Study on Permanent Thermal Insulation Formwork of Mass Concrete Prepared by Different Types of Nano-modified Lightweight Aggregate

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Abstract: Aiming at the problems of low strength, flammability, easy falling off, and aging of traditional organic thermal insulation materials, inorganic thermal insulation materials of different types of nano-modified lightweight aggregates were prepared in this paper. The feasibility of preparing permanent thermal insulation formwork of mass concrete with nano-modified lightweight aggregate was studied through experiments and calculation analysis of mechanical, durability, and thermal properties. The results show that the water absorption of shale ceramsite modified by nano-permeable hydrophobic agent is reduced to 1.21%, and the water absorption rate of inorganic precast hollow aggregate produced by nano-silica powder is lower, which is 0.79%. Inorganic precast hollow aggregate concrete, modified shale ceramsite concrete, and organic foamed aggregate concrete have the characteristics of high strength, fire resistance, aging resistance and low thermal conductivity. Inorganic precast hollow aggregate concrete and modified shale ceramsite concrete have excellent impermeability and frost resistance. Organic foamed aggregate concrete has the lowest thermal conductivity and good thermal insulation effect and its durability can be improved by surface protection technology. According to the principle of equivalent surface heat release coefficient, it is feasible to use lightweight aggregate precast formwork as permanent insulation formwork of mass concrete with thickness between 50 and 100 cm. The permanent thermal insulation formwork of nano-modified lightweight aggregate concrete can also be used as the formwork for concrete construction to realize the temperature control measures of tracking thermal insulation and slow cooling of mass concrete, reduce the risk of cracking, and improve the construction efficiency.

1. Introduction

In order to optimize the energy structure and rationally develop hydropower and water resources, China will plan and develop a number of water conservancy and hydropower projects in cold regions such as Xinjiang and Tibet. These areas are characterized by extreme temperature difference, large temperature difference between day and night, low annual average temperature, and dry and windy climate. Dam concrete is prone to produce harmful temperature cracks due to temperature drop shrinkage and dry shrinkage deformation, which seriously threatens the operation safety of the dam\(^{[1,2]}\).
The technology of temperature control and crack prevention for mass concrete is still in the stage of exploration and research under severe climatic conditions such as high cold and large temperature difference [3]. Thermal insulation of dam surface during construction and operation is one of the main measures to reduce the temperature difference between inside and outside, reduce the temperature stress and prevent the concrete cracking of dam body [4,5]. At present, polyurethane, polystyrene board, and other organic thermal insulation materials are mainly used for the concrete dam surface thermal insulation [6-8]. From the perspective of application effect, these organic thermal insulation materials have many problems, such as flammability, low safety, short service life, poor ice pull-out resistance and water durability, easy to fall off and so on [9]. These problems have appeared in the application of concrete for dams in many cold areas in China, especially in the upstream water level change area of the dam body. As a result, it is difficult to achieve the original design of permanent insulation. Inorganic thermal insulation materials such as foamed concrete and lightweight aggregate concrete have the characteristics of light weight, heat insulation, and fire resistance. They have been widely used in construction. However, they have not been applied in the thermal insulation of concrete in dam body due to their low strength, unclosed voids, high water absorption, poor impermeability, and frost resistance [10-12].

The existing research data [13,14] indicate that the Baishan Hydropower Station in Jilin Province, which was built in the late 1980s in China, has a concrete gravity arch dam with a height of 149.5m and a non-dismantling wooden formwork for dam construction; the overflow weir of Qinglong Hydropower Station has adopted reinforced concrete precast non-dismantling formwork. The precast concrete non-demolition formwork technology has the characteristics of fast construction, safety, and beautiful appearance of the concrete and has significant advantages in concrete insulation, moisture retention, and crack resistance. The permanent thermal insulation formwork of mass concrete should have the characteristics of low thermal conductivity, high strength, excellent impermeability and frost resistance durability, and convenient construction.

In view of the shortcomings of traditional thermal insulation materials, the surface of ceramsite was modified by hydrophobic method in this paper. The mechanical properties, durability, and thermal properties of different types of lightweight aggregate concrete, such as modified shale ceramsite, inorganic precast hollow aggregate, and organic foamed aggregate, were studied. The feasibility of preparing permanent thermal insulation formwork of mass concrete with lightweight aggregate was analyzed. It is expected to solve the problems of cracking, aging and falling off of surface thermal insulation materials during the construction and operation of mass concrete in alpine region.

2. Experimental Section

2.1 Raw Materials
The raw materials used in the experiment are P·O42.5 ordinary Portland cement, class F grade II fly ash, polycarboxylic acid high-performance water reducing agent, and polyether sulfonate air entraining agent.

