Preparation of a Composite Calcium Silicate Board with Carbide Slag and Coal-Based Solid Waste Activated by Different Alkali Activators

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ABSTRACT: Overall performance of composite calcium silicate boards (CCSBs) was investigated to further promote their application. The alkali activators were used to fully hydrate the calcium and silicon raw materials, which further improved the comprehensive performance of the CCSBs made of four pure industrial solid wastes. Within the range of dosage in this study, single doping of different proportions of the alkali activator improved the flexural strength of the CCSB. Based on this, the mechanical properties of the CCSB were further improved as the compounded alkali activator was optimized. Flexural strength is improved when the average pore diameter was refined. The freeze–thaw cycle test shows that a compound-doped alkali activator can effectively reduce the mass loss and strength loss, thereby improving the frost resistance of this material. This research discussed an economically affordable approach to prepare the CCSB material made of industrial solid waste.

1. INTRODUCTION

The rapid development of the national economy highly relies on the sufficient supply of energy and production materials. However, along with the massive supply of energy, huge amounts of fly ash, silicon powder, and carbide slag are also emitted into the atmosphere, aggravating water and air pollution. At the same time, the mass production of building materials will intensify the loss of natural, high-quality mineral resources such as quartz sand.1 At present, powders such as fly ash are widely used in cement mortars and green building materials due to their properties.2,3 However, in order to alleviate the tension of resource availability, more effort should be put into reducing the consumption of natural, high-quality mineral resources. Here, a novel method to utilize waste byproducts was introduced.

Composite calcium silicate boards (CCSBs) are a new kind of environment-friendly building material that gets widely used in building engineering such as ceilings,4,5 floor coverings, and drying furnace walls.6 By mixing and stirring raw materials containing calcium and silicon into a gelling system and then undergoing pressure forming, prenurturing, and autoclave curing, it obtains advantages such as high strength, impact resistance, thermal resistance, deformation resistance, and high-efficiency processing. At present, it is favored by many experts and scholars as a new type of building material with a long-term vision.

Alkali-activated cementitious materials have a long history in the world. Purdon7 first proposed the use of NaOH in stimulating blast-furnace slag and dissolving its silicon and aluminum structures to form hydration products. Glukhovsky8 put forward the concept of “soil cement”, using calcium aluminosilicate and alkali metal solution to prepare a cement material, as a high strength, acid and alkali corrosion-resistant material. Alkali-metal cations play a structure-directing role in gel hardening and eventual crystal formation.9,10 The addition of calcium compounds improves the mechanical properties of fly ash-based geopolymers.11,12 The use of Ca(OH)2 could increase the plastic shrinkage of the alkali-activated slag concrete and reduce the mesopore volume.13,14 The compressive strength of fly ash and granular blast-furnace slag preparation mortar is significantly correlated with the specific alkali quality coefficient range.15,16 The compressive strength of kaolin geopolymers reached the highest value when S/L and Na2SiO3/NaOH ratios were 1.00 and 0.32, respectively.17,18 With the increase of silica modulus, the micromechanical properties of sodium silicate-activated slag
showed a slight improvement as macroscale strength improved significantly.\textsuperscript{9,20} The slag mortar made from Na\textsubscript{2}SiO\textsubscript{3}, NaOH, and Na\textsubscript{2}CO\textsubscript{3} showed that the mechanical properties were sensitive to the change in alkali-activator temperature.\textsuperscript{21,22} The blast-furnace slag cement sample activated with a MgO–NaOH mixture and cured at 20 °C developed a strength of 54 MPa at 90 days.\textsuperscript{23} The alkali-silica reaction of these samples was significantly lower than that of the ordinary Portland cement-based concrete and far below the ASTM-specified threshold.\textsuperscript{24} The influence model of the alkali-slag concrete (ASC) air-void structure on the freeze–thaw resistance could be used to analyze and predict the freeze–thaw resistance of the ASC.\textsuperscript{25–27}

In this experiment, the CCSB was mainly made up of the volcanic ash-based composite gelling system composed of fly ash, silica fume, desulfurized gypsum, and carbide slag. Four different alkali activators were selected to analyze the overall performance of the CCSB based on the optimal ratio of raw materials.

