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The effect of polycarboxylate superplasticizer on the strength and hydration performance of alkali slag building materials

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ABSTRACT

To explore the effect of polycarboxylate superplasticizers on the strength and hydration performance of alkali slag building materials, this study prepared cross-linked polycarboxylate superplasticizers with different ratios of hydrogen peroxide, methyl allyl alcohol polyoxyethylene ether, acrylic acid, polyethylene glycol diacrylate, monomer aqueous solution, reducing agent, chain transfer agent, etc. according to certain ratios, and tested their effects on the hydration performance and strength of alkali slag building materials. Through experimental analysis, it was found that the higher the proportion of cross-linked polycarboxylate based high-efficiency water-reducing agents, the lower the initial flowability of building material slurry; The addition of cross-linked polycarboxylate water-reducing agent will prolong the initial and final setting time of alkali slag building materials, delaying the hydration time of building materials; Cross linked polycarboxylate superplasticizers can reduce the electrical conductivity of alkali slag building material slurry, delaying its hydration rate; Different ratios of water-reducing agents have a significant impact on the water reduction rate of alkali slag building materials, with V2 water-reducing agent having the highest water-reduction rate of 28.6%; Cross linked polycarboxylate superplasticizers can increase the flexural and compressive strength of alkali slag building materials. Therefore, cross-linked polycarboxylate water-reducing agents have shown great potential in regulating the properties of alkali slag building materials.

1. Introduction

Since the 21st century, with the continuous acceleration of modernization construction in China, construction engineering has become increasingly important in people's urban life [1]. Water-reducing agent is the most commonly used and widely used building material additive in modern construction, also known as dispersant or plasticizer. Water-reducing agents themselves have hydrophilic and hydrophobic groups in their structure, and they are essentially anionic surfactants [2]. Therefore, in the preparation of building materials, water-reducing agents have the function of adsorbing and dispersing particles [3]. In addition, water-reducing agents can also affect the hydration process of building materials, greatly affecting the durability and mechanical properties of the final building materials. Water-reducing agents are mainly used in engineering to reduce the water-to-cement ratio of materials and to reduce the amount of building materials used per unit. This method can effectively change the workability of building materials, increase the working performance of building materials, and improve the durability and volume stability of building materials [4].

Among water-reducing agents, polycarboxylate superplasticizer (PCE) is the third-generation high-efficiency water-reducing agent that is widely used and has the best comprehensive performance. It has the advantages of low dosage, high water reduction rate, and strong applicability to various building materials. The overall structure of PCE is characterized by a comb-like structure, consisting of a main chain and a side chain. This structure is more easily embedded into the interlayer of building materials, which can improve the adsorption rate [5]. The particularity of the molecular structure of PCE lies in its certain designability of molecular structure, which can meet various performance requirements in practical engineering by controlling the length, density, and types of side chain functional groups of the main side chain of PCE. Recently, more complex building structures are facing challenges. Based on this background, the requirements for high workability, environmental friendliness, high durability, and high strength of construction products are becoming increasingly strict, so new and efficient PCE materials urgently need to be proposed.

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Currently, many scholars have conducted research on the preparation of new PCE materials. Researchers such as Mi used acrylic acid and methyl allyl alcohol polyoxyethylene ether as raw materials and prepared a series of PCEs with different molecular structures using reversible addition fracture chain transfer polymerization. The structural characteristics of the novel PCE were characterized, and the dispersion performance of the new PCE on building material particles increased with the increase of carboxyl content and molecular weight. However, the study did not delve into the long-term durability and environmental impact of PCE in detail [6]. Scholars such as Song used modified silane to optimize the molecular structure of PCE. A study was conducted to improve the water-reducing performance of PCE by introducing siloxane groups, and the adsorption performance of PCE on the surface of building material particles was measured by TOC method. The research results showed that silane efficient PCE significantly increased the adsorption capacity of water-reducing agent molecules in building material particles. However, this research did not delved into the specific application of PCE in Alkali Slag Building Materials (ASBM) [7]. Ma and others used a controllable atom transfer radical polymerization method to synthesize PCE with a star-shaped structure based on precise molecular structure design, using hydroxyethyl acrylate and isobutene polyoxyethylene ether as reaction monomers. The micro mechanism of the synthesized star-shaped structure PCE was revealed in depth from the perspectives of adsorption capacity, Zeta potential, adsorption layer thickness, ion complexation, and intermolecular forces, but this study mainly focuses on molecular structure design and lacks evaluation of the hydration performance and strength of PCE in practical building material applications [8].

Although the above studies have made remarkable progress in the preparation of new PCE materials, and improved the understanding of the dispersibility, water reduction properties and microscopic mechanism of PCE through different synthesis strategies, certain limitations are still faced. In particular, the discussion on the durability and environmental impact of PCE materials in practical applications is not deep enough. As a kind of green building material, alkali slag material has been widely concerned because of its wide source, low cost and environmental friendliness. The material has shown significant advantages in promoting the resource utilization of industrial waste, reducing environmental pollution and reducing construction costs. Alkali slag material has high hydration reactivity and can significantly improve the performance of building materials, so it has important application value in construction engineering. The exploration of efficient PCE for ASBM can not only further optimize material properties but also help promote its application in the field of sustainable construction.

Therefore, this study aims to fill the gap in the aforementioned research, especially in the impact of PCE on the strength and hydration performance of ASBM. Research aims to evaluate the long-term effectiveness of PCE materials in practical applications by preparing cross-linked PCE with different ratios and testing their hydration performance and strength in ASBM. The study adopts high crosslinking degree and optimized molecular structure to enhance the durability of PCE, and through detailed analysis of its behavior in ASBM, ensures that the new PCE not only has excellent performance but also reduces negative impact on the environment.

