Construction and Building Materials 98 (2015) 8–16

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mesoscale model for thermal conductivity of concrete

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HIGHLIGHTS

- Influences of different factors on thermal conductivity of concrete were presented.
- The theory of composite materials was applied to calculate thermal conductivity.
- Porosity was chosen as a key parameter in a new thermal conductivity model.
- Interfacial thermal resistance was considered to predict thermal conductivity.
- Thermal conductivity models for unsaturated and damaged concrete were proposed.

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form 7 August 2015
Accepted 10 August 2015
Available online 24 August 2015

Keywords:
Thermal conductivity
Unsaturated concrete
Damaged concrete
Composite material
Mesoscale model
Interfacial thermal resistance

ABSTRACT

Thermal conductivity of coarse aggregate, cement mortar as well as concrete were measured by means of a guarded hot plate apparatus and/or a transient plane source. Influences of sand ratio, type and volume fraction of aggregate, water–cement ratio, saturation degree and load level on thermal conductivity of concrete were investigated. By using the theoretical model for thermal conductivity of composite materials, interfacial thermal resistance between cement mortar and coarse aggregate were studied further. The results show that thermal conductivity of concrete increases with the increasing saturation degree, volume fraction and thermal conductivity of aggregate, but decreases with the increasing water–cement ratio and load level. And interfacial thermal resistance coefficient decreases with the increasing saturation degree; therefore, interfacial thermal resistance must be considered when calculating thermal conductivity of concrete. Finally, mesoscale models were established for thermal conductivity of undamaged concrete in dry and unsaturated states based on the Maxwell's model. In addition, a mesoscale model was proposed for thermal conductivity of damaged concrete; this model is based on the assumption that damaged concrete was isotropic and damaged phase was served as an insulator. Mesoscale models can be used to predict the effective thermal conductivity of concrete under different states and the predicted values were all in acceptable agreement with the experimental values.

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1. Introduction

The temperature field in concrete is one of the important influencing factors for moisture transport [1] as well as carbonation [2,3], chloride penetration [1,4–6] and corrosion of embedded steel reinforcement [7–11], which leads to durability degradation of concrete structures. Concrete temperature field also affects the analysis of building energy conservation, the design of radiation shields in nuclear power plants, the structural analysis of bridge decks as well as other exposed structures under thermal loading [12–15].

Thermal conductivity of concrete is the key parameter in denoting the ability of concrete to transfer heat and in determining the temperature field in concrete. Previous studies reveal that water–cement ratio, type and volume fraction of aggregate, admixtures, moisture content and temperature have significant influences on thermal conductivity of concrete [15–21]. On this basis, a prediction model was proposed for thermal conductivity of concrete taking into account the influences of aggregate volume fraction, temperature and water–cement ratio by Kim et al. [20], and they found that thermal conductivity of concrete was also independent of age at the same time. On the other hand, concrete was seen as a two-phase composite material made up of cement mortar (continuous phase) and coarse aggregate (dispersed phase)

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.106
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in the mesoscale [15], and the theoretical models for effective thermal conductivity of concrete were developed based on the theory of composite materials, such as Campbell-Allen and Thorne's model [16] and Harmathy's model [17]. Subsequently, Khan [15] investigated the influences of aggregate types and moisture content on thermal conductivity of concrete by applying Campbell-Allen and Thorne's model [16]. Besides, a simple parallel model for thermal conductivity of fly ash concrete considering age, material and mix proportion was proposed by Choktaweekarn et al. [22].

In fact, the above factors all changed the porosity of concrete, and thereby influenced its thermal conductivity; moreover, interfacial thermal resistance occurs between cement mortar and coarse aggregate. Furthermore, concrete is always both unsaturated and damaged by loads in real concrete structures. These factors will all significantly affect the thermal conductivity of concrete. However, existing models are often available to calculate the thermal conductivity of undamaged concrete in dry or saturated states [23] and ignore the influences of porosity and interfacial thermal resistance on thermal conductivity of concrete. In order to establish general thermal conductivity models for unsaturated concrete and damaged concrete, it is necessary to investigate further the thermal conductivity of concrete.

In this paper, the relationships between thermal conductivity of concrete and that of coarse aggregate as well as cement mortar in a dry state were studied by means of a guarded hot plate apparatus, and the influences of sand ratio, type and volume fraction of aggregate and water–cement ratio on thermal conductivity of concrete were also investigated. Subsequently, the influences of saturation degree on thermal conductivity of coarse aggregate, cement mortar as well as concrete were studied by means of a transient plane source and interfacial thermal resistances between cement mortar and coarse aggregate with different moisture states were analyzed. Then, mesoscale models were established for thermal conductivity of undamaged concrete in dry and unsaturated states. Finally, the influence of load level on thermal conductivity of damaged concrete in a dry state was investigated by means of a guarded hot plate apparatus, and a mesoscale model was proposed for thermal conductivity of damaged concrete.

