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DOI

[10.1016/j.conbuildmat.2021.122731](https://doi.org/10.1016/j.conbuildmat.2021.122731)

Publication date

2021

Document Version

Final published version

Published in

Construction and Building Materials

Citation (APA)

Yao, X., Liao, H., Dong, H., Yang, F., Yao, Y., & Wang, W. (2021). Influence of water repellent on the property of solid waste based sulfoaluminate cement paste and its application in lightweight porous concrete. *Construction and Building Materials*, 282, 1-11. Article 122731. <https://doi.org/10.1016/j.conbuildmat.2021.122731>

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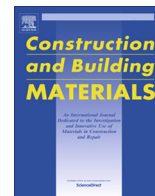
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Influence of water repellent on the property of solid waste based sulfoaluminate cement paste and its application in lightweight porous concrete



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HIGHLIGHTS

- It is feasible to use water repellents reduce the water absorption of LPC based on SW-CSA cement.
- The effect of water repellents on the properties of SW-CSA cement paste was presented.
- Using calcium stearate as the water repellent doesn't affect the hydration of SW-CSA cement.

ARTICLE INFO

Article history:

Received 24 December 2020
 Received in revised form 10 February 2021
 Accepted 12 February 2021

Keywords:

Sulfoaluminate cement
 Water repellent
 Lightweight porous concrete
 Water absorption
 Hydration reaction
 Mechanical property

ABSTRACT

Solid waste-based calcium sulfoaluminate (SW-CSA) cement is a type of low carbon cement that uses solid waste as raw material. It is usually used to prepare lightweight porous concrete (LPC) due to its short setting time. However, high water absorption of LPC based on SW-CSA cement limits its extensive application. Water repellent can be mixed into binder material to reduce the water absorption of LPC, but it may affect the hydration properties of SW-CSA cement paste, which influences the performance of LPC correspondingly. Calcium stearate (CS), sodium oleate (SO) and sodium methyl siliconate (SMS) are three familiar commercial water repellents. To find the suitable internal mixing water repellent for LPC based on SW-CSA cement, the effects of three CS, SO and SMS on the water absorption, hydration, compressive strength, fluidity, and setting time of SW-CSA cement paste were explored. Besides, the properties of LPC with CS and SO added were also studied. The results indicated that using CS as the water repellent could reduce the 1 day water absorption of SW-CSA cement paste by 45.9% and the water absorption of LPC by 33.0%. It also reduced the setting time of SW-CSA cement paste and increased the final compressive strength of LPC, which was conducive to the preferred rapid setting and high compressive strength of LPC. The hydrophobicity of SW-CSA cement paste with SO was better than that of SW-CSA cement paste with CS. But using SO and SMS as the water repellent retarded the early hydration of SW-CSA cement and prolonged the setting time of SW-CSA cement and reduced the final compressive strength of SW-CSA cement paste. Therefore, SO and SMS can't be used as the internal mixing water repellent of LPC based on SW-CSA cement, while CS is a promising internal mixing water repellent of SW-CSA cement to prepare LPC.

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1. Introduction

Lightweight porous concrete (LPC) is a promising low energy consumption material with a coarse pore structure. The coarse

pore structure results in a low density (400–1600 kg/m³) and low thermal conductivity (0.12–0.66 W/m·K) [1,2], which not only reduce the consumption of raw material but also can reduce the heat loss during the operation of the building. The most commonly LPC is autoclaved aerated concrete (AAC) and foamed concrete, neither of which contains coarse aggregates. AAC is produced from a few binders, lime and supplementary cementitious material pow-

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der. It needs to be cured at high-temperature and high-pressure for quick development of the mechanical strength. A lot of energy is consumed during the manufacturing process of AAC. Foamed concrete doesn't need autoclaved curing because the cementitious material of it is Portland cement. However, the compressive strength of foamed concrete is lower than that of the AAC. Moreover, the slow development of compressive strength also affects the production efficiency of foamed concrete. Thus, it is important to develop a LPC that doesn't need to be autoclaved but can quickly harden.

Many studies have used solid waste to prepare the solid waste-based sulfoaluminate (SW-CSA) cement because of its environment-friendly raw materials, low energy consumption and CO₂ emission [3–6]. More importantly, SW-CSA cement exhibits some unique properties such as rapid setting and high early strength. Thus, using SW-CSA cement to prepare LPC can also accelerate the setting and increase its early compressive strength. Furthermore, the LPC based on SW-CSA cement is cured at room temperature and humid environment. It doesn't need autoclaved curing, which further reduces the emission of CO₂. However, similar to AAC and foamed concrete, the high porosity of LPC based on SW-CSA cement also results in high water absorption. Poor water and moisture resistance seriously affect the mechanical properties and durability of concrete [7–9]. Thus, reducing the water absorption is critical for the application of LPC.

The waterproofing methods of LPC mainly include external coating and internal mixing [10–12]. External coating is achieved by spraying the water repellent on the LPC surface or dipping the LPC in the water repellent. It is applied after the full hardening of LPC. Therefore, water repellents just influence the water absorption but not the hydration property of LPC in the external coating method. The internal mixing method is achieved by mixing water repellent with fresh mixture. Comparing with the external coating method, when a water repellent is mixed with raw materials, it not only reduces the water absorption of LPC but also influences the hydration and mechanical properties of binder, which cause the change of the physical and mechanical properties of LPC.

Calcium stearate (CS), sodium oleate (SO), and sodium methyl silicate (SMS) are all water repellents commonly used in engineering. They are successfully used in paste or concrete based on Portland cement [11,13]. Some researchers also investigated the influence of CS, SO and siloxane on the properties of LPC based on SW-CSA cement in the internal mixing method [14–17]. They concluded that different water repellents effectively changed the properties of LPC, such as moisture absorption capacity, compressive and bending strength, volumetric density, size of pores, and humidity degree. These properties of LPC were closely related to the properties of cementitious material paste [18,19]. However, they only investigated the effect of water repellent on the properties of LPC, but few researchers revealed the reason of these changes from the perspective of cement paste. Thus, the influence of water repellents on the properties of SW-CSA cement paste should be investigated.

In order to explore the effect of water repellent on the properties of SW-CSA cement paste and LPC in the internal mixing method, three commercial anionic surfactants, including CS, SO, and SMS, were used to prepare the SW-CSA cement paste and LPC in this research. The water absorption, hydration, setting time, fluidity, and compressive strength of SW-CSA cement paste with different water repellents addition were studied. Then, based on the research results, LPC was prepared using SW-CSA cement added with different amounts of SO or CS. The effects of water repellents on density, water absorption, and compressive strength of LPC were also investigated.

2. Experiment

2.1. Raw materials

SW-CSA clinker was prepared from industry solid wastes in the laboratory, the preparation process was shown in previous studies [20,21]. The stoichiometric raw materials of C₄A₃–, CaSO₄, C₂S, and C₄AF were prepared by crushing the industry solid wastes in an agate mortar for 30 min. The mixtures were sintered at 1250 °C for 30 min. The samples were immediately cooled at 20 °C to obtain SW-CSA clinkers. The chemical composition of SW-CSA clinker is shown in Table 1 and the XRD pattern are shown in Fig. 1. The phases of this SW-CSA clinker were C₄A₃–S, C₂S, and a little amount of C₄AF, CaSO₄, and C₂AS. 15 wt% flue gas desulphurization gypsum was then blended with SW-CSA clinker to get SW-CSA cement, which was used as the cementitious material of LPC. The physical and mechanical properties of the SW-CSA cement were also shown in Table 1. Both the compressive strength and the flexural strength after 28 days were obtained by testing the SW-CSA cement mortar according to GB/T 20472-2006[22].

