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A laboratory investigation on thermal properties of virgin and aged asphalt mixture

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ABSTRACT

In this paper, the thermal properties of three dense graded asphalt mixtures, 20 mm DBM, AC 14, and AC 6, are presented. Density and air voids of the compacted specimens are also shown. Thermal conductivity was measured in the laboratory for non-aged, short-term aged and long-term aged asphalt mixtures at three different temperatures 19 (±1) °C, 65 (±5) °C, and 80 (±5) °C. Specific heat capacity and thermal diffusivity were calculated from equations derived from the literature. Heat penetration depth was also calculated and shows the heat from the thermal conductivity instrument heat source that dissipates into the asphalt specimens. The results were analysed to determine the effect of air voids content, transient line source (TLS) method, temperature and aggregate size in thermal conductivity and the effect of aging on the thermal properties of the asphalt mixtures studied. It was concluded that there is a minimal effect in thermal conductivity for 4% to 6.5% air voids. The method of measurement and temperature affect considerably thermal conductivity. However, the results were inconclusive in the effect of aggregate size on thermal conductivity. The effect of asphalt aging in thermal conductivity and thermal diffusivity varied between the asphalt mixtures studied and was relative to the temperature. Asphalt aging did not affect specific heat capacity.

1. Problem statement and objectives

Heat transfer and storage inside an asphalt pavement is affected by asphalt transport properties and thermodynamic properties. The transport properties are absorptivity (a), albedo (1-a), emissivity (ε), and thermal conductivity (k) and the thermodynamic properties are density (ρ) and specific heat capacity (c_p) [1]. Although these properties of asphalt mixtures are influenced by the environmental condition, age, mixture composition, and density, they are not considered during the maintenance and rehabilitation operation. For resurfacing and patching, a shallow 40–100 mm thick asphalt layer is laid on the old pavement. The age of old pavement could be 20 to 30 years. A layer of tack coat is also applied on the planned surface to promote bonding between layers. However, the difference in thermal properties between old and new pavement will inevitably have an impact on the heat transfer at the interface. This could lead to a thermal barrier and consequently inferior bonding and compaction. As the thickness of the new layer is relatively shallow and depending on the time of the year, the temperature of the planned surface is cold (~5 °C) to warm (~30 °C), the temperature at the interface could quickly reach to the cessation temperature, making it harder to achieve adequate compaction. It is, therefore, important to investigate to what extent the thermal properties of asphalt mixtures are changed due to aging. In a parallel study, the authors have investigated the positive impact of dynamic pre-heating on the interface bonding during asphalt patch repair [2].

The objective of this research is to investigate the changes in thermal properties of dense graded asphalt mixture, a widely asphalt mixture used for resurfacing and patching. This paper presents results from a comprehensive laboratory study to investigates the effect of mixture air voids content, temperature, and aging in thermal properties of 20 mm dense bitumen macadam (DBM), asphalt concrete (AC) 14 and AC 6 asphalt mixtures. The effect of the transient line source (TLS) method used to measure thermal conductivity (k) is also investigated.

2. Thermal properties

There are two techniques to measure thermal conductivity: the steady-state and the non-steady-state. Investigation of thermal conductivity with the steady-state technique implies that the measurement is done when the material has reached thermal equilibrium. Due to this

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requirement, the technique is time-consuming. The non-steady-state technique (such as the TLS used in this study) gives faster results since thermal conductivity is measured during the heating up of the material [3]. This technique consists of the hot wire and transient plane source (TPS) methods.

To measure thermal conductivity k with the hot wire method, the linear heat source is inserted at the center of the sample. A thermocouple is also put at a known distance from the hotline source. The thermocouple captures the temperature difference ΔT in the sample for a specific duration of time that heat flows from the hot wire. Then, k is calculated using Eq. (1) [4]. It is important to ensure that the test sample is put in a furnace to maintain its temperature during the testing [5]. The needle probe method is similar in execution with the hot-wire method. The difference between the methods is that the probe works as a heating element source and a sensor for the needle-probe method [6].

$$k = \frac{p}{4\pi[T(t_2) - T(t_1)]L}\ln\left(\frac{t_2}{t_1}\right) \quad (1)$$

where k = thermal conductivity, W/m K; t_1 and t_2 = time, s; L = distance between thermocouples, m; p = heating power, W.

The TPS method uses a very thin insulated metal disk that works both as a heat source and a sensor. The metal disk is put between two similar pieces of the sample with insulated external faces, a constant current is applied to the metal disk to heat the sample and the temperature difference over time is captured. Thermal conductivity is determined from Eq. (2) [7].

$$\Delta T(\varphi) = \frac{Q}{\pi^{1.5} rk} D(\varphi) \quad (2)$$

where ΔT = temperature difference, K; Q = heat flow, W/m; r = sensor radius, m; k = thermal conductivity, W/m K; D(φ) = a dimensionless theoretical expression of sensor time-dependent heat conduction; φ = defined as $\sqrt{\frac{ta}{r^2}}$ (where t = half period of the heating current in pulsed power technique, s; a = width, m; r = sensor radius, m).

Finally, thermal diffusivity (a) and specific heat capacity (c_P) can be calculated using Eq. (3) [1,8] and Eq. (4) [9] respectively below:

$$a = \frac{k}{\rho_{c_P}} \quad (3)$$

where k = thermal conductivity, W/m K; ρ = density, kg/m^3; and c_P = specific heat capacity, J/kg K.

$$c_P = \frac{1}{m_{total}}\left[m_{aggregate} \times c_{aggregate} + m_{bitumen} \times c_{bitumen}\right] \quad (4)$$

where m = mass of each material, kg; and c = specific heat capacity of each constituent, J/kg K.

