Influence of the Type of HMA and Free Space Content and the Thermal Conductivity Coefficient $\lambda$

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Abstract. The surface temperature is diversified in cross-section and varies with external conditions. The dynamics of these changes depend on the possibility of taking over heat through the top layer and from its further flow to the lower layers of the structure. The heat transfer through pavements takes place due to convective heat exchange with air and radiation. Further heat transfer through the surface layers is due to conduction and is defined by the Fourier equation. The solution to the equation is the method of separating variables in the form of the product of two functions: time and space. The parameter decisive for the heat flow rate into the surface is the thermal conduction coefficient $\lambda$. For the purpose or type of HMA the value of this coefficient is not constant, assigned to the layer or type of asphalt mixture. It depends on the type of aggregate (its thermal properties), the volume shares of individual components (asphalt, aggregate), the structure of the material and the content of free spaces. The value of the thermal conductivity coefficient is also influenced by the degree of material moisture and temperature. The article presents the results of tests of the thermal conductivity coefficient of sixteen HMA. They were different due to the type of mixture (asphalt concrete, stone mastic asphalt, porous asphalt, macadam mix), the type of aggregate used (granite, diabase), the volume of free space and the temperature of the designation. The choice of aggregates was dictated by their diversity in terms of origin, acidity and thermal and physical properties. In both cases, they are igneous rocks, where the diabase belongs to the vein group (with a composition similar to basalts), and the granite to the deep-sea ones. They differ from each other in terms of acidity (diabase is a basic rock - alkaline, whereas granite is an example of acidic rock - silic), thermal parameters (thermal conductivity, specific heat and emissivity of radiation) and physical (density). The choice of the type of binder was conditioned by the intended use of the mixture. 50/70 asphalt was used for the abrasive layer, while the binding layer and foundation as well as the 35/50 asphalt macadam mix were used. The content of free spaces in the mixes ranged from 2.0% to 33.8%. The test was carried out at 20 °C and 50 °C. The obtained results indicate that concrete-type mixes (AC) are characterized by higher thermal conductivity coefficients than mixtures with an increased grit fraction (SMA, PA, Macadam). The basic parameter influencing the value of the thermal conductivity coefficient was the content of free spaces. With its increase, the heat conductivity decreased.

1. Introduction

Prior knowledge of temperature distribution in asphalt pavement enables prediction of how individual layers of asphalt mixtures will behave due to external interactions. Surface temperature is not constant and changes along with external conditions. The dynamics of changes is dependent on the ability of top
layer to absorb heat and on its further flow into deeper layers [1–4]. Heat conductivity coefficient \( \lambda \) of bitumen mixes is one of the decisive factors of their heat flow rate. It is not a constant value ascribed to a layer or a mix type. It can be influenced by external factors; such as grass saturation rate or temperature. Heat flow in a layer of mineral-asphalt mix occurs due to conduction. Heat transfer rate in this way is expressed by heat conductivity coefficient \( \lambda \). It can be defined by Fourier transform (1) [5–9]

\[
dQ = -\lambda \frac{dT}{dx} \times dS \times dt
\]

where: \( dQ \) — heat transfer, J; \( \lambda \) — heat conductivity coefficient, W/(m×K); \( dS \) — cross-sectional area of heat transfer, m²; \( \frac{dT}{dx} \) — temperature gradient of layer thickness (heat conduction path) dx, K/m; \( dt \) — time, s.

According to kinetic theory, coefficient \( \lambda \) expresses the ability of a particle with higher energy to transfer some energy to particles with lower energy. This means that heat flows from high temperature to low temperature places. Heat conductivity coefficient is mainly influenced in solids by bulk density and a correlated parameter: void space content. Exemplary heat parameter values of selected materials are presented in Table 1.

Table 1. Heat parameters of materials [5,6,10,11]

| Material            | Temperature, K | Bulk density, kg/m³ | Heat conductivity coefficient \( \lambda \), W/(m×K) | Specific heat \( c_p \), kJ/(kg×K) |
|---------------------|----------------|---------------------|----------------------------------------------------|----------------------------------|
| Dry air             | 273,15         | 1,252               | 0,02373                                            | 1,011                            |
|                     | 293,15         | 1,164               | 0,02512                                            | 1,012                            |
|                     | 373,15         | 0,916               | 0,03070                                            | 1,022                            |
|                     | 473,15         | 0,723               | 0,03698                                            | 1,035                            |
| Saturated water vapour | 373,15       | 0,5974              | 0,0248                                             | 2,034                            |
| Water               | 293,15         | 998,2               | 0,597                                              | 4,182                            |
| Bitumen             | 293,15         | 1030                | 0,174                                              | 0,921                            |
|                     | 273,15         |                     | 1,651                                              |                                  |
|                     | 293,15         | 2900÷3100           | 1,675                                              | 0,795                            |
|                     | 373,15         | 1,768               | 0,963                                              |                                  |
| Basalt              | 293,15         | 2500                | 2,908                                              | 0,754÷0,918                      |
|                     | 3300           |                     | 4,071                                              |                                  |

