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Abstract

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**Mechanical behaviour of micro-fine steel fibre reinforced sulphoaluminate
cement composite**

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Abstract: In this study, a new cement-based composite with high early strength and toughness was developed by the addition of micro-fine steel fibre (MSF) in sulphoaluminate cement (SAC). The new composite is termed as MSF reinforced SAC composite (MSFRSC). The mechanical behaviour of MSFRSC was experimentally investigated, the flexural toughness and ductility of MSFRSC was evaluated. It was found that the compressive strength, flexural strength, shear strength, flexural toughness and ductility of MSFRSC were significantly influenced by the curing time and volume fraction of MSF. The compressive strength, flexural strength and shear strength of MSFRSC increased with the increase of curing time, especially during the first three days. The flexural strength and shear strength of MSFRSC improved significantly with the increase of the volume fraction of MSF. The flexural toughness of MSFRSC significantly improved and the ductility slightly improved with the increase of the volume fraction of MSF from 0.0% to 2.0%. The flexural toughness slightly increased and the ductility slightly decreased with the increase of the curing time from 1 day to 28 days. Also, the recommendations of different codes for the evaluation of the flexural toughness and ductility of MSFRSC were compared. The recommendations in ASTM C1609 fully reflected the flexural toughness and ductility of MSFRSC. The recommendations in JG/T 472-2015 distinguished the influence of MSF on the pre-peak and post-peak flexural load-deflection behaviours of MSFRSC. A simplified approach based on JG/T 472-2015 was proposed to evaluate the flexural ductility of MSFRSC.

Keywords: Sulphoaluminate cement; Micro-fine steel fibres; Strength; Flexural toughness and ductility

58 **Research Highlights**

- 59 * A new cement based composite (MSFRSC) with high early strength and toughness was developed.
- 60 * The mechanical behaviour of MSFRSC was experimentally investigated.
- 61 * The flexural and shear strength of MSFRSC were improved by the addition of MSF.
- 62 * The flexural toughness of MSFRSC was improved significantly by the addition of MSF.
- 63 * The flexural toughness of MSFRSC was evaluated based on different codes.

1. Introduction

Sulphoaluminate cement (SAC) is well known for its high early strength, fast setting, and high frost and permeation resistance. The SAC has been widely used in the rapid construction and repair of existing structures [1, 2], structures exposed to sub-zero temperature [3], as well as water retaining structures [4, 5] in the last few decades. Compared to the ordinary Portland cement (OPC), SAC is green cement with lower CO₂ emissions [6, 7, 8]. It uses industrial waste materials during the manufacturing process [9, 10]. Therefore, SAC is considered a suitable alternative to OPC and has the potential for wider applications in the environmentally sustainable construction industry [11].

Significant research attentions have been devoted in recent years on the SAC due to its superior mechanical properties. Ding et al. [12] developed high performance ultra-early strength SAC grout by using superplasticizer, early strength agent and anti-moisture dispersant. The test results showed that SAC grout achieved 8-hour compressive strength of 40 MPa and 28-day compressive strength of 65 MPa. Ma et al. [13] mixed nano-SiO₂ into SAC based composite materials to investigate the flowability and the compressive and flexural strength of the paste. It was found that the compressive and flexural strength of specimens increased and the flowability of paste decreased with the increase of nano-SiO₂ content in the paste. The compressive strengths at 8 hours and 28 days were 65.7 MPa and 92.1 MPa, respectively. The flexural strengths at 8 hours and 28 days were 8.5 MPa and 9.4 MPa, respectively. Li et al. [14] blended magnesium potassium phosphate cement (MKPT) and calcium sulphoaluminate cement (CSA) to develop a blended system (CSA-MKPT), which was cured in various relative humidity and temperatures. Li et al. [14] investigated the mechanical properties of CSA-MKPT. It was found that the humidity hardly had any effect on the compressive strength of CSA-MKPT. The compressive strengths of CSA-MKPC cured for 7 days with SAC contents of 20%, 30% and 40% of the weight of the MgO were 78.05 MPa, 74.75 MPa and 65.73 MPa, respectively, at a curing temperature of -5 °C. Chen et al. [15] developed a new artificial reef concrete (NARC) with SAC, sea sand, sea water and other admixtures. The measured compressive strengths of NARC cured

for 3 days, 7 days and 28 days were 55.3 MPa, 63.3 MPa and 71.3 MPa, respectively. The compressive strength at 3 days was nearly 80% of the compressive strength at 28 days.