The research content includes four parts. The first part is a background introduction to PCE materials. The second part is the experimental process of preparing Cross-Linked PCE (CL-PCE) with different ratios, including an introduction to experimental materials and instruments, as well as an introduction to performance testing methods. The third part is the analysis and discussion of the experimental results of CL-PCE. The fourth part is a summary of the entire article and provides an outlook.

2. Materials and methods

2.1. Raw material and chemical composition ratio

The main raw material for preparing PCE is as follows: methyl allyl alcohol polyoxyethylene ether (TPEG-2400), industrial grade purity, relative molecular mass 2400, industrial grade, produced at Hai'an Petrochemical Plant in Jiangsu Province; Acrylic acid (AA), analytical grade, Shanghai Dongtu Chemical Import and Export Co, Ltd; Polyethylene glycol diacrylate (PEGDA), analytical purity, with variable molecular weight, Hefei Anbang Chemical, Aladdin reagent; Monomer aqueous solution, Linyi Jingang Fine Chemicals; Reducing agent, Jinan Hongxin Material Technology Co, Ltd, analytical grade; Chain transfer agent, Guangzhou Sanwang Chemical Materials Co, Ltd; Sodium allyl sulfonate, Changzhou Baiyundeu Chemical Co, Ltd; Sodium hydroxide, analytically pure, Shandong Xingshi Chemical Co, Ltd. The ASBM used in the experiment is a mixture of the first ASBM clinker in Wuliang Town, Yuzhou City, Hebei Xuanhua slag, and Chongqing Mayuan gypsum. The chemical composition of clinker and slag is shown in Table 1.

The hydration of ASBM refers to the reaction of water slag, building materials, and gypsum with water to produce hydrated calcium silicate, calcium hydroxide, and

Table 1. Chemical composition of clinker and slag.

Chemical composition of clinker		Chemical composition of slag	
Component	Content/%	Component	Content/%
Titanium dioxide (TiO$_2$)	21.26	Titanium dioxide (TiO$_2$)	30.62
Alumina (Al$_2$O$_3$)	4.22	Alumina (Al$_2$O$_3$)	13.87
Magnesium oxide (MgO)	2.91	Calcium oxide (CaO)	37.82
Calcium oxide (CaO)	65.05	Manganese oxide (MnO$_2$)	0.48
Sodium oxide (Na$_2$O)	0.51	magnesium oxide (MgO)	8.54
Potassium oxide (K$_2$O)	0.98	Sodium oxide (Na$_2$O)	0.47
Sulfur trioxide (SO$_3$)	0.73	Potassium oxide (K$_2$O)	0.54
Red iron oxide (Fe$_2$O$_3$)	3.36	Sulfur trioxide (SO$_3$)	2.67
Phosphorus pentoxide (P$_2$O$_5$)	0.11	Red iron oxide (Fe$_2$O$_3$)	0.69
Titanium dioxide (TiO$_2$)	0.22	Burn vector	3.63
Manganese oxide (MnO$_2$)	0.08	/	/
Burn vector	0.57	/	/

Table 2 shows the ratio of slag.

Table 2. Mix ratio of building materials for alkali slag mine.

Number	1	2	3	4	5	6
Slag	25	35	45	55	65	75
Clinker	70	60	50	40	30	20
Gypsum	5	5	5	5	5	5

calcium sulfoaluminate, which continuously thickens and hardens the slurry of ASBM, and has a certain strength [9]. The hydration reactions of its main components C_3S $(3CaO \cdot SiO_2)$ and C_2S $(2CaO \cdot SiO_2)$ can be abbreviated as equation (1).

$$\begin{cases} C_3S + 5.3H = C - S - H + 3Ca(OH)_2 \\ C_2S + 4.1H = C - H - S + Ca(OH)_2 \end{cases} \quad (1)$$
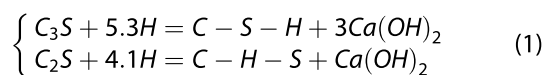
The hydrated calcium silicate (C-S-H) and calcium hydroxide (Ca(OH)$_2$) generated by these reactions gradually thicken and harden the slurry, affecting the strength and durability of the material. The hydration performance of ASBM is influenced by the initial fluidity, hydration rate, and pH value of the building material slurry [10]. The strength of ASBM is affected by the water reduction rate. Figure 1 shows the theoretical model of the reaction mechanism of alkali activated slag cement is shown in.

Figure 2 displays the SEM images of the cross-sections of slag and alkali slag. From the observation in the figure, it can be seen that the vast majority of the slag presents an amorphous morphology but is accompanied by some well-crystallized single crystal particles and a relatively large number of nanoscale microcrystals. The cross-section of alkali slag presents a flat and smooth morphology, and there are no obvious edges. In addition, there are many pores in the alkali slag matrix.

2.2. Experimental instruments

The BEC-520 conductivity control instrument was selected to measure the rate of acceleration; NJ-160A building material net slurry mixer (Shanghai Meiyingpu Instrument and Instrument Manufacturing Co, Ltd.), measuring net slurry; JJ-5 building material sand mixer (Shanghai Meiyingpu Instrument and Instrument Manufacturing Co, Ltd.), used to measure the flowability of ASBM slurry; SS-150 scanning electron microscope (Carl Zeiss AG), accelerated voltage of 30 KV, magnification of 150,000 times, to determine hydration products of building materials; LabSpec-4 infrared spectrometer (Carl Zeiss AG), used to determine the strength of building materials; BD600-S peristaltic pump (Baoding Rafer Fluid Technology Co, Ltd.) for sample preparation. Digital display constant temperature water bath pot (Changzhou Putian Instrument Manufacturing Co, Ltd.), HH-1 type [11].

