EXPERIMENTAL STUDY ON HEAT TRANSFER ENHANCEMENT OF HEAT STORAGE MATERIAL FOR ENERGY PILE

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As a kind of clean and renewable energy, shallow geothermal energy has the characteristics of wide distribution and huge reserves. The use of pile foundation heat exchange for building heating is a new technology to realize the effective utilization of geothermal energy. Improving the mechanical properties of the pile body material and improving the heat exchange efficiency of the pile foundation concrete will effectively promote the application of concrete in building structures. In this paper, the effect of steel fiber content on the thermal conductivity and mechanical strength of concrete is discussed by carrying out physical and mechanical properties test of concrete material of pile body. It is proposed to incorporate steel fibers into the concrete of the pile body to improve its thermal conductivity, thereby improving its heat transfer efficiency per unit time. At the same time, the role of steel fiber in enhancing heat transfer performance in pile material is analyzed from the microscopic mechanism, which provides theoretical support for the optimization process of concrete ratio of pile foundation in practical engineering.

Key words: *energy pile, steel fiber reinforced concrete, thermal conductivity, enhanced heat exchange, tensile strength*

Introduction

Currently, 78.3% of the world's energy comes from non-renewable fossil fuels, while all renewable energy sources only account for 19.2%, and RES such as geothermal, solar and wind energy only account for 3.9% of the total energy supply [1, 2]. In order to minimize the impact on the environment, renewable energy technologies must play a greater role in meeting the growing demand for energy, especially in developing countries, where market oil and gas development and geothermal energy development are particularly important [3]. Shallow geothermal energy is a clean, renewable resource that can be used for heating and cooling systems in buildings. Energy piles are widely respected as both building support members and building heat exchange members. At present, the research on energy piles is still focused on its heat transfer characteristics and mechanical coupling mechanism, and the analysis of suitable pile body materials is still rare.

Previous studies have shown that steel fibers can play an important role in improving the mechanical properties and heat transfer properties of concrete due to their high flexural resistance, tensile strength, and thermal conductivity [1-8]. You *et al.* [9-12] conducted in-situ

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tests to explore the heat transfer efficiency of different heat exchange pile forms. Kachouh *et al.* [13] studied the effect of different amounts of steel fibers on the mechanical properties of concrete. It was found that the ductility of recycled aggregate concrete was significantly improved after adding steel fibers. Liu *et al.* [14] analyzed the influence of steel fibers and carbon fibers on the thermal conductivity of concrete, and proposed a multiphase theoretical model for calculating the thermal conductivity of fiber-reinforced concrete. Their test results show that, due to the bridging of steel fibers in the matrix, the thermal conductivity of steel fiber reinforced concrete is higher than that of carbon fiber reinforced concrete and ordinary concrete, so it is beneficial to heat conduction. Sang *et al.* [15] investigated the effect of steel fibers on the properties of cement-based composites containing PCM. The results showed that the compressive strength and thermal conductivity of the cement-based composites increased by 40.6% and 51.3% respectively, when the steel fiber volume was increased to 3.5%.

Testing materials and methods

Preparation of concrete samples

The concrete samples refer to the *Concrete Mix Proportion Design Regulations*, which are C30, C40, C50 conventional concrete test blocks and steel fiber concrete test blocks with steel fiber content of 0.35%, 0.7%, and 1.05% with corresponding strength. The size of the test piece is 50 mm × 25 mm. After the samples were formed, they were cured in a standard curing box for 28 days under standard curing conditions.

The mix ratios of C30, C40, and C50 grades used in this test are the mix ratios used in the actual construction of the project, as shown in tab. 1. The steel fiber mixing ratios were 0.35% (A), 0.7% (B), and 1.05% (C).

Table 1. Proportion of concrete samples

Concrete strength	Water-cement ratio	Water [g]	Cement [g]	Fly ash [g]	Mineral powder [g]	River sand [g]	Water reducer [g]	Steel fiber content [%]
C30	0.40	163	300	56	55	929	8.5	0 , 0.35 0.7 , 1.05
C40	0.34	155	326	69	63	887	10.8	0 , 0.35 0.7 , 1.05
C50	0.30	150	340	80	80	850	1.4	0 , 0.35 0.7 , 1.05

When concrete is under load, the presence of steel fibers can inhibit the generation and expansion of tiny cracks, thereby improving the mechanical properties of concrete. During the loading process of the structure, the tensile force of the steel fibers maintains the stability of the structure, and can also absorb a large amount of energy, thereby improving the mechanical strength and durability of the concrete.

