

Damage Evolution and Thermal Insulation Performance of Mullite Powder-Based Foam Concrete under Hot-Rain Cycling

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Abstract: To solve the problem of cellular concrete tending to suffer damage under alternating conditions of high temperatures and precipitation, as well as undergoing a gradual deterioration of its performance in terms of thermal insulation, this study explored cellular concrete based on mullite powder. Two molding strategies were adopted – free foaming and restricted foaming – with different foaming agent dosages. Heat-rain cycle tests were performed to observe variations in indicators such as the rate of mass loss, the relative dynamic modulus of elasticity, the coefficient of thermal decay and the rate of temperature variation. The results showed that with the increase in heat-rain cycles, the rate of mass loss gradually increased, the relative dynamic modulus of elasticity continued to decrease, and the samples with higher doses of foaming agent exhibited more severe damage. After 80 cycles of heat-rain, the relative dynamic modulus of elasticity of the free foam and controlled foam samples, with a foaming agent dosage of 30%, decreased 42.0% and 27.3%, respectively, demonstrating that the controlled foam mitigates damage to the material. When the foaming agent dosage increases, the temperature attenuation coefficient first rises and then falls, and the constrained foamed specimen reaches a maximum value of 0.97 at a dosage of 20%. When the number of thermal-rain cycles increases from 20 to 80, the temperature attenuation coefficients between measuring points A and B, and between B and C, decrease by 12.9% and 31.6%, respectively, indicating that thermal-rain cycles weaken the temperature attenuation capacity of the material. These results can provide a reference for optimizing the mix proportion of mullite powder foam concrete and can also promote its application

in building wall insulation systems.

Keywords: Foam Concrete; Hot-Rain Cycling; Damage Evolution; Thermal Insulation Performance

1. Introduction

With continuous advancements in energy-saving technologies for residential buildings, the requirements for exterior wall insulation materials in terms of thermal performance and durability are also increasing. Aerated concrete is a highly regarded material in the field of building wall insulation; it is lightweight, offers excellent thermal insulation, is easy to install, and has other advantages. However, due to its porous internal structure, it is susceptible to minor damage, and over the long term, this porosity can degrade under the influence of natural factors. This gradually reduces its strength and thermal insulation performance. Therefore, to improve the long-term durability of aerated concrete, it is crucial to study its degradation mechanisms under thermal cycling and the resulting changes in its thermal resistance.

In recent years, the pore structure, mechanical properties, thermal insulation performance and durability of foam concrete have attracted extensive attention. Shankar et al.[1] reviewed the physical and mechanical properties of foam concrete and its preparation technology, and determined that the mixture ratio, foaming agent characteristics and molding process were the main factors affecting the density and strength. Li et al.[2] studied how glass fiber, polyvinyl alcohol fiber and polypropylene fiber affect the pore structure and thermal conductivity of foam concrete, paying special attention to the changes of pore characteristics related to fiber incorporation. Through the combination of experimental research and numerical simulation, Jia et al.[3] compared the thermal insulation

performance of foamed concrete produced by mechanical foaming method and chemical foaming method, and discussed the difference in heat transfer behavior between the two methods. Mydin et al.[4] studied the mechanical properties, durability and microstructure changes of foam concrete under different high temperatures to evaluate the effect of heat exposure on material properties. Wei et al.[5] studied the strength, shrinkage and thermal conductivity of lightweight aggregate foam concrete, providing a basis for considering the trade-off between mechanical properties and thermal insulation. Mohamed et al.[6] focused on ultra lightweight foam concrete, and discussed the relationship between its mechanical and thermal insulation properties and density and pore structure. The research on fiber reinforcement and void structure[7] further investigated the influence of fiber type and pore characteristics on compressive strength and thermal conductivity, while the research on freeze-thaw cycle[8] quantified the changes of pore structure and material properties before and after exposure, and linked these changes with the durability of foam concrete. Compaore et al.[9] reviewed the role of mineral admixtures in improving the microstructure, physical and mechanical properties and durability of foam concrete, and discussed the relationship between thermal conductivity and porosity, water content and cementitious material composition. Abdulazeez et al.[10] also studied the pore structure, strength, thermal conductivity and drying shrinkage of foam concrete, focusing on adjusting the material composition to meet different performance requirements. In conclusion, these studies provide a basis for understanding how material composition, pore characteristics and preparation conditions affect the mechanical, thermal and durability of foam concrete.

