New type of lightweight high-strength foamed concrete blocks

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Abstract. Lightweight high-strength concrete materials have been paid increasing attention with the development of the civil engineering technology. This study tested the effects of the admixture ratio on the properties of lightweight high-strength foamed concrete (LWHSFC) samples in a laboratory. The results demonstrated that a type of foamed concrete with 1200 kg/m³ density and >15 MPa uniaxial compressive strength can be produced by chemical foaming and by adding three types of materials (i.e., silica fume, slag, and fly ash) to the cement–fine sand matrix at an optimized mix ratio. The laboratory tests also showed that the failure mechanism of the LWHSFC was similar to ordinary concrete (i.e., longitudinal splitting failure). The angle between the failure surface and the vertical load direction was 53°–76°, indicating the material’s brittleness. The decreasing order of the compressive strength of the LWHSFC with one type of mineral powder when tested 28 days after casting was: silica fume to slag to fly ash. Moreover, the decreasing order of the compressive strength of the LWHSFC with two types of mineral powder admixtures when tested 28 days after casting was: silica fume + slag to silica fume + fly ash to slag + fly ash.

1. Introduction
Concrete is an artificial stone made of cementitious materials, coarse and fine aggregates, water, and admixtures taken in certain proportions mixed together and formed into shape by setting and hardening after a certain period [1-2]. It is characterized by a wide range of raw materials, easy preparation and processing, low cost, excellent mechanical properties, and many other features. Concrete is widely used in civil construction, bridges, tunnels, water conservation and hydropower, underground space engineering, and other construction projects [3-7]. It is the most widely utilized artificially prepared building material by amount in the world today. However, challenges, such as heaviness and high manual labor intensity and low construction efficiency, are encountered in its applications.

Foamed concrete is a lightweight material containing a large number of closed pores created through physical or chemical foaming, which provides many outstanding properties, such as weight reduction, earthquake resistance, environmental friendliness, energy savings, improved thermal insulation, improved fire protection, ease of use/production/handling, and high flowing capability [8-11]. However, it has many shortcomings, including low strength, large shrinkage, large water absorption, and easy cracking. The tensile strength of foamed concrete is also low. Foamed concrete is very easily cracked if its shrinkage is restricted, thereby negatively affecting its intended use [12-25].

In view of the abovementioned challenges, lightweight high-strength foamed concrete (LWHSFC) with the physical and mechanical properties of general concrete and is crack- and earthquake-resistant...
must be developed. Using this type of concrete can reduce the manual labor intensity and improve construction efficiency by reducing the weight of blocks.

2. Development of a new lightweight high-strength foamed concrete block

2.1. Raw material selection

The raw materials used are as follows:

(1) Cement: PO Portland cement (Huaxin Cement Co., Ltd.), whose performance and preparation satisfy the GB175-1999 requirements [25]

(2) Fly ash: first-grade fly ash, whose performance indicators comply with the GB/T1596–2005 provisions on “Fly Ash Used in Cement and Concrete”[25]

(3) Fine aggregate: commercially available standard sand (50 mesh)

(4) Foaming agent: commercially available industrial-grade hydrogen peroxide (concentration: 27.5%)

(5) Fiber: commercially available 9 mm monofilament fiber (Sheyang County Yonggu Engineering Fiber Equipment Co., Ltd., Jiangsu Province)

(6) Water-reducing agent: commercially available polycarboxylate high-performance, water-reducing agent

(7) Silica fume and slag: selected from ordinary varieties available on the market

(8) Home-made curing agent and activator

2.2. Test equipment

2.2.1 RMT multifunctional testing machine

The uniaxial strength tests were performed on an RMT-150B multifunctional fully automatic rigid concrete servo testing machine (Figure 1). The maximum axial load of the testing machine was 1000 kN.

Figure 1 RMT multifunctional testing machine

2.2.2 Other equipment used

The other equipment used are as follows:

(1) NJ-160A cement paste mixer

(2) KZJ-500 electric bending test machine

(3) Cement standard consistency and setting time tester (Vicat apparatus)
(4) 101A-2 electric heating constant-temperature drying oven

(5) SDF4000 test dispersion sand mill

2.3. Sample preparation method
The sample preparation method is elaborated below:

(1) Pre-treatment: Cement was passed through a 0.08 mm² hole screen to prevent hard particles from depositing in the foam mix.

(2) Raw material measurement

(3) Feeding and stirring: First, a small amount of water (approximately 1/20 of the total water consumption) was poured into the mixer to lubricate the barrel walls. Next, the mixer was turned on and stirred at a low speed of approximately 30–40 r/min. Subsequently, cement, fly ash, sand, silica fume, water reducer, fiber, curing agent, stimulant, and water in designed proportions were added at the same time with continuous stirring.

(4) Foaming and pouring into molds: Hydrogen peroxide was added while stirring the mix for additional 10–15 s. The mix was then poured into the molds.