When preparing the LPC, SW-CSA cement with 0.2 wt% polycarboxylate superplasticizer (Qjhe Xinronghe Chemical Co., Ltd., Shandong, China) was used as cementitious material. Three powder chemical reagents, including CS (Macklin Reagent Co., Ltd., Shanghai, China), SO (Macklin Reagent Co., Ltd., Shanghai, China), and SMS (Sinopharm Group Chemical Reagent Co., Ltd., Shanghai, China), were used as water repellents to mix with SW-CSA cement because they were usually used in the commercial concrete. Chemical-grade hydrogen peroxide (30 wt%, Shanghai Titan Technology Co., Ltd., Shanghai, China) was used as foaming agent. Chemical-grade absolute ethyl alcohol (Sinopharm Group Chemical Reagent Co., Ltd., Shanghai, China) was used to stop the hydration reaction of SW-CSA cement paste.

Then, SW-CSA cement mixtures with 0, 0.2, 0.4, 0.8 and 1.2 wt% CS added were designed and termed as CS-0, CS-2, CS-4, CS-8 and CS-12, respectively. Similarly, SO-0, SO-2, SO-4, SO-8 and SO-12, SMS-0, SMS-2, SMS-4, SMS-8 and SMS-12 were also designed and termed.

2.2. Preparation of SW-CSA cement paste cube and LPC

2.2.1. Preparation of SW-CSA cement paste cube

According to mix design, some water repellent contents were added into SW-CSA cement and mixed well. Paste cubes with dimensions of 20 mm × 20 mm × 20 mm were cast with a water to cement (w/c) ratio of 0.30 using the mixture. They were then cured by immersing in the water at 20 ± 1 °C for 1 day and 28 days until the measurement of their properties.

2.2.2. Preparation of hydration experiment samples

Hydration products of different modified SW-CSA cement were identified at the curing age of 1 day and 28 days. To provide enough water for the hydration reaction, modified SW-CSA cement paste slurry was prepared at a w/c ratio of 0.60. Then, the slurry was cured in a sealed container at 20 ± 1 °C until the measurement. Cement hydration was stopped by successively immersing the crushed paste into absolute ethyl alcohol. Then, they were dried in a drying oven to a constant weight at 40 ± 5 °C. Finally, paste samples were ground in absolute ethyl alcohol and dried for the X-ray diffraction and thermogravimetric measurement.

2.2.3. Preparation of LPC

A certain amount of water repellent was weighed and mixed well with 0.2 wt% superplasticizer and SW-CSA cement to be the cementitious materials of LPC. Then, water was added into the

Table 1
Chemical and physical properties of the SW-CSA cement.

Oxide	Chemical Composition (wt.%)		Physical properties of SW-CSA cement	
	SW-CSA clinker	FGD gypsum		
CaO	39.9	34.1	Particle size (D_{50} , μm)	16.4
Al_2O_3	26.0	0.2	Specific gravity (kg/m^3)	2942.2
SiO_2	7.6	0.3	28 days compressive strength (MPa)	64.7
SO_3	13.5	49.1	28 days bending strength (MPa)	8.4
Fe_2O_3	9.1	0.12	Initial setting time (Min)	45
LOI ^a	—	16.1	Final setting time (Min)	80

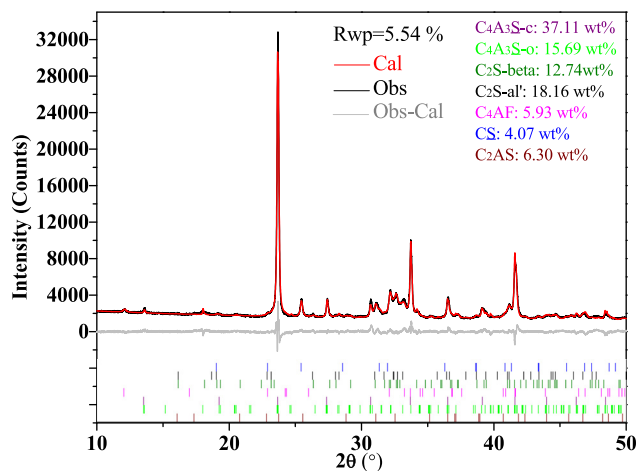


Fig. 1. XRD pattern and Rietveld refinement plots of SW-CSA clinker.

cementitious material at a w/c ratio of 0.36. The slurry was stirred quickly in a blender for 120 s until the slurry was uniform and flowed continuously. Afterward, hydrogen peroxide was added as a source of air during the pore formation process. The slurry was immediately stirred again in the blender for 15 s. Next, the slurry was poured into 100 mm × 100 mm × 100 mm molds, and the top of the mold was covered to obtain LPC blocks of the corresponding size. They were demolded after 4 to 6 h. Finally, the blocks were cured in humid air with relative humidity (RH) above 95% and a temperature of 20 ± 1 °C. In this section, three specimens were prepared for each mixture.

2.3. Characterization method

2.3.1. Contact angle

After 28 days of curing, three paste cubes for each mixture were taken out and dried at (60 ± 5) °C to a constant weight. Next, they were cut and sanded to obtain a relatively smooth surface. Then the contact angles between the water droplets and the hardened paste surface were determined at room temperature with the contact angle meter (JC2000X6, Zhongchen, Shanghai) using the sessile drop method and Ellipse fitting method. The contact angle between the flow interface and the solid interface at the junction of three phases was automatically measured by the tangent method on the droplet images. When a water drop contacted the cube surface for 1 min, the angle was measured and named as their contact angle.

2.3.2. Water absorption

The cured specimens with 100 mm × 100 mm × 100 mm were dried at (60 ± 5) °C to a constant weight and marked as m_g . Next, the specimens were placed in a water bath at (20 ± 5) °C, and then water was added to 1/3 of the specimen height to keep for 24 h.

Water was added to 2/3 of the height of the samples. After 24 h, the water was 30 mm higher than the specimen and remained 24 h. Finally, each surface of the specimen was wiped up twice using dry towels and 1 min at a time. Finally, the blocks were weighed immediately and named as m . The relative percentage of absorptive-water volume w was thus calculated according to the Eq. (1).

$$w = \frac{m - m_g}{\rho_w V_0} \quad (1)$$

Here, w represents the relative percentage of absorptive-water volume of LPC; ρ_w denotes the density of water; V_0 denotes the volume of LPC.

Differently to the water absorption measurement method of LPC, the paste cubes with the size of 20 mm × 20 mm × 20 mm were used to test the relative percentage of the absorptive-water volume of SW-CSA cement paste. Except for the height of the water and testing age, other procedures were the same as the measurement method of water absorption for LPC.

