Research and application of high performance GPES rigid foam composite plastic insulation boards

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Abstract: A new type of heat insulation board named GPES was prepared by several polymers and modified nano-graphite particles, injecting high-pressure supercritical CO2. Compared with the traditional thermal insulation material, GPES insulation board has higher roundness bubble and thinner bubble wall. Repeatability and reproducibility tests show that melting knot, dimensional stability, strength and other physical properties are significantly better than traditional organic heat insulation materials. Especially the lower and more stable thermal conductivity of GPES can significantly reduce thermal insulation layer thickness. Obviously GPES is the best choice of insulation materials with the implement of 75% and higher energy efficiency standard.

1. Introduction
With the implementation of 75% building energy efficiency in China, the thickness of insulation layer is increasing, therefore, the issue of structural safety in exterior insulation is more prominent. Since the enforcement of GB50016-2014 code for fire protection design of buildings (The Chinese national standard), the contradiction between exterior wall insulation and fire prevention has been more sharp than before. Firstly, building energy efficiency design standards has been raised from 65% to 75%, the thickness of insulation layer has been almost more than double. Especially for the passive building in our province, the thickness of EPS could be 25-30cm. The increased thickness of insulation layer, raises the proportion of combustible per unit area and total in external insulation system by two times, increases the risk of flame spreading during the fire.

At the same time, the insulation system’s ability of resisting gravity (the outer protective layer) to prevent shearing by itself has fallen sharply, the length of anchor bolt has been almost doubled as well, so it is inevitable that the structure safety of external thermal insulation system has high risks because of the low resistant capacity for stretching, torsion and shear.

In view of the above problems, project team developed GPES rigid foam plastic composite insulation board (hereinafter referred to as the GPES insulation board), which uses high barrier property materials as a primary structure, prepared by several polymers, modified nano-graphite and so on, via 30MPa high pressure and high temperature, injected high pressure supercritical carbon dioxide fluid, finally released from low temperature and high pressure. Its density is between 32 and 38 kg/m³. After a large number of repeatability and reproducibility tests, various property of the GPES are excellent. GPES can meet the requirement of 75% energy saving standards and higher passive building construction technology standard by combining with the different forms of insulation structure. It costs lower than other thermal insulation material such as EPS, XPS, PU etc..
2. GPES insulation boards

GPES rigid foam plastic insulation board was prepared by several polymers, modified nano-graphite and additives, via 30MPa high pressure and high temperature, injected high pressure supercritical CO2 fluid, finally released from low temperature and high pressure. It called GPES insulation board for short. Insulation board mixing modified material and various of high-molecular polymers, it adopt the foaming of high pressure supercritical carbon dioxide fluid rather than the blowing agent such as tetrachloroethane, pentane, or Freon etc. In this way, the bubble become more balance, shorter diameter (less than 50um), higher roundness bubble, most of Closed bubbles has lower heat conductive coefficient. Thus the thermal insulation material with better performance and lower heat conductive coefficient in friendly environment has been obtained.

2.1. Classification of GPES insulation board

GPES insulation board is divided into GPES-I and GPES-II according to the thermal conductivity, the range of its thermal conductivity are shown in table 1

| Category | Thermal Conductivity W/(m·K) |
|----------|-----------------------------|
| GPES-I   | ≤0.020                      |
| GPES-II  | ≤0.025 ~ >0.020             |

2.2. Research and development of GPES-I insulation board

After continuous efforts of three years, the second generation of GPES insulation board (GEPS-I) with better performance was developed by the project team. Its theory is based on the first generation of GPES insulation boards (GPES-II), and the technical formula was continued improving through 49 batch insulation board production experiment test. The insulation board has excellent physical and combustion performance as the first generation of GPES, but lower coefficient of thermal conductivity and more excellent long-term stability that its 28d heat conduction coefficient is less than 0.020 W/(m·K).