2.3. Preparation of CL-PCE samples

Pour the prepared 21 ml hydrogen peroxide aqueous solution and 29 g methyl allyl alcohol polyoxyethylene ether into a 200 ml three necked flask. Mix an appropriate amount of 3.37 g acrylic acid and polyethylene glycol diacrylate into a 10 ml aqueous solution, and prepare an appropriate amount of reducing agent and chain transfer agent into a 12.5 ml aqueous solution in a 6:2 ratio [12]. Heat up to 65 °C and use a peristaltic pump to simultaneously drip the monomer aqueous solution, reducing agent, and chain transfer agent aqueous solution. The dripping time for monomer aqueous solution, reducing agent, and chain transfer agent aqueous solution was 3.1 h, 3.6 h, and 3.6 h, respectively. All dripping is completed, and after a constant temperature reaction for 1 h, the temperature is raised to 80 °C. A 0.2 g of sodium allyl sulfonate and 0.2 g of ammonium sulfate aqueous solution
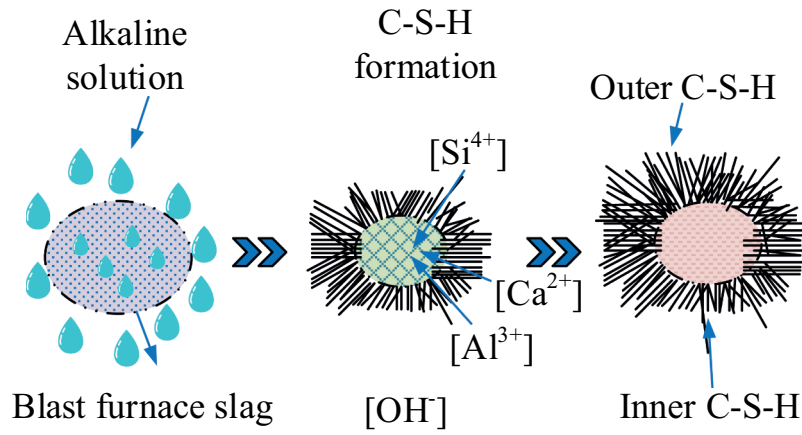
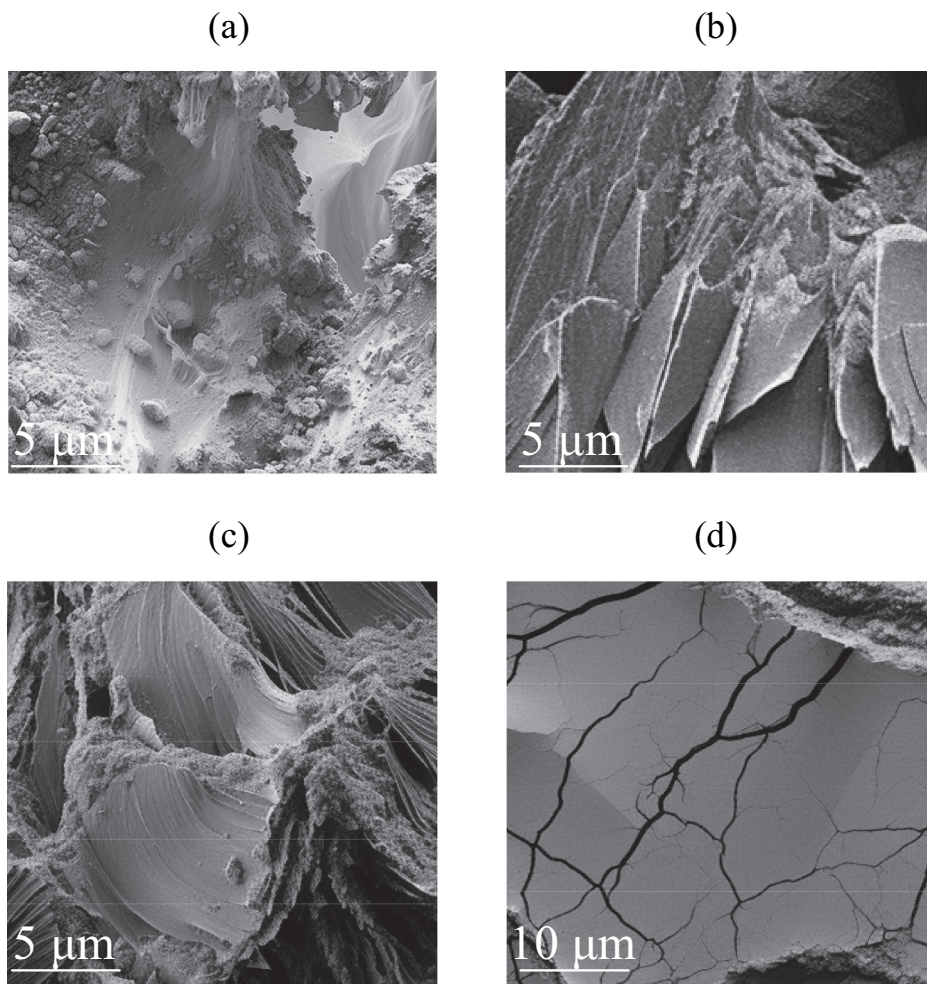**Figure 1.** Theoretical model of the reaction mechanism of alkali activated slag cement.