Although a significant number of studies were carried out on the development of SAC, the SAC-based composites are typically brittle in nature. For the OPC concrete, the most effective way of reducing the brittleness and improving the toughness or ductility is the addition of steel fibre (SF) [16] in the concrete mix. Relatively low cost and high effectiveness of steel fibre, especially the micro-fine steel fibre (MSF), in enhancing the performance of concrete, make the MSF an attractive choice for the addition in OPC concrete. The MSF is made of drawn wire and coated with copper. The diameter of MSF usually varies between 0.2 mm and 0.3 mm. The tensile yield strength is usually more than 2000 MPa. Compared to ordinary SF, MSF has the advantages of having a larger number of fibres per kilo, higher tensile strength and easier dispersion. The MSF was used to prepare the reactive powder concretes with the ultra-high compressive strength of more than 100 MPa. The addition of MSF improves tensile strength, flexural strength and ductility of the reactive powder concrete [17, 18, 19]. The effect of MSF on high performance alkali-activated slag/silica fume mortars was investigated by Aydin and Baradan [20]. The test results indicated that the alkali activated matrices achieved higher bond to the MSFs compared to OPC matrices and increase in the fibre content reduced the shrinkage cracking associated with the alkaline activation of slag systems. When MSF was used in engineered cementitious composites with SAC, the cracking strength, tensile strength and maximum tensile strain at failure of the composites were increased. The individual crack width in the multiple-cracking stage was decreased with the addition of MSF [21]. Hence, MSF has the potential to improve the brittleness of SAC composite.

In this study, a new cement-based composite with high early strength and toughness was developed by adding MSF in SAC. The new composite is named as MSF reinforced SAC composite (MSFRSC). The compressive strength, shear strength, flexural strength and flexural performance tests were conducted to investigate the effect of MSF volume fraction, curing time and water-binder ratio on the mechanical behaviour of MSFRSC. Afterward, the flexural behaviour of MSFRSC has been evaluated

based on the flexural load-midspan deflection curves and the flexural performance index calculated by the recommendations in different standards.

2. Experimental program

2.1. Materials

The SAC used for all the mixtures was Grade P.O 52.5R according to GB20472-2006 [22]. The properties of cement provided by the manufacturer [23] are reported in Table 1. The natural river sand with the fineness modulus of 2.0 was used as fine aggregate. Silica fume with SiO_2 content of 92% and apparent density of 150-250 kg/m^3 was used as an additional admixture. The Naphthalene sulfonate formaldehyde condensate (FDN) was used as a water reducing agent with a water reducing ratio of 0.18-0.25. Both ends of the micro-fine steel fibre (MSF) used in this study were deformed, as shown in Fig. 1. The properties of MSF provided by the manufacturer [24] are reported in Table 2.

2.2. Test parameters and mixture proportions

The aim of this study is to investigate the effects of MSF volume fraction (ρ_f), weight ratio of water to binder (w/b) and curing time (t) on the mechanical behaviour of SAC composite. The w/b ratio was taken as 0.22, 0.24 and 0.26 to achieve the target compressive strength of more than 40 MPa at 1-day curing. The MSF volume fraction (ρ_f) was taken as 0.0%, 1.0% and 2.0%. The curing time (t) was set as 3 hours (3 h), 6 hours (6 h), 9 hours (9 h), 12 hours (12 h), 1 day (1 d), 3 days (3 d), 7 days (7 d) and 28 days (28 d) for investigating the early and normal performance of MSF reinforced SAC composite (MSFRSC). Five groups of MSFRSC were used in this study. The mix proportions are listed in Table 3. In the group name in Table 3, A, B and C represent the weight ratio of water to binder (w/b) of 0.22, 0.24 and 0.26, respectively. Afterward, the number 0, 1 and 2 represent the volume fraction of MSF (ρ_f) of 0.0%, 1.0% and 2.0%, respectively. The binder included cement and

silica fume. The amount of FDN (Naphthalene sulfonate formaldehyde condensate) in all the groups was 2.0% of cement by weight.

