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# Thermo-physical Properties of Graphite Powder and Polyethylene Modified Asphalt Concrete

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## Abstract

Energy harvesting using asphalt solar collectors has opened a new era for the researcher and this study is an attempt to understand the thermo-physical properties of asphalt concrete. The study mainly focuses on the thermo-physical properties such as thermal conductivity, specific heat capacity, thermal diffusivity, thermal effusivity, and density of asphalt concrete in relation to thermal properties. Asphalt concrete incorporated with graphite powder 2.0%, 3.0%, 4.0%, 5.0%, and 6.0% by weight of quarry dust, polyethylene (PE) content was optimized 9.0% used dry method of mixing, granite coarse aggregate size asphalt concrete (AC-14) and bitumen 60/70 (4.5%) used to prepare the Marshall. Firstly, Marshall Stability optimization was evaluated and the best-performing Marshall Samples were produced to further analyze the thermal properties. Fox-50 steady-state heat flow meter was used to determine the thermal properties of the graphite polymer asphalt concrete (GPAC). The study found that graphite polymer asphalt concrete density decreased in the result thermal conductivity, specific heat capacity, thermal diffusivity, and thermal effusivity increased. In the conclusion, graphite polymer asphalt concrete thermal properties have increased, and by increasing the temperature thermal physical increased though.

*Keywords:* Graphite Polymer asphalt concrete (GPAC); Thermal conductivity; Specific heat capacity; Thermal diffusivity; Thermal effusivity; Density.

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## 1. Introduction

Over the past few decades, spending money on new road construction and maintenance has increased. As a result asphalt industry has rapidly grown because asphalt concrete is the most commonly used paved material used in road construction.[1] Road materials are subjected to excessive dynamic load conditions combined with direct exposure to daily temperature changes, water, and moisture contents, corrosive and adhesive effects, and other environmental factors.[2] Recently, large cities are facing the challenge of the urban heat island effect and the asphaltic concrete road is one major cause of increasing urban heat due to the black color having a high potential of absorbing heat during the day time.[3-5] Natural ground temperature in the urban area has drastically changed compared to the asphaltic concrete. Studies revealed that the temperature over the asphalt concrete surface is up to 65-70 °C which is significantly higher than the natural ground surface.[6,7]

Thermo-physical concept applied on the road is shown in Fig. 1, indicating that road surface material will perform unidirectional, non-stationary heat exchange through conduction, convection, and radiation between surface layers and the surrounding environment.[2,6] Researchers proposed different methods to reduce the heat/temperature effect on the pavement surface such as researchers[8,9] proposed phase change materials, studies[6,10–14] have proposed asphalt solar collector technique, thermo-chromic asphalt,[15] permeable pavements[16,17] and a high-thermal-conductivity road.[18] The proposed methods of reducing road surface heat (urban heat island effect) may possible by the addition of thermal/conductive materials to the asphalt concrete potentially increased conduction to absorb solar radiation that occurs on the road surface and transfer the heat to the lower layer of the paved surface rather reflecting the environment. A study[6] has explained the heat transfer mechanism in asphalt pavement and reported heat harvesting potential in asphalt

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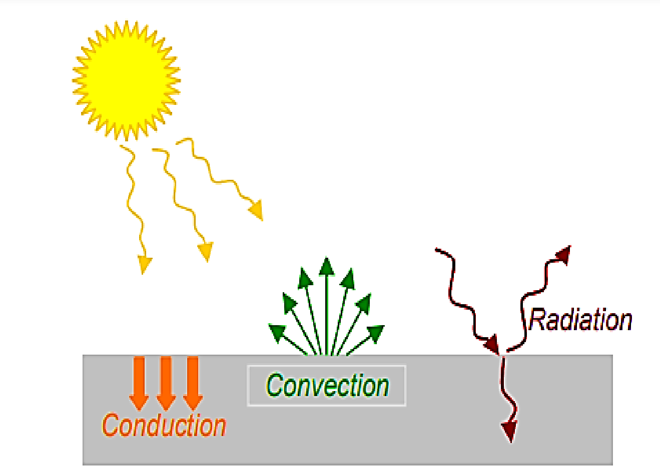


**Fig. 1** Schematic presentation of heat transfer model of pavement.[6]

pavement may significantly increase with the addition of conductive materials in the asphalt concrete.

Several studies conducted to investigate the thermo-physical properties of asphalt concrete by the addition of conductive materials such as asphalt pavement thermal conductivity has improved by the addition of graphite powder,[13,19,20] graphite powder and carbon fiber,[21,22], graphite and carbon black.[23]

Studies reported graphite-modified asphalt concrete significantly improves thermal properties and increase resistance to permanent deformation but has noticeably poor performance against moisture stability. Excessive addition of graphite powder into the asphalt concrete significantly reduces the marshall properties of asphaltic concrete. Steel slag aggregate,[5] Alumina micro-particles,[24] synthetic acrylic polymer substitute bitumen findings reported that asphalt concrete with synthetic acrylic polymer has a lower coefficient of thermal conductivity than conventional asphalt concrete.[2] Steel and carbon fibers modified asphalt concrete significantly improve the thermo-mechanical and physical properties however fibers modified asphalt produce clustered in the asphalt pavement.[25] Mineral aggregate, basalt, granite, dolerite and limestone powder and basic oxygen furnace (BOF) slag used to prepare the asphalt concrete result did not show much noticeable difference in the thermal properties of the modified asphalt over conventional asphalt concrete.[26] The process of heat transfer may accelerate in the summer using conductive asphalt concrete, contrary in the winter the process of heat transfer stored in a solar collector system beneath the road surface accelerates towards the upper layer of the road surface increasing the temperature could be helpful deicing of the road surface also keep the surface warmer.[27] Waste polyethylene addition to asphalt concrete significantly improves Marshall stability, flow, and volumetric properties,[28,29] rutting and moisture stability,[30] indirect tensile strength, compressive strength, fracture toughness, and rutting improved.[1,31,32] The comparison indicated that utilization of conductive fillers materials in asphalt concrete may reduce the urban heat island effect and meanwhile may increase the efficiency of solar energy harvesting in asphalt pavement. However, physical-mechanical properties such as marshall stability, indirect tensile strength, and longer sustainability against permanent deformation, creep, freeze-thaw resistance and dynamic modulus, moisture stability, and thermal cracking in the asphalt pavement experiencing heavy dynamic load in the large slab are ignored. Numerous studies have investigated the thermal-physical properties of asphalt concrete or materials used in asphalt concrete by adopting different methodologies and techniques. Thermal properties of asphalt concrete, we reviewed the techniques used previously to determine thermal properties are parallel hot-wire,[5,24] DRM-II thermal conductivity,[18] TCi thermal conductivity analyzer,[2] Heavy-Duty Thermal Constant Analyzer-Hot Disk TPS 1500,[21] surface probe type of QuickLine-30,[23] Thermal Constants Analyzer (TPS 2500S, Hot Disk,[26,33] transient heat flow meter,[34-37] MOM Derivatograph-C,[38] Flat wall heat conduction method,[39] Transient Plane Source (TPS) Method.[40]

