Performance Enhancement of Coal Gangue Aggregates through Chemical Composite Treatments

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Abstract. Coal gangue, a waste from coal mining, presents significant environmental challenges but has the potential to mitigate the environmental impact of conventional construction materials when used as coarse aggregate in concrete. This study explores its chemical modification with sodium silicate, calcium chloride, and surfactants. Results show a 39.8% reduction in crushing value and a 16.7% decrease in water absorption. Microscopic analysis confirms the formation of calcium silicate hydrate (C-S-H) and silica gel, enhancing strength and bonding. Chemically modified coal gangue offers a low-carbon, sustainable alternative for concrete, supporting resource recycling and lowering the construction industry's carbon footprint.

Keywords: Coal gangue aggregate, Composite modification treatment, Physical and mechanical properties, Microstructure, Modification mechanism

1 Introduction

The growing demand for sustainable construction materials has driven interest in using industrial waste like coal gangue, a by-product of coal mining with environmental risks [1-2]. Using coal gangue in concrete addresses waste disposal issues and reduces construction's environmental impact[3]. However, its high porosity and weak mechanical properties limit its direct use as a high-performance aggregate[4-5].

To improve coal gangue aggregate, various modification methods have been explored. Zhang et al.[6] used carbonate precipitation bacteria to induce eco-friendly $CaCO_3$, reducing water absorption and immobilizing heavy metals. Yang et al.[7] showed that soaking recycled aggregates in sodium silicate improved compressive strength and frost resistance showed that soaking recycled aggregates in sodium silicate improved compressive strength and frost resistance. Fan et al.[8] enhanced recycled aggregates using MMA monomer impregnation, reducing water absorption and improving strength.

This study focuses on composite chemical treatment of coal gangue using sodium silicate, calcium chloride, and surfactants to improve its physical and mechanical properties[9]. The goal is to make coal gangue a viable, low-carbon alternative to traditional

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aggregates, aligning with sustainable construction and low-carbon development principles[10-11].

2 Materials and Methods

2.1 Materials

The coal gangue coarse aggregate was obtained from the Wulanmulun coal preparation plant, part of the Shendong Coal and Carbon Branch. It underwent sampling, crushing, screening, and grading to produce a continuous grading of 5–20 mm.

The cement used was P.O. 42.5 ordinary Portland cement. The sodium silicate solution contained silicon dioxide (SiO_2) and sodium oxide (Na_2O). Anhydrous calcium chloride was of analytical grade (AR), and the activator mainly consisted of anionic surfactants, such as sodium alkyl sulfonate and fatty alcohol ether sulfate.

2.2 Coal Gangue Aggregate Treatment

The coal gangue was evenly divided and immersed in $CaCl_2$ solutions with concentrations of 4.5% and 5% for 1 hour. After soaking, the coal gangue was placed on a tray and dried to a constant weight using an electric blast oven. Subsequently, sodium silicate solutions with mass fractions of 5.5%, 6%, and 6.5% were prepared. To address the issue of high cohesiveness of the sodium silicate solution, 1% and 1.2% of surfactants were added to the solutions, respectively. The coarse aggregate was then soaked in the modified sodium silicate solution for 1 hour before being dried to a constant weight. The composite reinforcement ratio design for the coal gangue is shown in Table 1.

Table 1. Design of composite strengthening ratio of coal gangue

Number of experiments	A water glass concentration/%	B Calcium chloride concentration/%	C surfactant concentration/%
$A_0B_0C_0$	0	0	0
$A_1B_2C_1$	5.5	5	1
$A_2B_2C_1$	6	5	1
$A_3B_2C_1$	6.5	5	1
$A_3B_1C_1$	6.5	4.5	1
$A_3B_2C_2$	6.5	5	1.2

2.3 Testing Methods

Basic Performance of Coarse Aggregate. The water absorption and crushing index of the coal gangue coarse aggregate were measured both before and after the modification treatment, with each test conducted three times to ensure accuracy and reliability.

Microscopic Mechanism Analysis. Scanning electron microscopy (SEM) was used for microscopic analysis to examine the morphology, particle shape, surface roughness, and pore structure of the aggregate.

