

Research on the Preparation of Foam Concrete Based on Solid Waste and Its Application Performance in Prefabricated Lightweight Walls

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Abstract: To promote the resource-utilization of industrial solid wastes in prefabricated building wall panels, fly ash, slag, desulfurized gypsum and other solid wastes were used to partially replace cement for preparing foamed concrete. Single-factor tests and orthogonal tests were adopted to investigate the effects of solid-waste content, water-binder ratio, foam dosage (target dry density), and curing regime on properties including dry density, compressive strength, thermal conductivity, water absorption and pore structure. Furthermore, mechanical, thermal-insulation, sound-insulation, fire-resistance and durability performances of the material applied in prefabricated lightweight wall panels were analyzed. Planned experimental data indicate that the maximum 28-d compressive strength (3.4 MPa) is achieved at a total solid-waste content of 40 %. The mix proportion with a water-binder ratio of 0.50 and target dry density of 600 kg/m³ delivers a compressive strength of approximately 3.2 MPa at the thermal conductivity of 0.105 W/(m·K), satisfying the strength requirements for prefabricated lightweight walls. Dry density acts as the critical factor balancing thermal conductivity and mechanical strength. This preliminary analysis is developed based on planned data; actual values are pending verification by real experimental results.

Keywords: foamed concrete; solid waste; prefabrication; lightweight wall; compressive strength; thermal conductivity

1. Introduction

The development of prefabricated buildings imposes comprehensive requirements on enclosure walls, such as lightweight and high strength, thermal insulation and fire resistance, and efficient construction. Foamed concrete, with its characteristics of being lightweight, insulating, soundproofing, and easy to cast in place, has become one of the key choices for prefabricated lightweight wall materials. Meanwhile, the long-term stockpiling of large amounts of solid waste—such as slag, fly ash, and desulfurization gypsum—generated by industries like metallurgy, power, and building materials occupies land and imposes environmental burdens. Utilizing these wastes in foamed concrete production can both reduce cement usage and material costs while disposing of solid waste, aligning with the development direction of green building materials.

Regarding the application of solid waste in foam concrete, some progress has been made in research. Zhao et al. [1] prepared foam concrete using the pre-mixed cast-in-place process and found that when the steel slag powder and fly ash content reached 20% (mass fraction), the performance of cast-in-place foam concrete was optimal. The properties of foam concrete improved with the addition of fly ash. Zhao et al. [2] developed a ternary cementitious system based on slag micro-powder, fly ash, and desulfurization gypsum, combined with a foaming agent and polystyrene particles, to produce prefabricated composite wall panels for steel structure housing. Under the optimal mix ratio, the material exhibited a 28-day compressive strength of 11.12 MPa, a dry volume density of 973 kg/m³, and a thermal conductivity of 0.187 W/(m·K), achieving a balance of mechanical, lightweight, and thermal insulation properties. Wang et al. [3] discovered that the thermal conductivity of fly ash-slag-based foam materials was primarily determined by porosity, with an exponential negative correlation between the two, while compressive strength was closely related to pore connectivity, porosity, and pore size distribution. In foreign research, Dong et al. [4] ground waste incineration bottom ash and partially replaced cement to produce lightweight foam concrete wall panels, investigating the sound insulation performance of the

panels through experiments and numerical simulations; Cong et al. [5] optimized the preparation parameters of geopolymer-based foam concrete through orthogonal tests and range analysis, noting that the water-to-binder ratio and foam content significantly influenced thermal conductivity.

Overall, existing studies primarily focus on single solid waste or single performance indicators, with relatively insufficient systematic research on the interrelationships of "preparation process—material properties—wall application." The mix design and application performance validation of waste-based foam concrete for prefabricated lightweight walls still require improvement. This paper explores the preparation of waste-based foam concrete using fly ash, slag, and desulfurization gypsum as partial substitutes for cement, systematically investigating the influence of mix ratios and preparation processes on material properties, and analyzing its application performance in prefabricated lightweight wall panels, providing experimental evidence for waste resource utilization and lightweight prefabricated construction.

