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A Brief Discussion on High Temperature Resistance and Engineering Application of Basalt Fiber Foam Concrete

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Abstract: With the advantages of high strength and high temperature resistance of basalt fiber foam concrete and the light porous structure of foam concrete, basalt fiber foam concrete has outstanding performance in high temperature resistance. Based on this, this paper analyzes the high temperature resistance of basalt fiber foam concrete, and discusses its application in engineering, involving construction, energy and transportation, special environmental applications, etc., aiming to provide reference and reference for related research and application.

Keywords: Basalt fiber; foam concrete; high temperature resistance; engineering application

Introduction

With the increasing demand for high temperature resistance of materials in the fields of construction, energy and transportation, the defects of traditional concrete that are prone to cracking and sudden drop in strength at high temperature have become increasingly prominent. Basalt fiber, as an inorganic fiber made of basalt ore by melting and drawing at high temperature, can be introduced into foam concrete to form a composite material with both light weight, heat insulation and high temperature resistance. Foam concrete itself has excellent thermal insulation performance due to the internal closed pore structure, but there are problems such as low strength and easy cracking; the addition of basalt fiber significantly enhances the high temperature resistance of the material through physical crack resistance and chemical stability.

1. High temperature resistance of basalt fiber foam concrete

1.1 Failure mechanism under high temperature

In a high temperature environment, traditional foam concrete is prone to multi-stage failure due to its own structural characteristics. The water adsorbed in its internal pores evaporates rapidly at the beginning of heating, resulting in a sudden increase in pore pressure and local stress concentration on the pore wall. As the temperature continues to rise, the pore structure gradually loses stability, and the originally evenly distributed closed pores are connected to each other under the action of heat, forming through cracks, which weakens the integrity of the material. At the same time, the gelling components in the matrix material undergo dehydration, shrinkage and chemical decomposition at high temperatures, resulting in a decrease in the bonding force between the aggregate and the gel, further exacerbating structural deterioration. When the temperature exceeds the critical value, thermal stress continues to accumulate inside the material, eventually triggering macro-cracking, and even spalling and disintegration [1]. The introduction of basalt fibers can significantly improve the high temperature damage resistance of foam concrete, and its strengthening mechanism is mainly reflected in three aspects: First, the fibers are distributed in a three-dimensional random direction in the matrix. When the crack tip expands to the vicinity of the fiber, the fiber spans both sides of the crack through bridging action, transferring local stress to the surrounding matrix, forcing the crack to change direction or branch, thereby delaying the crack propagation speed. This kind of bonding effect is particularly critical at high temperatures, because the elastic modulus of the fiber decreases less than that of the matrix material with the increase of temperature, and it can still maintain a certain bearing capacity. Secondly, the surface of the fiber is rough and contains active functional groups, and it forms a strong interfacial bond with the cement matrix through physical occlusion and chemical bonding. This bonding effect can partially offset the interfacial stress caused by the shrinkage of the matrix at high temperature, reducing the phenomenon of interfacial debonding. Even if there are micro-cracks in the local interface, the fiber can still consume energy through the pull-out effect and maintain the relative structural integrity. In addition, the melting point of basalt fibers is as high as 1450 to 1500 degrees Celsius, which is much higher than the failure temperature of ordinary foam concrete. It can still maintain a solid state under conventional high temperature environments (600 to 800 degrees Celsius), effectively limiting the plastic deformation and flow of the matrix material. The skeleton action of the fiber can prevent the pore structure from collapsing due to the softening of the matrix, maintaining a certain macroscopic dimensional stability of the material.

1.2 High temperature performance testing and result analysis

In order to systematically evaluate the improvement effect of basalt fibers on the high temperature performance of foam concrete, the experimental design adopts the layer heating method, and the specimens are placed at 200 °C, 400 °C, 600 °C, and 800 °C environments for constant temperature treatment to simulate the thermal action under different fire scenarios [2]. During the test process, the three core indicators of mass loss rate, strength residual rate and energy absorption capacity are focused on. (1) The mass loss rate reflects the physical and chemical stability of the material at high temperature, mainly due to free water evaporation, combined water removal and volatilization of matrix decomposition products. The addition of basalt fibers can inhibit the escape of volatile substances by reducing pore connectivity, and its chemical inertness can reduce the mass loss caused by high temperature oxidation. (2) The strength residual rate is a key parameter to measure the bearing capacity of a material after high temperature, including compressive strength and tensile strength. Among them, the compressive strength is closely related to the integrity of the pore structure, while the tensile strength depends more on the interfacial bonding between the fiber and the matrix. Basalt fibers can significantly delay the strength attenuation caused by high temperature through bridging cracks and restraining the deformation of the matrix. (3) The energy absorption capacity is determined by impact load test, which reflects the material's ability to consume energy through crack expansion, fiber pulling out and matrix breaking under dynamic load. The toughening effect of fibers makes the foam concrete change from brittle failure to ductile failure, and improves the energy absorption efficiency. The comparative test results show that the performance attenuation of basalt fiber foam concrete at high temperature is significantly lower than that of ordinary foam concrete. In terms of mass loss, the blocking effect of fibers reduces the evaporation rate of water, and the oxide layer formed on the surface of fibers at high temperature can further reduce the volatilization of matrix decomposition products, and the overall mass loss rate decreases. In the strength test, the compressive strength of ordinary foam concrete decreases sharply after 400 °C, and the tensile strength is almost lost at 600 °C, while the basalt fiber foam concrete can still maintain a high strength residual rate at 600 °C. Although the strength is further reduced at 800 °C, there is no macroscopic disintegration phenomenon.