2. Laboratory tests of heat conductivity coefficient

Tests of heat conductivity coefficient \( \lambda \) were conducted on bitumen mix samples for various pavement layers. Samples of each mix type of different void space content were made. Selected properties of mixes based on diabase and granite aggregates are presented in Tables 2 and 3. Bitumen 50/70 was used for wearing course, bitumen 35/50 for contact structure mixes (M, PA), polymer modified bitumen (PMB) 45/80-65 for binding course and road base. Bulk density tests were conducted in accordance with PN-EN 12697-6, according to the procedure of void space prediction:

- under 7 % according to procedure B (SSD based on mass of the sample in dry state, in air, saturated, surface dry in air and in water);
- in the range of 7–10 % according to procedure C (based on mass of the sample in dry state, in air and on surface sealed samples in air and in water);
- above 10% according to procedure D (based on sample dimensions).
Table 2. Physical properties of HMA samples (diabase aggregate)

| HMA type     | Sample       | Parameter of Hot Mix Asphalt | \( B \) | \( \rho_{mv} \) | \( \rho_b \) | \( V \) | \( VMA \) | \( \lambda (20^\circ C) \) | \( \lambda (50^\circ C) \) |
|--------------|--------------|-------------------------------|--------|----------------|------------|------|--------|----------------|----------------|
| AC 8 S 50/70 | AC/8/1/D     | 6,0 2,705 2,644\(^{1)}\) 2,26 17,81 1,156                 |        |                |            |      |        |                |                |
|              | AC/8/2/D     | 6,0 2,705 2,644\(^{1)}\) 2,26 17,81 1,156                 |        |                |            |      |        |                |                |
| AC 1 S 5/70  | AC/11/1/D    | 4,8 2,745 2,680\(^{1)}\) 2,37 14,98 1,016                 |        |                |            |      |        |                |                |
|              | AC/11/2/D    | 4,8 2,745 2,680\(^{1)}\) 2,37 14,98 1,016                 |        |                |            |      |        |                |                |
| AC 16 W 35/50| AC/16/1/D    | 4,0 2,792 2,711\(^{1)}\) 2,90 13,53 1,151                 |        |                |            |      |        |                |                |
|              | AC/16/2/D    | 4,0 2,792 2,711\(^{1)}\) 2,90 13,53 1,151                 |        |                |            |      |        |                |                |
| AC 22 P 35/50| AC/22/1/D    | 3,8 2,815 2,697\(^{1)}\) 4,19 14,24 1,245                 |        |                |            |      |        |                |                |
|              | AC/22/2/D    | 3,8 2,815 2,697\(^{1)}\) 4,19 14,24 1,245                 |        |                |            |      |        |                |                |
| SMA 8 50/70  | SMA/8/1/D    | 6,3 2,674 2,593\(^{1)}\) 2,88 18,92 0,824                 |        |                |            |      |        |                |                |
|              | SMA/8/2/D    | 6,3 2,674 2,593\(^{1)}\) 2,88 18,92 0,824                 |        |                |            |      |        |                |                |
| SMA 1 50/70  | SMA/11/1/D   | 6,0 2,689 2,606\(^{1)}\) 3,09 18,42 0,792                 |        |                |            |      |        |                |                |
|              | SMA/11/2/D   | 6,0 2,689 2,606\(^{1)}\) 3,09 18,42 0,792                 |        |                |            |      |        |                |                |
| PA 11 PMB 45/80-65 | PA/11/D     | 5,7 2,705 2,257\(^{1)}\) 16,56 29,17 0,569                 |        |                |            |      |        |                |                |
| M 8-11 PMB 45/80-65 | M/8-11/D   | 3,5 2,819 1,9049\(^{1)}\) 32,36 38,90 0,536 0,553          |        |                |            |      |        |                |                |

\( B \) – asphalt content, \( \rho_{mv} \) – maximum density of the bituminous mixture, \( \rho_b \) – bulk density, \( V \) – air void content, \( VMA \) – voids in mineral aggregate, \(^{1)}\) – bulk density – procedure B (\( \rho_{bsd} \)), \(^{2)}\) – bulk density sealed – procedure C (\( \rho_{bsd} \)), \(^{3)}\) – bulk density by dimensions – procedure D (\( \rho_{bdim} \))

The tests were conducted in plate apparatus (Fig. 1), at the temperature of approximately 20ºC (averaged for both sides of the plate). Additional tests at approximately 50ºC were carried out for some mixes. All samples measured 250×250 mm. Their thickness was between 50 and 70 mm. Upper and lower surface was polished, to obtain parallel planes and to smoothen their roughness, which guaranteed good contact with hot and cold plates.

