

## Research Article

# Study on the Performance and Green Degree Evaluation of the Reference Cement–Sulfoaluminate Cement Composite System

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With the large-scale construction of infrastructure such as high-speed railways and the rapid development of building industrialization and prefabricated buildings, the precast concrete industry has ushered in vigorous vitality. However, there are many tricky problems such as high-energy consumption and unstable long-term performance in the existing production technology of steam-cured concrete. Based on the current research on concrete early strength technology, this paper focuses on the early strength performance and greenness evaluation of the reference cement–sulfoaluminate cement (C–SAC) system. The results confirm that when the 30% mineral admixture—60% C–10% SAC system is mixed with the composite early strength agent, the 1 day strength of mortar can reach 38.0 MPa under the condition of 45°C steam curing. The water absorption is 1.1% after 28 days. The carbon emission of the system (32.1%) is lower than that of the reference cement, and the production energy consumption and the initial resource energy are reduced by 14.4% and 8.2%, respectively. This paper provides a promising strategy for the development of low-carbon, and early strength concrete and ultimately provides technical support for the realization of high-quality and green production of precast concrete components.

## 1. Introduction

Early strength agents, special cements or high-curing temperatures are commonly adopted to improve the early strength of cementitious material systems in the industry [1–6]. Special cements mainly include high-alumina cement, sulfoaluminate cement, and ferroaluminate cement [7–11]. This paper aims to develop an early strength and low-carbon [12–14] cementitious material system by adding sulfoaluminate cement to the cementitious system. The production of tricalcium silicate emits 1.80 g/ml of carbon dioxide, while the production of tetracalcium sulfoaluminate is only 0.52 g/ml [15], and some low-cost raw materials or wastes can be used for the production of raw materials [16]. The hydration process of sulfoaluminate cement releases heat rapidly [17], and microcracks caused by internal and external temperature stress may appear in large-volume structures, and later strength development is unfavorable. Quite a few studies have focused on the strength properties of silicate-sulfoaluminate systems [18–20]. Chen et al. [21] believed that the strength performance of Portland cement and sulfoaluminate cement was related to the mixing ratio of the

Portland cement–sulfoaluminate cement system. Hong's [22] research showed that adding an appropriate amount of Portland cement clinker could improve the early compressive strength of sulfoaluminate cement.

In summary, few research pays attention to the early performance improvement of the reference cement–sulfoaluminate cement system. This article is devoted to find the “mineral admixtures–reference cement–sulfuraluminum cement-admixtures” cementitious system, and by adjusting traditional curing method to satisfy high early strength and its compression strength is improved at the late periods. In addition, the system should meet the purpose of energy conservation and consumption reduction. This study has contributed to the further exploration of green and efficient cementitious materials.

## 2. Experimentation

**2.1. Materials.** The chemical compositions of reference cement (C), sulfoaluminate cement (SAC), fly ash (FA), slag (Slag), silica fume (SF), and C-S-H seed crystal (CN) are shown in Table 1 [23–25]. Triethanolamine (TEA) is a chemical analytical reagent with a concentration of 99.99%. The polycarboxylic

TABLE 1: Chemical composition of materials (%).

Chemical composition	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	Na <sub>2</sub> O <sub>eq</sub>	f-CaO	Loss
C	22.37	4.36	3.38	61.08	2.43	2.45	0.506	0.86	1.33
SAC	5.81	10.8	1.54	56.73	0.60	9.78	0.23	—	—
FA	51.00	35.64	4.75	2.95	0.50	1.17	0.58	—	—
Slag	26.54	13.46	0.52	37.2	7.63	2.87	0.47	—	—
SF	95.18	0.30	0.07	0.28	1.68	1.01	0.49	—	—
CN	11.85	0.45	0.05	23.0	0.05	0.18	13	—	—

