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Research Article

Production of durable high strength flowable mortar reinforced with hybrid fibers

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ABSTRACT

This study deals with the production of durable high strength flowable mortar (HSFM). Firstly, the optimum percentage of silica fume was determined due to Pozzolanic Activity Index (P.A.I) test. Secondly, the selected mortar reinforced by different percentages of steel fibers or hybrid fibers of steel fibers , palm fibers and synthetic fibers (Barchip) to prepare HSFM mixes. Such mixes were tested in compressive strength, splitting tensile strength, static modulus of elasticity, flexural strength, toughness indices determination, and impact load for all the mixes. Lastly, the effects of seawater exposure on the properties of HSFM have been observed. The results show that the use of 10% silica fume as a partial replacement of cement indicate the best P.A.I. On the other hand, the hybridizations of such fibers enhance the performance of HSFM mixes. In addition, the hybrid fibers reduce the permeability of HSFM leading to significance improvement against seawater exposure.

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1. Introduction

High strength concrete or mortar subjected to axial compression is known to be a brittle material with almost no strain-softening behavior. Adding fibers to plain matrix has little or no effect on its pre-cracking behavior but enhances its post-cracking response, which leads to a greatly improved toughness and impact behavior (Burak et al., 2007). Fibers are known to affect the workability of concrete or mortar, the question arises as to whether or not the fibers are detrimental to the workability or flowability of these materials. The degree to which workability decreases depends on the type and content of the fibers used, the matrix in which they are embedded and the properties of the constituents of the matrix. A high fiber content is difficult to distribute uniformly; however, a good distribution, required to achieve optimum benefits of the fibers (Gang et al., 2008) The development of superplasticizer has proven to offer significant improvement in application of fibers like in slabs and floors, shell domes, rock slope stabilization, refractory linings, composite metal decks, seismic retrofitting, repair and rehabilitation of structure, fire protection coatings, concrete pipes, among others (Burak et al., 2007). Over the last three decades, fiber reinforced concrete (FRC) has been the subject of many investigations. Researches have been performed on the behavior of fiber reinforced concrete subjected to various types of loading and incorporating different fibers ranging from steel, glass, plastic and natural fibers in various sizes and shapes (Burak et al,. 2007; Okamura and Ouchi, 2003).

Steel fiber has a considerably larger length and higher Young's modulus, than the other fibers. This leads to an improved potential for crack control, although the volumetric density is high. As the result, the steel fiber content has to be reduced to a certain level. Optimizations of mechanical and conductivity properties can be achieved by combining different types and sizes of fibers, such as in the case of natural and synthetic fibers (Hayat and Morin, 2002; Bentur and Mindess, 2003).

The research concentrates on highlighting some properties of the produced high strength flowable mortar (HSFM) reinforced with hybrid fibers as well as the behavior of such mortar due to seawater exposure.

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2. Materials and Mix Proportions

2.1. Materials

The cement used in concrete mixtures was ordinary Portland cement type I from Tasek Corporation Berhad. Silica fume was obtained from Scancem Materials Sdn. Bhd. and was used as partial replacement of cement. The chemical compositions of ordinary Portland cement and silica fume are given in Table 1.

The superplasticizer (SP.) is Conplast SP1000 obtained from Fosroc Sdn. Bhd. and was used to establish the desired workability of mixes. The fine aggregate was natural sand, with fineness modulus of 2.86 and maximum size of less than 5 mm. The palm fiber was supplied by Fiber-X (M) Sdn. Bhd, and their characteristics as are shown in Table 2. The synthetic fiber (Barchip) was obtained from elasto-plastic concrete and its characteristics are presented in Table 3. The steel fiber is supplied by Hunan Sunshine Steel Fiber Co. Ltd, and their mechanical properties are shown in Table 4.

Table 1. Chemical composition of ordinary Portland cement and silica fume.

Constituent	Ordinary Portland Cement % by weight	Silica fume % by weight
Lime (CaO)	64.64	1.0% (max)
Silica (SiO_2)	21.28	90% (max)
Alumina (Al_2O_3)	5.60	1.2% (max)
Iron Oxide (Fe_2O_3)	3.36	2.0% (max)
Magnesia (MgO)	2.06	0.6%(max)
Sulphur Trioxode (SO_3)	2.14	0.5%(max)
N_2O	0.05	0.8%(max)
Loss of Ignition	0.64	6% (max)
Lime saturation factor	0.92	-----
C_3S	52.82	-----
C_2S	21.45	-----
C_3A	9.16	-----
C_4AF	10.2	-----

Table 2. Physical and mechanical properties of palm fibers.

Fiber Properties	Quantity
Average fiber length (mm)	30
Average fiber width (micron)	21.13
Tensile strength (MPa)	21.2
Elongation at break (%)	0.04
Specific gravity	1.24
Water absorption (%, 24/48 hrs)	0.6

Table 3. Physical and mechanical properties of synthetic fiber (Barchip) fibers.

Fiber Properties	Quantity
Average fiber length (mm)	30
Average fiber width (micron)	0.52
Tensile strength (MPa)	550
Elongation at break (%)	8.2
Specific gravity	0.92
Melting point (C°)	150-165

Table 4. Physical and mechanical properties of steel fibers.

Fiber Properties	Quantity
Average fiber length (mm)	30
Average fiber diameter (mm)	0.56
Aspect ratio	56
Tensile strength (MPa)	>1100
Ultimate elongation (%)	<2
Specific gravity	7.85

2.2. Mix proportions

For the selection of optimum percentage of silica fume as a partial replacement of cement the Pozzolanic Activity Index (P.A.I) test was adopted by ASTM C311. Thus different silica fume percentages (0, 8, 10, 12, 14 and 16%) were used to check the best performance of such substitution. The design of mortar mix is shown in Table 5. The mix design of the reference mortar mix (M0) was carried out according to the absolute volume method given by the American Concrete Institute (ACI 211.1) for the production of high strength flowable mortar (HSFM). A reference mortar mix (M0) was prepared using water-binder (Cement+ Silica fume) ratio of 0.43 and silica fume replacement which was selected depending on P.A.I results. The amount of superplasticizer was varied from 1.8% to 2.2% by weight of binder materials to maintain the flowability as 100-110% for all mixes. The different HSFM mixes reinforced with steel fibers or hybrid fibers are also shown in Table 5.