(5) Sprinkling water and maintaining the mix for 28 days

2.4. Test plan
According to previous research results [25-28], the benchmark formula for foamed concrete with 1200 kg/m³ density and 10–15 MPa uniaxial compressive strength is 80% PO Portland cement, 20% standard sand (50 mesh), 0.2% polycarboxylic acid water-reducing agent (solid inclusions: 40%), 0.2% curing agent, 0.6% activator, 4.5% foaming agent, 0.5% polypropylene fibers, and 0.3 water-to-material ratio (Table 1, Test scheme #1). Three materials, namely silica fume, slag, and fly ash, were used in combination with the cement–fine sand matrix to ensure that the uniaxial compressive strength of the blocks was above 15 MPa. Table 1 shows the test plan. Figure 2 depicts the test sample cross-section in the foaming direction.

| No. | Cement/ g | Other admixtures/g | Sand/g | Foaming agent/g | Polypropylene fiber/g | Water-reducing agent/g | Curing agent/g | Activator/g | Water-to-material ratio |
|-----|-----------|-------------------|-------|-----------------|----------------------|-----------------------|----------------|-------------|------------------------|
| 1   | 960       | 0                 | 240   | 45              | 5                    | 1.6                   | 20             | 6           | 0.3                    |
| 2   | 840       | 120 silica fume   | 240   | 45              | 5                    | 1.6                   | 20             | 6           | 0.3                    |
| 3   | 840       | 120 slag          | 240   | 45              | 5                    | 1.6                   | 20             | 6           | 0.3                    |
| 4   | 840       | 120 fly ash       | 240   | 45              | 5                    | 1.6                   | 20             | 6           | 0.3                    |
| 5   | 840       | 60 (slag) + 60 (fly ash) | 240 | 45 | 5 | 1.6 | 20 | 6 | 0.3 |
3. Test results and analysis

3.1. Analysis of the stress–strain test results of the LWHSFC blocks

The stress–strain tests herein were performed on specimens with different mix ratios. Figure 3 illustrates the specimen failure mechanism. Figure 4 depicts the stress–strain curves obtained at different times after casting in Test Scheme #1.

Similar to that of ordinary concrete, the failure process of the concrete prism specimens observed in this work can be divided into various stages.

The first stage is the stable crack generation stage, wherein the concrete stress is small ($\sigma < 0.3$ $f_c$–0.5 $f_c$, where $f_c$ is the ultimate load bearing capacity), and the generated cracks are mainly bonding cracks. No new cracks are generated when the load remained unchanged. Furthermore, concrete is essentially in the elastic range.

The second stage is the crack development stage, where the length and the width of the existing cracks begin to increase. The stress–strain curve begins to exhibit nonlinear characteristics, and its slope continues to decrease as the load increases. Keeping the load unchanged at this stage, the crack development immediately stops. The lateral deformation coefficient of concrete is generally in the range of 0.15 to 0.22. The microcracks in the concrete significantly grow when the test specimen stress reaches 0.7 $f_c$–0.9 $f_c$; however, no large cracks are visible on the test specimen surface. As the loading process continues, unsteady cracks will continue to develop under a constant load and begin to appear inside the concrete specimens. The lateral deformation coefficient of the LWHSFC rapidly increases, and the volume change of the specimen switches from compression to expansion. The concrete will soon reach the ultimate load bearing capacity (i.e., $f_c$).

In the third stage, after the concrete reaches the ultimate load bearing capacity ($f_c$), the load it can bear gradually decreases. In contrast, its strain increases. Shortly after entering the descending section of the stress–strain curve, the first visible crack begins to appear on the surface in the middle of the test specimen. This crack is thin, short, and parallel to the stress direction in the specimen. A number of short, longitudinal cracks appear on the concrete specimen surface as the strain increases. Moreover, the bonding cracks along the aggregate–mortar interfaces and the cracks inside the mortar continue to...
extend, expand, and connect. The load bearing capacity of the entire concrete specimen rapidly drops and finally fails. The angle between the failure surface and the vertical load direction is $53^\circ - 76^\circ$, indicating the material’s brittleness.

(a) Crack generation stage               (b) Crack development stage

(c) Crack penetration stage

**Figure 3** Progress of the specimen failure

(a) 3 days after casting               (b) 7 days after casting
Due to the limited length of the article, we will not include the stress–strain curves of the other test schemes conducted herein at different times after casting. We will only provide the data of the uniaxial compressive strength at different times after casting (Table 2).

Table 2  Uniaxial compressive strength of foamed concrete with different mixing ratios

| Sample # | Uniaxial compressive strength/MPa |
|----------|-----------------------------------|
|          | 3 days   | 7 days   | 28 days  |
| 1        | 8.52     | 10.51    | 12.27    |
| 2        | 9.89     | 12.83    | 14.72    |
| 3        | 9.64     | 13.32    | 14.38    |
| 4        | 7.20     | 10.68    | 13.26    |
| 5        | 11.04    | 13.96    | 14.75    |
| 6        | 10.80    | 12.40    | 15.02    |
| 7        | 11.40    | 12.20    | 15.55    |

3.2. Effect of adding single mineral powder on the compressive strength

The foamed concrete with added silica fume alone had the highest compressive strength 28 days after casting (Table 2) because silica fume has extremely fine sized particles of 0.1–1.0 μm, which is 1/50–1/100 of the cement particle size, and is a highly reactive blended material with a specific surface area of 20–25 m²/g. Its main component is amorphous silica. Due to its high reactivity, when mixed with a high-efficiency water-reducing agent in concrete, silica fume reacted with Ca(OH)₂ to form a hydrated calcium silicate gel, thereby filling the voids between the cement particles, improving the interface structure and cohesion, making the internal structure of the concrete relatively dense (Figure 5(a)), and improving the concrete strength.

