The application of broken expanded polystyrene particles in thermal insulation coating material

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Abstract. Thermal insulation coating material is a kind of green thermal insulation material with high efficiency, which is used in the exterior wall of buildings and has many advantages such as strong sticking strength, low heat conductivity, flame retardancy and water resistance. The aggregates, main insulation components, play an important role in the thermal insulation coating material. Expanded polystyrene (EPS) particle is a good material, which can be used as an aggregate for its low thermal conductivity coefficient of 0.029 W/(m·K). Accordingly, by using the broken particles prepared from wasted expanded polystyrene, (EPS), the abandoned resources can be recycled and used again, resulting to the reduction of “white pollution” and cost. In the environment of establishing an economical social, it has huge significance and broad market prospects. Studies have shown that the broken expanded polystyrene particles and expanded perlite have the lowest thermal conductivity according to the weight ratio of 1:2.96. By using wasted expanded polystyrene particles and expanded perlite as aggregates, the thermal insulation coating material has good crack resistance, thermal insulation and compressive strength.

1. Introduction
With the improvement of people’s awareness to save energy and protect environment, the technology of thermal insulation building has got great progress. Setting insulation layer is one of the most direct and effective way to save energy of the buildings. At present, the insulation material is moving to the direction of organic and inorganic compound, which has the special properties of negative temperature and fast curing construction [1, 2]. Compared with other insulation materials, thermal insulation coating material has the best integrity, and can achieve to prepare coatings without thermal defects. The main thermal insulation coating material is silicate composite adiabatic paint which is primarily used in pipeline insulation. However, if it is used in construction engineering, there is a problem of poor resistance to crack. The crack, usually called "chicken claw" crack [3], has a thin width and a low depth at early stage. It is arranged without rules. Besides, silicate compound also has the problem of long drying time, and it needs an improving research.

2. Materials and methods

2.1. Materials
The materials of silicate composite insulation coating usually consist of aggregates, fibers, fillers, binders, and a few additive agents. The role of the main raw materials is shown in table 1.
2.2. Choice of aggregates

Wasted expanded polystyrene particles have a large surface density, which are different from the structure of most of internal pores. It presents a cellular structure formed by epidermal layer and center layer. There is no porosity in epidermal layer, while the center layer contains a large number of completely closed micro-polyhedron honeycomb holes [4]. Accordingly, if not through crushing process, the smooth surface structure will not adhere well with the gelatinize materials and packing adhesive [5-7]. The broken expanded polystyrene particles have a large specific surface area, and the crushing processing destroys their original smooth interface. Therefore, their interface adsorption performance is stronger, and they are more likely to be compatible with other raw materials. Through the comparison test of broken expanded polystyrene plastic particles with different density levels, we found that the foam particles with stacking density between 10-20 kg/m³ have suitable compression strength, thermal insulation, crushing energy dissipation to well meet the requirements of the thermal insulation coating material. The materials-broken process relies on the impact of the high-speed rotating hammer crushe and wall friction or collisions between the material body and hammer. Through the process of hammer broken, screening, and back suction, we produce a type of broken expanded polystyrene particles with diameter of below or equal 3 mm and thermal conductivity coefficient of about 0.029 W/(m·K). The properties of broken expanded polystyrene particles and round expanded polystyrene particles are shown in table 2. It can be seen that the broken expanded polystyrene particles can occupy more space due to the continuous and reasonable gradation. Thus, they have lower thermal conductivity than the round expanded polystyrene particles, and the density also reflects the feature.

| Number | The raw material composition | The main effect | The main evaluation indicators |
|--------|------------------------------|----------------|-------------------------------|
| 1      | Fibers                      | Cracking resistance, improvement of the flexural strength and thermal insulation | Tensile strength and releasing performance |
| 2      | Aggregates                  | Playing the role of skeleton and guaranteeing the insulation performance in the heat preservation system | The thermal insulation performance and grain size distribution |
| 3      | Fillers                     | Improving flow performance                                   | Thermal insulation performance and thickening performance |
| 4      | Binders                     | Improving the binding strength                              | Binding strength |
| 5      | Additive agents             | Improving the special performance, such as water preservation, anti-corrosion, and time adjusting, etc | Depending on the type of additives |

