Experimental Study on Quasi-Static Energy Absorption Characteristics of Foam Concrete with Different Design Density by Hydroxypropyl Methyl Cellulose

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Abstract. The foam concrete test blocks with different design densities were prepared. Different dosages of hydroxypropyl methylcellulose on the quasi-static energy absorption characteristics of foam concrete were studied through comparative experiments. The results show that the foam nominal load-displacement curve can be divided into three stages: elastic compression stage, plateau stage, and a densification stage. The higher the density of the foam concrete, the higher the initial peak load, the more outstanding the load fluctuation, and the worse the protective performance. The smaller the density, the longer the compression platform stage. 0.06% of HPMC improves the energy absorption characteristics of foam concrete with different densities the most, and the smaller the density, the greater the improvement ratio.

1. Introduction
Foam concrete is a kind of lightweight porous concrete, and the density is generally between 400 kg/m³-1600 kg/m³[1]. Its composition is mainly Portland cement and Sulphoaluminate cement [2]. In the hydration reaction process, a lot of heat will be generated, which will quickly cause the foam's thermal rupture in the foamed concrete, resulting in an uneven pore structure[3]. Besides, the heat cannot be quickly dissipated due to the internal pore structure, resulting in more significant temperature stress and expansion of micro-cracks in the foam concrete. During the curing process, evaporation and loss of water will cause dry shrinkage. It is also prone to cracks, which seriously affects the durability and thermodynamic properties of foamed concrete. Therefore, the use of admixtures that can replace part of the cement can reduce the adverse effects of hydration's heat caused by using cement on the foam concrete's performance [4,5]. On the other hand, it also improves its compressive strength [6]. Common admixtures include fly ash, mineral powder, silica fume, etc.

Foam concrete has the advantages of a lightweight, good thermal insulation performance, low cost, etc., and has excellent development potential in the field of construction engineering and protection engineering [7]. Like other porous materials, foam concrete has excellent energy absorption properties, which is widely used as a protective material [8-10]. It also has a wide range of applications in aircraft arrest systems [11] and explosion protection projects [12]. The density of foam concrete greatly influences its compressive strength and energy absorption characteristics [13] and shows a tremendous positive correlation [14]. Also, the pore structure and pore size distribution significantly impact foam concrete's thermal and mechanical properties. HPMC can be used as a foam stabilizer and thickener in foam concrete to improve the pore size distribution, thereby improving its mechanical properties.
The effect of HPMC content on the energy absorption performance of foam concrete with different densities was be analyzed in this paper by a group of quasi-static compression experiments, and the improvement mechanism of HPMC on the energy absorption characteristics of foam concrete was studied.

2. Experimental program

2.1. Raw Materials
This study's Cementitious material was P.O.42.5 standard Portland cement produced by Jidong Cement Co., Ltd.

Fly ash is the main solid waste discharged from coal-fired power plants. Adding fly ash to the foam concrete to replace part of the cement can save resources and protect the environment and improve the workability of the foamed concrete, reduce the heat of hydration, and reduce shrinkage and cracking.

Nano-silica can fill the gaps between cement particles and produce gels with hydration products during structural preparation and maintenance.

The foaming agent used in the study is the polymer composite foaming agent, manufactured by Wanketu Energy Saving Building Materials Technology Co., Ltd. in Zhangzhou city, Fujian Province, China. The concentration of foaming agent to water used is 1:25 to obtain stable foam. The water reducer employed is a commercially available polycarboxylate superplasticizer. The thickening and foam stabilizer agent employed is 100k-unit HPMC; the hardening accelerators employed is CF manufactured by Tongfarong Industrial Co., Ltd. in Zigong city, Sichuan Province, China. And the water employed in this study is common to tap water.