3. Experiments

3.1. Materials and experimental program

The three dense graded asphalt mixtures studied (20 mm DBM, AC 14, and AC 6) cover mixtures that are normally used for binder and surface courses in asphalt pavement. The mixtures comprised of granite coarse and fine aggregate and limestone filler. The binder used was 100/150 penetration grade bitumen. The design of the mixture and the binder content complies with BS EN 13108, part 1 [10]. According to this standard, the binder content for 20 mm DBM, AC 14, and AC 6 asphalt mixtures should be 4.6%, 5.1%, and 5.2% respectively. However, to construct specimens with air voids close to 5%, different sets of filler and binder contents were performed for trial samples. The filler content in the trial mixtures was changed at 5 g increments and ranged from 145 g to 160 g for 20 mm DBM asphalt mixture, from 195 g to 207 g for AC 14 asphalt mixture and from 190 g to 210 g for AC 6 asphalt mixture. The binder content in the trial mixtures was changed at 0.5% increments and ranged from 53 g to 67 g for 20 mm DBM asphalt mixture, from 59 g to 71 g for AC 14 asphalt mixture and from 77 g to 82 g for AC 6 asphalt mixture. The gradation curves of the mixtures resulting from the trials are shown in Fig. 1.

Table 1 shows the executed experimental program and the materials used for the study. Forty-five cylindrical specimens were built in total, fifteen per asphalt mixture type comprising five non-aged, five short-term aged, and five long-term aged specimens. All specimens were used to measure thermal conductivity (k) in the laboratory at three different temperatures 19 (±1) ^{o}C, 65 (±5) ^{o}C, and 80 (±5) ^{o}C.

3.2. Preparation of test specimens

3.2.1. Non-aged asphalt mixtures

To prepare the specimens, before sieving, the aggregates were dried for 24 h at 110 (±5) ^{o}C in a ventilated oven. The preparation of the aggregate, filler, and binder before mixing, the asphalt mixing and the procedure followed to control the mix temperature conform with BS EN 12697, part 35 [11]. The preparation of the Marshall compaction hammer and the mould prior to compacting the specimens and the number of blows per specimen side for compacting the specimen conforms to BS EN 12697, part 30 [12]. Fifty compaction blows were chosen for this study per specimen side.

A trial specimen for each asphalt mixture type was first prepared before making the batches for all specimens. The compacted specimen diameters and heights were 101.3 (±0.2) mm and 62.0 (±0.7) mm respectively. The amount of asphalt mixture for a specimen was 1100 g. The mixture for each specimen was prepared separately and compacted immediately after mixing. The mixture temperature before compaction was 110 (±5) ^{o}C which differs from the one suggested in BS EN 12697, part 35 [11]. The temperature was monitored using an infrared camera [13]. At the end of compaction, the specimens were allowed to cool down for 3 h, and then they were de-molded with an extruding device. The specimens were stored in a hermetically closed container at 19 (±1) ^{o}C until testing.

3.2.2. Short-term aged asphalt mixtures

Short-term aged asphalt mixtures were prepared as described for non-aged asphalt mixtures but before compaction and immediately after mixing, the loose mixture was placed in a pan, evenly spread out and put for 4 h at 135 (±3) ^{o}C to a ventilated oven to achieve short-term aging. The mixture was stirred every 60 min to maintain uniform conditioning. The described method of short-term aging asphalt mixtures complies with AASHTO R30 [14]. The mixtures were compacted immediately after conditioning. The compaction method, cooling time after compaction, extraction from the mould, and storing of specimens after extraction was done as described in the previous section.

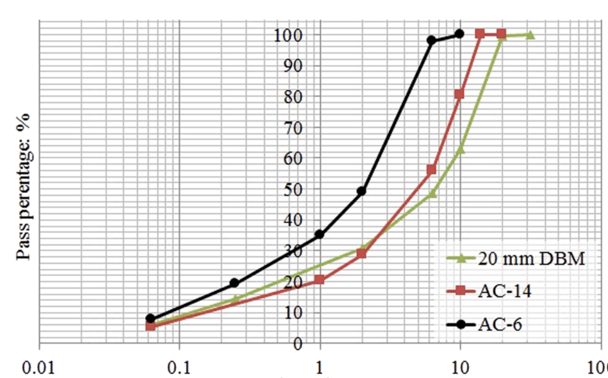

Fig. 1. Composition of slab asphalt mixture.

Table 1
Materials and experimental program.

Specimen no.	Asphalt mixture type	Asphalt mixture condition	Temperatures for thermal conductivity *k* measurements		
			19 (±1) °C	65 (±5) °C	80 (±5) °C
C1-C5	20 mm DBM	Non-aged	✓	✓	✓
C6-C10		Short-term aged	✓	✓	✓
C11-C15		Long-term aged	✓	✓	✓
C16-C20	AC 14	Non-aged	✓	✓	✓
C21-C25		Short-term aged	✓	✓	✓
C26-C30		Long-term aged	✓	✓	✓
C31-C35	AC 6	Non-aged	✓	✓	✓
C36-C40		Short-term aged	✓	✓	✓
C41-C45		Long-term aged	✓	✓	✓

3.2.3. *Long-term aged asphalt mixtures*

The specimens were prepared as described above. After the specimens were extracted from the molds, they were stored for 16 h in a hermetically closed container at 19 (±1) °C. Then, they were covered with a steel mesh and put for conditioning for 5 days at 85 (±3) °C into a ventilated oven for long-term aging. The steel mesh was used to protect the specimens from expanding during conditioning. At the end of conditioning, the oven was turned off and the specimens were allowed to cool at room temperature for 16 h. The described method of long-term aging asphalt mixtures complies with AASHTO R30 [14]. In the end, the specimens were removed from the oven and stored inside a hermetically closed container.