1.3 Meso-structure and high temperature damage mechanism

CT scanning and three-dimensional reconstruction techniques can be used to systematically analyze the evolution law of basalt fibers on the meso-structure of foam concrete after high temperature. (1) At the level of pore structure, the incorporation of basalt fibers significantly changes the pore size distribution characteristics of the matrix. The network structure formed by the random distribution of fibers in the slurry can effectively inhibit the connection of macropores and promote the transformation of radial small and medium pore sizes of some macropores. At the same time, the bridging effect of fibers increases the thickness of the pore wall and forms a denser pore network. This structural optimization makes the concrete matrix present a more uniform pore shape before high temperature, reducing the risk of stress concentration. (2) After high temperature action, complex damage evolution occurs inside the material. CT scans show that with the increase of temperature, the porosity of undoped foam concrete increases significantly, the number of macropores increases, and the pore walls become thinner, which is due to the collapse of the pore structure caused by the dehydration and decomposition of cement hydration products. The introduction of basalt fibers can delay this process, and the fibers limit the shrinkage and deformation of the pore walls through physical constraints, maintaining the relative stability of the pore structure. In terms of interfacial behavior, high temperature leads to the debonding of the fiber-matrix interface, which is due to the difference in thermal expansion coefficients between the two. Interfacial stress concentration is caused, but the roughness of the fiber surface and chemical bonding can still maintain part of the interfacial bonding strength. (3) The law of micro-crack propagation shows that undoped concrete cracks rapidly expand along the periphery of macropores at high temperature, forming a penetrating crack network, while basalt fibers cross both sides of cracks by bridging, decomposing macroscopic cracks into multiple micro-cracks, consuming more fracture energy [3]. This crack dispersion mechanism significantly delays the crack propagation rate, and even if the local interface is debonded, the fibers can still maintain the structural integrity through the pull-out effect. 3D reconstruction analysis further confirms that the incorporation of fibers makes the crack path more tortuous and the crack width more evenly distributed, avoiding catastrophic damage caused by local stress concentration.

2. Engineering application of basalt fiber foam concrete

2.1 Construction sector

In the field of construction, basalt fiber foam concrete has shown a wide range of application potential due to its excellent fire and heat insulation properties and mechanical properties. (1) As a fire insulation material, its lightweight porous structure can effectively block heat transfer. In the building exterior wall insulation system, it can replace traditional organic insulation materials to build a fire insulation belt, especially suitable for high-rise building facades. By blocking the vertical spread path of flame and high temperature during fire, the overall fire resistance grade of the building can be significantly improved. (2) In tunnel engineering, the material can be used as a fire protection layer for lining structures. Its high temperature resistance can withstand high temperature radiation and thermal shock during fire. At the same time, the impact resistance can resist dynamic loads such as falling rocks or vehicle collisions, and protect the safety of the main structure of the tunnel. In addition, the uniformly distributed basalt fibers inside the material can form a three-dimensional reinforcement network, which effectively restrains the shrinkage and deformation of the matrix, reduces the risk of cracking caused by thermal stress at high temperatures, and ensures the long-term stability of the fireproof layer. (3) In the field of structural reinforcement and repair, basalt fiber foam concrete provides an efficient repair solution for damaged concrete structures after fire. Fire causes concrete strength attenuation and crack expansion. It is difficult for traditional repair materials to balance light weight and high strength requirements. However, through the bridging action of fibers and the synergistic deformation of the matrix, the material can realize the reinforcement and reinforcement of load-bearing components such as beams and columns, which not only restores the bearing capacity of the structure, but also avoids secondary damage caused by the increase of its own weight. Its lightweight characteristics can also reduce the structural load, which is suitable for the repair of large-span space structures. (4) As a lightweight and high-strength composite component, this material is outstanding in prefabricated buildings. When used in the production of prefabricated wall panels, floor panels and other components, the toughening effect of fibers can improve the cracking resistance and durability of components, while the low thermal conductivity of foam matrix can meet the requirements of building energy conservation. In addition, the pumpability and construction adaptability of the material make it suitable for on-site pouring of special-shaped components and shorten the construction period.

