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Properties and microstructure of basic magnesium sulfate cement:
Influence of silica fume

Yongshan Tan a,b,c,⇑, Hongfa Yu c,e, Shikuan Sun d, Chengyou Wu e, Hao Ding d

a College of Civil Science and Engineering, Yangzhou University, Yangzhou 225127, China
b Research Institute of Green Building Materials, Yangzhou University, Yangzhou 225127, China
c Department of Civil and Airport Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
d Department of Materials Science and Engineering, University of Sheffield, Sheffield S1 3JD, UK
e School of Civil Engineering, Qinghai University, Xining 810016, China

HIGHLIGHTS

• Industrial waste silica fume (SF) is used to improve the performance of basic magnesium sulfate cement (BMSC).
• Incorporation of SF can enhance the mechanical properties of BMSC significantly.
• Hydration behavior and process of BMSC influenced by SF are studied.
• Microstructure and phase evolution of BMSC are characterized and analyzed.

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ABSTRACT

Silica fume (SF) as an important supplementary cementitious material has been widely used in Portland cement, but few published articles have reported on the effect of SF on the performance and hydration mechanism of basic magnesium sulfate cement (BMSC). In the present work, the properties, microstructure and hydration mechanism of BMSC influenced by SF was studied systematically. The results show that the setting time and compressive strength of BMSC may increase with the increase of SF content, while the hydration heat will decrease with the increase of SF content. Mercury intrusion porosimetry (MIP), X-ray computed tomography (X-CT), scanning electron microscope-energy dispersive spectrometer (SEM-EDS) results show that SF exhibits filling effect in the BMSC matrix, which makes the microstructure of BMSC matrix with SF more compact. In addition, solid-state magnetic resonance (NMR) and SEM-EDS analysis indicate that the activity of SF was excited in the BMSC matrix, resulting in the formation of M–S–H gel.

1. Introduction

As the foundation of the progress and development of human society, Portland cement is the largest and most widely used man-made building material worldwide [1]. However, because the production of Portland cement will release a large amount of carbon dioxide (0.7–1.0 tons of carbon dioxide per ton of OPC), consume the excessive non-renewable mineral resources
(limestone), and require higher calcination temperatures (1450 °C). Traditional Portland cement is leading to severe environmental, energy and resource problems during the production process [2–4]. Therefore, the development of sustainable alternative cementitious materials is an urgent need for sustainable development.

In recent years, magnesite, waste sulfuric acid and industrial waste (fly ash, slag and byproduct of magnesia) were adopted as main raw materials and through chemical additive technology [5] in the author’s research group, a new type of MgO-MgSO4-H2O cementitious material (Basic magnesium sulfate cement, BMSC) was developed. Basic magnesium sulfate whisker was the main hydration product of BMSC, whose the mechanical properties were greatly improved compared to Portland cement [6,7]. The chemical composition and this new whisker were analyzed to be 5 Mg(OH)2·MgSO4·7H2O (referred to as 5–1–7 phase) [8]. The crystal structure data has been determined to be I 121/(c 121) (selected to the International Inorganic Crystal Structure Database). The calcination temperature of the BMSC cementitious material was only 850°C, and it enable the incorporation of a large amount of industrial waste residues such as fly ash or slag, without consuming limestone and clay resources. The production of BMSC only consumes magnesite and industrial waste sulfuric acid. Therefore, the energy consumption of BMSC production was estimated at least 30% lower than that of Portland cement. Therefore, BMSC was recognized as a new type of green and low carbon cement with low energy consumption, low resource consumption and low pollution.

As a new type of green high-performance cementitious material, BMSC is attractive in the field of building materials due to its low thermal expansion, low deformation and cracking resistance, good high temperature resistance, no moisture absorption and dehalogenation, and excellent mechanical properties such as high compression resistance, high tensile strength and high toughness [9–11]. In the prevention and control of pneumonitis caused by the novel coronavirus (2019-nCoV) that occurred in Wuhan, China in December 2019, in order to effectively alleviate the development and spread of the epidemic, two hospitals named Huoshenshan Hospital and Leishenshan Hospital were completed within 14 days. According to statistics, >50,000 square meters of BMSC building boards were used in the construction of 4,950 in negative-pressure isolation wards, which played an important role in controlling and alleviating the epidemic situation in China [12].