2. RESULTS AND DISCUSSION

2.1. Effect of the Single-Doped Alkali Activator on Flexural Performance of the CCSB. The position of the dotted line in Figure 1 represents the standard sample strength (11.53 MPa), where no alkali activator is doped. The flexural strength of the CCSB is optimal when the NaOH dosage is 6%. However, it is much lower than the standard sample strength when the dosage reaches 12%. This trend indicates that NaOH can stimulate the volcanic ash in the composite gelling system when the dosage is low. However, it will lead to mechanical defects of the CCSB when the dosage is too high.

The content of CaO on the flexural strength of the CCSB is apparent. The flexural strength of the CCSB reaches a maximum when the content of CaO is 3%. The flexural strength shows a sharp decline with the increasing amount of CaO and the billet is even challenging to form when the CaO content reaches 12%. The Ca(OH)\textsubscript{2} content in the system finally saturates and crystallizes out when CaO is highly doped. The excess Ca(OH)\textsubscript{2} crystal dissolves again and forms many holes in the product when the low-strength board billet is steamed and maintained in an autoclave;\textsuperscript{28} these Ca(OH)\textsubscript{2} crystals intersperse between hydrated bodies, which result in insufficient strength.

It can be seen from Figure 1 that incorporating a small amount of Na\textsubscript{2}CO\textsubscript{3} into the cementitious material can slightly increase the strength of the CCSB. Because Na\textsubscript{2}CO\textsubscript{3} is a strong base weak acid salt, the OH\textsuperscript{−} generated by hydrolysis can provide an alkaline environment for raw material reactions. A large amount of CO\textsubscript{3}\textsuperscript{2−} will consume Ca\textsuperscript{2+} in the system to form CaCO\textsubscript{3} precipitates, which can adversely affect the strength when the amount of Na\textsubscript{2}CO\textsubscript{3} is continuously increased. The combination of Na\textsuperscript{+}, active silicon, and aluminate ions contribute to the formation of the monoclinic sodalite. This phenomenon subsequently causes a decrease in the production of C–A–S–H. Therefore, the incorporation of Na\textsubscript{2}CO\textsubscript{3} will both promote the pozzolanic effect and inhibit the production of the C–A–S–H gel.\textsuperscript{29}

Na\textsubscript{2}SiO\textsubscript{3} hydrolyzes to form some OH\textsuperscript{−} and active Si(OH)\textsubscript{4} when it is dissolved. The active silicon tetraedral content in the composite system is continuously supplemented with the continuous incorporation of Na\textsubscript{2}SiO\textsubscript{3}. Moreover, more hydration products are formed in the early stage of the hydration reaction, which gives the board billet an early initial strength. Therefore, the flexural strength of the CCSB is enhanced as the amount of Na\textsubscript{2}SiO\textsubscript{3} (Na/Si = 1.03 ± 0.03) is continuously increased, and the flexural strength reaches a maximum at a dosage of 9%.

In summary, appropriate doping of the abovementioned four alkali activators individually can increase the mechanical strength of the CCSB. Within the range of the current dosage of the alkali activator, based on the increase in strength, the activating effect of the four alkali activators can be ranked as CaO > NaOH> Na\textsubscript{2}SiO\textsubscript{3} > Na\textsubscript{2}CO\textsubscript{3}.