Modified Shale ceramsite: the shale ceramsite was immersed in permeable hydrophobic agent for 24 h and then taken out and dried to form a hydrophobic membrane on the surface of the modified shale ceramsite. The water absorption was reduced to 1.21%.

Inorganic precast hollow aggregate: the inorganic hollow aggregate is formed by calcining alumina, mullite, kaolin, and nano-silica powder at high temperature, with a water absorption rate of 0.79%, as shown in Figure 1.

Organic foamed aggregate: it is made of special organic materials and internal foaming process. The section structure of organic foamed aggregate is shown in Figure 2. The water absorption rate is 1.95%.
2.2 Methods
The compressive strength, tensile strength, impermeability and frost resistance tests of lightweight aggregate concrete were carried out according to SL 352-2006 "Test Code for Hydraulic Concrete". The size of the compressive strength and tensile strength specimens is 100mm × 100mm × 100mm.

The thermal conductivity test of lightweight aggregate concrete was conducted using the protective hot plate method in the steady-state method, which was in accordance with GB/T 10294-2008 "Thermal insulation–Determination of steady-state thermal resistance and related properties–Guarded hot plate apparatus". The test period was 28 days.

3. Results and Analysis

3.1 Mechanical properties
The compressive strength and tensile strength of different types of lightweight aggregate concrete are shown in Table 1. At the age of 28 days, the compressive strength of different types of lightweight aggregate concrete is between 10.6 and 21.9MPa, and the tensile strength is between 1.10 and 1.91MPa. The compressive strength and tensile strength of inorganic precast hollow aggregate concrete are the highest, followed by modified shale ceramsite concrete. Those of organic foamed aggregate concrete are the lowest. This may be due to the relatively smooth surface of the organic foamed aggregate and the low bonding strength of the interfacial transition zone between the aggregate and the cement stone, which leads to the decrease of the strength of the organic foamed aggregate concrete.

| Aggregate type        | Test Number | Water-Binder Ratio | Volume Ratio of Lightweight Aggregate (%) | Compressive Strength (MPa) | Tensile Strength (MPa) |
|-----------------------|-------------|--------------------|------------------------------------------|---------------------------|-----------------------|
| Inorganic Precast     | WYZ         | 0.40               | 70                                       | 10.7                      | 21.9                  |
| Hollow Aggregate      |             |                    |                                           | 1.32                      | 1.91                  |
| Modified Shale        | GXYY        |                    | 11.4                                     | 17.9                      | 0.97                  |
| Ceramsite             |             |                    |                                           | 1.75                      |                       |
| Organic Foamed        | YJFP        |                    | 7.7                                      | 10.6                      | 0.58                  |
| Aggregate             |             |                    |                                           | 1.10                      |                       |

3.2 Impermeability
Improving the impermeability of concrete is one of the important measures to improve the durability of concrete. The test results of impermeability of different types of lightweight aggregate concrete are shown in Table 2. During the test, the water pressure started from 0.1MPa and increased by 0.1MPa every 8h. The water seepage at the end face of the specimen was observed at any time. When the pressure reached 0.7MPa or there were more than two specimens with water seepage on the surface, the water pressure was recorded and the machine was shut down. The test results show that the impermeability grades of the inorganic precast hollow aggregate concrete and the modified shale ceramsite concrete are both ≥W6, and the water seepage height of the modified ceramsite concrete is the lowest, which is 2.3cm. Therefore, the impermeability of concrete can be significantly improved by surface modification of porous shale aggregate. When the water pressure was increased to 0.6MPa, water seepage was found on the surface of the organic foamed aggregate concrete specimen, so the impermeability grade of the organic foamed aggregate concrete is ≥W4.
3.3 Frost resistance

