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Influence of conductive fillers on the mechanical and thermal performance of stone mastic asphalt (SMA) mixtures

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ABSTRACT

This paper examines the thermal and mechanical properties of asphalt mixtures incorporating conductive fillers such as graphene, graphite, and magnetite. In terms of mechanical properties, conductive mixtures showed improved compaction with lower voids content at the same compaction temperature and effort. The stiffness values of all conductive mixtures were approximately 40 %–60 % higher than those of the control mix, potentially better load spreading ability. Thermal conductivity was assessed at three test temperatures (5°C, 25°C, and 40°C) under both virgin and aged conditions. The highest thermal conductivity was observed at 25°C, where a mixture containing 3 % graphene, 10 % graphite, 10 % magnetite, and 10 % limestone demonstrated an 84.08 % increase in thermal conductivity compared to the control mixture with limestone filler. Furthermore, while thermal conductivity decreased with ageing across all mixes and test temperatures, conductive mixtures still exhibited 15 %–20 % higher thermal performance than the control mixture. These findings suggest that conductive fillers help to mitigate oxidative ageing, thereby enhancing long-term resistance to cracking. In terms of durability, all conductive mixtures demonstrated superior ageing and moisture resistance, retaining stiffness values 10 %-20 % higher than the control mixture after long-term ageing and moisture conditioning cycles 5 %–20 % more stiffness compared to control mixture. These results are promising and indicate that incorporating cost-effective conductive fillers can not only enhance thermal performance leading to improved self-healing characteristics but also improve mechanical properties.

1. Introduction

The performance of asphalt mixtures under traffic and environmental loading is significantly influenced by the properties of its constituents. Although aggregate forms approximately 92 % of the total mixture and mastic (bitumen and filler mixture) is only around 5–7 %, the behaviour of the mastic plays a crucial role in the compaction quality and long-term durability [1–3]. This, in turn, affects the susceptibility of the asphalt to failures such as ravelling, cracking, potholes, and other major forms of distress. Furthermore, the mastic's ability to accommodate temperature variations also has an impact on how the overall mixture responses under different temperatures. For example, asphalt pavements weaken, and bitumen oxidise as temperature rises, while it suffers thermal stresses at lower temperatures, leading to cracking [4–8]. Minerals filler such as limestone and granite are widely used in asphalt mixture. In recent years, researchers have explored the impact of various conductive fillers on the mechanical and thermal performance of asphalt

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Table 1
Properties of the fillers [29–32].

Properties	Filler types			
	Graphene	Graphite	Magnetite	Limestone
				
Density (g/cm^3)	2.25	2.26	4.6	2.0
Surface area(m^2/g)	2600	~416	~101	2–5
Physical properties	Insoluble, crystal structure, hexagonal honeycomb lattice one-atom thin (0.345 μm),	Insoluble, synthetic-300 mesh (95 % <53 μm), plentiful carbon allotrope in nature, highly conductive	*Water-soluble,* spherical shape & > 96 % < 63 μm, highly conductive and dense	> 1.5 %, closer to a spherical shape and 63 μm
Thermal Conductivity (WK^{-1}/m)	4840–5300	Up to1950	9.7	0.9–2.5
Elasticity Module (MPa)	~10E+ 06	1.15E+ 04	2.0E+ 05	3.4E+ 03
Chemical Composition	Bond type- sp^2 hybridised state, strong carbon bond and, highly conductive.	98.6 % Carbon,0.05 % Sulphur, 0.05 % Nitrogen, 0.8 % ash, 0.3 % Volatile, 0.3 % Moisture	Fe3O4 > 98.1 %, SiO2 < 0.3 %	Silica 15–18 %, Alumina 2–6 %, Lime 36–40 %, Mg & Na 1–3 %, Loss on ignition 31–34 %

Table 2
6 mm SMA mixture constituents (based on total aggregates of 1.5 % filler).

Constituent		Mixture				
		M1	**M2**	**M3**	**M4**	**M5**
Aggregate (%)		93.5	93.5	93.5	93.5	93.5
Bitumen (%)		5	5	5	5	5
Total filler (%)		**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Filler type	Limestone (%)	1.5	1.44	0.485	0.970	1.38
	Graphene (%)	x	0.06	0.045	0.045	0.045
	Graphite (%)	x	x	0.485	x	x
	Magnetite (%)	x	x	0.485	0.485	0.075

mixtures [9].

A significant number of research has been conducted to study thermal properties of asphalt mixtures. Juliana et al. [10] investigated the variation of thermal conductivity at different ageing conditions on dense asphalt mixtures, how test temperatures potentially, density and air voids content impact thermal conductivity at different mixes i.e., 20 mm, 14 and 6 mm asphalt concrete at different temperatures. They reported, mixture thermal conductivity changes 15–20 % (1.2–1.65 W/m.k at unaged condition, short-term ageing 0.85–1.85 and long-term ageing 0.82–1.62 W/m.k). Other researcher, like Jiang et al., [11] found thermal conductivity of SMA-13 was 1.66 W/m.k. Refaa et al. [12] and Luca and Mrawira [13] found thermal conductivity of dense graded HMA vary from 0.5 to 2 W/m.k and 1.4–1.8 W/m.k. Khan and Mrawira [14] showed that the thermal conductivity of lightweight aggregate HMA the ranges of 0.77–0.87 W/m.k. Yan et al. [15] found that thermal conductivity of asphalt mixture changes largely ranging from 0.70 to 2.10 W/m.k.

In terms of the impact of the filler on thermal properties of asphalt mixtures, there are limited past studies. Some carbon-based fillers such as graphene, graphite, and carbon nanotubes have shown improved thermal properties, self-healing, and de-icing capabilities [16,17]. When properly dispersed, even when added in small amounts, these fillers have also been found to increase stiffness, fatigue resistance, deformation resistance and low temperature stability and fracture energy. They also offer improved water and ageing resistance [18–22].