Roughness of surface would have significantly affected measured parameter values. A local layer of air would have developed between the sample and the hot (or cold) plate of apparatus, resulting in varied heat flow. Air is characterised with low heat conductivity coefficient. Averaged results of heat conductivity coefficient \( \lambda \) tests conducted for selected samples on individual layers are presented in Tabs. 2-3.

![Figure 1. Diagram of plate apparatus used to measure heat conductivity coefficient \( \lambda \) ![Figure 1. Diagram of plate apparatus used to measure heat conductivity coefficient \( \lambda \)
Table 3. Physical properties of HMA samples (granite aggregate)

| HMA type     | Sample   | Parameter of Hot Mix Asphalt | B (20°C) | ρw (g/cm³) | ρb (g/cm³) | V (%) | VMA (%) | λ (20°C) (W/m×K) | λ (50°C) (W/m×K) |
|--------------|----------|-----------------------------|----------|------------|------------|--------|---------|------------------|------------------|
| AC 8 S 50/70 | AC/8/1/G | 6.2, 2.449                   | 2.404¹   | 1.96       | 16.45      | 1,133  | 1.141   |                  |                  |
|              | AC/8/2/G |                           | 2,333¹   | 4.93       | 18.99      | 0.938  |         |                  |                  |
| AC 11 S 50/70| AC/12/1/G| 5.2, 2.465                   | 2.396¹   | 2.80       | 15.01      | 0.993  |         |                  |                  |
|              | AC/12/2/G|                           | 2.325¹   | 5.68       | 17.53      | 0.822  |         |                  |                  |
| AC 16 W 35/50| AC/16/1/G| 4.4, 2.493                   | 2.396¹   | 3.89       | 14.23      | 1.122  |         |                  |                  |
|              | AC/16/2/G|                           | 2.299²   | 7.88       | 17.70      | 0.843  | 0.849   |                  |                  |
| AC 22 P 35/50| AC/22/1/G| 4.1, 2.506                   | 2.405¹   | 4.03       | 13.70      | 1.182  |         |                  |                  |
|              | AC/22/2/G|                           | 2.306²   | 7.98       | 17.25      | 1.024  |         |                  |                  |
| SMA 8 50/70  | SMA/8/1/G| 6.6, 2.426                   | 2.370¹   | 2.31       | 17.64      | 0.888  |         |                  |                  |
|              | SMA/8/2/G|                           | 2.297¹   | 5.32       | 20.18      | 0.733  |         |                  |                  |
| SMA 11 50/70 | SMA/11/1/G| 6.2, 2.435                  | 2.373¹   | 2.55       | 16.97      | 0.865  |         |                  |                  |
|              | SMA/11/2/G|                          | 2.301¹   | 5.50       | 19.49      | 0.713  | 0.716   |                  |                  |
| PA 11 PMB 45/80-65 | PA/11/G | 5.9, 2.462                  | 1.989³   | 19.21      | 30.72      | 0.587  |         |                  |                  |
| M 8-11PMB 45/80-65 | M/8-11/G | 3.6, 2.552                  | 1.692³   | 33.70      | 39.67      | 0.542  | 0.559   |                  |                  |

3. Analysis of results

Measurement results of heat conductivity coefficient $\lambda$ were in the range of 0.5 - 1.3 W/(m×K). It places bitumen mixes closer to thermal insulation materials rather than those with good thermal conduction. Coefficient $\lambda$ value is variable and depends on many factors, which can be divided into two groups. The first consists of material properties, i.e. aggregate type, mix type and content of constituent components. The second comprises physical properties of the mix and temperature in which the test is conducted.

Analysis of material properties showed that the type of rock had little effect on coefficient $\lambda$. It was igneous rock in both cases. Diabase belongs to intrusive rock (with content similar to that of basalt) and granite to plutonic rock type. Even substantial differences of the properties of a material did not affect coefficient $\lambda$ of mix samples. For example, rock heat conductivity coefficient was 1.65–1.78 W/(m×K) for diabase and 2.9–4.1 W/(m×K) for granite. Diabase and granite density was approximately 3.1 g/cm³ and approximately 2.7 g/cm³, respectively. Coefficient $\lambda$ depends to a larger degree on the share of bitumen and air, or to be more precise on the structure of bitumen mix consisting of the two components.