2. Experimental raw materials and testing methods

2.1 Experimental raw materials

The cementitious material adopts P · O42.5 grade ordinary Portland cement, with a compressive strength of 48.6 MPa at 28 days. Solid waste includes fly ash, slag powder, and desulfurization gypsum, all of which are dried and ground to the specified fineness before use. The specific surface areas of fly ash and slag powder are about 420 m²/kg and 450 m²/kg, respectively. The desulfurization gypsum is dried and ground before use; The main chemical compositions of the three types of solid waste are shown in Table 1. Animal protein composite foaming agent is selected as the foaming agent, with a foaming ratio of not less than 25 times and a settling distance of not more than 5 mm within 1 hour; modified polyacrylamide foam stabilizer is used as the foam stabilizer; The water reducing agent adopts polycarboxylate high-efficiency water reducing agent; The mixing water is tap water, as is shown in Table 1.

Table 1. Main chemical composition of raw materials (mass fraction/%)

Raw materials	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	Loss on ignition	Other
Fly ash	49.3	27.6	6.2	5.4	1.2	1.1	0.8	1.3	4.2	2.9
Slag powder	33.8	14.5	0.6	40.2	7.5	1.8	0.3	0.4	0.9	0
Desulfurized gypsum	2.4	1.1	0.5	32.6	1.0	43.2	0.2	0.3	18.7	0

2.2 Mix proportion design

In the test, the total amount of solid waste (cement replacement rate), water binder ratio, and foam amount (target dry density grade) were taken as the main variables. The single factor test was used to investigate the influence of various factors on the performance, and L9 (3³) orthogonal test was used to determine the optimal mix ratio. The total amount of solid waste is designed to be 30% -70% of the cement quality, the water binder ratio is 0.40-0.60, the foam amount is controlled based on the target dry density of 400-900 kg/m³, the ternary cementitious ratio is fixed as fly ash: slag: desulfurization gypsum=1 :1 :3, the amount of foam stabilizer is 0.10% of the cementitious material quality, and the amount of water reducer is 0.40%. The levels of each factor are determined based on the results of the pilot test, and the specific mix proportions are shown in Table 2.

Table 2. Mix proportion design of solid waste based foam concrete

Number	Water-cement ratio	Total amount of solid waste mixed/%	Fly ash: slag: desulfurization gypsum	Target dry density/(kg · m ⁻³)	Foaming agent dosage/%
F1	0.50	30	1: 1: 3	600	1.2
F2	0.50	40	1: 1: 3	600	1.2
F3	0.50	50	1: 1: 3	600	1.2
F4	0.50	60	1: 1: 3	600	1.2
F5	0.50	70	1: 1: 3	600	1.2
F6	0.45	50	1: 1: 3	600	1.2
F7	0.55	50	1: 1: 3	600	1.2
F8	0.50	50	1: 1: 3	400	1.8
F9	0.50	50	1: 1: 3	800	0.8

2.3 Performance testing methods

The size and test method of the test piece shall refer to JG/T 266 foam Concrete and corresponding test standards. Dry density is calculated based on the ratio of mass to volume after drying to a constant weight; The compressive strength is measured using cubic specimens on a universal testing machine, and the average value of three specimens is taken; The thermal conductivity is measured using the transient hot wire method; The water absorption rate is calculated based on the mass increment of the specimen after saturation with water; The pore structure is characterized by image analysis to determine porosity, pore size distribution, and pore connectivity, and the microstructure is observed by scanning electron microscopy.

3. Results and analysis

3.1 Effect of solid waste dosage on dry density and compressive strength

The change of total solid waste content directly affects the hydration activity of cementitious system and the pore structure of foam concrete. Planning data shows (F1-F5, target dry density of 600 kg/m³): When the solid waste content is increased from 30% to 40%, the compressive strength at 28 days increases from 3.1 MPa to 3.4 MPa, and then decreases as the content continues to increase. At a content of 70%, it drops to 2.2 MPa; The dry density slightly decreases with the increase of solid waste content, from 612 kg/m³ to 586 kg/m³. When the dosage is low, the filling effect of fly ash and the potential activity of slag are beneficial for strength development; When the dosage is too high, the cement content decreases, the hydration products are insufficient, and the pores increase, leading to a decrease in strength. The effect of solid waste content on compressive strength and dry density is shown in Figure 1.