Graphite, a significantly cheaper alternative to graphene, was also found improves anti-ageing properties, especially against UV ageing of bitumen [23]. Adding Magnetite (Fe3O4) nanoparticles in bitumen shown promising to promote self-healing properties of asphalt [24].

However, despite these promising results, several challenges remain. The cost of most conductive fillers is a significant issue, as they are often expensive and used in other high-value applications. Additionally, the durability of some metal-based fillers may decrease over time, and the workability and dispersion of hard fillers can lead to inconsistent performance. There are also environmental concerns, particularly regarding the potential for leaching into the soil. Nonetheless, ongoing research is focused on developing cost-effective, durable, and environmentally friendly conductive fillers. For example, hybrid fillers that combine mineral or recycled materials with conductive substances are being investigated to optimise both mechanical and environmental performance [25,26].

In earlier research by the authors, various types of hybrid fillers were used to assess the consistency, workability, thermal, and rheological properties of asphalt mastics [27]. The results were promising, demonstrating that conductive mastic significantly enhanced thermal properties and provided better resistance to cracking and rutting. However, for widespread adoption, it is crucial to evaluate their effectiveness within asphalt mixtures, where they constitute only around 1–1.5 % of the total weight of the aggregate.

The use of conductive mastic in asphalt pavements offers environmental benefits by enhancing heat distribution, can lead to reduction in the necessary delivery temperature of hot mixes, enabling raised surface temperature for efficient de-icing and snow melting. This reduces reliance on chemical de-icers, lowering harmful runoff and improving winter road safety. While conductive fillers may have higher embodied energy than traditional materials, long-term advantages such as reduced maintenance, fewer repairs, and extended pavement life can offset initial environmental costs. Improved durability leads to fewer emissions from maintenance equipment and decreased raw material use, contributing to overall sustainability and reduced carbon footprint in road infrastructure

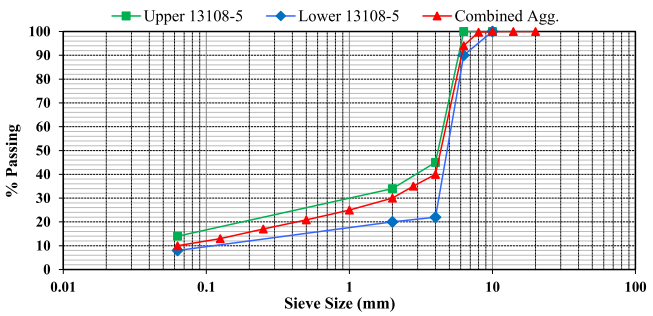


Fig. 1. Asphalt mixture design (BS EN 13108–5:2016).

Fig. 2. a: Procedure for asphalt sample production b: Asphalt mixture specimens.

[44–48].

The objective of this paper, therefore, is to investigate the influence of conductive fillers on the thermal and mechanical properties of asphalt mixtures when partially replacing conventional limestone filler. The research is further extended to evaluate long-term performance, specifically in relation to ageing and water damage resistance. Three conductive fillers graphite, magnetite, and graphene are combined with conventional limestone filler to produce stone mastic asphalt (SMA), a widely used road surfacing material globally. All results are compared with control SMA mixtures containing only limestone filler.

2. Experimental programme

2.1. Material

The physical, chemical, thermal, and mechanical properties of fillers used in this study are presented in Table 1. The size of the filler particles was less than 0.063 mm to comply with BS EN 13108–5:2016 [28]. A softer grade of bitumen (100–150 pen) was used to make the mixture easier to handle. Additionally, limestone filler and granite aggregates were used in mixture production, as these materials are commonly used for road surfaces in the UK.

Due to the varying densities of the fillers, the binder-to-filler ratio was adjusted to assess the impact of different proportions on the thermal and rheological properties. A detailed investigation was previously carried out on conductive mastic, exploring various combinations of fillers and bitumen to evaluate their thermal and rheological properties [27]. From which, the five mixes with superior consistency, thermal, and rheological properties were selected for further evaluation of their effects on the mixture. The selected filler and bitumen proportions are given in Table 2.

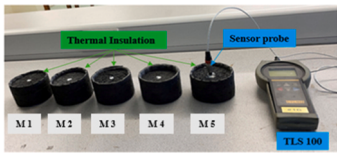
2.2. Mixture design

A Stone Mastic Asphalt (SMA) mixes were produced in compliance with BS EN 13108–5:2016, with a nominal maximum aggregate size of 6 mm. The gradation curve is shown in Fig. 1, and the mixture constituents are presented in Table 2.

The proportions of individual filler components were calculated relative to a total filler content of 1.5 % within the mixture. For instance, in the M2 mixture, 96 % limestone corresponds to 1.44 % (i.e., 96 × 1.5 / 100), while 4 % graphene equates to 0.06 % (i.e., 4 × 1.5 / 100). The same method was applied to determine the filler proportions in the M3, M4, and M5 mixtures.

A softer-grade bitumen (100–150 penetration) was used, with the mixing temperature maintained at 150 ± 5℃ to accommodate the inclusion of hard fillers. Cylindrical specimens with dimensions of 60 mm in height and 100 mm in diameter were prepared following

Table 3
Test specification.