2.3.3. Isothermal calorimetry

An eight-channel TAM AIR isothermal calorimeter equipped with an admix ampoule was used to test the hydration heat of the modified SW-CSA cement. Experiments were performed using 2 g cement with 1 g water. The heat flow and cumulative heat were recorded for 72 h at a constant temperature of 20 °C.

2.3.4. X-ray diffraction

The mineral compositions of different hydration products of SW-CSA cement were identified using an X-ray diffractometer (Aeris, MalvernPanalytical, Netherlands) with Cu-K α radiation at 40 kV and 15 mA. The XRD patterns were gotten with a scanning speed of 1.2 °/min over a 35-min period in the 2θ range of 8–50 °.

2.3.5. Thermogravimetric analysis

Simultaneous thermogravimetric and differential scanning calorimeter (TG-DSC, Mettler Toledo TGA/DSC 1/1600) was used to heat the hydration product of different modified SW-CSA cements. All samples were heated in a nitrogen gas atmosphere from 30 °C up to 600 °C at a heating rate of 10 °C/min.

2.3.6. Setting time and fluidity of SW-CSA cement paste

The setting time of the SW-CSA cement paste was determined using the Vicat apparatus according to Chinese standard GB/T 1346-2011[23]. The fluidity of SW-CSA cement paste was measured according to Chinese standard GB/T 8077-2012[24]. In this measurement, the SW-CSA cement paste was prepared with a w/c ratio of 0.36, which is the same as the w/c ratio of LPC.

2.3.7. Compressive strength of SW-CSA cement paste and LPC

The compressive strengths of different SW-CSA cement paste cubes and LPC blocks were tested by two electronic universal testing machines at the curing age of 1 day and 28 days. The paste

cubes were tested at a loading rate of 2.5 ± 0.5 kN/s, while the LPC blocks were tested at a loading rate of 0.5 ± 0.1 kN/s.

3. Results and discussion

3.1. Effect of water repellents on the hydrophobicity and water absorption of SW-CSA cement paste

When different water repellents are mixed with the SW-CSA cement, the water absorptions of paste are also obtained by measuring the relative percentage of absorptive-water volume. As shown in Fig. 2, when SMS is used as the water repellent of SW-CSA cement in the internal mixing method, with the increase of SMS, the water absorption of the specimen only reduces by less than 1%. Therefore, using SMS as a water repellent has a limited effect on reducing the water absorption of SW-CSA cement.

When CS is used as a water repellent, with the increase of CS content, the water absorptions of modified SW-CSA cement paste at 2 h drop from 7.63% to 4.13%, which is a decrease of about 45.9%. Similarly, the water absorption of SW-CSA cement paste with SO added decreases by 51.7%. Similarly, with the increase of CS or SO, the water absorption of specimens at 1 day also decreases. Furthermore, the water absorption of SW-CSA cement paste with SO added is higher than that of CS added. To explain the reason of these changes, the hydrophobicity of SW-CSA cement paste was investigated.

The magnitude of contact angle of water reflects the hydrophobicity of the solid specimens. The larger contact angle means the SW-CSA cement has better hydrophobicity. Fig. 3 and Fig. 4 show the contact angles of water to SW-CSA cement paste with different types and amounts of water repellent added. As shown in Fig. 4(a), after water droplets contacting with the paste surface, the contact angles of water to the SW-CSA cement paste with different CS decrease dramatically within 10 s. After 10 s, the changes in contact angle decrease gradually to be stable levels. Thus, stable contact angles at 60 s are used as the contact angle of water to SW-CSA cement paste.

As shown in Fig. 3 and Fig. 4(b), the contact angles without water repellent addition are about 25° . It is because the capillary pores of the contact surface of water and paste are filled with water in a short time, the flow velocity of water in the capillary pores

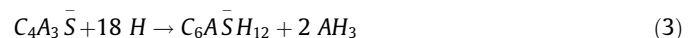
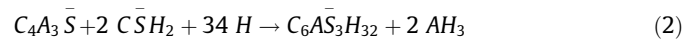
becomes very small, thereby forming a relatively stable contact angle. When some amounts of SO or CS are added into the mixture, the contact angles correspondingly increase with the increasing amount of water repellents regardless of the type. The maximum contact angle is up to 82° , but it is less than 90° . It means that the SW-CSA cement paste with SO or CS added is still not hydrophobic, but SO or CS can increase the hydrophobicity of SW-CSA cement paste. In addition, the hydrophobicity of paste with CS added is better than that of SO added, but the paste with CS added presents larger water absorption than the paste with SO added at 1 day. The different effects of CS or SO may be related to their solubility. SO is soluble in water and can be more evenly distributed in cement paste, while CS is insoluble and agglomerates in cement. Thus, the water absorption rate of paste with SO is lower than that of CS after 1 day immersion. Besides, regardless of the type and amount of water repellent, the water absorptions of modified SW-CSA cement paste at 28 days have little difference. Thus, according to the water absorption of modified SW-CSA cement paste, SO presents a better effect to reduce the water absorption than CS for SW-CSA cement paste in the internal mixing method.

When SMS is used as the water repellent of SW-CSA cement paste in the internal mixing method, the contact angles increase slightly with increasing in SMS content. However, they are much smaller than the contact angle of water to paste with the same SO or CS added. Thus, the water absorption of SW-CSA cement paste with SMS added remains almost unchanged at 2 h.

In a word, CS and SO can be used as the water repellent of SW-CSA cement in the internal mixing method. They can improve the hydrophobicity and reduce the water absorption of SW-CSA cement paste. SMS has minor effect on reducing the water absorption and improving the hydrophobicity of SW-CSA cement paste.

3.2. Effect of water repellent on the hydration reaction of SW-CSA cement

When water repellent is added into SW-CSA cement, it may affect the hydration reaction of SW-CSA cement. The hydration performance of SW-CSA cement with different water repellents is presented. The hydration reactions of SW-CSA cement are shown as Eqs. 2–4. When gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, $\text{C}\bar{\text{S}}\text{H}_2$) exists in the SW-CSA cement, it will react with ye'elimite ($\text{C}_4\text{Al}_6\text{O}_{12}\text{SO}_4$, $\text{C}_4\text{A}_3\bar{\text{S}}$) and water (H_2O , H) to form ettringite ($\text{C}_6\text{Al}_2\text{S}_3\text{O}_{18} \cdot 32\text{H}_2\text{O}$, $\text{C}_6\text{A}\bar{\text{S}}_3\text{H}_{32}$) according to Eq. (2). After complete consumption of gypsum, ye'elimite can also react with water to form monosulfate ($\text{C}_6\text{Al}_2\text{SO}_{12} \cdot 12\text{H}_2\text{O}$, $\text{C}_6\text{A}\bar{\text{S}}\text{H}_{12}$) as shown in Eq. (3). Besides, brownmillerite ($\text{C}_4\text{Al}_2\text{Fe}_2\text{O}_{10}$, C_4AF) reacts with water according to Eq. (4) at the early hydration process. Belite (C_2SiO_4 , C_2S) also reacts with water according to Eq. (5), which is responsible for the later strength development.