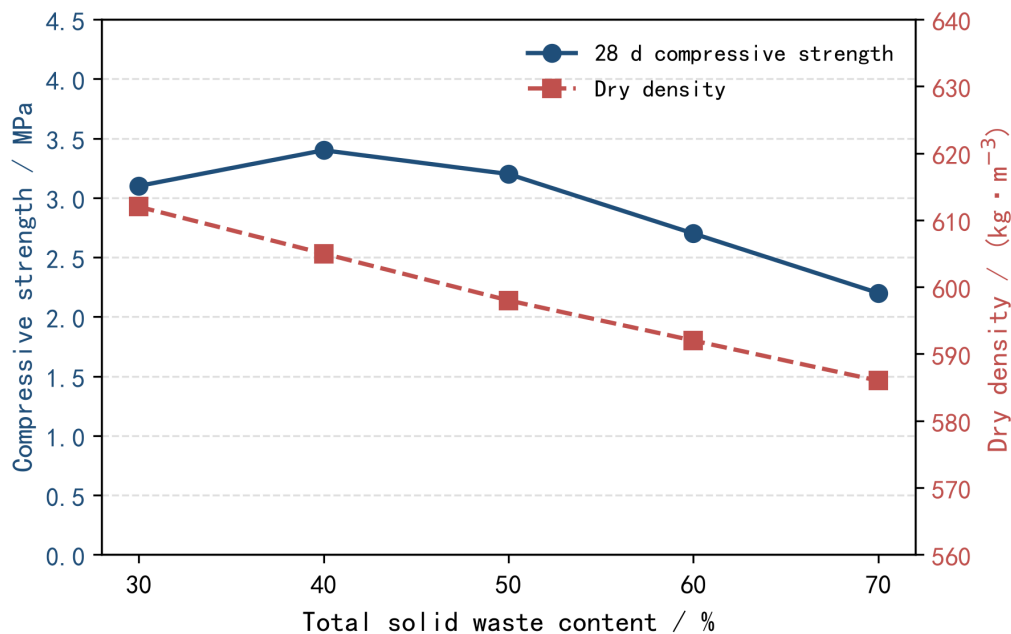


Figure.1 Effect of total solid waste content on compressive strength and dry density

3.2 Influence of water cement ratio on strength and workability

Water binder ratio affects slurry consistency, foam stability and cement hydration degree. Planning data shows (F6, F3, F7): When the water cement ratio increases from 0.45 to 0.55, the flowability of the slurry increases from 165 mm to 235 mm, the compressive strength at 28 days decreases from 3.5 MPa to 2.6 MPa, and the water absorption rate increases from 18% to 24%. When the water binder ratio is too low, the slurry is too thick, and foam is easy to break during mixing; When the water cement ratio is too high, the amount of free water increases, and after hardening, it evaporates to form connected pores, resulting in a decrease in strength and an increase in water absorption rate.

3.3 Effect of foam content (target dry density) on thermal conductivity and mechanical properties

The content of foam directly determines the porosity and dry density of foam concrete, and is a key variable to balance thermal insulation and mechanical properties. Planning data shows (F8, F3, F9): When the target dry density increases from 400 kg/m³ to 800 kg/m³, the 28 day compressive strength increases from 1.1 MPa to 5.8 MPa, and the thermal conductivity increases from 0.072 W/(m · K) to 0.148 W/(m · K). When the dry density is 600kg/m³, the compressive strength is 3.2 MPa, the thermal conductivity is 0.105 W/(m · K), and the insulation and mechanical properties are relatively balanced. This is consistent with the conclusion of Wang et al. [3] that porosity controls thermal conductivity and pore connectivity affects strength. The effect of dry density on compressive strength and thermal conductivity is shown in Figure 2.