Properties	Mixture	Sample No	Protocol	Test Condition	Measured properties
Thermal properties	M 1 M 2 M 3 M 4 M 5	3 3 3 3 3	Test Temp: 5 °C, 25 °C 40 °C. Equipment: [34]. Test duration: 3 mins. 	U STA LTA[a]	Thermal conductivity (k)[b]W/m.k, Specific heat capacity (Cp) = Q/MΔT and Thermal diffusivity (***α***)[b] Diff = k/ρCp
Mechanical properties	M 1 M 2 M 3 M 4 M 5	6 6 6 6 6	Test type: ITSM [35]. Test Temp: 20 °C Frequency: 0.333 Hz, Horizontal deformation: 5 μm. 	U[a]	Stiffness
Durability Long-term ageing	M 1 M 2 M 3 M 4 M 5	3 3 3 3 3	 Long-term oven ageing protocol AASHTO R30:2006 [37] Temp: 85^0 C, duration: 5 days	A	Stiffness ratio: unaged / aged
Durability Moisture damage	M 1 M 2 M 3 M 4 M 5	3 3 3 3 3	Cycle: 16 h @ 5 °C, 2 h @ 20 °C, 6 h @ 60 °C [36]. 	U[a]	Stiffness ratio: original stiffness / stiffness after each cycle

a: U =unaged condition, STA: short-term aged at 140^0 C for 6 hours at loose stage, LTA: Long-term aged @ 85^0 C for five days, b: k = Thermal conductivity, Cp= Specific heat capacity = k/ MΔT [38]. Where, K = Heating power, M = Mass and ΔT = Changing time according to TLS-100. ***α***= Diffusivity, Diffusivity = k/ρCp [39], where, k is thermal conductivity, ρ is density, and Cp is specific heat capacity.

Table 4
Average and standard deviation of height, mass, density & air voids content.

ID	No of sample	Height (mm)		Mass (g)		Density (kg/m^3)		Voids content (%)	
		Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev
M 1	6	58.67	0.52	1054.00	27.79	2366.62	14.64	7.20	0.57
M 2	6	59.00	0.89	1078.10	25.79	2423.64	20.86	5.86	0.81
M 3	6	59.67	0.52	1076.53	24.29	2442.86	7.19	5.32	0.28
M 4	6	58.33	0.52	1092.23	7.68	2466.89	13.38	4.45	0.52
M 5	6	59.00	0.89	1072.17	11.35	2427.10	14.65	5.79	0.57

the Marshall compaction procedures, comply with BS EN 12697, Part 30 [33]. Fig. 2a and b shows asphalt mixtures procedure and compacted mixture specimens. For each mix, six specimens were prepared, their volumetric properties were determined and subsequently used for both thermal and mechanical testing.

2.3. Testing

The testing programme comprises of determining mixture volumetrics in terms of density and voids content according to BS EN 12697–6 (bulk density), BSEN 12697–5:2018 (maximum density) and BS EN 12697–8:2018 (voids content).

2.3.1. Thermal conductivity

According to ASTM D5334:2000 [34] standard Test Method for Determination of Thermal Conductivity. The specimen was then tested for thermal conductivity at virgin, short-term aged and long-term aged conditions at temperature 5^0 C, 25^0 C and 40^0 C. The test procedure is briefly outlined in the following Table 3.

2.3.2. Test sequence-indirect tensile stiffness modulus (ITSM)

The stiffness modulus of asphalt mix specimens was measured according to BS EN 12697–26:2018 [35], Annex C, using the Indirect Tensile Stiffness Modulus (ITSM) method. Test parameters included a target rise time of 124 ± 4 ms, mean horizontal deformation of 5 ± 2 μm, Poisson's ratio of 0.35, specimen dimensions of 100 mm diameter and 60 mm thickness, and a test temperature of 20°C. Specimens were conditioned at 20°C for at least four hours before testing. For each mix type, six specimens were tested. Stiffness, a key mechanical property, was calculated as the ratio of uniaxial stress to corresponding strain.

The stiffness modulus was automatically computed by the using Eq. (1)

$$\mathrm{Sm} = \frac{F(v + 0.27)}{z.h} \cdots\cdots\cdots \quad (1)$$

Where *Sm* is the indirect tensile stiffness modulus (MPa); *F* is the applied vertical load's peak value in Newtons (N); *z* is the horizontal deformation's amplitude measured in millimetres (mm) during the load cycle; *h* is the test specimen's mean thickness in millimetres (mm); and ν is the Poisson's ratio, which is set to 0.35 for bituminous materials [42]. The test protocol is shown in Table 3.

After ITSM testing, all specimens were divided into two parts, three went for moisture sensitivity test using link-bitu test protocol [36] and three for long-term ageing using AASHTO R30:2006 [37].

2.3.3. Long-term ageing and durability

According to AASHTO R30:2006 [37], long-term ageing of asphalt mixtures can be simulated in the laboratory to assess their expected performance after several years of service. In the field, asphalt pavements are continuously exposed to environmental and mechanical stresses such as ultraviolet radiation, elevated temperatures, oxygen, and traffic loads. These factors gradually harden the asphalt binder, leading to brittleness, cracking, and reduced durability. To replicate this ageing process, asphalt samples were placed in a forced-draft oven at 85°C for 120 hours (5 days), ensuring uniform oxygen exposure. The test specifications are given in Table 3.

2.3.4. Water sensitivity testing

According to link-bitu test protocol [36] toward evaluating the water sensitivity of an asphalt mix, a conditioning cycle is applied to simulate environmental stresses. The cycle includes exposing the samples to 16 h at 5°C to replicate cold conditions, followed by 2 h at 20°C to allow for thermal equilibrium. Subsequently, the samples were subjected to 6 h at 60°C to mimic high-temperature conditions that could weaken the binder-aggregate bond. The test specifications are presented in Table 3.

3. Results and analysis

3.1. Mechanical properties

3.1.1. Mixture volumetrics

The average and standard deviation of density and voids content of the compacted specimens are presented in Table 4.

The data indicates that, irrespective of the filler type, the density and voids content are relatively consistent, demonstrating that

Table 5
Stiffness modules.

