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Experimental measurement and microstructure-based simulation of thermal conductivity of unbound aggregates

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HIGHLIGHTS

- Measured thermal conductivity of unbound aggregates with back-calculation approach.
- Developed and validated microstructure-based simulation models to predict thermal conductivity.
- Evaluated effects of aggregate size, air void content, and rock thermal conductivity.

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ABSTRACT

Unbound aggregates are widely used for roadway and railway infrastructure. The thermal conductivity of unbound aggregates is important for predicting temperature field and thermal stress of structures. This paper developed laboratory measurement methods and microstructure-based simulation models to evaluate effective thermal conductivity of unbound aggregates. An image-aided method was used to randomly generate three-dimensional (3-D) geometry of aggregate. The aggregate particles were packed with discrete element method and then imported into finite element model for steady heat transfer analysis. Laboratory experiments were conducted to measure temperature profiles in the specimens of unbound aggregates and determine effective thermal conductivity through back-calculation. The effective thermal conductivity measured from the experiment was used to validate the results obtained from the simulation model. The analysis results show that smaller aggregate with the size of 2.36–4.75 mm has the smaller porosity and the greater thermal conductivity as compared to the aggregates with the size of 4.75–9.5 mm. However, the effective thermal conductivity of unbound aggregates is affected by volume fractions of the components and the contacts between aggregate particles. When the original rock is crushed into aggregates, the decrease in thermal conductivity is more significant for the rock with the higher thermal conductivity. The effective thermal conductivity could be underestimated if two-dimensional (2-D) cross sections of 3-D models were used in the simulation. The study results can be used for better consideration of thermal responses in the design and analysis of roadway and railway structure.

1. Introduction

Unbound aggregate is one of widely used granular materials for various built infrastructures. In the pavement structure, the base course is usually constructed with unbound aggregates to provide support to surface layer, distribute wheel loading, and enhance drainage [1]. For the similar purpose, the unbound coarse aggregate is used as the ballast layer to support crossties in railroad track [2]. The thermal conductivity of unbound aggregates affects the temperature field in pavement and railway, which has impact on the resulted thermal stress in the structures, and further affects thermal cracking of pavement [3], and buckling of rail track [4]. In the permafrost regions, unbound aggregate is used to construct the air-convection crushed-rock embankment for roadway and railway to provide cooling effect [5]. Therefore, accurate determination of the effective thermal conductivity of unbound aggregate is very important for thermal and mechanical analysis of roadway and railway.

However, it is not an easy task to determine the effective thermal conductivity of unbound aggregate. Due to the contact resistance between aggregate particles and the insulation effect of air void, the effective thermal conductivity of unbound aggregate is usually much lower than that of rock stone [6]. As a result, the effective thermal conductivity of unbound aggregate cannot be determined based on the mineral composition of rock

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stone. Experiment is the most widely used method to determine thermal conductivity of various construction materials, such as asphalt concrete [7,8], cement concrete [9,10], aggregate course [11], and fine soils [12,13]. The commonly used experiments include heat flow meter method, transient plane source method, and thermal needle probe method.

However, compared with the dense concrete and soil with small grain size, the microstructure of unbound aggregate is much more heterogeneous, with high porosity and large particle size, which causes challenge for the traditional thermal experiment. In the previous work on analysis of thermal responses of pavements, the effective thermal conductivity of unbound aggregate is usually estimated from a wide range of values reported in existing literature [14–16]. The analysis accuracy of temperature field and thermal stress can be further improved if the thermal properties of unbound aggregate are accurately characterized.

In addition to experiment techniques, theoretical and numerical models based on heterogeneous microstructure provide alternative ways to evaluate mechanical, hydraulic, and acoustic properties of composite infrastructure materials [17–23]. Several microstructure-based models have been developed to investigate thermal behavior of cement concrete and asphalt concrete [24–27]. In these models, discrete aggregates were distributed in the continuous phase such as asphalt or cement matrix. Therefore the contacts between aggregates were not necessary since heat flux could transfer through either aggregates or the continuous matrix. However, for unbound aggregates, the solid particles are discrete but not continuous, so that the contacts between the aggregates are necessary for the transfer of heat flux from aggregate to aggregate. Therefore, in order to predict effective thermal conductivity of unbound aggregate, the microstructure model with contacts between aggregates need to be used.