Table 2. Physical properties comparison of two kinds of expanded polystyrene particles.

| Foam particles type                  | Coefficient of thermal conductivity (W/(m·K)) | Usage temperature (°C) | Packing density (kg/m³) |
|-------------------------------------|-----------------------------------------------|------------------------|-------------------------|
| Round expanded polystyrene particles| 0.035                                         | 70                     | 15                      |
| Broken expanded polystyrene particles| 0.029                                         | 70                     | 18                      |

The particle size and density of broken expanded polystyrene used in thermal insulation coating materials are required below 3 mm and between 10 to 20 kg/m³, respectively. The photographs of two kinds of expanded polystyrene particles are shown in figure 1. The cement-styrofoam insulation board is used as model, and the effect difference of two kinds of expanded polystyrene particles sticking to cement is shown in figure 2. From the link interface between cement and expanded polystyrene particles, it can be seen that the binding effect between broken expanded polystyrene particles and gelled material is much better. Figure 3 presents the comparison of compression strength and coefficient of thermal conductivity when using round expanded polystyrene particles and broken expanded polystyrene...
particles from 25% of waste polystyrene plastic packaging material. It can be seen that the strength and thermal insulation of broken expanded polystyrene particles are superior to the circular expanded polystyrene particles. It is mainly attributed to that the broken expanded polystyrene particles possess continuous particle size distribution and can be filled more fully [8]. Thus, the mechanical and thermal defects caused by large gaps in internal structure are largely decreased. In addition, the interface layer on the surface is damaged, causing better adhesion between cement and expanded polystyrene particles and less numbers of connecting hole in the structure compared with circular expanded polystyrene particles.

![Image](a) ![Image](b)

**Figure 1.** Particle shape contrast. Continuous gradation of broken expanded polystyrene particles and (b) Single gradation of round expanded polystyrene particles.

When the volume ratio of cement to expanded polystyrene particles is less than 1:5, it is uneconomical. If it exceeds 1:9, it will not stick. Therefore, the results of the suitable volume ratio are shown in figure 3 below.

![Image](a) ![Image](b)

**Figure 2.** Comparison of the binding effect between two kinds of expanded polystyrene particles in the cement-styrofoam board. Broken expanded polystyrene particles and (b) Round expanded polystyrene particles.

The two major factors for the selection of aggregates insulation are thermal conductivity and bulk density. It can be seen from figure 3, as expanded polystyrene increases, the strength and thermal conductivity of the cement-styrofoam board show a downward trend. The performance of broken expanded polystyrene particles is better than round expanded polystyrene particles. The recycled broken expanded polystyrene particles can be used as an efficient thermal insulation aggregate with its low coefficient of thermal conductivity. Alternative insulation aggregates are given in table 3.
Figure 3. Performance comparison of the cement-styrofoam board made by two kinds of expanded polystyrene particles. (a) compression strength and (b) thermal conductivity.

Table 3. List of alternative insulation aggregates.

| Serial number | Name                        | Production area          |
|---------------|-----------------------------|--------------------------|
| 1#            | Expanded perlite            | Honggu District of Lanzhou|
| 2#            | Expanded perlite            | Anning District of Lanzhou|
| 3#            | Expanded vermiculite        | Shajingyi of Lanzhou     |
| 4#            | Expanded vermiculite        | Baiyin                   |
| 5#            | Drift beads                 | Chengguan District of Lanzhou|
| 6#            | Drift beads                 | Xigu District of Lanzhou  |
| 7#            | Clay ceramsite              | Honggu District of Lanzhou|
| 8#            | Expanded polystyrene particles | Lanzhou              |

The values of density and thermal conductivity at room temperature of alternative insulation aggregates are listed in table 3 and shown in figure 4.

Figure 4. Comparison of insulation aggregates properties: (a) density; and (b) thermal conductivity.