Thermo-physical properties such as thermal conductivity coefficient (k), specific heat capacity ($C_p$), and thermal diffusivity (α) values have been investigated for years through laboratory testing and numerical analysis. Thermo-physical properties were studied for many years yet no uniform standards to regulate the test methods and conditions for determining the thermo-physical properties of asphalt concretes are defined. The thermo-physical values of asphalt concrete are highly dependent on the material composition, compaction, density, testing method, and temperature.[2,41] The purpose of this study is to utilize waste polyethylene (PE) and graphite powder to optimize thermo-physical properties of asphalt concrete by using FOX-50 Thermal analyzer (heat flow meter method on the principle of steady state technique) ASTM C518 and ISO 8301. This study is mainly focuses on the thermal-physical properties where mechanical investigation has completed and will be the part of next study. Table 1 summarizes the filler/additive added to the asphalt concrete to improve thermal-physical properties together with methods used for the determination of thermal conductivity, specific heat capacity, volumetric heat capacity, and thermal diffusivity.

## 2. Material characterization and specimen preparation

### 2.1 Raw material

Asphalt concrete (AC) has been modified by using locally available asphalt materials composed of asphalt binder (Bitumen 60/70), conventional granite coarse and fine aggregate materials where graphite powder added due to highest thermal conductive value and waste plastic bags (Polyethylene-PE) has substituted the asphalt binder to enhance the Marshall stability to prolong the lifetime, strength, indirect tensile, aging, moisture stability and other parameter causing permanent deformation in the asphalt concrete. The asphalt is modified based on the conductive material (graphite)

**Table 1.** asphalt fillers/ Techniques and thermo-physical properties.

| Reference | **Filler/Additive** | **Method/techniques used to investigate Thermo-physical** | **Thermal conductivity coefficient (k), k, W/m/K** | **Specific heat capacity J kg$^{-1}$ K$^{-1}$ Or Volumetric Heat capacity (J/(m$^3$·K))** | **Thermal Diffusivity (α) 10$^{-6}$ m$^2$ s$^{-1}$** |
|---|---|---|---|---|---|
| Rositsa and penka[2] | synthetic acrylic polymer | TCi thermal conductivity analyzer | 1.296 | 1.91 J kg$^{-1}$ K$^{-1}$ | 6.844 |
| Raheb *et al*.,[40] | Asphalt concrete without additive | Transient plane source (TPS) | 1.39 | 2.16 | 6.64 |
| Wenxiu *et al*.,[5] | Steel slag, diabase | parallel hot-wire | 1.70-1.75 | - | - |
| Mingyu *et al*.,[13] | Graphite powder | 2D finite element simulation/Ansys | 2-3 | 2.14 | - |
| Yingfeng *et al*.,[24] | Alumina micro-particles | hot-wire method | 0.99 (Asphalt-0.20) increased 400%) | - | - |
| Hai & dae[21] | Graphite powder and carbon fibers | Heavy-Duty Thermal Constant Analyzer-Hot Disk TPS 1500 | 1.90-2.45 | 1.69-2.15 | - |
| Byong *et al*.,[23] | Graphite powder and carbon black | surface probe type of QuickLine-30 | 1.97-2.089 | 1.60-1.97 | 1.004 |
| Pan *et al*.,[26] | SBS modified asphalt | Thermal Constants Analyzer(TPS 2500S, Hot Disk | 1.62 | 2.16 | 7.48 |
| Xijun *et al*.,[33] | EPP/Graphite powder | Thermal Constants Analyzer (TPS 2500S, Hot Disk | 1.93-2.65 | 1.89-2.009 | - |
| Andrew *et al*.,[35] | Lime Stone asphalt concrete<br>Partial Quartzite<br>Copper slag<br>Fully Quartzite<br>Fully Quartzite /2% copper Fiber | Transient heat flow meter | 1.21<br>1.46<br>1.05<br>2.46<br>2.86 | 919 J/m$^3$ K<br>880<br>814<br>870<br>836 | 5.53<br>7.06<br>4.15<br>12.30<br>13.64 |
| Pan *et al*.,[42] | Graphite | Thermal Constants Analyzer (TPS 2500S, Hot Disk | 0.96 | - | 6.37 |

and polyethylene (PE-Polymer) so we have named Graphite polymer asphalt concrete (GPAC). The asphalt binder (Bitumen 60/70) was collected from Kajang rocks and Premix Sdn.Bhd. Bitumen (60/70) performance tests were conducted in the IKRAM pavement and engineering laboratory, one of the well-recognized Pavement laboratories in Malaysia, following the Standard Test Method of Bitumen and Bituminous Mixtures for Highway Engineering (ASHTO, ASTM, BS, and MS), technically specification of bitumen is listed in Table S1. Granite and mineral powder/material fine aggregate is abundantly available and used as a conventional asphalt material in Malaysia, mechanical-physical properties of coarse and fine aggregate are listed in Table S2, and sieve analysis is shown in Table S3 followed by a graphical representation in Fig. S1. Thermal additive/filler material Graphite powder was obtained from Honworld chemical and machinery Sdn. Bhd and polyethylene waste plastic were collected locally.