Existing research on foamed concrete primarily focuses on pore structure, mechanical properties, thermal insulation performance, and issues related to environmental durability. However, the progression of damage in mullite powder foamed concrete under alternating high-temperature and rainfall conditions, as well as the degradation of its thermal insulation performance, have not yet been fully investigated. Furthermore, the effects of different foaming methods and foaming agent dosages on the material's resistance to thermal-rain cycles have not yet been fully elucidated. To further investigate these issues, this study

employed two forming methods—free foaming and constrained foaming—to examine the trends in mass loss rate, relative dynamic modulus of elasticity, and temperature decay coefficient of mullite powder foam concrete during thermal-rain cycles under different foaming agent dosage conditions. At the same time, temperature changes under different numbers of cycles were analyzed to determine the material's damage progression and identify the causes of thermal insulation performance decline. Based on this, the effects of foaming methods and foaming agent dosage on the material's durability and thermal insulation performance were systematically evaluated. These results can provide theoretical guidance and experimental support for the application of mullite powder foam concrete in building thermal insulation projects.

2. Experimental Materials and Methods

2.1 Materials

Raw materials adopted in this research consist of cement, fine aggregate, fibers, mineral admixtures and chemical admixtures. Ordinary Portland cement (P·O 42.5) manufactured in Bagongshan, Huainan, China, served as the cementitious binder. Medium sand from the Huai River with a fineness modulus of 2.3 was adopted as fine aggregate, and alkali-free glass fibers of 10 μm length were added. High-purity sintered mullite powder and Class II fly ash acted as mineral admixtures. Hydrogen peroxide (H_2O_2) functioned as the foaming agent; an alcohol ether-modified polyhydroxy polymer (FM-550G) and manganese dioxide (MnO_2) were introduced as foam stabilizer and catalyst, respectively, to construct the foaming system. A polycarboxylate ether superplasticizer (PCE) was utilized as water reducer, and municipal tap water from Huainan was applied for specimen fabrication.

2.2 Experimental Design

Based on preliminary experiments, the optimal dosages of fly ash, mullite powder, and glass fibers were determined to be 8%, 15%, and 10%, respectively. On this basis, four foaming agent dosages of 0%, 10%, 20%, and 30% were selected, and mullite powder-based foam concrete specimens were prepared using two molding methods: free foaming and confined foaming. A total of 80 hot-rain cycles were conducted, with each cycle lasting 8 h.

Performance tests were performed after every 20 cycles. The mullite powder-based foam concrete wall panels used in the experiments had dimensions of 300 mm × 300 mm × 30 mm.

2.2.1 Hot-rain cycling damage tests

Mullite powder-based foam concrete specimens with dimensions of 100 mm × 100 mm × 100 mm were used in this study. The degree of damage induced by hot-rain cycling was evaluated by determining the mass loss rate and relative dynamic elastic modulus of the specimens.

(1) mass loss rate

After curing, measure the initial mass of each specimen to determine the reference value. During the subsequent hot rain cycle, the sample is weighed every 20 cycles, and the mass loss rate is determined according to the difference between the initial mass and the mass measured at each interval. The resulting mass change is used to evaluate the cumulative damage of the specimens exposed to repeated hot rain.

(2) relative dynamic elastic modulus

Ultrasonic velocities of specimens are measured using a non-metallic ultrasonic testing machine. Before the measurement, the surface of the test piece is cleaned, and the two surfaces, which are flat, non damaged, and parallel to each other, are selected as measurement surfaces to mark the position of the measurement point. An ultrasonic transmitter and a receiver are arranged on both sides of the test piece to measure the ultrasonic velocity. Three measurement points are set on each test piece, and the measurement is repeated three times at each point. Three parallel specimens are prepared for each test group, and finally the average value of the measured value is the representative ultrasonic velocity of the group. The measurement of the relative dynamic elastic modulus is performed based on the change of the ultrasonic velocity. Figure 1 shows the arrangement of measurement points.

