

Study on the Effect of Glass Bead Incorporation on the Performance of 3D Printed Glass Bead Insulating Cement-Based Materials

Zhuang Li *

Henan Polytechnic University, Jiaozuo, Henan 454000, China

*Corresponding Author: Zhuang Li (Email: lz3116242385@163.com)

ABSTRACT

To address the issues of low strength and poor construction efficiency of traditional insulation materials, this study prepared insulation cement-based materials using glass microspheres as lightweight aggregates through 3D printing technology. Through orthogonal experimental design, the influence of glass microsphere dosage (70% to 110%) on the working performance, mechanical properties and insulation performance of the materials was systematically investigated. The results show that as the dosage of glass microspheres increases, the fluidity of the slurry gradually decreases, and the 28-day compressive strength drops from 5.85 MPa to 0.74 MPa, but the thermal conductivity significantly decreases from 0.1445 w/(m·k) to 0.0632 w/(m·k). When the dosage of glass microspheres is 100%, the material has both good mechanical properties (1.48 MPa) and insulation performance (0.0718 w/(m·k)), meeting the requirements of Type II products in the building insulation mortar standard GB/T 20473-2021. This study provides theoretical basis and technical support for the engineering application of 3D printed insulation cement-based materials.

KEYWORDS

3D printing; Vitrified microsphere; Thermal insulation cement-based material; Mechanical properties; Thermal conductivity

1. INTRODUCTION

With the rapid development of industrialized construction and digital technology, 3D printing technology, as a new construction method, has shown tremendous application potential in the field of architecture [1]. Compared with traditional construction methods, 3D printing technology has significant advantages such as high construction efficiency, high material utilization, and great design flexibility, and is considered an important technological means to promote the transformation and upgrading of the construction industry [2]. However, at present, 3D printed building materials are mainly ordinary cement mortar, which has a high thermal conductivity and poor thermal insulation performance, making it difficult to meet the requirements of building energy efficiency [3].

Vitrified microbeads are a lightweight porous material made from perlite as the raw material, which are expanded at high temperatures and vitrified on the surface. They have characteristics such as low density, low thermal conductivity, and good chemical stability, and are widely used in building insulation mortar, lightweight concrete, and other fields [4]. Introducing vitrified microbeads into cement-based materials can effectively reduce the thermal conductivity of the material and improve insulation performance. However, the incorporation of vitrified microbeads can also have adverse effects on the workability and mechanical properties of the material [5]. How to optimize the mix design of vitrified microbead insulating cement-based materials while ensuring the 3D printing

construction performance, achieving a balance between mechanical properties and insulation performance, is a key issue that urgently needs to be addressed. At present, domestic and international scholars have conducted extensive research on 3D printed cement-based materials and perlite bead insulation mortar, respectively. In terms of 3D printed cement-based materials, research mainly focuses on optimizing printing process parameters, regulating rheological properties, and improving interlayer bonding performance [6-8]. Regarding perlite bead insulation mortar, research mainly concerns the effects of perlite bead content, particle size distribution, and surface modification on material properties [9-10]. However, there is relatively little research that combines the two to systematically study the preparation process and performance rules of 3D printed perlite bead insulation cement-based materials.

Based on this, this study uses ordinary Portland cement as the binder and vitrified microbeads as lightweight aggregates, employing 3D printing technology to prepare thermal insulation cement-based materials. Through orthogonal experimental design, the study systematically investigates the effects of different amounts of vitrified microbeads on the workability, mechanical properties, thermal insulation performance, and microstructure of the materials, and explores the mechanism by which vitrified microbeads improve the thermal insulation performance, aiming to provide theoretical basis and technical support for the engineering application of 3D-printed thermal insulation cement-based materials.

2. EXPERIMENTAL DESIGN

2.1. Experimental Materials

Cement: P·O 42.5 Ordinary Portland Cement, produced by Jiaozuo Qianye Cement Co., Ltd., with its main chemical components shown in Table 1.