**2.2 Marshall specimen optimization**

Conventional asphalt concrete (AC-14) composed of granite aggregate nominal maximum size of 14 mm as sieve analysis result is shown in Table S3 and graphically represented in Fig. S1. Physical properties of coarse and fine aggregate are shown in Table S2. Asphalt binder grade 60/70 physical testing such as penetration, and softening point results are reported in Table S1. Graphite powder is added to 2.0%, 3.0%, 4.0%, and 5% respectively. Polyethylene (PE) has substituted/replaced asphalt bitumen content (60/70) by weight 3.0%, 6.0%, 9.0%, and 12% respectively. The appropriate Marshall Sample (MS) was prepared following Malaysian standards for highway engineering premix design. The quantities of coarse aggregate, fine aggregate cement, and quarry dust were used in sample preparation by using Marshall specimen size 64 mm thick (height) and 100mm diameter. Marshall Sample containing no graphite and polyethylene (Control sample) asphalt aggregate ratio 4.0%-4.5%-5.0% and 5.50% asphalt binder-aggregate ratio 4.5% was optimized. After optimization of the control sample conductive asphalt concrete Marshall samples were produced by adding 2.0%, 3.0%, 4.0% and 5.0% graphite powder and bitumen content have substituted by 9.0% addition of polyethylene (PE). Importantly, the dry method of marshall Preparation is used, meaning polyethylene is substituted when the marshall was cooking at 160 °C-185 °C, so we have added waste polyethylene. The whole process of best performing marshall Optimization and selection graphite powder –and polyethylene ratio is carried out in the control environment of Ikram pavement engineering laboratory Malaysia since this study mainly focuses on the thermo-physical properties of thermal conductive polymer asphalt concrete (TCPAC) thus mechanical findings of Marshall will discuss in the following objectified study. Maximum 6 (six) samples of graphite-polymer asphalt concrete were created for each Marshall mixture to further analyzed the thermo-physical properties.

### 2.3 Heat flow meter–fox-50 Apparatus

Thermo-physical properties of graphite polymer asphalt concrete were investigated using the Fox-50 thermal analyzer function based on the steady-state technique of the heat flow meter method followed by international standards ASTM C-518-IS08301 and DIN EN 12667. The fox-50 heat flow meter is accurate and easy to use due to the rapid result function more common among industry professionals. All tests were conducted at room temperature using two thicknesses method of measuring thermal conductivity where the same material specimen is tested for two different thicknesses. Fox-50 specification sample size thickness 25 mm, diameter 50 mm to 62 mm. Thermal conductivity analysis using the Fox-50 test was carried out at UNITEN (Tenaga Nasional Universiti, Malaysia-Year June2020-November20).

### 2.4 Thermo-physical characteristics analysis

In this study, Fox-50 (Heat flow meter) is used; a specimen is positioned between two temperature-controlled plates. The heat flow meter consists of the upper and lower plate and to avoid heat losses the plates are properly protected in the casing. The upper plate is stationary and the lower plate moves vertically to provide good contact with the sample and minimize interface resistance. The temperature difference between the upper and lower plate should be defined as ± 20 °C. Due to the high sensitivity of the asphalt binder material would not allow us to go higher temperature than 50 °C, so we have calibrated a lower temperature of 18 °C and a higher 38 °C for point one where data was recorded at the temperature of 28 °C and for second point temperature recorded for 38 °C, lower plate temperature was calibrated 28 °C and the upper plate was calibrated 48 °C. Fox-50 was calibrated for thermal conductivity and specific heat capacity ($C_p$).

### 2.5 Specimen preparation

Graphite polymer asphalt concrete marshall specimen thickness 65 mm × 100 mm diameter was cored to obtain an appropriate specimen size of maximum 25 mm thickness and 50mm diameter as per Fox-50 specification, the prepared sample thickness was 11 mm-13 mm, thickness negligibly (very less) effect on the thermal conductivity of specimen.[43] Fig. S2a) shows the cored specimen followed by Fig. S2b), cutting and polishing of the specimen prepared for the Fox-50 specification.

Asphalt is a highly temperature-sensitive material and due to the heat flow process during thermal analysis may soften the bitumen in the resulting sensor of the Fox-50 instrument (heat flow meter) may damage so thermal analysis was carried out at a lower 28 °C and upper temperature 38 °C was set because bitumen (60/70) used has softening point 54 °C. Most of the past studies were unclear about the setting of the upper and lower testing temperature while conducting thermal analysis for asphalt concrete using any technique for thermal conductivity. Thus, this study has set the lower and maximum upper temperatures while conducting thermal analysis. Two thickness methods are employed to determine the thermal properties of the graphite polymer asphalt concrete (GPAC).

### 2.6 Equations for thermo-physical properties

#### 2.6.1 Thermal conductivity

The general principle of the FOX50 apparatus is based on one-dimensional Fourier law Equation (1) The average heat flux is used to calculate the thermal conductivity (l) and thermal resistance (R) by using Fourier's Law.[44]

$$q = q_x = -\lambda\frac{\delta T}{\delta x} \approx \lambda\frac{\Delta T}{\Delta x} = \lambda\frac{T_1 - T_2}{d} \quad (1)$$

where $q$ = heat flux flowing through the specimen (W/m$^2$); λ = thermal conductivity (W/(m·K)); $T$ = temperature (K); $d$ = thickness of specimen (m) and T/x = temperature gradient (K/m). The calibration of the Fox-50 is necessary and should be with a known thermal conductivity material value $\lambda_{cal}$ at the temperature $T_{cal.}$ The factors used to calibrate the Fox-50 are determined from Equation (2)[43] and those were used in actual tests in Equation (3)[45] and presented in past studies.