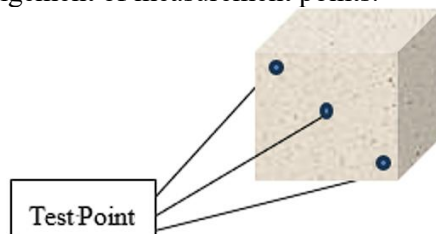


Figure 1. Ultrasonic Test Point Distribution

2.2.2 Thermal insulation performance tests

The transient test method was used to study the temperature response characteristics of mullite powder foam concrete wallboard. The experimental device includes three temperature

probes, a thermal stability analyzer and a foam insulation box containing the sample. The two temperature probes are in close contact with the upper and lower surfaces of the sample respectively, while the third probe is installed in the foam insulation box to monitor the internal ambient temperature. The test is carried out at a constant temperature of 45 ° C, and the temperature reading is taken at the designated measuring point every 10 minutes. Then the recorded data are used to determine the temperature attenuation coefficient and temperature change rate of the wall panel. Through the analysis of these two parameters, the thermal response of the specimen was evaluated, and its thermal insulation performance under the specified test conditions was characterized.

3. Results and Discussion

3.1 Damage Induced by Hot-Rain Cycling

The relative dynamic elastic modulus and mass loss rate of mullite powder-based foam concrete with different foaming agent dosages under varying numbers of hot-rain cycles are presented in Figure 2 (a) and (b).

As shown in Figure. 2, as the number of heat-rain cycles increased, the mass loss rates of both free-foaming and confined-foaming specimens gradually increased, while their relative dynamic elastic moduli exhibited an overall downward trend. Furthermore, as the amount of foaming agent increased, the extent of damage became increasingly pronounced. After 80 thermal-rain cycles, the mass loss rates of the free-foamed specimens with foaming agent contents of 0%, 10%, 20%, and 30% were 17.02%, 18.26%, 19.12%, and 21.64%, respectively, while their relative dynamic elastic moduli decreased by 18.7%, 21.2%, 27.4%, and 42.0%, respectively. For specimens prepared using the restricted foaming method, the mass loss rates were 16.98%, 18.06%, 18.65%, and 21.35%, respectively, while the relative dynamic elastic moduli decreased by 19.3%, 19.8%, 21.6%, and 27.3%, respectively. Compared with free foaming, restricted foaming generally results in a slightly lower mass loss rate, and at higher foaming agent dosages, the specimens are able to maintain a higher relative dynamic modulus of elasticity. These results show that limiting foaming is helpful to reduce the internal damage caused by repeated hot rain cycles. The degradation observed during cycling is closely

related to the repeated deformation of the material under alternating temperature and humidity conditions. During high temperature exposure, the specimen undergoes a drying process and is then rapidly cooled by water spray. The resulting hygrothermal deformation causes stress concentration at the interface between the pore wall and the cement matrix, which may trigger microcracks and promote their subsequent propagation and interconnection. As the cycle continues, the internal structure gradually loses its integrity, and the delamination and spalling of surface particles become more and more obvious. The increase in the amount of foaming agent further aggravates this process: it not only increases the porosity of the sample, but also reduces the thickness of the pore wall and

the continuity of the solid matrix, thus weakening the ability of the material to withstand repeated temperature and humidity fluctuations.

However, controlled foaming can inhibit the excessive expansion and coalescence of bubbles during the molding process, which is helpful to form a more uniform and stable pore structure. With the improvement of pore distribution and structural stability, the pore wall and solid matrix can better resist the accumulation of damage, thus limiting the propagation of microcracks to a certain extent. Therefore, compared with free foaming, constrained foaming has advantages in reducing the internal damage of mullite powder based foam concrete during the hot rain cycle and enhancing its resistance to repeated exposure to moisture and heat.