Table 1. Chemical Composition and Physical Properties of Cement

Material	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	MnO	SO ₃	LOI
Cement	18.72	63.08	4.73	3.13	4.28	0.35	1.2	–	–	4.23

Glazed Hollow Bead (GHB), particle size range 0.5~2.0 mm, bulk density 120~150 kg/m³, thermal conductivity 0.045~0.055 w/(m·k), cylinder compressive strength 0.3~0.5 MPa.

Mineral admixtures: Grade S95 slag powder, specific surface area 450 m²/kg; Class I fly ash, water demand ratio 95%.

Additives: Polycarboxylate high-efficiency water-reducing agent (SP), water reduction rate 30%; Hydroxypropyl methylcellulose (HPMC) thickener, viscosity 200,000 mPa·s; Redispersible latex powder, solid content 98%.

2.2. Mix Proportion Design

This study adopts an orthogonal experimental design, taking the amount of vitrified microbeads (as a percentage of the mass of cementitious material) as the main variable, and designs 6 groups of mix proportions, with the amount of vitrified microbeads being 70%, 80%, 90%, 100%, and 110%, respectively. To ensure printability, the water-to-cement ratio is not fixed and depends on the specific conditions of the experiment. The total amount of cementitious materials is 450 kg/m³, with a ratio of cement:slag powder:fly ash = 7:1:2. The dosage of water-reducing agent is 1.0% of the cementitious material mass, HPMC is 0.5%, and latex powder is 2.0%. The mix proportions of each group are shown in Table 2.

Table 2. Mix Design of 3D Printed Glazed Microsphere Insulating Cement-Based Materials (kg/m³)

Number	Mass / kg·m ⁻³					SP	GHB content
	Cement	Fly ash	Slag powder	HPMC	Glue powder		
1	315	90	45	2.25	9	0.7	315
2	315	90	45	2.25	9	0.7	360
3	315	90	45	2.25	9	0.7	405
4	315	90	45	2.25	9	0.7	450
5	315	90	45	2.25	9	0.7	495

2.3. Sample Preparation

Using a frame-type 3D printer, the printer's printing space has geometric dimensions of 2 m × 3 m × 3 m, the nozzle diameter is 20 mm, the extrusion speed is adjustable from 0 to 100 mm/s, and the positioning accuracy is ±0.1 mm. The specific preparation process is as follows: first, add cement, mineral admixtures, and vitrified microspheres into a forced mixer and dry mix for 2 minutes; then add mixing water containing water-reducing agent and HPMC, and wet mix for 3 minutes; finally, add latex powder and continue mixing for 2 minutes until uniform. The mixed slurry is loaded into the hopper of the 3D printer, with the printing parameters set as follows: layer height 10 mm, printing speed 30 mm/s, extrusion pressure 0.3 MPa. According to the GB/T 17671-2021 standard, print and cut specimens with dimensions of 40 mm × 40 mm × 160 mm prismatic specimens for mechanical performance testing; 100 mm × 100 mm × 30 mm flat specimens for thermal conductivity testing. The specimens are cured in a standard curing room (temperature 20±2 °C, relative humidity ≥95%) until the specified age.

2.4. Test Methods

- (1) Workability Test: According to GB/T 20473-2021 "Thermal Insulation Mortar for Buildings," use the table-tapping method. Tap the table 25 times, measure the diameters of the mortar spread in two vertical directions, and take the average value as the flow result.
- (2) Mechanical Performance Test: Use a YAW-300 press testing machine to measure the compressive strength and flexural strength of specimens, with a loading rate of 2.4 kN/s. The test ages are 3 days, 7 days, and 28 days.
- (3) Thermal Insulation Performance Test: According to GB/T 10294-2008 "Determination of Steady-State Thermal Resistance and Related Properties of Insulating Materials by Protective Plate Method," form specimens of 300 mm × 300 mm × 30 mm, standard cure for 28 days, then dry to constant weight, and test the thermal conductivity at an average temperature of 25°C.