2.2. Effect of Compounded Alkali Activators on Flexural Performance of the CCSB. The flexural strength of the CCSB after incorporating composite alkali activators is shown in Table 1. The flexural strengths of S1, S10, and S11 exceed 14 MPa, and the flexural strength of S11 reaches a maximum of 14.72 MPa. When 3% NaOH and CaO are mixed as a composite activator, the alkalinity in the gelation system and the content of Ca\textsuperscript{2+} are increased. Therefore, the fly ash particles can be activated efficiently during the preconservation period. A lot of C–A–S–H gel is produced, thereby increasing the compactness of the billet. However, it hinders the pozzolanic effect of the raw material when the OH\textsuperscript{−} concentration is too high. Therefore, the flexural strength of

| samples | NaOH | CaO | Na\textsubscript{2}CO\textsubscript{3} | Na\textsubscript{2}SiO\textsubscript{3} | flexural strength/MPa |
|---------|------|-----|-------------|-----------------|-----------------------|
| S0      | 0    | 0   | 0           | 0               | 11.53                 |
| S1      | 3    | 3   | 0           | 0               | 14.53                 |
| S2      | 6    | 3   | 0           | 0               | 10.62                 |
| S3      | 3    | 0   | 3           | 0               | 13.41                 |
| S4      | 6    | 0   | 3           | 0               | 10.06                 |
| S5      | 6    | 0   | 6           | 0               | 11.03                 |
| S6      | 3    | 0   | 0           | 6               | 13.61                 |
| S7      | 6    | 0   | 0           | 6               | 10.52                 |
| S8      | 0    | 3   | 3           | 0               | 10.32                 |
| S9      | 0    | 3   | 6           | 0               | 9.61                  |
| S10     | 0    | 3   | 0           | 6               | 14.25                 |
| S11     | 0    | 3   | 0           | 9               | 14.72                 |
| S12     | 0    | 0   | 3           | 6               | 13.56                 |
| S13     | 0    | 0   | 6           | 6               | 11.87                 |
the CCSB is lower than the strength of the standard sample S0 when NaOH incorporation is increased to 6%.

The flexural strength of the CCSB can reach 13.41 MPa when 3% NaOH and 3% Na2CO3 is compositely added to it. However, it rapidly drops to 10.06 MPa when the dosage of NaOH increases to 6%. The significant decrease in mechanical strength is caused by the early precipitation or even dissolution of the aluminosilicate gel due to excess NaOH. After increasing the content of Na2CO3 to 6%, the flexural strength rebounded to 11.03 MPa, suggesting that the increase in CO3^2- concentration can effectively prevent the precipitation of the hydrated gel. Test results also show that the incorporation of 6% NaOH and Na2SiO3 is invalid for increasing the flexural strength of the CCSB, and the composite of CaO and Na2CO3 even makes the flexural strength lower than the standard sample S0 due to the hydrolysis limitation of Na2SiO3 in a strong alkaline environment. However, the combination of CaO and Na2SiO3 benefits the mechanical properties of the CCSB. The flexural strength of the CCSB reaches 14.72 MPa when the CaO dosage is 3% and the Na2SiO3 dosage is 9%. This is because the combination of these two alkalis provides not only an appropriate alkaline environment but also the main substances involved in the hydration reaction. The combination of 3% Na2CO3 and 6% Na2SiO3 can increase the flexural strength to 13.56 MPa. However, with the increase of the Na2CO3 dosage, excessive CO3^2- consumes Ca^2+ in the system to form calcium carbonate crystals, eventually reducing the strength of the product.

According to the flexural strength test results of the CCSB, the compounded alkali activator to some extent further improved the flexural strength of the CCSB compared to the single-doped alkali activator. The rank of the strengthening effect by four alkali activators on the strength of the CCSB is (CaO + Na2SiO3) > (NaOH + CaO) > (Na2SiO3 + Na2CO3) > (NaOH + Na2CO3) > (Na2CO3 + CaO). The S11 CCSB (CaO + Na2SiO3) possesses the best strength. Therefore, the S11 CCSB is used as a representative of the best alkali activator to perform various performance tests.