2.3. Morphology of GPES-I insulation plate under electron microscope

Figure 1 is a SEM photo of GPES-I insulation board bubble hole section, it shows the microcellular structural characteristics of GPES-I insulation board. Figure 2 is a SEM photo of the GPES-I insulation board bubble wall. It can be seen that the ultra-thin bubble wall is less than 0.5um. Microporous structure, ultra-thin bubble wall, high barrier properties to fundamentally ensure that the GPES-I excellent thermal barrier. The composite plastic with high performance was processed by the special mixing, so that its thermal performance and physical properties are significantly better than the traditional organic insulation materials.
3. Performance analysis of GPES thermal insulation boards

3.1. Coefficient of thermal conductivity

3.1.1. GPES-Ⅰ coefficient of thermal conductivity long-term stability. Coefficient of thermal conductivity is the main indicator of thermal properties of materials and is also a key index to ensure its heat preservation performance. GPES adopt supercritical CO₂ foaming by a specific process, which makes high obturator rate of block foam obturator structure with bubbles of uniform size and thinner wall. GPES-Ⅱ coefficient of thermal conductivity is stable within 0.025 W/(m·K) for long-term. Based on this, after many times of technological formula adjustments, GPES-Ⅰ coefficient of thermal conductivity is stable within 0.020 W/(m·K) for long-term. We test coefficient of thermal conductivity of some lots of GPES-Ⅰ insulation board that aged 0-90d. As can be seen from table 3 the test result, 28d thermal conductivity coefficient of 48# of the samples can reach 0.0176 W/(m·K), 90d coefficient of thermal conductivity is 0.0178 W/(m·K).

Table 3 The results of orthogonal experiment of GPES-Ⅰ insulation boards (Aged 0-90d) W/(m·K)

| No. | 14d | 28d | 45d | 60d | 75d | 90d |
|-----|-----|-----|-----|-----|-----|-----|
| 35  | 0.0192 | 0.0198 | 0.0195 | 0.0196 | 0.0199 | 0.0198 |
| 2   | 0.0180 | 0.0175 | 0.0183 | 0.0190 | 0.0194 | 0.0195 |
| 29  | 0.0183 | 0.0183 | 0.0190 | 0.0185 | 0.0184 | 0.0185 |
| 48  | 0.0158 | 0.0176 | 0.0173 | 0.0179 | 0.0180 | 0.0178 |
| 49  | 0.0178 | 0.0187 | 0.0185 | 0.0190 | 0.0193 | 0.0196 |
| 32  | 0.0187 | 0.0189 | 0.0192 | 0.0193 | 0.0197 | 0.0196 |

3.1.2. GPES-Ⅱ coefficient of thermal conductivity long-term stability. GPES-Ⅱ was maintained accordingly to GB/T 30595-2014, and aged 90 d. The coefficient of thermal conductivity was tested according to GB/T 10294-2008. Table 4 and figure 3 are respectively coefficient of thermal conductivity and change curve of GPES-Ⅰ and GPES-Ⅱ that aged 90 d.
Table 4  GPES-Ⅰand GPES-Ⅱ’s coefficient of thermal conductivity （Aged 0-90d） W/(m·K)

| Thermal Conductivity | 3d  | 7d  | 14d | 28d | 45d | 60d | 75d | 90d |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| GPES-Ⅰ               | 0.0190 | 0.0182 | 0.0174 | 0.0192 | 0.0190 | 0.0192 | 0.0195 | 0.0194 |
| GPES-Ⅱ               | —   | —   | 0.0222 | 0.0230 | 0.0235 | 0.0239 | 0.0242 | 0.0243 |

FIG.3 Curves of thermal conductivity of GPES-Ⅰ and GPES-Ⅱ （Aged 0~90d）

From the experimental results, coefficient of thermal conductivity within 90 d basically remain unchanged of GPES-Ⅰ, while that of GPES-Ⅱ increases slightly. Tendency curves of thermal conductivity of GPES-Ⅰand GPES-Ⅱ illustrates that GPES-Ⅰ has more excellent long-term stability of thermal performance.