Figure 2. SEM images of ordinary slag and alkali slag cross-sections (a, b, c show the SEM images of slag at 5 μm scale; d show the SEM image of alkali slag cross-section at 10 μm scale).

are added to a three necked flask, and the dripping time is 2.1 h. After the drip addition, the reaction was carried out at a constant temperature for 4.1 h and then cooled to room temperature, so that the amount of sodium allylsulfonate used was 16% of the total mass of the monomer. Adjust the ratio of acrylic acid and monomer aqueous solution, and use a 21% sodium hydroxide solution with a mass concentration to adjust its pH value to 8–9, resulting in 5 sets of CL-

Table 3. Proportioning of five CL-PCE samples.

Sample code	Ratio of cross-linked monomers to acrylic acid
V1	1:2
V2	2:2
V3	4:2
V4	6:2
V5	8:2

PCEs. Cross-linked PCEs with different ratios of acrylic acid and monomer aqueous solutions are represented by V1, V2, V3, V4, and V5, as shown in Table 3.

Based on peak and functional group analysis, the structure and molecular formula of the CL-PCE obtained in this study are shown in Figure 3. Compared with traditional comb shaped PCE, CL-PCE structures exhibit multi-arm branching structures at low crosslinking degrees. Under high connectivity, PCE exhibits a network-like body structure. Therefore, CL-PCEs have greater steric hindrance compared to traditional comb shaped PCEs with the same molecular weight.

3. Results and discussion

3.1. Influence of CL-PCE on the hydration performance of ASBM

3.1.1. Effect of CL-PCE on the initial flowability of ASBM in net slurry flow

The initial flowability of ASBM slurry affects the hydration performance of ASBM. Therefore, to test the effect of different ratios of CL-PCE on the properties of ASBM, it is necessary to test the impact of different ratios of CL-PCE on the initial flowability of ASBM slurry. Set the water cement ratio to 0.28 and the CL-PCE content to 1.1%. Calculate the changes in the flowability of the ASBM slurry, as shown in Figure 4. From Figure 4, it can be concluded that the initial flowability of the ASBM slurry mixed with V2 water reducer is the best, with a value of 292 mm. Moreover, after 30 and 60 min, the net slurry flowability of V2 water reducer was also the highest, indicating that V2 water reducer has the best adaptability to ASBM. This result indicates that an increase in the proportion of CL-PCE will lead to a decrease in the initial flowability of the ASBM slurry. This is due to the increase in the ratio of acrylic acid and monomer aqueous solution in the water-reducing agent, resulting in a greater steric hindrance effect, making it difficult for the particles of ASBM to agglomerate, reducing the plastic viscosity of ASBM, improving the fluidity of ASBM, and allowing the particles of building materials to be completely hydrated. The specific chemical interactions between CL-PCE and ASBM components are mainly achieved through hydrogen bonding, van der Waals forces, and other interactions between acrylic monomers and water molecules. With the increase of CL-PCE ratio, the proportion of acrylic acid and monomer aqueous solution in the water reducer increases, enhancing the steric hindrance effect between molecules, thereby reducing the plastic viscosity of the material, improving flowability, promoting hydration reaction, and thus affecting the flow behavior of the slurry.

3.1.2. Effect of CL-PCE on the setting time of ASBM

The setting time of ASBM can delay the hydration of building materials. To determine the impact of CL-PCE on the hydration performance of ASBM, the effects of five CL-PCE on the setting time of ASBM and the setting time of blank building materials without water-reducing agents were tested. In Figure 5a, the initial and final setting times of the ASBM are significantly prolonged after the addition of water-reducing agent. For example, the initial setting time of the blank sample is 150 min, V5 is 550 min. Figure 5b shows that the water-reducing agent increases the initial flowability of the slurry and increases the flowability loss after 30 min. The initial fluidity of V2 was 292 mm, and after 30 min, it decreased to 228 mm (a decrease of 22%). This indicates that the combination of anionic groups with calcium ions reduces the concentration of free calcium ions, inhibits the crystallization process of calcium hydroxide, prolongs the setting time, and thus delays the hydration process. In Figure 5b, as different ratios of cross-linked PCE are added, the initial flowability of the building material slurry gradually decreases. The cross-linking characteristics of cross-linked structures lie in their ability to simultaneously adsorb multiple particles, increase the binding force between particles, and promote the formation of flocs. This effect leads to a decrease in the dispersion of particles in the slurry, increases the initial and final setting times, and reduces the initial fluidity. The flowability data in Figure 5b shows that as the proportion of cross-linked PCE increases, the flowability loss after 30 min significantly increases, such as a 27% decrease in V5. These results indicate that the adsorption and floc formation ability of cross-linked structures are the main reasons for the changes in the fluidity of the slurry.

