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Strength properties and thermal conductivity of concrete with the addition of expanded perlite filled with aerogel

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HIGHLIGHTS

- Expanded perlite is used as a carrier for aerogel into concrete.
- Different sizes of expanded perlite filled with aerogel are assembled to compare gradation aggregate to compared with non-gradation aggregate.
- The performance of concrete can be modified by changing the volume of the aggregate.

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ABSTRACT

In this study, expanded perlite filled with aerogel is used as a new material as the aggregate in concrete. Graded and non-graded expanded perlite filled with aerogel are added into concrete separately. The natural aggregate is partially replaced by the new material, and both the mechanical strength and the thermal conductivity of the concrete decreased when the new material's content increased. When the aggregate content and the water-cement ratio are the same, the mechanical strength and the thermal conductivity of the non-graded material concrete is larger than for the graded material. The water-cement ratios of 0.5 and 0.7 are applied to explore the influence of the water-cement ratio on the properties of the new concrete material. The role of aerogel in complexes is analysed, and the results show that the concrete with a 100% volume content of graded expanded perlite filled with aerogel has a thermal conductivity of 0.098 W/(m K) and compressive strength of 3.71 MPa.

1. Introduction

Aerogel is a porous material that has a low thermal conductivity because its pore size is small [1]. The application of aerogel as a building material has shown promise due to its high-performance thermal insulation property [2]. There have been many past attempts to add aerogel to concrete. Sughwan Kim mixes aerogel with cement paste and identifies the thermal performance of the insulation building material, finding a thermal conductivity of 0.135 W/(m K) [3]. Tao Gao prepares a lightweight and thermal insulating concrete material by incorporating silica aerogel particles into the concrete mixture [4]. Serina Ng studies the thermal conductivity and mechanical strength of 80 vol% aerogel incorporate into the mortar [5]. Zhao-hui Liu studies the density, mechanical properties, softening coefficient and thermal conductivity properties of silica aerogel mortar with different aggregate replacement ratios [6]. Jaroslaw Strzalkowski examines the influence of aerogel particles on the properties of cement composites [7].

Thefragile and brittle nature of aerogels make their use in load-bearing applications a challenge [8]. This fragility could be attributed to the disordered network morphology with the irregular pore structure, its low densitiy, poorly defined interparticle linkages, and dense agglomerations resulting in density gradients and a poorly organized material [9]. Because of the fragility of the aerogel, the main concern of this paper is not its mechanical properties but its low thermal conductivity.

Expanded perlite is produced by heating perlite to 760–1100 °C. The water inside the material is converted to vapor and causes the material to expand to 4–20 times its original volume [10]. Expanded perlite can be used in light weight mortars and concrete to reduce the thermal conductivity of the materials [11–13]. The fly ash–lime–gypsum mixture's bulk density and the thermal conductivity would be decreased with the addition of expanded perlite [13].

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Many studies have focused on complexes of expanded perlite. Lulu Fu develops a nonflammable thermal storage material by composing expanded perlite with a salt hydrate of $CaCl_2{\cdot}6H_2O$ and $SrCl_2{\cdot}6H_2O$ [14]. similarly, Liu Jiesheng studies the form-stable lauric acid/expanded perlite (LA/EP) composite and found that it have great potential in building applications due to its thermal energy storage capacity [15]. Xiangfei Kong fills the expanded perlite with liquid paraffin to synthesize a phase change material, which can decrease a building's energy consumption [16]. Xiangyu Li makes granular phase change materials by absorbing paraffin into the pores of expanded perlites particles to reduce indoor temperature oscillations [17]. Xiaoguang Zhang enhances the thermal conductivity of phase-change materials by introducing carbon nanotubes as a filler in the paraffin/expanded perlite [18]. Dan Sun applies paraffin/expanded perlite materials to cement mortar, which has good heat storage properties and thermal stability compared to ordinary cement mortar [19].

Most complexes of expanded perlite are synthesized to increase their ability to store energy or transfer heat [20]. In this study, the complex of expanded perlite is used to reduce heat transfer. Aerogel's native thermal conductivity is 0.023 W/(m K) at room temperature (25 °C), and a new method is invented to insert the aerogel into expanded perlite [21]. Based on this method, expanded perlite filled with aerogel was applied as a concrete aggregate, and the mechanical and thermal properties of the concrete were studied.

Herrero attempts to insert rubber from end-of-life tires into mortar [22]. He studies the rubber's proportion and particle size gradation influencing the mortar' mechanical, thermal and acoustic properties. Three different rubber particle sizes are used separately without combination. To explore the role of particle gradation of the aggregate in concrete, the mechanical and thermal properties of its concrete were measured and compared with non-particle gradation aggregate concrete. The optimal ratio of graded expanded perlite was obtained through a uniform experimental design [23].

The strength of concrete is influenced by the water-cement ratio, showing lower strengths with higher water-cement ratios and vice versa [24]. In this study, the mechanical and thermal properties of the concrete were compared with water-cement ratios of 0.5 and 0.7.

2. Experiments

2.1. Materials

In this study, expanded perlite (EP) was supported by the Shangtianti industry zone located in the Xinyang region of China. The EP mainly consisted of 71.33% SiO_2 and 11.08% Al_2O_3. In the vacuum state, expanded perlite can adsorb 8 times its mass in water. Tables 1 and 2 show non-graded expanded perlite (NEP) and graded expanded perlite (GEP). Non-graded expanded perlite's particle size was mainly distributed in the range 1.18–4.75 mm, while graded expanded perlite's particle size was distributed in 4 particle size ranges.

