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Thermal properties of asphalt concrete: A numerical and experimental study

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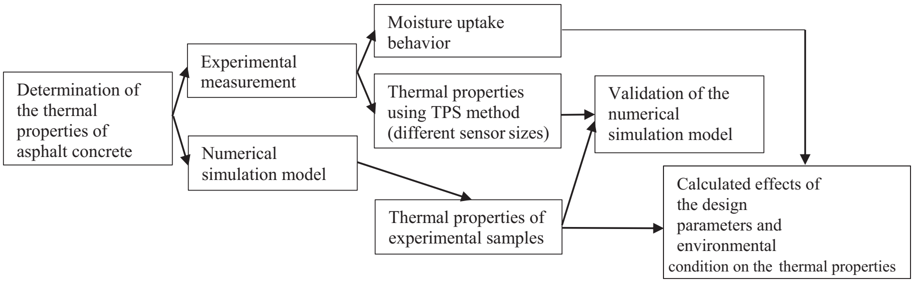
HIGHLIGHTS

- Determination of thermal properties by the Transient Plane Source method.
- Generation of a two-dimensional numerical model of asphalt concrete microstructure.
- Prediction of the thermal conductivity of asphalt concrete model using finite elements.
- Validation of predicted thermal conductivity with experimental measurements.
- Investigation of the effects of different design parameters on the thermal properties.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study is to investigate the effects of different design parameters of asphalt concrete and environmental conditions on the thermal properties (thermal conductivity, diffusivity and volumetric heat capacity). A two-dimensional (2-D) numerical model of the asphalt concrete was developed based on the Finite Element Method (FEM). The numerical model was validated by the experimental results using the Transient Plane Source (TPS) method. The experimental results showed that an increase in the ratio of the TPS sensor size to maximum aggregate size improves the accuracy of the thermal properties measurements. A comparison between the thermal properties obtained by the numerical model and the TPS method exhibited a relative error in the range of 2–10%. The numerical model was used to study the effects of the type of aggregates, aggregate gradation, graphite filler in the binder, air void content as well as moisture and freezing conditions on the thermal properties of asphalt concrete.

1. Introduction

During summer months, the surface temperature of an asphalt road pavement can rise up to 70 °C, due to absorbed solar radiation [1]. The high temperature of the road surface usually degrades asphalt concrete by accelerating the thermal oxidation and plastic deformation, rutting, under traffic loads. In addition, the high temperature of the road creates environmental matters such as the Urban Heat Island (UHI) effect. The UHI is referred to as areas of a city which are considerably warmer than their surroundings [2]. Furthermore, cold weather in winter reduces the road surface temperature. Low temperatures ‘harden’ the asphalt concrete and subsequently induce thermal cracks on the surface of the road. Also, cold weather leads to the formation of ice on the road surface. Icy condition increases the risk of traffic accidents and causes transportation safety problems [3]. A method to overcome these problems is to use the Hydronic Heating Pavement (HHP) system

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[4]. The HHP system consists of embedded pipes inherently to the pavement which contain a circulating fluid such as brine, oil or glycol-water [5]. The HHP system harvests solar energy during sunny days, stores it in seasonal thermal energy storages and releases stored thermal energy for ice-melting during cold periods [6]. The investigation of the heat transfer between the embedded pipes and the road surface, through the asphalt road pavement, requires accurate determination of the thermal properties of asphalt concrete.

The scope of this paper is to investigate the effects of the different design parameters of asphalt concrete and environmental conditions on the thermal properties: thermal conductivity, diffusivity and volumetric heat capacity. A Finite Element Method (FEM) was developed and validated to investigate the effects of different parameters including: i) types of aggregates, ii) aggregate gradation, iii) modified binder with graphite, iv) air void content, v) moisture content vi) moisture saturation and vii) freezing conditions on the thermal properties of asphalt concrete. The developed model is based on material microstructure and distribution of both small and coarse size aggregates. The thermal properties of each individual component were obtained from the literature. To validate the model, thermal properties of asphalt concrete samples were also measured using the Transient Plane Source (TPS) method. Gustafsson [7] was the one who introduced the TPS method which is a transient technique for the measurement of thermal conductivity and diffusivity of solid materials. The accuracy of a measurement with the TPS method is highly dependent on the size of the employed sensor. Therefore, different measurements were taken using different TPS sensor sizes in order to investigate the effect of the sensor size vs. the maximum aggregate size ratio on the thermal property measurements.