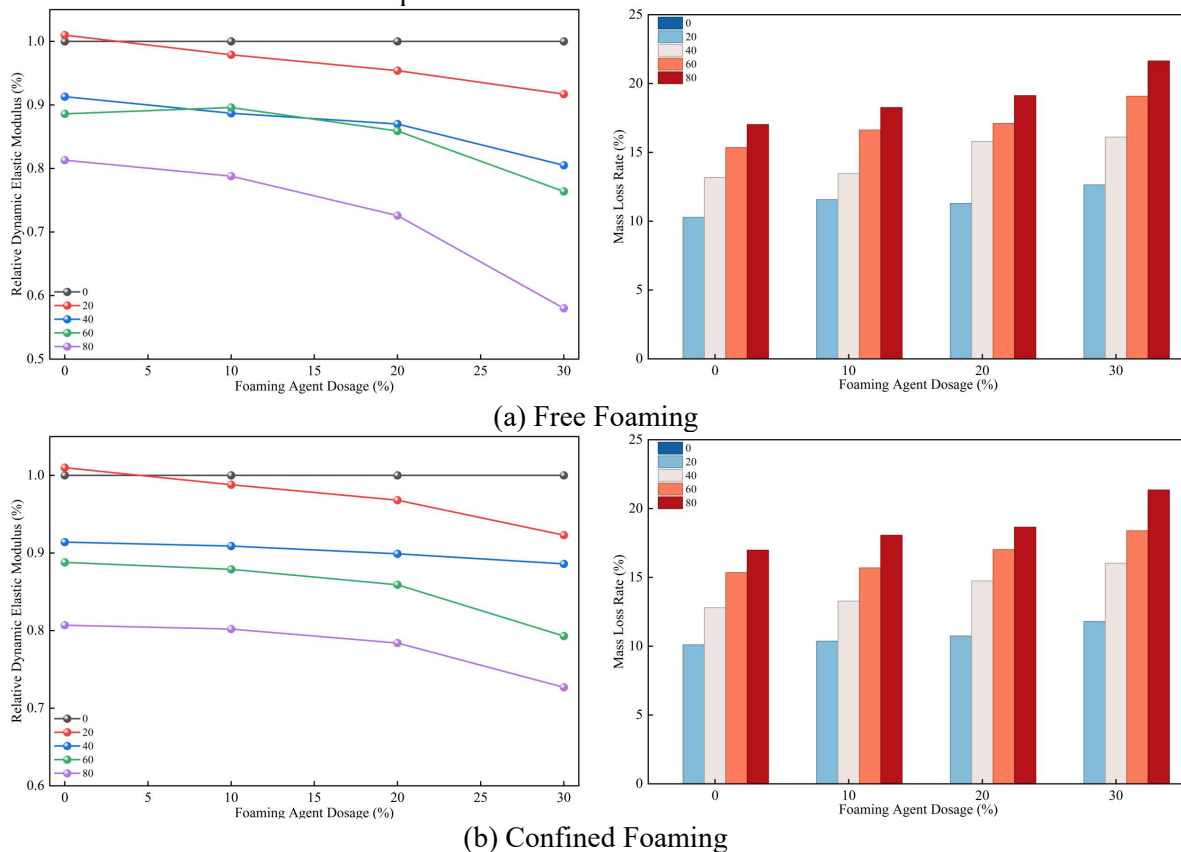


Figure 2. Relative Dynamic Elastic Modulus and Mass Loss Rate of Concrete under Different Number of Thermal Rain Cycles

3.2 Temperature Attenuation Capacity

The temperature attenuation coefficient was used to characterize the ability of mullite powder foam concrete to suppress temperature fluctuations in the process of heat conduction. It reflects the extent to which the temperature fluctuation amplitude decreases when heat passes through the material. The coefficient can be calculated by comparing the temperature fluctuation amplitude

of two adjacent points, so as to provide a quantitative basis for evaluating the temperature attenuation performance of materials. It reflects the ability of the material to attenuate temperature fluctuations and serves as the basis for evaluating its thermal insulation performance. The temperature attenuation coefficient was calculated using Eq. (1).

$$f_{AB} = \frac{(T_B^{max} - T_B^{min}) - (T_A^{max} - T_A^{min})}{T_B^{max} - T_B^{min}} \quad (1)$$

Where f_{AB} is the temperature attenuation coefficient between measurement points A and B; $T_A^{\max}$ and $T_A^{\min}$ are the maximum and minimum temperatures at measurement point A ($^{\circ}\text{C}$), respectively; $T_B^{\max}$ and $T_B^{\min}$ are the maximum and minimum temperatures at measurement point B ($^{\circ}\text{C}$), respectively.

