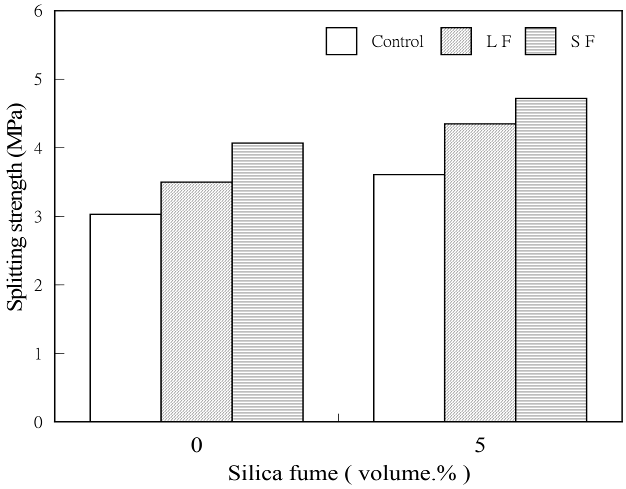


Fig. 6 Splitting tensile strength histogram (w/cm=0.55)

Combining polyolefin fibers and silica fume in PFCC also creates a higher splitting tensile strength than for the other specimens. The specimens with short fibers and long fibers have 33 %, 15 %, 56% and 44 % higher splitting tensile strengths than the control specimens with w/cm ratios of 0.35 and 0.55, respectively. The effect is more evident in specimens containing short-polyolefin fiber or specimens at a higher w/cm ratio. It may results from refined pore structure achieved by increasing dense hydrated calcium silicate in the PFCC. Silica fumes also improve the bond between fiber and matrix with extra dense calcium-silicate-hydrate gel obtained from silica fume addition, especially at higher w/cm ratio.

3.3 DIRECT TENSILE STRENGTH

The curves between loading and strain are shown in Figures 7 and 8. It indicates that the specimens containing polyolefin fibers or silica fumes have higher direct tensile strength. The area under tensile loading-strain curves of PFCC represents the strain capacity and the toughness. At the higher w/cm, the strain capacity of A0L, A0S, A5, A5L and A5S specimens increases by about 118 %, 142 %, 202 %, 221 % and 260% compared to the control specimens. At the lower w/cm, the strain capacity of B0L, B0S, B5, B5L and B5S specimens increases by about 245 %, 295 %, 185 %, 433 % and 493% compared to the control specimens. The composites with high strain capacity and toughness reflect higher ability to arrest cracks. In summary, fiber content affects the ability of crack arresting and silica fume affect the interfacial bonding. Combination silica fume with polyolefin fiber, the interfacial structure is improved effectively and the advantage of PFCC would be expanded. Two aligned rebars are embedded in the cylindrical specimen to transmit the uniaxial force to concrete. The fracture is located in the middle portion as illustrated in Figure 9.

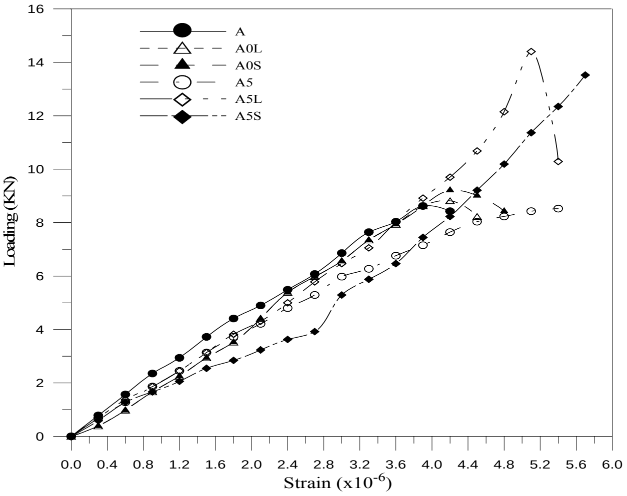


Fig. 7 Relationship between loading and strain curves (w/cm=0.35)