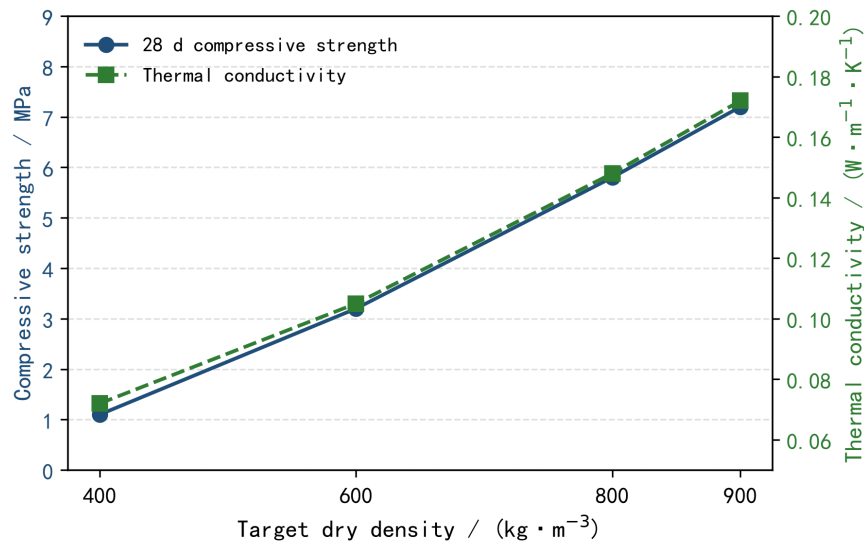


Figure 2. Effect of target dry density on compressive strength and thermal conductivity

3.4 The impact of maintenance system on performance

The maintenance temperature and humidity affect the hydration process of active components in solid waste. According to the planning data (dry density of 600 kg/m³, solid waste content of 50%), the compressive strength at 3, 7, and 28 days under standard curing is 1.2, 1.9, and 3.2 MPa, respectively; Under 60 °C wet and hot curing, the corresponding strengths were 1.8, 2.6, and 3.5 MPa. Wet heat curing can accelerate the reaction of active components such as slag and improve early strength, but the increase in strength after 28 days is limited; The hydration of desulfurization gypsum in humid environments is beneficial for the formation of products such as ettringite, which contributes to its strength. The impact of different maintenance systems on strength development is shown in Figure 3.

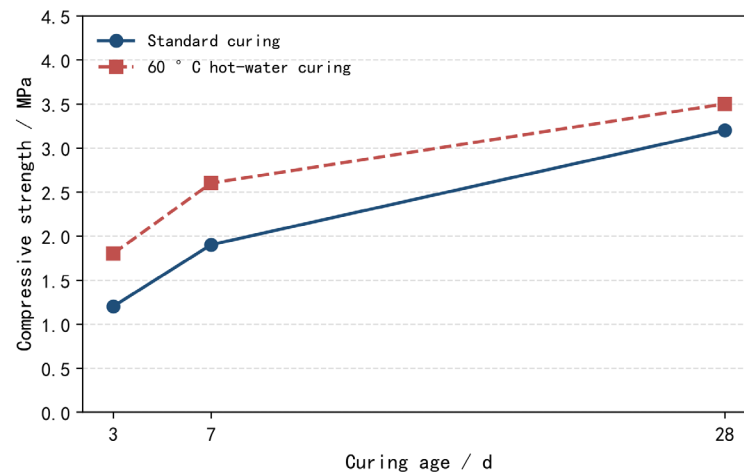


Figure.3 Development of compressive strength with curing age under different curing regimes

3.5 Orthogonal experiment mix proportion optimization

This paper using the total solid waste content (30%, 40%, 50%), water cement ratio (0.45, 0.50, 0.55), and foaming agent content (0.8%, 1.2%, 1.8%) as three factors, experiments were arranged according to an L9 (3³) orthogonal table, and range analysis was conducted with 28 day compressive strength and dry density as assessment indicators. Under the planning data, the analysis of compressive strength range shows that the total amount of solid waste is the main controlling factor affecting strength, followed by water cement ratio and foaming agent dosage; Taking into account the requirements for lightweight and strength, the optimal mix ratio is 40% solid waste content, 0.50 water cement ratio, and a target dry density of 600kg/m³, which is consistent with the results of single factor tests. The orthogonal optimization results need further review.