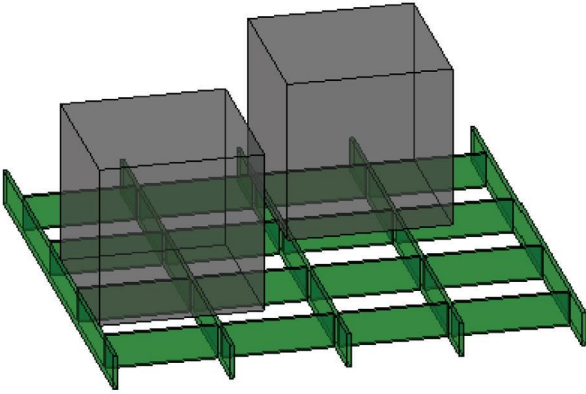


FIGURE 1: Schematic diagram of mortar water absorption test.

acid water-reducing agent is used as the water-reducing agent. The mixed water used in the experiment was deionized water.

## 2.2. Methods

**2.2.1. Compressive Strength.** Put cement, water, and river sand into the mixing pot in proportion in turn. A cement mortar mixer (Wuxi Jian Gong Test Equipment Co., Ltd., Wuxi, China) was used: after selecting the automatic mode of the mixer, turn on the mixing and add additives at the same time, slow mixing for 120 s and fast mixing for 180 s. After mixing, fill the mixture into the standard mold. The mixtures (40 mm × 40 mm × 160 mm and 70.7 mm × 70.7 mm × 70.7 mm) were kept in a horizontal position for 24 hr at different temperatures. Then they were extracted and moved to standard curing (20 ± 1°C, RH ≥ 90%) room until testing time. Compressive strength tests were conducted on the specimens cured for 1, 28, and 90 days according to GB/T 17671-2021 [26, 27].

**2.2.2. Water Absorption.** Each group was prepared with three mortars (70.7 mm × 70.7 mm × 70.7 mm), under standard curing conditions for 28 days, and then placed in a drying oven at 105°C for 48 hr. The oven naturally cooled to standard temperature, and then the specimens were removed and immersed in water for 48 hr (20 ± 1°C). This ensured that the bottoms of the mortars were fully in contact with water, with the top of the mortars below the water surface at least 2 cm, as shown in Figure 1. This paper set the measurement time point during the period according to DL/T 5148-2021 [28, 29] and finally obtained the water absorption curve.

**2.2.3. Thermal Analysis.** The TAM Air eight-channel isothermal calorimeter produced by the American TA Company

(New Castle, DE, USA) was used to measure the specific heat flow released during the hydration process at 20°C. Add cement, water, and admixtures to the mixing pot in the proportion shown in Table 2. Mixing was performed for 1 min at 860 rpm. Afterward, approximately 1.8 g of the mixture was cast into ampoules and inserted into the calorimeter. Samples were temperature-equilibrated for 72 hr prior to the measurements [30–33].

## 3. Results and Discussion

**3.1. Compressive Strength.** The control group (C: SAC = 9 : 1) was determined by the preliminary exploratory experiment conclusion. To reduce energy consumption, mineral admixtures, and 0.02% TEA–1.0% CN composite early strength agent are added to the system. The proportion is determined by previous tests, and the proportion is shown in Table 2. Take six bars of mortar from each group at each age, break them into 12 pieces, measure the compressive strength, and take the average of 12 data. Data exceeding 5% of the average value will not be used, and the remaining valid data will be averaged.

Mortar was prepared according to the ratio in the above table. Each group was provided with two curing systems, a standard curing group and a 45°C steam curing group. After demolding, the mortar was transferred to the standard curing room. At the target age, it was taken out to test the compressive strength. The strength test results of each specimen are shown in Figure 2.

It can be seen from Groups 0 and 1 in Figure 2(a) that the early strength of the system mixed with the composite early strength agent under standard curing conditions is 23.07% higher than that of the blank group, and the increase in curing temperature promotes the early strength of the system. Under the condition of 45°C steaming, the strength of the No. 2 and No. 3 groups can reach 40 MPa in 24 hr. The reference cement of the No. 5 and the No. 6 group was reduced to 60%, and the strength at 24 hr could be guaranteed under 45°C steaming conditions. According to Figure 2(b), the 28-day compressive strength of the No. 1 group is 11.55% higher than that of the No. 0 group under standard culture conditions. The reference cement content was reduced to 70%, and the 28-day strength of No. 3 was 64.25 MPa under standard culture conditions, which was 15.60% higher than that of No. 0. The results confirm that the compound early strength agent still promotes the late hydration of the system, and the promotion effect is more obvious under the condition of low-temperature evaporation. When the reference cement

TABLE 2: Cement–SAC system mix proportions (mass ratio).