4. Air voids content

The percentage of air voids in the mixture was calculated with Equation (6). This was done after cooling the specimens for 16 (±1) hours at 19 (±1) °C after their extraction from the compaction mould [14]. The bulk specific gravity (G_{mb}) was determined through the AASHTO T166, method A [15], and the maximum theoretical specific gravity (G_{mm}) was calculated with Eq. (5) [16]. In this equation, the effective specific gravity of aggregate (G_{se}) was taken as 2.65, and the specific gravity of bitumen (G_b) as 1.01 (measured at 25 °C).

$$G_{mm} = \frac{W_T}{\frac{W_{agg}}{G_{se}} + \frac{W_{AC}}{G_b}} \tag{5}$$

where W_T = total eight of asphalt mixture, g; W_{agg} = weight of aggregate, g; W_{AC} = weight of total asphalt binder, g.

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100\% \tag{6}$$

where VTM = air voids in total mix, %.

5. Asphalt thermal properties and TLS heat penetration depth

5.1. *Thermal conductivity (k), thermal diffusivity (a) and specific heat capacity (c_P)*

Thermal conductivity was measured with the TLS instrument shown in Fig. 2(a). These measurements were conducted after the air voids of the specimens were determined. Therefore, before measuring thermal conductivity, the specimens were dried at 40 °C to constant mass in a ventilated oven. This was adopted after Islam and Tarefder [17] study and it took approximately 24 h to complete. After drying, the specimens were allowed to cool in a room at 19 (±1) °C for 24 h. After cooling, thermal conductivity was measured.

To measure thermal conductivity, first, a hole 4 mm (D) × 50 mm (H) was drilled in the middle of the specimen. Second, the hole was cleaned from excess powder with compressed air. Lastly, the needle was covered with a thermal paste called Arctic Alumina [18] and inserted completely into the specimen. In addition, the specimens were covered with an insulating sheet that was held in place with a steel mesh to ensure no loss of heat during the measurements. However, the manufacturing company of the TLS equipment assured that the insulating sheet was not needed. This could probably be justified by the results of the heat penetration depth to be shown in the sections below which demonstrate that the heat applied by the TLS penetrates the mixture does not reach the boundaries of the specimen outer diameter.

Fig. 2(a) and (b) show the test set-up for measuring thermal conductivity at 19 (±1) °C and at 65 (±5) °C and 80 (±5) °C respectively. For the tests shown in Fig. 2(b), the specimens were put for 24 h in a ventilated oven at 65 (±5) °C. Then, thermal conductivity was measured

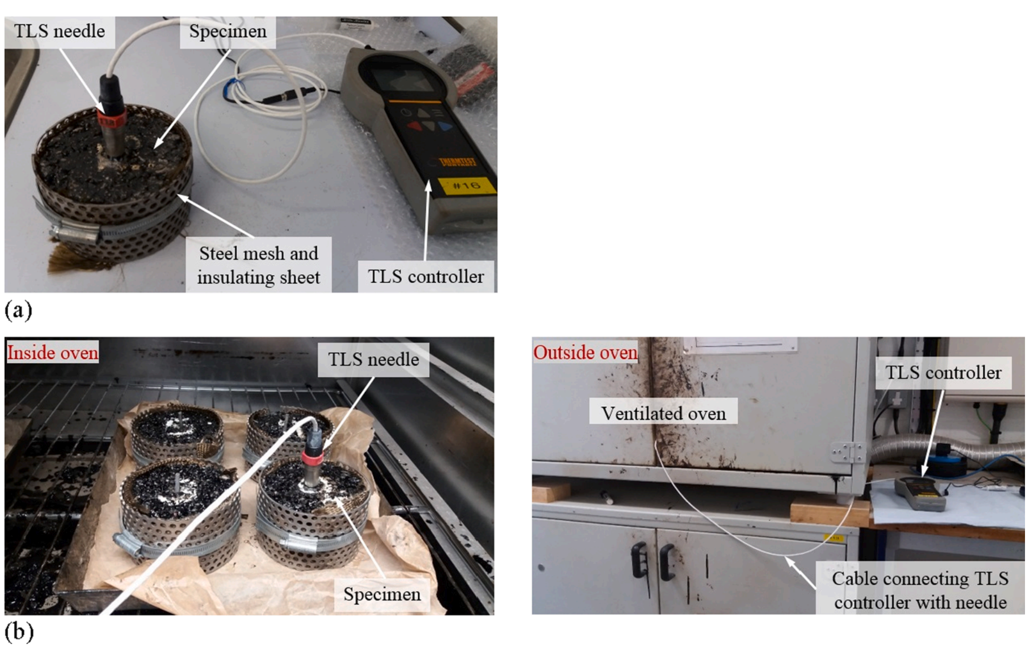

Fig. 2. Measurement of thermal conductivity (k) at: (a) 19 (±1) °C; (b) 65 (±5) °C and 80 (±5) °C (temperatures achieved with a ventilated oven).

inside the oven. After this, the specimens were let for another 24 h in the oven at 80 (±5) °C and thermal conductivity measured at the end of conditioning. Thermal diffusivity (a) and specific heat capacity (c_P) were calculated using Eqs. (3) and (4) shown in the introduction section.

5.2. Heat penetration depth (d)

Heat penetration depth was calculated using Eq. (7) [19]. It measures the depth a heatwave travels inside the asphalt mixture in the direction of heat flow. In this study, the calculation of the heat penetration depth helps in understanding the volume of mixture that participates and may affect the measurements of thermal conductivity.

$$d = \kappa\sqrt{a t_{tot}} \tag{7}$$

where d = heat penetration depth, mm; κ = 2, temperature recording sensitivity constant of the TLS method used in this study; a = thermal diffusivity, (mm2/s); t_{tot} = 150s, total time of TLS to measure thermal conductivity.

