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Effect of air voids content on thermal properties of asphalt mixtures

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HIGHLIGHTS

- Asphalt mixture with high air voids content has lower thermal conductivity and specific heat capacity than asphalt mixture with lower air voids content. In addition, the emissivity of dense asphalt mixture is higher than the emissivity of porous asphalt mixture by a value of 0.02. This value is very small when compared to the emissivity of asphalt concrete; for this reason, the air voids content does not affect the emissivity of asphalt mixtures.
- Asphalt mixtures with high thermal conductivity and specific heat capacity, dense asphalt mixture, have lower heating and cooling rates than asphalt mixtures with lower thermal conductivity and specific heat capacity, porous asphalt mixture.
- The surface of asphalt slabs with high air voids content reaches higher steady state temperature than the surface of asphalt slabs with lower air voids content. The average temperature of asphalt mixture during heating and cooling is almost independent of the air voids content in the mixture.
- The total amount of energy accumulated in asphalt mixtures with different air voids content, but with the same constituting materials, during heating and cooling depends only on the density of the mixtures. Convective and radiative heat losses can be considered constant for mixtures with different air voids contents.
- In general, asphalt mixture with high air voids content accumulates less energy than asphalt mixture with lower air voids content. For this reason, mixtures with high air voids content are recommended to alleviate heat urban island effect while mixtures with low air voids content are recommended for harvesting solar energy from the pavement.

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ABSTRACT

Air voids content is considered as one of the factors that may affect heat transfer through asphalt mixture, although their specific role on the asphalt mixture temperature is still unclear. The objective of this research is to have a deep insight of the effect of air voids content on the temperature evolution, transport and storage of heat in asphalt mixture under dry conditions. With this objective, asphalt mixture slabs with different air voids content have been built and their thermal conductivity, specific heat capacity, light absorptivity and thermal diffusivity related to their temperature evolution have been measured when they are exposed to infrared light and during the cooling process. It was observed that asphalt mixture with high air voids content exhibited slightly higher steady state temperatures than denser asphalt mixture and that the heating and cooling rates are higher in porous asphalt mixture than in denser materials. The reason for the faster increase and decrease in temperature of porous mixture and for the higher temperature reached by porous asphalt is its lower specific heat capacity and thermal conductivity. Finally, it could be observed that the connectivity of air voids in asphalt mixture did not play an important role on the temperature reached by asphalt mixture.

1. Introduction

Approximately half of the world's incoming solar energy is absorbed by the Earth's surface [1]. Specifically, asphalt pavements can be heated up to 70 °C due to solar irradiation in summer, because of their high heating absorbing properties [2]. The high temperatures reached by asphalt mixture are the origin of problems such as the urban heat island effect, which may cause discomfort to urban residents [3] and damage to pavements, such as rutting [4]. In addition, these elevated temperatures can be used to harvest energy, by integrating pipes with water or air circulating through the pavement structure [5–7]. For this reason, understanding the thermal properties of asphalt materials is of the foremost importance to design new types of

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energy harvesting pavements and to select the most appropriate pavement type for every region.

Pavement temperature is an energy balance between the irradiation from the heat source (e.g. the Sun) and the heat absorption, transport and storage properties of asphalt mixture (i.e. the ability of the material to absorb and conduct heat). Evaluating the thermal behaviour of asphalt pavements requires understanding the surface and thermo-physical properties that affect transport and storage of heat [8]. There are two distinct categories of these properties: those related to transport of energy through a system and those related to the thermodynamic or equilibrium state of a system [9]. Heat transfer properties of asphalt mixture are absorptivity (α), albedo (1-α), emissivity (ε) and thermal conductivity (k). Heat transfer or energy transfer can occur by means of conduction, radiation, and convection. Thermodynamic properties of asphalt concrete include density (ρ) and specific heat capacity (c_p) which is related to the equilibrium state of the system [9].

At the present, it is known that the thermal behaviour of asphalt mixture is mainly influenced by its air voids content, aggregate type and moisture content, although the interactions between these factors are mostly unknown and have been studied mainly from on-site observations under diverse climatic conditions, not from controlled laboratory tests [8]. In addition, previous research has attempted to change the factors influencing the thermal properties of asphalt pavements, e.g. the influence of moisture on the temperature of porous and dense asphalt mixture [10]; the thermal conductivity of aggregates, such as graphite, steel fibres or steel particles [11–13]; or the surface colour of the pavements [4]; but there is not any extensive study about the effect of air voids content on the thermal properties of asphalt roads.

For this reason, the main objective of this paper is to quantify the extent to which the air voids content of asphalt mixture influences its thermal conductivity, specific heat capacity or light absorptivity and explain the influence of these factors on the temperature evolution of asphalt mixture slabs when their surface is exposed to a source of heat.