3. Test Methods

Each test result is represented by three cube samples 50 mm and tested to determine the pozzolanic activity index and compressive strength for mortar mixes at after undergoing water curing. The Flow test for the mixes was performed according to ASTM C1437. The compressive strength test was done immediately according to ASTM C109 at 90 days age. The flexural strength of the specimens were conducted on 40 × 40 × 160 mm samples at same age according to ASTM C348. The impact resistance test was conducted using 100 × 100 × 500 mm specimens for all mixes. The impact test was determined using a steel rod blow of weight 4.5 Kg and dropping at a vertical height of 450 mm. The load was transferred from the hammer to the surface of specimen through a 50 mm steel half-ball. The test of oxygen permeability was achieved according to the recommendation stated by Cembureau. However, some adjustments were prepared for the test according to Dawood and Ramli (2012).

Table 5. Mortar mix proportions.

Index	Cement (kg/m³)	Silica fume (kg/m³)	Water (kg/m³)	SP (%)	Sand (kg/m³)	W+SP/B	Steel fiber (SF) (%)	Palm fiber (PF) (%)	Barchip fiber (BF) (%)
M0	550	55	260	1.8	1410	0.43	0	--	--
M1	550	55	260	1.8	1410	0.43	0.25	--	--
M2	550	55	260	1.8	1410	0.43	0.50	--	--
M3	550	55	260	1.8	1410	0.43	0.75	--	--
M4	550	55	260	2.0	1410	0.43	1.0	--	--
M5	550	55	260	1.8	1410	0.43	1.25	--	--
M6	550	55	260	1.8	1410	0.43	1.50	--	--
M7	550	55	260	1.8	1410	0.43	1.75	--	--
M8	550	55	260	2.0	1410	0.43	2.0	--	--
M9	550	55	260	2.0	1410	0.43	1.75	0.25	--
M10	550	55	260	2.0	1410	0.43	1.5	0.5	--
M11	550	55	260	2.0	1410	0.43	1.25	0.75	--
M12	550	55	260	2.0	1410	0.43	1.0	1.0	--
M13	550	55	260	2.2	1410	0.43	1. 0	0. 50	0. 50
M14	550	55	260	2.2	1410	0.43	1.250	0.50	0.25
M15	550	55	260	2.2	1410	0.43	1.25	0.25	0.50
M16	550	55	260	2.2	1410	0.43	1.5	0.25	0.25

4. Results and Discussion

4.1. Pozzolanic activity index (P.A.I.)

The results are shown in Table 6. It can be concluded that the Pozzolanic Activity Index (P.A.I) of cement mortar increases at a higher silica fume content and the highest P.A.I was obtained using 10% of total cementitious materials. It has been seen that this percentage of the silica fume as a partial replacement of cement improves the compressive strength of the cement-mortar due to the pozzolanic reaction between the amorphous silica in silica fume and calcium hydroxide produced by the hydration of Portland cement and silica fume (Neville, 1995; Roy, 2002).

However, the use of more than 10% of silica fume lessens the enhancement in compressive strength due to the fact that C-S-H produced by silica fume has a lower C: S ratio than the C-S-H resulting from the hydration of Portland cement alone.

The C: S ratio is lower at a high content of silica fume in the cementitious material. At the same time the dense microstructure of hydrated cement paste makes it difficult for water from outside to penetrate toward the unhydrated remnants of Portland cement or silica fume particle (Hotton, 1993). Fig. 1 shows the relation between the silica fume percentage and P.A.I for cement mortar mixes.

Table 6. Pozzolanic activity index.

Mix Type	Cement (kg/m³)	Silica fume (kg/m³)	SP (%)	Sand (kg/m³)	W+SP/B	P.A.I. (MPa)
P0	540	---	1.5	1485	0.48	28
P1	508	32	1.7	1485	0.48	33
P2	497	43	1.9	1485	0.48	37.1
P3	486	54	2.0	1485	0.48	39.8
P4	475	65	2.1	1485	0.48	39.3
P5	464	76	2.2	1485	0.48	38.1
P6	453	87	2.4	1485	0.48	37.7

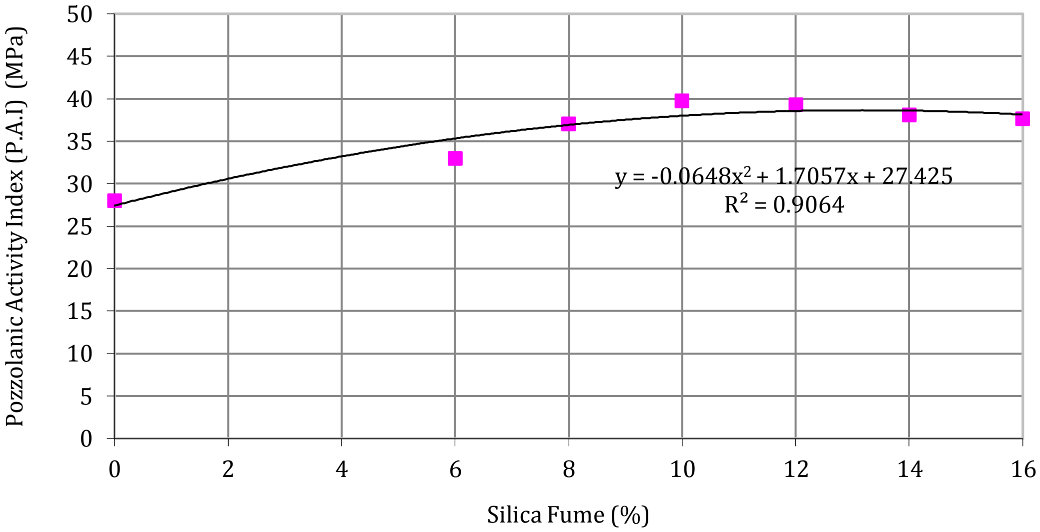

Fig. 1. Relationship between silica fume and pozzolanic activity index (P.A.I.).