3.1.3. Effect of CL-PCE on the hydration rate of ASBM

Cross linked PCE contains active gene groups on the main and side chains of polymers that can interact with cations in ASBM during the hydration process, such as anionic surfactants with polyoxyethylene side chains, carboxyl groups, and ester groups, which can affect the hydration process of ASBM. The plasma concentration in the liquid phase of building material slurry changes over
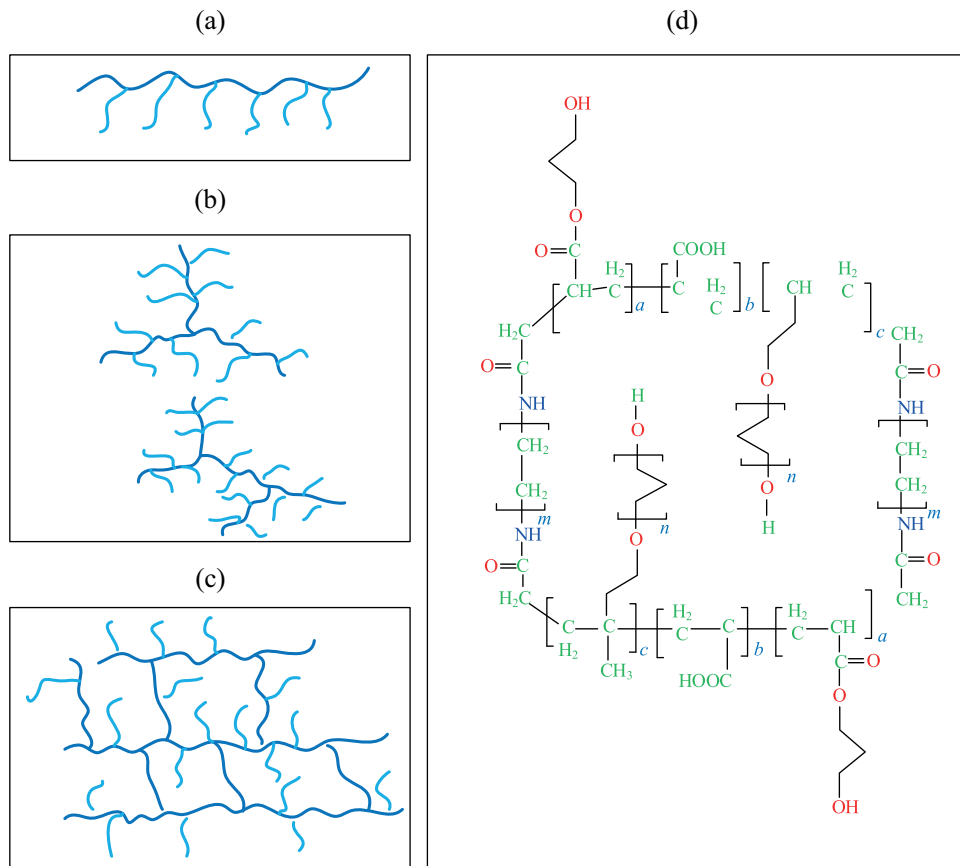
Figure 3. Structure and molecular formula of CL-PCE (a, b, c, and d denote the structural formulas of traditional comb shaped PCE structure, low crosslinked multi arm PCE structure, high crosslinked body shaped PCE structure, and crosslinked PCE, respectively).
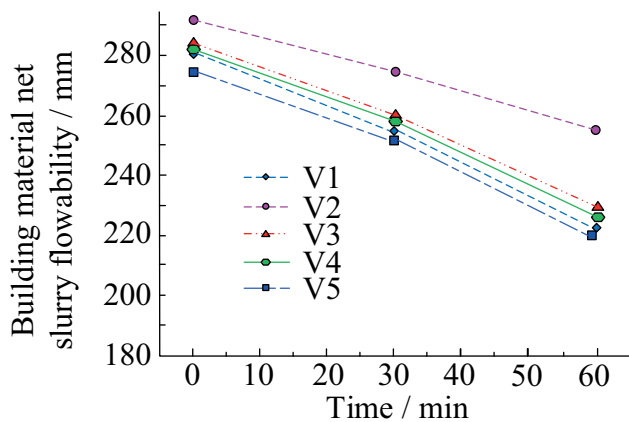

Figure 4. Changes in net slurry flowability of ASBM.

time during the hydration process of ASBM, which involves the dissolution of ions (hydration, increased conductivity, etc.) and precipitation (generation of hydration products, decreased conductivity). Due to the fact that the change in hydration rate of ASBM can be expressed by the change in electrical conductivity of the building material slurry phase. Therefore, the experimental study on the effect of CL-PCE on the hydration

process of ASBM can compare the measurement results of the change in electrical conductivity of the slurry of ASBM with different dosages of water-reducing agents, and the measurement results of the change in electrical conductivity of the slurry of building materials with 0% water-reducing agents, and analyze them. The results are described in Table 4. Here, 1 min ~ 60 min is the initial hydration stage; 100 min–400 min is the early stage of hydration, and 500 min–800 min is the late stage of hydration.

Through the observation of Table 4, the electrical conductivity of the ASBM slurry without the addition of CL-PCE is higher than the ASBM slurry with the addition of CL-PCE. Moreover, as the amount of CL-PCE added increases, the electrical conductivity of the ASBM slurry gradually decreases, indicating that the hydration of ASBM is affected by water-reducing agents.

The reasons for the decrease in electrical conductivity of building material slurry are as follows [13]:

(1) Due to the decrease in liquid phase conductivity of ASBM with the increase of water-reducing agent addition, polycarboxylate copolymers contain
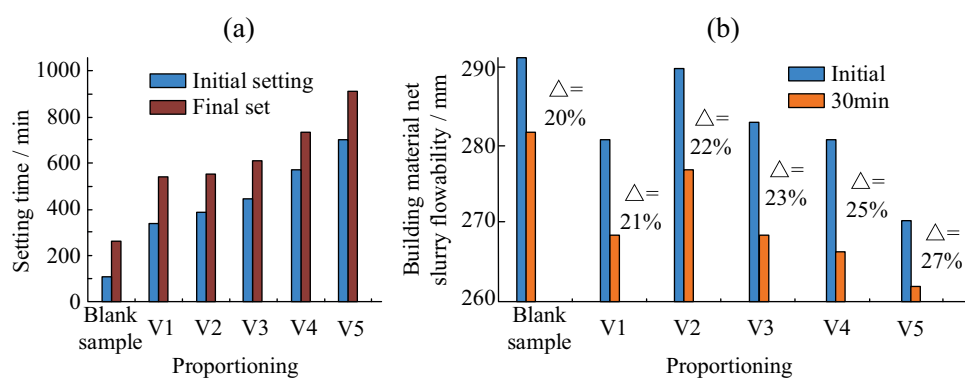
Figure 5. Setting time and time loss of CL-PCE on ASBM (a and b represent the setting time of CL-PCE for ASBM and time loss, respectively).