2.3. Specimen preparation

The MSFRSC was mixed using a shaft mixer. At first, SAC, silica fume and sand were mixed in the shaft mixer for 3 minutes. Afterward, MSF was added and mixed for another 3 minutes. Finally, water and FDN were added and mixed for another 5 to 6 minutes to obtain the desired mortar with no segregation. The mixing process of MSFRSC is shown in Fig. 2.

For every curing period, three prism specimens of 40 mm ×40 mm ×160 mm were cast using steel moulds for the compressive strength and flexure strength tests. Three prism specimens of 100 mm×100 mm×300 mm were cast using plastic moulds for shear strength test. Three prism specimens of 100 mm×100 mm× 400 mm were cast using plastic moulds for flexural toughness test. All specimens were vibrated on a vibration table for 30 seconds to ensure adequate compaction. After 1 hour, the specimens were demoulded. Then, the specimens were cured in standard curing room (approximately a relative humidity of 95% and a temperature of 20° C) until the time of testing.

2.4. Test procedure

The compressive strength and flexural strength tests were conducted according to GB/T17671-1999 [25]. A universal testing machine with a capacity of 300 kN was used for the compressive strength and flexural strength tests, as shown in Fig. 3. At first, the 40 mm×40 mm×160 mm prism specimens with the span length of 100 mm were loaded in the middle to measure the flexural strength. The loading rate was 50 N/s (Fig. 3a). Afterward, the two parts of each fractured prism specimen were placed on the test setup with a compression area of 40×40 mm to test the compressive strength at a loading rate of 2.4 kN/s (Fig. 3b).

The 100 mm×100 mm×300 mm prism specimens were tested for shear strength according to JG/T472-2015 [26] by using a universal testing machine with capacity of 500 kN, as shown in Fig. 4. The two cross-sections of the prism specimen were sheared at a loading rate of 0.08 MPa/s.

The 100 mm×100 mm ×400 mm prism specimens were tested for flexural performance (toughness and ductility) according to JG/T472-2015 [26] and ASTM C1609 [27]. The test was conducted by using a universal testing machine with a capacity of 2000 kN. The third-point loading was applied on the prism specimen with a loading rate at 0.1 mm/min. To achieve accurate net deflection at the midspan excluding the effects of seating or twisting of the specimen on its supports, the specimens were surrounded by a rectangular jig. The jig was clamped to the specimen at the mid-depth directly over the supports. Two linear variable displacement transducers (LVDTs) were mounted on the jig at midspan, (one on each side), to measure the midspan deflection (Fig. 5). The average of the two measurements represented the midspan deflection. The load was recorded by a load transducer with a capacity of 100 kN. All the readings (load and deflection) were collected by a data logger at every two seconds.

3. Results and discussion

3.1. Compressive and flexural strength

The average compressive strength (f_c') and average flexural strength (f_t) of MSFRSC at the curing time (t) from 3 h to 28 d are presented in Table 4. It can be seen that for the addition of MSF by volume from 0.0% (Group B0) to 1.0% (Group B1), the compressive strength of MSFRSC increased by 4.8%, 11.8%, 11.3% and 13.9% for specimens cured for 3 h, 12 h, 3 d and 7 d, respectively, as shown in Fig. 6(a). When the addition of MSF by volume increased to 2.0% (Group B2), the compressive strength of MSFRSC increased by 16.8%, 18.4%, 8.8% and 12.7% for specimens cured for 3 h, 12 h, 3 d and 7 d, respectively. Therefore, the addition of MSF of 1.0% by volume had the most significant positive effect on the improvement of compressive strength of MSFRSC, especially

at the curing time of 3 d and 7 d. The compressive strength of MSFRSC increased significantly for the addition of MSF of 2.0% by volume at the curing time of 3 h and 12 h. However, the rate of increase was not higher for the addition of MSF of 2.0% by volume at the curing time of 3 d and 7 d compared to the addition of MSF of 1.0% by volume, as the addition of MSF of 2.0% by volume might have caused an uneven distribution or balling of fibres, which partially compromised the reinforcing effect of the fibres.

The addition of MSF significantly improved the flexural strength (f_f) of MSFRSC, as shown in Fig. 6(b). For the addition of MSF by volume from 0.0% (Group B0) to 2.0% (Group B2), the flexural strength of the specimens increased by 72.5%, 68.3%, 26.1% and 121.2% at the curing time of 3 h, 12 h, 3 d and 7 d, respectively. The improvement of the flexural strength was significantly larger than the improvement of the compressive strength. The MSF mainly arrested the propagation of cracks and delayed the onset of cracks and improved the flexural strength of MSFRSC.