Up to now, researchers have focused on the modification of BMSC with chemical additives. The results showed that some weak acids had obvious effects on the mechanical performance and water resistance improvement of BMSC, and the hydration mechanism of BMSC was studied as well [13–16]. In addition, the effects of supplementary cementitious material (SCM) on the properties and microstructure of BMSC were also investigated. Wu et al. [15] found that as the addition of fly ash increases, the compressive strength of BMSC would gradually decrease. Zhang et al. [17] studied the effects of high-/low-calcium bearing fly ash on the mechanical properties, microstructure, and water resistance of BMSC. The results showed that, high calcium fly ash could improve the mechanical properties, volume stability and water resistance of BMSC compared with low calcium fly ash. Li et al. [18] found that the incorporation of fly ash and slag can increase the water resistance of BMSC, and it was speculated that the good water resistance of BMSC was due to the M–S–H gel generated in the BMSC matrix. Meanwhile, it was found that that the mechanical properties of BMSC was significantly improved when the addition content of the circulating fluidized bed combustion (CFBC) was 20% [19]. Qin et al. [20] found that the incorporation of rice hull ash significantly reduced the compressive strength of BMSC, and also reduced the thermal conductivity and apparent density of BMSC.

From the above analysis, it can be inferred that the incorporation of SCM (fly ash, slag, and rice husk ash, etc.) significantly improve the microstructure and water resistance of BMSC [21]. The main reason is that the SCM exerts a filling effect in the BMSC matrix. Similar to fly ash and slag, silica fume (SF), as a common SCMs, is widely used in the application of Portland cement [22,23]. The difference is that silica fume possess a larger specific surface area and higher activity than fly ash and slag. SF is often used in the application of ultra-high performance concrete [24,25]. The previous studies proved that the pH value of the BMSC system was about 10.5 [26]. Therefore, in addition to the possible filling effect of SF in BMSC, its potential activity effect may be excited in the BMSC system. Therefore, there is great of interest to study the influence of SF on the performance, microstructure and hydration mechanism of BMSC.

Therefore, this present work investigated the effect of SF on the properties, mechanical properties and microstructure of BMSC. Firstly, the influences of SF on the setting time, compressive strength and hydration heat evolution of BMSC were studied. XRD, SEM-EDS, MIP, X-CT and NMR were employed to study the effects of SF on the microstructure development and hydration mechanism of BMSC.

2. Experiments

2.1. Raw materials

Light-burned MgO with purity of 80 wt%, was sourced from Haicheng Jinsha Magnesium Mining, Co. Ltd., Liaoning, China. The content of active magnesia (α-MgO) was around 60.0 wt% by the standardized hydration method [27]. MgSO4·7H2O as industrial-grade was provided by Nanjing Chemical Reagent, Co. Ltd., Jiangsu, China. and the purity was 99.0%. The previous research work confirmed that citric acid was able to induce the formation of the main hydration product (5–1–7 phase) in BMSC, as such BMSC demonstrated excellent mechanical properties [13]. Therefore, all the BMSC samples in this work were mixed with citric acid. Citrate acid (C6H8O7) as a chemical admixture was supplied by Aladdin China at purity of 99.5%. Silica fume (SF) was supplied by Suizhong Power Pant, Co. Ltd., Liaoning, China. The chemical compositions of Light-burned MgO and SF were analyzed by X-ray fluorescence (XRF) oxide analysis are given in Table 1. The particle size distributions of Light-burned MgO and SF were performed by Laser Particle Size Analyzer (LPSA) and the results are listed in Fig. 1.

2.2. Specimen preparation

In this study, the mixing ratio of all samples was expressed by molar ratio, and the molar ratio of MgO, MgSO4·7H2O and H2O was fixed at 8:1:20. The amount of SF in the systems were set as SF: the light-burned MgO = 0 wt%, 10 wt%, and 30 wt%.

The addition contents of SF in the specimens were 0 wt%, 10 wt%, and 30 wt% by weight of the light-burned MgO, respectively, and the addition content of citric acid was 0.5 wt% by weight of the light-burned MgO. The preparation process was as follows: Firstly, citric acid was added to the weighed water and stirred to form a solution. After that, the MgO, MgSO4·7H2O and SF batches were dry-mixed for 5 min to form a binder. Subsequently, the solution was added to the binder and stirred at a low speed for 1 min, then at a high speed for 3 min. Finally, the obtained slurry was casted in a PVC mold with a size of 20 × 20 × 20 mm3. After removing bubbles by vibration, the sample was cured (20 ± 3 °C, humidity:60 ± 5%) for 12 h before demoulding.
2.3. Test method

2.3.1. Setting time test

In this work, according to ASTM standard C807-05 “Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle”, the setting time of the BMSC was performed by Vicat needle.

