Development and performance characterization of ultra-light foam thermal insulation material based on ordinary Portland cement modified by sulfoaluminate cement

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Abstract. In this study, an ultra-light ordinary Portland cement-based thermal insulation material (ULCFTIM) with an apparent density of less than 300 kg/m³ was developed using physical foaming technology. The problem of ULCFTIM collapse during the preparation process was solved by adding sulfoaluminate cement (SAC). The influence of SAC mass fraction and water-cement ratio on the thermal conductivity and compressive strength of ULCFTIM was researched. The experimental results show that increasing the SAC is beneficial to the compressive strength of ULCFTIM at 3 days, but decrease the compressive strength of ULCFTIM at 28 days. The optimal mass fraction for SAC in a cementitious material is 10%. With the water-cement ratio increases, the compressive strength first increases and then decreases, and the thermal conductivity decreases first and then stabilizes. When w/c values ranging from 0.26-0.30, ULCFTIM has a good performance with compressive strength between 0.185 MPa and 0.201 MPa and thermal conductivity between 0.701 W·m⁻¹·K⁻¹ and 0.714 W·m⁻¹·K⁻¹.

Keywords: Thermal insulation materials; Ordinary Portland cement; Ultra-light; Sulphoaluminate cement.

1. Introduction
In recent years, with the increase of indoor comfort of buildings, the global demand for building energy supply is increasing, which exacerbates the energy crisis [1]. Many countries have introduced various policies for building energy conservation to reduce building energy consumption and improve energy efficiency. People pay great attention to building energy consumption, which promotes the rapid development of wall thermal insulation materials. [2, 3]. Cement-based foam thermal insulation material is more attractive than organic insulation material (such as foamed polystyrene, polyurethane board) due to its outstanding fire resistance and economy.

Cement-based foam thermal insulation material (CFTIM) are usually prepared in two methods. One is to add aluminum powder or H₂O₂ to the cement slurry to produce gas bubbles through a chemical reaction [7]. However, the CFTIM prepared by chemical foaming usually have problems such as large
internal cells, different cell sizes, and high inter-cell connectivity, which seriously affect the thermal insulation performance and strength of the material. Another way to prepare CFTIM is to pre-form the foam into the slurry. The method of injecting preformed foam into the slurry has fine and uniform internal cells, high pore sphericity, and low inter-cell connectivity [5]. But this method in the preparation of ultra-light cement-based foam thermal insulation materials (ULCFTIM) causes the mixed slurry to collapse or sink during the hardening process due to the inconsistency of cement setting time and foam survival time. In order to solve the problem of collapse during hardening, many researchers chose special cements (aluminate cement, sulfoaluminate cement and quick-hardening cementitious materials) to prepare CFTIM. Because it has the characteristics of rapid setting and hence high strengths can be attained in the initial stages of curing. However, a shortage of the raw materials required for special cement, high cost, and low durability hinder the development and application of CFTIM [8, 9]. In addition, the higher apparent density (>300 kg/m$^3$) of cement-based foam thermal insulation materials limits its thermal insulation performance and increases manufacturing costs [5]. Therefore, the development of ULCFTIM based on ordinary Portland cement and prepared by physical foaming process has important application value.

In this study, the setting time of ordinary Portland cement was adjusted by adding SAC and the physical foaming process was used to prepare ULCFTIM with an apparent density of less than 300kg/m$^3$. In addition, the influence of water-cement ratio on the thermal conductivity and compressive strength of ULCFTIM was also studied. This research has further promoted the development of wall thermal insulation materials.

2. Materials and tests

2.1. Materials.
ULCFTIM mixtures were prepared from ordinary Portland cement, sulfoaluminate cement, foaming agent, and water. The ordinary Portland cement (P.O 42.5, in accordance with Chinese standard: GB175-2007) was produced at the Jidong cement plant, Tangshan, Hebei Province, China. The sulfoaluminate cement (P.O 42.5, in accordance with Chinese standard: GB175-2007) was produced at the Shili cement plant, Xi’an, Shanxi Province, China. The foaming agent adopts the foaming agent developed by the laboratory.

2.2. Preparation process.
First, the cement is made into cement slurry according to the proportion, and the foaming liquid is added to the high-speed mixer to generate foam. Secondly, add foam to the cement slurry according to the mixing ratio and stir evenly for 3 minutes. Third, the uniformly stirred slurry is injected into a mold of 100mm×100mm×100mm. Fourth, leave the sample at room temperature for 24 hours to remove the mold. The preparation process of ULCFTIM is shown in Fig. 1.