Mixture ID	No of sample	Stiffness (MPa)	
		Average	Stdev
M 1	6	1155	39
M 2	6	1481	296
M 3	6	1639	149
M 4	6	1802	179
M 5	6	1606	142

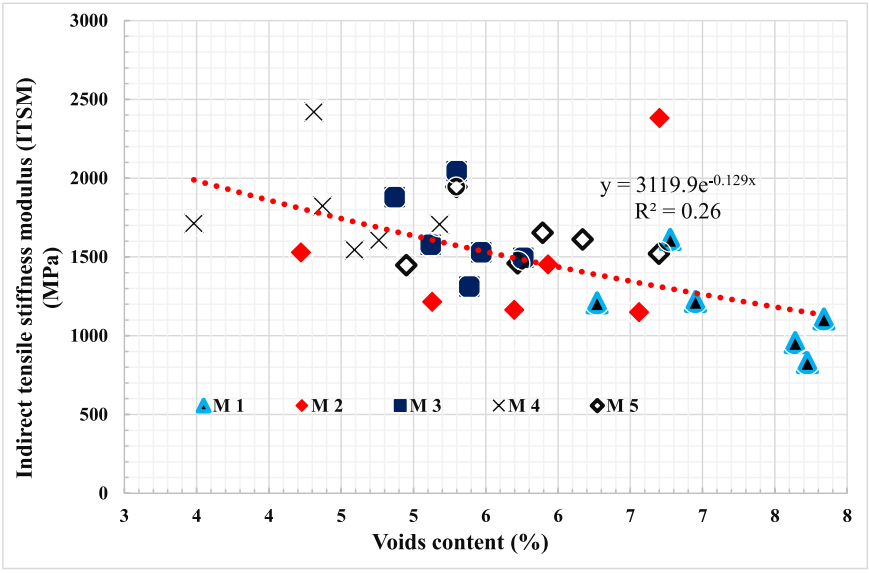


Fig. 3. Air voids content vs Stiffness modulus.

conventional mixing and compaction methods can produce uniform mixtures with hard filler. The control mixture (M1), however, exhibited a voids content of 7.20 %, compared to mixtures with conductive fillers, where the average voids content ranged from 4.45 % to 5.86 %. While the voids content of 7.20 % in the control mixture is marginally higher, it aligns with typical values reported in the literature for conventional SMA mixtures. Notably, the addition of conductive fillers appears to enhance the heat storage capacity of the mixture, potentially improving the compaction at the same temperature and compaction effort. This is advantageous, as mixtures with fewer air voids result in denser matrix, which are more resistant to ravelling and early cracking.

3.1.2. Stiffness modules

The stiffness modulus for all mixtures is presented in Table 5, and stiffness modulus against voids content for individual samples across all mixtures is presented in Fig. 3.

In general, mixtures containing conductive fillers exhibit 43 %-63 % higher stiffness compared to control mixtures. However, as noted in the earlier section, the control mixture (M1) generally has slightly higher voids content, which may have contributed to its lower stiffness, as stiffness tends to decrease with increasing voids content, as shown in Fig. 3. Despite this, a few samples of M2, with voids content close to 6 %, demonstrate marginally better stiffness compared to the corresponding control samples. This suggests that conductive fillers are generally beneficial for achieving good compaction without significantly increasing stiffness. It is also worth noting that, despite the use of a high penetration grade bitumen (100/150 pen), the stiffness remains comparable to that reported in previous studies [49,51], where ITSM values ranging from 800 MPa to 3000 MPa were observed for various filler-modified stone mastic asphalt (SMA) mixtures [43].

The relationship between stiffness and voids content was found non-linear exponential as given in the following equation.

$$E = 3119.9 \bullet e^{-0.129 V_a}$$

Where, E is the predicted stiffness in MPa, Va is the air voids content in percent (%), The constants: E_0= 3119.9 MPa (estimated stiffness at 0 % voids), k = 0.129 (rate at which stiffness decreases with more voids). Although the correlation coefficient was relatively low at 0.26, the results are consistent with previous studies in which researchers also reported an inverse relationship between stiffness and air voids content [50].

3.2. Thermal properties

3.2.1. Thermal conductivity

The thermal conductivity of all mixtures, measured at different temperatures and in unaged, short-term, and long-term aged conditions, is shown in Fig. 4a to c. Generally, the conductivity ranges from 0.33 to 0.36 W/m.k for the control mix (M1) but increases to 0.38–0.63 W/m.k for mixtures with conductive filler (M2 to M5). These results are consistent with previous studies on mixtures with modified bitumen and modified asphalt mixtures [14,40], where the values ranged from 0.29 to 0.39 W/m.k for mixtures with modified bitumen [40] and 0.77–0.87 W/m.k for mixtures with modified mastics [14]. The impact of temperature, material types, compaction (voids content), and ageing on thermal conductivity is analysed and presented below.

3.2.1.1. Impact of temperature. The thermal conductivity of asphalt mixture is significantly affected by temperature due to the