2.2. Mix proportion
The mix proportion and specification of the mix are discussed in Table 1. The trial mixes were made by changing the HPMC, and the mix with three design densities with 400 kg/m³, 500 kg/m³, 700 kg/m³ is used in the study. The cement's mass ratio, fly ash and nano-silica fume in the dry cementitious material is 0.8: 0.18: 0.02. The content of calcium formate and PCE are 1.0% and 0.05% of the mass of all dry cementitious materials, respectively. Hydroxypropyl methylcellulose (HPMC) with mass fraction 0.02%, 0.04%, 0.06%, 0.08% and 0.1% of all the dry cementitious material were added. And a control group without any HPMC was set.

Table 1. Design mix proportion (kg/m³).

| Group     | HPMC | Water | Cement | Fly ash | Nano-silicon | Calcium formate | PCE    | foam  |
|-----------|------|-------|--------|---------|--------------|-----------------|--------|-------|
| FC-400-1  | 0.0696 |       |        |         |              |                 |        |       |
| FC-400-2  | 0.1392 |       |        |         |              |                 |        |       |
| FC-400-3  | 0.2088 | 114.84| 278.4  | 62.64   | 6.96         | 3.48            | 0.1740 | 111.34|
| FC-400-4  | 0.2784 |       |        |         |              |                 |        |       |
| FC-400-5  | 0.3480 |       |        |         |              |                 |        |       |
| FC-500-1  | 0.087  |       |        |         |              |                 |        |       |
| FC-500-2  | 0.174  |       |        |         |              |                 |        |       |
| FC-500-3  | 0.261  | 143.55| 348.0  | 78.30   | 8.70         | 4.35            | 0.2175 | 107.39|
| FC-500-4  | 0.348  |       |        |         |              |                 |        |       |
| FC-500-5  | 0.435  |       |        |         |              |                 |        |       |
| FC-700-1  | 0.1218 |       |        |         |              |                 |        |       |
| FC-700-2  | 0.2436 |       |        |         |              |                 |        |       |
| FC-700-3  | 0.3654 | 200.97| 487.2  | 109.62  | 12.18        | 6.09            | 0.3045 | 99.49 |
| FC-700-4  | 0.4872 |       |        |         |              |                 |        |       |
| FC-700-5  | 0.6090 |       |        |         |              |                 |        |       |

Notes: The density of the foam in this paper is 89 kg/m³. The contrast group without any HPMC is defined as FC-400-C, FC-500-C, and FC-700-C, respectively.
2.3. Experimental techniques

2.3.1. Mixing Procedure and Specimen Preparation
The sample preparation process is divided into five steps. According to Table 5, the accurately weighed cement, fly ash, nano silicon, calcium formate, PCE, and HPMC were poured into a horizontal type blender and stirred at 40 rpm without water for 180 seconds. In the second step, the accurately weighed water is added to the blender and mixed with other materials for 120 seconds to produce a uniformly mixed cement slurry. The third step is to dilute the foaming agent with water in a ratio of 1:25, add the foam produced by the air compressor to the cement slurry according to the designed ratio and stir for 120 seconds. There is no floating on the surface, then pour it into the mold. In the fourth step, scrape the excess foam slurry on the mold's surface, cover the test sample with plastic wrap and let it curd for 24 hours. Finally, the demoulded foam concrete was cured for 28 days in a standard curing chamber (YH-101, Experimental Instrument and Equipment Factory in Xian county, Hebei Province, China) with the temperature at 20±2°C and the relative humidity at 95%. In the chamber, the foam concrete samples were placed on stacks with 10-20mm between each other, and the surface of the samples shall remain moist but avoid exposure to rushing water for 28 days.

2.3.2. Dry density Test
The foam concrete's dry density and moisture content were detected according to the Chinese Foam Concrete standard JG/T 266[15]. The test specimens were a cubic concrete test block with a specification of 100mm×100mm×100mm through onsite molding, demolded after 24 hours, and cured for 28 days.

2.4. Quasi-static compression test
The microcomputer-controlled electro-hydraulic servo compression testing machine (300 kN) produced by Jinan Time Shijin Testing Machine Co., Ltd. was used to conduct a quasi-static compression test on the foam concrete specimens in Table 5, record the compression failure process and collect nominal load-displacement data. The strain rate range of quasi-static loading is wide. Considering that the low loading rate has almost no effect on the test results and will increase the time cost. This test adopts the displacement control loading method, and the loading speed is 5 mm/min. The whole typical process of quasi-static compression of foam concrete is shown in Fig.1.

