Mechanical properties and thermal conductivity of lightweight thermal insulation composites

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Abstract. Lightweight thermal insulation composites with different mass percentages of expanded polystyrene (EPS) were prepared, and the effects of Polypropylene fiber (PPF) and redispersible polymer powder (RPP) addition on mechanical properties of lightweight thermal insulation composites were investigated. The results indicated that the density, thermal conductivity, flexural and compressive strength of lightweight thermal insulation composites significantly decreased with the increase of EPS. Besides, PPF and RPP both had a positive effect on the mechanical properties of lightweight thermal insulation composites.

1. Introduction
In recent years, EPS has been used in thermal insulation applications such as building wall insulation material due to its low bulk density, small thermal conductivity, excellent durability and low cost [1-2]. However, just like other organic thermal insulation materials such as polyurethane foam and phenolic foam, it tends to aggravate the fire and cause loss of life and properties in case of fire due to its inherent flammability [3-4]. Therefore, it is significant to develop thermal insulation material with superior fire retardant performance.

The inorganic cementitious materials such as ordinary Portland cement, gypsum and composite cementitious materials are non-combustible, but they also possess some defects in density and thermal insulation properties compared to organic thermal insulation materials [5]. Based on the above view, lightweight thermal insulation composites composed of EPS and the inorganic cementitious materials have given rise to broad interests of many pieces of research owing to their advantages of non-combustible, low bulk density and thermal conductivity [6-7]. Besides, industrial solid wastes such as flue gas desulphurization gypsum (FGD), silica fume (SF), fly ash (FA) and steel slag (SS) have been used to prepare inorganic composite cementitious materials, which solves the problems of occupying land resources and polluting the environment caused by the industrial solid wastes [8-9]. Nevertheless, further application of lightweight thermal insulation composites made up of EPS, and industrial solid wastes is limited by poor mechanical properties. To improve the mechanical properties, PPF [10] and RPP [11] can be added as additives.

In this paper, lightweight thermal insulation composites were prepared by mixing EPS used as lightweight aggregate and composite cementitious materials consisting of FGD, FA, and SS. The effects of PPF and RPP on mechanical properties of lightweight thermal insulation composites were researched.

2. Experimental
2.1. Raw materials
FGD and FA were supplied from Shandong Laiwu Power Plant, and SS was supplied from Laiwu Iron and Steel Group. The chemical compositions of these materials were listed in Table 1. EPS (thermal conductivity ≤ 0.041 W·(M·K)⁻¹, packing density: 15 kg/m³) was used as lightweight aggregate mainly designed to reduce the density and thermal conductivity of the material. NaOH was used as activators to improve the activity of fly ash and steel slag. PPF with 850 kg/m³ of bulk density and 25 mm in length and RPP mainly composed of Ethylene–vinyl acetate (EVA) were used as additives to improve the mechanical performance of lightweight thermal insulation composites.

2.2. Sample preparation and test methods
The FGD was calcined at 155 °C for 200 min and placed at room temperature for 7 days before using it to transform it into hemihydrate gypsum. The FA and SS were ball-milled using a planetary ball milling machine at a speed of 300 rpm for 6 h before the experiment to enhance hydration activity of FA and SS. The ternary cementitious composites (TCC) were made of FGD, FA, and SS with a mass ratio of 7:2:1. The ratio of water-to-binder (TCC) in this study was 0.51. EPS was added as a lightweight aggregate at different mass percentages (0-8wt%), as shown in Table 2. PPF and RPP were combined with varying proportions of mass (0-1.0wt% and 0-5.0wt%, respectively) into lightweight thermal insulation composites (Sample A5). The above material mixtures were mixed using a mortar mixing machine (UJZ-15) at a speed of 180 rpm for 200 s. After mixing, the mixtures were placed into a steel mold and cured at room temperature in a sealed condition for 7 days. Finally, the samples were demolished (as shown in Figure 1) and tested.