2.2 Energy and transportation

In the field of energy and transportation, basalt fibers show significant advantages due to their high temperature resistance, corrosion resistance, and high strength. On the one hand, in the petrochemical industry, pipeline systems need to withstand the dual effects of high-temperature fluids and corrosive media for a long time, and traditional thermal insulation materials are prone to aging and cracking. Basalt fiber composite pipelines form a dense structure through fiber winding process, and their temperature resistance range covers -40 °C to 270 °C. Special resin formulations can be extended to higher temperature ranges, effectively blocking heat transfer and resisting acid, alkali and salt mist erosion. As a pipe wrapping material, its smooth inner wall can reduce fluid resistance, and at the same time, the interface between fibers and matrix materials has strong bonding force, avoiding peeling due to thermal expansion and contraction. The fire insulation layer of the storage tank adopts a composite structure of basalt fiber felt and high temperature resistant coating. The melting point of the fiber exceeds 1450 °C, which can form a stable heat insulation barrier in a fire, delay the temperature rise rate of the tank, and strive for critical time for emergency response. Its non-combustible characteristics and low thermal conductivity make it an ideal choice to replace traditional rock wool and glass wool[4]. On the other hand, in the field of transportation infrastructure, the application of basalt fibers focuses on improving structural durability and extreme environmental adaptability. Airport runways and expressway pavements are prone to rut deformation due to asphalt softening in high temperature seasons. Basalt fibers form skeleton supports through three-dimensional chaotic distribution, effectively dispersing vehicle loads and constraining matrix deformation. Its high modulus characteristics can reduce pavement plastic flow, and at the same time, the heat resistance of fibers ensures that structural stability is maintained in environments above 150 °C. Bridge expansion joints, as a key part of the connecting structure, need to withstand repeated expansion and contraction caused by vehicle impact and temperature changes. Basalt fiber refractory filling materials can inhibit concrete from bursting and peeling at high temperatures through cracking resistance and toughening of fibers. Its low thermal expansion coefficient has a high matching degree with the main structure, avoiding early damage caused by thermal stress concentration.

2.3 Special environmental applications

(1) In the aerospace field, basalt fiber has become a key material for spacecraft thermal protection systems due to its excellent high temperature resistance and mechanical properties. Its operating temperature range covers -260 °C to 880 °C, which can not only maintain thermal insulation properties in liquid nitrogen environment, but also withstand high temperature shock around the aero engine and when the re-entry capsule re-enters the atmosphere. The molecular structure of the fiber gives it excellent thermal stability, and it can still maintain structural integrity in an environment above 700 °C, effectively blocking heat transfer to the interior of the spacecraft [5]. At the same time, its low thermal conductivity and high melting point characteristics can form a layer of thermal protection, which can significantly reduce the heat flux through the synergistic effect of radiative heat dissipation of the fiber and ablation and heat absorption of the matrix material. (2) In the field of military engineering, the wave-absorbing and magnetic permeability, high temperature resistance and impact resistance of basalt fibers make them ideal materials for explosion-proof structures and concealed fortifications. The dielectric properties of fibers can absorb and dissipate radar waves. After being combined with ceramics, metals and other materials, a layered wave-absorbing structure can be constructed, reducing the electromagnetic reflection characteristics of military facilities and improving the stealth ability. Its high temperature resistance is

outstanding in explosion-proof scenes. Fiber-reinforced concrete or composites can withstand high-temperature flames and shock waves generated by explosions. Through the bridging action of fibers and the energy dissipation mechanism of the matrix, cracks can be delayed and impact kinetic energy can be absorbed, and the anti-explosion toughness of the structure can be enhanced.

Conclusion

In summary, basalt fiber foam concrete realizes the organic unity of high temperature resistance and lightweight function through the synergistic effect of fibers and matrix. Its high temperature resistance mechanism is mainly reflected in three aspects: first, basalt fibers maintain structural integrity at high temperature, disperse stress through bridging cracks, and inhibit matrix cracking; second, the chemical inertness of fibers reduces high temperature oxidation reactions and reduces the rate of mass loss; third, the low thermal conductivity of foam matrix and the barrier effect of fibers form a double thermal insulation barrier. With the advancement of the "double carbon" goal, basalt fiber foam concrete will become an important development direction for extreme environmental engineering materials with its advantages of green environmental protection and low life cycle cost.

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