3 Results and Discussion

3.1 Physical and Mechanical Properties of Coarse Aggregate

Crushing Value of Aggregate. Fig. 1 shows that untreated coal gangue ($A_0B_0C_0$) has the highest crushing value (32.5%), indicating weak strength. Increasing sodium silicate concentration ($A_1B_2C_1$ to $A_3B_2C_1$) lowers the crushing value, with $A_3B_2C_1$ achieving the lowest (19.6%) and best reinforcement. Reducing calcium chloride to 4.5% ($A_3B_1C_1$) raises the value slightly to 21.6%, while increasing surfactant to 1.2% ($A_3B_2C_2$) results in 20.3%. Sodium silicate concentration is key, with $A_3B_2C_1$ showing optimal performance.

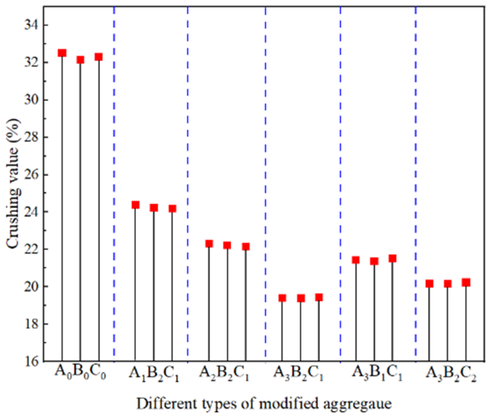


Fig. 1. Crushing index variation of coal gangue after reinforcement.

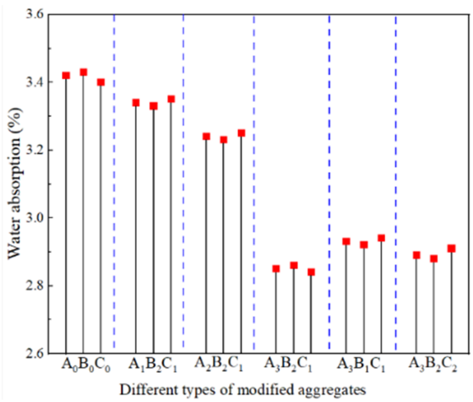


Fig. 2. Water absorption variation of coal gangue after reinforcement.

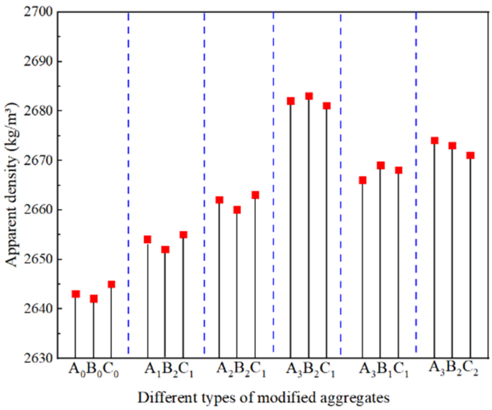


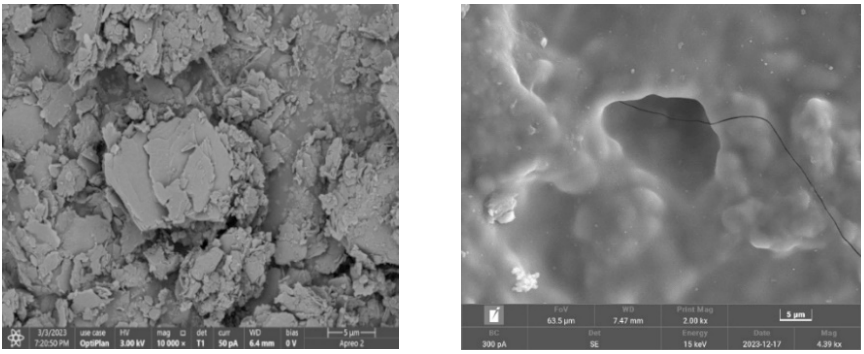
Fig. 3. Variation law of apparent density of coal gangue after reinforcement