6. Results and discussion

Tables 2–4 show density, air voids, thermal conductivity, calculated specific heat capacity, thermal diffusivity and heat penetration depth for all the asphalt mixtures studied. For each specimen, thermal conductivity was measured three times. Thus, the results show the average of the three readings.

Further, the results show the thermal conductivity measured at three different temperatures. However, the calculations of the other parameters demonstrated in Tables 2–4 were done based on values measured at 25 (±1) °C in the case of density and air voids content and at 19 (±1) °C in the case of specific heat capacity, thermal diffusivity and heat penetration depth.

6.1. Density and air voids content

The air voids content obtained for all specimens ranged from 4.98% to 6.37% for 20 mm DBM, from 4.67% to 6.43% for AC 14 and from 4.20% to 5.73% for AC 6 asphalt mixture. However, the target air voids content was 5%. The variation of air voids from the target air voids content happened because when using an impact compactor it is difficult to prepare the samples with specific air voids content. An impact compactor is a static compression method of compaction that needs high pressures to apply to the mix to achieve the required density. The method lacks a kneading action to re-orientate the aggregates and fails to optimize the distribution of aggregates, binder, and air voids content [20]. This affected the density of the mixture which for this study for all specimens ranged from 2261 kg/m^3 to 2297 kg/m^3 for 20 mm DBM, from 2278 kg/m^3 to 2320 kg/m^3 for AC 14 and from 2240 kg/m^3 to 2279 kg/m^3 for AC 6 asphalt mixture.

6.2. Effect of air voids content and TLS method in thermal conductivity (k)

As is seen from the results in Tables 2-4, thermal conductivity measured at 19 °C for 20 mm DBM asphalt mixture ranged: from 1.33 W/m K to 1.907 W/m K for non-aged specimens; from 1.411 W/m K to 1.788 W/m K for short-term aged specimens; and from 1.561 W/m K to 1.761 W/m K for long term-aged specimens. At the same test temperature, the thermal conductivity of specimens constructed with AC 14 mixture ranged: from 1.135 W/m K to 1.748 W/m K for non-aged specimens; from 1.751 W/m K to 1.971 W/m K for short-term aged specimens; and from 1.681 W/m K to 1.970 W/m K for long-term aged specimens. For specimens with AC 6 mixture, thermal conductivity ranged: from 1.346 W/m K to 1.625 W/m K for non-aged specimens; from 1.664 W/m K to 1.883 W/m K for short-term aged specimens; and from 1.521 W/m K to 1.731 W/m K for long-term aged specimens.

As expected, the results showed that the thermal conductivity does not change significantly within the close range of void contents in the densely compacted mixture. This is in line with the previous studies, where researchers found that 2/3 times increase in void contents, leads to up to 10% change in the thermal conductivities. For example, Hassn et al. [9] and Mirzanamadi, Johansson, and Grammatikos [21] found that for a large variation of air voids content (from 5.0% to 25.3% for the study of Hassn et al. [9] and from 2.0% to 10.0% for the study of Mirzanamadi, Johansson, and Grammatikos [21]) thermal conductivity decreases when air voids increase. Hassn et al. [9] used 20 mm maximum limestone aggregate size and 60/40 penetration grade bitumen, whereas, Mirzanamadi, Johansson, and Grammatikos [21] used three types of asphalt mixture named ABT11, ABS11 and AG22 which are classified as dense-graded mixtures with 11 mm and 22 mm maximum aggregate sizes respectively. Further, the authors used 70/100 penetration grade bitumen for ABT11and ABS11 and 100/150 penetration grade bitumen for AG22. However, it should be noted that the impact of gradation, type of aggregates, and additives in the mixture

Table 2
Main parameters of the 20 mm DBM asphalt mixture specimens studied.

No.	Density (kg/m^3)	Air voids content (%)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Thermal diffusivity ($\times 10^{-7}$) (m^2/s)	Heat penetration depth (mm)		
Non-aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C1	2,297	4.98	1.455	1.062	0.873	883.96	7.17	20.74
C2	2,296	4.99	1.330	1.183	0.853	884.17	6.55	19.82
C3	2,290	5.25	1.906	1.464	1.053	884.64	9.41	23.76
C4	2,289	5.28	1.727	1.161	0.922	884.04	8.53	22.63
C5	2,280	5.55	1.907	1.142	0.928	885.29	9.45	23.81
Short-term aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C6	2,287	5.30	1.624	0.915	0.753	884.94	8.02	21.94
C7	2,287	5.35	1.697	0.997	0.884	884.46	8.39	22.44
C8	2,285	5.48	1.411	0.699	0.631	884.03	6.99	20.47
C9	2,274	5.83	1.920	0.927	0.753	884.95	9.54	23.92
C10	2,266	6.08	1.788	0.808	0.611	886.06	8.90	23.11
Long-term aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C11	2,297	4.99	1.761	1.016	0.595	884.07	8.67	22.81
C12	2,289	5.23	1.561	0.831	0.365	884.73	7.71	21.50
C13	2,280	5.57	1.564	0.829	0.517	885.19	7.87	21.73
C14	2,265	6.17	1.626	0.822	0.436	885.40	8.11	22.05
C15	2,261	6.37	1.582	0.873	0.392	884.99	7.90	21.78

Table 3
Main parameters of the AC 14 asphalt mixture specimens studied.