3.2. The durability of GPES

In order to investigate the durability of GPES insulation board's thermal performance, contrast experiment was carried on 5 groups of samples taken from GPES-Ⅰ, GPES-Ⅱ and PU plate, which has already aged 90d. The method is shown below:

Test method: (1) raise its temperature up to (70 ± 5)℃ within 1 h, relative humidity (90 ± 5)%, and keep it for 3 h; (2) cool down its temperature to (-20±5)℃ within 1 h, and keep it for 3 h; Temperature (23 ± 2)℃, relative humidity (50 ± 5) %, keep it for 16h, and then 15, 30, 45 and 60 times of durability test was adopted respectively, each cycle is 24h. The results of synchronized test can be seen in below table and figure.

Table 5 Endurance test curves of GPES-Ⅰ and GPES-Ⅱ’s thermal performance W/(m·K)

| Number of cycles | 0   | 15  | 30  | 45  | 60  | Loss rate |
|------------------|-----|-----|-----|-----|-----|-----------|
| Thermal conductivity coefficient | GPES-Ⅰ  | 0.0194 | 0.0198 | 0.0207 | 0.0211 | 0.0210 | 8.25% |
|                  | GPES-Ⅱ  | 0.0244 | 0.0256 | 0.0263 | 0.0267 | 0.0265 | 8.60% |
|                  | PU     | 0.0237 | 0.0261 | 0.0268 | 0.0272 | 0.0272 | 14.7% |
FIG.4 Endurance test curves of GPES-I and GPES-II’s thermal performance

After 60 times of humid-hot-cold cycles, GPES-I and GPES-II’s thermal conductivity are 0.0210 and 0.0265 W/(m·K), PU is 0.0272 W/(m·K), increased by 8.25%, 8.6% and 14.7% than their initial thermal conductivity coefficient. As you can see, after a long-term of humid hot and cold cycle, the structure of GPES tends to be stable. It means that being used over the years, GPE-I and the loss thermal conductivity of GPES-II could reach 8.25% and 8.6%, but far less than that of the PU 14.7%. The conclusion is GPES has more excellent durability of thermal performance.

3.3. Mechanical property

3.3.1. Tensile strength. As the main mechanical performance indexes, tensile strength of insulation board is to ensure that building external thermal insulation engineering maintain its normal function. Every day we sliced same size of sample from the GPES insulation board production line after steady production. We sorted the sample and aged for 28 days, then tested its tensile strength perpendicular to the direction of the plate. Test results are shown in table 6.

| Items                                | Sample number | Average | GB/T 30595-2014 |
|--------------------------------------|---------------|---------|-----------------|
|                                      | 1 2 3 Average |         |                 |
| Tensile strength perpendicular to the direction of the plate | GPES-I 0.33 0.32 0.34 0.33 | ≥0.20   |
|                                      | GPES-II 0.34 0.33 0.34 0.34 |         |

It can be seen from the results in the table, the GPES-I and GPES-II insulation board’s tensile strength perpendicular to the direction of the plate were 0.33 and 0.34 MPa, which is very excellent. Considering the smooth surface and high hydrophobicity of GPES may cause bonding interface with mortar is not strong, a special interface agent applicable to GPES insulation board has been developed. The interface agent has excellent adhesion and water resistance that the bonding strength of GPES
insulation board and mortar remain above 0.40 MPa after the application of the agent.