2.3.2. Compressive strength test

After curing for 3 days, 7 days and 28 days, the compressive strength test of hardened BMSC specimens at various ages was performed by a compression testing machine (HYE-300B-C) with a maximum load of 50 kN at a loading rate of 2.4 kN/s.

2.3.3. Isothermal calorimetry test

Hydration heat flows of all samples were monitored by isothermal conduction calorimetry (TA instruments TAM Air) at 20 °C. According to the mix design, powders of MgO, MgSO₄ 7H₂O, citrate and SF were batched into an ampoule and well dry mixed; the corresponding amount of deionized water was stored in a syringe. When the calorimeter reached thermal equilibrium, deionized water was injected into the vessel.

2.3.4. XRD

The crushed specimens were ground into powder (Dₐₙₐ < 80 μm) for phase composition analysis. The crystalline phases of the hydration products of BMSC specimens were identified by an X-rays powder diffractometer (PANalytical X-Pert Pro) with Cu Kα radiation (λ = 0.15419 nm, 40 kV voltage and 30 mA current), over a 2θ range of 5° to 70° with 0.017° step size.

2.3.5. Scanning electron microscope

Microstructures were performed by scanning electron microscope (SEM, JSM-5610LV) coupled with energy dispersive X-ray spectroscopy system (EDX) at a working distance of 8 mm using a silicon drift detector. The sample preparations included mount-}

Table 1

| Raw materials | Mass fraction/% |
|---------------|-----------------|
|               | MgO  | CaO  | SiO₂ | Fe₂O₃ | Al₂O₃ | Na₂O | SO₃ | K₂O | LL |
| MgO           | 79.67 | 1.30 | 6.07 | 0.51  | 0.26  | 0.23 | 0.23 | 0.24 | 11.49 |
| SF            | 2.71  | 1.72 | 92.0 | 0.79  | 0.78  | 0.17 | 1.16 | 0.67 | - |

Fig. 1. Particle size distribution curves of the raw materials.

2.3.6. Mercury intrusion porosimetry test

For pore size distribution and porosity analysis, the samples were initially crushed and cut in small pieces after 28 d of curing and dried at 60 °C for 4 h. Mercury intrusion porosimetry (MIP) analysis was performed using a Micromeritics Autopore V 9600. The maximum pressure applied was 208 MPa, the surface tension was 485 mN/m and the contact angle was 130°.

2.3.7. X-ray computed tomography test

Samples with sizes of 20 × 20 × 20 mm were prepared for micro-CT scans. Micro-CT scans were performed with a micro YXLON Precision 5 X ray CT to determine the cement porosity in a large field of view of mm size range. Scans were performed at 195 kV and 280 μA with 1470 projections (angle step of 0.225° from – 180 to 180°) and a 6 s exposure time per projection.

2.3.8. Solid-state magnetic resonance test

The Brook III Advance III 500 MHz nuclear magnetic resonance (NMR) spectrometer was used for NMR test. The main test parameters are as follows: the field strength was 9.4 T; the operating frequency of ²⁹Si was 79.5 MHz; the control temperature range was –150°C – 180°C, and the temperature control accuracy was about 0.1°C; the resonant frequency of ²⁹Si was 79.5 MHz, and the magic angle rotation speed They are 8 MHz, pulse width was 2 μs, sampling time is 0.0426 s, cycle time was 2 s, and the number of scans was 2000 times.

3. Results and discussion

3.1. Effect of SF on the setting time of BMSC

For the applications of cement, it is very important to understand the setting time. Fig. 2 shows the effect of different dosages
of SF on the setting time of BMSC. As seen from Fig. 2, the BMSC samples with incorporation of various content SF show the different setting time. The setting time of the BMSC sample without SF was 224.4 min. As for samples with SF, the setting time of the BMSC samples increased with the increasing content of SF. When the addition content was increased from 10 to 30 wt%, the setting time of BMSC increased from 226.8 min to 257.4 min. Therefore, the SF addition will retard the hydration of BMSC. This shows that the SF particles in the slurry as a powder filler dispersant the hydration reaction of BMSC. As the addition content of SF increased, the longer the setting time of BMSC was resulted.