Table 4. Conductivity of building material slurry with different dosages of water-reducing agents.

Time/min	0% dosage	0.3% dosage	0.7% dosage	1.1% dosage
1	0.28	0.26	0.21	0.19
20	0.33	0.31	0.23	0.21
60	0.35	0.33	0.24	0.22
100	0.43	0.34	0.24	0.22
200	0.45	0.34	0.24	0.21
300	0.49	0.37	0.23	0.23
400	0.53	0.45	0.23	0.21
500	0.69	0.53	0.21	0.21
600	0.74	0.62	0.24	0.23
700	0.81	0.67	0.21	0.19
800	0.87	0.71	0.22	0.18

$-COO^-$, which can form complexes with Ca^{2+} in the liquid phase, resulting in a decrease in ion concentration in the liquid phase.

(2) ASBM particles adsorb water-reducing agents and participate in particle hydration, entering their hydration products.

(3) The initial hydration products covering the surface of particles form a thick three-dimensional barrier (folded CSH gel and a small amount of acicular ettringite) to prevent the contact between building material particles and water and further hydration, increase the repulsive force between building material particles, reduce the consumption of water by building material particles, and undergo flocculation and dispersion.

In summary, as the amount of water reducer increases, the decrease in conductivity becomes more pronounced. The conductivity of the ASBM slurry with a dosage of 0 is higher than that of the original slurry with the addition of water reducer. Therefore, the hydration of building materials is affected by the water reducer, which slows down the hydration rate of building materials. Geng et al. also discussed the conductivity of PCE and reached the conclusion that water-reducing agents can affect the conductivity. However, this study focused on the effect of water-reducing agents on the performance of lithium-sulfur

batteries and did not discuss the related content of building materials [14].

3.2. Influence of CL-PCE on the strength performance of ASBM

3.2.1. Influence of CL-PCE on the water reduction rate of slag building material mortar

Different ratios of CL-PCE were added to the ASBM mortar, and the effect of different ratios of CL-PCE on the water reduction rate and adsorption performance of the ASBM mortar was tested when the flow of the ASBM mortar was 181 ± 6 mm, as shown in Figure 6. In Figure 6a, the water-reducing agent increased the water reduction rate of ASBM at different ratios. The water reduction rate of CL-PCE under the V2 ratio is the highest, at 28.6%. Prove that its water reduction effect is the best. The reason why water-reducing agents can affect the water reduction rate of ASBM mortar is that PCE has many side chain groups that can form adsorption, resulting in the hydration products of tricalcium aluminate not covering all these branches, making the building material particles unable to agglomerate, thereby affecting the water reduction rate. The higher the water reduction rate, the more beneficial it is to reduce the bleeding of ASBM during the configuration of building

materials, resulting in an increase in the strength of ASBM. The specific mechanism of the interaction between CL-PCE and hydration products is that multiple side chain groups of Cl-PCE are adsorbed on the surface of hydration products, hinding the formation and growth of hydration products, and thus inhibiting the hydration reaction between cement particles. This adsorption makes the hydration product unable to completely cover the cement particles, resulting in an increase in particle spacing, reducing the bonding force between particles, thereby increasing the fluidity of the mortar and improving the water reduction rate. Figure 6b shows the adsorption curves of CL-PCE with different ratios in building material slurries. The experimental results show that CL-PCE with different ratios can adsorb quickly and achieve high adsorption capacity within 30 min. As the content of cross-linked monomers increases. The cross linking degree and molecular weight of PCE increase accordingly, and its network structure is enhanced. This enhances the adsorption capacity of PCE for calcium ions in aqueous solutions, while reducing the dispersion of molecular chains, resulting in enhanced adsorption between particles. The experimental results show that the higher the cross linking degree, the better the adsorption performance, which in turn affects the dispersion effect and water reduction rate of building material particles in mortar. In addition, the transition from the comb-like structure of PCE to a mesh-like structure is more conducive to further improving the adsorption performance. Therefore, the content of cross-linked monomers affects the adsorption performance of CL-PCE in aqueous solution, thereby affecting its dispersion performance in building material particles.

3.2.2. Effect of CL-PCE on the flexural and compressive strength of ASBM

Five types of water-reducing agents were added to the building materials made of ASBM, and the building materials made of ASBM (i.e., blank samples) were cured under standard curing conditions. The flexural strength and compressive strength were tested at 5 days, 15 days, and 25 days, respectively. The test results are shown in Figure 7. From Figure 7(a,b), as the curing time increases, CL-PCE can slightly increase the flexural strength of ASBM and significantly increase the compressive strength of ASBM. The compressive strength of the ASBM in the V2 sample increased the fastest, and compared with the blank sample, the increase was greater at 5d and 15d. The experimental results show that when the ratio of acrylic acid and monomer aqueous solution in the water reducer is 2:2, it can further increase the strength of ASBM.