Table 7 Bonding tensile strength of GPES and mortars treated with special interface agent MPa

| Items                    | 28d original intensity | Water resistant to 48h, dry 2h | Water resistant to 48h,dry 7d |
|--------------------------|------------------------|--------------------------------|-------------------------------|
|                          | GPES-I     | GPES-II   | GPES-I     | GPES-II   | GPES-I     | GPES-II   |
| Bonding mortar           | 0.42       | 0.44      | 0.40       | 0.41      | 0.43       | 0.45      |
| GB/T 30595-2014 standard | ≥0.20      |           | ≥0.10      |           | ≥0.20      |           |
| Rendering coat mortar    | 0.45       | 0.46      | 0.42       | 0.42      | 0.45       | 0.45      |
| GB/T 30595-2014 standard | ≥0.20      |           | ≥0.10      |           | ≥0.20      |           |

XPS’s tensile strength perpendicular to its surface and bond strength with mortar are below 0.25 MPa, while GPES’s tensile strength perpendicular to its surface is higher than 0.30 MPa. After treatment the interface by special interface agent, GPES’s bonding strength with mortar could be higher than 0.40 MPa. Main mechanical performance of GPES insulation board is more than 1.5 times superior to the XPS.

3.3.2. Other mechanical properties. Compression strength, bending load and bending deformation are also important indicators. The GPES-I and GPES-II insulation board’s compression strength and bending load, bending deformation has been tested respectively, the results are shown in table 8.

Table 8 Other mechanical properties of GPES- I and GPES- II insulation board

| Items                                | Category | GB/T 30595-2014 |
|--------------------------------------|----------|-----------------|
|                                       | GPES-I   | GPES-II         |
| Bending load of fracture /N           | 43       | 41              |
| Bending deformation /mm               | 50       | 48              |
| Compression strength /MPa             | 0.33     | 0.32            |

The results indicate that the bending deformation of GPES is excellent and more than 2 times superior to standard of GB/T 30595-2014. Its compression strength is more than 0.30 MPa, which is superior to XPS by more than 50%

The internal structure of insulation board is the important factors influencing its compression strength and bending deformation, the higher its value, the stronger of durability and impact resistance of insulation board. The mixed grafting technology used in the process of forming the GPES insulation board, makes high degree of polymer crosslinking, compact structure, and high obturator rate, which contributed to the excellent bending properties and compression strength of GPES.

3.4. Water absorption

Water absorption is an important indicator for the performance of insulation materials, high water absorption will lead to gradually reduce the thermal insulation properties. This result also shows that in the following four kinds of insulation materials, the smallest water absorption rate insulation plate
of GPES-Ⅰand GPES-Ⅱis 0.3%, compared with the board water absorption of XPS decreased by 60% and more. According to the heat transfer theory of porous materials, the lower the water absorption of the material, the more stable the insulation effect. The very low water absorption for GPES plate is to ensure that its thermal insulation performance to the perfection.

| Performance parameters | GPES-Ⅰ | GPES-Ⅱ | XPS | EPS | PU |
|-------------------------|--------|--------|-----|-----|----|
| Water absorption per volume | 0.3 | 0.3 | 0.8 | 1.5 | 2.0 |
| GB/T 30595-2014 | ≤1.5% |

### 3.5. Dimensional stability
Insulation board with poor Dimension stability performance is easy to bending deformation, causing the wall to crack or fall off, thereby reducing the external thermal insulation system security. In regard to GPES-Ⅰ and GPES-Ⅱ dimension stability, prescriptive indicator of XPS board’s dimension stability used for external thermal insulation system is: 1.2% or less which according to GB/T 30595-2014 standard. The dimensional change rate of the GPES-Ⅰand GPES-Ⅱ along length, width and thickness direction are tested after 48h at the temperature 70℃. As the test results, the dimension stability of GPES-Ⅰand GPES-Ⅱ are better than the prescriptive indicator.

| Items | Model | GB/T 30595-2014 |
|-------|-------|-----------------|
| Length | GPES-Ⅰ | 0.6 |
|       | GPES-Ⅱ | 0.1 |
| Width | GPES-Ⅰ | 0.6 |
|       | GPES-Ⅱ | 0.4 |
| Thickness | GPES-Ⅰ | 0.4 |
|       | GPES-Ⅱ | 0.2 |
|       | ≤1.2% |     |

### 3.6. Combustion Performance
The combustion performance of the insulation board concerns the safety of the entire external wall insulation project, therefore it attracts much attention. GPES insulation board adopted CO₂ fluid foaming, which not only reduce VOC emissions, but also play a role in flame retardant. Through the test of combustion experiments, GPES-Ⅰand GPES-Ⅱ insulation boards are up to B₁ level.