### 2.3. Effect of the Alkali Activator on the Freeze–Thaw Performance of CCSB Samples

The S0 and S11 CCSBs were selected as the test subject. The appearances of the two CCSBs before and after the freeze–thaw cycle (FTC) are shown in Figure 2, while the cut surface of the CCSB before and after the FTC is shown in Figure 3. Neither “rotten angle”, cracking, nor delamination was found on the CCSBs, which have clean surfaces and corners after 25 FTCs. Therefore, these two types of CCSBs meet the requirements of the Chinese national standards. The flexural strength of the S11 246.54 235.44 14.72 13.30 4.21 9.65

| samples | mass of the CCSB (g) | strength of the CCSB (MPa) | loss rate (%) |
|---------|----------------------|-----------------------------|--------------|
| S0      | BF 265.65 AF 252.43 | BF 11.87 AF 10.18           | 4.98 14.22   |
| S11     | 246.54 235.44        | 14.72 13.30                 | 4.21 9.65    |

*BF is before the freeze–thaw cycle. AF is after the freeze–thaw cycle.

Both the mass loss and strength loss of the two CCSBs comply with the specification in GB/T11969-2008. Moreover, the mass loss and strength loss of the CCSBs are effectively reduced after incorporating an alkali activator into the raw material. Colombo points out that the main reason for the damage of the product during the FTC is due to the 9% volume expansion of water in the void hole during freezing.30 Free water in the gap of the product keeps moving during the continuous growth of the ice crystals. When the moisture in the capillary reaches the saturation point, pressure is generated and causes mechanical defects at weak points of the product. This promotes the continuous expansion of this mechanical defect and eventually leads to the destruction of the product during the reciprocating FTC. Therefore, the frost resistance of the product has an important relationship with the internal void volume.

### 2.4. Effect of the Alkali Activator on Pore Structure Performance of CCSB Samples

Figure 4a,b shows desorption/adsorption isotherm curves of S0 and S11 CCSBs, respectively. The curves in both figures are anti-S shape, which is closest to the type IV desorption/adsorption isotherm of the adsorption isotherm by IUPAC.31 The adsorption curves show a slow increase in nitrogen adsorption at P/P0 ≤ 0.4, while microporous filling or N2 monolayer adsorption occurs in the pores of the sample. The adsorption amount of the adsorption curve starts to increase slowly when 0.4 ≤ P/P0 ≤ 0.8. The N2 multilayer adsorption occurs and gradually transitions to capillary condensation at this stage. The adsorption curve tends to be vertical when P/P0 reaches 1, but its adsorption amount is still not saturated. N2 capillary condensation occurs in voids with large pore size at this stage, which indicates that a large number of mesopores exist in the sample. The desorption curve running above the adsorption curve indicates that the denitrification rate is higher than the nitrogen adsorption rate. This indicates that no new crack or pore is formed inside the sample as P/P0 increases.32 Both
desorption and adsorption isotherms of the two figures separate at $P/P_0 = 0.4$ and thus form a hysteresis loop. The curves can describe characteristics of the pore structure via the shapes of hysteresis and desorption/adsorption. The almost same shapes of hysteresis loops shown in Figure 4 indicate that the shape, size, and distribution range of the pores in the sample are similar. De Boer\textsuperscript{33} divided the hysteresis loop into four categories. However, the pore structure in the actual sample is relatively complicated, and the hysteresis loop of the pores is often a combination of multiple types. The desorption isotherm curve is coincident, and no hysteresis loop is generated when the relative pressure $P/P_0 \leq 0.4$. Such a phenomenon indicates that the micropores in the sample are mostly cylindrical, parallel plate, or ink bottle pores with one end closed. The shape of the desorption isotherm curves in the high-pressure zone is almost parallel. In addition, it could form a hysteresis loop as the relative pressure rises close to the hysteresis loop $H_1$. Besides, the amount of nitrogen adsorbed keeps increasing with relative pressure (Figure 4) and is still not saturated in the pressure saturation region, which is close to the hysteresis loop $H_3$. This phenomenon indicates that cylinder-shaped pores opening at both ends and parallel plate-slit pores are the main types of pores when the relative pressure is over 0.4. Therefore, the hysteresis loop in the CCSB is a hybrid of $H_1$ and $H_3$ and micropores and mesopores are the majority inside the board.