The result is similar to the theory proposed by Lu et al. in the study of building waterproof coating with high performance composite polymer emulsion. Lu et al. found that high-performance polymer emulsions can improve the waterproof and mechanical properties of building materials, which is consistent with the effect of cross-linked PCE on improving the initial fluidity and compressive strength of ASBMs. This indicates that highly efficient polymer emulsions have a wide range of potential applications in improving the properties of building materials [15]. In addition, the research results of Yang show that polycarboxylic acid series materials can effectively improve the working and mechanical properties of building materials, which is consistent with the results of crosslinking PCE in this study to improve the performance of ASBM, and further confirms the application value of polycarboxylic acid series materials in building materials [16].
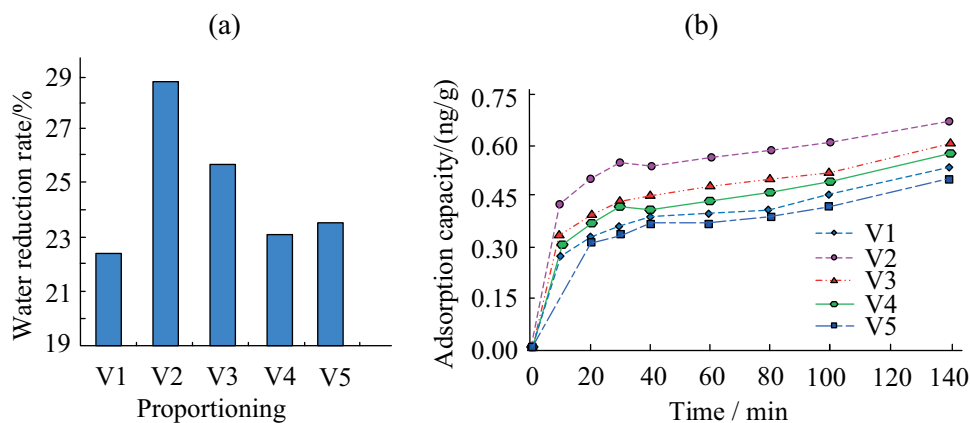

Figure 6. The impact of CL-PCE on the water reduction rate and adsorption properties of ASBM mortar (a and b represent the water reduction rate of ASBM mortar and changes in adsorption capacity of CL-PCE).
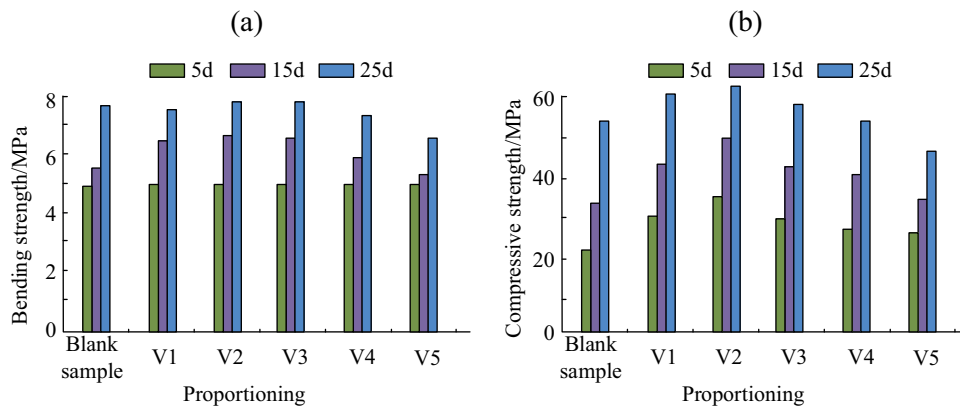
Figure 7. Changes in flexural and compressive strength of ASBM (a and b represent the flexural strength and compressive strength of ASBM, respectively).

3.2.3. Effect of CL-PCE on hydration products of ASBM

The ASBM mixed with V2 water-reducing agent and the blank ASBM with a slag content of 69% without water-reducing agent were used as experimental objects. The hydration products of the two were tested using scanning electron microscopy at 5 days and 25 days of curing time, respectively. The test results are shown in Figure 8. The morphological differences in SEM images reflect the hydration process and product formation of building materials under different conditions. Through SEM observation, the type and distribution of hydration products can be accurately determined, and the hydration performance and strength development trend of the material can be inferred. The morphological differences directly reflect the crystal morphology, distribution density, and connection mode of hydration products, thus revealing the influence of water-reducing agents on the hydration process and their regulatory effect on material properties. From the comparison of changes in Figure 8(a,b)
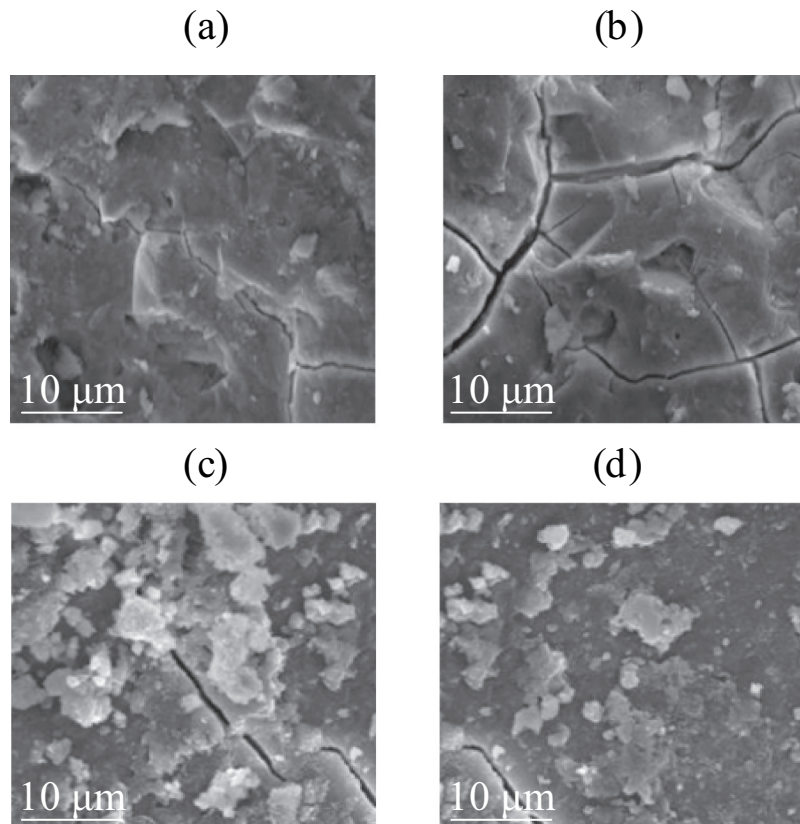