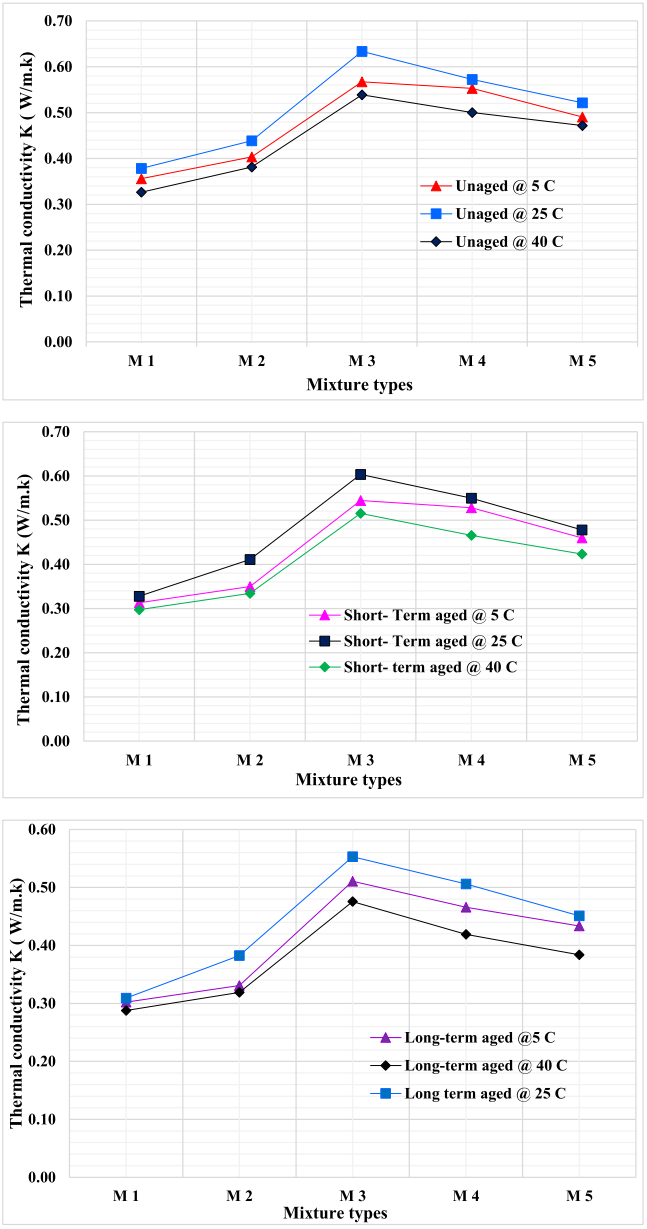


Fig. 4. a: Effect of Conductive fillers in thermal conductivity of unaged mixtures. b: Effect of conductive fillers in thermal conductivity of short-term mixtures. c: Effect of conductive fillers in thermal conductivity of long-term mixtures.

composite nature of the material and the distinct properties of its components. As shown in Fig. 4a–c, irrespective of mixture ageing condition, thermal conductivity decreases with increasing temperature between 25 °C to 40 °C, and in cold conditions, for example at 5 °C, it decreases compared to 25 °C. This is consistent with the previous research on temperature and thermal conductivity of asphalt mixtures [12,13]. As reported by other researcher [13], aggregates, and bitumen aid heat transfer, but as temperature increases, bitumen softens and becomes more viscous, reducing thermal conductivity. At 25°C, asphalt transitions between brittle and viscous states and therefore, understanding its behaviour at this moderate temperature is important for assessing its performance under typical operating environment.

3.2.1.2. Material type. As shown in Fig. 4a–c, compared to control mixture (M1), all mixtures with conductive filler exhibits improved thermal conductivity for both unaged and aged condition and at all test temperatures. The percentage increase compared to control mixture is calculated and presented in Table 6**.** It can be observed that, in general, M3 (comprising 3 % graphene, 10 % graphite, 10 % magnetite, and 10 % limestone filler) exhibited the highest enhancement in thermal conductivity, ranging from 56 % to 84 % compared to the control mix. Mixes 4 and 5 also demonstrated significant improvements, with average increases between 30 % and

Table 6
Percentage increases in thermal conductivity of mixtures compared to control mixture.

Ageing condition	Test temperature (°C)	Percentage of thermal conductivity (%) increased compared to control mixture (M 1)			
		M 2	M 3	M 4	M 5
Unaged	5	17.73	56.86	52.93	35.62
	25	15.96	67.44	51.22	37.84
	40	16.79	65.07	53.31	44.55
Short-term aged	5	11.76	73.93	68.75	46.84
	25	25.32	84.08	67.72	47.04
	40	12.31	73.22	56.56	42.23
Long-term aged	5	9.53	69.03	59.56	43.48
	25	23.6	78.85	63.71	45.92
	40	8.58	64.47	42.89	30.63

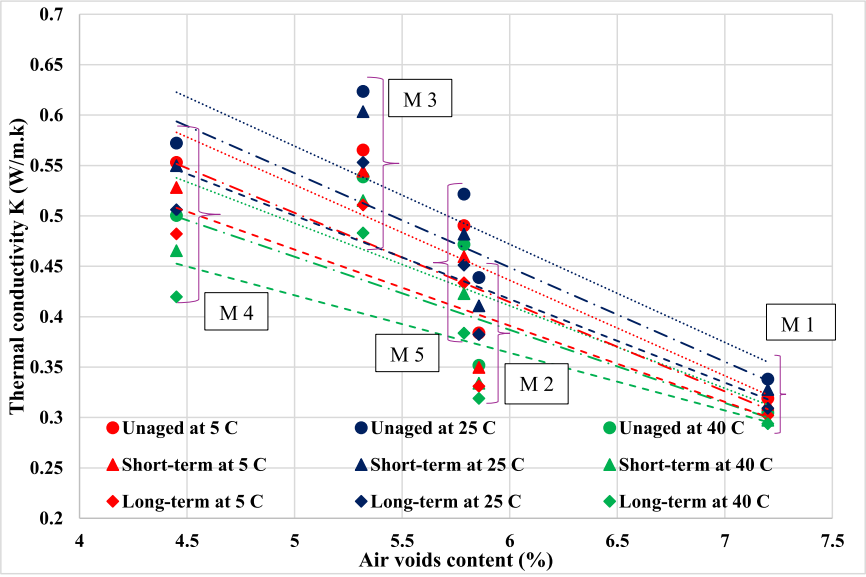


Fig. 5. Mix type vs Air voids content and thermal conductivity.

Table 7
Thermal conductivity % changes unaged to short-term, unaged to long-term-aged & short-term to long-term.