3.6 Analysis of pore structure characteristics and microscopic morphology

The pore structure is an intermediate link between preparation parameters and macroscopic properties. According to the planning data, when the target dry density increases from 400 kg/m³ to 900 kg/m³, the porosity decreases from 82% to 59%, and the average pore size decreases from 0.38 mm to 0.20 mm, corresponding to an increase in compressive strength and thermal conductivity; After adding a foam stabilizer, the pore size distribution becomes more uniform and the proportion of closed pores increases, which is beneficial for improving strength and insulation performance. Scanning electron microscope observation shows that the solid waste hydration products are wrapped in the foam wall in the form of gel, and needle bar ettringite crystals can be seen to fill the pores when desulfurization gypsum and slag are mixed. The comprehensive performance and pore structure data of each group of specimens are shown in Tables 3 and Table 4.

Table 3. Comprehensive performance of solid waste based foam concrete

Number	Dry density/(kg · m ⁻³)	7-day compressive strength/MPa	28 day compressive strength/MPa	Thermal conductivity/(W · m ⁻¹ · K ⁻¹)	Water absorption rate/%
F1	612	2.2	3.1	0.108	19
F2	605	2.5	3.4	0.104	19
F3	598	2.4	3.2	0.105	20
F4	592	2.0	2.7	0.103	21
F5	586	1.7	2.2	0.101	23
F6	612	2.6	3.5	0.106	18
F7	585	1.9	2.6	0.104	24
F8	415	0.8	1.1	0.072	28
F9	805	4.3	5.8	0.148	15

Table 4. Corresponding relationship between pore structure and performance of foam concrete under different target dry density

Target dry density/(kg · m ⁻³)	Porosity/%	Average aperture/mm	Compressive strength/MPa	Thermal conductivity/(W · m ⁻¹ · K ⁻¹)
400	82	0.38	1.1	0.072
600	73	0.31	3.2	0.105
800	64	0.24	5.8	0.148
900	59	0.20	7.2	0.172

4. Performance analysis of application in prefabricated lightweight walls

4.1 Prefabricated lightweight wall panel construction design

Solid waste based foam concrete can be used as core material or overall material of fabricated lightweight wallboard. Referring to the existing research on solid waste based composite wall panels [2], wall panels can be designed as ribbed or sandwich structures, and their bending performance can be improved through reinforcement or fiber reinforcement. The specifications, thickness, and connection structure of the board are determined according to the design requirements of prefabricated building walls. The board thickness is usually taken as 100-200mm to meet the requirements of self weight, insulation, and sound insulation. Based on a dry density of 600kg/m³ core material, the densities of wall panels with thicknesses of 100, 150, and 200mm are approximately 60, 90, and 120kg/m², respectively.

4.2 Wall panel mechanics and node performance

According to the planning data, when the thickness of the wall panel prepared with a dry density of 600 kg/m^3 core material increases from 100 mm to 200 mm, the flexural bearing capacity increases from $6.5 \text{ kN} \cdot \text{m}$ to $18.0 \text{ kN} \cdot \text{m}$, the impact resistance increases from 25 times to 35 times, and the hanging force increases from 1200N to 1800 N. All indicators can meet the requirements for the use of prefabricated lightweight wall panels; When the dry density is low, the weight of the wall panel is significantly reduced, which is beneficial for reducing the difficulty of assembly and lifting. The nodes adopt prefabricated dry connections or specialized connectors, and the performance of the connection nodes needs to be verified through full-scale component tests. The mechanical performance indicators of the wall panels are shown in Table 5.

Table 5. Mechanical performance indicators for prefabricated lightweight wall panel planning

Plate thickness/mm	Bending capacity/($\text{kN} \cdot \text{m}$)	Impact resistance performance/time	Hanging force/N	Surface density/($\text{kg} \cdot \text{m}^{-2}$)
100	6.5	25	1200	60
150	12.0	30	1500	90
200	18.0	35	1800	120

4.3 Wall insulation, sound insulation and fire resistance performance

According to the planning data, a 150mm thick wall panel is prepared using a core material with a dry density of 600 kg/m^3 and a thermal conductivity of $0.105 \text{ W}/(\text{m} \cdot \text{K})$. The heat transfer coefficient of the wall is about $0.7 \text{ W}/(\text{m}^2 \cdot \text{K})$, and with reasonable construction, it can meet the requirements of building enclosure insulation; The porous structure of foam concrete has a certain sound insulation effect on medium and high frequency noise. The sound insulation planning value of 150mm thick composite wallboard is about 40dB, which can be combined with numerical simulation to optimize the sequence [4]. Foam concrete is an inorganic incombustible material, and its combustion performance grade can reach Grade A, which meets the requirements of prefabricated wall for fire rating.