Figure 1. The whole typical process of quasi-static compression, (a) Initial stage of compression, (b) Sudden decrease in compressive strength (broken) stage, (c) Smooth compression (deformation and energy absorption) stage, (d) Compaction stage

2.5. The Parity Index of the Energy Absorption Characteristics of Foam Concrete
At present, parameters such as initial peak stress, average compressive strength, total energy absorption, specific energy absorption, and crushing force efficiency are usually used to evaluate materials' energy absorption capacity.
2.5.1. Initial peak stress $\sigma_{\text{max}}$

The initial peak load $F_{\text{max}}$ refers to the maximum value in the structural load response history during the compression process. It is an important parameter that reflects the impact resistance of the structure. The smaller the initial peak force for foam concrete porous materials, the better the corresponding impact resistance. The initial peak stress $\sigma_{\text{max}}$ is the corresponding compressive stress when $F = F_{\text{max}}$.

2.5.2. Total energy absorbed of the material $E_t$

In materials protection, the more energy absorbs, the better its protection and impact resistance. It can be obtained by integrating the nominal load-displacement relationship curve:

$$E_t = \int P \cdot dl$$  \hspace{1cm} (1)

The displacement value measured by the experimental instrument when the materials were reaching the densification strain, mm; $P$ is the load value corresponding to the displacement value.

2.5.3. Average compressive load $F_m$

The average compressive stress is the structure's average stress before reaching the compaction strain during the compression process. This value can indirectly reflect the energy absorption capacity of the structure per unit area and can be calculated by the following formula:

$$F_m = \frac{E_t}{L} = \frac{1}{L} \int P \cdot dl$$ \hspace{1cm} (2)

2.5.4. Crushing load efficiency $C_{\text{le}}$

Crushing force efficiency is a practical description of the volatility of the mechanical response of an energy-absorbing material. The more excellent the crushing force efficiency, the better the defensive performance. It refers to the ratio of an average compressive load to initial peak load:

$$C_{\text{le}} = \frac{F_m}{F_{\text{max}}}$$ \hspace{1cm} (3)

2.5.5. Specific energy absorption $E_{sa}$

$E_{sa}$ is the ratio of the total energy absorbed to the total mass. It is an essential indicator for evaluating the unit energy absorption and the material's lightweight energy absorption design.

$$E_{sa} = \frac{E_t}{m}$$ \hspace{1cm} (4)

3. Results and discussion

3.1. Nominal load-displacement curve analysis

It exhibits an analogous load-displacement relationship with porous metal materials when foam concrete is subjected to quasi-static compression[16,17]. The test block sequentially undergoes an elastic stage, a platform stage, and a densification stage.

Figure 2(a) shows the relationship curve between the nominal load and the foam concrete specimen's nominal displacement. The low-density foam concrete (400 kg/m$^3$, 500 kg/m$^3$) has no obvious initial peak load. Foam concrete (700 kg/m$^3$) can observe obvious initial peak load. The higher the density of foam concrete, the greater the energy absorption. According to formulas (1)-(3), the crushing load efficiency of foam concrete with design densities of 400 kg/m$^3$, 500 kg/m$^3$ and 700 kg/m$^3$ are 0.629, 0.629, and 0.629, respectively.
0.565, and 0.411, respectively. Therefore, the greater the density of the foam concrete, the greater the fluctuation of the material.

Figure 2(b)-(d), in the foam concrete samples of the same design density, the change of HPMC content has a significant impact on the nominal load-displacement curve, and the peak load change is the most obvious. At the same time, the total amount of quasi-static energy absorption is also different. In the same group, the end positions of the plastic compression platform are the same. With the increase in the foam concrete's design density, the nominal peak load and the total energy absorption of the foam concrete have increased significantly. The plateau stage positions are 60mm, 55mm, and 50mm, respectively, showing a decreasing trend. In the plateau stage, the external load overcomes the friction between the concrete components and the collapse of the wall of the pores and absorbs a large amount of energy. The higher the density, the smaller the porosity, and the higher the concrete component's content in the same volume. Correspondingly, space where the pore wall collapses can be compressed becomes smaller.