3.2.1. Early hydration activity

Although the hydration reaction of SW-CSA cement is already known, when water repellents are mixed with SW-CSA cement, the hydration properties of modified SW-CSA cement are changed. The hydration heat flow and cumulative heat curves of different

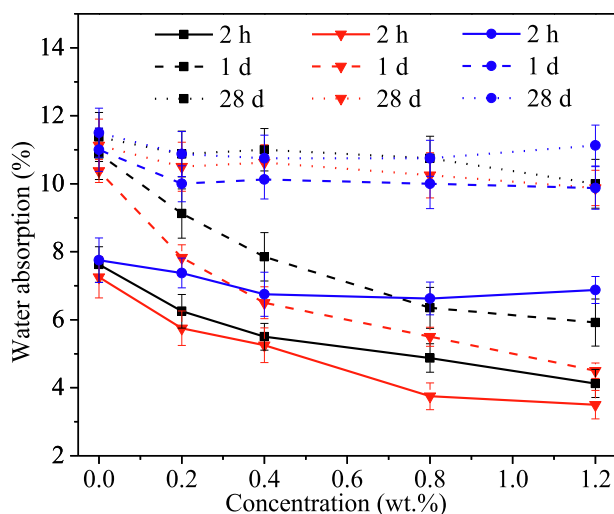


Fig. 2. Relative percentage of absorptive-water volume of SW-CSA cement paste with different water repellents (Black: CS; Red: SO; Blue: SMS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

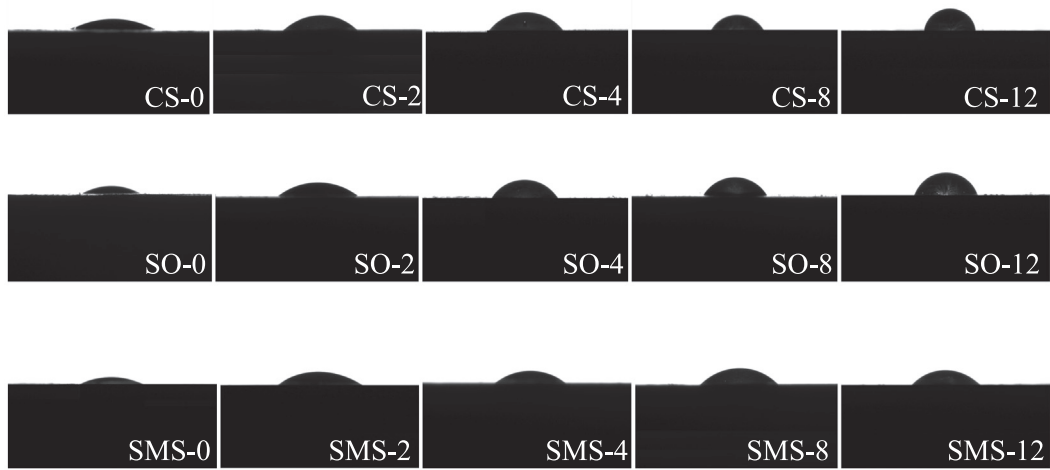


Fig. 3. Contact angles of water to modified SW-CSA cement paste with different water repellents.

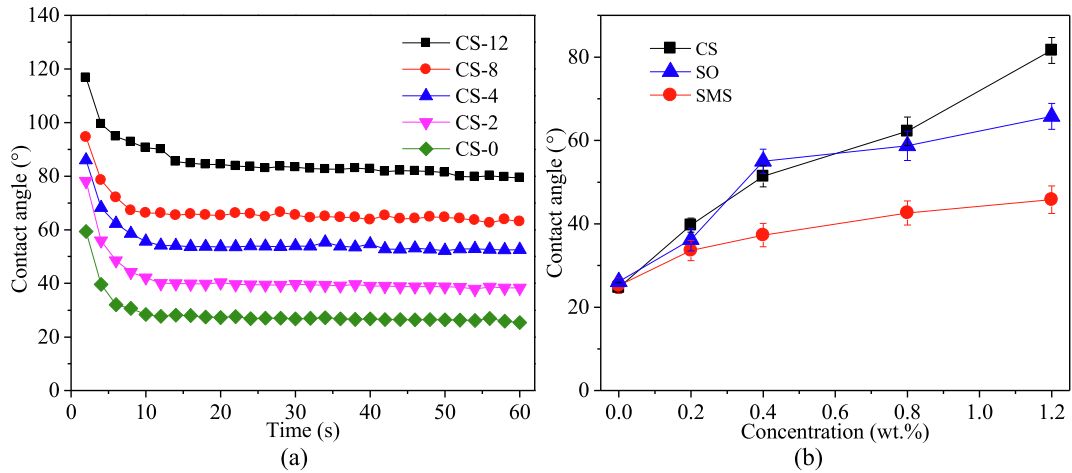


Fig. 4. Contact angles of water to modified SW-CSA cement paste (a: variation of contact angles with the time, b: different types and amounts of water repellent).

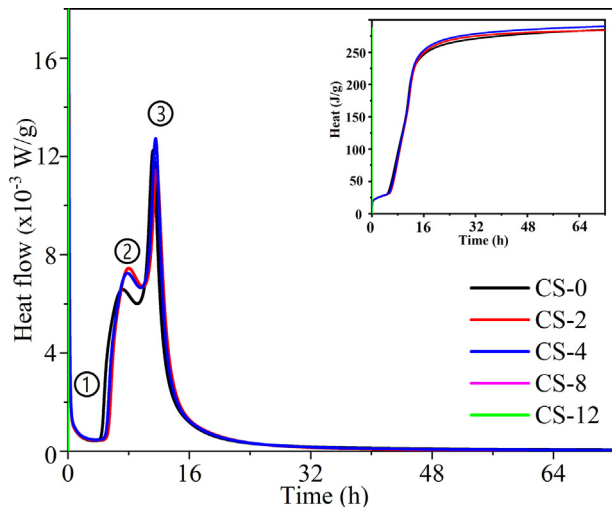


Fig. 5. Cumulative heat and heat flow of SW-CSA cement with different CS contents.

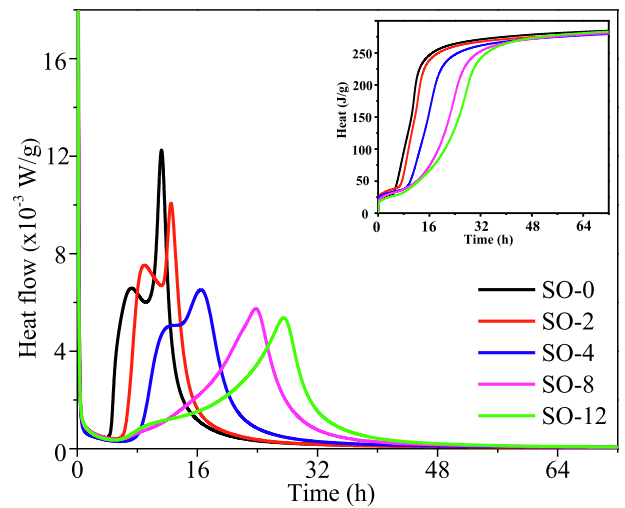


Fig. 6. Cumulative heat and heat flow of SW-CSA cement with different SO contents.

mixtures within the first 72 h are shown in Figs. 5–7. As shown in Fig. 5, the first peak at the beginning mainly attributes to the dissolution of anhydrous phase in SW-CSA cement, which is named as the initial period. After an induction period of low thermal activity, the second peak is observed. It is because ye'elimite quickly reacts with gypsum to form ettringite when gypsum is sufficient according to Eq. (2). Afterward, the third heat flow peak caused by a renewed fast formation of ettringite is observed. In this process, ye'elimite is quickly consumed again, while little gypsum participates in the reaction due to a little amount of gypsum remained [25]. It should be noted that no matter how much CS is added, the cumulative heat and heat flow for different mixtures are almost the same. Thus, CS doesn't affect the early hydration reaction of SW-CSA cement.