For the specimens with the addition of 1.0% MSF by volume, when water-binder ratio (w/b) increased from 0.22 (Group A1) to 0.26 (Group C1), the compressive strength of the specimens decreased by 31.5%, 32.3%, 13.1% and 36.9% at the curing time of 3 h, 12 h, 3 d and 7 d, respectively, as shown in Fig. 7(a). The flexural strength of the specimens also noticeably decreased by 39.4%, 30.1%, 29.1% and 25.3% at the curing time of 3 h, 12 h, 3 d and 7 d, respectively, when w/b ratio increased from 0.22 (Group A1) to 0.26 (Group C1), as shown in Fig. 7(b). This indicated that higher w/b ratio reduced the compressive strength and flexural strength of MSFRSC.

With the increase of curing time (t) from 3 h to 28 d, the specimens showed a continuous increase of the compressive strength and flexural strength for the addition of 1.0% MSF by volume, especially for the specimens cured for less than 3 d, as shown in Fig. 8. For Group B1 specimens, the compressive strength of the specimen cured for 3 d was 81.8% of the compressive strength of the specimen cured for 28 d. Also, the flexural strength of the specimen cured for 3 d was 71.7% of the

flexural strength of the specimen cured for 28 d. Group B2 specimens with the addition of 2.0% MSF by volume showed a similar increase in the compressive and flexural strength as observed for the addition of 1% MSF by volume for Group B1 specimens. The early development of compressive strength and flexural strength were positively influenced by the fast hydration of SAC.

3.2. Shear strength

The average shear strength (f_s) of MSFRSC specimens with the addition of MSF from 0.0% to 2.0% by volume and cured for 1 d, 3 d and 28 d are shown in Table 5. It can be observed that the shear strength of MSFRSC increased significantly with the increase of curing time from 1 d to 28 d. The shear strength of Group B1 specimens with 1.0% MSF by volume cured for 3 d attained 81.7% of the shear strength of specimens cured for 28 d. For Group B2 specimens, the shear strength of specimens with 2.0% MSF by volume cured for 3 d attained 73.6% of that cured for 28 d, as shown in Fig. 9(a). The specimens cured for 3 d, the shear strength increased with the increase of volume fraction of MSF from 0.0% to 2.0%, as shown in Fig. 9(b). The shear strength of Group B2 specimens was 1.75 times of the shear strength of Group B0 specimens which did not include MSF at curing time of 3 d. The reason for the improvement of shear strength was similar to the reason for the improvement of compressive strength and flexural strength. With the non-uniform distribution fibres across the potential shear damage section, the resistance of shear failure was provided by the cement matrix and fibres. When the shear failure occurred, the fibres were cut or pulled out. The tensile and shear strength of steel fibres are much higher than those of cement matrix. Hence, with the increase of fibre content, the shear resistance provided by the steel fibre increased and the shear strength of the MSFRSC increased.

3.3. Flexural load-midspan deflection curve

3.3.1. Effect of MSF

Figure 10 presents the flexural load-midspan deflection curves of specimens with 0-2.0% MSF by volume cured for 1 d, 3 d and 28 d. Due to the absence of MSF, Group B0 specimens cured for 28 d failed suddenly after reaching the peak load. However, Groups B1 and B2 specimens with MSF showed a ductile failure with a descending post-peak flexural load-midspan deflection branch, representing a ductile response after the peak flexural load. For the addition of MSF of 2.0% by volume, Group B2 specimens showed greater load carrying capacities than Group B1 specimens with 1.0% MSF by volume. Moreover, due to the development of bond between MSF and SAC matrix, the reinforcing effect of 1.0% to 2.0% MSF by volume increased with increasing curing time (t) from 1 d to 28 d (Figure 10). It is noted that the specimens with 1.0% and 2.0% MSF by volume at the same curing time showed a similar midspan deflection at the flexural peak load with similar shape of the flexural load-midspan deflection curves. This phenomenon reflects that the effect of increasing MSF influenced the load carrying capacity more than it influenced the ductility.