	Cement	SAC	FA	Slag	W/B	S/B	TEA	CN
0. Control	90	10	—	—	0.3	1.64	—	—
1. Control-T/C	90	10	—	—	0.3	1.64	0.02	1.0
2. 20% FA	70	10	20	—	0.3	1.64	0.02	1.0
3. 20% SLAG	70	10	—	20	0.3	1.64	0.02	1.0
4. 10% FA–10% Slag	70	10	10	10	0.3	1.64	0.02	1.0
5. 20%FA–10% Slag	60	10	10	10	0.3	1.64	0.02	1.0
6. 10% FA–20% Slag	60	10	10	20	0.3	1.64	0.02	1.0
7. 20% FA–20% Slag	50	10	20	20	0.3	1.64	0.02	1.0

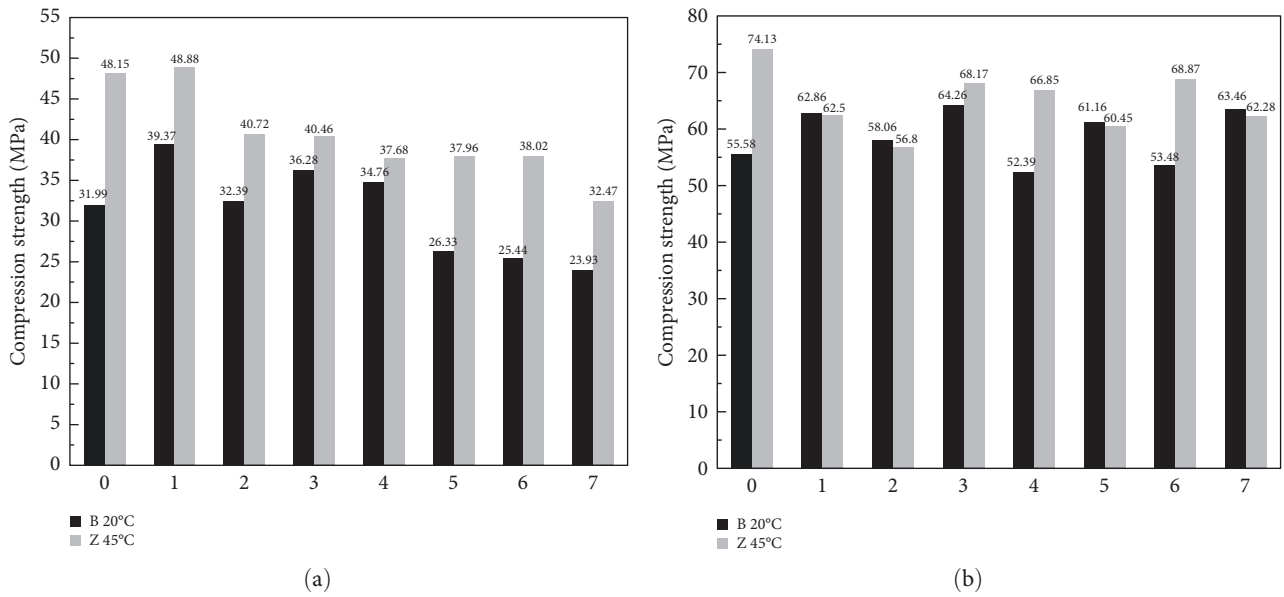


FIGURE 2: Compression strength of the cement-SAC system with different curing temperatures: (a) 24 hr compression strength. (b) 28 days compression strength.

is reduced to 50% of the early strength agent, the 28-day compressive strength of Group 7 can reach more than 60 MPa, which caters to the trend of green environmental protection and lower energy consumption.