The frost resistance of concrete is one of the important factors that affect the durability, especially in the cold area. Therefore, improving the frost resistance of concrete plays an important role in improving the structural durability. The frost resistance test results of different types of lightweight aggregate concrete are shown in Table 3, Figure 3, and Figure 4. The results show that the aggregate type has a significant effect on the frost resistance of concrete. The frost resistance of modified shale ceramsite concrete is excellent, reaching F300 frost resistance grade. The frost resistance grade of inorganic precast hollow aggregate concrete is F200. The relative dynamic elastic modulus of organic foamed aggregate concrete is less than 60% after 100 freeze-thaw cycles, which reaches the frost resistance grade of F100. The relative dynamic elastic modulus of concrete decreases with the increase of freeze-thaw cycles, but the quality variation of different types of aggregate concrete is different. The quality of inorganic precast hollow aggregate concrete decreases with the increase of freeze-thaw cycles because the surface mortar falls off during the freeze-thaw process. Since the modified shale ceramsite is a porous aggregate, it can absorb water during the freeze-thaw process. The quality of concrete increases with the increase of the number of freeze-thaw cycles. After reaching the saturation state, the surface quality of concrete is slightly lost because of freeze-thaw damage. Therefore, the quality of concrete decreases with the increase in the number of freeze-thaw cycles, but the total quality and appearance of the concrete does not change much. Because the organic foamed aggregate is also a porous material and has a certain water absorption effect, the quality of concrete first increases with the increase of freeze-thaw cycles. However, due to the low bond strength between the organic aggregate and the cement stone, the concrete is easy to be damaged by freezing. As shown in Figure 5, after 100 freeze-thaw cycles, concrete spalling occurs at the aggregate interface and the quality decreases significantly.

Table 2 Impermeability of different types of lightweight aggregate concrete

| Aggregate type                 | Test Number | Test Period (d) | Maximum Water Pressure (MPa) | Seepage Height (cm) | Impermeability grade |
|-------------------------------|-------------|-----------------|------------------------------|---------------------|---------------------|
| Inorganic Precast Hollow Aggregate | WJYZ        | 28              | 0.7                          | 4.0                 | ≥W6                |
| Modified Shale Ceramsite      | GXYY        |                 | 0.7                          | 2.3                 | ≥W6                |
| Organic Foamed Aggregate      | YJFP        |                 | 0.5                          | /                   | ≥W4                |

![Figure 3](image_url) Figure 3 The relative dynamic elastic modulus of different types of lightweight aggregate concrete
Figure 4 The percentage change in the mass of different types of lightweight aggregate concrete

Table 3 Frost resistance of different types of lightweight aggregate concrete

| Aggregate type                   | Test Number | Test Period (d) | Relative Elastic Modulus (%) | Percentage Change in Mass (%) |
|----------------------------------|-------------|-----------------|------------------------------|-------------------------------|
|                                  |             | 0   25  50  75  100  150  200  250  300 | Frost Resistance Grade       |                               |
| Inorganic Precast Hollow Aggregate | WYZ         | 100  98.8  95.5  97.6  80.5  71.2  67.6  /  /  F200 |
| Modified Shale Ceramsite         | GXYY        | 100  98.0  97.6  94.0  90.9  87.2  83.5  75.2  65.2  F300 |
| Organic Foamed Aggregate         | YJFP        | 100  91.1  84.4  79.9  69.9  /  /  /  /  F100 |

3.4 Thermal Properties

The smaller the thermal conductivity of a material is, the better its thermal insulation performance is. The test results of thermal conductivity of different types of lightweight aggregate concrete are shown in Table 4. The test results show that the bulk density and thermal conductivity of the three types of lightweight aggregate concrete are within the normal range of thermal insulation materials. The type of aggregate is closely related to the thermal conductivity of concrete. The thermal conductivity of organic foamed aggregate concrete is the lowest, that of modified shale ceramsite concrete is slightly higher, and that of inorganic precast hollow aggregate concrete is the highest. This is mainly related to the pore structure of aggregate. Previous studies\[12, 15, 16\] have shown that when the porosity of the material is constant, the closer the pore structure is to the spherical shape, the smaller the equivalent radius is, and the lower the thermal conductivity of material is. As can be seen from Fig. 2, the inside of the organic foamed aggregate are all small closed circular air holes. The smaller the size of the air
holes, the greater the resistance to the air convection amplitude. As a result, the reduces the efficiency of convection heat transfer and the thermal conductivity are reduced and the thermal insulation performance of concrete is improved. Shale ceramsite is made by firing clay minerals at high temperature. The pore size and connectivity degree of the aggregate are uncertain. Although the inorganic precast hollow aggregate has a closed circular pore size, the pore size is larger than that of organic foamed aggregate.

Table 4 Thermal conductivity of different types of lightweight aggregate concrete

| Aggregate type                | Test Number | Size (cm) | Bulk Density (kg/m³) | Thermal Conductivity W/(m·K) |
|------------------------------|-------------|-----------|----------------------|-----------------------------|
| Inorganic Precast Hollow Aggregate | WJYZ        | 30×30×3   | 1376                 | 0.394                       |
| Modified Shale Ceramsite     | GXYY        | 30×30×3   | 1108                 | 0.307                       |
| Organic Foamed Aggregate     | YJFP        |           | 752                  | 0.269                       |

3.5 Permanent thermal insulation formwork of lightweight aggregate concrete

As inorganic thermal insulation materials, the three types of lightweight aggregate concrete have the characteristics of high strength, aging resistance, and low thermal conductivity. Among them, the inorganic precast hollow aggregate concrete and the modified shale ceramsite concrete have excellent impermeability and frost resistance. For organic foamed aggregate concrete, the durability can be improved through surface protection.

