Lightweight thermal insulation composites with redispersible polymer powder addition

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Abstract. Lightweight thermal insulation composites with different mass percentages of redispersible polymer powder (RPP) addition were prepared and the effects of RPP addition on mechanical properties, water resistance, thermal conductivity and interfacial bonding of lightweight thermal insulation composites were studied and analysed. The results showed that flexural and compressive strength of samples were improved by the addition of RPP due to improvement of pore structure and enhancement of interfacial bonding. Besides, RPP had a positive effect on thermal conductivity and interfacial bonding of lightweight thermal insulation composites.

1. Introduction
In recent years, organic thermal insulation materials have attracted much attention of worldwide researchers, which have been extensively applied in energy-saving building market because of their low density and superior thermal insulation performance [1-3]. There are many types of organic thermal insulation materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS) [4-7]. As a major member of organic thermal insulation materials, EPS possesses a great many advantages such as excellent durability and low cost which has been widely used as lightweight packaging and building exterior wall materials. However, organic thermal insulation materials have a potential fire accident fatalness due to their inherent combustibility which severely limits their application in building industry.

Inorganic cementitious materials such as ordinary Portland cement (OPC) and calcium sulfoaluminate cement are non-combustible which can be added to the organic thermal insulation materials to improve their fire resistance. Sayadi [8] reported that foamed concrete made with EPS, OPC and fly ash (FA) possessed many excellent properties such as excellent fire resistance, low density and superior thermal insulation capability which made it a promising material. At present, OPC has been the most widely used cementitious material. However, a large amount of CO₂ emission tends to come into being in the production process of cement. The use of industrial solid waste to produce composite cementitious materials for replacing or partly replacing cement has become a topic of interest [9, 10]. Flue gas desulphurization gypsum (FGD) and FA are two major solid wastes produced by power plants which both occupy land resources and pollute the environment. Thermal insulation materials produced by these industrial solid wastes are expected to become a promising material for application in building energy efficiency in virtue of their environmental protection and low energy consumption. However, little research about it has been done.

In this paper, lightweight thermal insulation composites composed of FGD, FA, OPC and EPS were prepared and the effects of RPP addition on mechanical properties, water resistance, thermal conductivity and interfacial bonding were studied.
2. Experimental section

2.1. Raw materials

OPC was purchased from Shandong Shanshui Cement Group Co., Ltd. In addition, FGD and FA were provided from Shandong Laiwu Power Plant. Table 1 showed the chemical compositions of these materials that were used as composite cementitious materials. The EPS with bulk density of 15 kg·m⁻³, particle diameter of 1-3 mm and thermal conductivity of 0.041 W·(m·K)⁻¹ was used as lightweight aggregate in order to decrease density and thermal conductivity. RPP composed of Ethylene–vinylacetate (EVA) was added with different mass percentages (0-5wt%) into lightweight thermal insulation composites, as shown in Table 2.

| Table 1. Chemical compositions (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 | -    |
| OPC | 3.52 | 3.26 | 19.67 | 55.81 | 6.48 | 3.19 |

| Table 2. Mixture proportions of samples (wt%). |
|---------------------------------------------|
| Samples | FGD | OPC | FA | Water | EPS | RRP |
|--------|-----|-----|----|-------|-----|-----|
| A0     | 60  | 25  | 15 | 52    | 9   | 0   |
| A1     | 60  | 25  | 15 | 52    | 9   | 1   |
| A2     | 60  | 25  | 15 | 52    | 9   | 2   |
| A3     | 60  | 25  | 15 | 52    | 9   | 3   |
| A4     | 60  | 25  | 15 | 52    | 9   | 4   |
| A5     | 60  | 25  | 15 | 52    | 9   | 5   |

2.2. Samples preparation and test

The FGD was calcined at 155 °C for 200 min and placed at room temperature for 7 days before using it in order to transform it into hemihydrate gypsum. The RPP was thoroughly dissolved in water and mixed evenly with FGD, OPC and FA. After that, EPS and above mixed slurry were stirred together using as a mortar mixer at a speed of 180 rpm for 240 s. The final mixtures were put into the mold for 24 hours. Finally, the samples were demoulded and cured at room temperature for 28 days.