Table 1. The chemical composition of raw materials (wt%).

|       | SO₃  | MgO  | SiO₂  | CaO  | Al₂O₃ | Fe₂O₃ |
|-------|------|------|-------|------|-------|-------|
| FGD   | 43.11| 2.01 | 1.45  | 31.80| 0.53  | 0.21  |
| FA    | 0.64 | 0.93 | 47.13 | 4.13 | 40.33 | -     |
| SS    | 1.14 | 4.83 | 15.44 | 46.01| 5.57  | 18.25 |

Table 2. Mixture proportions of samples (wt%).

| Sample | TCC | Water | NaOH | EPS |
|--------|-----|-------|------|-----|
| A1     | 100 | 51    | 1.2  | 0   |
| A2     | 100 | 51    | 1.2  | 2   |
| A3     | 100 | 51    | 1.2  | 4   |
| A4     | 100 | 51    | 1.2  | 6   |
| A5     | 100 | 51    | 1.2  | 8   |

Figure 1. Samples demolded.
According to the standard GB/T 5486-2008, the apparent density of samples with a size of 300 mm $\times$ 100 mm $\times$ 40 mm was determined as the ratio of the mass to a volume by weighing using an electronic balance (JM-1001). The flexural strength with of samples with a size of 300 mm $\times$ 100 mm $\times$ 40 mm and compressive strength with a size of 100 mm $\times$ 100 mm $\times$ 40 mm were evaluated by an electromechanical universal testing machine (CMT5105, China) and the values reported were acquired by the average of three strength tests. According to the standard GB/T 10294-2008, the samples with a size of 300 mm $\times$ 300 mm $\times$ 25 mm was prepared, and the thermal conductivity was measured by a double-plate thermal conductivity tester (IM-DRY3001).

3. Results and Discussion

3.1. The effect of EPS on properties of lightweight thermal insulation composites

The density, thermal conductivity, flexural and compressive strength of lightweight thermal insulation composites with different mass percentages of EPS added are presented in Figures 2 and 3. It can be seen that the density, thermal conductivity, flexural and compressive strength of samples significantly are affected by the addition of EPS. According to the figures, the density, thermal conductivity, flexural and compressive strength of lightweight thermal insulation composites have substantially the same variation tendency. These properties decrease with the increase of EPS from 0 to 8wt%. When the content of EPS is 8wt%, the density, thermal conductivity, flexural and compressive strength of lightweight thermal insulation composites reach a value of 213 kg·m$^{-3}$, 0.053 W·(m·K)$^{-1}$, 0.11 MPa and 0.26 MPa which decline by 83.96, 93.23, 96.37, and 97.86%, respectively, as compared to the samples without EPS addition. EPS is a porous material that is used widely for thermal insulation applications due to its excellent performance such as low density and superior thermal insulation ability [1-2].

Therefore, the samples with a high proportion of EPS addition possess the advantages of low density and thermal conductivity. However, it can also be found that the addition of EPS has a disadvantageous effect on flexural and compressive strength. Given the above-mentioned defects caused by EPS addition, PPF and RPP are added to improve flexural and compressive strengths of lightweight thermal insulation composites, as discussed in Sections 3.2 and 3.3.

![Figure 2](image.jpg)

**Figure 2.** The flexural and compressive strength of lightweight thermal insulation composites with different mass percentages of EPS added.
3.2. The effect of PPF on mechanical properties of lightweight thermal insulation composites