2. Experimental method

2.1. Materials

Asphalt mixtures with various target air voids (TAV) contents: 4.5%, 10.0%, 13.0%, 17.0%, 21.0% and 26.0%, were produced using a 60/40 penetration grade bitumen binder and 20 mm maximum aggregate size. Limestone aggregate was used for all the test samples. Fig. 1 shows the gradation curves and bitumen content for the asphalt mixtures analysed.

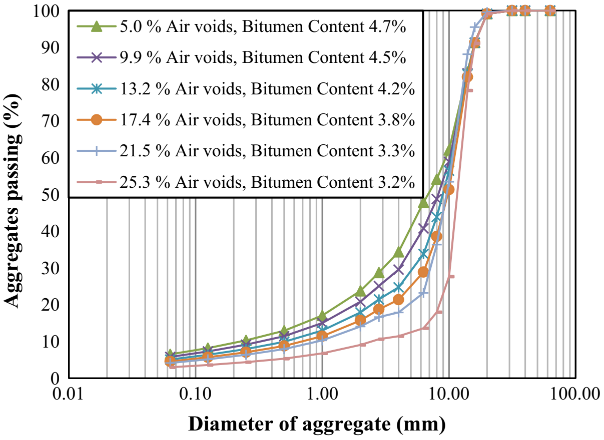

Fig. 1. Composition of asphalt mixtures.

2.2. Test specimens preparation

Three slabs (306 × 306 × 50 mm^3) were manufactured for each TAV and compacted to the target density using a roller compactor. The mixing temperature for all the mixes was approximately 160 °C. The air voids content obtained in the slabs was 5.0%, 9.9%, 13.2%, 17.4%, 21.5% and 25.3%, for mixtures with target air voids 4.5%, 10.0%, 13.0%, 17.0%, 21.0% and 26.0%, respectively.

2.3. Density

The maximum density of asphalt mixture was determined through the BS EN 12697, part 5 (2009) [14] by the mathematical method. In addition, the bulk densities of the test specimens were determined through the BS EN 12697, part 6 (2003) [16] by the dimensions method from the average of three test specimens for every asphalt mixture type analysed.

2.4. Air voids content

The air voids content of asphalt mixture was calculated based on the previous calculation of the maximum and bulk densities. The percentage of air voids in the mixture can be calculated as:

$$V_m = \frac{\rho_m - \rho_b}{\rho_m} \times 100\%. \tag{1}$$

where ρ_m is the theoretical maximum density of the mixture without voids, measured in kg/m^3, ρ_b is the bulk density in the mixture, measured kg/m^3, and V_m is the air voids content in the mixture, measured in %.

2.5. Experimental setup and measurements

Fig. 2 illustrates the apparatus and experimental setup used to carry out the laboratory testing of asphalt concrete slabs. With this purpose, a rectangular box of 18 mm thick birch ply wood sheet, with an area of 392 × 392 mm^2 and a height of 75 mm was constructed to insulate the test samples during testing. The bottom and all four edges of the box were insulated using 25 mm Polyisocyanurate boards in order to minimize heat loses or gains. This mould contained asphalt mixture slabs of 306 × 306 × 50 mm^3.

Infrared lamps were used as a source of heat. The heat source was comprised of four 250 W infrared lamps installed in two rows at approximately 730 mm above the asphalt slab surface, covering the whole asphalt area (see Fig. 2).

2.6. Light intensity measurements

Solar intensity was measured using a pyranometer (Kipp & Zonen CMP 11) that measures the solar intensity up to 4000 W/m^2 with an accuracy of ±3%. The pyranometer was levelled and positioned under the infrared lamps at the centre of the asphalt concrete slabs. To measure the light intensity received by the asphalt concrete surface from the heat source at the position of the thermocouple, the height of the pyranometer sensor from the ground was set up at 730 mm.

2.7. Temperature measurements

The temperature of the air, the surface of the asphalt concrete slabs and the bottom of the asphalt concrete slabs was measured by using J-type thermocouples. The test samples cross-section and the position of thermocouples in the pavement are shown in Fig. 2. The temperature profile was recorded for 20 min under a constant environmental temperature of 25 °C. The temperature evolution of test samples was measured during 12 h heating and during 12 h cooling down as shown in Fig. 3, to simulate day and night, under a real conditions.

2.8. Data acquisition system

The thermocouples and pyranometer were connected to a data logger (omega OMB-DAQ-54) where temperature profile and intensity rate were recorded at 2 s intervals.

2.9. Emissivity measurements

The surface emissivity of the pavement was measured using a high resolution infrared camera (FLIR SC7000), with a spectral range of 3.5–5.0 μm and a sensitivity of 0.07 °C, connected to the FLIR system software (ALTAIR). The infrared camera was installed at a vertical angle of approximately 70 degrees from the test samples.

The emissivity was tested following this procedure:

1. The slabs were heated using the infrared lamps until the surface and bottom temperatures were stable (both temperatures were monitored using readings obtained from thermocouples).