As seen in figure 4, the best indexes of heat preservation performance and density are Nos. 2 and 8, which represent the expanded perlite produced in Anning district of Lanzhou city and homemade broken foam particles, respectively. These two kinds of insulation aggregates are the optimal choices. The expanded perlite produced in Anning district of Lanzhou city is shown in figure 5. The maximum particle size is 5 mm.
Combining broken foam polystyrene particles with expanded perlite can effectively relieve the defect of material and fully exert the heat preservation performance of expanded polystyrene particles.

3. Results and discussions
The thermal insulation coating material is suitable for the insulation of building roof and internal or external wall. In order to prevent the environmental pollution caused by waft when stirring the broken expanded polystyrene particles, composite fibers and filling materials in the building site, the product takes the form of slurry. Because the product has a gelled material, it is composed of two components containing powder components and slurry components. The powder components are composed by special gelled material (JT), gelled material (BS), and coagulation agent. The slurry components are composed by broken expanded polystyrene particles, industrial residue filler, composite fiber made up by inorganic environmental protection fiber and short-cutting vinyl on fiber, preservatives, penetrating agents, polymer powder and so on.

3.1. Correlation of the thermal insulation coating material
In order to get the best product performance, the formula design can not only focus on single component performance but should take account of the correlation between different indexes in the production process. The correlation indicators need to be paid attention as follows:

- Relationship between density and coefficient of thermal conductivity of materials.
  Low density and large porosity of materials provide low coefficient of thermal conductivity. It usually increases with the density except for fiber materials. As for fiber, its diameter, porosity and the amount of binder have significant effect on its performance. The relationship between the density and the coefficient of thermal conductivity depends on specific conditions. For example, when using material in high temperature, the high density materials have low thermal conductivity. Therefore, there is a problem to choose the best density. If the density of material is small, the coefficient of thermal conductivity decreases as the density increases, but then increases with the further increase of density. Accordingly, there is a density value related to the minimum thermal conductivity, known as the best density.
  Figure 6 presents the relationship between the material coefficient of thermal conductivity and density of the cement-styrofoam insulation board. We can know that the best density range is between 260 ~ 280 kg/m$^3$, which relates to the best heat preservation performance. For insulation coating system, the heat insulation performance is different due to the various aggregate grades, but the best dry density still exists.

- Relationship of density and compressive strength
  There is a proportional relationship between compressive strength and density of material. The compressive strength increases with the improvement of density. However, the thermal conductivity
also increases as the density increases. Thus, the selection of density should be fully considered and can not only demand one certain performance index.

![Figure 6. Relationship between the coefficient of thermal conductivity and density of the cement-styrofoam insulation board.](image)

3.2. Optimization of composition

The results show that the powder components mainly contain special gelled material JT, gelled material BS and thickening time control agent. Through actual test, we find the best crack effect ratio of special gelled material JT and gelled material BS is 2:1.

The coating components are formed of expanded perlite, broken expanded polystyrene particles, polymer powder, lightweight filler, fiber material, preservatives, penetrating agents and water.

![Figure 7. Relationship between thermal conductivity coefficient and compressive strength of aggregate specimens at different ratios.](image)

The system of composite gelled material and insulation aggregates are built to explore the ratio relationship between expanded perlite and broken expanded polystyrene particles. By using broken expanded polystyrene particles as aggregate, the performance of heat-preservation of thermal insulation coating material has been able to reach the established requirements. In order to further increase the strength of the insulation system, the perlite type is added to replace part of broken expanded polystyrene particles to achieve the purpose of optimization between the thermal insulation performance and compressive strength. So, the perlite amount of optimal alternative is studied. It is known that the volume ratio is approximately 1:6 between the gelled material and the aggregate in the cement-styrofoam insulation board. On the basis of the proportion of the gelled material and the insulation aggregate at 1:6 scale, we replace broken expanded polystyrene particles with perlite and then form specimens with different proportions. The results summary of relationship between thermal conductivity coefficient and
compressive strength of the specimens is shown in figure 7.

