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HIGH-STRENGTH FLOWABLE MORTAR REINFORCED BY STEEL FIBER

ABSTRACT

An experimental study was conducted on High-Strength Flowable Mortar (HSFM) reinforced at different percentages of steel fiber (0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 and 2.0% as volumetric fractions) to determine the density, compressive strength, static modulus of elasticity and flexural strength. The load-deflection curves under a static flexural load were established, and the flexural toughness indices were obtained in accordance with ASTM C1018. The results indicate that by increasing the fiber content up to 1.75%, the flexural strength and toughness indices are increased. The density, compressive strength and static modulus of elasticity also increased using steel fiber.

KEY WORDS

- *Steel fiber,*
- *reinforcing material,*
- *high- strength mortar,*
- *flowable mortar.*

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 a plain matrix has little or no effect on its precracking behavior but does substantially enhance its post-cracking response, which leads to greatly improved toughness and impact behavior (Al-Oraimi & Seibi, 1995). Besides, ductility in fiber-reinforced cementitious composites is enhanced because the fibers bridge cracked surfaces and delay the onset of the extension of cracks (Aydin, 2007). Many researchers have conducted investigations to study fiber-reinforced concrete in the past. Shah & Naaman (1976) conducted tensile strength, flexural strength and compressive strength tests on mortar specimens reinforced with steel and glass fiber and found that the tensile or flexural strength of steel fiber-reinforced mortar was at least two to three times that of plain mortar specimens. Similarly, Nataraja, et al. (1999) observed that the effect on the compressive strength of adding steel fibers to concrete ranges from negligible and sometimes up to 25%, whereas the addition of steel fibers significantly increases the strain capacity and elastic deformation toughness of the concrete matrix by about 75%. Modern concrete can be designed to have a great degree of flowability, which allows the concrete to flow in congested reinforcement areas and fill complicated formwork segregating (Okamura & Ouchi, 2007; Gang, et al., 2003). Mortar serves as the basis for the properties of flowing concrete, and assessing the properties of flowable mortar is an integral part of the design of flowing concrete, (Domone & Jin, 1999). On the other hand, the repair mortar applied to concrete is usually hard to compact well; therefore, repair mortar with a high degree of flowability may bring considerable advantages to a narrow mould system (Khayat & Morin, 2002). The main concern with high-strength mortar is increasing the brittleness when increasing the strength; thus it becomes a more acute problem to improve the ductility of High-Strength Flowable Mortar (HSFM) (Zhou, et al., 1994). The experience gained using normal strength fiber-reinforced concrete may be applicable to high-strength flowable mortar, but the effectiveness of fiber reinforcement in high-strength flowable mortar may be different and needs to be investigated (Balendran, et al., 2002). Therefore, the objective of this study is to assess the effects of using steel fiber at different volume fractions in a mix of High-Strength Flowable Mortar (HSFM) and study some properties of this mortar.

2. MATERIALS AND MIX PROPORTIONS

2.1. Materials

The cement used in the mortar mixtures was ordinary Portland cement type I, a product of Tasek Corporation Berhad. Silica fume from Scancem Materials Sdn. Bhd. was used as a partial replacement of the cement. The chemical compositions of ordinary Portland cement and silica fume are given in Table 1. An amount of 1.8-2.2 % of the superplasticizer (SP) Conplast SP1000 Fosroc Sdn. Bhd. was used in the weight of the binder to enhance the flowability of all the mixes. The fine aggregate used was natural sand with a fineness modulus of 2.86 and a maximum size of less than 5 mm.