2. Objective and scope

The primary objective of this study is to develop laboratory measurement methods and microstructure-based simulation models to evaluate effective thermal conductivity of unbound aggregates. An image-aided method was used to randomly generate three-dimensional (3-D) geometry of aggregate. The generated 3-D aggregates were packed with discrete element method, and then imported into finite element model to calculate effective thermal conductivity. Laboratory experiments were conducted to measure temperature profiles in the unbound aggregate specimens and determine the effective thermal conductivity through back-calculation. The effective thermal conductivity measured from the experiment was used to validate the results obtained from the microstructure-based simulation model. The relationship between the thermal conductivity of the original rock stone and the effective thermal conductivity of unbound aggregate specimen was analyzed. The simulation results obtained from two-dimensional (2-D) simulation models were compared to 3-D model results. The developed experimental and simulation methods can be used for better understanding of heat transfer mechanism in heterogeneous medium. The accurate characterization and prediction of thermal properties of unbound aggregate can help better consideration of thermal responses in the design and analysis of roadway and railway structure.

3. Laboratory measurement

3.1. Experimental setup

The typical values of thermal properties for the rocks such as granite, limestone, basalt, sandstone, and marble could be found from the literature [28,29]. However, in practice, the mineral composition of individual rock particle could be complex. Therefore, the thermal properties of rock stone were determined by experiment. The cuboid rock specimen was cut from the original rock, while the aggregates used in the experiment was crushed from the same kind of original rock.

The thermal conductivity and specific heat capacity of the rock specimen was measured using Thermal Constant Analyzer (Hot Disk, Sweden). This device is based on transient plane heat source (TPS) method, following ASTM D7984-16 [30]. In this experiment, a plane sensor was fixed between two cuboid rock samples with 5 cm in width, 5 cm in length, and 3 cm in height, as shown in Fig. 1. The sensor acted as both heat source for heating samples and thermometer for measuring time-dependent temperature change. Before testing, the rock specimens were heated in an oven at 110 °C. Then the rock specimens were placed on the dry tray at room temperature (controlled at 20–22 °C) for two days to reach an equilibrium temperature and dry state. Totally five sets of rock samples were tested and the average values of thermal conductivity and specific heat capacity were used as thermal properties for the original rock. Based on the experiment, the thermal conductivity of rock was found as 2.998 $W{\cdot}m^{-1}{\cdot}K^{-1}$, and the specific heat capacity of rock was found as 804.8 $Jkg^{-1}\,K^{-1}$.

On the other hand, the effective thermal conductivity of unbound aggregates was backcalculated using the measured temperature profiles. This experiment method was inspired by the previous study that measured thermal conductivity of granular material with cylindrical heat exchanger [6]. The experimental setup and the schematic diagram of experiment are shown in Fig. 2(a) and (b), respectively. Before testing, the aggregates were heated in an oven at 110 °C and then placed on the dry tray at room temperature (controlled at 20–22 °C) for two days to reach an equilibrium temperature and dry state. As shown in Fig. 2(a), the aggregate particles were placed on the heating plate to form a cylindrical specimen. The bottom of the specimen was in contact with the heating plate, while the other boundaries were surrounded with insulation material. The compaction was achieved by putting the static weight on top of the specimen. The dimensions of the unbound specimen were 100 mm in diameter and 40 mm in height, respectively. Three resistance temperature detectors were placed along the depth of the specimen to record the temperature profiles at the bottom, top, and middle layer of the specimen, when the specimen was heated by the heating plate.

Fig. 1. TPS experiment for original rock.