As shown in Figure 5, the cumulative pore-size distribution of two CCSBs was obtained according to the BJH model processing data by the nitrogen adsorption method. The total adsorption volume of nitrogen increases linearly with the expansion of pore size as the pore size does not exceed 20 nm and subsequently stabilizes after exceeding 20 nm. This phenomenon indicates that the size of the pores in two CCSBs is less than 20 nm. At the same time, the curve of S11 is beneath S0 for all pore radii. This curve suggests that the pore-size distribution range and the total adsorption pore volume of the CCSB doped with the composite alkali activator are significantly reduced. Besides, the addition of the alkali activator significantly improves the total pore volume in the CCSB.

The pore-size distribution of the CCSB is 1–93 nm (Figure 6). The bimodal distribution of the pore-size distribution curve indicates that the pore size of the CCSB accounts for a large proportion in the corresponding range. The distribution of the pore size over 20 nm shows a downward trend, indicating that there are fewer pores with a pore diameter greater than 20 nm in the CCSB. Peaks of the S0 CCSB are at 1.926 and 4.869 nm. Two peak positions of the S11 CCSB, which is doped with the composite activator in the raw material, are shifted left to 1.525 and 4.779 nm, respectively. This phenomenon indicates that the incorporation of alkali activators can refine the average pore size of the CCSB.
pore diameter in the CCSB. In addition, the specific surface area of the CCSB without the alkali activator is 67.48 m$^2$·g$^{-1}$ and reduces to 47.05 m$^2$·g$^{-1}$ after incorporating the alkali activator, which can be calculated by applying the BET model. Therefore, the average pore size of the CCSB is refined under the activation of the alkali activator, which converts some harmful pores and less harmful pores into harmless pores. This reduces the total pore volume and pore-size distribution range, and the overall mechanical properties of the CCSB are improved. As can be seen from Table 2, the mass-loss rate and the strength-loss rate of the S11 CCSB are lower than those of the standard sample S0. It is known that the alkali activator contributes to the refinement of the average pore size and the void volume inside the sample, thereby improving the frost resistance of the CCSB.

2.5. Effect of the Alkali Activator on the Physical Performance of CCSB Samples. The test results are shown in Table 3. The physical properties of the CCSBs, prepared using four industrial solid wastes, 3% CaO, and 9% Na$_2$SiO$_3$, meet the requirements. The ball drop impact resistance test verified that there is no crack on the surface; no dripping on the reverse side of the board was observed, which qualified the board to be impervious. The strength of the CCSB can reach the class III standard in the DI.5 series.

| index                  | standard request | result |
|------------------------|------------------|--------|
| thermal conductivity   | ≤0.35            | 0.31   |
| density                |                  | 1.45 g·cm$^{-3}$ |
| dry shrinkage ratio    | <0.19%           | 0.05%  |
| moisture content       | ≤10%             | 8%     |
| swelling ratio         | ≤0.25%           | 0.22%  |
| heat shrinkage ratio   | ≤0.50%           | 0.37%  |
| nonflammable           | level A          | qualified |

2.6. XRD Analysis. From the microscopic point of view, the S11 CCSB has the best strength. Its X-ray diffraction (XRD) pattern is shown in Figure 7. The main mineral components consist of tobermullite, calcium carbonate, calcium hydrated calcium aluminate, and a small amount of ettringite. By adding the alkali activator to the pozzolan-based composite gelling system, silicon and calcium raw materials undergo a complete hydration reaction and then produce calcium silicate crystals composed of tobermullite with good crystallinity. This can be proven by the sharp diffraction peak seen in Figure 7. The production of CaCO$_3$ may result from the carbonization of Ca(OH)$_2$ crystals and the hydrated gel by CO$_2$ in the high-temperature curing process.