Mixture type	Test temperature (°C)	Thermal conductivity K (W/m.k)			% decrease		
		Unaged	STA	LTA	U to STA	U to LTA	STA to LTA
M 1	5	0.36	0.31	0.30	13.44	19.66	3.45
M 1	25	0.38	0.33	0.31	13.37	22.38	5.67
M 1	40	0.33	0.31	0.29	6.45	13.79	6.89
M 2	5	0.40	0.35	0.33	13.42	22.05	5.37
M 2	25	0.44	0.41	0.38	6.38	14.75	6.91
M 2	40	0.38	0.33	0.32	11.41	18.18	4.49
M 3	5	0.57	0.54	0.51	4.02	11.04	6.17
M 3	25	0.63	0.60	0.55	3.24	12.77	8.35
M 3	40	0.54	0.52	0.48	4.38	11.51	6.21
M 4	5	0.55	0.53	0.48	4.48	14.68	8.71
M 4	25	0.57	0.55	0.51	3.91	13.04	7.93
M 4	40	0.50	0.47	0.42	6.95	19.20	9.84
M 5	5	0.49	0.46	0.43	6.28	13.10	5.66
M 5	25	0.52	0.48	0.45	7.59	15.60	6.39
M 5	40	0.47	0.42	0.38	10.34	22.93	9.27

69 % compared to the control. Similarly, M2 (containing 4 % graphene and 30 % limestone filler) showed an enhancement of 8–25 % relative to the control. These results indicate that the addition of conductive fillers consistently enhances the thermal conductivity of asphalt mixtures across all tested temperatures and ageing conditions. This could be beneficial for long-term performance of mixture to

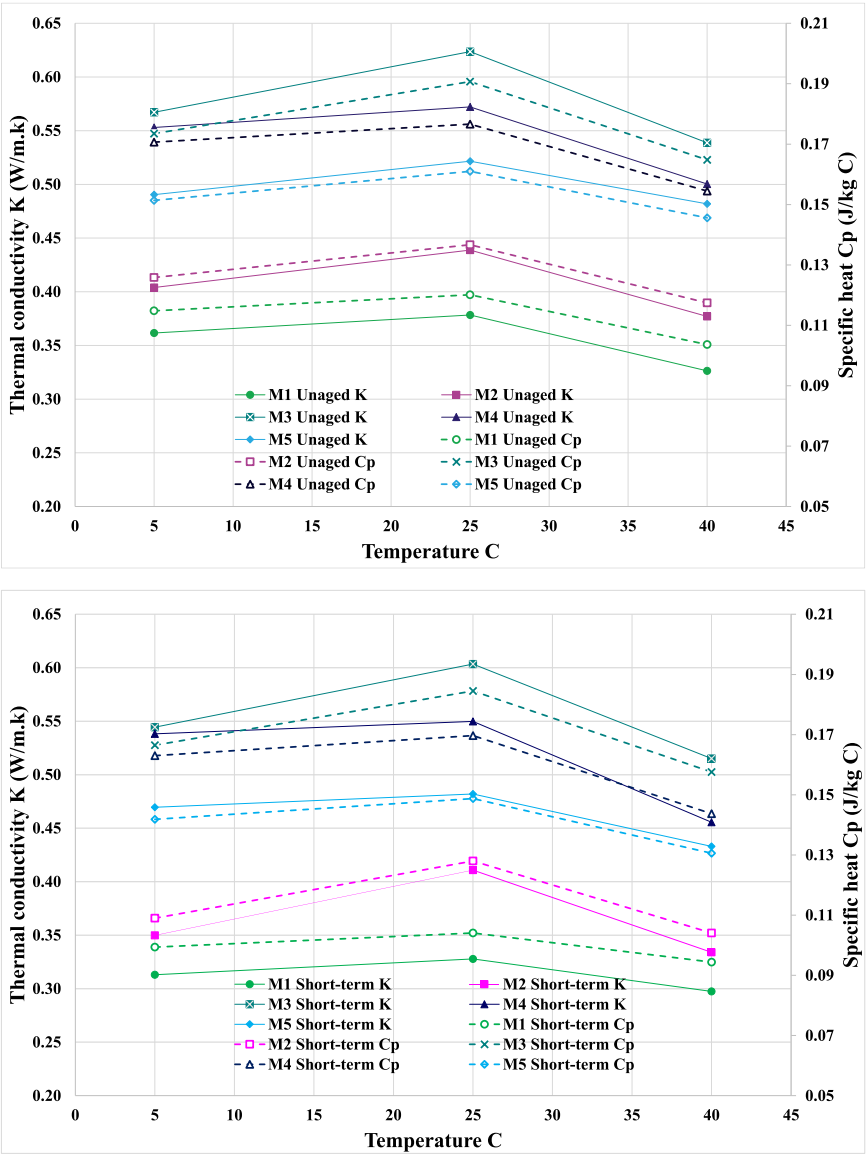


Fig. 6. a: K and Cp vs temperatures at unaged condition. b: K and Cp vs Temperatures at short-term condition. c: K and Cp vs Temperatures at long-term condition.

enhance self-healing characteristics of the material.

3.2.1.3. Voids content. In order to evaluate the impact of compaction on thermal conductivity, the average thermal conductivity against the average voids content of the mixtures at unaged, short-term aged and long-term aged condition are presented in Fig. 5.

It can be seen that, from Fig. 5 irrespective of the mixture type, while the relationship between thermal conductivity and air voids is not strictly linear, the general trend is that more air voids lead to lower thermal conductivity. High-thermal conductivity asphalt mixtures heat and cool more slowly than low-thermal conductivity of asphalt mixtures, and the total energy stored in asphalt mixtures with varying air voids content is also determined by these factors.

3.2.1.4. Ageing. Table 7 presents the average reductions in thermal conductivity across different test temperatures and ageing stages. The transition from unaged to short-term ageing resulted in a 3.24 % decrease, from unaged to long-term ageing led to a 12.77 % reduction. Additionally, the decrease from short-term to long-term ageing was 8.35 % for mix M3 at 25°C.