When different amounts of SO or SMS are added into SW-CSA cement, the hydration heat flow curves are diverse. As shown in Fig. 6, when the amount of SO is less than 8 wt%, although only a slight shoulder exists in the heat flow curve, there are still two peaks after the induction period. When 8 wt% and 12 wt% are added into SW-CSA cement, only a significant heat flow peak is visible. Furthermore, with the increase of SO, the heat flow peaks gradually shift backward and the hydration reactions slow down. It is because SO reacts with calcium ions to form calcium oleate precipitate, which consumes some calcium ion from gypsum [26]. Besides, the solubility of SO makes it easier to adhere to the surface of the cement particle at a short time, which retards the hydration reaction between cement and water [27]. However, although the reaction rates of different mixtures are different in early hydration time, the cumulative heats during 72 h are almost the same. When the amounts of SMS added increase from 0 wt% to 12 wt%, as shown in Fig. 7, the cumulative heats of different mixtures during 72 h are the same, and after that the hydration reaction rates slow down. Polymeric silicate formed from SMS chokes up or seals the pores in the system, which also reduces the permeation of water in the matrix [28,29]. Thus, SMS also delays the hydration reaction rate of SW-CSA cement.

In a word, CS doesn't influence the early hydration of SW-CSA cement, while SO or SMS retards the early hydration of SW-CSA cement. Furthermore, when the same amounts of SO or SMS are added into SW-CSA cement, the hydration reaction rate of the mixture with SMS is slower than that with SO.

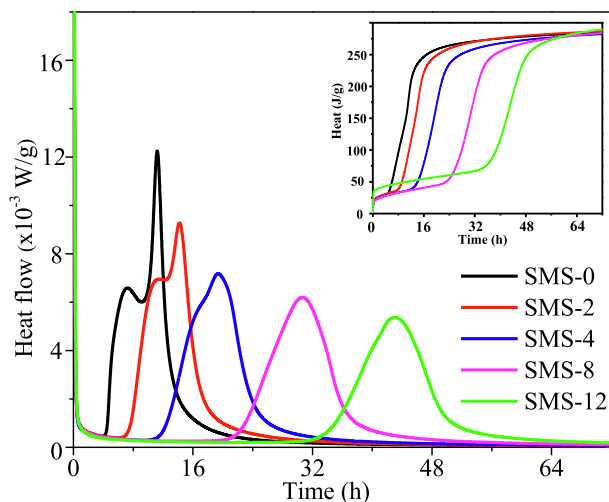


Fig. 7. Cumulative heat and heat flow of SW-CSA cement with different SMS contents.

3.2.2. Hydration products

When water repellents were mixed with SW-CSA cement, the hydration products at 1 day and 28 days were tested by XRD. The results are shown in Figs. 8–10. The weight loss between 50 °C and 120 °C is corresponding to water loss of ettringite. Afterward, the peaks of the dehydration of gypsum are observed at around 130 °C. Third peaks reflect the dehydration of strätlingite. Finally, the fourth peaks mean the decomposition of $\text{Al}(\text{OH})_3$ between 220 °C and 300 °C. When the amount of gypsum is sufficient, ettringite is formed through the hydration reaction. As gypsum decreases, monosulfate is gradually formed during the hydration process [30].

When different CS contents are mixed with SW-CSA cement, as shown in Fig. 8a and Fig. 8c, the hydration product types of different specimens are almost the same after 1 day and 28 days. However, with increasing in CS content, the amounts of the hydration products increase slightly after 1 day and 28 days, according to Fig. 8b and Fig. 8d. With the increase of CS content, the hydration heat of the mixture increases within 24 h, which are consistent with the change of hydration product content after 1 day. Thus, CS doesn't hinder the progress of the hydration reaction of SW-CSA cement, regardless of early or final hydration.

As shown in Fig. 9, when SO is used as a water repellent and mixed with SW-CSA cement, the type of hydration products are the same as that of SW-CSA cement, but there is some difference in the amount of hydration products at 1 day. With increasing in SO content in the mixture, according to Fig. 9a and b, the amounts of hydration product decrease, which is consistent with the results from the hydration rate of SW-CSA cement with SO. After 28 days, the heat losses of different samples are almost the same. Thus, using SO as a water repellent has little influence on the final hydration product of SW-CSA cement.

According to the change in hydration heat, when SMS is used as a water repellent in the internal mixing method, it significantly retards the early hydration of SW-CSA cement. Similarly, as shown in Fig. 10a and b, with the increase of SMS content in the mixture, the amount of hydration products at 1 day significantly reduces. When SMS content exceeds 4 wt%, there is little of ettringite formed at 1 day in specimens SMS-4, SMS-8, and SMS-12. In addition, as shown in Fig. 10c, except for SMS-8, the peaks corresponding to gypsum almost disappear, which means that gypsum has been completely consumed at 28 days of hydration. Furthermore, as shown in Fig. 10d, with the increase of SMS content in mixture, the amount of hydration products at 28 days increases. Thus, using SMS as a water repellent in the internal mixing method retards the early hydration, but doesn't affect the final hydration reaction.

In words, using CS as a water repellent has little effect on the hydration of SW-CSA cement. Using SO or SMS as a water repellent also doesn't harm the final hydration of SW-CSA cement but retards the early hydration of SW-CSA cement. When SW-CSA cement is used as cementitious material to prepare aerated concrete, a slower early hydration rate will affect the stability of the pores in the slurry. Therefore, CS is more suitable as a water repellent of SW-CSA cement than SO and SMS during the preparation process of aerated concrete.

3.3. Effect of water repellents on the mechanical properties of SW-CSA cement paste

When water repellent is mixed with SW-CSA cement, it will influence the setting time, fluidity and compressive strength of cementitious material, which will affect the preparation process and properties of LPC. The influence of water repellents on the setting time, fluidity, and compressive strength of SW-CSA cement paste are presented in this section.