The density of lightweight thermal insulation composites was calculated by dividing mass by volume. The flexural strength and compressive strength were evaluated by an electromechanical universal testing machine (CMT5105, China) and the final numerical results were obtained by the average of three strength tests. The samples were produced and thermal conductivity was evaluated through using a double-plate thermal conductivity tester (IM-DRY3001). The water absorption of samples was measured according to the equation (1) as follow:

\[
W = \frac{(G₂ - G₁)}{G₁} \times 100\%
\]

where \(W\) was water absorption of samples, \(G₁\) was mass of the completely dried samples before putting in water, \(G₂\) was mass of the samples after absorbing water for 24 hours. The softening coefficient was evaluated using the following equation (2):

\[
f = \frac{R₂}{R₁}
\]

where \(f\) was softening coefficient of samples, \(R₁\) was compressive strength of the completely dried samples, \(R₂\) was compressive strength of samples whose water content reached the saturate point.
3. Results and discussion

3.1. The effect of RPP addition on mechanical properties of composites

The density, flexural strength and compressive strength of composites with different mass percentages of RPP added are exhibited in Figure 1. It can be clearly seen that density of lightweight thermal insulation composites basically remain unchanged with the increase of RPP addition. Density is a significant indicator for lightweight thermal insulation materials which is mainly determined by mass ratio of EPS and composite cementitious materials comprised of FGD, OPC and FA in this study. Therefore, RPP has little effect on density of lightweight thermal insulation composites. As exhibited in Figure 1, flexural strength and compressive strength of lightweight thermal insulation composites gradually increase with the increase of RPP addition from 0 to 3wt%, while they exhibit a downward tendency with the increase of RPP addition from 3wt% to 5wt%. When the addition of RPP is 3wt%, the flexural strength and compressive strength of the samples run up to the maximum value of 0.19 MPa and 0.38 MPa which increase by 58.33% and 35.71% respectively compared to those of the samples without PPF addition. The possible reason for improvement of mechanical properties is that the pore structure of composite cementitious materials is improved by adding RPP [11] which is equivalent to the improvement of defects for lightweight thermal insulation composites. Besides, interface bonding force with cementitious materials and EPS is very weak due to the poor wettability between them. When composites are subjected to external forces, the poor interface is easily destroyed resulting in the decline of mechanical properties. Interface combining effect can be enhanced by the addition of RPP leading in the increase of mechanical properties, as explained in Section 3.4. However, excess RPP has a disadvantageous effect on mechanical properties of composites which is may attributed to the adhesion of RPP on the unreacted FGM, OPC and FA impeding the hydration of composite cementitious materials [11], resulting in the decrease of mechanical strength.

![Figure 1. The density, flexural and compressive strength of samples.](image)

3.2. The effect of RPP addition on water resistance of composites

Figure 2 presents that the effect of RPP addition on the water absorption and softening coefficient of lightweight thermal insulation composites. It is vital to improve water resistance of lightweight thermal insulation composites because poor water resistance of composites (containing FGD) can limit their practical application and the water resistance is mainly judged by water absorption and softening coefficient. As can be seen from Figure 2, water absorption gradually decreases and softening coefficient increases step by step when the content of RPP ranges from 0 to 3wt% indicating that the water resistance of lightweight thermal insulation composites is gradually improved. When the content of RPP reaches 3wt%, water absorption runs up to a minimum value of 14.13% and softening
coefficient reaches a maximum value of 0.71 which increases by 73.17% compared to the samples without RPP addition. The possible reason may be that the addition of RPP has a beneficial effect on pore structure \cite{11} which is propitious to reduce the water permeation into composite cementitious materials leading to decrease of water absorption and increase of softening coefficient. Furthermore, RPP tends to be adsorbed to the surface of the hydration products which hinders the solubility of hydration products especially for \( \text{CaSO}_4 \cdot \text{H}_2\text{O} \) resulting in improvement of water resistance. However, RPP exhibits a counterproductive influence on softening coefficient and water absorption when the content of RPP is higher than 3wt\% (shown in Figure 2), which is attributed to the adhesion of RPP on the unreacted composite cementitious materials \cite{11} leading to the decrease of water resistance.