**3.2. Water Absorption.** Good durability is very important for the structure of cement-based materials. Considering that the durability of cement-based materials involves many factors, this section focuses on the water absorption rate of mortar specimens in full immersion. Take three mortar cubes from each group, and take the average of the test results. The experimental proportions are shown in Table 2. The test lasted for 48 hr with time points set in the middle. After that, the samples are removed and the excess water on the surface is wiped away. The mass of the samples was recorded, and the curve of water absorption was drawn.

As shown in Figure 3, the water absorption of the specimens in each group under the steaming condition at 45°C was generally lower than that under the standard condition. In Figures 3(a) and 3(b), the water absorption of the experimental groups (Nos. 1–7) with the composite early strength agent was lower than that of the control group (No. 0).

Under steaming at 45°C, 0.02% TEA–1.0% CN can significantly reduce the water absorption rate of the system, and the rate gradually increases with increasing the mineral admixture. In Figures 3(c) and 3(d), the water absorption of Nos. 1–7 was higher than that of the steaming groups at 45°C. With the increase in mineral admixture, the rate of the specimens gradually increased but was still lower than that of No. 0.

**3.3. Thermal Analysis.** To further explore the influence of the compound early strength agent on the early hydration of the system, the paste prepared with the mix ratio in Table 2 was placed in ampoules and transferred into a 20°C isothermal calorimeter to monitor the early hydration behavior, as shown in Figure 4.

In Figure 4, the hydration process of each group presents an “accelerated–latency–reaccelerated–slow” period. The addition of SAC significantly shortened the latency stage and the hydration heat showed a double peak trend in the reacceleration stage, which was more obvious after adding an early strength agent. In Figure 4(a), the accumulated heat release of hydration in No. 1 during 0–72 hr was always higher than that in No. 0, and the heat release in 72 hr was 1.91% higher