2. Experimental program

2.1. Materials and specimen preparation

Three plate specimens with dimensions of 250 × 250 × 40 mm were cut from their limestone or granite parent rocks along three orthogonal directions, respectively, as shown in Fig. 1, and were used to measure thermal conductivity of coarse aggregate. The remaining parent rocks were made into crushed stones by a crusher and were subsequently divided into two kinds of particle sizes by a sieve shaker sized 5–10 mm and 10–16 mm, respectively. Crushed stones with particle sizes of 5–16 mm were obtained for concrete specimens preparation by mixing the above two kinds of particle sizes in equal mass. Crushed limestone and granite stones as well as natural river sand were used as coarse and fine aggregates, respectively, with the apparent density of 2733 kg/m^3, 2642 kg/m^3 and 2639 kg/m^3, respectively. Ordinary Portland cement with a density of 3097 kg/m^3 and tap water were also used in the test. Mix proportions for cement mortar and concrete specimens are given in Table 1.

Four prism cement mortar specimens were cast and used to study the influence of volume fraction of fine aggregate on thermal conductivity of cement mortar. Thirteen prism limestone concrete (LC) specimens and four prism granite concrete (GC) specimens were also cast and used to study the influences of sand ratio, type and volume fraction of aggregate, water–cement ratio and saturation degree on thermal conductivity of concrete. The dimensions of cement mortar and concrete specimens were all 250 × 250 × 50 mm, as shown in Fig. 2. All specimens were kept in a standard curing room at 20 ± 2 °C and 95% relative humidity (RH) for 28 days before they were used to measure thermal conductivity.

2.2. Methods to obtain the damaged concrete specimens

In order to study the influence of load level on thermal conductivity of concrete, 14 prism limestone concrete specimens sized at 200 × 200 × 400 mm were cast with the same mix proportion of the LC1 concrete specimen, as shown in Table 1. After curing for 28 days, six specimens were tested under uniaxial compression, and the average compressive strength and modulus of elasticity were 34.77 MPa and 3.62 × 10^4 MPa, respectively. Each pair of the other eight specimens were loaded under uniaxial compression to 25%, 40%, 55%, or 70% of the compressive strength with a sustained duration of 30 min, corresponding to different damage levels. Six plate specimens with dimensions of 200 × 200 × 40 mm were cut from the two specimens subjected to the same load level, as shown in Fig. 3, and were used to measure thermal conductivity of damaged concrete with different damage levels.

2.3. Measurement of thermal conductivity

According to the temperature field distribution inside the object whether or not to change with time in the heat transfer process, test methods for thermal conductivity can be divided into two categories as: steady-state and unsteady-state (transient) methods.

Thermal conductivity of dry aggregate, cement mortar and concrete were measured by means of a guarded hot plate apparatus [24] as a kind of steady-state method in a steady-state conductivity tester where the temperature was kept at 35 °C. Prior to conducting the test, all specimens were dried in an oven at 105 °C for 24 h to achieve dry specimens. They were then cooled to test temperature to measure their thermal conductivity. Actually, the guarded hot plate apparatus has a strict requirement concerning the surface flatness of the specimen. However, it is very difficult to obtain the required surface flatness, which means the contact thermal resistance between interfaces will bring some errors. Consequently, the temperature difference between both sides of the specimen was measured directly by a thermocouple in the test, so the error caused by the specimen's surface irregularity could be minimized.

Thermal conductivity of wet aggregate, cement mortar and concrete were measured by means of a transient plane source [25,26] in an unsteady-state conductivity tester where the temperature was also kept at 35 °C. After the thermal conductivities of dry specimens were measured, some of them were immersed in water and boiled for five hours to achieve saturated specimens, which were used to measure thermal conductivity after they were cooled to test temperature. Subsequently, the specimens were dried in an oven at 60 °C to achieve specimens with different moisture states, and they were then cooled to test temperature to measure their thermal conductivity.

3. Analysis of experimental results

3.1. Thermal conductivity of coarse aggregate

The measured thermal conductivities of limestone in dry and saturated states as well as granite in a dry state are given in Table 2. Three measured values by means of a guarded hot plate apparatus were obtained by different plate specimens along three orthogonal directions, while three measured values by means of a transient plane source represent three different measurements of the same plate specimen.

No significant difference was found in the thermal conductivity of limestone or granite along three orthogonal directions, and limestone has a slightly greater thermal conductivity than granite in a dry state. In addition, the thermal conductivity of limestone in

(a) Limestone

(b) Granite

Fig. 1. Limestone and granite plate specimens.

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