Values of heat conductivity coefficient $\lambda$ for different types of (concrete and medium/macadam) mixes are presented in Figs. 2-3. Comparison of asphalt concrete (AC) with stone matrix asphalt (SMA) mixes showed decrease of coefficient $\lambda$ by an average of 20%. A greater difference of 40% was observed between concrete and contact (macadam) mixes. Average value of coefficient $\lambda$ of AC mix was 1.022 W/(m×K) and that of PA and M mix was 0.699 W/(m×K). Such substantial differences of coefficient $\lambda$ values can be due to total contact area between mix components surrounded by mastic film. It is the biggest in concretes and the smallest in macadams. It is therefore fair to assume that the size of contact area between MM grains will to some degree affect energy transfer rate (in the form of heat) in the whole mix. Heat flow through conduction is definitely greater than that due to natural convection in closed pores of a material.
Test results confirmed no influence of the amount of bituminous binder (both in weight and volume proportion) and its type (35/50, 50/70, PMB 45/80-65) on heat conductivity coefficient $\lambda$. In the group of physical properties, void space content in mineral and mineral-asphalt mixes had the greatest effect on heat conductivity coefficient $\lambda$. Temperature has little impact on the coefficient. Test results of heat conductivity coefficient relative to void space content in mineral and mineral-asphalt mixes are presented in Figures. 4-5.
Figure 4. Effect of void space content in MM (VMA) on coefficient $\lambda$ at 20ºC

Figure 5. Effect of void space content in MMA (VA) on coefficient $\lambda$ at 20ºC

Increase of pore volume by 1% in mineral mix caused decrease of coefficient $\lambda$ by 0.08 W/(m×K) in mineral mix and by 0.07 W/(m×K) in mineral-asphalt mix. The phenomenon is attributable to two factors. The first factor is void space filled with air. Air (with coefficient $\lambda$ of 0.0251 W/(m×K) at 20ºC) in MMA plays the role of insulation barrier, which inhibits heat flow. The second factor is contact area between mineral mix grain, surrounded by mastic film (binder and filler mixture). The greater the area, the bigger the ability to transfer heat. It is due to high $\lambda$ values of aggregate. If we compare concrete (AC S) and medium (SMA) wearing course mixes, the former has markedly greater conduction than the latter, although their void space is comparable.
4. Conclusions

Analysis of coefficient $\lambda$ tests showed that the minimum conductivity was found for contact mixes (PA, M). Despite significant differences in void space content in the range of 15-16%, their thermal conductivity was on a similar level (0.54–0.59 W/(m×K)). This demonstrates that thermal conductivity does not change much from a certain level of void space in MMA and MM. This is further evidenced by $\lambda$ values of 0.61–0.68 W/(m×K) obtained for medium type SMA mixes with increased void space (increase by approximately 5%). Much higher $\lambda$ values of concrete mixes, given similar void space, confirm the assumption that immediate contact area between aggregate grains is the decisive factor of heat flow ability.

Pore formation can also have an effect on heat conductivity coefficient $\lambda$ of mineral-asphalt mixes. If pores are closed and have small size, heat flow occurs through conduction. In case of air voids of substantial size, an additional effect that accelerates heat flow rate can be obtained through convection, or even radiation, mainly in surface layer. These two additional types of heat flow can occur in material pores given temperature difference between opposite areas of air void when void space is large enough. This can generate lift flux (in free convection), energy transfer through heated gas particles and heat flow through radiation.

Air flow between pores in a material of substantial content of void space (> 10÷16%) can in certain conditions determine coefficient $\lambda$ values. It primarily applies to placement stage when mixes are cooled. After spreading, mineral-asphalt mixes can be characterised by void space above 10%. For porous concrete, void space can even exceed 30%. Adverse weather conditions, including wind, low air temperature and high humidity, conducive to quick cooling of surface layer, can trigger additional heat flow in line with chimney effect, given open pores. Chimney effect is driven by temperature and pressure differences at the top and bottom of connected air pores. Higher temperature and pressure occur at bottom layer, which drives buoyancy force upwards. The narrower and longer the fissure, the greater air flux inside it. The above description clearly shows that the phenomenon is forced convection in micro scale. It causes quicker cooling of a layer if the condition of air flow in pores is met. When pores are closed, e.g. following road roller pass, the phenomenon is halted.

To sum up, thermal conductivity of mineral-asphalt mixes depends on many factors. The main factors include void space content and packing density of mineral parts (total contact area between them). They can be classified in a group of materials with relatively low conductivity, in the range of 0.5-1.3 W/(m×K). The study showed that these are extreme values, on the one hand limited by minimum void space and extensive contact area between aggregate grain and on the other by mixture stability and maximum distance between grains. Pores with large volume can disturb conduction process and introduce convection, an additional form of heat transfer.

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