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An experimental study on thermal conductivity of iron ore sand cement mortar

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HIGHLIGHTS

- IOS was used as aggregate at different replacement levels to make IOS cement mortar.
- Hot-wire method and laser flash method were used to test the thermal conductivity.
- The effects of five major factors on thermal conductivity were evaluated.
- SPSS partial correlation analysis was conducted to determine the precedence factors.
- A prediction formulation between thermal conductivity and the factors was developed.

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ABSTRACT

The objective of this paper is to determine the effect of water–cement ratio, total sand–cement ratio, river sand–iron ore sand ratio, temperature and density on the thermal conductivity of iron ore sand (IOS) cement mortar. The IOS was filtered by wet magnetic separator and incorporated in a cement mortar mixture. The hot-wire method and the laser flash method were used to test the thermal conductivity of the IOS cement mortar. Meanwhile, the SPSS partial correlation analysis was conducted to determine the precedence of the five factors according to their effects on thermal conductivity. After that, a prediction formulation of thermal conductivity was developed with MATLAB. Experimental results show that among the five factors, river sand–iron ore sand ratio ranks the best effect on thermal conductivity, followed by water–cement ratio, total sand–cement ratio, temperature and density in sequence.

1. Introduction

In recent years, the application of electric technology such as deicing and snow melting rapidly increases [1–4]. The key problem in deicing and snow melting is the way to heat up. However, conventional materials such as the ordinary Portland cement concrete and conventional cement mortar often hold low thermal conductivity in heat conduction and result in significant energy loss. Meanwhile, inorganic heat transfer cement is too expensive to be widely applied. The present focus in pavement industry is to find a material with high thermal conductivity as well as low price.

The thermal conductivity of concrete and mortar can be easily reduced or raised by replacing one or more of its constituents with thermally insulating or thermally conductive materials. The concrete without glass bubble shows the mean conductivity of 2.25 W/m·K and as the amount of glass bubble increases, the conductivity values decreases down to 1.32 W/m·K [5]. Foamed concrete can be used as thermal insulation materials in many application cases, the thermal conductivity at different temperatures can be changed from 0.131 W/m·K to 0.484 W/m·K [6]. The non-structural grade oil palm shell foamed concrete with a density of 1.10 g/cm^3 holds the lowest thermal conductivity of 0.40 W/m·K [7]. Wood-based materials have been incorporated in concrete products with the aim to reduce the thermal conductivity and the lightening of concrete by wood shavings increases the thermal insulation capacity by decreasing the thermal conductivity and diffusivity, the lowest thermal conductivity can be about 0.20 W/m·K [8]. Rice husk concrete can compete with hemp concrete in terms of thermal insulation with a dry thermal conductivity ranging from about 0.10 W/m·K to 0.14 W/m·K depending on the mix proportion [9]. Cement paste with natural sand content and the effect of silica

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fume, class C fly ash and blast furnace slag on the thermal conductivity of mortar is investigated, the thermal conductivities change from 0.72 W/m·K to 1.02 W/m·K [10]. Encapsulated phase change materials are used in concrete to improve thermal properties of the concrete, called PCM-concrete, the biggest predictions of the effective thermal conductivity of PCM-concrete can beyond 2.0 W/m·K [11]. In order to improve the efficiency of melting snow and deicing, pavement concrete material such as common concrete, steel fiber concrete and carbon fiber concrete are studied with the thermal conductivity no less than 1.5 W/m·K, the biggest can be 3.02 W/m·K [12]. Another study on steel fiber concrete shows that the biggest thermal conductivity is 2.47 W/m·K [13]. The thermophysical characteristics of reactive sand concrete with different fiber volumes under different temperatures are analyzed, and the upper limit of the thermal conductivity of that concrete is 2.28 W/m·K [14]. The thermal conductivity of four types self-consolidating concrete ranges between 2.8 W/m·K and 3.6 W/m·K at room temperature [15].

As is known to us, if we want to lighten the concrete, it can be just obtained by introducing gas or foam into the concrete paste, or by totally or partially replacing standard aggregate with low weight and preferentially low cost components [16]. Similarly, the effective thermal conductivity of composites is strongly dependent on the volume fraction and corresponding properties of each of the constituents [17,18]. Metal sand with high thermal conductivity can improve the thermal conductivity of mortar or concrete. Compared with metal sands such as aluminum sand and copper sand, iron ore sand is more suitable for its low cost in engineering fields. Researches on mechanical properties of concrete or mortar that contains iron as aggregate have been conducted [19,20]. Besides, the possibility of using iron ore tailings to replace natural aggregate to prepare ultra-high performance concrete under two different curing regimes is investigated [21]. Concrete and mortar are heterogeneous and porous solid materials, and the heat propagation in concrete at normal operating temperatures is primarily by conduction. So many factors, such as aggregate type, cement paste proportion, aggregate gradation, porosity, moisture and temperature, will affect the thermal conductivity of concrete [22–25]. Therefore, the work of this paper mainly consists of six steps. First, the IOS was used as aggregate at various replacement levels to make IOS cement mortar. Second, several specimens were modeled with different mix proportions. Thirdly, based on these specimens, the thermal conductivities were detected by hot-wire method and laser flash method. Fourthly, each relationship between each factor and the thermal conductivity can be obtained with regression analysis. Fifthly, SPSS partial correlation analysis was conducted to determine the precedence factors. At last, a prediction formulation between thermal conductivity and the five factors was developed then. The new thermal conductive material presented in this paper facilitates applications in fields such as chemical industries, petroleum pipeline, deicing and snow melting, and heating.