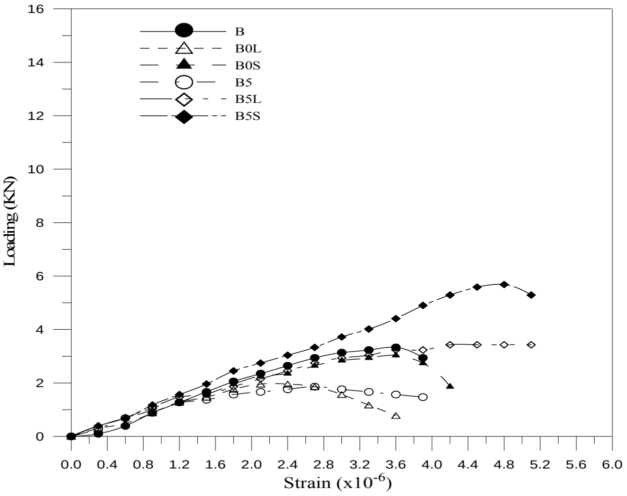


Fig. 8 Relationship between loading and strain curves (w/cm=0.55)

3.4 RESISTIVITY, RCPT AND SEM OBSERVATION

Resistivity and RCPT is a convenient test to evaluate the permeability of PFCC. The resistivities and RCPT of PFCC are listed in Table 3. The resistivities increase with the polyolefin fibers or silica fumes increase. The resistivity of silica fume composites is higher than that of polyolefin fiber composites. Polyolefin fiber specimens containing silica fume have highest resistivities. The A5S, A5L, B5S and B5L have a increase resistivity of up to 104 %, 94 %, 131% and 107 %, respectively. The high pozzolanic reactivity and pore filling effects of silica fume may lead to increase resistivity of composites as highlighted by compressive strength.

(a) control specimen (b) PFCC specimen

Fig. 9 Failure model of specimens

Table 3 Results of resistivity and total charge passed

Mix no.	Resistivity (kΩ-cm)	Total charge passed (coulombs)
A	14.35	5611
A0L	16.75	5148
A0S	18.35	4505
A5	25.50	2077
A5L	27.88	1492
A5S	29.30	1210
B	6.98	9260
B0L	8.13	8766
B0S	9.88	8578
B5	12.18	4627
B5L	14.43	2733
B5S	16.15	2165

The total charge passed decreases with increasing silica fumes and polyolefin fibers addition. The inclusion of polyolefin fibers and silica fumes in composites has lowest value. At the higher w/cm, the total charge passed of B5S and B5L specimens shows a decrease ranged from 9260 to 2165 and 2733 coulombs compared to the control specimens. At the lower w/cm, the total charge passed of A5S and A5L specimens shows a decrease ranged from 5611 to 1210 and 1492 coulombs compared to the control specimens. The total charge passed of A5S and A5L specimens below 2000 coulombs, which indicates very low chloride ion penetrability in concrete specimen. Specimens with pozzolanic had a denser internal structure providing an effective barrier against chloride-ion penetration. In addition, the use of polyolefin fiber decreases pore interconnectivity because the fibers could bridge cracks in the composites. The presence of fiber in the composites ultimately also increases the strength by transmitting the force between fiber and matrix as shown in Figure 10 and the polyolefin fiber acts as the crack arresters in the composites as shown in Figure 11, which are consistent with the results of compressive and tensile strength.