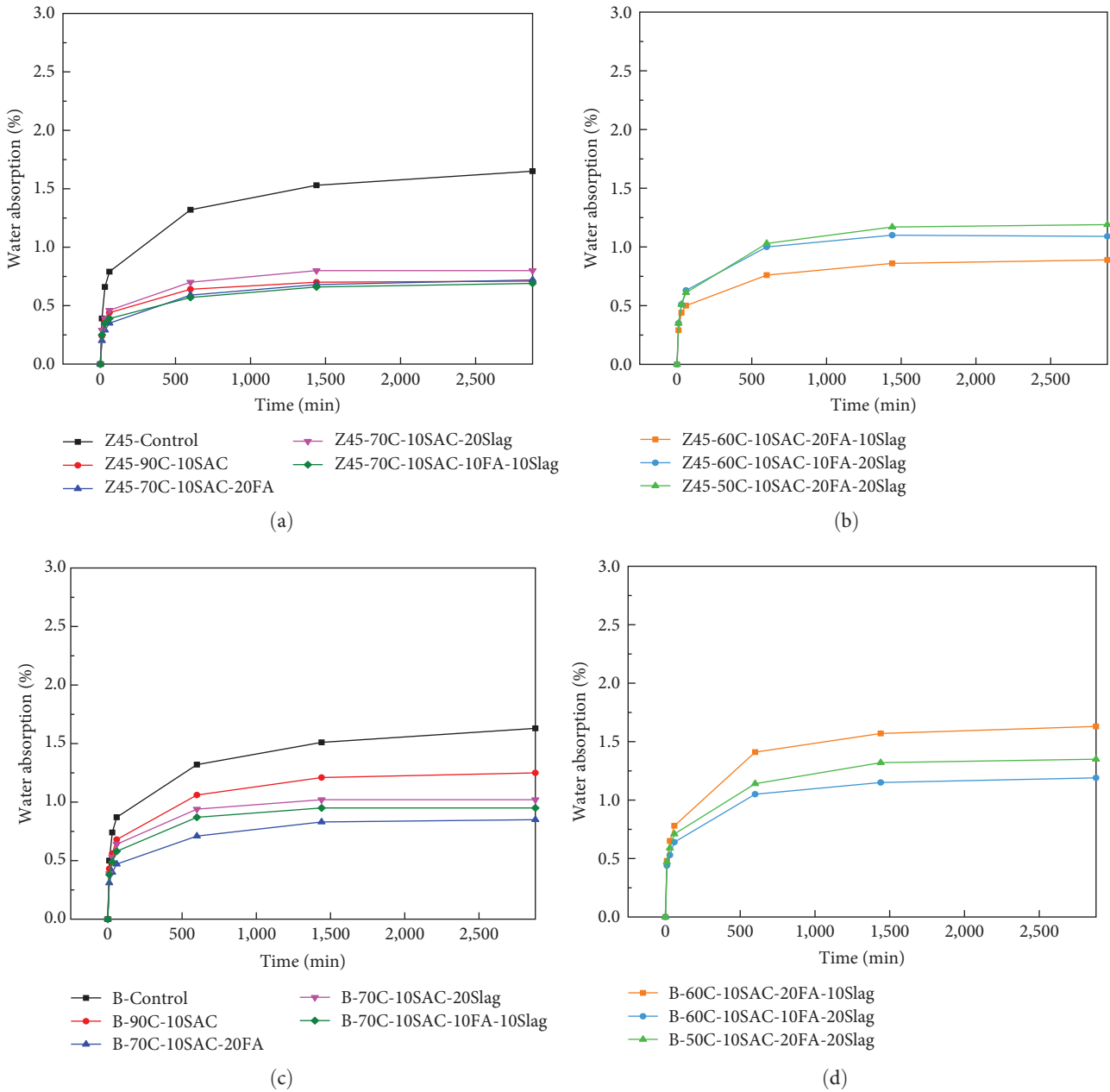
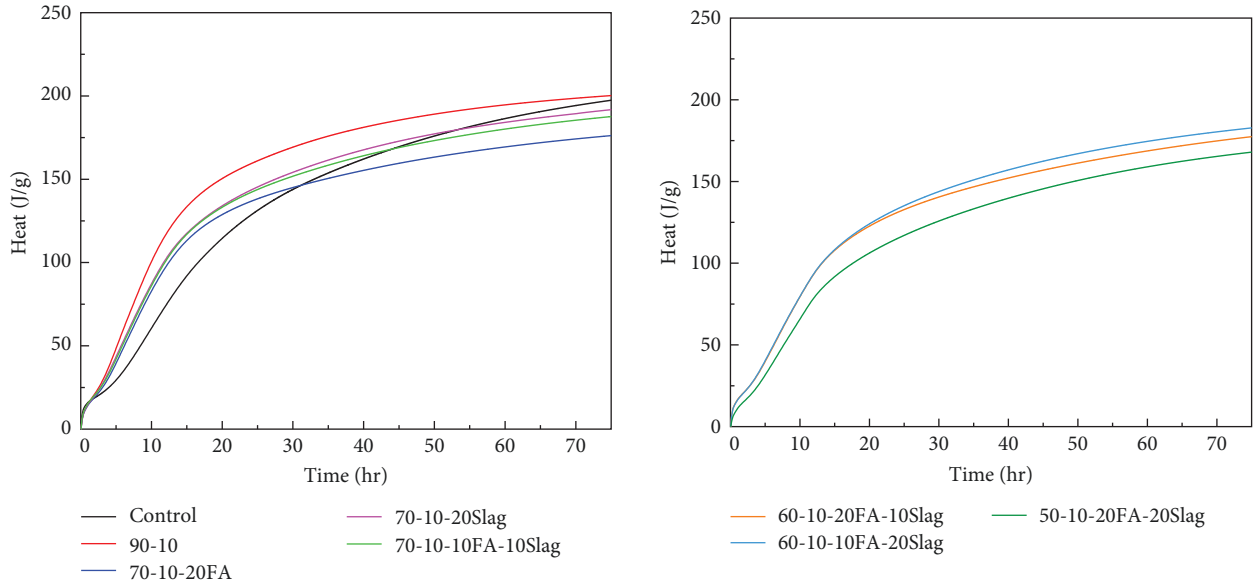


FIGURE 3: Water absorption of the cement-SAC system. (a) 45°C curing Temperature-1. (b) 45°C curing Temperature-2. (c) 20°C curing Temperature-1. (d) 20°C curing Temperature-2.