2. Materials and methods

2.1. Source materials

The ordinary Portland cement with a 28-day compressive strength of more than 42.5 MPa is used as a basic cementitious material for all the mixtures in accordance with the Chinese Standard GB 175-2007. The mixing water is tap water. River sand and IOS are used as aggregates in this mixture. The river sand is excavated from the lower reaches of a river and it has an apparent density of 2.68 g/cm^3. Its fineness modulus is 3.0 and average diameter is 0.35 mm. The river sand meets the requirement of Chinese Standard GB/T 14684-2011. IOS is filtered by wet magnetic separator. The apparent density of IOS is on the order of 4.37 g/cm^3. Its natural water proportion is 12.4%. The results of sieving test are shown in Table 1. Besides, the Fe-grade in IOS is 81% while the rest in IOS is mineral powder and impurity. The weight of each adopted material is calculated according to different mix proportion and then these materials are well stirred for molding.

Table 1
Sieving test of IOS.

Mesh size/mm	Accumulated sieve residue (by mass)/% results of sieving test one	Accumulated sieve residue (by mass)/% results of sieving test two	Accumulated sieve residue (by mass)/% results of sieving test three
0.6	7.1	7.4	7.9
0.3	15.1	15.7	15.4
0.15	23.8	24.4	23.6
0.075	55.2	56.3	54.7
Less than 0.075	98.2	99.1	98.7

2.2. The test parameters and mix proportions

Thermal conductivity measurements are performed with particular reference to their dependence on some other contributing factors such as water–cement (W/C) ratio, total sand–cement ratio (S/C), river sand–iron ore sand ratio (R/I) and temperature (*T*). To analyze the sensitivity of each test parameter, a series of different values is selected. W/C ratio, S/C ratio and R/I ratio are all mass ratio. Each specimen with a specific mix proportion is shown in Table 2. If the specimen does not contain river sand, the total sand only contains IOS; otherwise, the total sand contains river sand and IOS.

2.3. Preparation of specimens

Two types of specimens are prepared according to the type of tests to be realized: one is cuboid specimen with the size of $4 \times 4 \times 16$ cm^3, the other is a cylinder specimen with the diameter of 12.5 mm and 3 mm in thickness. These different sizes are related to measuring devices whose dimensions are imposed. Pure IOS specimen is made of cement, water and IOS. The mixed sand specimen is formed by cement, water, river sand and IOS. Cuboid specimen is mixed by mortar mixer, vibrated and molded by plain bumper. After that, they should be maintained 28 days in curing box in constant temperature (20 ± 1 °C) and humidity (not less than 90%). The durations of the different phases of mixing must be sufficiently long to allow a good homogenization and short enough to avoid leaving too much water to evaporate in ambient air. The ages of cuboid specimens are all specified as 28 days by experimental control. All specimens are dried enough before the thermal conductivity test.

Cylinder specimen is used to test the thermal conductivity at different temperatures. A PVC test tube with the diameter of 13 mm is used as a mold because the cylinder specimen is difficult to prepare. A bamboo sign is used to tamp the test tube until the mold is filled up with mortar. The specimens in the PVC test tubes will also be maintained in 20 ± 1 °C and the humidity is no less than 90%. After 28 days, the mold will be cut into a cylinder with the thickness of 3 mm. After that, the cylinder specimen will be taken out and polished with a file carefully until the specimen meets standard size. Similar with cuboid specimens, all cylinder specimens are specified as 28 days and dried enough before the thermal conductivity test. The IOS cement mortar can be used in heat conduction layer for road deicing and snow melting. The position of the heat conduction layer is under the waterproof tack coat. Therefore, the IOS cement mortar would be waived of the effect of water from road deicing and snow melting.

2.4. Measurement method

There are various testing devices and their interpreting methods for measurement of thermal conductivity. They can be broken into four distinct methods. First, the two-linear-parallel-probe method [26,27] has been widely accepted to determine thermal conductivity, Two probes are inserted into two parallel holes drilled in the sample, where one probe is used as a heating source and the other as a temperature sensor. Also used are the plane-heat-source method [28] and the hot-guarded plate method [29]. They are similar to the two-linear-parallel-probe method in their basic principle but require additional efforts to cut the sample thin, and then firmly place the thermal probe on with epoxy [23]. Laser flash method [30–32] is a kind of thermal diffusion method, which also be used these years for a better accuracy.

In this study, the QTM-300 device manufactured from KEM in Japan (Fig. 1(a)) and NETZSCH LFA457 laser thermal conductivity meter made in Germany (Fig. 2) are used to measure the thermal conductivity of these specimens.

The basic principle of QTM-300 is the same as that of the two-linear-parallel-probe method. However the thermal conductivity is measured by the probe method, which has been modified from the transient-hot-wire method. The QTM-300 device makes it possible to measure the thermal conductivity of the sample within 60 s by using probes containing temperature sensors. The measurement