No.	Density (kg/m^3)	Air voids content (%)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Thermal diffusivity ($\times 10^{-7}$) (m^2/s)	Heat penetration depth (mm)		
Non-aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C16	2,320	4.67	1.427	1.339	0.996	885.32	6.95	20.42
C17	2,318	4.73	1.409	1.287	0.821	885.56	6.86	20.29
C18	2,317	4.75	1.748	1.284	0.944	886.06	8.51	22.60
C19	2,301	5.37	1.135	0.699	0.559	886.40	5.56	18.27
C20	2,295	5.65	1.184	1.041	0.835	886.27	5.82	18.69
Short-term aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C21	2,316	4.80	1.971	1.074	0.865	886.20	9.61	24.01
C22	2,311	5.04	1.820	1.121	0.914	885.60	8.89	23.10
C23	2,298	5.40	1.751	1.076	0.898	887.59	8.58	22.69
C24	2,293	5.65	1.871	0.875	0.975	887.31	9.20	23.49
C25	2,287	6.01	1.886	0.812	0.722	885.88	9.31	23.64
Long-term aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C26	2,294	5.76	1.681	1.055	0.829	885.38	8.28	22.29
C27	2,287	5.94	1.857	1.175	0.816	886.36	9.16	23.44
C28	2,284	6.09	1.738	1.041	0.858	886.34	8.59	22.70
C29	2,282	6.18	1.832	0.985	0.703	886.15	9.06	23.32
C30	2,278	6.43	1.970	1.140	0.840	885.14	9.77	24.21

Table 4
Main parameters of the AC 6 asphalt mixture specimens studied.

No.	Density (kg/m^3)	Air voids content (%)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Thermal diffusivity ($\times 10^{-7}$) (m^2/s)	Heat penetration depth (mm)		
Non-aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C31	2,272	4.55	1.472	1.241	1.033	872.68	7.42	21.11
C32	2,270	4.61	1.346	1.121	0.896	872.79	6.79	20.19
C33	2,265	4.78	1.351	1.111	0.836	873.17	6.83	20.24
C34	2,263	5.04	1.625	1.296	0.963	871.70	8.24	22.23
C35	2,256	5.22	1.503	1.255	0.937	872.85	7.63	21.40
Short-term aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C36	2,279	4.20	1.670	0.779	0.855	873.31	8.39	22.44
C37	2,270	4.40	1.883	1.061	0.826	874.57	9.48	23.85
C38	2,257	5.09	1.741	0.744	0.732	873.42	8.83	23.02
C39	2,254	5.09	1.664	0.788	0.816	874.52	8.44	22.51
C40	2,248	5.42	1.741	0.798	0.817	873.74	8.86	23.06
Long-term aged asphalt mixture								
	25 °C	19 °C	65 °C	80 °C	19 °C			
C41	2,265	4.77	1.521	0.901	0.629	873.30	7.69	21.48
C42	2,265	4.81	1.673	0.981	0.712	873.04	8.46	22.53
C43	2,262	4.92	1.587	0.963	0.720	873.14	8.04	21.96
C44	2,249	5.39	1.731	1.037	0.729	873.60	8.81	22.99
C45	2,240	5.73	1.631	0.929	0.680	873.94	8.33	22.36

may lead to greater impact on thermal conductivities within the close proximity of void contents.

Nevertheless, excluding a direct effect of air voids in thermal conductivity, there is still a variation in the thermal conductivity of specimens for each asphalt mixture type and conditioning. This happened because, as previously noted, compaction with an impact compactor affects the uniformity of air voids in the mix. This means that the area used by the TLS instrument to measure thermal conductivity may have a different distribution of air voids, aggregate, filler, and binder. The amount of exposure of these parameters also after drilling a hole in the middle of the specimens to measure thermal conductivity and their properties will affect thermal conductivity.

Thus, when thermal conductivity is measured with the TLS (or else the needle method) only a part of the sample is used. This can be seen by the heat penetration depth results shown in Tables 2–4 which for 20 mm DBM, AC 14, and AC 6 mixtures ranged from 19.82 mm to 23.92 mm, from 18.27 mm to 24.21 mm and from 20.19 mm to 23.85 mm respectively. The specimens of this study consisted of coarse and fine granite with an average thermal conductivity of 2.68 W/m K (this is affected by the porosity of the stone water content, local characteristics, sampling dependence and mineralogical composition with granite depending considerably on its quartz and albite content, Eppelbaum, Kutasov and Pilchin [22], limestone filler of 2.92 W/m K [23], binder without additives of 0.39 W/m K [24], air of 0.025 W/m K [22] and water of 0.565–0.615 W/m K (depending on the test temperature).

The thermal contact between the needle and asphalt mixture surface may also affect thermal conductivity measurements. This contact may be disturbed by entrapped air or remains of granite and limestone dust from the drilling of the hole in the sample. It can also be affected by the non-uniformity of heat that moves away from the needle during the thermal conductivity measurement.

6.3. *Effect of temperature in thermal conductivity (k)*

For all asphalt mixtures studied, thermal conductivity was considerably decreased between test temperatures 19 °C and 80 °C Fig. 3 (Figs. 4–6). The average decrements of thermal conductivity between those test temperatures are shown in and for 20 mm DBM mixture were

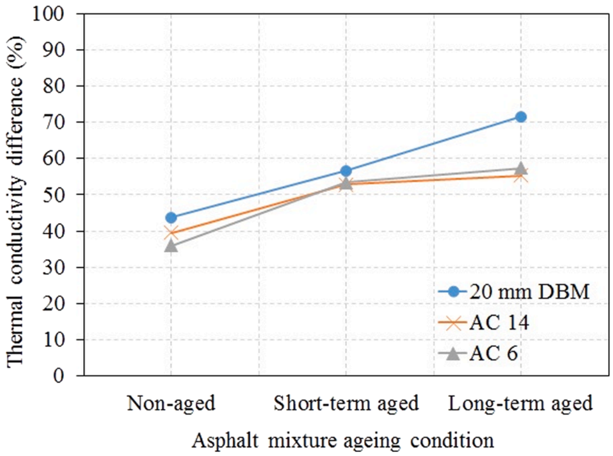

Fig. 3. Average decrements of thermal conductivity for 20 mm DBM, AC 14 and AC 6 between 19 °C and 80 °C test temperatures.