Tab. 1 *Chemical composition of ordinary Portland cement and silica fume.*

Constituent	Ordinary Portland Cement	Silica fume
	% by weight	% by weight
Lime (CaO)	64.64	1.0
Silica (SiO_2)	21.28	90
Alumina (Al_2O_3)	5.60	1.2
Iron Oxide (Fe_2O_3)	3.36	2.0
Magnesia (MgO)	2.06	0.6
Sulphur Trioxode (SO_3)	2.14	0.5
N_2O	0.05	0.8
LOI	0.64	2.4
Lime saturation factor	0.92	-----
C_3S	52.82	-----
C_2S	21.45	-----
C_3A	9.16	-----
C_4AF	10.2	-----

Tab. 2 *Characteristics of Steel fiber.*

Fiber Properties	Quantity
Average fiber length, mm	30
Average fiber diameter, mm	0.56
(I/d) aspect ratio	54
Tensile strength (MPa)	> 1100
Ultimate elongation%	< 2
Specific gravity	7.85

The steel fiber used in this study is hook ends low carbon cold drawn produced by Hunan Sunshine Steel Fiber Co. Ltd, and its characteristics are shown in Table 2.

2.2 Mix proportions

The design of the mortar's composition is given in Table 3. Nine mixes were evaluated. In all the mixes the amounts of cement, silica fume, sand and free water were kept constant. The water-binder (cement+ silica fume) ratio was 0.43, and the silica fume replacement was 10%. The amount of superplasticizer was changed from 1.8% to 2.2% by the weight of the binder materials, content to maintain the appropriate flowability for all the mixes. The control mix (M0) was designed according to the absolute volume method given by the American Concrete Institute (ACI). Steel fiber at volumetric fractions of 0.25, 0.5, 0.75, 1.0, 1.25.1.5, 1.75 and 2.0 % of the mixes was used in preparing the M1-M8 mixes.

3. TEST METHODS

Three 50mm cube samples were prepared for each mix to test the density and compressive strength of the mortar after curing them in water until the time of the test. The flow test for the mixes was performed according to EN 1015-3. The mixes were designed for a flow of 150 mm ±10mm. The cube specimens were left in the molds for 24 hours at 20 °C after casting. After demolding, the specimens were kept in plain water until the time of the test. The test for the saturated surface dry density of the specimens at the time of the test was adopted and implemented according to EN 1015-6. The test for compressive strength was performed directly after the density test according to EN 1015-11 at each stage of the test. The static modulus of elasticity test was achieved using 150 × 300 mm cylinders according to ASTM C469. Besides, three 40 × 40 × 160 mm prismatic steel molds were used to prepare the specimens for the flexural strength test according to EN 1015-11, and the toughness indices were determined according to ASTM C1018.

Tab. 3 *Mortar Mixes proportions.*

Index	Cement Kg.m^{-3}	Silica fume Kg.m^{-3}	Water Kg.m^{-3}	SP %	Sand Kg.m^{-3}	W+SP/B	Steel Fiber %	Flow %
M0	550	55	260	1.8	1410	0.43	0	160
M1	550	55	260	1.8	1410	0.43	0.25	155
M2	550	55	260	1.8	1410	0.43	0.50	150
M3	550	55	260	1.8	1410	0.43	0.75	150
M4	550	55	260	2.0	1410	0.43	1.00	145
M5	550	55	260	2.0	1410	0.43	1.25	145
M6	550	55	260	2.0	1410	0.43	1.50	140
M7	550	55	260	2.2	1410	0.43	1.75	140
M8	550	55	260	2.2	1410	0.43	2.00	140

4. RESULTS AND DISCUSSION

4.1. Saturated surface dry density

Table 4 shows the results of the saturated surface dry density for all the mixes. The saturated surface dry density at 7 and 28 days for the different mixes show that there is a rise in the density as the volume fraction of the steel fiber is increased, which is due to the specific gravity of the fiber, which increases the overall density of the mortar as shown in Figure 1.