3. RESULTS AND DISCUSSION

3.1. Work Performance

Figure 1 shows the changes in the flowability of the slurry with different amounts of glass beads. It can be seen that as the amount of glass beads increases, the flowability of the slurry gradually decreases. When the amount of glass beads increases from 70% to 110%, the flowability decreases from 215 mm to 167 mm, a reduction of 22.3%. This is mainly because the surface of the glass beads is rough and has a high water absorption rate, which absorbs some of the free water during stirring, leading to a decrease in the effective water-to-cement ratio of the slurry and a decrease in fluidity [11].

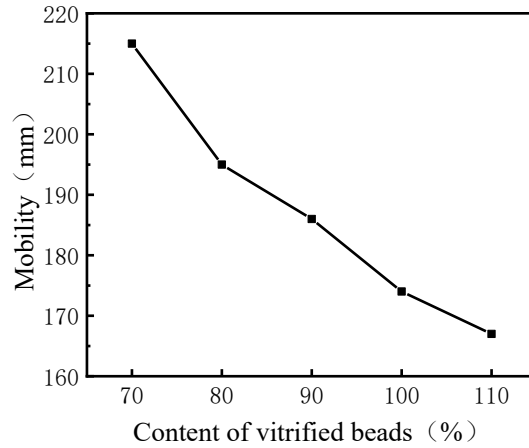


Figure 1. Effect of Glazed Microsphere Content on Material Fluidity

When the amount of vitrified microspheres is 110%, the slurry fluidity still remains above 155 mm, which can meet the workability requirements of the slurry for 3D printing [12]. However, at this time, due to the excessive amount of vitrified microspheres, the fluidity decreases too much, which can easily cause microsphere breakage, nozzle clogging, and poor interlayer bonding during the printing process. Therefore, from the perspective of workability, the appropriate amount of vitrified microspheres should be controlled within 110%.

3.2. Mechanical Properties

Figure 2 shows the compressive strength development curves of specimens with different amounts of glass microspheres. It can be seen that the compressive strength decreases with the increase in the amount of glass microspheres. The 28-day compressive strength drops from 5.85 MPa for the 70% mixture to 0.74 MPa for the 110% glass microsphere group, a decrease of 87.4%.

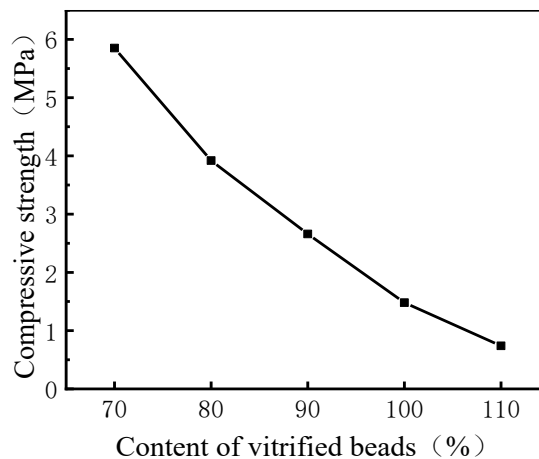


Figure 2. The effect of the amount of glass microbeads on the compressive strength of the material

The adverse effects of vitrified microbeads on mechanical properties mainly stem from the following two aspects: first, the vitrified microbeads themselves have relatively low strength, with tube compressive strength only 0.3~0.5 MPa, far lower than the cement matrix, making them prone to fracture under compression and forming stress concentration points [13]; second, the bonding between vitrified microbeads and the cement matrix is relatively weak, and there are many microcracks in the interface transition zone, which can easily become channels for crack propagation under external forces [14].