3.3.2. Effect of curing time

Fig. 11 presents the flexural load-midspan deflection curves of specimens with 1.0% and 2.0% MSF by volume cured for 1 d, 3 d and 28 d. The increase of the curing time (t) substantially improved the peak flexural load and corresponding midspan deflections, as shown in Fig. 11(a) and 11(b). However, the post-peak descending branches of the flexural load-midspan deflection curves were steeper with the increase of the curing time. Therefore, the longer curing time can increase the load carrying capacity, but may reduce the flexural ductility of MSFRSC.

3.4. Flexural toughness index

Four methods recommended by ASTM C1018 [28], ASTM C1609 [27], JSCE SF-4 [29] and JG/T 472-2015 [26] can be used to evaluate the flexural toughness for fibre reinforced composites. Since

the initial cracking load required by ASTM C1018 is difficult to be captured [30], the other three methods were adopted herein to evaluate the flexural toughness of MSFRSC.

3.4.1. Flexural toughness and ductility index calculated by ASTM C1609 [27]

The ASTM C1609 [27] defines the total area under the flexural load-midspan deflection curve up to $L/150$ (L is beam span; $L=300$ mm for this test) as flexural toughness T_{150}^D (N·mm). The equivalent flexural strength ratio $R_{T,150}^D$ can be calculated by Eq. (1):

$$R_{T,150}^D = \frac{150T_{150}^D}{f_1bh^2} \times 100\% \quad (1)$$

where f_1 is the first peak flexural strength (MPa); b is the width of the specimen ($b = 100$ mm for this test); h is the height of the specimen ($h = 100$ mm for this test). The flexural toughness T_{150}^D and the equivalent flexural strength ratio $R_{T,150}^D$ calculated by Eq. (1) for the specimens tested are shown in Table 6 and Fig. 12.

The flexural toughness, T_{150}^D reflects the energy absorption capacity of MSFRSC, as shown in Fig. 12. With the increase of the curing time from 1 d to 28 d, the flexural toughness increased slightly by 11.09% and 3.25%, respectively for the addition of 1.0% and 2.0% MSF by volume. With the increase of the addition of MSF from 1.0% to 2.0% by volume, the flexural toughness increased significantly by 38.55%, 35.70% and 28.77%, respectively for 1 d, 3 d and 28 d curing. At every curing time, Group B2 specimens had much higher T_{150}^D than Group B1 specimens, which revealed the important effect of MSF on the flexural toughness T_{150}^D .

The equivalent flexural strength ratio, $R_{T,150}^D$ of MSFRSC calculated from the test results are shown in Fig. 12. The equivalent flexural strength ratio, $R_{T,150}^D$ of MSFRSC slightly increased by 19.26%, 0.87% and 1.60%, respectively for 1 d, 3d and 28 d curing with the increase of the addition of MSF from 1.0% to 2.0% by volume. The $R_{T,150}^D$ slightly decreased by 4.69% and 18.80%, respectively for the addition of 1.0% and 2.0% MSF by volume with the increase of the curing time from 1 d to 28 d. The $R_{T,150}^D$ reflected the flexural ductility of MSFRSC determined by the plump degree (fat or thin) of a flexural load-midspan deflection curve. Thus the $R_{T,150}^D$ did not indicate the height (tall or short) of the curve, i.e., peak load or flexural strength. Therefore, the flexural ductility of MSFRSC slightly increased with the increase of the addition of MSF by volume and slightly decreased with the increase of the curing time from 1 d to 28 d. It is noted that the $R_{T,150}^D$ combined with T_{150}^D can fully describe the flexural performance (ductility and toughness) of MSFRSC.

3.4.2. Flexural toughness index calculated by JSCE SF-4 [29].

The definition of flexural toughness specified in JSCE SF-4 [29] is the same as the definition of the flexural toughness specified in ASTM C1609 [27]. The flexural toughness factor (FT) according to JSCE SF-4 [29] can be obtained by Eq. (2):

$$FT = \frac{A_{(L/150)} L}{(L/150) b h^2} \quad (2)$$

where $A_{(L/150)}$ is the flexural toughness, N·mm; L is the span length, mm; b is the width of the specimen, mm; h is the height of the specimen, mm.