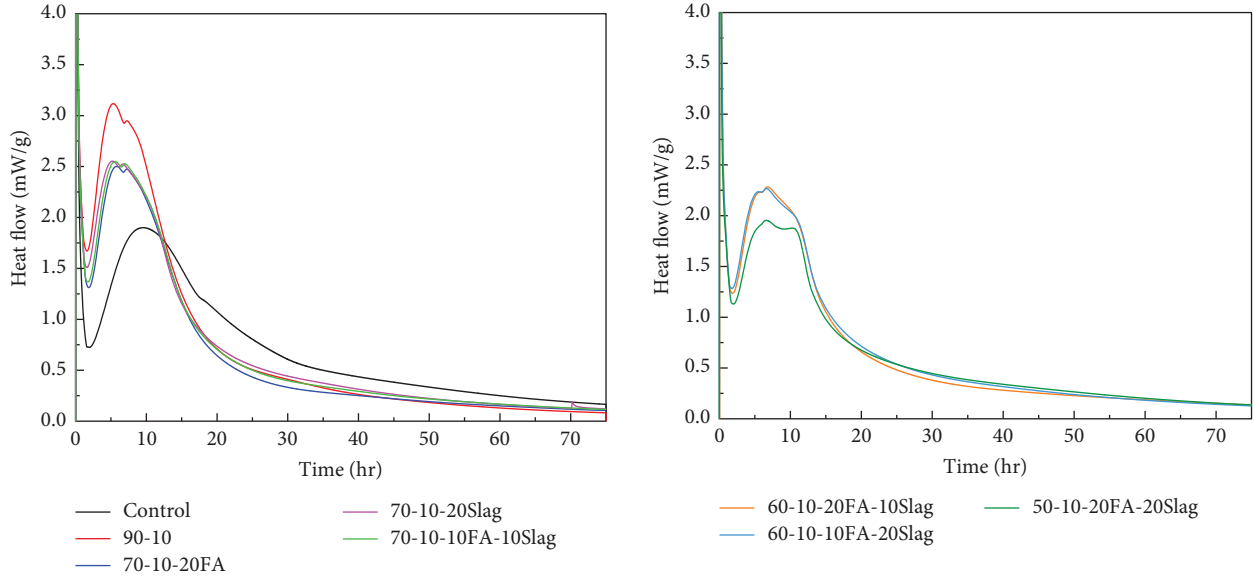
than that in No. 0. Compared with Nos. 2–7, the hydration heat release of the system gradually decreased with increasing the amount of mineral admixture. When 30% mineral admixture was added, the heat release of No. 6 was 3.12% higher than that of No. 5 in 72 hr. Figure 4(b) exhibits that, the hydration rate of Nos. 1–7 was higher than that of No. 0 during 0–15 hr, and the peak of the hydration rate appeared earlier. With the increase in the mineral admixture, the peak of the hydration rate of the system decreased gradually. The peak of hydration rate of No. 7 was higher than that of No. 0. The results demonstrated that 0.02% TEA–1.0% CN significantly promoted the early hydration of the C–SAC system.

**3.4. Greenness Evaluation.** The production, maintenance, transportation, and other links of the concrete industry need to consume a large amount of energy and emit a large amount of carbon dioxide, so environmental problems are prominent. At present, the understanding and quantitative calculation of “green concrete” remain to be further explored [34]. Many studies have paid attention to this topic [35–38]. This section analyzes and compares the green performance of different systems from the different perspectives.