![Fig. 1 Preparation process of ultra-light cement-based foam thermal insulation materials](image-url)
2.3. The test method.
The setting time of the mixed cementitious material should be determined according to the requirements of the Chinese standard GB/T1346-2001. The thermal conductivity of ULCFTIM should be tested according to the method provided by the Chinese standard GB10295-2008. Before testing the thermal conductivity, the sample has been cured in a standard curing environment for 3 days and dried to constant weight. The compressive strength of ULCFTIM is tested in accordance with the method required by the Chinese standard JC/T2357-2016.

3. Results and discussion

3.1. The influence of mass fraction of SAC on ULCFTIM performance

3.1.1. The influence of different mass fraction of SAC on the setting time of cement. The hardening speed of the matrix material is an important factor affecting the molding effect of ultra-light cement-based foam insulation materials. In this experiment, by measuring the setting time of the mixed cementitious material, the molding condition of the ultra-light cement-based foam thermal insulation material is inferred, so as to determine the optimal mixing amount of SAC. The measurement results of the setting time of mixed cementitious materials with different SAC mass ratios have been shown in Figure 2.

It can be seen from Figure 2 that SAC can effectively shorten the setting time of cementitious materials. As the mass fraction of SAC increases, the setting time of the cementitious material is gradually shortened. But when the SAC mass fraction is greater than 10%, the shortening of the setting time of cement gradually decreases. It can be inferred from this that the use of sulfoaluminate cement as a setting accelerator will have a significant effect on the setting time of the mixed cementitious material, making it possible to use ordinary Portland cement as the matrix to prepare ultra-light cement-based foam thermal insulation materials.

![Fig. 2](image1.png) The influence of SAC mass fraction on the setting time of cementitious materials

![Fig. 3](image2.png) The influence of SAC mass fraction on ULCFTIM compressive strength
3.1.2. The influence of different mass fractions of SAC on compressive strength of ULCFTIM. In this study, ULCFTIM with dry apparent density less than 300kg/m$^3$ was preliminarily designed, and the influence of SAC mass fraction on ULCFTIM performance and molding was studied. Experimental mix ratio is shown in Table 1. Fig.3 shows the effect of SAC mass ratio on ULCFTIM compressive strength.

| Samples | SAC/g | OPC/g | Water/g | foam/g | Molding situation       | Dry apparent density/ kg·m$^{-3}$ |
|---------|-------|-------|---------|--------|-------------------------|----------------------------------|
| 1-1     | 41    | 779   | 264     | 180    | Easy to stir and collapse | -                               |
| 1-2     | 61.5  | 758.5 | 264     | 180    | Easy to stir and sink    | -                               |
| 1-3     | 82    | 697   | 264     | 180    | Easy to mix and shape    | 273.3                           |
| 1-4     | 102.5 | 717.5 | 264     | 180    | Easy to mix and shape    | 260.7                           |
| 1-5     | 123   | 697   | 264     | 180    | Easy to mix and shape    | 266.9                           |
| 1-6     | 143.5 | 676.5 | 264     | 180    | Easy to mix and shape    | 271.5                           |
| 1-7     | 164   | 656   | 264     | 180    | Easy to mix and shape    | 269.4                           |

It can be seen from Table 1 that only when the mass fraction of SAC in the cementitious material is greater than 10%, ULCFTIM can be formed. The reason for the above phenomenon is that the mixed cementitious material with less mass fraction of SAC cannot form a support frame before the foam burst. It is worth noting that adding too much dosage of SAC will cause the foam mixing slurry to be difficult to mix uniformly. This can also explain that too much dosage of SAC will cause the cement slurry to set too fast, thereby preventing the foam and cement slurry from mixing uniformly.

More importantly, it can be seen from Figure 3 that compressive strength of the ULCFTIM at 3 days shows an upward trend with increasing mass fraction of SAC. This is because SAC promotes the formation of early strength of cement paste. However, with increasing mass fraction of SAC, compressive strength of the thermal insulation material at 28 days shows a downward trend. This is because increasing the mass fraction of SAC promotes the early strength development of the foamed cement mixture, but weakens the long-term strength development. Similar results have also appeared in the research on mixed cementitious material [10-11]. There is the most suitable mixing ratio of SAC and OPC, so ULCFTIM obtains higher compressive strength. Therefore, according to the mixed cementitious material setting time and compressive strength of ULCFTIM, it can be known that the optimal mass fraction of SAC is 10%.