$$S_{cal} = \frac{\lambda_{cal}\,\Delta T(Q_1 - Q_2)}{(\Delta x_2 - \Delta x_1)(Q_1 * Q_2)} \quad (2)$$

where, $S_{cal}$ = temperature dependent calibration factor (W/ (m$^2$ μV)); $Q1$, $Q2$ = signal values of two separate tests (μV); $\Delta x_1$ and $\Delta x_2$ = thicknesses of two separate specimens (m).

$$\lambda_{test} = S_{Cal}\,(T_{test}) \cdot Q \cdot \frac{d_{test}}{\Delta T_{test}} \quad (3)$$

There is an upper and lower plate in the Fox-50 apparatus in the result two different values of thermal conductivity of the specimen are obtained which will be further analyzed to get the average thermal conductivity at the average test temperature $T_m$. Equations (3) and (4) are used if plain specimen thermal conductivity is required. In this study rubber sheet specimens were used to determine the thermal conductivity using Equation (4).[45] The main reason to use rubber sheets or thermocouples is to eliminate errors caused by air gaps and poor contact between the specimen's surfaces and the apparatus' plates.

$$\lambda = \frac{d_{total} - d_r}{(\frac{d_{total}}{\lambda_{total}} - \frac{d_r}{\lambda_r})} \quad (4)$$

where $d_{total}$ = thickness of both the rubber sheets and the specimen together (m); $d_r$ = thickness of two rubber sheets and $\lambda_r$ = thermal conductivity of two rubber sheets.

### 2.6.2 Specific heat capacity (J/(kg·K))

Specific heat capacity ($C_p$) is defined as the heat required to increase the temperature of the material of a certain mass by 1 °C, in the unit of J/(kg·K). Volumetric heat capacity is the required heat to change the unit volume of a material by a unit of temperature and expressed with (J/(K·m$^3$)). The difference is the mass and volume we can either choose one but where most of the past studies have worked on the specific heat capacity in this study we have resulted in both. Specific heat capacity at the constant pressure is determined using Equation (5).[44]

$$C_P = \frac{1}{m}\frac{d_Q}{dT} = \frac{Q}{m \cdot \Delta T} \quad (5)$$

where, $C_p$ = specific heat capacity at a constant pressure (J/(kg·K)); Q = heat energy (J); m = mass (kg) and T = temperature (K). The heat flow meter Fox-50 apparatus followed the ASTM-C1784-13 manual and determine the specific heat capacity using Equation (6).[45]

$$C_p \cdot \rho = \frac{H - H_{hfm}(T).\Delta T}{x \cdot \Delta T} \quad (6)$$

where $C_p$ = specific heat of the specimen (J/(m$^3$ K)); $\rho$ = density (kg/m$^3$)); $x$ = thickness of the specimen (m); ΔT = temperature change (K); $H$ = amount of heat energy per square meter (J/m$^2$) and $Hhfm(T)$ = correction factor to remove the effect of the plates (J/(m$^2$·K))

### 2.6.3 Thermal effusivity (W/K m$^2$ S$^{1/2}$)

Thermal effusivity is the ability of a material to exchange thermal energy with its surroundings. Thermal effusivity is the square root of the product of the material's thermal conductivity and its volumetric heat capacity. Equation (7)[46]

$$e = (k \cdot \rho \cdot C_P)^{\frac{1}{2}} \quad (7)$$

where $e$ is the thermal effusivity, $\rho$ is density, $C_p$ is the mass-specific heat capacity at constant pressure, and $k$ is the thermal conductivity. Thermal effusivity may be expressed equivalently in units of $Ws^{1/2}/m^2K$ or $J/s^{1/2}m^2K$.[47]

### 2.6.4 Thermal diffusivity (m$^2$/s)

Thermal diffusivity is the measurement of the heat transfer rate of one material from the hot to the cold end. Thermal conductivity divided by density and specific heat capacity at constant pressure gives thermal diffusivity (m$^2$/s).[46-48]

$$\alpha = \frac{k}{\rho \cdot C_p}\left(\frac{m^2}{s}\right) \quad (8)$$

where α is the thermal diffusivity, $k$ the thermal conductivity, $\rho$ the density, and $c_p$ the specific heat capacity at constant pressure

### 2.6.5 Density of asphalt concrete (Kg/m$^3$)

Specimen density before thermal conductivity and after thermal conductivity was determined using the saturated surface dry (SSD) method and calculated for each sample according to Equation (9)[49]

$$\rho_{bssd} = \frac{m_1}{m_3 - m_2} \times \rho_w \quad (9)$$

where $\rho_{bssd}$ bulk saturated surface density (SSD) (kg/m$^3$); $m_1$ mass of the dry specimen (g); $m_2$ mass of the specimen in water (g); $m_3$ mass of the saturated surface-dried specimen (g) and $\rho_w$ density of water at test temperature (kg/m$^3$)

## 3. Results and discussion

Thermal properties of asphalt concrete were determined using a steady-state technique heat flow meter-Fox-50 instrument. The control sample (Unmodified asphalt) was followed by graphite polymer asphalt concrete (GPAC) using 2.0%, 3.0%, 4.0%, 5.0%, and 6.0% graphite powder without polyethylene (PE). The Marshall was optimized with a 4.0% addition of graphite for the highest Marshall stability so we have added 9.0% polyethylene (PE) with optimized graphite asphalt concrete to further analyze the thermal properties. A total of 6 samples for each mixture were tested for thermal properties and an average result is summarized in Table 2.

### 3.1 Thermal conductivity of rubber sheet

Fox-50 was calibrated with a rubber sheet thickness of 1.42 mm and Equation (4) was used to determine the average thermal conductivity for two points at 28 °C, λ = 0.17 and average thermal conductivity at 38 °C is 0.19 W/(m·K).