![Figure 2](image.png)

**Figure 2.** The softening coefficient and water absorption of samples.

### 3.3. The influence of RPP addition on thermal conductivity of composites

Figure 3 exhibits that the influence of RPP addition on the thermal conductivity of samples. According to the Figure 3, the thermal conductivity decreases step by step with increase of RPP addition at the initial stage (0-3wt\%) and then basically remains unchanged with the continually increase of RPP from 3wt\% to 5wt\%. Thermal conductivity runs up to a value of 0.053 W\( \cdot \)m\( \cdot \)K\(^{-1} \) which is 15.87\% less than the samples without RPP addition when the addition of RPP reaches 3wt\%. As one of the most important properties, thermal conductivity plays a crucial role in lightweight thermal insulation composites which determines efficiency of energy conservation in construction industry. In this study, the thermal conductivity is mainly related to two factors: EPS contents in lightweight thermal insulation composites and pore structure of composite cementitious materials. The more the content of EPS, the lower the thermal conductivity indicating the better the thermal insulation performance which can be explained as the thermal conductivity of EPS much lower than that of composite cementitious materials. As a result of constant proportion of EPS in lightweight thermal insulation composites, the change of thermal conductivity should be related to pore structure, unrelated to EPS contents. As mentioned in the Section 3.2, pore structure can be improved by the addition of RPP that probably reduces the content of interconnected pores tending to become a channel for heat dissipation. Besides, interface bonding effect between composite cementitious materials and EPS is enhanced with the addition of RPP (shown in Figure 4) which may hinder outflow of heat from gaps in the interface resulting in the decrease of thermal conductivity.
3.4. The influence of RPP addition on interfacial bonding of composites

The optical photographs of fracture surface for lightweight thermal insulation composites with different mass percentages of RPP added are shown in Figure 4. It can be seen from Figure 4 (A0) that the surface of EPS is smooth and composite cementitious materials are not adhered to EPS surface which illustrates that poor interfacial bonding of EPS/composite cementitious materials. When the samples (A0) are subjected to external forces, the route of fracture always occurs along the interface between EPS and composite cementitious materials which gives rise to a decline in mechanical properties. Moreover, poor interfacial bonding also has an adverse effect on thermal conductivity (explained in the Section 3.3). As can be seen from Figure 4 (A1-A5), composite cementitious materials are absorbed on the surface of EPS which reveals that the addition of RPP tends to enhance interfacial bonding of EPS/composite cementitious materials. Besides, it can be found that some fractured EPS (marked with red in the Figure 4) appears on the fracture surface of lightweight thermal insulation composites with RPP addition while there is not fractured EPS on the fracture surface of samples without RPP addition (A0) which can prove indirectly that interfacial bonding of lightweight thermal insulation composites are exactly strengthen by the addition of RPP.

Figure 4. The optical photographs of fracture surface of samples.
4. Conclusion
RPP had little effect on density of lightweight thermal insulation composites because the decisive factor of density is mainly mass ratio of EPS and composite cementitious materials. The mechanical strengths of samples gradually increased with the increase of RPP at initial stage which was chiefly attributed to improvement of pore structure and enhancement of interfacial bonding of EPS/composite cementitious materials. However, it showed a downward tendency when the addition of RPP was over 3wt%. The water resistance of samples with RPP addition are better than that of samples without RPP addition due to improvement of pore structure. The thermal conductivity gradually decreased with the increase of RPP addition from 0-3wt% and then maintained the peak value with the continually increase of RPP from 3wt%-5wt%. The interfacial bonding of EPS/composite cementitious materials was enhanced by the addition of RPP which resulted in the improvement of mechanical properties and decrease of thermal conductivity.

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