3.2. The effect of water-cement ratio on the performance of ULCFTIM

The water-cement ratio is an important factor affecting the performance of cement-based materials. ULCFTIM with different water-cement ratios were prepared in this study. The sample mix ratio and molding situation are shown in Table 2.

| Samples | SAC/g | OPC/g | w/c  | foam/g | Molding situation        | Dry apparent density/ kg·m$^{-3}$ |
|---------|-------|-------|------|--------|--------------------------|----------------------------------|
| 1       | 88    | 792   | 0.24 | 180    | Not easy to stir and shape| 296                              |
| 2       | 88    | 792   | 0.26 | 180    | Not easy to stir and shape| 294                              |
| 3       | 88    | 792   | 0.28 | 180    | Not easy to stir and shape| 293                              |
| 4       | 88    | 792   | 0.30 | 180    | Easy to mix and shape     | 291                              |
| 5       | 88    | 792   | 0.32 | 180    | Easy to mix and shape     | 285                              |
| 6       | 88    | 792   | 0.34 | 180    | Easy to mix and shape     | 278                              |
| 7       | 88    | 792   | 0.36 | 180    | Easy to mix and shape     | 274                              |
| 8       | 88    | 792   | 0.38 | 180    | Easy to stir, collapse    | -                                |
As shown in Table 3, When the water-cement ratio is too small, the consistency of the cement paste is so high that the resistance of the foam and cement is increased, so the mixing process of the mixture is difficult. The increase in the water-cement ratio improves the fluidity of the cement slurry. The binding force of the cement slurry on the foam is reduced so that the foam is easy to float on the surface of the mixed slurry. Therefore, when a large amount of gas came out of the slurry, ULCFTIM collapsed.

### 3.2.1. The effect of water-cement ratio on the compressive strength of ULCFTIM at 3 days.

As can be seen from Fig. 4, The compressive strength of ULCFTIM at 3 days increases first and then decreases with the increase of water-cement ratio. When the water-cement ratio is too small, the consistency of the cement slurry increases so that the cement slurry cannot evenly wrap the foam when the foam is mixed with the cement slurry. This causes the ULCFTIM to form an uneven support structure that weaken compressive strength of ULCFTIM. When the water-cement ratio is greater than 0.26, the compressive strength of ULCFTIM decreases as the water-cement ratio increases. The explanation for this phenomenon is that the evaporation of water reduces the apparent density of ULCFTIM and makes it easier to form connecting holes. Therefore, choosing a suitable water-cement ratio to prepare ULCFTIM can make it have higher compressive strength.

![Fig. 4](image1.png)

**Fig. 4** The effect of water-cement ratio on the compressive strength of ULCFTIM at 3 days

### 3.2.2. The effect of water-cement ratio on the apparent density and thermal conductivity of ULCFTIM.

As shown in Fig. 5, the thermal conductivity first decreases and then tends to be stable with the increase of water-cement ratio. When the water-cement ratio is moderately increased from 0.24 to 0.28, the wrapping property of cement paste to foam is more uniform, and a large number of uniform and closed pores can be formed, which reduces the convective heat transfer effect of gas molecules inside the ULCFTIM, so the thermal conductivity is constantly reduced. The water-cement ratio is greater than 0.28, and the thermal conductivity of the material will not decrease as the apparent density decreases. This is due to the evaporation of water causing more connected holes in ULCFTIM [8]. It is the simultaneous effect of the decrease in apparent density and the increase in the number of connected holes that the thermal conductivity tends to steadily. Considering the influence of water-cement ratio on the compressive strength and thermal conductivity of ULCFTIM, the optimal water-cement ratio for ULCFTIM is 0.26-0.3.

![Fig. 5](image2.png)

**Fig. 5** The effect of water-cement ratio on the apparent density and thermal conductivity of ULCFTIM
4. Conclusion
This study revealed that ULCFTIM based on ordinary Portland cement modified by sulphoaluminate cement can be prepared by using the pre-foaming method. The following conclusions can be drawn from the results of this work:

(1) The stability of ULCFTIM can be increased by addictioning a suitable SAC to the ULCFTIM, and thereby prevent the collapse of the ULCFTIM. Although the increasing mass fraction of SAC is beneficial to the formation of the early compressive strength of ULCFTIM, it will adversely affect the compressive strength of ULCFTIM at 28 days. The experimental results show that the optimal mass fraction for SAC in a cementitious material is 10%.

(2) The performance of the ULCFTIM is best when w/c values ranging from 0.26-0.30. The test result indicates that the compressive strength of ULCFTIM is 0.185 MPa to 0.201 MPa at 3 days, and the thermal conductivity is within the range of 0.701 W·m⁻¹·K⁻¹ and 0.714 W·m⁻¹·K⁻¹.

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