### 3.2 Thermal properties of asphalt concrete

Thermo-physical properties such as density of the asphalt, thermal conductivity, volumetric heat capacity, specific heat capacity, thermal diffusivity, and thermal effusivity of control /unmodified asphalt concrete (no additive or fillers added) and modified asphalt by addition of graphite by 2.0%, 3.0%, 4.0%, 5.0%, and 6.0% have presented in Table 2.

All specimens were dried at room temperature to ensure the minimum moister content in asphalt concrete cannot be dried in an oven due to highly sensitive material. These findings are the mean value of 6 samples tested for each mixture.

### 3.2.1 Density of the asphalt concrete

The standard density of asphalt concrete is 2322 kg/m$^3$ - 2451 kg/m$^3$.[50-52] Study has noted that the addition of graphite 4% gives the highest Marshall stability and further addition reduces the strength of the asphalt concrete. The density of the asphalt concrete will decrease as the addition of graphite content increases in the mix. The average density of the control sample is 2329.11 kg/m$^3$ which is in line with the literature results and GPAC by 4.0% graphite and 9.0% PE density is 2292.18 kg/m$^3$, where the addition of graphite 2.0%, 3.0%, 4.0%, 5.0% and 6.0% modification of asphalt resulted from densities are 2316.23; 2309.18; 2297.14; 2284.05 and

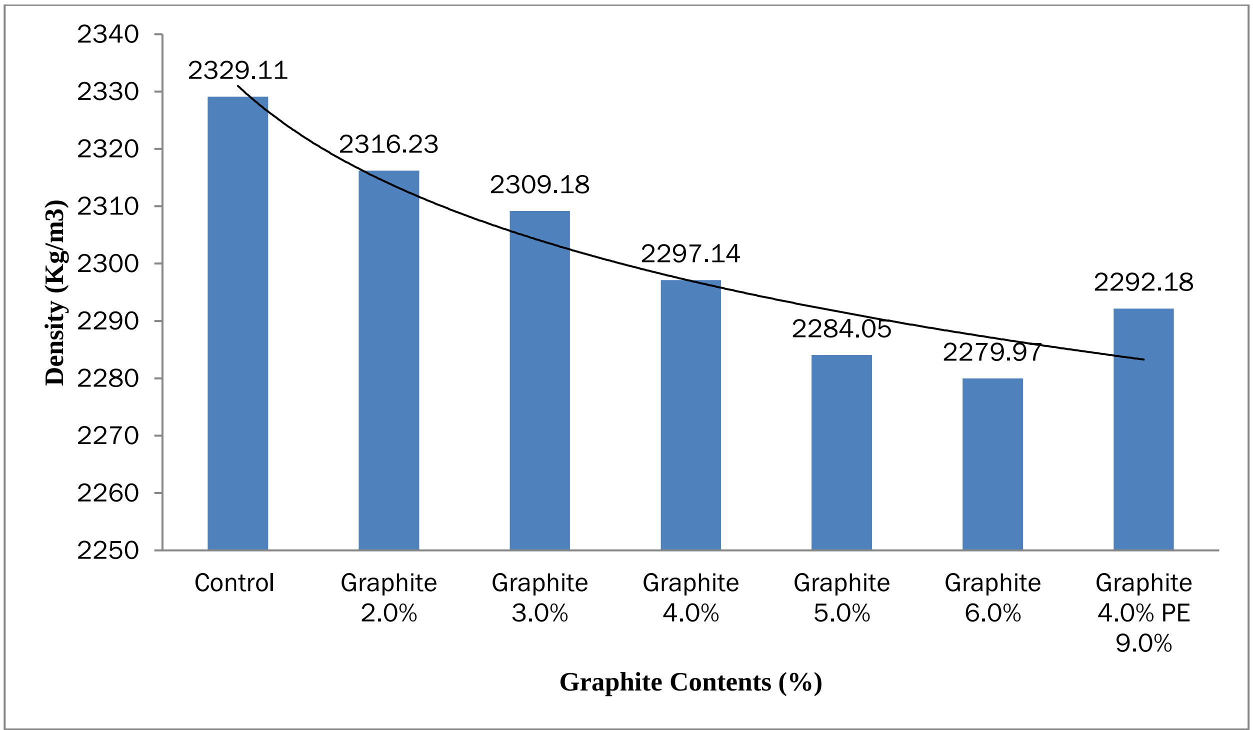


**Fig. 2** Graphite polymer asphalt concrete density.

**Table 2.** Two-point thermal Properties of Asphalt concrete.

| Samples | Bulk Density ($Kg/m^3$) | Thermal Conductivity (W/m K) | | Specific heat capacity (J/kg K) | | Thermal Diffusivity ($m^2/s$) | | Thermal Effusivity W. $m^{-2}$ $K^{-1}$ $s^{-1}$ | |
|---|---|---|---|---|---|---|---|---|---|
| | | 28°C | 38°C | 28°C | 38°C | 28°C | 38°C | 28°C | 38°C |
| Control | 2329.11 | 0.89 | 0.97 | 421.25 | 439.48 | 0.635 | 0.644 | 1101.61 | 1089.592 |
| Graphite 2% | 2316.23 | 1.17 | 1.21 | 527.10 | 562.82 | 0.772 | 0.945 | 1425.64 | 1499.98 |
| Graphite 3% | 2309.18 | 1.56 | 1.67 | 617.90 | 683.71 | 0.981 | 1.029 | 1767.31 | 1819.42 |
| Graphite 4% | 2297.14 | 2.09 | 2.19 | 747.28 | 782.04 | 1.055 | 1.070 | 1972.88 | 1982.94 |
| Graphite 5% | 2284.05 | 2.05 | 2.17 | 756.19 | 791.31 | 1.087 | 1.059 | 2030.30 | 2092.79 |
| Graphite 6% | 2279.97 | 1.97 | 2.04 | 781.40 | 812.02 | 1.008 | 0.964 | 2045.79 | 2114.05 |
| Graphite 4%, E-9% | 2292.18 | 2.09 | 2.16 | 759.10 | 784.53 | 1.029 | 1.0984 | 1987.21 | 2016.18 |

2279.97 $kg/m^3$ respectively results are drawn in Table 2 and graphically shown in Fig. 2 The findings indicated that density of the asphalt concrete decrease by increasing the graphite content and findings show the incorporation of polymer 9.0% and graphite 4.0% has lower density compared to the control sample. Density has a strong relation with thermal conductivity, the lower density higher will be the thermal conductivity.[23,42,53] Density significantly affect the thermal conductivity of asphalt concrete more than water.[37] The improvement of the efficiency of solar asphalt concrete is necessary to utilize a material highly thermal and lower in density graphite has the highest thermal conductivity and lower density has significantly reduced the density. Moreover, the study observed that thermal conductivity has increased by almost 110% with the addition of 2-6% graphite powder compare to the control sample.