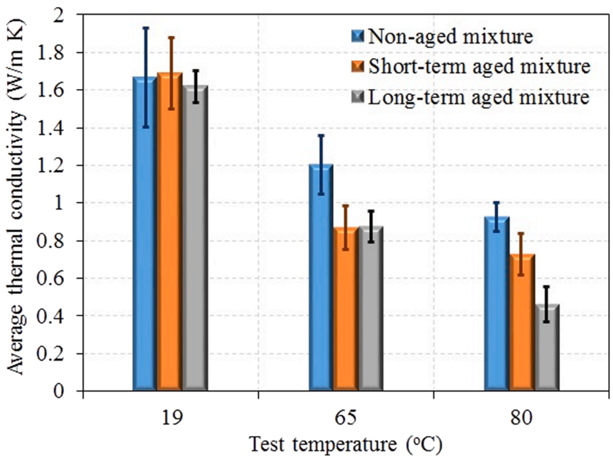

Fig. 4. Effect of temperature in thermal conductivity of 20 mm DBM asphalt mixture (the error bars show the standard deviation (SD) of each value).

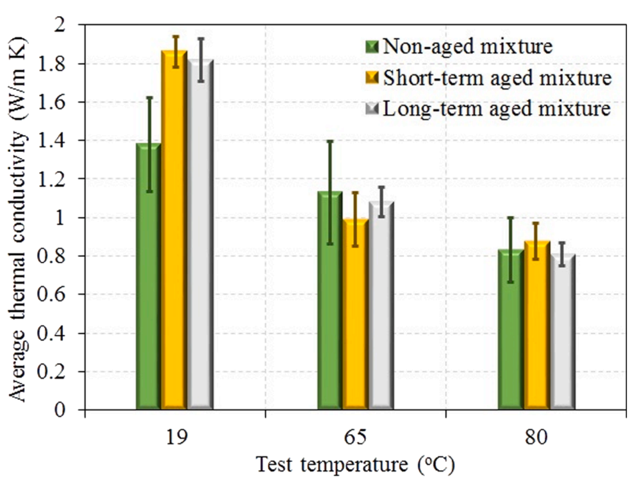

Fig. 5. Effect of temperature in thermal conductivity of AC 14 asphalt mixture (the error bars show the SD of each value).

43.7% (non-aged mix), 56.7% (short-term aged mix), 71.6% (long-term aged mix); for AC 14 mixture were 39.6% (non-aged mix), 52.8% (short-term aged mix), 55.3% (long-term aged mix); and for AC 6 mixture were 36.0% (non-aged mix), 53.4% (short-term aged mix), 57.4% (long-term aged mix). The results also show that the effect of temperature in thermal conductivity was larger for aged asphalt mixtures and specimens designed with large aggregate size, those with a 20 mm DBM mixture.

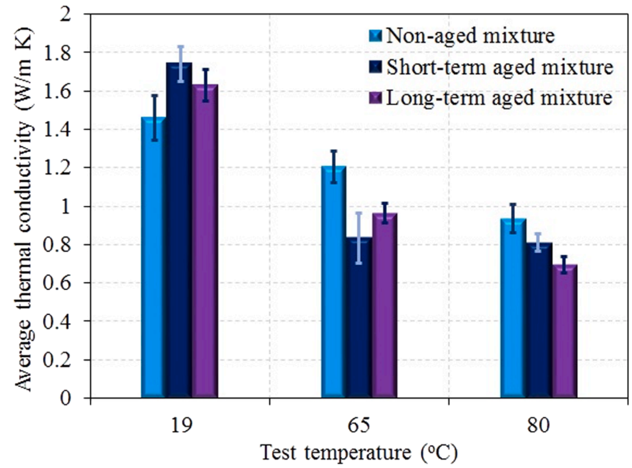

Fig. 6. Effect of temperature in thermal conductivity of AC 6 asphalt mixture (the error bars show the SD of each value).

The evolution of thermal conductivity of asphalt at temperatures from 19 °C to 80 °C does not depend on the thermal conductivity of asphalt binder at high temperatures but on the thermal properties and proportion of aggregate and filler that account for more than 90% of asphalt. A previous study conducted by Pan et al. [23] (for AH-70 (penetration 73 dmm), AH-90 (penetration 87 dmm) and SBS modified asphalt binder (penetration 48.1 dmm) showed a minimal reduction of thermal conductivity of binder for temperatures between −20 °C and 60 °C of 8.9%, 7.1% and 7.5% respectively. Maqsood, Gul and Anis-ur-Rehman [25] in their study about thermal properties of granite showed that thermal conductivity decreased with temperature increase (from −20 °C to 60 °C). The authors note that the effect of aggregates in thermal conductivity depends on the chemical composition, density, porosity, and specific gravity of aggregate. The decreasing trend of thermal conductivity of asphalt mixtures with the rise in temperature has been also reported by Chadbourn et al. [8]. The authors studied asphalt mixtures of dense graded (DG) and 15.9 mm maximum size (SMA) granite and river gravel mixed with 120/150 penetration grade binder. For DG with 1970 kg/m3 density, thermal conductivity decreased from approximately 1.5 W/m K to 1.2 W/m K for test temperatures from 25 °C to 75 °C. For SMA with 1880 kg/m^3, thermal conductivity decreased from approximately 2.5 W/m K to 2.2 W/m K for test temperatures from 25 °C to 75 °C.