Figure 3 shows the effect of different foaming agent dosages and foaming conditions on the temperature decay coefficient of mullite powder-based foam concrete.

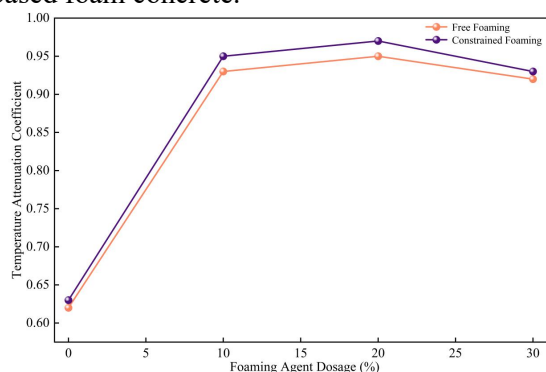


Figure 3. Temperature Decay Coefficient of Different Blowing Agent Dosage

Figure 3 shows that the temperature drop coefficients of foam concrete on a multi-powder basis first increase with free and controlled foaming and then increase again with increasing foaming dosage lose weight. Samples with controlled foaming always have higher temperature drop coefficients than those with free foaming. When the foaming agent content increases from 0% to 20%, the coefficients of the free and under pressure foamed samples increase from 0.62 and 0.62 respectively. 0.63 to 0.95, respectively. 0.97 and fall to 0.92 and/or 0.92 at a foaming agent content of 30%. The group with 20% foam content has the best resistance to temperature cooling. An appropriate dosage of the foaming agent contributes to the formation of evenly distributed closed pores within the cement paste, which increases the thermal resistance and reduces the effective thermal conductivity. An excess of foaming leads to the fusion of bubbles and the formation of interconnected pores, which are formed by larger pores, feature thinner walls and uneven pore distribution, which impairs thermal insulation performance. The controlled foaming limits excessive bladder expansion and optimizes the uniformity and stability of the pore structure, resulting in a better temperature drop coefficient.

Figure 4 shows the changes in the temperature decay coefficient of mullite powder-based foam

concrete with a foaming agent content of 20% after undergoing different numbers of heat-rain cycles.

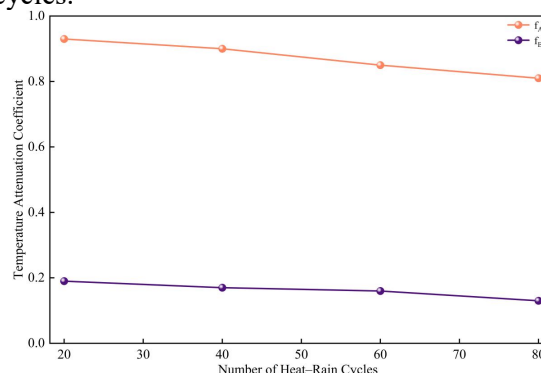


Figure 4. Temperature Attenuation Coefficients for Different Numbers of Thermal Rain Cycles

Figure 4 shows that under closed-cell foaming conditions and at a 20% foaming agent dose, the temperature reduction coefficient of mullite powder-based foamed concrete decreases steadily with an increase of 20 to 80 hot-rain cycles. The temperature attenuation coefficient between a and B decreased from 0.93 to 0.81, and the temperature attenuation coefficient between B and C decreased from 0.19 to 0.13, which decreased by 12.9% and 31.6%, respectively. The observed changes show that repeated hot rain cycles gradually weaken the temperature attenuation ability of mullite powder based foam concrete. This decline may be related to the alternating hot and humid deformation caused by the repeated cycles of high temperature drying and water spray cooling. The continuous change of temperature and humidity conditions leads to local stress concentration in the hole wall and at the interface of cement-based matrix. When these stresses accumulate, microcracks may form and expand, eventually connect with each other, and gradually destroy the integrity of the original pore structure. This structural degradation weakens the ability of the material to buffer temperature fluctuations during heat transfer. At the same time, the growth of microcracks and the increase of pore connectivity may change the internal heat transfer path, thus reducing the heat transfer resistance provided by the originally closed pores. In addition, the change of moisture content in pores caused by repeated moisture absorption and desorption may affect the effective thermal conductivity of the material, thus further accelerating the degradation of its temperature attenuation ability. Therefore, the deterioration of pore structure and the