Figure 7 shows that with the replacement amount of perlite increasing within 40%, the variation of thermal conductivity coefficient of the insulation system is still small. When the replacement amount is more than 40%, thermal conductivity coefficient clearly shows a rising trend with replacement amount increasing. However, the compressive strength rises obviously within 40% but decreases more than 40%. It shows that the particle size distribution of the thermal insulation system becomes more reasonable with the replacement amount of expanded perlite increasing. Then because the expanded perlite gradation is unitary and the size of most particles is large, the compressive strength presents a downward trend. Although the insulation performance of perlite is poorer than expanded polystyrene particles, the coefficient of thermal conductivity has no apparent rising trend when the expanded perlite replacement amount is lower than 40%, for that the perlite and broken expanded polystyrene particles form a reasonable continuous gradation at low replacement amount of perlite. However, with the replacement amount further increasing, both particle gradation and perlite addition presents a negative effect on the heat-preservation performance. Considering the two aspects, the best pearlite replacement amount to broken expanded polystyrene particles is 40%. Due to narrow shrink and no volume change of the coating insulation material, it is mainly composed of aggregates, while gelled material, thin lightweight packing, and fiber just fill the gaps.

The density of broken expanded polystyrene particles is ρ1=18 kg/m³, and the density of perlite is ρ2=80 kg/m³. The volume ratio of broken expanded polystyrene particles and expanded perlite is taken by 6:4. If each side needs broken expanded polystyrene particle of X kg and perlite of Y kg, the weight of perlite and broken expanded polystyrene particles can be calculated by the following equation:

\[
\begin{align*}
\frac{X}{\rho_1} + \frac{Y}{\rho_2} &= 1 \\
\frac{4X}{18} - \frac{6Y}{80} &= 1
\end{align*}
\] (1)

The solution of equation (1) yields that X = 10.8 (kg) and Y = 32.0 (kg). Therefore, the mass ratio between the broken expanded polystyrene particles and expanded perlite is 1: 2.96. With rounding numbers, the dosage of broken expanded polystyrene particles in each side thermal insulation coating material should be 11 kg, and the perlite usage should be 32 kg.

The thermal insulation coating material is composed of 12 kinds of raw materials. It’s difficult to consider each material’s influence to the thermal insulation coating materials at the same time. In this case, it is thought to simplify the composition of the thermal insulation as follows:

Due to the components of powder formula are determined, we can put the powder as a single component to treat. Then, the quantity of the inorganic environmental protection fiber is too much important compared with the chopped vinylon fiber, so we can neglect the dosage of short-cut vinylon fiber. In this way, the fiber materials also can be simplified as a single component. Additionally, aggregates component are seen as single based on the proportion of broken expanded polystyrene particles and expanded perlite. Besides, we regard the lightweight filler as a component. Finally, we take the polymer powder, preservatives, and water repellent reagent as the additive components. In this way, the formulation of thermal insulation coating material can be simplified to four components, which greatly simplifies the complexity of the problem.

These four components are powder, fiber, aggregate, and filling components.

- Orthogonal experiment scheme orthogonal experiment was carried out with the four components.

According to the proportion of the cement-styrofoam insulation board, the quality of powder is calculated to be 140 kg, so these three significances can be set as 120, 140, and 160 kg. The insulation aggregates should be 43 kg/m³, set as 35, 40 and 45 kg. The fiber components should be 25 kg, set as 30, 35 and 40 kg, and the lightweight filler is set as 30, 40 and 50 kg according to the content of silicate composite insulation coating. With the selected 4 factors and 3 levels and based on the orthogonal table L9 (3⁴) for experimental analysis, test results and intuitive analysis results are shown in the following
Table 4. Selection factors levels of orthogonal table (kg/m³).

| Level | Powder | Insulation aggregates | Fiber components | Filling material |
|-------|--------|-----------------------|------------------|-----------------|
| 1     | 120    | 35                    | 30               | 30              |
| 2     | 140    | 40                    | 35               | 40              |
| 3     | 160    | 45                    | 40               | 50              |

Table 5. L₉(3⁴) Orthogonal table test.