### 3.2.2 Thermal conductivity of asphalt concrete

The thermal conductivity of asphalt concrete at different temperatures has not been studied in the past. Secondly adopted methods of determining thermo-physical properties is different irrespectively used in the past thirdly materials description were not clear in the past studies, this study has explained materials in the methodology section clearly. The average result of thermal conductivity is determined using the Fox-50 heat flow meter and listed in Table 2.

According to the Wiedemann–Franz law thermal conductivity (k) of the material is proportional to the temperature (T).[54] Thermal conductivity is temperature dependent and varies with temperature.[34] Thermal conductivity relation with temperature is highly debated among researchers and found liquid thermal conductivity decreased by increasing the temperature, gases thermal conductivity increases by increasing temperature. In the case of solid materials (Alloy, metal, non-metals, homogenous and non-homogenous, *etc.*) lattice distortions may affect temperature variation. The thermal conductivity of the materials in the solid-state body is temperature dependent. Therefore, we assumed due to the non-homogenous texture thermal conductivity may increase by increasing temperature. The study performed for soil shows by increasing temperature significantly increases the thermal conductivity[55] of the soil.

Asphalt concrete is a highly temperature-sensitive material. We cannot increase the temperature and this is the reason most of the researchers carried out asphalt thermal conductivity tests at room temperature. However, most of the researchers in the past did not mention the temperature effect on the thermal conductivity of asphalt concrete. Though, this research has determined two points 28 °C and 38 °C thermal conductivity, and found that by increasing temperature thermal conductivity of asphalt concrete has slightly increased as reported in Table 2.

Thermal conductivity of the control sample (28 °C = 0.89; 38 °C = 0.98) followed respectively as by graphite modified asphalt 2.0% (28 °C = 1.17; 38 °C = 1.21), 3.0% (28 °C = 1.56; 38 °C = 1.67), 4.0% (28 °C = 2.09; 38 °C = 2.19), 5.0% (28 °C = 2.05; 38 °C = 2.17), 6.0% (28 °C = 1.97; 38 °C = 2.04) and graphite 4.0% and polymer 9.0% (28 °C = 2.09; 38 °C = 2.16). The respective findings indicated that by increasing the temperature thermal conductivity of the asphalt concrete increased. This is the reason when external temperature increases the conduction in the asphalt concrete occurred and heat transfer from the pavement surface to the subsurface in the asphalt concrete referring to Fig. 1 thermal conduction process occurred in asphalt concrete. By utilization of high thermal conductive materials in the resulting asphalt concrete thermal conductive enhancement. Therefore, the literature shows thermal conductivity of asphalt concrete increased with the addition of graphite powder.[13,42] Thermal conductivity of graphite polymer asphalt concrete (GPAC) increased as shown in Fig. 3.

### 3.2.3 Specific heat capacity of asphalt concrete

The specific heat capacity or the heat storage capacity of the modified asphalt concrete is listed in Table 2 and graphically shown in Fig. 4. The specific heat capacity ($C_p$) of asphalt concrete has increased by increasing the graphite contents in the mixture. Moreover, at the higher temperature of 38 °C the $C_p$ of the asphalt concrete significantly increased. Specific heat capacity ($C_p$, J/kg K) of the control sample (28 °C = 421.25; 38 °C = 439.48) followed respectively by graphite modified asphalt 2.0% (28 °C = 527.10; 38 °C = 562.82), 3.0% (28 °C = 617.90; 38 °C = 683.71), 4.0% (28 °C = 747.28; 38 °C = 782.04), 5.0% (28 °C = 756.28; 38 °C = 791.31), 6.0% (28 °C = 781.40; 38 °C = 812.02) and graphite 4.0% and polymer 9.0% (28 °C = 759.10; 38 °C = 784.53). Study shows that specific heat capacity is temperature dependent and vary with temperature.[34]

Similar results were found in the studies[23-33] showing that increasing graphite contents increase the volumetric and specific heat capacity of the asphalt concrete. However, this study further contributed and added that the heat capacity of the asphalt concrete increased by increasing temperature similarly as the graphite contents in the asphalt concrete increased the specific heat capacity.

### 3.2.4 Thermal diffusivity of the asphalt concrete

Table 2 indicated that the constant addition of 2-6% of graphite powder to the asphalt concrete increased the thermal diffusivity of the modified asphalt concrete as graphically shown in Fig. 5. Thermal diffusivity is obtained using Equation (8) as stating thermal conductivity divide by density and specific heat capacity at constant pressure gives thermal diffusivity ($m^2/s$).[46-48] The findings listed for two point temperature 28 °C and 38 °C shows that the thermal diffusivity of the control sample (28 °C = 0.635; 38 °C = 0.644) followed respectively by graphite modified asphalt 2.0% (28 °C = 0.772; 38 °C = 0.945), 3.0% (28 °C = 0.981; 38 °C = 1.029), 4.0% (28 °C = 1.055; 38 °C = 1.070), 5.0% (28 °C = 1.087; 38 °C = 1.059), 6.0% (28 °C = 1.008; 38 °C = 0.964) and graphite