Table 2. Energy absorption of different foam concrete specimens

| Group | Design density (kg/m³) | Measured density (kg/m³) | Initial peak load (kN) | Total energy absorbed (J) | Average compressive load (kN) | Specific energy absorption (J/g) |
|-------|------------------------|--------------------------|------------------------|--------------------------|-----------------------------|--------------------------------|
| FC-C  | 400                    | 392.1                    | 3.67                   | 138.73                   | 2.31                        | 0.354                          |

3.2. Quasi-static energy absorption characteristics analysis

Table 2 shows the energy absorption index of the quasi-static compression test of different foam concrete specimens. Figure 3 shows the influence of the change of HPMC content on the energy absorption capacity of foam concrete specimens under different design densities.
Figure 3. The influence curve of HPMC content on various energy absorption characteristics of foam concrete with different densities, (a) Initial peak load, (b) Average compressive load, (c) Total energy absorbed, (d) Specific energy absorption.

Figure 3(a)-(d) shows that when HPMC is increased from 0 to 0.06%, compared with the calculation results of the control group test block without the HPMC, the initial peak load of foam concrete with design densities of 400 kg/m³, 500 kg/m³ and 700 kg/m³ are increased 265.94%, 132.04%, and 48.29%, respectively. Average compression load increased 218.61%, 173.89%, and 78.71%, total energy absorption increased 218.45%, 173.76%, and 78.69%, the specific energy absorption increased 206.78%, 159.55%, and 80.82%, respectively.
The above data shows that the smaller the foamed concrete's density, the more pronounced the improvement of the quasi-static energy absorption index of the material by HPMC. However, when the content of HPMC exceeds 0.06%, all indicators show a decreasing trend. HPMC has water retention and thickening effects, and it is relatively stable in aqueous solutions. An appropriate amount of HPMC can increase the viscosity and uniformity of the foam concrete slurry, enhance the toughness and mechanical strength of the bubble liquid film, so it can improve the pore structure of the foam concrete to a certain extent, and increase the foam concrete's Compressive strength. When an excessive amount of HPMC is added, the foam slurry will become too dense, prolong the setting time, and decrease the bubble stability, which will hinder the uniform distribution and stable existence of the foam in the slurry. Therefore, it can be considered that an appropriate amount of HPMC can effectively increase the initial peak load, average compressive load, total energy absorption rate, and specific energy absorption of the foam concrete. In engineering applications, each energy absorption index has different selection principles, so it is not that the higher, the better. It needs to be analyzed according to the specific problems.

4. Conclusions

Due to the foam stabilization and thickening effect of HPMC in concrete, it has a greater promotion effect on the pore structure and compressive strength of foam concrete. Furthermore, in order to study the influence of HPMC on the quasi-static energy absorption characteristics of foam concrete, this paper the foam concrete with different design densities mixed with fly ash and silica fume was prepared, and the nominal load-displacement curve of the foam concrete with different densities and the effect of HPMC on the energy absorption performance were studied. The following are the conclusions of this paper:

The nominal load-displacement curve of the foam concrete with different densities and the effect of HPMC on the energy absorption performance were studied. The following are the conclusion of this paper:

1. Foam concrete has similar compression characteristics to porous metal materials. The nominal load-displacement curve can be divided into three stages, elastic compression stage, platform compression stage, and densification stage.

2. The higher the density of foamed concrete, the higher the initial peak load, the lower the crushing load efficiency, and the worse the material's protective performance.

3. The lower the foam concrete density, the longer the material's compression plateau stage. When a smaller initial peak load is required, the material's energy absorption characteristics can be relatively improved.

4. HPMC can significantly improve the energy absorption characteristics of foamed concrete. The smaller the density, the more pronounced the effect of improvement. Excessive HPMC will weaken the energy absorption effect of the material.

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