4.4 Durability performance

The durability of solid waste based foam concrete is mainly affected by porosity and pore structure. According to the planning data, the water absorption rate of the specimen with a dry density of 600 kg/m^3 is about 20%. The water absorption rate increases with the decrease of dry density, which may affect the frost resistance and impermeability performance; Adding an appropriate amount of slag and desulfurization gypsum promotes the generation of hydration products, which helps improve pore density. Durability indexes such as dry wet cycle, freeze-thaw cycle and long-term shrinkage shall be verified by special tests and compared with ordinary foam concrete of the same density grade.

4.5 Engineering application and comprehensive benefits

Solid waste based foam concrete is used for fabricated light wall. On the one hand, it can absorb industrial solid wastes such as fly ash, slag and desulfurized gypsum, reduce cement consumption, reduce carbon emissions and solid waste storage pressure; On the other hand, the lightweight feature can reduce the weight of the structure, improve construction efficiency, and have competitive overall cost. The comprehensive benefits need to be calculated based on specific engineering conditions, and this article only provides qualitative analysis.

5. Conclusion

In this paper, fly ash, slag, desulfurization gypsum and other solid wastes are used to partially replace cement to prepare foam concrete, and its application performance in fabricated light wall is analyzed. Based on the planning data, the following conclusions are drawn:

(1) The total amount of solid waste is one of the primary factors affecting compressive strength. According to the planning data, the highest compressive strength at 28 days (3.4 MPa) is achieved when the solid waste content is 40%, and the strength significantly decreases after the content exceeds 50%; The increase in water cement ratio leads to a decrease in strength and an increase in water absorption rate, with a performance equilibrium point near the water cement ratio of 0.50.

(2) Dry density is a key parameter for balancing compressive strength and thermal conductivity. When the target dry density is 600kg/m^3 , a balanced combination of 3.2MPa compressive strength and $0.105\text{ W/(m} \cdot \text{K)}$ thermal conductivity can be obtained, which meets the basic requirements for insulation and strength of prefabricated lightweight walls.

(3) 60°C moist heat curing can improve the early strength of solid waste based foam concrete, and the 28d strength increase is limited; The pore structure (porosity, pore size, and connectivity) is the core link between preparation parameters and macroscopic properties.

(4) Solid waste based foam concrete has good application potential in mechanics, heat preservation, sound insulation and fire prevention in fabricated lightweight wallboard, and can bring comprehensive benefits of solid waste absorption, weight reduction and carbon reduction.

(5) The values in this paper are planning data. The specific optimal values and performance indicators of total solid waste content, water binder ratio and foam content need to be determined after a complete test and supplemented with durability and component level verification.

Acknowledgement

This work was supported by Science and Technology Program Project of Shandong Provincial Department of Transport(2022B101, 2023B92-03, 2025BAI14-02).

References

- [1] Zhao J, Xu J W, Shi F T, et al. Preparation and performance of premixed cast-in-place foam concrete [J]. *Journal of Anhui University of Technology (Natural Science Edition)*, 2020, 37 (1): 87-93.
- [2] Zhao M Y, Zhang L, Huang W. Synthesis and flexural performance of solid waste based ternary cementitious integrated composite wall panel materials [J]. *Journal of Anhui University of Technology (Natural Science Edition)*, 2025, 42 (2): 198-208.
- [3] Wang H, Gao S, Guo M L, et al. Micro pore structure and macro performance of fly ash slag based foam geopolymer [J]. *Journal of Building Materials*, 2024, 27 (5). 107-112.
- [4] Dong Y, Wang Y, Zhou Z, et al. Study on the Preparation and Performance of Lightweight Wallboards from MSWIBA Foam Concrete[J]. *Materials*, 2024, 17(17): 4402.
- [5] Cong M, Zhang S, Sun D, et al. Optimization of Preparation of Foamed Concrete Based on Orthogonal Experiment and Range Analysis[J]. *Frontiers in Materials*, 2021, 8: 778173.