This paper refers to the achievements of Long et al. [39] to calculate the carbon emissions and other green indicators of the composite system. The formula is as follows:



(a)



(b)

FIGURE 4: Heat of hydration curves of the cement-SAC system. (a) Hydration heat release. (b) Hydration heat release rate.

$$CI = \frac{\text{Embodied-CO}_2 \text{ (kg/m}^3\text{)}}{\sigma \text{ (MPa)}}, \quad (1)$$

$$EI = \frac{\text{Embodied-energy (MJ/m}^3\text{)}}{\sigma \text{ (MPa)}}, \quad (2)$$

$$RI = \frac{\text{Embodied-primary-resources (kg/m}^3\text{)}}{\sigma \text{ (MPa)}}, \quad (3)$$

CI—the amount of CO<sub>2</sub> emitted during production (kg/m<sup>3</sup>); EI—energy consumption during production (MJ/m<sup>3</sup>); RI—the amount of initial resources (kg/m<sup>3</sup>); σ—compressive strength at 28 day.

The above parameters of different cementing materials can be found in the literature [40–44], as shown in Table 3.

Compared with the ordinary Portland cement, sulfoaluminate cement has obvious advantages in energy savings and low-carbon emissions. The calcination temperature is low, and the carbon dioxide emission is significantly reduced in the production process [45]. According to Formulas (1)–(3), the mix ratio with better performance is selected for calculation, as shown in Table 4.

The greenness index of each group in the above table was calculated and the results are shown in Figure 5.

According to the above results, it can be seen that adding mineral admixture to the composite cement material can

TABLE 3: Green degree parameters.

Items	e-CO <sub>2</sub>	e-Energy	e-Resource
SAC	0.56	4.07	1.16
Cement	0.83	4.727	1.73
Fly ash	0.009	0.833	0
Slag	0.019	1.588	0
River sand	0.001	0.022	1.0
Water	0.0003	0.006	0
TEA	0.72	18.3	0
CN	0.15	3.85	0

TABLE 4: Green degree sample mix proportions.

	Cement	SAC	FA	Slag	S/B	W/B
0. Control	90	10	—	—	1.64	0.3
1. 20Slag	70	10	—	20	1.64	0.3
2. 10FA-20Slag	60	10	10	20	1.64	0.3
3. 20FA-20Slag	50	10	20	20	1.64	0.3