Figure 4 shows the impact of different mass percentages of PPF addition on mechanical properties of lightweight thermal insulation composites. It is apparent that the flexural strength and compressive strength of the lightweight insulation material increase at the initial stage (0-0.8wt%) and then decrease (0.8wt%-1.0wt%) with the increase of polypropylene fiber. When the content of PPF is 0.8wt%, the flexural strength and compressive strength of the sample reach the maximum values of 0.18 MPa and 0.27 MPa which are 63.64 and 7.69% higher than those of the samples without PPF. When lightweight insulation materials are subjected to external forces, cracks will produce and then propagate quickly in the matrix of composites which cause a rapid loss in mechanical properties. However, PPF distributed among the matrix will intercept the development of crack or make the crack propagation path longer resulting in the improvement in flexural strength and compressive strength [10]. Besides, another reason why PPF can improve the mechanical properties of composites is that PPF is a material with excellent mechanical properties such as high strength and outstanding wear resistance. Nevertheless, when the content of fibers is too high, the fibers are difficult to disperse uniformly and aggregate together inside the material matrix which leads to the decline of mechanical properties.
Figure 4. The flexural and compressive strength of lightweight thermal insulation composites with different mass percentages of PPF added.

3.3. The effect of RPP on mechanical properties of lightweight thermal insulation composites

The impact of RPP addition on flexural strength and compressive strength of lightweight thermal insulation composites (adding 0-5wt% RPP into A5 sample) are presented in Figure 5. It is seen that the flexural strength and compressive strength of lightweight thermal insulation composites gradually increase when the content of RPP ranges from 0 to 3wt%. While continually increasing from 3wt% to 5wt%, it remains the peak value. When the RPP addition is 3wt%, flexural strength and compressive strength reach a maximum value of 0.16 and 0.35 MPa, which increase by 45.45 and 34.62%, respectively, as compared to the samples without RPP addition. On the one hand, the increase of mechanical properties is attributed to the improvement of pore structure by the addition of RPP [11]. On the other side, the interface combining effect of TCC and EPS is not stable due to the poor wettability between them which leads to a decline in mechanical properties. It can be seen from Figure 6 that the EPS surface of samples without RPP added is smooth, while the EPS surface of samples with RPP added adheres in no small amount of cementitious materials, which illustrates that RPP can improve interface combining effect increasing mechanical properties.

Figure 5. The flexural and compressive strength of lightweight thermal insulation composites with different mass percentages of RPP added.

Figure 6. The images of fracture surface for lightweight thermal insulation composites with (a) 0wt%, (b) 3wt% RPP added.
4. Conclusion

The density, thermal conductivity, flexural and compressive strengths of lightweight thermal insulation composites sharply decreased with the increase of EPS which was mainly attributed to low bulk density, small thermal conductivity and poor mechanical strength of EPS. PPF could improve the mechanical properties of lightweight thermal insulation composites to a certain extent. When the content of PPF exceeded 0.8wt%, it was proven to be counterproductive due to the aggregation effect of PPF in the composites. The flexural and compressive strength of lightweight thermal insulation composites gradually increased with the increase of RPP and then attained the peak value with the continual rise of RPP from 3wt% to 5wt%.

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References

[1] Brooks A L, Zhou H and Hanna D 2018 Constr. Build. Mater 159 316–328
[2] Miskinis K, Dikavicius V, Buska A and Banionis K 2018 Appl. Acoust 137 62–68
[3] Hu X M and Wang D M 2013 J. Appl. Polym. Sci 129 238–246
[4] Zhou L, Chen A, Gao L and Pei Z 2017 Fire. Safety. J 91 155–164
[5] Zhang Y, Pan F and Wu R 2016 Constr. Build. Mater 128 1–11
[6] Colangelo F, Roviello G, Ricciotti L, Ferrándiz-Mas V, et al. Concrete. Comp 86 66–272
[7] Sayadi A A, Tapia J V, Neitzert T R and Clifton G C 2016 Constr. Build. Mater 112 716–724
[8] Duan S, Liao H, Cheng F, Song H and Yang H 2018 Constr. Build. Mater 187 1113–20
[9] Jiang Y, Ling T C, Shi C and Pan S Y 2018 Resour. Conserv. Recy 136 187–197
[10] Li L G, Chu S H, Zeng K L, Zhu J and Kwan A K H 2018 Concrete. Comp 93 196–204
[11] Ma C and Chen B 2016 Constr. Build. Mater 113 255–263