3.2. Effect of SF on the compressive strength of BMSC

Fig. 3 shows the effect of the SF addition on the compressive strength of the specimens. The incorporation of SF had a significant effect on the compressive strength of BMSC. In the early and late stages of hydration (3 days and 28 days), the compressive strength of BMSC with 10 wt% SF was the highest indicating that the incorporation of 10 wt% in BMSC was the optimal ratio. However, in the middle stage of hydration, the compressive strength of BMSC increased with the increase in the addition amount of SF (7 days). when the SF content was 10 wt%, 20 wt%, and 30 wt%, the compressive strength increased by 11.4%, 14.9%, and 25.1%, respectively, compared to the control sample. Overall, the incorporation of SF improved compressive strength of BMSC, and its enhancement mechanism would be explained by microstructure and NMR results.

3.3. Effect of SF on the hydration heat of BMSC

Fig. 4 depicts the curve of hydration heat flow of BMSC. Based on the curve characteristics, the setting reaction process of BMSC could be divided into five stages: pre-induction period (I), induction period (II), acceleration period (III), deceleration period (IV), and stable period (V).

Fig. 5 is the hydration exothermic curve of BMSC system with different content of SF. Two exothermic peaks occurred in the hydration exothermic curve of the BMSC sample, the first exothermic peak appears at 0.5 h and the second exothermic peak appears about 13 h. It can be inferred that the first exothermic peak of hydration is due to the release of a large amount of heat when MgO encounters water. At this stage, MgO undergoes a hydrolysis reaction to
produce \([Mg(OH)\cdot H_2O]_{\text{surf}}^+\) and \(OH^-\). This hydration reaction starts at an early stage and the rate is faster, so a considerable amount of heat during hydration was released. The hydration process of MgO is shown in Formula 1:

\[
(MgO + (x + 1)H_2O \rightarrow [Mg(OH)\cdot H_2O]_{\text{surf}}^+ + OH^- (aq))
\] (1)

The second exothermic peak is the hydration heat generated by the hydration reaction of different ions in the BMSC slurry. In this stage, different ions such as \([Mg(OH)\cdot H_2O]^+, Mg^{2+}, SO_4^{2-}\) and \(OH^-\) in the solution react to form 5-1-7 crystal phase. The formation process of 5-1-7 crystal phase is given by Eq. (2).

\[
2[Mg(OH)\cdot H_2O]_{\text{surf}}^+ + SO_4^{2-} + 4Mg^{2+} + 8OH^- \rightarrow 5Mg(OH)_2 \cdot MgSO_4 \cdot 7H_2O(s) + (2x - 7)H_2O
\] (2)

The hydration and heat release curve of BMSC can be expressed by the following formula:

\[
Q(\text{BMSC}) = Q(\text{MgO}) + Q(H)
\] (3)

where \(Q(\text{BMSC})\) is the total exothermic of BMSC, \(Q(\text{MgO})\) is the exothermic of raw material MgO when dissolved in water and \(Q(H)\) is the exothermic of hydration reaction between different ions. According to the characteristics of pore size, the pore distribution of BMSC divides into three ranges, as listed in Table 3. The volume proportions of gel pores (<10 nm) and small capillary pores (10 nm–100 nm) in the control sample were 1.02% and 62.24%, respectively. When the SF content was 10 wt% and 30 wt%, the gel pore volume ratio of BMSC increased to 2.37% and 11.24%, respectively, and the volume ratio of small capillaries pores increased to 86.54% and 80.14%, respectively. In addition, the volume fractions of gel pores (<100 nm) and small capillary pores (10 nm–100 nm) in the control sample were 1.02% and 62.24%, respectively. When the SF content was 10 wt% and 30 wt%, the total porosity of BMSC with SF was lower than that of the control sample (without SF). For example, the total porosity of the BMSC of the control sample was 19.37%. However, the total porosity of the BMSC with 10 wt% and 30 wt% SF decreased to 17.35% and 16.84%, respectively.

3.5. MIP

Fig. 7 plots the pore structure of the BMSC specimens cured for 28 days. It is shown that the micro-pore structure of BMSC varies with the SF addition, the total porosity of BMSC with SF was lower than that of the control sample (without SF). For example, the total porosity of the BMSC of the control sample was 19.37%. However, the total porosity of the BMSC with 10 wt% and 30 wt% SF decreased to 17.35% and 16.84%, respectively.