6.4. *Effect of aggregate size in thermal conductivity (k)*

The effect of aggregate size on the thermal conductivity of the three asphalt mixtures was also studied. The results are shown in Figs. 7–9 and result from the measurements presented in Tables 2–4. As is observed from the figures, for all mixtures, there is a higher difference of thermal conductivity between 20 mm DBM and AC 14 than between 20 mm DBM and AC 6 for all aging conditions and test temperatures studied. For example, for non-aged mixtures (Fig. 7), at 19 °C, thermal conductivity between 20 mm DBM and AC 14 changes by 18.65% and between 20 mm DBM and AC 6 thermal conductivity changes by 13.19%. For short-term aged mixtures (Fig. 8), at 19 °C, thermal conductivity between 20 mm DBM and AC 14 changes by 9.70% and between 20 mm DBM and AC 6 thermal conductivity changes by 3.03%. Further, for long-term aged mixtures (Fig. 9), at 19 °C, thermal conductivity between 20 mm DBM and AC 14 changes by 11.47% and between 20 mm DBM and AC 6 thermal conductivity changes by 0.62%. It seems that between 20 mm DBM and AC 6 the heat from the needle of the TLS is conducted

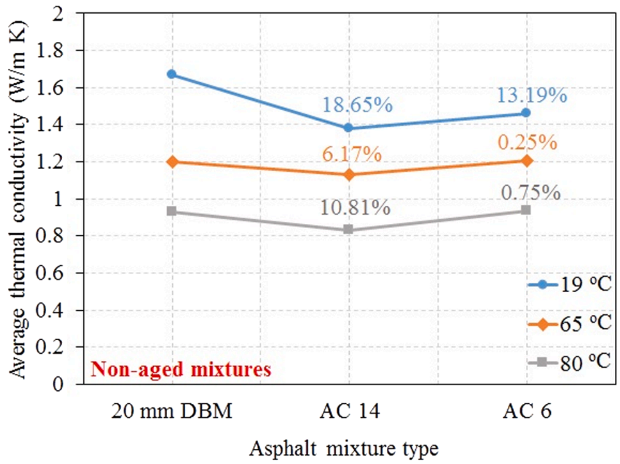

Fig. 7. Effect of aggregate size in thermal conductivity of non-aged mixtures (the percentage values represent the thermal conductivity change between 20 mm DBM and the other two mixtures displayed in the figure).

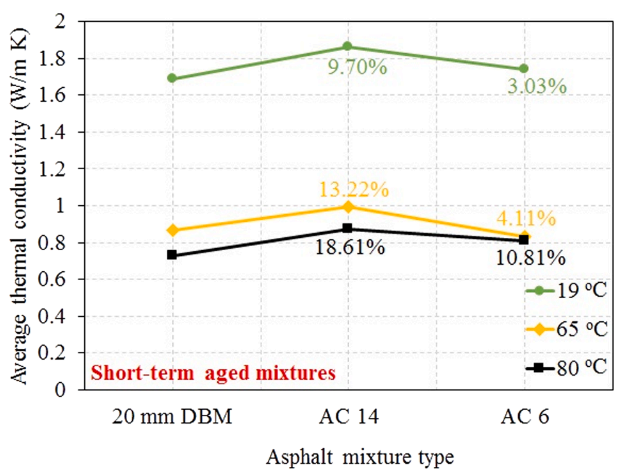

Fig. 8. Effect of aggregate size in thermal conductivity of short-term aged mixtures (the percentage values represent the thermal conductivity change between 20 mm DBM and the other two mixtures displayed in the figure).

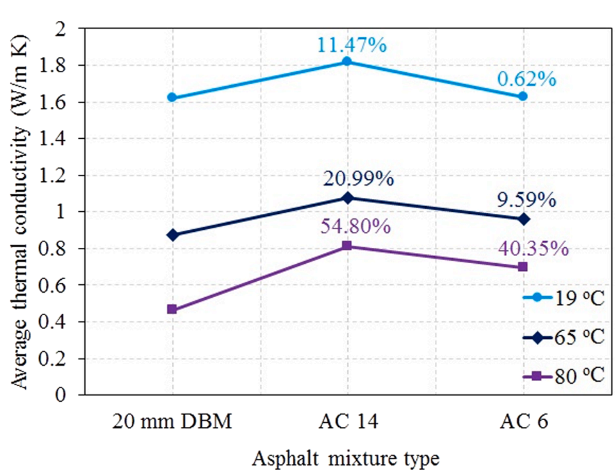

Fig. 9. Effect of aggregate size in thermal conductivity of long-term aged mixtures (the percentage values represent the thermal conductivity change between 20 mm DBM and the other two mixtures displayed in the figure).

similarly. This means that for AC 6 mixtures, the closer contacts of small aggregates improve heat conduction during the measurement of thermal conductivity. However, no specific conclusion could be made as to why thermal conductivity between 20 mm DBM and AC 14 had the highest difference for all aging conditions and test temperatures. Therefore, further work is suggested in this matter as well as in the overall effect of aggregate size in thermal conductivity.