accumulation of microcrack damage caused by thermal rain cycle are considered to be the potential mechanisms leading to the decline of temperature attenuation performance. However, even after 80 hot rain cycles, the sample still maintains a certain temperature attenuation ability.

3.3 Rate of Temperature Change

Figure 5 (a) through (d) show the rate of temperature change for foam concrete made from closed-cell mullite powder after 20, 40, 60, and 80 thermal-rain cycles, respectively.

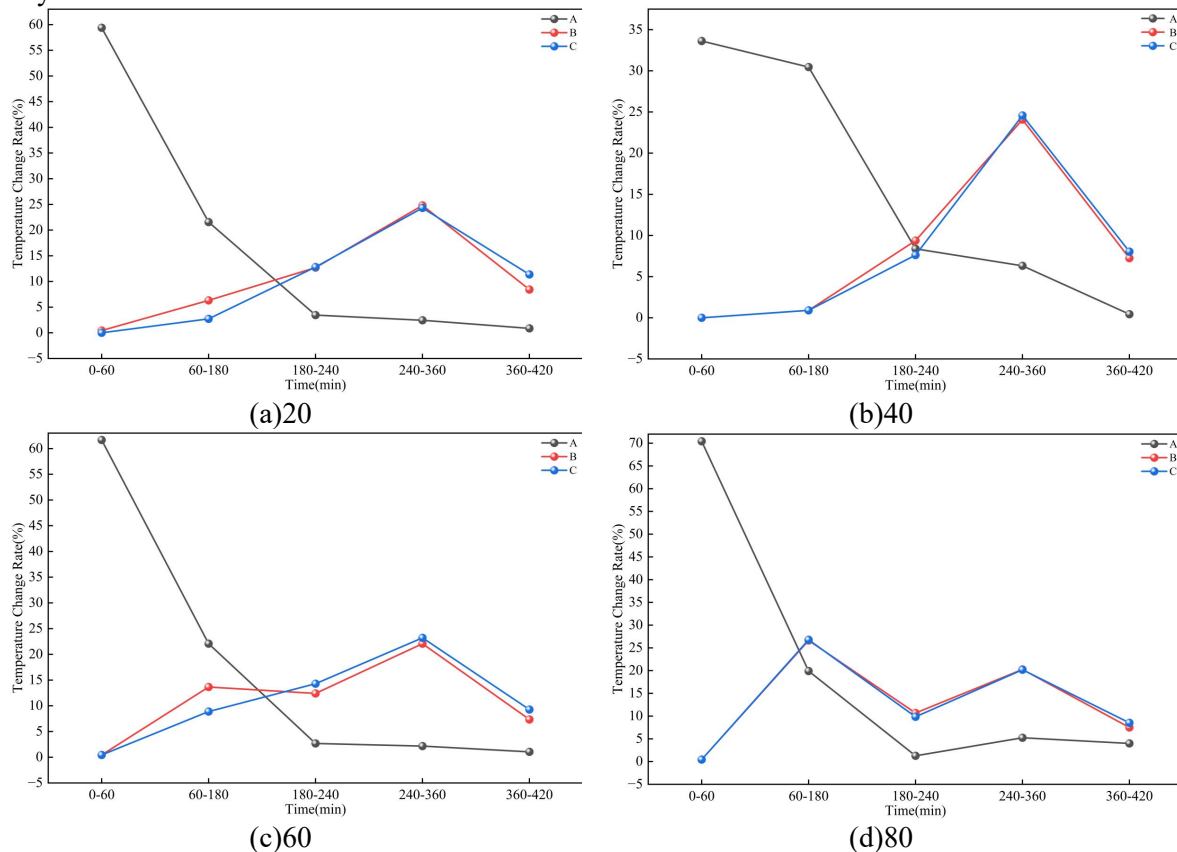


Figure 5. Rate of Temperature Change under Different Number of Thermal Rain Cycles