| Test number | Test combination | Coefficient of thermal conductivity |
|-------------|------------------|-------------------------------------|
| 1           | 1111             | 0.065                               |
| 2           | 1222             | 0.054                               |
| 3           | 1333             | 0.055                               |
| 4           | 2123             | 0.059                               |
| 5           | 2231             | 0.053                               |
| 6           | 2312             | 0.057                               |
| 7           | 3123             | 0.071                               |
| 8           | 3213             | 0.068                               |
| 9           | 3321             | 0.067                               |

Table 6. Orthogonal test results of coefficient of thermal conductivity (W/(m·K)).

| Test number | Test combination | Coefficient of thermal conductivity | Arithmetic mean |
|-------------|------------------|-------------------------------------|-----------------|
| 1           | 1111             | 0.065                               | 0.066           |
| 2           | 1222             | 0.054                               | 0.052           |
| 3           | 1333             | 0.055                               | 0.057           |
| 4           | 2123             | 0.059                               | 0.056           |
| 5           | 2231             | 0.053                               | 0.052           |
| 6           | 2312             | 0.057                               | 0.055           |
| 7           | 3123             | 0.071                               | 0.072           |
| 8           | 3213             | 0.068                               | 0.066           |
| 9           | 3321             | 0.067                               | 0.066           |

Table 7. Visual analysis of test results (W/(m·K)).

| Test number | Powder | Insulation aggregates | Fiber component | Filling material |
|-------------|--------|-----------------------|-----------------|-----------------|
| 1           | 0.0582 | 0.0652                | 0.0629          | 0.0612          |
| 2           | 0.0552 | 0.0574                | 0.0587          | 0.0602          |
| 3           | 0.0684 | 0.0592                | 0.0603          | 0.0604          |

- Orthogonal experiment results
  It can be seen from the above table that the value of thermal conductivity coefficient of powder 2# is lowest. It means that in the case of other unchanged conditions, 2# has the best level. Accordingly, the best thermal conductivity level is obtained by the combination of powder 2#, Insulation aggregate 2#, fiber composition 2# and filling material 2#. In conclusion, the best insulation level corresponding to the dosage combination is shown in table 8.

Table 8. The best dosage combination of thermal insulation.

| Components | Powder | Insulation aggregates | Fiber components | Filling material |
|------------|--------|-----------------------|------------------|-----------------|
| Dosage (kg/m³) | 140    | 40                    | 35               | 40              |

Through the above formula design and after fine-adjustment, the detailed formula is shown in table 9.
### Table 9. Raw materials distribution ratio of the thermal insulation coating materials.

| Ingredient                          | JT | BS | Broken expanded polystyrene particles | Expanded perlite | Environmental inorganic fiber | Short vinylon fiber | Open lightweight filler | Other components |
|-------------------------------------|----|----|--------------------------------------|------------------|-------------------------------|---------------------|------------------------|------------------|
| Weight ratio                        | 9  | 5  | 1                                    | 3                | 2.2                           | 0.3                 | 4                      | 0.8              |

The test method is based on the silicate composite insulation coating of GB/T 17371. The properties of coating thermal insulation materials with formula optimization are listed in Table 10.

### Table 10. Properties of the thermal insulation coating materials with formula optimization.

| Project                          | Unit   | Test values |
|----------------------------------|--------|-------------|
| Slurry density                   | kg/m³  | 723         |
| PH value                         | /      | 9           |
| Dry density                      | kg/m³  | 243         |
| Drying shrinkage ratio           | %      | 0.1%        |
| Setting time                     |        |             |
| Initial setting                  | h      | 6           |
| Final setting                    | h      | 12.5        |
| Adhesive strength                | kPa    | 75          |
| Coefficient of thermal conductivity (25℃±5℃) | W/(m·K) | 0.052 |
| Tensile strength                 | kPa    | 154         |
| Compressive strength (28 d)      | kPa    | 424         |
| Softening coefficient (Soak in water for 24 h) | / | 0.89 |
| Combustion performance(700℃/2h) | /      | Non-combustible |
| Durable performance              | /      | There is no frost crack phenomena |
| Radioactive                      |        |             |
| Internal exposure index IRa      | /      | 0.03        |
| External exposure index Ir       | /      | 0.07        |

The main performance comparison between the thermal insulation coating materials (TIC) and other thermal insulation materials, as shown in Table 11. It includes the following materials: 1) expanded vermiculite coated expanded polystyrene /cement composite foams (CEPS) [9]; 2) perlite cement polystyrene foam roof insulation material (PCP) [10]; 3) cement polystyrene board (CPB) [11].