2.7. Comparative Analysis. Industrial cement, river sand, or machine sand is commonly used as the main calcium and silicon raw materials in the traditional CCSB preparation process. Addition of solid waste raw materials in the cement slurry was widely applied when preparing CCSB materials. Nowadays, much attention is focused on industrial transformation and upgrading. River sand excavation is prohibited due to environmental issues. Raw materials including sand and cement cannot meet the increasing demands. Average prices of river sand and PO42.5 cement are 150−220 and 440−510 yuan·t$^{-1}$ in China, respectively. Shortages are occurring in some areas, triggering downstream soaring prices of products such as concrete. In this experiment, fibers were blended into a composite gelling system composed of four kinds of pure solid wastes. Ideally, the flexural strength of the CCSB can reach a maximum of 14.72 MPa. At this point, a large volume of solid waste can be consumed and the related environmental pollution caused by cement production can be eliminated. This provides a new idea for the manufacture and application of the CCSB. The raw materials used in this experiment are cheap and easily accessible. The price of carbide slag is very low (10−30 yuan·t$^{-1}$) or free. Compared with the traditional

![Figure 7. XRD pattern of the S11 CCSB](https://dx.doi.org/10.1021/acsomega.0c00709)
process, the cost of calcium and silicon raw materials can be reduced by about 200 yuan·t⁻¹.

3. CONCLUSIONS

In this paper, the effects of CaO, NaOH, Na₂SiO₃, and Na₂CO₃ on the flexural strength, frost resistance, and pore structure parameter of laboratory-prepared pure solid ratios were studied. Besides, the effects of different alkali activator types and dosages on the performance (strength, heat shrinkage rate, dry shrinkage rate, water absorption, and density) of CCSBs were also investigated. Based on the experimental test results, the main conclusions can be drawn as follows:

1. Four alkali activators (CaO, NaOH, Na₂SiO₃, and Na₂CO₃) were added to raw materials in both the single-doped form and compound-doped form. Within the range of the current dosage, the single-doped form of different proportions of the alkali activator enhanced the flexural strength of CCSBs. Furthermore, the mechanical properties of CCSBs were further improved by the optimization of the compounded alkali activator. The single-doped activation effect of the four alkali activators ranking by their significance level is CaO > NaOH > Na₂SiO₃ > Na₂CO₃, while the activation effect of the compound-doped is (CaO + Na₂SiO₃) > (NaOH + CaO) > (Na₂SiO₃ + Na₂CO₃) > (NaOH + Na₂CO₃) > (Na₂CO₃ + CaO). The flexural strength of the CCSB can reach 14.72 MPa when compounded with 3% CaO and 9% Na₂SiO₃.

2. The main types of pores in the CCSB are micropores and mesopores. The addition of a compound-doped alkali activator to the raw materials can effectively reduce the total pore volume and the pore-size distribution range of the board. The average pore size can also be refined, thereby improving the flexural strength of the CCSB significantly.

3. The FTC of the CCSB shows that the compound-doped alkali activator can effectively reduce the mass and strength loss of the CCSB and enhance the frost resistance of the board. Also, test results show that the physical properties of the obtained CCSB are compliant with the national standard, and the strength can reach the level III standard in DLS series.

Consequently, the results of this study can be used to develop a cost-efficient and composite calcium silicate board material with a long-term vision for mining solid waste treatment. The measurements show that it is possible to predict the performance required to reach a specific value of strength and the performance properties of a given CCSB sample. There is, however, no doubt that there is a lack of research related to the preparation of CCSBs using pure solid waste and alkali activators. Some of them are different solid waste mineralogies, possibly more effective types and levels of alkali activators, and solid contents. Most of the above aspects are now under investigation.