As shown in Figure 5, under confined foaming conditions with a foaming agent dosage of 20%, the rates of temperature change at different measurement points of mullite powder-based foam concrete exhibited different trends with increasing numbers of hot-rain cycles. After 20 hot-rain cycles, the rates of temperature change at measurement point A were 33.63% and 30.46% during the 0–60 min and 60–180 min intervals, respectively, whereas those at measurement points B and C remained close to zero. This indicates that the material effectively impeded heat transfer toward its interior during the initial heating stage, demonstrating favorable thermal insulation performance. As the heating duration increased, the rates of temperature change at points B and C gradually increased, reaching 24.08% and 24.58%, respectively, during the 240–360 min interval, indicating a delayed thermal response. As the number of hot-rain cycles increased to 40 and 60, the rate of

temperature change at point A during the 0–60 min interval increased to 59.38% and 61.67%, respectively. Meanwhile, the rates of temperature change at points B and C during the 60–180 min interval also gradually increased, suggesting a reduction in the ability of the material to attenuate temperature fluctuations. After 80 hot-rain cycles, the rate of temperature change at point A during the 0–60 min interval further increased to 70.43%, while those at points B and C during the 60–180 min interval reached 26.64% and 26.79%, respectively, markedly higher than those observed at earlier cycling stages. These results suggest that the internal temperature response to heat transfer became progressively faster, indicating further deterioration in thermal insulation performance. From a mechanistic perspective, the repeated cycles of high-temperature drying and water-spray cooling during the thermal rain cycle induce alternating wet-heat deformation within

the material, thereby promoting the gradual formation and propagation of microcracks at the interfaces between the pore walls and the cement matrix. As damage progresses, some closed pores may gradually become interconnected, leading to changes in the original pore structure and heat conduction pathways. Furthermore, repeated moisture absorption and desorption cause fluctuations in pore moisture content, which may alter the material's effective thermal conductivity and increase the sensitivity of internal measurement points to external temperature changes. Under the continuous action of heat-rain cycles, the cumulative degradation of the pore structure and the accompanying changes in heat transfer behavior may shorten the thermal response lag time of mullite powder-based foamed concrete, leading to a gradual decline in its temperature decay capability. Despite this degradation, the material still retains a certain level of thermal insulation performance after undergoing 80 heat-rain cycles, indicating that, under the test conditions, its ability to impede heat conduction has not been completely lost.

4. Conclusions

(1) With increased heat-rain cycles and foaming agent doses, the mass loss rate of mullite-based foamed concrete increases progressively, while the relative dynamic elastic modulus shows an overall downward trend. After 80 cycles of rain, free foam and bound foam specimens containing 30% foaming agent show reduction. The relative dynamic elastic modulus is 42.0% and 27.3% respectively. These findings reveal that bonded foam effectively reduces damage accumulation inside. (2) With increasing foaming agent dosage, the temperature attenuation coefficient initially increased and then decreased. At a foaming agent dosage of 20%, the temperature attenuation coefficients of the free-foamed and confined-foamed specimens reached 0.95 and 0.97, respectively, demonstrating that confined foaming provided superior temperature attenuation performance. (3) Hot-rain cycling progressively deteriorated the thermal insulation performance of mullite powder-based foam concrete. Under confined foaming conditions with a foaming agent dosage of 20%, the temperature attenuation coefficients between measurement points A and B and between points B and C decreased by 12.9% and 31.6%, respectively, as the number of hot-rain cycles increased from 20 to 80. This deterioration

was primarily associated with pore structure degradation and microcrack propagation induced by repeated hygrothermal deformation. Overall, a foaming agent dosage of 20% combined with confined foaming exhibited favorable temperature attenuation performance and a certain degree of resistance to hot-rain cycling.

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