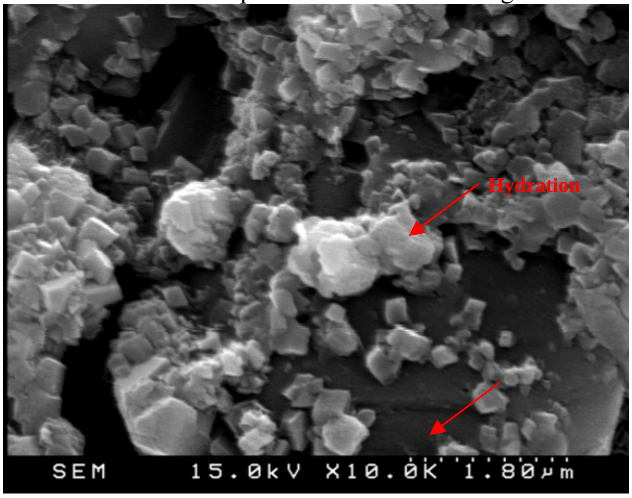


Fig. 10 SEM observation from the surface of fiber

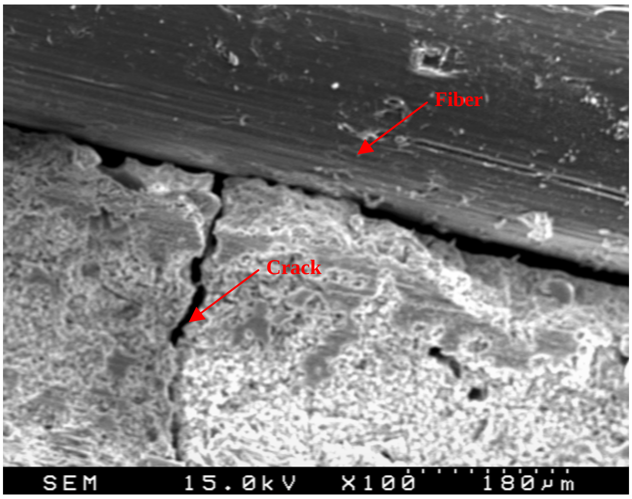


Fig. 11 Crack arresting effect of polyolefin fiber

4. CONCLUSIONS

1. The inclusion of polyolefin fibers and silica fumes in cement-based composites benefit to enhance the compressive strength and tensile strength. The short-polyolefin fibers in composites have a significant effect on strength properties compared to the long-polyolefin fibers in composites.
2. Including silica fumes or polyolefin fibers in PFCC also improve the permeability including resistivity and total charge passed. Adding silica fumes to composites greatly influence the permeability and the polyolefin fibers marginally decrease the permeability.
3. The composites combined with polyolefin fibers and silica fumes exhibit better compressive strength, tensile strength and resistivity, and present lower total charge passed due to the reinforcement between the fiber and matrix by silica fume addition.
4. SEM observations revealed that the microstructural properties of PFCC are denser and perfect bond between polyolefin fiber and matrix than that of control specimen. SEM observations also revealed that the polyolefin fiber acts as the crack arresters in PFCC.

REFERENCES

[1] Sahmaran, M., and Li, V. C., “Influence of Microcracking on Water Absorption and Sorptivity of ECC”, *Materials and Structures*, Vol. 42(5), pp.593-603, 2009.

[2] Chang, P. K., Peng, Y. N., Hwang, C. L., “A Design Consideration for Durability of High-performance Concrete”, *Cement and Concrete Composites*, Vol. 23(4-5), pp. 375–380, 2001.

[3] Lin, W.T., Huang, R., Lee, C.L., Hsu, H.M., “Effect of Steel Fiber on the Mechanical Properties of Cement-based Composites Containing Silica Fume”, *Journal of Marine Science and Technology*, Vol. 16(3), pp. 214-221, 2008.

[4] Al-Amoudi, O. S. B., Maslehuddin, M., Shameem, M., Ibrahim, M., “Shrinkage of Plain and Silica Fume Cement Concrete under Hot Weather”, *Cement and Concrete Composites*, Vol. 29(10), pp. 690-699, 2007.

[5] Lin, W.T., Huang, R., Chang, J. J., Lee, C. L., “Effect of Fiber on the Permeability of Cement-based Composites Containing Silica Fume”, *Journal of the Chinese Institute of Engineers*, Vol. 32(4), pp. 531-541, 2009.

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

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

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

[9] Swaddiwudhipong, S., Lu, H. R., Wee, T. H., “Direct Tension Test and Tensile Strain Capacity of Concrete at Early Age,” *Cement and Concrete Research*, Vol. 33(12), pp.2077-2084, 2003.