4.2. Compressive strength

The results of the compressive strength of HSFM mixes shown in Table 7, indicate that the inclusion of steel fibers improves the compressive strength due to the enhancement in the mechanical bond strength between the steel fibers and mortar. The fibers play a major role to delay of micro-crack formation and arrest their propagation afterwards up to a certain extent of fiber volume fraction (Felekoğlu et al, 2009; Sahmaran and Yaman, 2007).

The relationship between the compressive strength and the percentage of steel fibers in HSFM mixes is given in Fig. 2. It can be noticed from this figure that the maximum value of the compressive strength obtained using 1.25% of steel fiber in the HSFM.

Table 7. Mechanical Properties of HSFM.

Index	Steel fiber (%)	Palm fiber (%)	Barchip fiber (%)	Compressive strength (MPa) at 90 days	Flexural strength (MPa) at 90 days	Modulus of elasticity (GPa) at 90 days
M0	0	--	--	59.6	9.12	36.3
M1	0.25	--	--	66.5	9.88	36.8
M2	0.50	--	--	68.1	11.24	38.1
M3	0.75	--	--	69.1	12.68	38.9
M4	1.0	--	--	70.4	14.43	40.1
M5	1.25	--	--	71.8	14.85	41.1
M6	1.50	--	--	68.4	15.33	43.7
M7	1.75	--	--	66.1	18.42	45.2
M8	2.0	--	--	61.4	17.36	46.3
M9	1.75	0.25	--	65.6	17.64	48.3
M10	1.5	0.5	--	67.7	19.22	45.8
M11	1.25	0.75	--	61.1	14.95	43
M12	1.0	1.0	--	60.9	13.26	42.2
M13	1. 0	0. 50	0. 50	59.8	14.15	41.5
M14	1.250	0.50	0.25	61.9	15.11	48.4
M15	1.25	0.25	0.50	63.8	15.24	49.7
M16	1.5	0.25	0.25	68.2	19.67	51.7

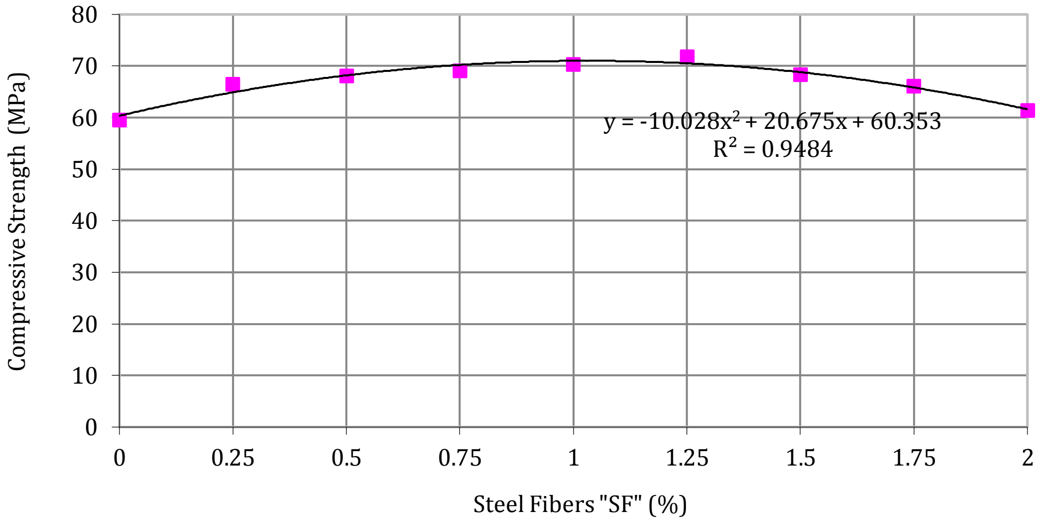

Fig. 2. Relationship between steel fibers and compressive strength of HSFM.

The comparison between control mortar mix (M0) and the mix of the highest volume fraction of steel fiber (2%) used in this study (M8) shows that there is no enhancement of compressive strength of HSFM.

This behavior maybe caused by a non- homogeneous distribution of the fibers within the mortar mix leading to a drop in the compressive strength of such mortar (Markovic et al., 2003).

The results of hybrid fiber (M9-M16) in the HSFM also illustrate that the use of low volume fraction of palm fiber or palm and Barchip fibers (0.25% to 0.5%) enhances the compressive strength as observed from mixes. This is can be attributed to the fact that hybrid fibers with different sizes and types offer different restrain (Chen and Liu, 2005).

Figs. 3 and 4 show the relative compressive strength of hybrid fibers HSFM by using steel fibers with palm fibers and also the using of steel, palm and Barchip fibers, respectively.

4.3. Static modulus of elasticity

Table 7 presents the results of modulus of elasticity for the different mortar mixes. The moduli of elasticity results reveal that there is a significant improvement in static modulus of elasticity for HSFM mixes by the inclusion of the steel fibers. The comparison between (M0) with (M8) shows that the use of 2.0% steel fibers leads to an increase in static modulus of elasticity. The relationship between steel fibers inclusion and static modulus of elasticity for HSFM is shown in Fig. 5.