Across all mixes and test temperatures, thermal conductivity reductions ranged from 3.24 % to 13.44 % for unaged to short-term ageing, 11.04–22.93 % for unaged to long-term ageing, and 3.45–9.84 % for short-term to long-term ageing. The results suggest that

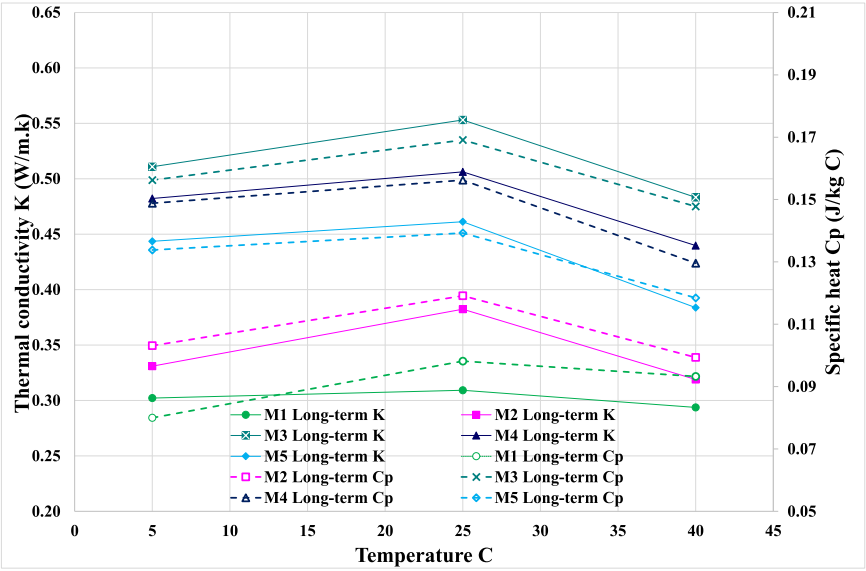


Fig. 6. (*continued*).

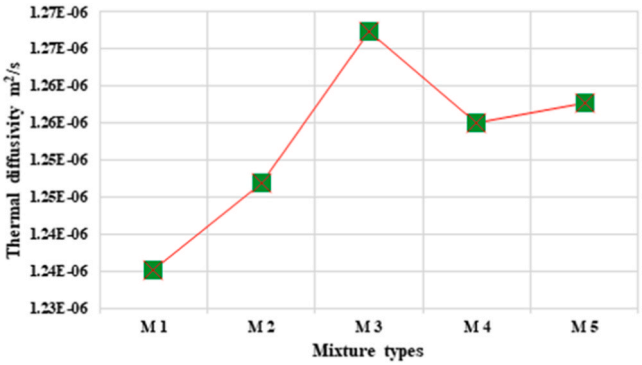


Fig. 7. Mixture types vs thermal diffusivity.

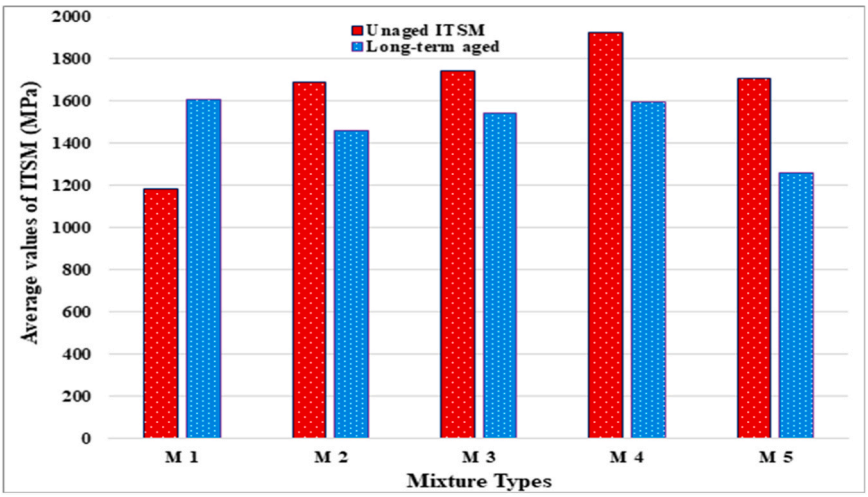


Fig. 8. Types of mixture vs ITSM unaged and aged condition.

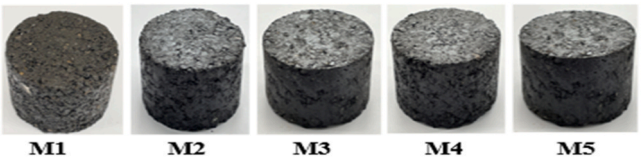


Fig. 9. Specimens after long-term ageing.

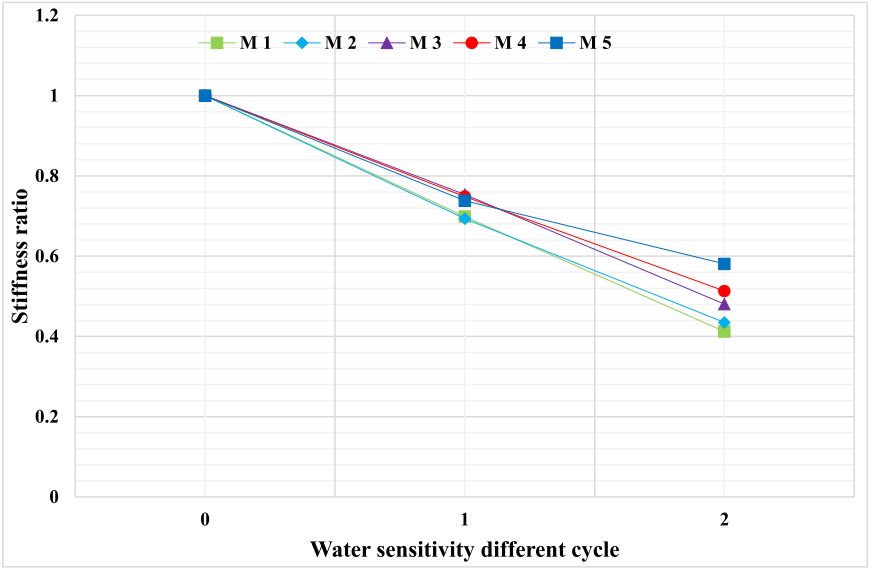


Fig. 10. Water conditioning cycle against stiffness ratio.

incorporating conductive fillers can help mitigate oxidative ageing, thereby enhancing long-term resistance to cracking.