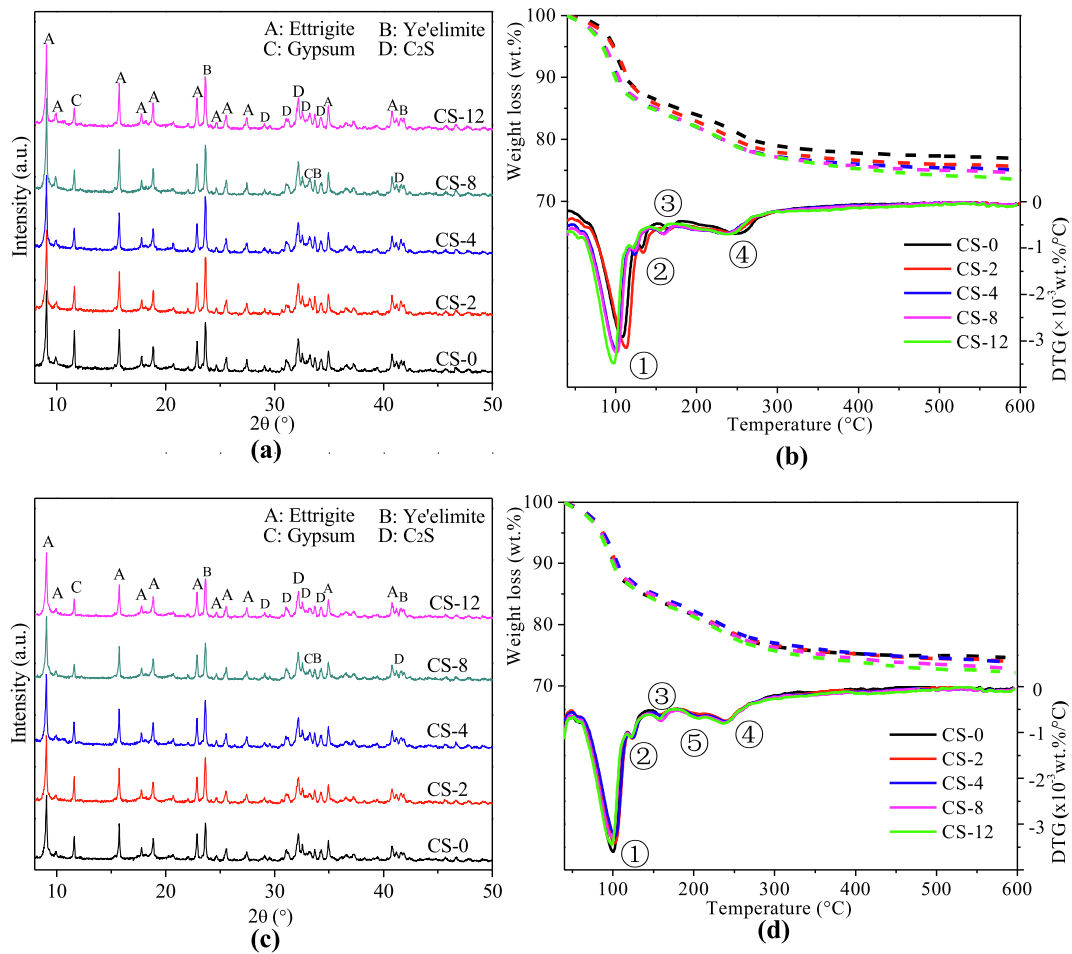


Fig. 8. XRD patterns of hydration products for SW-CSA cement with CS (a and b: 1 day; c and d: 28 days).

3.3.1. Setting time and fluidity

The setting time and fluidity of SW-CSA cement paste with different water repellents are shown in Fig. 11 and Fig. 12, respectively. With the increase of CS content in SW-CSA cement, both of the setting time and fluidity of SW-CSA cement paste decrease. It is because that CS powder is hydrophobic and insoluble in water. Some water drops are covered by CS powder, which also reduces the w/c ratio in SW-CSA cement. Thus, the setting time and fluidity of SW-CSA cement reduce. When SO or SMS is used as the water repellent in SW-CSA cement, the hydration rates of SW-CSA cement decrease, leading to decrease in the formation rate of ettringite and consumption rate of water correspondingly. Thus, the initial setting time and final setting time of SW-CSA cement paste increase. In addition, SO and SMS are soluble in water, when they are mixed in SW-CSA cement, the water volume maintains unchanged. So the fluidity of SW-CSA cement paste has little changes.

3.3.2. Compressive strength

When different water repellents are mixed with SW-CSA cement, the compressive strengths of SW-CSA cement paste are shown in Fig. 13. With the increase of CS content in SW-CSA cement, 1 day compressive strength of SW-CSA cement paste decreases from 67.3 MPa to 54.8 MPa. When 0.1 wt% and 0.2 wt % CS are added into mixture, 28 days compressive strength of SW-CSA cement pastes remain almost unchanged. When the mix-

ing content of CS increase from 0.4 wt%, the 28 days compressive strength of SW-CSA cement pastes decrease slightly. However, the hydration degree of SW-CSA cement at 1 day is the same and the amount of hydration product for SW-CSA cement increases after 28 days curing. The changes in compressive strength and hydration degrees are inconsistent. The reason may be that CS can add the air content in SW-CSA cement paste [26], which can reduce the compressive strength slightly. When SO is used as the water repellent, 1 day compressive strength of SW-CSA cement paste decreases, which is consistent with the changes in hydration degree and hydration product amount of SW-CSA cement. Although SO can react with Ca²⁺ forming calcium oleate precipitates to occupy the pore volume of SW-CSA cement paste, this also produces some air content in the paste [31], which makes the 28 days compressive strength of SW-CSA cement paste also decrease after mixing with SO. When SMS is used as a water repellent, with the increase of SMS in SW-CSA cement, the 1 day compressive strength of SW-CSA cement paste decreases, which is consistent with the changes in the hydration degree of SW-CSA cement with SMS. The amounts of 28 days hydration products for SW-CSA cement does not reduce, but 28 days compressive strength of SW-CSA cement paste with SMS reduce from 89.2 MPa to 60.2 MPa. SMS achieve the hydrophobicity by generating a hydrophobic film on the surface of cement particles but has little effect on the filling of pores. Thus, the 28 days compressive strength of SW-CSA cement pastes with SMS doesn't increase