Table 7 and Fig. 13 illustrate the flexural toughness and flexural toughness factor based on JSCE SF-4. It is evident that the flexural toughness, $A_{(L/150)}$ and the flexural toughness factor, FT followed the similar order.

314

315 In order to make a clear comparison, Eq. (2) can be written as Eq. (3):

$$316 \quad FT = \frac{150A_{(L/150)}}{f_1bh^2} f_1 = R_{T,150}^D \times f_1 \quad (3)$$

317 The FT is a comprehensive index combining the ductility index, $R_{T,150}^D$, calculated according to the
 318 ASTM C1609 [27] and flexural strength, f_1 . Therefore, FT is unable to independently reflect the
 319 ductility and it is similar to the flexural toughness. Also, the total area under the curve up to the end
 320 point deflection ($L/150$) was used to calculate the flexural toughness of MSFRSC, which was unable
 321 to distinguish between the pre-peak and post-peak flexural load-midspan deflection behaviours.

322

323 3.4.3. Flexural toughness index calculated by JG/T 472-2015 [26]

324 In order to distinguish the effect of the addition of fibre on the pre-peak and post-peak flexural load-
 325 deflection behaviours, a new method is recommended by JG/T 472-2015 [26]. In JG/T 472-2015 [26],
 326 the equivalent initial flexural strength, $f_{e,p}$ (MPa), initial toughness index, $R_{e,p}$, equivalent residual
 327 flexural strength, $f_{e,k}$ (MPa), and residual toughness index, $R_{e,k}$, can be calculated by Eq. (4-7).

$$328 \quad f_{e,p} = \frac{\Omega_p L}{bh^2 \delta_p} \quad (4)$$

$$329 \quad R_{e,p} = \frac{f_{e,p}}{f_{ftm}} \quad (5)$$

$$330 \quad f_{e,k} = \frac{\Omega_{p,k} L}{bh^2 (L/k - \delta_{p,k})} \quad (6)$$

$$331 \quad R_{e,k} = \frac{f_{e,k}}{f_{ftm}} \quad (7)$$

where δ_p is the midspan deflection at peak flexural load, mm; Ω_p is the pre-peak flexural toughness (the pre-peak area under the flexural load-deflection curve up to δ_p), N·mm; L is the span length, mm; b is the width of the specimen, mm; h is the height of the specimen mm; f_{tm} is the flexural strength, MPa; $\Omega_{p,k}$ is the post-peak flexural toughness (the post-peak area under the flexural load-deflection curve between δ_p to L/k , $k = 500, 300, 250, 200$ and 150). The $R_{e,p}$ and $R_{e,k}$ can reflect the degree to which the fibre changes the pre-peak and post-peak behaviours, respectively, of MSFRSC.

Table 8 and Fig. 14 present the test results calculated based on JG/T 472-2015 [26]. The residual toughness index $R_{e,k}$ ($R_{e,500}$, $R_{e,300}$, $R_{e,250}$, $R_{e,200}$ and $R_{e,150}$) showed almost the same order and are nearly in line with the order of $R_{T,150}^D$ calculated according to ASTM C1609 [27]. The $R_{e,k}$ effectively reflected the ductility, but not the energy absorption.

The deflection-hardening behaviour of MSFRSC specimens was observed for the midspan deflection between 0 to approximately 0.5 mm. As shown in Fig. 14 and Table 8, the $R_{e,500}$ of Group B2-1 d and Group B1-3 d was greater than 1.0, which revealed the deflection-hardening behaviour of MSFRSC and explained the little difference of $R_{e,k}$ for $k = 500$ and $R_{e,k}$ for $k = 300, 250, 200$ and 150 . For this method, the flexural toughness indices were calculated at some specified deflections (L/k , $k = 500, 300, 250, 200$ and 150). However, the calculation of flexural toughness index at various deflections was a complex and time-consuming procedure. As shown in Fig. 14 and Table 8, when $k = 300, 250, 200$ and 150 , $R_{e,k}$ showed a consistent tendency. Therefore, the k can be considered as $k = 500$ and $k = 150$. The flexural toughness index, $R_{e,k}$ for $k = 500$ reflected the ductility at a minor deflection (less than 0.6 mm) and it also reflected the deflection-hardening behaviour of

MSFRSC. The flexural toughness index, $R_{e,k}$ for $k = 150$ reflected the overall ductility of MSFRSC at a major deflection (2.0 mm).