The static modulus of elasticity increased by about 27% with the inclusion of steel fibers. This could be due to the fact that steel fibers have high stiffness resulting in a higher modulus of elasticity for HSM (Kayali et al., 2003). However, the effect of using hybrid fibers on the static modulus of elasticity is depicted in Figs. 6 and 7.

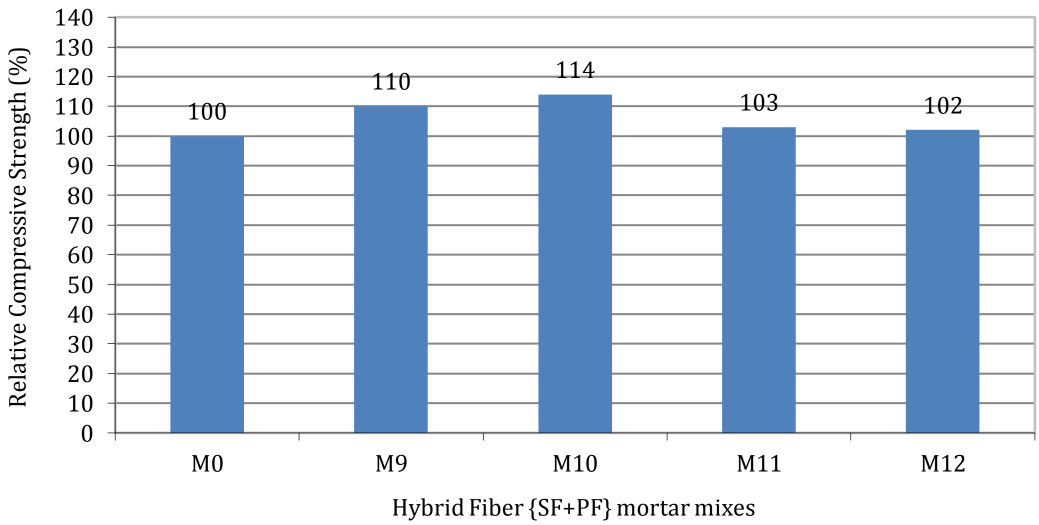

Fig. 3. Relationship between hybrid fibers {SF+PF) mortar mixes and relative compressive strength of HSFM.

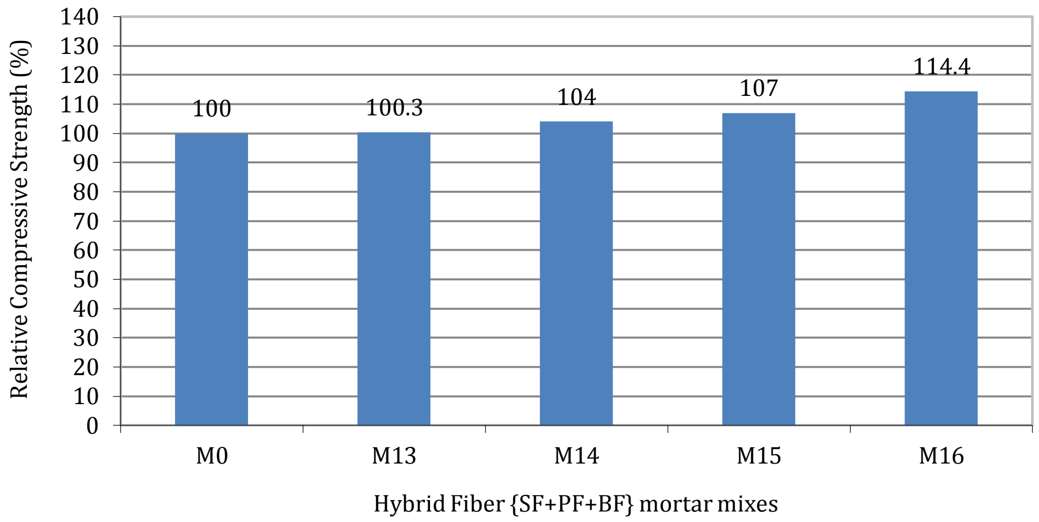

Fig. 4. Relationship between hybrid fibers {SF+PF+BF) mortar mixes and relative compressive strength of HSFM.

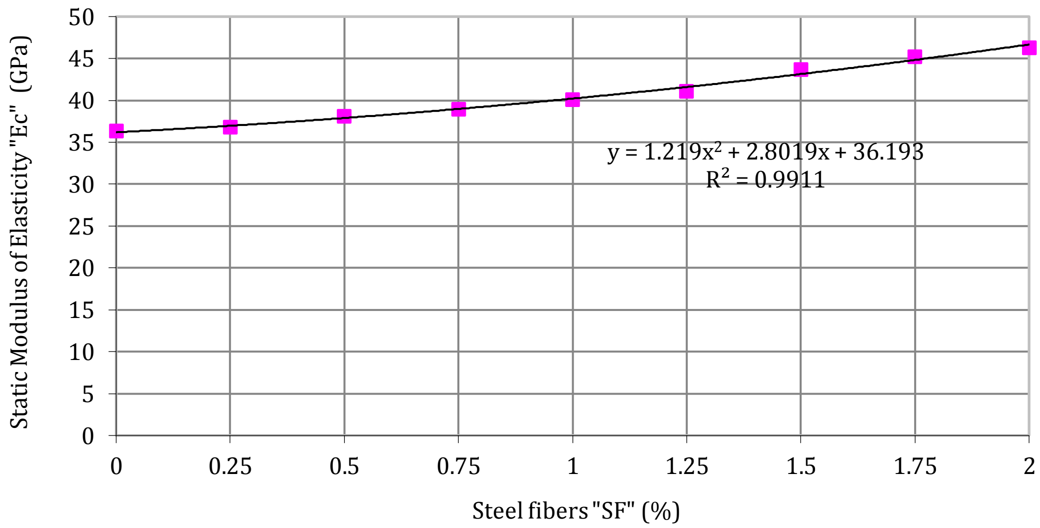

Fig. 5. Relationship between steel fibers and static modulus of elasticity for HSFM.