According to the calculation method of the equivalent surface heat release coefficient\(^{[17]}\) (formula (1)), the equivalent heat release coefficient (βs) of the concrete surface through the insulation layer to the surrounding medium is inversely proportional to the thickness of the insulation material and directly proportional to the thermal conductivity of the insulation material, that is, the thicker the insulation material, the lower the thermal conductivity, and the better the insulation effect. The available data show that the thermal conductivity of polyurethane material is about 0.03W/(m·K) and the thickness of thermal insulation layer of mass concrete is between 5 and 8 cm. According to formula (1), if lightweight aggregate concrete is used as permanent thermal insulation formwork, the thickness of formwork should be between 50 and 100 cm if it achieves the same thermal insulation effect as polyurethane. Moreover, the volume weight of lightweight aggregate concrete is only 1/3 to 1/2 of ordinary concrete. Since the prefabricated formwork is easy to be lifted and assembled, it is feasible for construction.

\[
\beta_s = \frac{1}{\beta_0 \cdot e^{\frac{-h_i}{\lambda_i}}} \tag{1}
\]

Where \(\beta_0\) is the equivalent heat release coefficient of the uninsulated concrete surface, \(h_i\) is the thickness of the insulation material \(i\), and \(\lambda_i\) is the thermal conductivity of the insulation material \(i\).

Lightweight aggregate concrete precast formwork can be used not only as the formwork for mass concrete pouring construction, but also as the permanent insulation formwork of concrete. It can not only realize the permanent heat insulation of the concrete surface and improve the overall aesthetics, but also facilitate the implementation of the process control of "early thermal insulation, small temperature difference, and slow cooling" of mass concrete temperature control measures. As a result, the risk of concrete cracking can be reduced and the construction efficiency can be improved.

4. Conclusion

(1) The water absorption of shale ceramsite modified by nano-permeable hydrophobic agent is reduced to 1.21%. The water absorption rate of inorganic precast hollow aggregate produced by nano-silica powder is lower than modified shale ceramsite, which is 0.79%. The water absorption of porous lightweight aggregate can be effectively reduced by modifying or preparing aggregate with nano
materials.

(2) For the 28-day-old inorganic precast hollow aggregate concrete, the compressive strength and tensile strength of the are 21.9MPa and 1.91MPa respectively, the thermal conductivity is 0.394W/(m·K), the impermeability grade is ≥W6, and the frost resistance grade is F200. For the 28-day-old modified shale ceramsite concrete, the compressive strength and tensile strength are 17.9MPa and 1.75MPa respectively, the thermal conductivity is 0.307W/(m·K), the impermeability grade is ≥W6, and the frost resistance grade reaches F300. For the 28-day-old organic foamed aggregate concrete, the compressive strength and tensile strength are 10.6MPa and 1.10MPa respectively, the thermal conductivity is 0.269W/(m·K), the impermeability grade is ≥W4, and the frost resistance grade is F100.

(3) Compared with the traditional organic insulation materials, the inorganic precast hollow aggregate concrete, the modified shale ceramsite concrete and the organic foamed aggregate concrete have the characteristics of high strength, fire resistance, aging resistance, and low thermal conductivity. They can be made into prefabricated formwork through structural design and construction process optimization, taking into account the dual functions of permanent thermal insulation on the surface of mass concrete and the formwork for pouring construction. It is not only conducive to the implementation of tracking thermal insulation and slow cooling temperature control measures for mass concrete, solving the problems of cracking, aging, and falling off of surface thermal insulation materials of mass concrete in cold areas, but also improving the construction efficiency, which has good economic and social benefits.

(4) Inorganic precast hollow aggregate concrete and modified shale ceramsite concrete have excellent impermeability and frost resistance. Due to the low bonding strength between the organic foamed aggregate and the cement stone, the impermeability and frost resistance of concrete are limited. However, the organic foamed aggregate concrete has the lowest thermal conductivity and good thermal insulation effect. Its durability performance can be improved by surface protection.

(5) The use of lightweight aggregate precast formwork as permanent insulation and construction formwork of mass concrete can not only improve the construction quality and operation efficiency, but also innovate the dam construction technology in cold areas. The problems such as the design of light aggregate precast thermal insulation formwork, the coordination and safety of splicing and mass concrete construction need to be further examined and solved in practice.

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