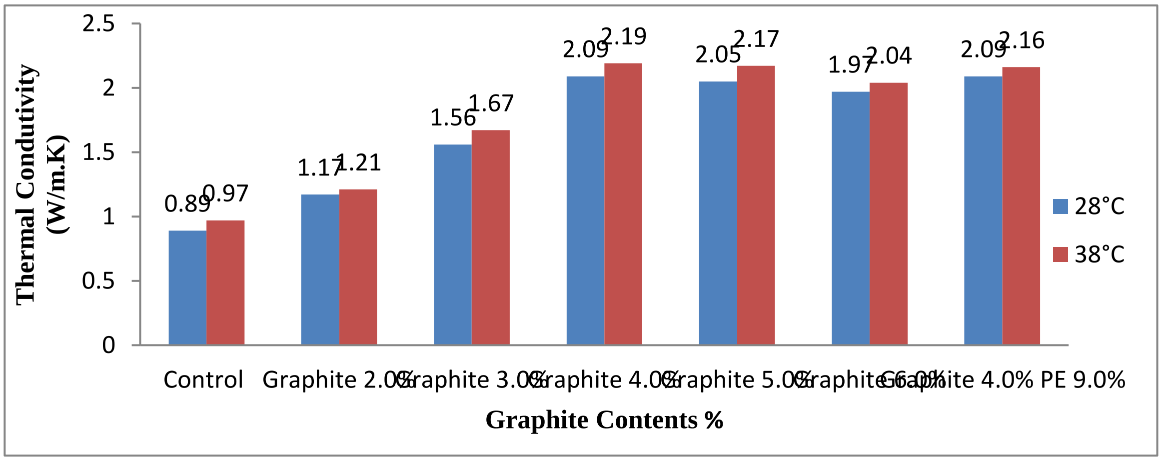


**Fig. 3** Thermal Conductivity of Graphite Polymer Asphalt concrete.

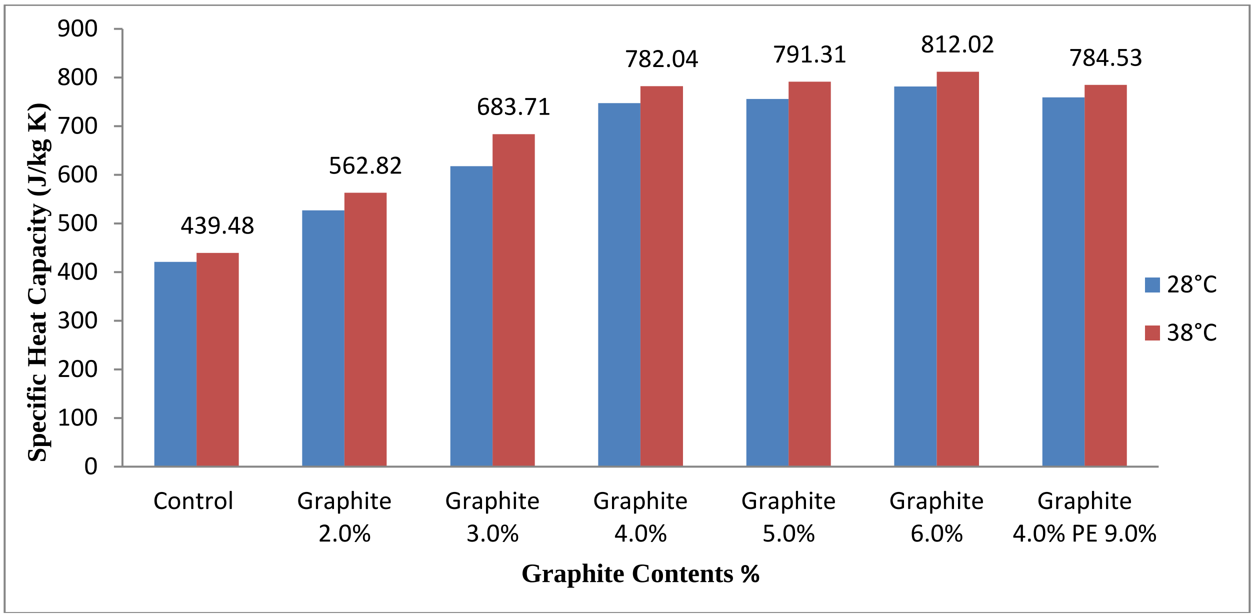


**Fig. 4** Specific Heat capacity of Graphite Polymer asphalt concrete.

4.0% and polymer 9.0% (28 °C = 1.029; 38 °C = 1.0984). Thermal diffusivity indicated the heat transfer from the hot material to the cold material.

The result shows that by increasing the graphite content thermal diffusivity of the asphalt concrete increased. Meanwhile, thermal diffusivity is temperature dependent as the temperature increased from 28 °C to 38 °C notably diffusivity of the asphalt concrete increased. Literature shows thermal diffusivity of the modified asphalt concrete increased with the addition of graphite.[23,35,42]

### 3.2.5 Thermal effusivity of the asphalt concrete

Thermal effusivity is the square root of the material thermal conductivity (λ) and its specific heat capacity ($C_p$) was determined using Equation (7) and the result is expressed as $Ws^{1/2}/m^2K$ as shown in Table 2. None of the past studies discussed or determined the thermal effusivity of asphalt concrete thus, the result validation of this part is not possible to update no literature information is available for the thermal effusivity of asphalt concrete. The findings of the thermal effusivity shown in Table 2 and Fig. 6, indicated that the thermal effusivity of the asphalt concrete increased with the addition of graphite powder and it is also temperature dependent property which is increased by increasing the temperature from 28 °C to 38 °C. Thermal effusivity ($Ws^{1/2}/m^2K$) of the control sample (28 °C = 1101.61; 38 °C = 1089.59) followed respectively as by graphite modified asphalt 2.0% (28 °C = 1425.64; 38 °C = 1499.98), 3.0% (28 °C = 1767.31; 38 °C = 1819.42), 4.0% (28 °C = 1972.88; 38 °C = 1982.94), 5.0% (28 °C = 2030.30; 38