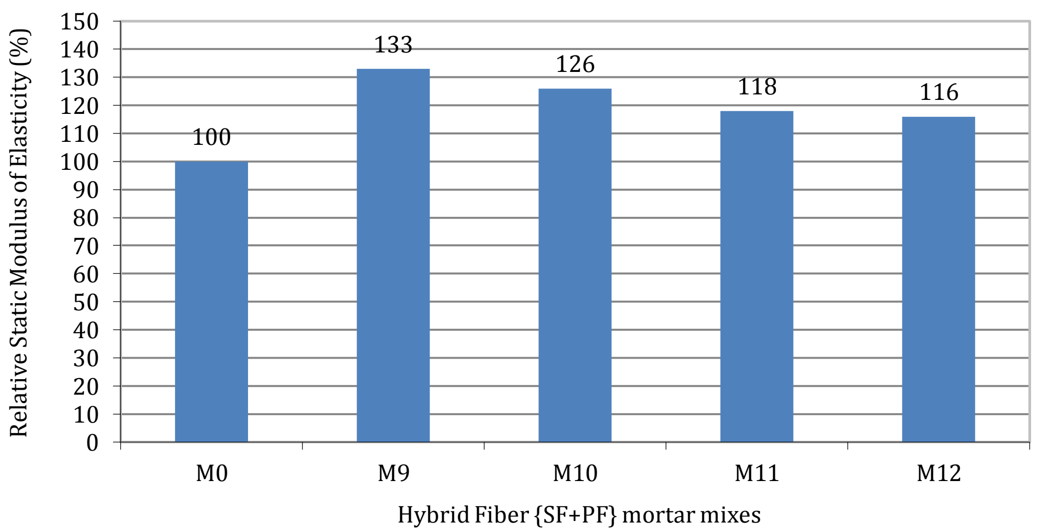

Fig. 6. Relationship between hybrid fibers {SF+ PF) mortar mixes and relative static modulus of elasticity for HSFM.

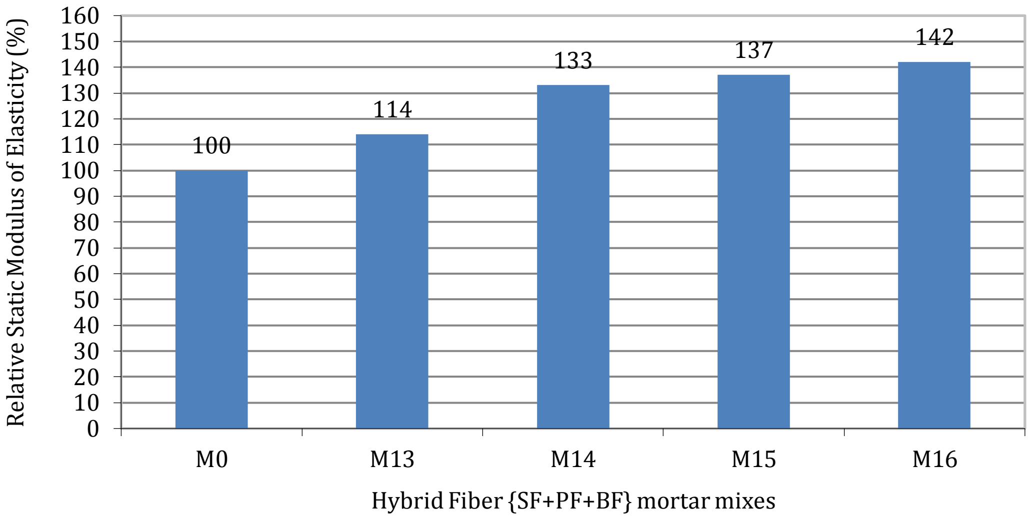

Fig. 7. Relationship between hybrid fibers {SF+ PF+BF) mortar mixes and relative static modulus of elasticity for HSFM.

These figures illustrate that the use of 0.25% of palm fibers or 0.5% of palm fibers and Barchip fibers in hybrid combination was found to be much affective. The increase percentages in static modulus of elasticity for these uses were found to be 25% and 34% respectively. This is probably due to the optimization of these percentages of fibers to operate the higher bond strength behavior and thus a higher modulus of elasticity (Chen and Liu, 2005). The increase in *Ec* for the HSFM mixes reinforced with hybrid fibers (steel fiber + palm fiber) is shown in this figure. The HSFM mix with 1.75% Steel Fiber + 0.25% Palm Fiber (M9) recorded a significant increase in the static modulus of elasticity with age. The *Ec* increased for the latter mix was 47.8 GPa at age of 28 days. Finally, the development of the static modulus of elasticity for HSFM reinforced by hybrid fibers (Steel fiber + Palm fiber + Barchip fibers) is given in Table 7. It can be seen from this figure that the inclusion of mixes with the hybrid fibers exhibited significant increases. Therefore, the HSFM reinforced with 1.5% Steel Fibers + 0.25% Palm Fibers + 0.25% Barchip Fibers (M16) shows an increase in static modulus of elasticity to 50.4 GPa at the age of 28 days.

4.4. Flexural strength

The results of flexural strength of mortar mixes are given in Table 7. The Flexural strength results of HSFM mortar mixes show that the increase of the flexural strength is compatible with the increase of steel fiber volume fractions. Fig. 8 illustrates the relationship between the steel fiber percentages in HSFM with the flexural strength. The increase of the flexural strength of the mix containing 1.75% volumetric fraction of steel fiber (M7) is about 94% higher than the control mix (M0), and this possibly due to the better compaction and homogeneity of fiber distribution in HSFM (Kayali et al., 2003; Nataraja et al., 1999; Sahmaran et al., 2003).