4.2. Compressive strength

From Table 4 and Figure 2, it can be concluded that the increase in the volume fraction of the steel fiber in the mix increases the compressive strength due to the improvement in the mechanical bond strength between the steel fibers and mortar, where the fibers provide the ability to delay formation of micro-cracks and arrest their propagation afterwards up to a certain extent of the fibers' volume fraction (Mustafa & Yaman, 2007, Burak et al., 2007). The percentage

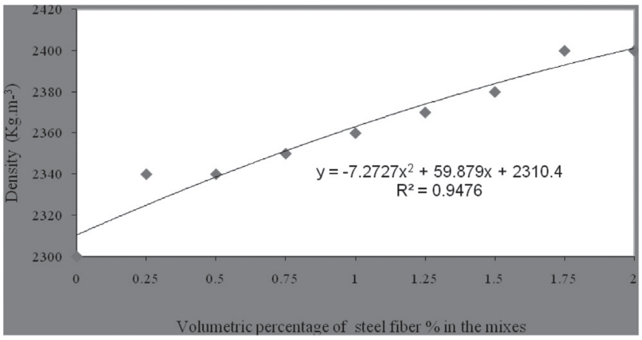

Fig. 1 *Relation between fiber content with saturated surface dry density at 28 days.*

Tab. 4 *Mechanical Properties of Mortar Mixes.*

Index	Steel Fiber %	Density Kg.m^{-3} (7days)	Density Kg.m^{-3} (28days)	Compressive strength (MPa) (7days)	Compressive strength (MPa) (28days)	Static modulus of elasticity (GPa) (28 days)
M0	0	2280	2300	43.9	55.3	33.1
M1	0.25	2310	2340	45.6	57.2	35.4
M2	0.50	2320	2340	46.8	58.9	37.8
M3	0.75	2335	2350	47.9	59.8	39.8
M4	1.00	2340	2360	49.8	60.9	41.1
M5	1.25	2355	2370	50.7	63.1	43
M6	1.50	2365	2380	48.3	59.8	44.1
M7	1.75	2380	2400	46.1	57.1	44.9
M8	2.00	2385	2400	44.2	55.7	46.1

increase in compressive strength by using 1.25 % of the steel fiber in the HSFM was about 14%. The comparison between the control mortar mix (M0) and the mix with the highest volume fraction of steel fiber (2%) used in this study (M8) shows that there is no enhancement of the compressive strength, which is mainly due to the non-homogeneous distribution of the fibers within the mortar mix, which causes a drop in the compressive strength (Markovic, et al., 2003).
The effect of steel fiber with each increase in density and compressive strength (as shown in Figure 2) illustrates that at volume fractions of 1.25% or less, the compatibility of the increments for density and compressive strength related to the inclusion of steel fiber can be noted.

4.3. Static modulus of elasticity

The results of the static modulus of elasticity test are presented in Table 4. It can be concluded that the static modulus of elasticity increases with the volume fraction of steel fiber as shown in Figure 3. The static modulus of elasticity is increased by about 39% when using 2% of the steel fiber as a volumetric fraction.
This is attributed to the high elastic modulus of the elasticity of the steel fibers , which enhances the elastic deformation capacity of the mortar mixes with the inclusion of steel fibres (Nataraja et al., 1999).

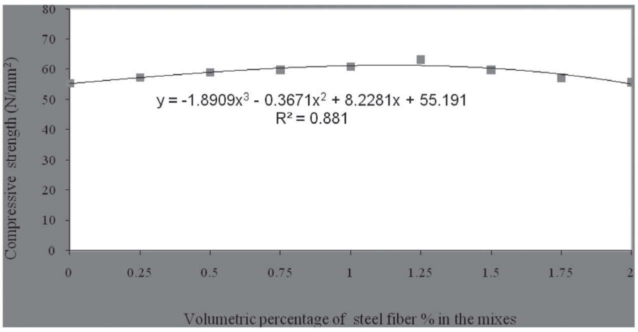

Fig. 2 *Relation between fiber content with saturated surface dry density at 28 days.*