4. Conclusions

The mechanical behaviour of micro-fine steel fibre (MSF) reinforced sulphoaluminate cement (SAC) composite (MSFRSC) with varying water-binder ratios, curing time and MSF volume fractions has been experimentally investigated. Also, the flexural performance of MSFRSC has been evaluated according to the recommendations of three codes. Based on the experimental and analytical investigations, the following conclusions can be drawn:

- (1) Due to the fast hydration, the compressive, flexural and shear strength of MSFRSC were significantly improved with the increase of the curing time, especially in the first 3 days.
- (2) The addition of MSF slightly improved the compressive strength of MSFRSC. With the increase of addition of MSF from 0.0% to 2.0% by volume, the effect of fibre obstructing cracks increased. The flexural and shear strength of MSFRSC were improved significantly, and the improvement of the flexural and shear strength was higher than the improvement of the compressive strength. Meanwhile, the increase of the addition of MSF was found to be beneficial for the improvement of early compressive strength.
- (3) The increasing water-binder ratio from 0.22 to 0.26 resulted in a decrease of the compressive and flexural strength of MSFRSC.
- (4) The failure mode changed from brittle to ductile by the addition of MSF. With the increase of the addition of MSF from 0.0% to 2.0% by volume, the flexural toughness of MSFRSC increased significantly and the ductility increased slightly. With the increase of the curing time from 1 day to 28 days, the flexural toughness of MSFRSC increased slightly but the ductility decreased slightly.

(5) The recommendations in ASTM C1609 [27] fully reflected the flexural toughness and flexural ductility of MSFRSC. The evaluating results of the flexural toughness of MSFRSC according to the flexural toughness factor (FT) in JSCE SF-4 [29] were similar to that according to the flexural toughness (T_{150}^D) in ASTM C1609 [27]. The recommendations of JG/T 472-2015 [26] distinguished the influence of the addition of MSF on the pre-peak and post-peak flexural load-midspan deflection behaviours of MSFRSC. Also, the recommendations of JG/T 472-2015 [26] reflected the deflection-hardening behaviour by defining a flexural toughness index at a minor deflection.

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496 Table 1

497 Properties of SAC [24]

w/c	s/c	Compressive strength (MPa)		Flexural strength (MPa)		Setting time (min)		Surface area (m ² /kg)	Normal consistency	Free calcium oxide
		1 d	3 d	1 d	3 d	Initial setting	Final setting			
0.45	3.0	43.8	55.9	6.6	7.1	27	32	455	24%	0%

498 Note: w/c is the weight ratio of water to cement and s/c is the weight ratio of sand to cement

499 Mechanical properties were determined according to GB/T 17671-1999 [23].

500 Table 2

501 Properties of MSF [25]

Equivalent diameter (mm)	Length (mm)	Aspect ratio	Tensile strength (MPa)	Number per kilo
0.22	13	60	2850	224862

502

503 Table 3

504 Mix proportions of MSFRSC

Group	w/b	Fibre volume fraction ρ_f	Cement	Water	Silica fume	Sand	FDN
A1	0.22	1.0%	1	0.242	0.1	1.2	0.02
B0	0.24	0.0%	1	0.264	0.1	1.2	0.02
B1	0.24	1.0%	1	0.264	0.1	1.2	0.02
B2	0.24	2.0%	1	0.264	0.1	1.2	0.02
C1	0.26	1.0%	1	0.286	0.1	1.2	0.02

505 Note: All numbers are weight ratios to cement except fibre contents (volume fraction). The w/b is
 506 the weight ratio of water to binder and FDN is naphthalene sulfonate formaldehyde condensate.