Thermophysical properties test

In the test of concrete thermophysical parameters, the HotDisk thermal constant analyzer TPS-2500S manufactured by Shanghai Kaigonas Instrument Trading Co., Ltd. is selected, and its thermal conductivity test range is 0.005-500 W/Mk. The test instruments and equipment are shown in fig. 1, and the schematic diagram of test principle is shown in fig. 2.

The test method adopted by the test instrument Hot Disk is the transient flat plate heat source method. The transient plate heat source method is the most accurate and convenient heat conduction method, which can provide the basis for the thermal conductivity, thermal diffusivity and specific heat of the measured object. This measurement is based on the application of an instantaneously heated flat-panel detector, a Hot Disk, which is a coil of two conductive coils. This coil uses a photolithographic metal foil between two insulating thin layers.

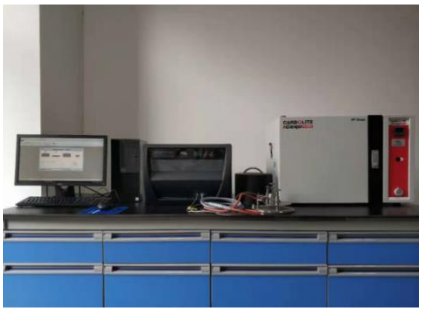

Figure 1. Test equipment and instrument accessories

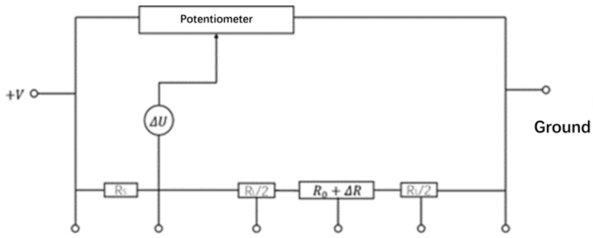

Figure 2. Schematic diagram of test principle

Mechanical property test

In order to explore the effect of steel fiber content on the tensile properties of concrete, ordinary concrete specimens and steel fiber concrete specimens with different proportions were studied by the Brazilian splitting method. The rigid pressure testing machine used is TAW2000 single-axis hydraulic servo machine, and the maximum test force of the test bench is 2000 KN. Select C30, C40, C50 conventional concrete test blocks (2-3 per group) and concrete test blocks with corresponding strength steel fiber content of 0.35%, 0.7%, 1.05% (2-3 per group). Each group of samples was subjected to variable temperature treatment, and the acting temperatures were set to 25 °C, 30 °C, 35 °C, and 40 °C, respectively. The concrete samples were placed in the oven for heat preservation, and the concrete to be tested was continuously heated at a heating rate of 5 °C per 30 minutes. After reaching the specified temperature, the specimens were placed in a furnace at a constant temperature for 30 minutes to test their thermophysical parameters. The Brazilian splitting test load adopts the uniform loading method. According to the provisions of *GB/T 50081-2002 Standard for Test Methods of Mechanical Properties of Ordinary Concrete*, in the case of C30~C50, the load speed should be 0.05~0.08 MPa/s, in the case of concrete strength level greater than C50, the load speed should be It should be 0.08~0.10 MPa/s. Record the load until the specimen breaks.

Results

Meso-structural characteristics of steel fiber reinforced concrete

In order to further study the effect of different steel fiber content on the compactness of concrete microstructure, the microstructure of the concrete was studied by Hitachi TM4000 SEM, and the micro-structure of the steel fiber mortar was observed using a Zeiss analytical grade polarizing microscope. Figure 3 shows the observation results of the meso-structure of 30 group of ordinary concrete, 30A group of concrete, 30B group of concrete, and 30C group of concrete. The results show that the steel fibers do not chemically react with the cement mortar, but are embedded directly into the cement matrix. There will be many tiny protrusions that strengthen the bond between the two, making it firmly attached to the concrete. When subjected to external force, the crack will spread out from the inside of the matrix and destroy the steel fibers distributed along the crack propagation path. Because the steel fiber itself has high tensile strength, its toughening-crack resistance effect will consume a certain amount of energy, thereby improving the mechanical properties of the material.