4. MATERIALS AND METHODS

4.1. Raw Materials and Characteristics. The primary raw material for preparing the CCSB was the industrial solid waste source containing calcium and silicon. Fly ash, carbide slag, and silica fume were taken from the Ordos Electric Metallurgical Group, and flue gas desulphurization gypsum (FGD gypsum) was from the Datang Tokto Power Plant. The fiber was a blend of cellulose fibers and paper fibers. The content of the main elements in the raw materials is listed in Table 4. Analysis of the chemical composition showed that the content of SiO₂ in silica fume was 92%. The content of SiO₂ in fly ash was 47.68%, and Al₂O₃ was 42.07%. The content of CaO in carbide slag reached 67.54% followed by Al₂O₃ and SiO₂. The main chemical compositions of FGD gypsum powder were CaO and SO₃. The particle size distribution of the four raw materials is given in Table 5. The median diameter (D₅₀) of FGD gypsum and carbide slag was 19.27 and 21.55 μm, respectively. Four different alkali activators were selected for reinforcement and they are listed in Table 6.

The XRD patterns of raw materials are shown in Figure 8. The sharp and unique characteristic peak of FGD gypsum indicates that the main mineral component of FGD gypsum is highly crystalline CaSO₄·2H₂O. The XRD patterns of silica fume in which the main mineral component was SiO₂, had a “hill”-shaped typical glassy diffused peak in the range of 20°–40°. The internal silicon in silica fume mainly exists in an indefinite form with high pozzolanic activity. Hence, it could be used as a valuable inorganic nonmetal material after removing the impurities. The characteristic peak of carbide slag was sharp, suggesting that the main mineral composition is Ca(OH)₂ and a small amount of CaO. Therefore, it could replace quicklime as the raw material for producing the CCSB, thereby avoiding the influence of the heat released by hydration on the performance of the calcium silicate billet. The disordered characteristic peaks of fly ash represented the complex mineral composition. According to the XRD pattern of fly ash, the main mineral components were mullite crystal, quartz, corundum, and an amorphous vitreous structure. It could promote the hydraulic gelling activity of cement products and improve the performance of products thanks to the pozzolanic activity of fly ash.

4.2. Experimental Program. CCSBs were prepared by the compression molding method in the laboratory. The XRD analysis shows that these four industrial solid wastes are suitable as substitute materials of CCSBs. Therefore, in combination with the optimal raw material ratio obtained in the previous study, the four different alkali activators were separately incorporated into the pozzolan-based composite gelling system by 3, 6, 9, and 12%. The four alkali activators were mixed two by two according to different mass ratios and then added to the composite gelling system. After stirring for 5 min, the mixture was evenly poured into two homemade molds (150 mm × 150 mm × 10 mm) and pressed (pressure: 40 MPa) for 15 min. After standard pre curing (RT 20 ± 2 °C, RH 95%), the samples were demolded after 12 h and then steam-cured (180 °C, 1.05 MPa) for 8 h. In order to reduce the experimental errors, the average test results of three samples were taken from each group.
4.3. Experimental Installations and Tests. In order to study the properties of alkali activator-reinforced CC SBs, a set of tests (flexural strength, frost resistance, pore structure parameter, moisture content, water absorption, density, dry shrinkage rate, swelling ratio, and heat shrinkage rate analysis) were conducted, which are given below.

4.3.1. Flexural Strength Test. The flexural strength $F$ of the CC SB was measured by a three-point bending test. It can be determined according to the following equation:

$$F = \frac{3PL}{(2be^2)}$$  

(1)

where $F$ is the flexural strength of the sample (MPa); $P$ is the failure load (N); $L$, $b$, and $e$ are offset, section width, and thickness of the sample, respectively (mm).

4.3.2. Frost Resistance Test. The temperature difference between day and night in winter varies greatly. Therefore, the requirements for material durability are more stringent. To confirm the freeze–thaw resistance of products, 25 FTCs were performed on the samples. The samples were stored in a naturally ventilated environment for 7 days and then submerged in water at no less than 5 °C for 24 h. After wiping with a wet towel, these samples were kept in a freezer (−20 ± 2 °C) for 30 min. When thoroughly frozen, samples were taken out and thawed in water at 20 ± 5 °C. Such a process of undergoing a circulation of freeze and thaw is called an FTC. CCSBs after 25 FTCs were tested for cutting.