507

508 Table 4

509 Average compressive strength and average flexural strength

Group	Average compressive strength (f'_c) / Average flexural strength (f_f) (MPa)							
	3 h	6 h	9 h	12 h	1 d	3 d	7 d	28 d
A1	18.1/7.1			43.0/10.3		81.9/11.0	85.0/16.6	
B0	16.7/4.0			38.0/6.3		73.5/9.2	79.0/8.2	
B1	17.5/4.6	25.4/5.0	32.0/6.0	42.5/7.4	55.0/8.95	81.8/10.4	90.0/12.4	100.0/14.5
B2	19.5/6.9			45.0/10.6		80.0/11.6	89.0/17.4	
C1	12.4/4.3			29.1/7.15		71.2/7.8	53.6/12.5	

510 Table 5

511 Average shear strength

Group	Average shear strength (f_s) (MPa)		
	1 d	3 d	28 d
B0		5.9	
B1	6.0	7.6	9.3
B2	8.7	10.3	14.0

512 Table 6

513 Flexural toughness and ductility index according to ASTM C1609 [28]

Group	Curing time	Flexural toughness T_{150}^D (kN·mm)	Equivalent flexural strength ratio $R_{T,150}^D$ (%)
B1	1 d	19.12	71.66
B2	1 d	26.49	85.46
B1	3 d	20.31	75.49
B2	3 d	27.56	76.15
B1	28 d	21.24	68.30
B2	28 d	27.35	69.39

514 Note: the reported values are the average value for each Group.

515

516 Table 7

517 Flexural toughness index according to JSCE SF-4 [29]

Group	Curing time	Flexural toughness $A_{(L/150)}$ (kN·mm)	Flexural toughness factor FT (MPa)
B1	1 d	19.12	2.86
B2	1 d	26.49	3.97
B1	3 d	20.31	3.04
B2	3 d	27.56	4.13
B1	28 d	21.24	3.18
B2	28 d	27.35	4.10

518 Note: the reported values are the average value for each Group.

519 Table 8 Flexural toughness index according to JG/T 472-2015 [26]

Group	Curing time	$R_{e,p}$	$R_{e,500}$ ($L/k = 0.6 \text{ mm}$)	$R_{e,300}$ ($L/k = 1.0 \text{ mm}$)	$R_{e,250}$ ($L/k = 1.2 \text{ mm}$)	$R_{e,200}$ ($L/k = 1.5 \text{ mm}$)	$R_{e,150}$ ($L/k = 2.0 \text{ mm}$)
B1	1d	0.86	0.95	0.89	0.85	0.79	0.71
B2	1d	0.89	1.02	0.98	0.96	0.92	0.85
B1	3d	0.88	1.03	0.96	0.91	0.84	0.75
B2	3d	0.92	0.99	0.92	0.88	0.83	0.76
B1	28d	0.84	0.97	0.88	0.84	0.77	0.68
B2	28d	0.76	0.97	0.87	0.83	0.78	0.69

520 Note: $R_{e,p}$ is the initial toughness index; $R_{e,k}$ is the residual toughness index corresponding to the
521 midspan deflection of L/k (where $k = 500, 300, 250, 200$ and 150) and L is the span length.

522 The reported values are the average value for each Group.

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Fig. 1 Micro-fine steel fibres

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Fig. 2 Mixing process of MSFRSC mixture

Fig. 3 Compressive and flexural strength test:

(a) Schematic representation of flexural strength, (b) Schematic representation of compressive strength and (c) Photo of the test

(a)

(b)

Fig. 4 Shear strength test: (a) Schematic representation and (b) Photo of the shear strength test

(a)

(b)

Fig. 5 Flexural toughness test: (a) Schematic representation and (b) Photo of the test

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(a)

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543

(b)

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545

Fig. 6 Effect of volume fraction of MSF on: (a) average compressive strength, f'_c and (b) average flexural strength, f_f

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(a)

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(b)

551 Fig. 7 Effect of water-binder ratios on: (a) average compressive strength, f'_c and (b) average flexural
552 strength, f_f

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555 Fig. 8 Average compressive strength, f'_c and average flexural strength, f_f with varying curing time,

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t

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(a)

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(b)

563 Fig. 9 Average shear strength, f_s with varying (a) curing time, t and (b) MSF volume fractions, ρ_f

(a)

(b)

(c)

Fig. 10 Flexural load-midspan deflection curves of specimens with the addition of MSF by volume at curing time: (a) 1 d, (b) 3 d and (c) 28 d

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(a)

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(b)

577 Fig. 11 Flexural load-midspan deflection curves of specimens with varying curing time added MSF:

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(a) 1.0% and (b) 2.0% by volume

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Fig. 12 Flexural toughness and ductility index according to ASTM C1609 [27]

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Fig. 13 Flexural toughness index according to JSCE SF-4 [29]

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Fig. 14 Flexural toughness index according to JG/T 472-2015 [26]

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