However, the results of hybrids fibers reveal that the increases in flexural strength are much effective. Fig. 9 shows the relative flexural strength of hybrid fibers HSFM by using steel fibers with palm fibers.

It can be seen that the increase in flexural strength by hybrid fibers containing 1.5% steel fiber + 0.5% palm fiber was found to be about 101% higher than that of the control mortar. The relative flexural strengths of hybrid fibers HSFM by using steel fibers, palm fibers and Barchip fibers, are shown in Fig. 10. It can be observed that the highest increase in flexural strength is 107% which was derived from the mix containing hybrid fibers of 1.5% steel fibers + 0.25% palm fibers + 0.25% Barchip fibers. This effective increase in flexural strength maybe resulted from better compaction and homogeneity of fibers distribution in mortar mixes and the ability of different types of fibers to restrain and bridge the cracks (Sahmaran et al., 2003).

4.5. Impact load test

The results of the impact resistance performances for all HSFM mixes are shown in Table 8 and Fig.11. The numbers of blows at the first crack appearance, the number of blows for failure, and the percentage increase in the number of blows at first crack with respect to number of blows at failure were determined. The results showed that the incorporating of 2% steel fibers into the HSFM, the number of blows to first crack increased by about 8 times. The other thing that can be observed clearly that the number of first crack appearance and the number of blows to failure are the same in case of control HSFM mix (M0). That's why; the percentage of post crack resistance increase was zero.

However, the use of 2% by volume of steel fibers increased this percentage from zero to 57.89%.

On the other hand, the results of impact load for hybrid fibers showed that the addition of different types of fiber may change the crack pattern from a single large crack to tiny multiple cracks, demonstrating the beneficial effects of fiber-reinforcement subjected to impact loading [26]. For the hybridization of fibers with 1.75% steel fibers plus 0.25% palm fibers, the post crack resistance increase was 61.11%. Whereas, the hybridization of fibers using 1.5% steel fiber + 0.25% palm fiber + 0.25% Barchip fiber increased the post crack resistance by about 58.82%.

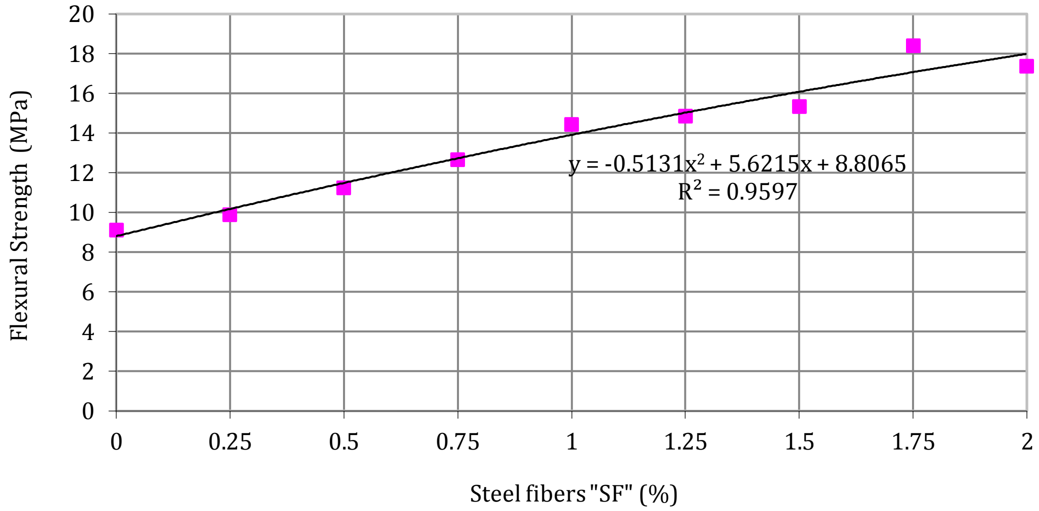

Fig. 8. Relationship between steel fibers and flexural strength of HSFM.

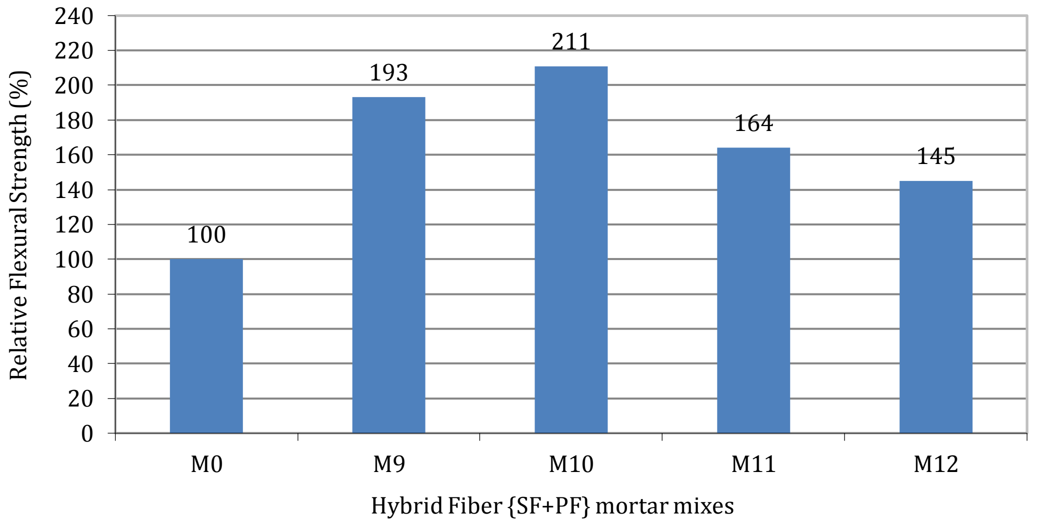

Fig. 9. Relationship between hybrid fibers {SF+ PF) mortar mixes and relative static flexural strength of HSFM.