After presenting the background literature and the theory employed in the study (Sections 2 and 3), Section 4 presents the experimental measurements of the thermal properties of various asphalt concrete samples and the moisture uptake behavior of one type of asphalt concrete. In Section 5, the generation of a numerical two-dimensional (2-D) model is demonstrated. The results of the experimentally defined thermal properties of asphalt concrete are used to validate the numerical model in Section 6. In Section 7, the validated numerical model is used to determine the effects of different design parameters and environmental conditions on the thermal properties of asphalt concrete.

2. Background

Different design parameters of asphalt concrete such as the types of aggregates, gradation and air void contents usually result in different thermal properties [8,9]. Mravira and Luca [9] investigated the effect of different design parameters namely two types of aggregates, three aggregate gradations and four compaction levels on the thermal properties of asphalt concrete. The results of these studies revealed a 50% variation between the lowest and highest thermal property values of asphalt concrete, after modifying the design parameters. Mravira and Luca [9] also emphasized that among others, the type of aggregates has the most significant effect on the thermal properties of the asphalt concretes. Dawson et al. [10] replaced limestone aggregates with quartzite in asphalt concrete samples and reported twice as high thermal conductivity values compared to the original version. Côté et al. [11] investigated the effects of aggregate size, air void content, density and the thermal conductivity of the aggregates and bitumen on the thermal conductivity of asphalt concrete. The results of their study showed that the thermal conductivity of asphalt concrete depends on the mineral origin of aggregates and the amount of air voids. Moreover, Côté et al. [11] concluded that the type of bitumen has no significant influence on the thermal conductivity of asphalt concrete. Hassan et al. [12] investigated the effect of air void content on the thermal properties of asphalt concrete. In their work, asphalt concrete samples having different air void content were fabricated. Then, the thermal properties of the different samples were assessed in dry and wet conditions. It was shown that by increasing the air void content from 5% to 25%, the thermal conductivities and volumetric heat capacities of asphalt concrete dropped to 40% and 30%, respectively. Moreover, the incorporation of additives in asphalt concrete has been reported to have a significant impact on its pristine thermal properties. Chen et al. [13] studied the effects of different Phase Change Materials (PCM) on the thermal behavior of asphalt concrete. It was demonstrated that PCMs may affect thermal properties in either an increasing or decreasing way. Dawson et al. [10] investigated the effects of different additives such as copper fibers and copper slag on the thermal properties of asphalt concrete. It was shown that the addition of copper fibers in asphalt concrete can lead to a 14% increase in thermal conductivity. Also, a combination of copper slag and light-weight aggregates was found to reduce the thermal conductivity of asphalt concrete by 13%.

Experimentally determined thermal properties of asphalt concrete may result in inconsistencies; e.g. in the work presented by Mravira and Luca [9], it was expected that by increasing the compaction efforts, the air void content in the asphalt concrete will diminish and thus the interconnection among aggregates will improve. As a result, a combination of reduced air void content together with enhanced aggregate interconnection was expected to lead to higher thermal conductivity of the asphalt concrete. However, Mravira and Luca [9] concluded that varying the air void content does not have a systematic interrelation with the thermal conductivity of asphalt concrete. The unexpected trend was attributed to the size variation of air voids, asphalt binder film thickness as well as the small range of coarse aggregate fraction. Another drawback of the experimental methods is the determination of thermal properties under wet conditions. Hassan et al. [14] investigated the thermal conductivity of wet-conditioned asphalt concrete samples using a steady-state experimental method. In their work, the surface of asphalt concrete was exposed to infrared lighting employed as a heat source. Then, surface and bottom temperatures as well as heat flux through the asphalt concrete were measured to calculate the thermal conductivity. The obtained results showed a steep change in the experimentally determined thermal conductivity. This steep change was attributed to the evaporation of the pre-absorbed moisture within the asphalt samples, during heating.

Islam and Tarefder [15] developed a FEM model to estimate the thermal conductivity of asphalt concrete. This model employed specific heat capacity of 1464 J/(kg K), which was experimentally obtained. The tested asphalt concrete was a dense graded pavement with 4.4% bitumen content (by mass) and 4.3% air void (by volume). The modelled thermal conductivity of the asphalt concrete was found to be 2.11 W/(m·K), which agrees with reported values by previous studies [16]. The developed model combined with experimental measurements was proposed as a solution for an accurate estimation of the thermal conductivity of asphalt concrete. Moreover, Chen et al. [17] developed a numerical model to determine the thermal conductivity of asphalt concrete, by considering the volumetric compositions of each individual component. Their model was validated with experimental data and resulted in a 10% deviation. In their work, the effects of different design parameters on the thermal conductivity of asphalt concrete were also interrogated. In particular, (i) air void content and air void distribution, (ii) coarse aggregate content, (iii) aspect ratio of aggregates, (iv) asphalt binder with conductive and insulating additives and (v) lightweight aggregates were examined. Chen