Water Absorption of Aggregate. Fig. 2 demonstrates that the untreated coal gangue ($A_0B_0C_0$) has the highest water absorption rate at 3.45%. As the sodium silicate concentration increases ($A_1B_2C_1$, $A_2B_2C_1$, $A_3B_2C_1$), the water absorption rate significantly decreases, with $A_3B_2C_1$ showing the lowest value (2.88%), indicating improved compactness and water resistance. When the calcium chloride concentration is reduced to 4.5% ($A_3B_1C_1$), the water absorption rate slightly increases to 2.93%. Increasing the surfactant concentration to 1.2% ($A_3B_2C_2$) results in a water absorption rate of 2.91%, slightly higher than $A_3B_2C_1$, but still much lower than the control. Overall, increasing sodium silicate concentration is key to reducing water absorption, with $A_3B_2C_1$ showing the best performance.

Apparent Density of Aggregate. For the same coal gangue, an increase in apparent density after reinforcement indicates a denser internal structure, while a decrease suggests porosity. As shown in Fig 3., different concentrations of chemical composite reinforcement affect the apparent density of coal gangue. As sodium silicate concentration rises, the apparent density increases. At 5.5%, 6%, and 6.5% concentrations of sodium silicate, the average apparent density increases by 0.39%, 0.69%, and 1.46%, respectively, compared to untreated coal gangue. The apparent density peaks at 6.5%, indicating the densest structure. The study also examined the effect of different concentrations of calcium chloride and surfactant solutions. Using $A_3B_1C_1$ (4.5% calcium chloride) resulted in a 0.53% decrease in apparent density compared to $A_3B_2C_1$. At 1.2% surfactant concentration ($A_3B_2C_2$), the apparent density decreased by 0.35% compared to 1% ($A_3B_2C_1$). Sodium silicate concentration has a more significant effect on apparent density than calcium chloride and surfactant concentrations. The chemical composite reinforcement coats the surface and fills internal pores, reducing porosity and significantly increasing apparent density.

3.2 SEM Analysis of Aggregates

Fig. 4.(a) (before modification) shows that the surface of coal gangue aggregate is rough, with visible pores and cracks, loose particle bonding, and a porous structure, resulting in high water absorption and low mechanical strength. Fig.4.(b) (after modification) shows that the pores are filled, cracks are reduced, and the surface of the particles is covered with dense reaction products, leading to a significantly denser structure and improved mechanical properties. This indicates that the modification process enhances the compactness and strength of coal gangue aggregate by filling pores and cracks.



(a) Strengthening pre coal gangue (b) Reinforced coal gangue

Fig. 4. Comparison of microscopic morphology of raw gangue and modified gangue.

Mechanism of Chemical Composite Treatment on Coal Gangue Aggregates:

(1) Sodium silicate reacts with CO_2 to form silica gel, filling pores and bonding cracks, thereby improving the structure and strength:

$$Na_2O\cdot nSiO_2+mH_2O=2NaOH+nSiO_2\cdot(m-1)H_2O \tag{1}$$

(2) Soaking removes surface impurities, enhancing chemical penetration and increasing density.

(3) Calcium chloride reacts with sodium silicate to form calcium silicate hydrate, filling pores and cracks. The solution also forms a protective film on the aggregate:

$$Na_2O\cdot nSiO_2+CaCl_2+nH_2O\rightarrow mSiO_2\cdot(n-1)H_2O+2NaCl+Ca(OH)_2 \tag{2}$$

$$Ca(OH)_2+SiO_2\cdot nH_2O\rightarrow CaO\cdot SiO_2\cdot(n+1)H_2O \tag{3}$$

4 Conclusion

This chapter mainly focuses on the chemical composite treatment of coal gangue coarse aggregates at different concentrations and evaluates the performance of the treated aggregates. Additionally, a microscopic mechanism analysis of the modification of coal gangue aggregates was performed. The conclusions are as follows:

(1) The modification process significantly reduces water absorption and the crushing index, while improving the apparent density and mechanical properties of the aggregate, positioning coal gangue as a sustainable alternative to traditional aggregates in construction.

(2) Microscopic analysis confirms the formation of calcium silicate hydrate and silica gel, which fill pores and cracks, improving structural integrity and reducing the environmental impact of aggregate production.

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