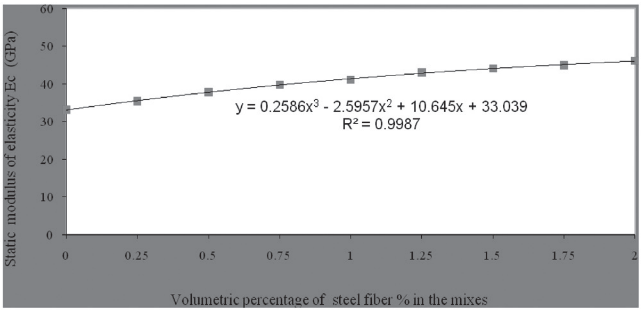

Fig. 3 *Relation between fiber content and static modulus of elasticity (Ec) at 28 days.*

4.4. Flexural strength

The flexural strength of the high-strength flowable mortar mixes is shown in Table 5 and Figure 4. An inspection of Figure 3 indicates that a linear relationship exists between the flexural strength and the steel fibers' volume fraction. The increase in the flexural strength of the mix containing a 1.75% volumetric fraction of steel fiber is 42% higher than the control mix, which may be due to the better compaction and homogeneity of the fiber distribution in HSFM. It can also be noted that the use of more than 1.75% of steel fiber slightly decreases the improvement in flexural strength, which

Tab. 5 *Flexural & Toughness Indices for Mortar Mixes.*

Index	Steel fiber %	Flexural strength (MPa) (7days)	Flexural strength (MPa) (28days)	Toughness Index (I 5) (7days)	Toughness Index (I 5) (28 days)	Toughness Index (I 10) (7days)	Toughness Index (I 10) (28 days)
M0	0	7.26	8.44	1	1	1	1
M1	0.25	7.68	8.72	1	1	1	1
M2	0.50	7.96	9.49	3.35	3.64	4.95	5.42
M3	0.75	10.17	11.65	3.45	3.85	5.25	5.93
M4	1.00	10.43	13.25	3.89	4.10	5.68	6.16
M5	1.25	10.85	13.52	4.12	4.28	6.38	6.73
M6	1.50	11.27	14.28	4.75	5.10	7.52	7.93
M7	1.75	14.74	17.1	4.95	5.35	7.93	8.45
M8	2.00	12.1	15.9	4.65	5.05	7.78	8.22

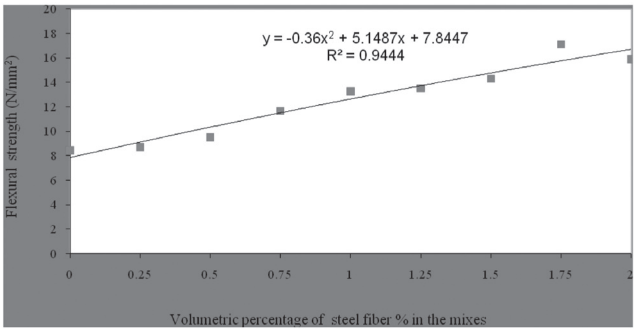

Fig. 4 *Relation between fiber content and flexural strength at 28 days.*

may be due to the physical difficulties in providing a homogenous distribution of the fibers within the mortar mix (Markovic, et al., 2003).

4.5. Toughness Indices

The Toughness indices can be determined according to ASTM C1018. The I5 and I10 indices can be calculated from this test as the ratio of the area under the load deflection curve up to 3 and 5.5 times the first crack deflection, divided by the area up to the first crack deflection respectively as shown in Figure 5. Table 5 summarizes the results of the I5 & I10 indices for 7 and 28-day specimens. It can be observed that fiber fractions of more than 0.5% have a clear effect on the toughness indices, which increase as the fiber fraction also increases. This can be attributed to the ability of the fibers to arrest cracks at both the micro and macro levels. At the micro level, the fibers inhibit the initiation of cracks, whereas at the macro level, the fibers provide effective bridging and impart sources of toughness and ductility (Balaguru & Shah, 1992; Banthia & Sappakittipakorn, 2007). This has also been determined by other researchers (Mohammadi, et al., 2008), whereas the flexural toughness can be increased as the fiber volume fraction increases for a certain aspect ratio. However, the use of 1.75% steel fiber can be considered as the most appropriate percentage to be employed in HSFM for the toughness indices. Figures 6 and 7 show the effects of using different volume fractions of steel fiber after 7 and 28 days of normal water curing.