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3.6. X-CT

In order to visualize the effect of SF on the pore structure of BMSC, three-dimensional reconstruction of the internal pore structure of the sample with 30 wt% SF and without SF was performed, and the three-dimensional reconstruction map is rendered using VG studio software; the three-dimensionally rendered X-CT images is shown in Fig. 8, and the blue indicates small pores (<100 μm), green indicates medium pores (>100 μm–300 μm), and red indicates large pores (300 μm–500 μm).

Fig. 8 shows that when SF was not added, more blue pores and a larger pore distribution density are consisted, which indicates that the porosity is larger and consistent with the previous MIP test results. In addition, green mesopores and red macropores were also found in the three-dimensional rendering without SF, leading to increasing of the porosity of the cement matrix. Compared with
Fig. 7. The effect of SF on the pore structure of BMSC cured for 28 days (a) Pore diameter versus; and Cumulative intruded pore volume (b) Pore diameter versus differential intruded volume.

Table 3

| No     | Average pore diameter (nm) | Pore volume distribution (%) |
|--------|-----------------------------|-----------------------------|
|        |                            | >100 nm | 10 nm–100 nm | <10 nm |
| Control| 42.8                       | 36.74   | 62.24       | 1.02   |
| SF10   | 27.6                       | 11.09   | 86.54       | 2.37   |
| SF30   | 19.4                       | 8.62    | 80.14       | 11.24  |

Fig. 8. X-CT images of BMSC with and without SF. (a) BMSC without SF, (b) BMSC with 30% SF.
the X-CT images without SF, the three-dimensional rendering images of BMSC cement matrix with SF were basically blue pores, and the pore size and density distribution of blue pores were significantly smaller than those of the samples without SF. In addition, only a few mesopores in the sample with SF were present. These mesopores might be caused by agglomeration of MgO particles and uneven mixing of slurry. The results demonstrated that the porosity of the hardened BMSC was significantly reduced by adding SF, and SF mainly plays a role of filling in the BMSC matrix. The results of X-CT agreed well with the MIP results.

3.7. SEM-BSE

Fig. 9 shows SEM-BSE images and elemental maps of BMSC samples incorporated with 30 wt% SF after 28 days of curing. From the elemental map, it was found that the Mg and S elements were homogenously distributed throughout the sample, which indicates that a large amount of 5-1-7 crystal phases were generated. This was consistent with the XRD results. The uniform distribution of the Si element indicates that the SF was embedded in the 5-1-7 crystal phases, resulting in a very dense microstructure of the BMSC sample with SF. In addition, the Mg element map also shows that some unreacted MgO particles were embedded in the 5-1-7 crystal phase, similar to SF, which plays a positive role in improving the microstructure of BMSC, resulting in excellent mechanical properties of SF-BMSC samples. Through grey-scale and elemental map analysis, it was observed that some grains rich in Al and Ca were also embedded in the BMSC matrix. Combining the XRF results of the raw materials (Table 1), this suggested that these Al and Ca-rich grains were impurities in the raw materials (MgO). In addition, it was found from the elemental map that Mg, Si, and S elements existed in some areas at the same time, it was possible that SF has undergone a secondary hydration reaction in the BMSC slurry. Due to the small particle size of SF, the micro-morphology of SF was not clearly captured in the backscatter mode. Whether the SF participates in the secondary hydration reaction in the BMSC matrix, it will be investigated further by the authors in subsequent experiments.

In order to study and explore the influence of SF on the microstructure of BMSC more intuitively, SEM was also used to characterize the microstructure of BMSC, as shown in Fig. 10. A large amount of needle like 5-1-7 crystal phases and residual MgO [28] can be found in the BMSC matrix. When BMSC sample without SF, it can be seen that the 5-1-7 crystal phases in the BMSC matrix were staggered and intersected, so there were many pores between the needle-like crystals. When SF was incorporated, the spherical SF exists in the BMSC matrix and was embedded in the interpenetrating needle like crystals. The morphology shows that the compactness of BMSC matrix was obviously improved by SF, which gives full play to the filling effect of SF. In addition, the enlarged matrix picture shows that the surface of SF particles was very rough, and the surface of globules also has corrosion phenomenon, which indicates that the activity of SF particles was excited in the BMSC system, and a secondary hydration reaction occurs. At this time, it means that SF also plays an active role in the BMSC system.