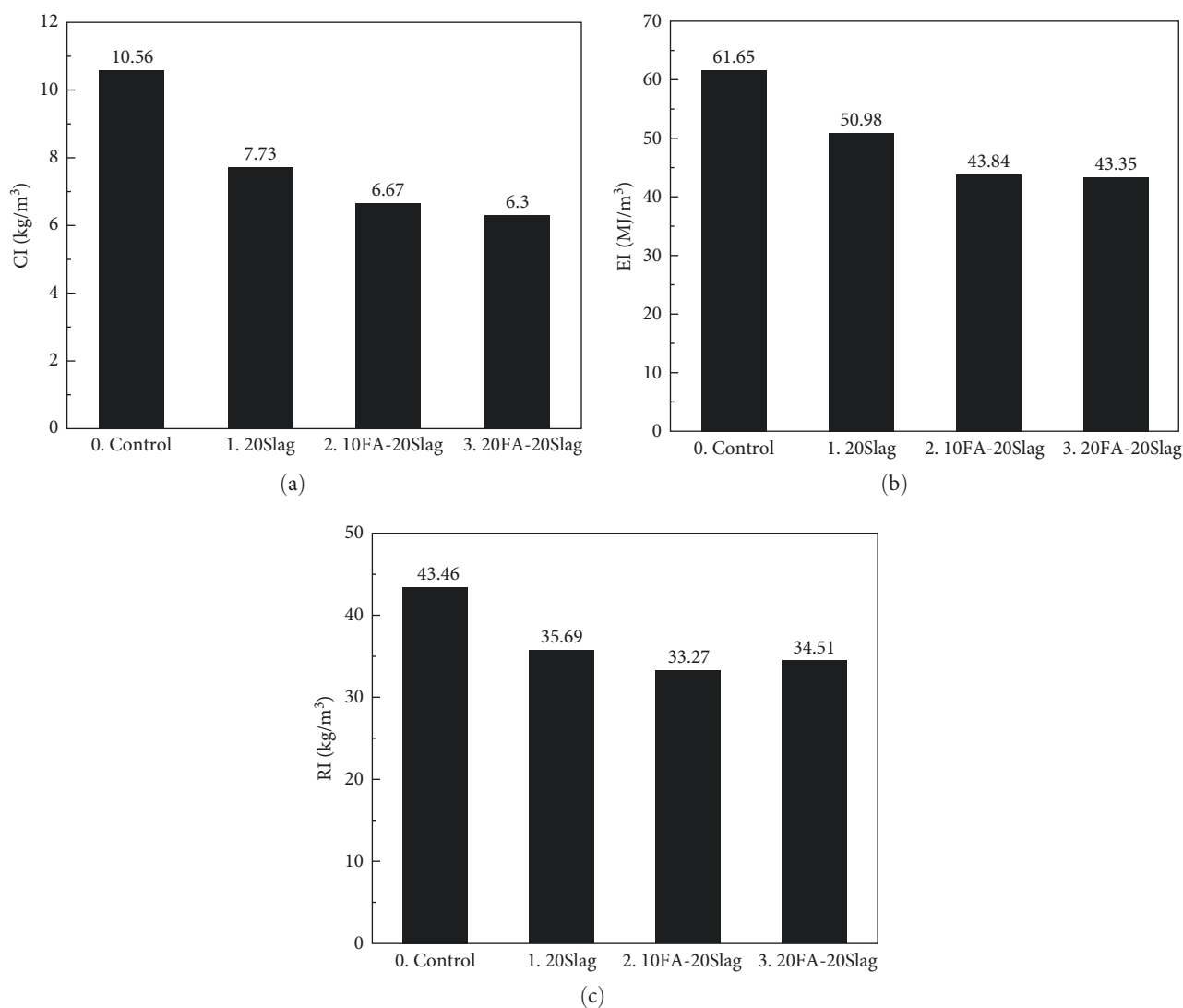


FIGURE 5: Green degree: (a) carbon emissions, (b) energy consumption, and (c) initial resource energy.

effectively reduce the greenness index of the system and each index value decreases significantly with increasing the amount of mineral admixture. The strength of No. 0 decreased slightly at 28 days when the early strength agent was added, while the strength of No. 1–No. 3 was greatly reduced with continuously increasing mineral admixture.

#### 4. Conclusions

- (1) Under standard conditions, the TEA–CN compound early strength agent can not only hydrate the C–SAC–mineral admixture system in the early stage but also promote a stable increase in its strength in the late stage. The strength of the C–SAC composite system can be significantly improved by increasing the slag content at 45°C.
- (2) When 10% FA–10% Slag and 0.02% TEA–1.0% CN early strength agent were added into the C–SAC system, the water absorption rate of 48 hr was only 0.69% under steaming at 45°C.
- (3) Adding 0.02% TEA–1.0% CN early strength agent to the C–SAC system can significantly accelerate the early hydration process and increase the peak hydration rate of the system. The peak hydration rate of the system is related to the amount of mineral admixture. The higher the amount of slag is, the higher the accumulation of hydration heat in the early stage of the system.
- (4) Under the condition of 45°C evaporation, 60% cement–10% SAC–10% FA–20% slag system mixed with 0.02% TEA–1.0% CN early strength agent presents the best performance. The strength of the system is 38.02 MPa for 1 day and 68.87 MPa for 28 days. The water absorption is only 1.09%. The carbon emission, the production energy consumption, and the initial resource energy are 6.07, 43.84, and 33.27 kg/m<sup>3</sup>, respectively. This result provides a direction for the preparation of low-carbon concrete structures. This cementitious system fully utilizes industrial waste such as fly ash and slag to reduce the consumption of cementitious materials while ensuring the workability of mortar, which is in line with the current global development goals of energy conservation and emission reduction.

#### Data Availability

Data for this research article are included within this study.

#### Disclosure

The authors wrote two other articles: Bulletin of the Chinese Ceramic Society 2020,39 (4) DOI:10.16552/j.cnki.issn1001-1625.2020.04.010 Materials 2021, 14(19), 5677; <https://doi.org/10.3390/ma14195677>.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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