3.2.2. Specific heat capacity and thermal diffusivity

The specific heat capacity, and thermal diffusivity is calculated by using the formula presented in Table 3. Fig. 6a–c shows the relationship between specific heat capacity and thermal conductivity for all mixtures at unaged, short-term, and long-term aged conditions and at all tested temperatures. As expected, despite some variations across different mixture types, the results generally show a linear relationship between K and Cp under unaged, short-term aged, and long-term aged conditions, as well as across the tested temperatures.

A high thermal conductivity typically leads to faster heat transfer, while a high specific heat allows a material to store more heat energy for a given temperature change [41]. This is beneficial for the material when used in shallow repair and thin surfacing applications allowing better compaction.

The thermal diffusivity of all mixtures at all ageing conditions, as shown in Fig. 7, indicates that the addition of conductive fillers results in an increase in thermal diffusivity. Compared to the control mix, M2 shows an increase of 1.62 %, M3 by 3.25 %, M4 by 1.86 %, and M5 by 2.43 %. Thermal diffusivity remains largely constant despite ageing, ensuring its reliability as a parameter for assessing thermal performance, even under conditions where thermal conductivity and specific heat capacity may vary with temperature. Furthermore, mixtures M2-M5 with higher thermal diffusivity facilitate rapid heat distribution.

3.3. Durability

3.3.1. Impact of long-term ageing

The average mixture stiffness for all mixtures at unaged and long-term aged conditions are presented in Fig. 8.

The average stiffness modulus for control mixture was 1181 MPa, but using conductive fillers that values increase to 1690–1928 MPa, an increase of 43–63 %. In contrast, the stiffness modulus for all conductive mixtures (M2-M4) decreased after long term ageing by an average 20 %-30 %, compared to control, which showed around 33 % increase. Despite stiffness reduction, the stiffness values of the all-aged conductive mixtures (M2-M3) remain 15–20 % higher compared to unaged control mixtures and only marginally lower than aged control mixture, highlighting no significant deterioration. The visual inspection of the sample also showed no visible sign of damage (Fig. 9).

3.3.2. Impact of water conditioning

Fig. 10 shows the stiffness ratio (virgin stiffness divided by post-conditioning stiffness) versus the number of cycles. As expected, all mixtures experienced a stiffness reduction of approximately 40–60 % after two cycles. However, the conductive mixtures (M2 > M3 > M4 > M5) retained 5–20 % more stiffness than the control, indicating greater resistance to moisture damage. The stiffness modulus of asphalt specimen decreases under moisture conditions due to mechanical, chemical, and physico-chemical effects that weaken its internal structure. Moisture compromises the adhesion between binder and aggregates and softens the binder, making the mix more flexible and less resistant to deformation. It also promotes internal damage through microcracking, pore pressure, and freeze-thaw cycles, which further degrade the pavement's load-bearing capacity. Overall, moisture reduces aggregate interlock and mechanical integrity, leading to a significant drop in stiffness [22].

4. Conclusions

Key conclusions are summarised below.

Mixture volumetrics: Standard mixing, temperature, and compaction practices can be used to produce asphalt mixtures with partial replacement of limestone filler by conductive materials such as graphene, graphite, and magnetite. These modified mixtures demonstrated improved compaction, with 20–38 % lower voids content on average compared to conventional mixtures.

Stiffness modulus: Mixtures containing conductive fillers exhibited approximately 40–60 % greater stiffness than the control mixture. However, the control mixture generally had slightly higher voids content, which may have contributed to its reduced stiffness, as stiffness typically decreases with increased voids. Additionally, some conductive mixtures with voids content near 6 % demonstrated slightly better stiffness compared to control mixtures.

Thermal properties: Conductive mixtures showed enhanced thermal conductivity, specific heat, and diffusivity across all tested temperatures (5°C, 25°C, and 40°C). While thermal performance declined with higher voids content, values remained 15 %–20 % above those of conventional mixtures. These advantages persisted after both short- and long-term ageing, suggesting improved thermal properties benefit both production and in-service performance.

Durability: With long-term ageing, stiffness in conductive mixtures dropped by 20 %–30 %, while the control increased by ~33 %. Despite this, aged conductive mixtures remained 10 %–20 % stiffer than their unaged state and only slightly below the aged control, indicating minimal degradation. After two moisture conditioning cycles, all mixtures lost 40 %–60 % stiffness, but conductive mixtures retained 5 %–20 % more, showing better resistance to moisture damage.

Further studies are underway to explore heat distribution in conductive mixture when using recycling material and the performance in terms of interface bonding when applied on existing pavement as an inlay or overlay.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: M, Hossain, M. Rahman, D Chamberlain, T. Kasim; data collection: M, Hossain, M. Rahman; analysis and interpretation of results: M, Hossain, M. Rahman, D. Chamberlain, draft manuscript preparation: M, Hossain, M. Rahman, D. Chamberlain, T. Kasim. All authors reviewed the results and approved the final version of the manuscript.

CRediT authorship contribution statement

Kasim Dr Tala: Writing – review & editing, Visualization. **Chamberlain Professor Denis:** Writing – review & editing, Validation, Supervision, Methodology. **Rahman Professor Mujib:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Moinul Hossain:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Moinul Hossain reports financial support was provided by Aston University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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