### Table 11. Properties of the thermal insulation coating materials with formula optimization.

| Type of insulation material | Property       | Dry density (kg/m³) | Thermal conductivity (W/(m·K)) | Compressive strength (MPa) |
|-----------------------------|----------------|--------------------|-------------------------------|-----------------------------|
| TIC                         |                | 243                | 0.052                         | 0.42                        |
| CEPS                        |                | 270                | 0.054                         | 0.43                        |
| PCP                         |                | 223                | 0.056                         | 0.50                        |
| CPB                         |                | 305                | 0.09                          | 0.28                        |

4. Conclusions

According to the raw materials’ composition of traditional silicate composite adiabatic paint, the thermal insulation coating material should be composed of aggregates, fiber material, fill material, and adhesive agent and few additives. In this paper, by comparing the properties of broken polystyrene particles and round polystyrene particles, a new thermal insulation coating based on silicate composite thermal insulation coating suitable for building needs was developed. Through test research, we select expanded perlite and broken expanded polystyrene particles as aggregates, special gelled material JT and gelled material BS as gelled material, inorganic environmental fiber and short-cut vinylon fiber as fiber material, and lightweight filler as filler.

After the thermal insulation coating material on the surface of building, the internal is fully filled...
with composite fiber, broken expanded polystyrene particles and lightweight filler. The microstructure presents mesh-arranged fiber beam with hollow-needle and hole-like shapes, and contains many closed tiny air sacs and pores made by organic and inorganic materials. Thus, heat is difficult to go through the structure. In conclusion, the thermal insulation performance of the whole insulation system is effective, and the thermal conductivity coefficient can reach 0.052 W/(m · K).

References
[1] Wang S P 2005 Building insulation coating thermal insulation material and its research progress J. Shanghai Coatings 3 13-5
[2] Yang L, Chen H and Liu Y 2018 Numerical simulation on size effect of expansive polystyrene granule cement form latticed concrete walls J. Shenyang University of Technology 40 582-7
[3] Aitcin P C, Necille A M and Acker P 1997 Integrated view of Shrinkage deformation J. Concrete International 19 35-41
[4] Wu F and Xu X J 2003 The building external wall’s energy-saving thermal insulation coating in cold and freezing area J. Coating Industry 4 10-12
[5] Zhang Y, He T S, Cao W Z et al 2007 Influence of fiber brucite on properties of compound energy-saving and thermal insulation plaster J. Non-Metallic Mines 30 1-4
[6] Mei L F and Xu G L 2016 Preparation and mechanical properties of fiber expanded polystyrene particle lightweight soil J. Acta Materiae Compositae Sinica 33 2356-61
[7] Zhu H B, Zhang H L, Liu X and Li C 2014 Research on the acoustic performance of porous materials with polystyrene and cement J. Adv. Mater. Res.-Switz 22 23-7
[8] Fan X 2016 The analysis of structural adjustment and hot points of foamed plastics insulation materials J. Chem. Indust. 34 25-7
[9] Wang Z Z and Yang T 2018 Preparation and properties of expanded vermiculite coated expanded polystyrene /cement composite foams J. Chem. J. Chinese. U. 39 1098-104
[10] Mai S Y, Li L and Mai J 1998 Perlite cement polystyrene foam roof insulation J. New Building Materials 1998 33-4
[11] Tian J K, Zhu M and Wang Z D 2000 Research and application of cement polystyrene board in energy-saving building in cold area J. Low Temperature Building Technology 81 58