The results also showed that between 20 mm DBM and AC 14 or AC 6 aged mixtures, thermal conductivity changed the most for measurements done at 80 °C test temperature. For example, for short-term aged mixtures (Fig. 8), between 20 mm DBM and AC 14, thermal conductivity at 19 °C changed by 9.70% whereas at 80 °C thermal conductivity changed by 18.61%. For the same aging conditions, between 20 mm DBM and AC 6, thermal conductivity at 19 °C changed by 3.03% whereas at 80 °C thermal conductivity changed by 10.81%. For long-term aged mixtures (Fig. 9), between 20 mm DBM and AC 14, thermal conductivity at 19 °C changed by 11.47% whereas at 80 °C thermal conductivity changed by 54.80%. For the same aging conditions, between 20 mm DBM and AC 6, thermal conductivity at 19 °C changed by 0.62% whereas at 80 °C thermal conductivity changed by 40.35%. However, it is not apparent if this change happens due to aging or due to the effect of temperature in thermal conductivity. Nevertheless, as described previously, temperature dramatically affects thermal conductivity. Meanwhile, below it is shown that aging doesn't necessarily change thermal conductivity if the effect of air voids, method of measurement, and thermal properties of binder into it are excluded.

6.5. *Effect of aging in thermal conductivity (k), specific heat capacity (c_p) and thermal diffusivity (a)*

The increase of the proportion of the colloid and asphaltene and the decrease of the proportion of saturates and aromatics of binder due to aging changes the thermal properties of asphalt mixture. However, the effect of aging in the thermal properties of aggregate and filler is minimal [23]. Therefore, the effect of aging on thermal conductivity of 20 mm DBM, AC 14 and AC 6 asphalt mixtures is expected to be minimal. The results are demonstrated in Tables 2–4.

The results show that for 20 mm DBM mixture the differences in thermal conductivity, specific heat capacity, and thermal diffusivity at 19 °C were less than 3% between non-aged specimens and short-term or long-term aged specimens. The lowest difference, less than 0.1%, was observed for specific heat capacity between the different aging conditions. For the same mix, thermal conductivity measured at 65 °C decreased by 27.7% between non-aged and short-term aged specimens and by 27.3% between non-aged and long-term aged specimens. For measurements done at 80 °C, thermal conductivity decreased by 21.5% between non-aged and short-term aged specimens and by 50.2% between non-aged and long-term aged specimens.

For specimens with AC 14 and AC 6 asphalt mixtures, the Fig. for most thermal parameters changed differently from that of 20 mm DBM asphalt mixture. However, the differences in specific heat capacity remained lower than 0.2% between non-aged specimens and short-term or long-term aged specimens.

For AC 14 mixture specimens and measurements done at 19 °C, the differences in thermal conductivity and thermal diffusivity were from 30% to 35% between non-aged specimens and shot-term or long-term aged specimens. For thermal conductivity measured at 65 °C, the differences were 12.2% between non-aged and short-term aged specimens and 4.5% between non-aged and long-term aged specimens. For thermal conductivity measured at 80 °C, the differences were less than 5.5% between non-aged specimens and short-term aged or long-term aged specimens.

For AC 6 mixture specimens and measurements done at 19 °C, the differences in thermal conductivity and thermal diffusivity were 19.2% between non-aged and short-term aged specimens and from 11% to 12% between non-aged and long-term aged specimens. For thermal conductivity measured at 65 °C, the differences were 30.8% and 20.1% between non-aged specimens and short-term aged and long-term aged specimens respectively. For thermal conductivity measured at 80 °C, the differences were 13.3% and 25.6% between non-aged specimens and short-term aged and long-term aged specimens respectively.

7. Conclusions

The following conclusions are drawn from the research:

- The variation of air voids (from approximately 4% to 6.5%) in compacted asphalt specimens was not found to considerably affect thermal conductivity measurements of this study.
- The results showed that thermal conductivity is affected by the volume of asphalt used by the TLS to find thermal conductivity (this can be estimated by the heat penetration depth) and the thermal contact between the needle and the asphalt surface. To increase the thermal contact, the thermal paste should be applied to the needle before testing and the hole where the needle is inserted should be cleaned from dust and be of the right diameter.
- The most significant factor that affected thermal conductivity was temperature. Thermal conductivity considerably decreased for all asphalt mixtures at high test temperatures (from 65 °C to 80 °C). This showed that when thermally analysing asphalt mixtures either experimentally or via finite element modelling, the effect of thermal conductivity of asphalt mixture should be taken into consideration.
- The effect of aging in thermal conductivity and thermal diffusivity varied between the asphalt mixtures studied. For 20 mm DBM specimens, thermal conductivity between non-aged and aged specimens remained at similar levels at 19 °C test temperature. However, at 65 °C test temperature, thermal conductivity decreased by approximately 27.5%. At 80 °C, it decreased by almost 50% between non-aged and long-term aged specimens. For the same mixture conditioning at 19 °C, thermal diffusivity increased when thermal conductivity was increasing.
- For AC 14 and AC 6 asphalt mixture specimens, no increasing or decreasing trend was observed for thermal conductivity between non-aged and aged specimens and for test temperatures between 19 °C and 80 °C. For AC 14 mixture, thermal diffusivity increased in average by 34.2% between non-aged and aged specimens. For AC 6 mixture, thermal diffusivity increased by 19.2% between non-aged and short-term aged specimens and by 12% between non-aged and long-term aged specimens.
- The effect of aging on specific heat capacity was not significant and remained almost unchanged for all asphalt mixtures and aging conditions.
- The conducted study was not conclusive in the effect of aggregate size on thermal conductivity.

CRediT authorship contribution statement

Juliana Byzyka: Conceptualization, Methodology, Validation, Writing - review & editing. **Mujib Rahman:** Conceptualization, Methodology, Validation, Writing - review & editing. **Denis Albert Chamberlain:** Conceptualization, Methodology, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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