### 4. GPES insulation board exterior insulation system
The system was mainly consist of high-performance GPES insulation board, fixed material (adhesive mortar, anchoring parts), fireproof screed-coat (composite sizing agent coat), plaster coat and finish coat. It contains two systems, namely high-performance insulation board paste- compound slurry ( the basic structure can be seen in Table 11) and the system of high-performance insulation board double-deck break joint paste -compound slurry ( the basic structure can be seen in Table 12).

The engineering design of high-performance thermal insulation board can select a appropriate external insulation system according to the building energy efficiency requirements. High-performance insulation board paste - composite slurry system has been applied for public buildings in 65% energy saving and residential buildings in 75% energy saving , high-performance insulation board double-deck break joint paste -compound slurry system has been applied for public buildings in 65% energy saving, residential buildings in 75% energy saving and the passive green construction with ultra-low energy consumption.
Table 11 The basic structure of high-performance insulation board paste-compound slurry system

| System basic structure |
|------------------------|
| Base wall               |
| Bonding layer①         |
| Thermal insulation layer② |
| Fire screed-coat③      |
| Protective layer        |
| Renderring coat④       |
| Finish coat⑤           |
| Plate seam⑥            |
| Structure diagram       |
|                        |

Concrete wall and all kinds of masonry walls

| System basic structure |
|------------------------|
| Bonding mortar         |
| Special interface agent + GPES + Special interface agent |
| 20mm composite layer of insulation coating |
| Renderring coatmortar + Alkali resistant fiberglass mesh |
| Coating materials      |
| 10mm Joints with embeded full of composite insulation coating |

Table 12 The basic structure of high-performance insulation board double-deck break joint paste-compound slurry system

| System basic structure |
|------------------------|
| Base wall               |
| Bonding layer①         |
| Thermal insulation layer② |
| Bonding layer③         |
| Thermal insulation layer④ |
| Fire screed-coat⑤      |
| Protective layer        |
| Renderring coat⑥       |
| Finish coat⑦           |
| The inner seam⑧        |
| The outer seam⑨        |
| Structure diagram       |
|                        |

Concrete wall and all kinds of masonry walls

| System basic structure |
|------------------------|
| Bonding mortar         |
| Special interface agent + GPES insulation board + Special interface agent |
| Special interface agent + GPES insulation board + Special interface agent |
| 20mm mcomposite layer of insulation coating |
| Rendering coatmortar + Alkali resistant fiberglass mesh |
| Coating materials      |
| 5mm Joints with embeded full of bonding mortar |
| 10mm Joints with embeded full of composite insulation coating |

5. Conclusion
Comparing with current insulation board, this new type of insulation board has many advantages such as lower thermal conductivity, relatively larger apparent density and high compressive strength and tensile strength, lower water absorption, better moisture resistance and dimensional stability etc. Under the same energy efficiency standards, its thickness can be 30% thinner than EPS and XPS board, it has more advantages than polyurethane insulation board—high cost-effective, the price is 1/3 of polyurethane insulation board, it is better than other insulation materials in current marketing.

The development and popularization of the GPES insulation board can impel a high-level step for
energy efficiency standards of building energy-saving work, and provide reliable product and technical support. It has the huge practical significance for popularization and implementation of high-level energy efficiency standards such as 75% power-saving and passive ultra-low energy consumption, and at the same time, it can provide huge economic benefits for the building energy-saving industry and it has a broad application prospects.

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