Local river sand with a fineness modulus of 2.89 was used in this experiment. Its particle size and percentage are listed in Table 3.

Fig. 1 shows the aerogel production process. A 1:4 volume ratio of water glass (silica content 27.45 wt%, SiO_2:Na_2O = 3.28) to deionized water is used. The gel time is affected by the pH value of the solution, which is adjusted by changing the dosage of nitric acid added into the solution. The gel time of the solution is approximately 1 h when the pH is adjusted to approximately 3.2. In (a), the upper surface of the liquid cannot be kept horizontal in the beaker, and the fluid gradually solidifies. In (b), after the gel ages for 24 h, it is placed in the TMCS, N-heptane and EtOH solution. In (c) and (d), the gel gradually rises from the bottom of the solution to the upper layer of the solution, and the colour of the underlying solution gradually becomes yellow. Replacement occurs in this step; the water inside the gel is replaced by n-heptane; thus, the gel becomes lighter and floats upwards. The gel is made of water glass that contains Fe^{3+}. During the replacement step, the water and Fe^{3+} in the gel are transferred to the lower solution, turning it yellow. After completion of the replacement, the gel is dried in an oven, and the aerogel can be seen in (e).

Expanded perlite filled with aerogel was synthesized before the experiment, as described by Liang Wang [21]. Expanded perlite can be considered as a carrier of aerogel, and it has been used to reduce the aerogel's breakage in the mixing process and provide the possibility aerogel gradation in concrete. After the silica acid solution with pH = 3.2 was prepared, the expanded perlite was poured into the solution and placed in a vacuum box. Fig. 2 shows the process of making the aerogel-expanded perlite mixture. (a) More solution is absorbed by the expanded perlite with the vacuum pressure in the vacuum box of −0.1 MPa over 5 min. (b) The beaker is inverted on a larger beaker so that the extra silica acid solution outflows. The silica acid inside the expanded perlite gradually turns into gel over one hour. (c) 24 h later, the TMCS, *N*-heptane and EtOH solutions are poured into the jar containing the expanded perlite filled with gel. The TMCS, *N*-heptane and EtOH solutions replace the water from the gel inside the expanded perlite. (d) The expanded perlite with gel suspend on the upper side of the reaction solution is shown. Replacement fluid is drained, and the expanded perlite composites are dried in an oven for 24 h until the quality no longer changes. (e) The expanded perlite filled with aerogel floats on the water surface and absorbs no water.

In China, Aerogel sells at 500–800 RMB per kg, which limits its application in the field of thermal insulation. Expanded perlite normally sells for 1.34–1.52 RMB per kg, so expanded perlite is significantly cheaper than aerogel. The values used in later calculations are the median value of the price. A cubic metre of concrete can accumulate approximately 110 kg of aerogel, worth 71,500 RMB, and a cubic metre can accumulate approximately 70 kg of expanded perlite, worth 100 RMB. One cubic metre of EPA contains 35 kg of aerogel, worth 22,750 RMB. Although EPA is still expensive, this composite method has greatly reduced the application cost of aerogel in the field of thermal insulation, and the thermal conductivity of the composite is still very low.

The thermal conductivities of the aerogel, expanded perlite and the complex of the two are listed in the Table 4. The NEPA and GEPA were new thermal insulation materials filled with aerogel. The thermal conductivity of the aerogel is 0.023 W/(m K) which is lower than the air's thermal conductivity of 0.026 W/(m K). Aerogel can reduce the air's heat transfer inside the EP, causing the NEPA/GEPA thermal conductivity to be lower than that of NEP/GEP.

The aerogel's thermal conductivity was tested according to the National Standards of the People's Republic of China—*Determination of thermal conductivity and thermal diffusivity of building materials: transient plane heat source method*. The Xi'an Xia xi TC3000E thermal conductivity instrument is used, and the transient plane heat source method needs only a small amount of aerogel. The aerogel is ground into powder and put into the groove to contact the test sensor, and the thermal conductivity is tested.

The thermal conductivity of EPA (Expanded perlite filled with aerogel) and EP was tested according to the National Standards of the People's Republic of China: *Thermal insulation—Determination of steady-state thermal resistance and related properties—Guarded hot plate apparatus*. The DRH-III thermal conductivity tester is used to measure the thermal conductivity of EPA and EP with a sample size of 30 cm × 30 cm × 3 cm. Since the EP and EPA are granular, this large contact area facilitates accurate test data.

The cement used in this study was 42.5 Ordinary Portland cement made in Xinyang, China. A silica fume with SiO_2 content of 95.5% was added to improve the concrete strength. A highly effective polycarboxylate water reducing agent can reduce the water-cement ratio, which effectively improves the concrete strength effectively.

2.2. GEPA's particle gradation

In this experiment, the volumetric replacement method was adopted. The NEPA and GEPA were used to replace all or a portion of the sand aggregate in concrete for its good thermal insulation performance.

The insulation materials NEPA and GEPA were used as the aggregate. The thermal conductivity of the NEPA and GEPA concrete was mainly related to the density of its internal cement slurry skeleton. Good particle gradation can minimize the gap between the expanded perlite particles while the gap is filled with grout. As Fig. 3 shows (b) requires less cementitious material than (a), and less heat transferred by cementitious materials in (b), while the non-graded aggregate (a) left a relatively large space that needs to be filled with cementitious material. In theory, the more

Table 1
Non-graded expanded perlite particle size and relative percentages.

Particle size (mm)	4.75	2.36–4.75	1.18–2.36	0.6–1.18	0.3–0.6	0.15–0.3	0–0.15
Percentage (%)	0.06	72.39	24.33	2.30	0.17	0.12	0.63