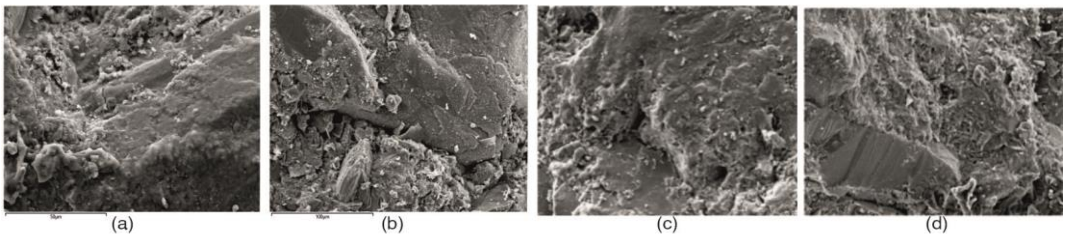

Figure 3. Microscopic observation results of concrete specimens; (a) 30, (b) 30A, (c) 30B, and (d) 30C

Effect of fiber on thermal conductivity of concrete

By analyzing the heat conduction characteristic curves in fig. 4, it is found that the thermal conductivity of concrete is positively correlated with the content of steel fibers, and the thermal conductivity of concrete increases with the increase of the content of steel fibers. Figure 4(a) shows the thermal conductivity test results of C30 concrete samples. When the steel fiber is 0-0.35%, the thermal conductivity of the 30A group of samples is increased by 6.4%. When the steel fiber is 0.35-0.7%, the thermal conductivity of the 30B group of samples is increased by 2%, and the thermal conductivity is increased by 7.2% compared with the 30 group. Compared with the 30B group, the thermal conductivity of the 30C group is increased by 3%, and the thermal conductivity is increased by 14% compared with the 30 group. Figure 4(b) shows the test results of C40 concrete samples. When the steel fiber content is 0-0.35%, the results show that the thermal conductivity of the 40A group sample is 2.8% higher than that of the 40 ordinary group concrete sample, while the steel fiber content is 0.35~0.7%, the thermal conductivity increases by 3%. Compared with the 40 group of samples, the thermal conductivity is increased by 6%, the 40C group of samples is 1% higher than the 40B group, and the thermal conductivity is increased by 7% compared with the 40 group of samples. Figure 4(c) shows the test results of C50 concrete group specimens. When the steel fiber content is 0-0.35%, the thermal conductivity of the 50A group sample is increased by 3%. When the steel fiber content is 0.35-0.7%, the thermal conductivity of the 50B group is increased by 2.3%, compared with the 50 group, the thermal conductivity is increased by 3.2%, and the 50C group is 4% higher than the 50B group. Compared with the 50 group, the thermal conductivity is increased by 7.4%.

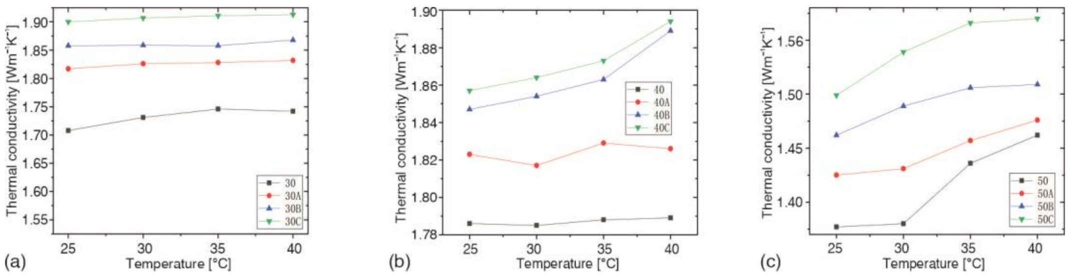

Figure 4. Thermal conductivity change diagram; (a) C30, (b) C40, and (c) C50

After adding steel fiber to concrete, since steel fiber is a metal material with high thermal conductivity, it can improve the thermal conductivity of concrete.

Mechanical tensile properties of steel fiber reinforced concrete

Concrete is mainly affected by the compressive strength in practical engineering, but the splitting tensile strength has important research significance on the cracking of concrete. The Brazilian splitting method is also called radial fracturing method. It is a test method invented by the Brazilian scholar Hendros. It is also called the Brazilian method.

The splitting tensile strength of concrete samples is calculated according to the following formula:

$$f_{ts} = \frac{2F}{\pi l d} \tag{1}$$

where f_{ts} is splitting tensile strength of concrete specimens, F – the maximum load when the specimen is crushed under compression, l – the concrete sample length, and d – the diameter of concrete specimen section.