Table 3 lists the 28-day compressive strength, flexural strength, and compression-flexural ratio of each group of specimens. It can be seen that when the content of vitrified microbeads is 110%, the specimens have a 28-day compressive strength of 0.74 MPa, a flexural strength of 0.31 MPa, and a

compression-flexural ratio of 0.419, which does not meet the requirement of compressive strength ≥ 1.0 MPa for type II products in the GB/T 20473-2021 standard for building thermal insulation mortar [15]. Considering both workability and mechanical properties, 100% is determined to be the optimal content for vitrified microbeads.

Table 3. Mechanical properties of specimens with different amounts of vitrified microbeads (28 days)

Number	Content of vitrified beads (%)	compressive strength /MPa	break off strength /MPa	compressive to flexural ratio
1	70%	5.85	2.42	2.42
2	80%	3.92	1.45	2.70
3	90%	2.66	1.21	2.20
4	100%	1.48	0.68	2.18
5	110%	0.74	0.31	2.39

3.3. Thermal Insulation Performance

Figure 3 shows the effect of the addition of vitrified microspheres on the thermal conductivity of the material. It can be seen that the thermal conductivity decreases significantly with the increase in the content of vitrified microspheres. When the content of vitrified microspheres increased from 70% to 110%, the thermal conductivity dropped from 0.1445 W/(m·K) to 0.0632 W/(m·K), a decrease of 56.3%. This is mainly because the vitrified microspheres contain a large number of closed pores, whose thermal conductivity is much lower than that of the cement matrix [16]. The introduction of vitrified microspheres increases the gas phase content in the material, forming a porous structure, thereby significantly reducing the thermal conductivity of the material.

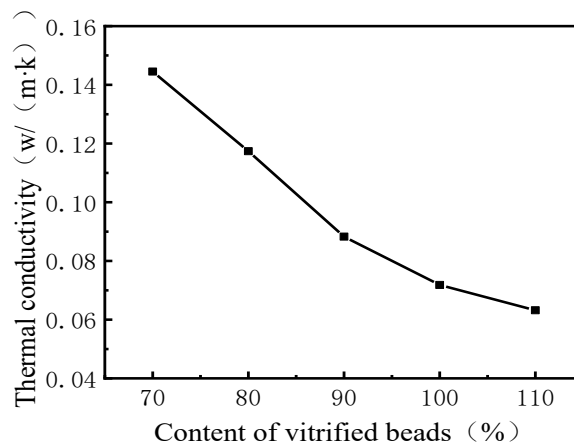


Figure 3. Effect of the amount of vitrified microbeads on the thermal conductivity of the material

4. CONCLUSION

This study used vitrified microbeads as lightweight aggregates and prepared a thermal insulation cement-based material using 3D printing technology. The study systematically investigated the effects of the amount of vitrified microbeads on the working performance, mechanical properties, and thermal insulation performance of the material, and the following main conclusions were drawn:

(1) With the increase of vitrified microbead content, the fluidity of the slurry gradually decreased. When the content did not exceed 110%, the fluidity remained above 155 mm, which could meet the construction requirements of 3D printing.

(2) The introduction of vitrified microbeads had an adverse effect on the mechanical properties of the material. The 28-day compressive strength decreased from 5.85 MPa in the control group to 0.74 MPa in the group with 110% vitrified microbead content. When the content was 100%, the 28-day compressive strength was 1.48 MPa, meeting the requirements of Type II products in the GB/T 20473-2021 standard.

(3) Vitrified microbeads significantly improved the thermal insulation performance of the material. The thermal conductivity decreased with increasing content, from 0.1445 W/(m·K) in the 70% content group to 0.0632 W/(m·K) in the 110% content group, a reduction of 56.3%. When the content was 100%, the thermal conductivity was 0.0718 W/(m·K).

(4) Considering the working performance, mechanical properties, and thermal insulation performance together, the recommended optimal content of vitrified microbeads is 110%. At this content, the material has good construction performance, sufficient mechanical strength, and excellent thermal insulation, making it suitable for the insulation layer of 3D-printed building walls.

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