Figure 8. Microscopic view of hydration products of ASBM (a, b, c, and d show Scanning SEM images of blank samples for 5 days, V2 water reducer for 5d, blank sample 25d, V2 water reducer for 25 days, respectively).

it can be seen that after 5 days of hydration, a large amount of wrinkled CSH gel is produced in the blank sample, and a small amount of needle-shaped ettringite is produced in the pores. After adding V2 water reducer, a wrinkled CSH gel with less amount than shown in Figure 8a was formed, indicating that the addition of water reducer inhibited the hydration of tricalcium silicate in building materials, resulting in fewer hydration products and lower strength than the blank sample. After 25 days, both of them formed flat and irregular CSH gels with needle-shaped ettringite, indicating that after 25 days of curing, the hydration products formed by the blank ASBM and the ASBM mixed with V2 water reducer were similar and of equal strength. By comparing Figure 8(a,b,c,d), ettringite increases significantly with the increase of curing time, indicating that the strength increases with the progress of hydration. Wu et al. also studied the effect of polymer PCE on the properties of hydration products of building materials, and the results showed that hydration products of building materials could be effectively regulated, which was consistent with this study [17].

Figure 9 shows the scanning electron microscopy images of ASBM with CL-PCE added at 25 days. Among them, the ratio of CL-PCE is V2, with dosages of 0.0%, 0.03%, and 0.05%, respectively. In the figure, when the dosage of CL-PCE is 0.03% and 0.05%, respectively, the alkali slag cementitious material contains a large amount of sheet-like crystals, which can effectively improve the bonding strength of the cementitious material and thereby enhance its toughness. Therefore, CL-PCE can effectively improve the toughness of alkali slag cementitious building materials after 25 days, and the dosage of PCE will directly affect the long-term durability of the hardened structure. This result is consistent with the research of Chen M. et al., who found that the modified starch-based curing agent can maintain stability under alkali environment, which provides a theoretical basis for studying the stability and efficiency of CL-PCE in ASBM [18].

4. Conclusions

Cross-linked PCE changes the surface state and electrochemical properties of building material particles through adsorption, resulting in a dispersion effect of building material particles under spatial repulsion. The performance of water-reducing agents with different dosages also varies, and the same water-reducing agent has different performance manifestations in different applications. After analyzing examples, the following conclusions can be drawn:

(1) Initial flowability and setting time: The cross-linked PCE with a V2 ratio achieves the optimal initial flowability of 292 mm for the ASBM slurry, and the addition of cross-linked PCE prolongs both the initial and final setting times of the material.
(2) Changes in flowability and conductivity: With the addition of cross-linked PCE with different ratios, the initial flowability of the slurry gradually decreases, and the time loss after 30 min increases. Meanwhile, the conductivity of the slurry without cross-linked PCE was higher than that of the slurry with cross-linked PCE.
(3) Improved water reduction rate: The cross-linked PCE of each ratio significantly increased the water reduction rate of ASBM, with the V2 ratio having the highest water reduction rate of 28.6%.
(4) Strength performance improvement: The cross-linked PCE slightly enhances the flexural strength of ASBM and significantly increases the compressive strength, indicating that it has a positive impact on the material's strength performance.

Therefore, CL-PCE has an impact on the hydration performance related to the initial fluidity, hydration rate, and setting time of ASBM, as well as the
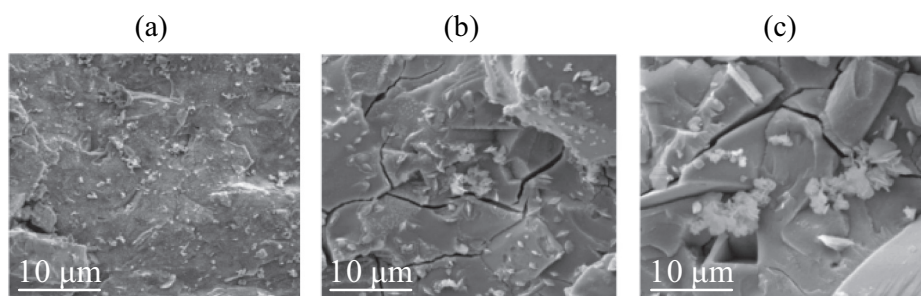
| (a) | (b) | (c) |

Figure 9. Scanning electron microscopy images of ASBM with CL-PCE added at 25 days (a, b and c show the Scanning SEM images of CL-PCE with dosages of 0.0%, 0.03%, and 0.05%, respectively).

strength performance related to the water reduction rate, flexural strength, and compressive strength of building materials. The limitation of this study is that it failed to compare the effects of different alkali slag on material properties, and future research directions can start from this.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

Ethical compliance

This experiment did not involve humans or animals.

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