4.3.3. Pore Structure Parameter Test. The pore structure has a crucial influence on the macroscopic mechanical properties of the CC SB. Therefore, the low-temperature nitrogen adsorption method was chosen to analyze the pore-size distribution, total pore volume, and specific surface area of the CC SB. An SI-3MP three-station automatic surface and porosity analyzer (pore-size measurement range is 0.35–400 nm) was used as a measuring instrument. The nitrogen adsorption volume under different relative pressures ($P/P_0$) was measured at 77 K with high purity nitrogen as the adsorbate.

4.3.4. Moisture Content, Water Absorption, and Density Test. The physical performance testing was performed according to the national standards (GB/T 7019-2014 and JC/T 564.2-2018). The moisture content $\omega$, water absorption $W$, and density $\rho$ were determined according to the following equations

$$\omega(\%) = \left(\frac{m_0 - m_1}{m_1}\right) \times 100$$  

(2)

$$W(\%) = \left(\frac{m_3 - m_1}{m_1}\right) \times 100$$  

(3)

$$\rho = \frac{m_0}{V_{\text{dry}}}$$  

(4)

where $m_0$ is the weight of the sample under natural ventilation conditions for 7 days (g); $m_1$ is the weight of the sample after drying in a drier at 105 °C ± 5 °C for 24 h (g); $m_3$ is the weight of the sample after putting into water at 5 °C or higher for 24 h (g); and $m_3$ is the weight of the sample after taking out from water and wiping off the attached water (g).

4.3.5. Dry Shrinkage Rate and Swelling Ratio Test. The dry shrinkage rate $\Delta l$ and the swelling ratio $\varepsilon$ were determined according to the following equations

$$\Delta l = \left(\frac{l_1 - l_2}{l_1}\right) \times 100$$  

(5)

$$\varepsilon = \left(\frac{l_3 - l_2}{l_2}\right) \times 100$$  

(6)

where $l_1$ is the length of four sides of the sample under natural ventilation conditions for 7 days (mm); $l_2$ is the length of four sides of the sample after drying in a drier at 60 ± 5 °C for 24 h (mm); $l_3$ is the length of the four sides of the sample after drying in a drier at 105 ± 5 °C for 24 h (mm); and $l_4$ is the length of the four sides of the sample after taking out from water and wiping off the attached water (mm).

4.3.6. Heat Shrinkage Rate Test. The heat shrinkage rate $\Delta S$ was determined according to the following equation

$$\Delta S = \left(\frac{s_2 - s_1}{s_1}\right) \times 100$$  

(7)

where $s_1$ is the length of four sides of the sample after heating to 100 ± 5 °C in a drier and $s_2$ is the length of four sides of the sample after heating to 600 °C for 3 h.

Table 5. Particle Size Composition of Raw Materials (μm)

| materials | D03 | D06 | D10 | D16 | D25 | D50 | D75 | D85 | D90 | D97 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FA        | 29.13 | 18.50 | 70.13 | 99.23 | 135 | 412.5 | 576 | 657.6 | 715.2 | 820 |
| SF        | 0.138 | 0.202 | 0.291 | 0.412 | 0.529 | 4.250 | 15.19 | 26.04 | 38.52 | 75.75 |
| CS        | 0.622 | 1.354 | 2.692 | 5.047 | 9.095 | 21.55 | 40.71 | 55.58 | 67.81 | 103.5 |
| FGDG      | 0.082 | 0.117 | 0.207 | 0.684 | 2.096 | 19.27 | 46.85 | 62.46 | 74.18 | 106.5 |

Table 6. Experimental Alkali Activators

| reagents(AR) | purity | production |
|--------------|--------|------------|
| Na₂CO₃       | ≥97%   | Tianjin    |
| Na₂SiO₃·9H₂O | Na/Si = 1.03 ± 0.03 | Tianjin |
| NaOH         | ≥96%   | Tianjin    |
| CaO          | ≥98%   | Tianjin    |

Figure 8. XRD patterns of raw materials.
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Notes
The authors declare no competing financial interest.

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