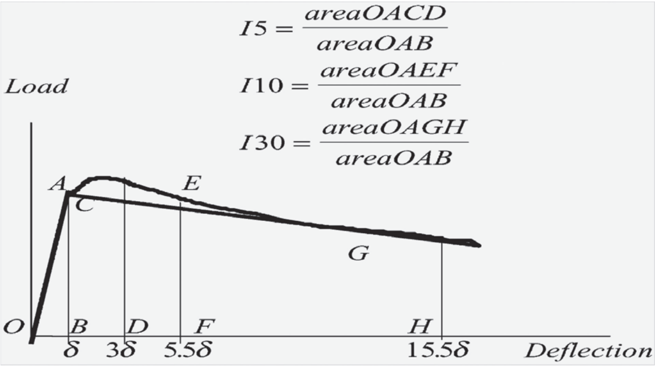

Fig. 5 *Toughness indices according to the testing method ASTM C1018.*

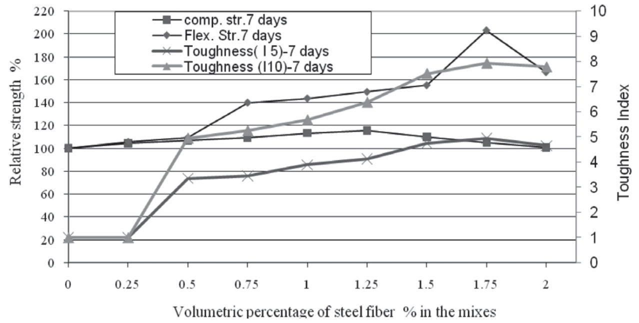

Fig. 6 *Influence of fiber content at 7 days with relative strength and toughness indices.*

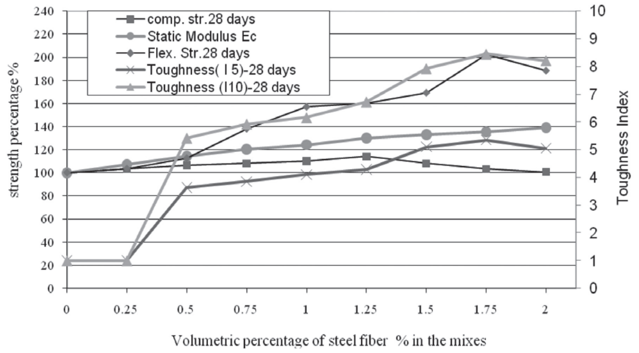

Fig. 7 *Influence of fiber content at 28 days with relative strength and toughness indices.*

5. CONCLUSIONS

This paper describes the results of an experimental study performed on high-strength flowable mortar reinforced with various volume fractions of steel fiber. The major findings of this study are:

1. The use of steel fiber at small volume fractions (0.5% volume fraction) has clear effects on the properties of high-strength flowable mortar.

2. The compressive strength results show that the use of the steel fiber increases the compressive strength and that the best improvement is obtained when the steel fiber is 1.25% of the mortar mix. This is due to the mechanical bond between the cement paste and the steel fiber.
3. The static modulus of elasticity of the flowable mortar increases with the inclusion of steel fiber. The use of 2% steel fiber in the mortar mix increases the Ec by about 39%.
4. The flexural strength results show that there is a compatible increase in flexural strength by increasing the fiber content. The use of 1.75% steel fiber as a volumetric fraction gives the highest increase, but beyond this percentage there is a slight decrease in this improvement.
5. The toughness indices results illustrate that the inclusion of steel fiber leads to significant improvements in the ductility and the absorption capacity as the volume fraction of the steel fiber is increased.

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