By analyzing the tensile strength of steel fiber reinforced concrete, it is found that there is a certain linear relationship between the tensile strength of concrete and the amount of steel fiber added. The test results of each group are shown in fig. 5. The test results of the 30 group show that in the range of 0-0.35%, the tensile strength of group 30A increases by 2.3%, and in the case of 0.35-0.7%, the tensile strength of group 30 B increases by 7.9%, 10.5% higher than 30 group, group 30C is 34% higher than 30B group and 49% higher than 30 group.

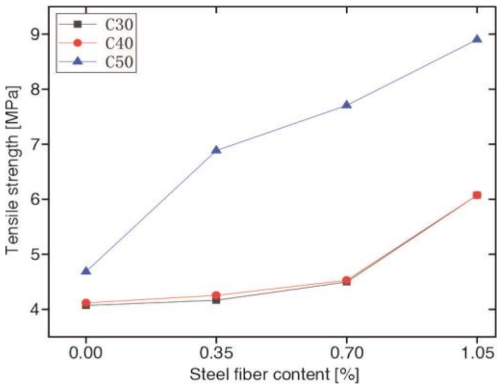

Figure 5. Tensile strength variation curve

The test results of the 40 group show that in the range of 0-0.35%, the tensile strength of the 40 A group increases by 3.2%, and in the case of 0.35-0.7%, the tensile strength of the 40B group increases by 6.5%, which is 10% higher than that of 40 group, group 40C is 34% higher than group 40B, and 47% higher than group 40. The mechanical strengthening effect of group 40 is the same as that of group 30.

The test results of the 50 group show that in the range of 0-0.35%, the tensile strength of the 50A group increases by 46%, and in the case of 0.35-0.7%, the tensile strength of the 50B group increases by 7.9%, 64% higher than the 50 group, group 50C is 15% higher than the 50B group, 89% higher than the 50 group, and the group 50 sample has a better effect of improving the mechanical strength.

The freeze-thaw resistance, heat resistance and wear resistance of steel fiber reinforced concrete have been greatly improved. Steel fiber reinforced concrete will not crack when it is stressed, only cracks will occur when it is stressed. After the steel fiber reinforced concrete is cracked, the fiber reinforced layer can effectively prevent the expansion and aggravation of the crack, thereby improving its tensile strength. When the concrete is mixed with steel fibers, three groups of comparative test analysis show that when the steel fiber content increases from 0-1.05%, the tensile strength enhancement effect of the concrete samples is ideal. The increase in the splitting tensile strength of concrete mortar is mainly due to the fact that the internal tensile stress of the specimen increases with the increase of the load during the loading process, and the steel fibers dispersed in the middle of the specimen play a bridging role to prevent deformation. During the splitting tensile failure process, the steel fibers scattered around the cracks and the splitting surface will bear part of the stress at the time of failure and consume part of the load energy, thereby improving its mechanical splitting tensile strength.

Conclusion

A new type of heat-transfer-enhancing heat-exchange pile foundation material is made by adding steel fibers that can enhance its mechanical properties and thermal conductivity to the pile concrete of the heat-exchange pile foundation to improve its heat-transfer performance. Through experiments, the effects of different amounts of steel fibers on the thermal conductivity and mechanical strength of cement-based composites were studied, and the role of steel fibers in cement matrix was discussed from the microscopic mechanism. At the same ambient temperature, with the increase of steel fiber content, the thermal conductivity and heat transfer effect are significantly enhanced, and the thermal conductivity is positively correlated with the steel fiber content. When the proportion of steel fiber is 1.05%, the thermal conductivity of concrete can reach about 1.95 W/mK. Through the SEM analysis of steel fibers in cement, it is found that when the amount of steel fibers added is small, the contact between steel fibers and concrete particles is very small, and uniform heat transfer paths cannot be formed, thus reducing heat conduction. With the increase of the amount of steel fiber, the combination between the steel fiber and the concrete gradually forms a heat conduction strengthening path, thereby improving the heat transfer coefficient. The cracks in the sample decrease with the increase of the amount of steel fiber substituted for cement, while the morphology of the steel fiber doped in the section is more significant, and its tensile strength is greatly improved. The maximum strengthening efficiency of steel fiber on its mechanical properties is 89%, and the best strengthening effects of group 30 and group 40 are 47% and 49%.

According to the comprehensive analysis of the thermophysical parameter test results, split tensile test results and SEM observation results of the steel fiber reinforced concrete samples, the C30 heat transfer reinforced concrete with a steel fiber content of 1.05% is an ideal construction scheme, its heat transfer enhancement effect and mechanical parameter enhancement effect are good. The results can provide some theoretical support for the proportioning process of heat exchange pile foundation.

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