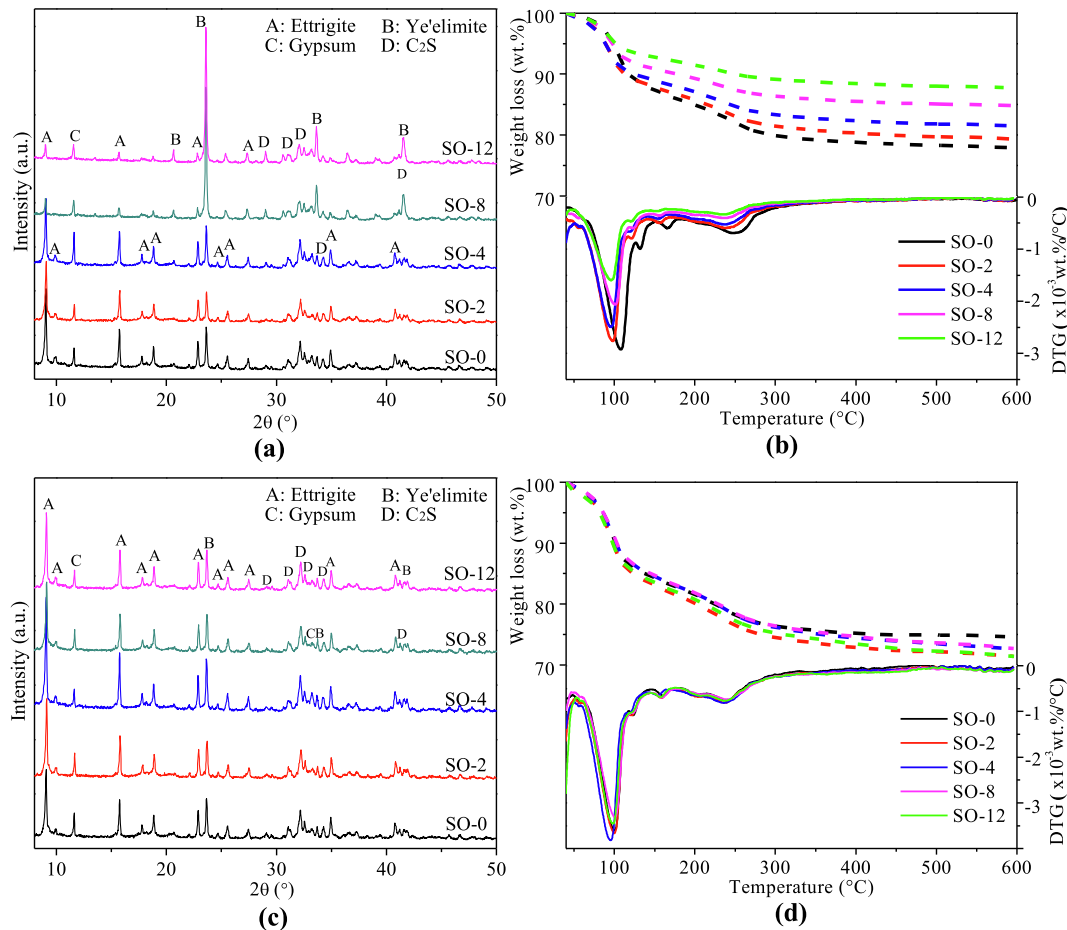


Fig. 9. XRD patterns of hydration products for SW-CSA cement with SO ((a and b: 1 day; c and d: 28 days).

due to the increased amount of hydration products. Thus, all of three water repellents make the compressive strength of SW-CSA cement paste reduce.

3.4. Effect of water repellents on water absorption and compressive strength of LPC

When SMS is used as a water repellent by the internal mixing method, it only slightly reduces the water absorption of the SW-CSA cement paste. Moreover, the compressive strength of SW-CSA cement paste with SMS added is significantly reduced compared with that of CS and SO added. Thus, CS or SO is only mixed with SW-CSA cement to prepare LPC. The dry density, 28 days compressive strength, and water absorption of LPC with different water repellents are shown in Fig. 14. As shown in Fig. 14, when the densities of LPCs maintain between 600 and 620 kg/m³, with increasing in CS content, the compressive strength of LPC with CS added increases by 1.10 MPa and the water absorption of LPC decreases by 33.0%. When the amount of SO in LPC increases from 0 to 1.2 wt%, the water absorption of LPC reduces by 24.2%, which isn't consistent with the water absorption reduction of cement paste. When CS is used as additive in LPC, it is not only a water repellent but also used as a surfactant to increase the viscosity of cement slurry [32]. The higher viscosity of SW-CSA cement slurry can improve the stability of bubbles. Thus, the number of closed pores increases in the LPC block, which leads to reduction of water absorption. In addition, when CS increases from 0 to 1%, the compressive strength and water absorption of LPC change dramatically. With the increase of CS, the changes in strength and water absorp-

tion gradually become smaller. When SO added into LPC, the compressive strength of LPC is almost unchanged, which means that although calcium oleate precipitation can fill some micropores in the matrix, comparing to LPC with CS added, high open porosity of LPC with SO added leads to high water absorption and low compressive strength of LPC.

In a word, CS is not only a suitable internal mixing water repellent on SW-CSA cement paste but also beneficial to the compressive strength and water absorption of LPC. Thus, CS is a more suitable internal mixing water repellent than SO and SMS.

4. Conclusion

Using CS, SO or SMS as the water repellent significantly influences the properties of SW-CSA cement materials. It not only affects the water absorption but also influences the hydration and mechanical properties of SW-CSA cement paste, which can result in different properties of LPC.

Using CS as the water repellent can increase the hydrophobicity of SW-CSA cement paste and reduce the 2 h and 1 day water absorption of SW-CSA cement paste by 45.9% and 45.6%. The water absorption of LPC with CS added also decreased by 33.0%. In addition, although CS has little effect on the hydration and compressive strength of SW-CSA cement paste, it increases the compressive strength of LPC due to high viscosity of cement slurry after CS added. Furthermore, CS can also reduce the setting time and fluidity of SW-CSA cement paste, which is beneficial for the preferred rapid setting and high compressive strength of LPC.