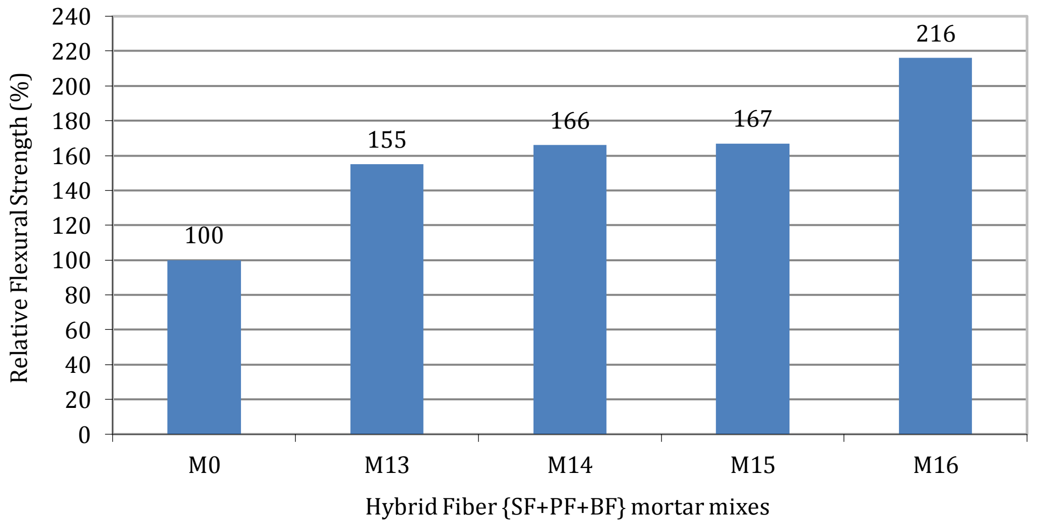

Fig. 10. Relationship between hybrid fibers {SF+ PF+BF) mortar mixes and relative static flexural strength of HSFM.

Table 8. Impact load of HSFM mixes.

Index	Steel fiber (%)	Palm fiber (%)	Barchip fiber (%)	First crack resistance (blows) (B1)	Ultimate crack resistance (blows) (B2)	Percentage of post crack resistance increase (%) {(B2-B1)/B1}X 100
M0	0	--	--	2	2	0
M1	0.25	--	--	3	4	33.3
M2	0.50	--	--	3	4	33.3
M3	0.75	--	--	5	7	40
M4	1.0	--	--	8	11	37.5
M5	1.25	--	--	14	19	35.7
M6	1.50	--	--	16	23	43.75
M7	1.75	--	--	17	25	47.05
M8	2.0	--	--	19	30	57.89
M9	1.75	0.25	--	18	29	61.11
M10	1.5	0.5	--	14	21	50
M11	1.25	0.75	--	11	16	45.45
M12	1.0	1.0	--	9	12	33.33
M13	1. 0	0. 50	0. 50	10	12	20
M14	1.250	0.50	0.25	11	14	27.27
M15	1.25	0.25	0.50	11	14	27.27
M16	1.5	0.25	0.25	17	27	58.82

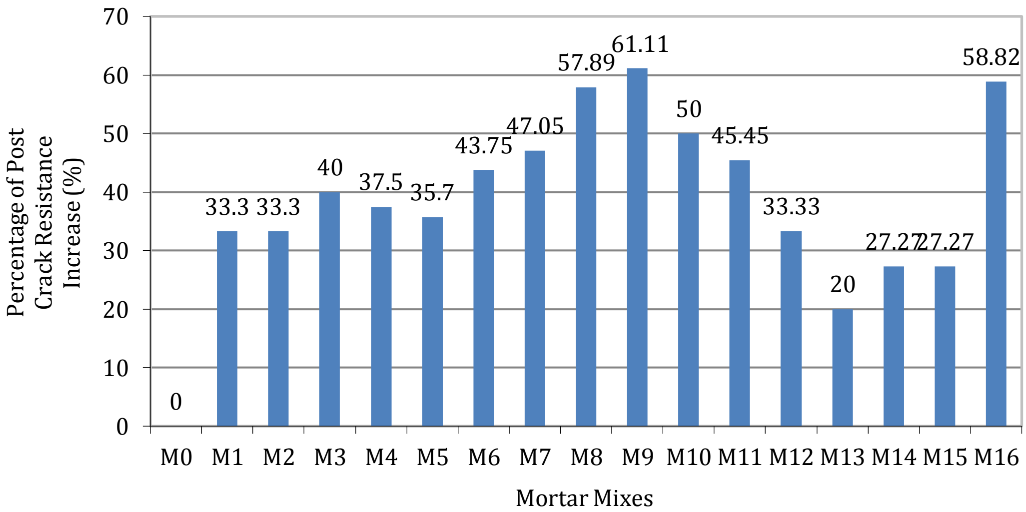

Fig. 11. Relationship between mortar mixes and percentage of post crack resistance increase.

4.6. Seawater exposure effects

The results of the HSFM mixes exposed to sea-water are represented from Table 9. The reduction in compressive strength for the HSFM mixes was between 5-10% after 180 days of exposure to sea-water. The use of hybrid fibers recorded the minimum reduction in compressive strength which were obtained from the mixes of hybrid fibers in both cases of using steel fibers with palm fibers and also the use steel, palm and Barchip fibers. This is possibly due to ability of different types of fibers reinforcement to make the mortar more impermeable (Hoseini et al., 2004; Atis and Karahan, 2009).