The effect of adding slag alone was better than that when adding fly ash alone if the amount of additive is the same because the former is more reactive than the latter and can provide more hydration products (Figures 5(b) and (c)), thereby exhibiting a positive effect on the concrete porosity reduction. After substituting a part of cement with fly ash, the cement concentration in the concrete mix was reduced, and the effective water–cement ratio controlling the cement hydration rate was relatively increased. Therefore, the calcium ion concentration in the solution, the connection between the particles, and the compressive strength at the early stage were reduced. When the fly ash–cement mix was hydrated at room temperature, the degree of the hydration reaction of fly ash was very low.
because the alkalinity of the mix cannot meet the fly ash activation requirement. Furthermore, less CSH gel can be formed because fly ash is low in calcium, which reduces the compressive strength of concrete. The slag reactivity mainly depends on the glass content and the CaO/SiO$_2$ ratio in the composition. The larger the glass content in slag, the higher the reactivity. For the same glass volume, the higher the CaO/SiO$_2$ ratio in the composition, the lower the degree of polymerization in glass and the higher the reactivity. The glass content of most slags available in China is more than 80%, while the CaO/SiO$_2$ ratio is approximately 1.0. Therefore, slag is a good substitute for cement.

![SEM images of concrete with different additives 28 days after casting](image)

**Figure 5** SEM images of concrete with different additives 28 days after casting

### 3.3. Comparison of the compressive strengths of concrete with mineral micropowder admixtures

The compressive strength of concrete with silica fume and slag admixtures 28 days after casting was the highest. A large amount of CH formation was caused by the volcanic ash effect of slag and silica fume; hence, in the later period, an additive effect was generated, which continuously reacted with CH to reduce the CH content in the interface transition zone while increasing the volume of the generated CSH gel. The resulting gel effectively filled the large pores of the mix (Figure 6), such that the pore structure of the mix was improved, and the compressive strength of concrete increased.
3.4. *Comparison of the compressive strengths of concrete with single mineral micropowder or admixtures*

The compressive strength of concrete with two types of powder admixtures 3 days after casting was higher compared to that with fly ash or slag powder alone (i.e., two types of powder admixtures were added to concrete in the early period, which exhibited a more marked “superposition effect” and a “super-stacking effect”). When tested 28 days after casting, the compressive strength of concrete with fly ash and slag admixtures exceeded that of concrete with fly ash or slag powder alone. This result is attributed to the following reason: when fly ash and slag admixtures were added in the concrete, their chemical components were complementary, despite the reactivities of the two powders being quite different; hence, when fly ash and slag were added at an appropriate ratio, they together exerted a “superposition effect” and a “super-stacking effect” on the concrete strength. The “super-stacking effect” was conditional on fineness and admixture ratio. Even if fineness was the same, the reactivity of fly ash was generally lower than that of slag because it is related not only to the chemical composition, but also to the particle structure and the CaO/SiO$_2$ ratio. On the one hand, fly ash and slag filled the pores remaining after the hydration and hardening process. On the other hand, the fine particles in the composite admixtures evenly dispersed in the concrete mix and became the seeds for a large number of hydration product volumes. As the hydration process progressed, these fine particles and their hydration products filled the voids in concrete, thereby improving the concrete pore structure and increasing its compressive strengths. The microscopic inspection results further confirmed that the harmful pores and macropores in the composite high-performance concrete were reduced; the pore structure was uniform and dense (Figure 7); and the mechanical properties of concrete were improved, thereby fully reflecting the compounding superposition effect of various admixtures.

*Figure 6* SEM image of concrete with silica fume and slag admixtures 28 days after casting
4. Conclusions
This study tested the effects of the admixture ratio on the properties of LWHSFC blocks in a laboratory. The results demonstrated that a type of foamed concrete with 1200 kg/m³ density and >15 MPa uniaxial compressive strength can be produced by chemical foaming and by adding three types of materials (i.e., silica fume, slag, and fly ash) to the cement–fine sand matrix at an optimized mix ratio. The primary conclusions of this study are as follows:

(1) The failure mechanism of LWHSFC is similar to that of ordinary concrete (i.e., longitudinal splitting failure). The angle between the failure surface and the vertical load direction is 53°–76°, indicating the material’s brittleness.

(2) The decreasing order of the compressive strength of LWHSFC with one type of mineral powder when tested 28 days after casting is as follows: silica fume to slag to fly ash.

(3) The decreasing order of the compressive strength of LWHSFC with two types of mineral powder admixtures when tested 28 days after casting is as follows: silica fume + slag to silica fume + fly ash to and slag + fly ash.

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