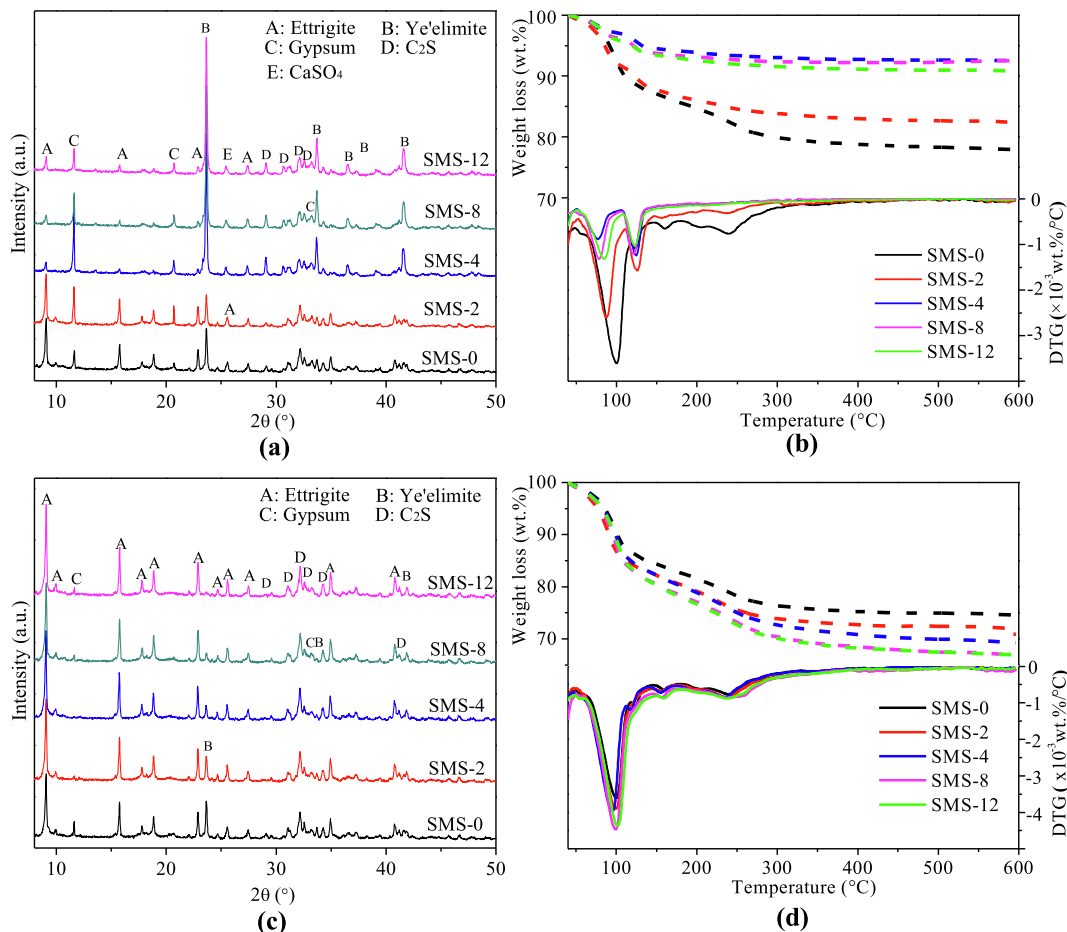


Fig. 10. XRD patterns of hydration products for SW-CSA cement with SMS ((a and b: 1 day; c and d: 28 days).

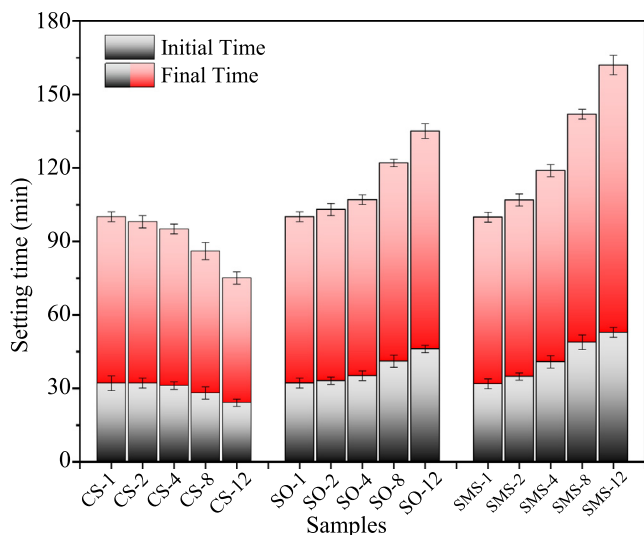


Fig. 11. Setting time of SW-CSA cement paste with different water repellents.

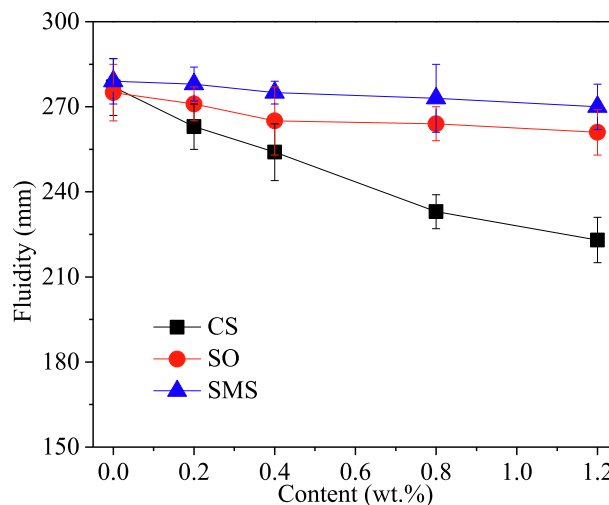


Fig. 12. Fluidity of SW-CSA cement paste with different water repellents.

When SO is used as the water repellent of SW-CSA cement, SW-CSA cement paste presents better initial hydrophobicity than that of CS added, but the LPC with SO added has higher water absorption than that with CS added. Furthermore, using SO as the water repellent retards the early hydration and prolongs the setting time of SW-CSA cement, which is not conducive to the preparation of LPC.

When SMS is mixed with SW-CSA cement, it not only retards the hydration reaction of SW-CSA cement but also reduces the compressive strength of SW-CSA cement paste. Furthermore, using SMS as the internal mixing water repellent has little effect on the hydrophobicity of SW-CSA cement paste. The effects of SMS on SW-CSA cement paste aren't conducive to the preparation and performance improvement of LPC.

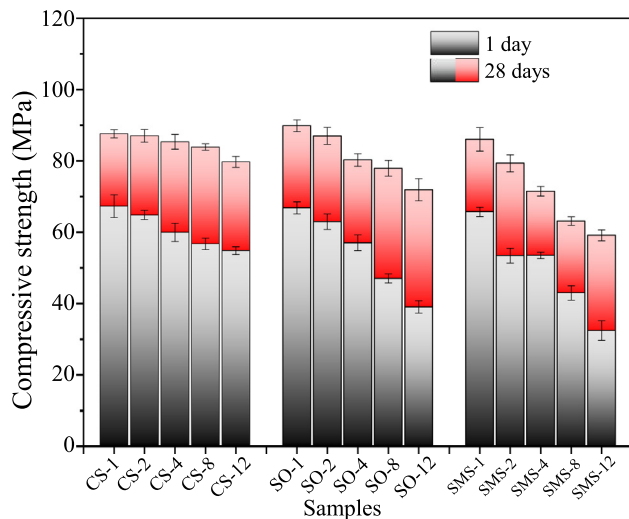


Fig. 13. Compressive strength of SW-CSA cement paste with different water repellents.

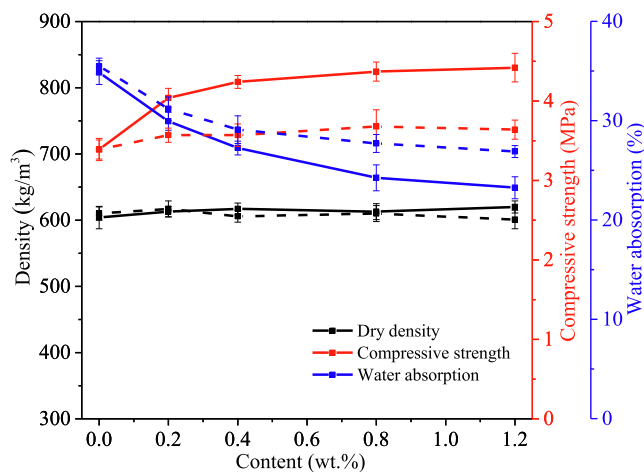


Fig. 14. Properties of LPC with different water repellents (solid line: CS; dash line: SO).

Thus, CS is suitable water repellent to improve the hydrophobicity and compressive strength of SW-CSA cement paste, which is also beneficial to improve the water absorption and mechanical properties of LPC based on SW-CSA cement.

CRediT authorship contribution statement

Xingliang Yao: Methodology, Investigation, Writing - original draft. **Hongqiang Liao:** Formal analysis, Resources. **Hua Dong:** Writing - review & editing. **Fengling Yang:** Formal analysis, Resources. **Yonggang Yao:** Data curation, Validation. **Wenlong Wang:** Conceptualization, Resources, Project administration.

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.

Acknowledgments

The authors acknowledge the support of the National Key Research & Development Program of China (No. 2017YFC0703100), The Shandong Provincial Major Scientific and Technological Innovation Project (No. 2019JZZY020306).

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