For the flexural strength results of HSFM mixes, it can be seen that the maximum reduction in flexural strength of HSFM obtained also when the mono-steel fibers used as 2% in mortar mixes. The reduction of flexural strength was about 8% after 180 days of sea-water exposure. This is also was found by other researchers (Atis and Karahan, 2009), where the surface deterioration of steel fibers is worse under sustained flexural stress due to the increased cracking and vulnerability of steel fibers. Therefore, the hybridization of different types of fibers improve the resistance of the HSFM as it can be noted for the results of the mortar mixes with hybrid fibers of steel and palm fibers and also for the use of steel fiber + palm fiber + Barchip fiber.

Table 9. Properties of HSFM exposed to seawater.

Index	Steel fiber (%)	Palm fiber (%)	Barchip fiber (%)	Compressive strength (MPa) 180 days (90 days normal water curing + 90 days seawater curing)	Flexural strength (MPa) 180 days (90 days normal water curing + 90 days seawater curing)	Modulus of elasticity (GPa) 180 days (90 days normal water curing + 90 days seawater curing)	Permeability 90 days normal water curing ($m^2 x 10^{-18}$)	Permeability 180 days (90days normal water curing +90 days seawater curing) ($m^2 x 10^{-18}$)
M0	0	--	--	58.1	8.96	35.8	9.11	9.49
M1	0.25	--	--	64.3	9.64	35.9	8.45	8.82
M2	0.50	--	--	64.7	11.02	36.9	7.59	7.96
M3	0.75	--	--	65.1	12.32	37.7	6.58	6.97
M4	1.0	--	--	66.1	13.95	39	6.01	6.38
M5	1.25	--	--	66	14.28	39.9	5.45	5.78
M6	1.50	--	--	64.5	14.72	42.1	4.94	5.21
M7	1.75	--	--	63.6	17.72	44	4.76	4.94
M8	2.0	--	--	58.6	16.56	44.7	4.45	4.68
M9	1.75	0.25	--	62.9	17.10	46.8	4.36	4.58
M10	1.5	0.5	--	65.5	18.70	44.9	4.48	4.73
M11	1.25	0.75	--	59.5	14.58	42	5.12	5.39
M12	1.0	1.0	--	58.7	12.85	41.3	5.67	5.89
M13	1. 0	0. 50	0. 50	58.2	13.90	40.4	5.49	5.73
M14	1.250	0.50	0.25	60.4	14.70	47.2	5.11	5.28
M15	1.25	0.25	0.50	61.7	14.81	48.6	4.88	5.11
M16	1.5	0.25	0.25	65.9	19.15	50.6	4.29	4.52

The results of static modulus of elasticity show that there is a reduction between 4-7% in elastic modulus of elasticity of mortar after 180 days of exposure to seawater. The minimum reduction of static modulus of elasticity was also obtained for the mixes of hybrid fibers of 1% steel, palm with 1% of either palm fiber or a combination of palm and Barchip fibers. This is also can be attributed to the same causes listed above where the palm and Barchip fibers have better durability performance against the sea-water (Hoseini et al., 2004; Atis and Karahan, 2009; Dawood and Ramli, 2012).

The most important test for the mortar specimens is the permeability test. It is well known that the permeability of the mortar is the key for improving the durability of the mortar against the aggressive solutions. From the results in Table 9, it can be seen that the presence of fibers can significantly reduce the permeability values.

The results of normal curing specimen shows that the comparison of mix (M0) with mix (M8) provided a significant reduction in permeability value from 9.11×10^{-18} m^2 to 4.45×10^{-18} m^2 by using 2% of steel fibers in the HSFM mixes. The results of hybrid fibers also revealed that a significant reduction of permeability was obtained by using 1.75% steel fibers + 0.25% palm fibers (M9) and the use of 1.5% steel fiber + 0.25% palm fiber + 0.25% Barchip fiber (M16). The values of permeability were changed from 4.29×10^{-18} m^2 to 5.67×10^{-18} m^2. The lowest value was obtained from M16.

The results indicated that the hybrid fibers mixes give the least value of permeability. The comparison between mix (M8) with mix (M16) shows that the use of 1.5% steel fibers+ 0.25% palm fibers + 0.25% Barchip fibers instead of using mono-steel fibers as 2% reduces the permeability values from 4.9×10^{-18} m^2 to 4.71×10^{-18} m^2.

This is can be attributed to the densification of the matrix adjacent to the filaments and enhancement of the fibers–matrix bond with continued hydration and precipitation of hydration products in the interface between filaments and matrix as well as in empty spaces between the filaments of multi-filament yarn which can be named as bundle filling (Chin and Liu, 2004; Hannat, 1987).

5. Conclusions

Some conclusions are revealed for this study which deals with the production of flowable high strength mortar as follows:

- The incorporation of 10% silica fume in concrete and mortar mixes as a partial replacement for cement increases the compressive strength which is due to the Pozzolanic Activity Index of the silica fume.
- Hybridization of fibers was found to be effective in enhancing the modulus of elasticity of HSFM. Combining the volume fractions of 1.75% steel fiber and 0.25 % palm fibers or 1.5% steel fibers, 0.25% palm fibers and 0.25% Barchip fibers, increase the static modulus of elasticity by about 25% and 34%, respectively.
- The hybridization of fibers by 1.75% steel fibers + 0.25% palm fibers increases the number of blows to first crack appearance by about 25 times compared to that of a normal HSFM mix. Consequently, the percentage increase in the post crack is 78.6% which also implied that the effects of these fibers on the initial crack zone and post crack zone are significant
- In term of durability, after sea-water exposure, the minimum reduction in compressive strength was obtained for the HSFM of hybrid fibers in the cases of using steel fibers with palm fibers and also for the use of steel, palm and Barchip fibers.
- The use of 2% of steel fibers in HSFM mixes reduces the permeability value from 7.36×10^{-18} m^2 to 4.21×10^{-18} m^2 .The results of hybrid fibers as 1.5% steel fibers + 0.25% palm fibers + 0.25% Barchip fibers shows a significant reduction in permeability up to 4.29×10^{-18} m^2.

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