3.8. NMR

Fig. 11 shows the $^{29}$Si NMR curve of raw material SF and BMSC sample mixed with 30 wt% SF. It can be seen from the figure that the amorphous SiO$_2$ in SF shows polymerized Q$_4$ in the $^{29}$Si NMR
curve, the molecular structure was a three-dimensional network, and the corresponding chemical shift was $-114.4$ ppm. The $^{29}$Si NMR fitting curve of BMSC sample mixed with 30 wt% SF was processed by deconvolution technology. It was found that the chemical shift of the $^{29}$Si NMR spectrum was caused by the addition of 30 wt% SF, and the corresponding three chemical shifts were 97.4 ppm, 100.8 ppm, and 104.4 ppm. After comparative analysis of the spectra, it was found that the chemical shifts of 100.8 ppm and 104.4 ppm were the tetrahedral structure ($Q_3$) and three-dimensional network structure ($Q_4$) at the branch of silicate, respectively. These two chemical shifts overlap with the map of the raw materials, so it was determined that these two chemical shifts were unreacted SF. According to published research, it is found that the molecular structure of hydrated magnesium silicate ($M-S-H$ gel) is different from that of C-S-H gel. The coordination of the siloxane tetrahedron in C-S-H gel is mainly $Q_2$ and $Q_3$, which exists in a chain structure. The coordination of the siloxane tetrahedron in $M-S-H$ gel was mainly $Q_3$, which exists in a layered structure [29,30]. Therefore, in Fig. 11, the chemical shift = 97.4 ppm was the coordination of the silicon-oxygen tetrahedron of $Q_3$, which indicates that SF has undergone a secondary hydration reaction in the BMSC system, and the chemical activity of SF was excited by the hydration product ($Mg(OH)_2$) of the BMSC system, resulting in the formation of secondary hydration product $M-S-H$ gel.

In order to clarify the specific structure of the secondary hydration product $M-S-H$ gel, we can analyze it according to the crystal structure of standard magnesium silicate minerals. Typical magnesium silicate minerals that exist in nature are sepiolite ($Mg_4SiO_13(OH)_6H_2O$), talcum ([($Mg_6$]$Si_8$)$O_{20}$(OH)$_4$), and serpentine ($Mg_6Si_4O_{10}$(OH)$_8$) [31]. Fig. 12 shows the molecular structure of sepiolite, talcum and serpentine and the results of $^{29}$Si NMR analysis [32]. It can be seen from the figure that the molecular structures of three typical magnesium silicate minerals are quite different. Talcum belongs to the monoclinic system. The basic structure layer is a trioctahedral structure composed of [$MgO_4$(OH)$_2$], and the Si-O tetrahedron is co-oxygenated to form a continuous network layer. All active oxygen is directed to one side. Two reticular active oxygen species are connected to each other by an
octahedron. Talcum is a typical layered structure with a 29Si NMR chemical shift of -97.6 ppm (Q2). Therefore, it can be concluded that the secondary hydration product M-S-H gel formed in the SF-BMSC system has a talcum-like structure.

4. Conclusion

(1) The incorporation of SF has obvious effect on the setting time and compressive strength of BMSC. The setting time and compressive strength increases with increasing SF content. From the results of mechanical properties, mixing 10% SF is the optimal ratio for BMSC.

(2) The hydration process of BMSC is divided into five stages (pre-induction period, induction period, acceleration period, deceleration period and stable period). The addition of SF affects the hydration process of BMSC. With the increase of SF content, the induction and acceleration periods of BMSC with SF may gradually extend due to the filler dispersion effect.

(3) The main hydration product of the BMSC sample mixed with or without SF is needle-like 5-1-7 crystal. SF plays a role of filling in the BMSC matrix, which leads to an increase in the compactness of the BMSC matrix. In addition to the filling effect, SF also exerts an active effect in BMSC system. The SF particles are excited by Mg(OH)2 to generate secondary hydration products, a M-S-H gel with a talcum-like structure, which facilitates the formation of interconnected and dense microstructure. Thus, the improvement of mechanical properties is mainly attributed to the microstructure improvement of BMSC by SF.

CRediT authorship contribution statement

Yongsan Tan: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing - original draft. Hongfa Yu: Methodology, Validation, Data curation, Supervision, Funding acquisition, Writing - review & editing. Shikuan Sun: Methodology, Investigation, Formal analysis, Writing - review & editing. Chengyou Wu: Conceptualization, Funding acquisition, Supervision, Writing - review & editing. Hao Ding: Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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