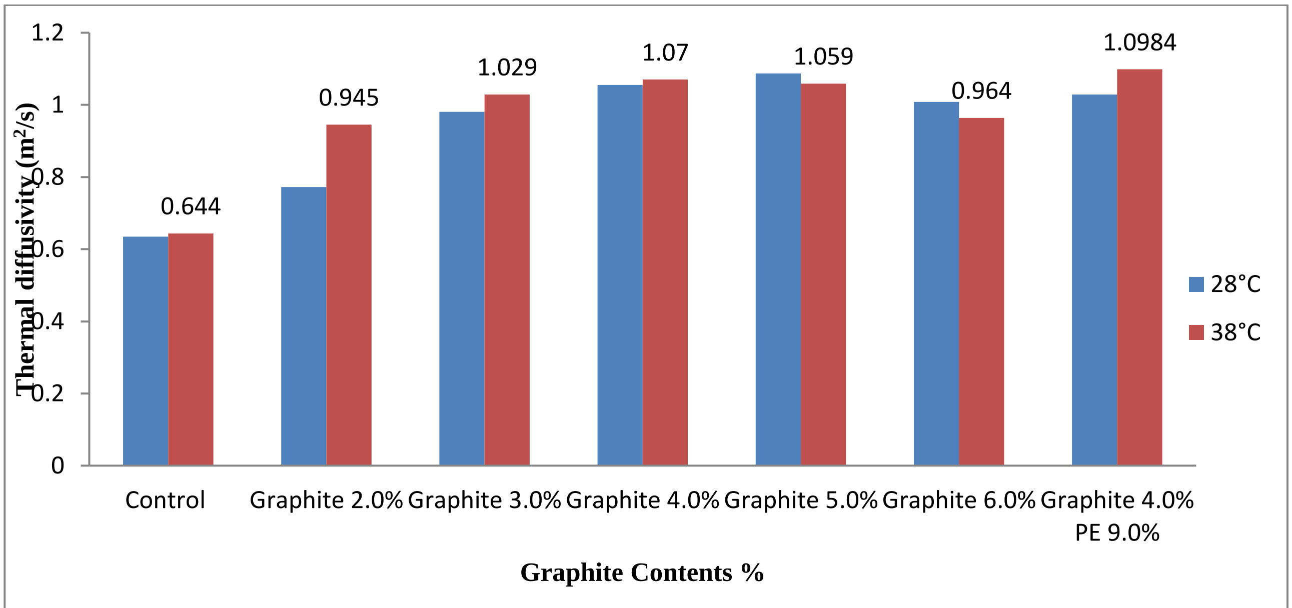


**Fig. 5** Thermal Diffusivity of the Graphite polymer asphalt concrete.

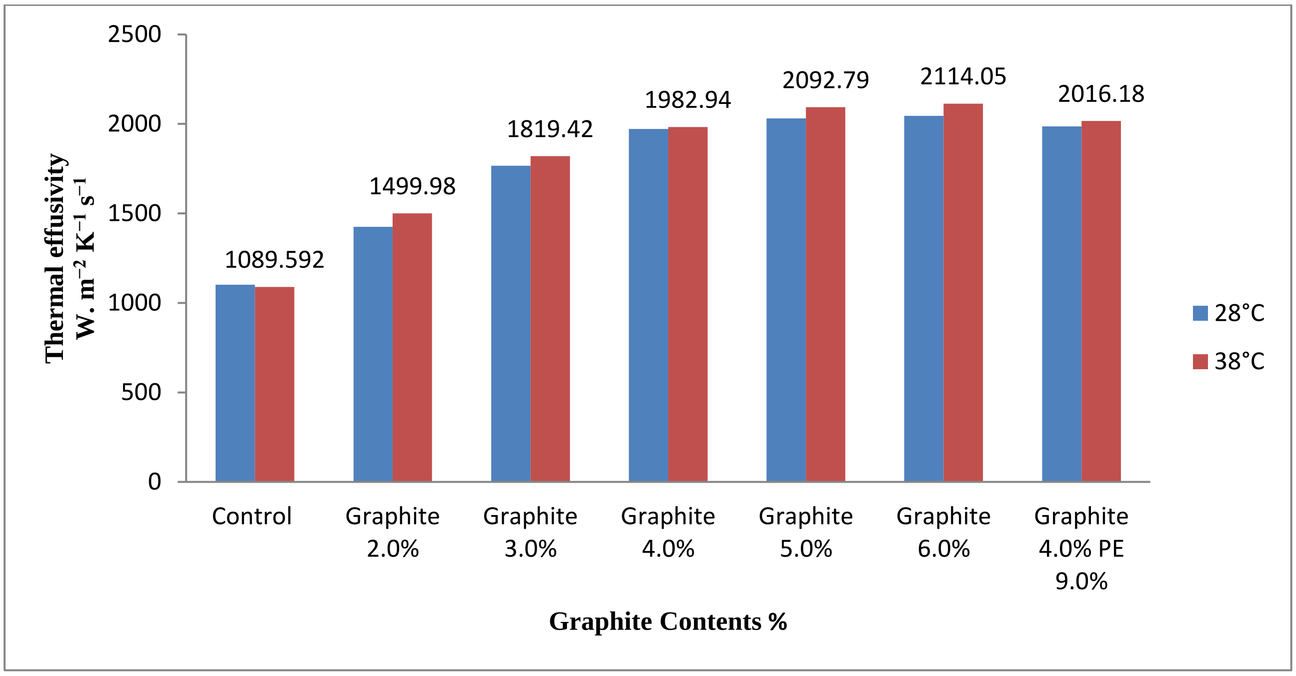


**Fig. 6** Thermal Effectivity of the Graphite asphalt concrete.

°C = 2092.79), 6.0% (28 °C = 2045.79; 38 °C = 2114.05) and graphite 4.0% and polymer 9.0% (28 °C = 1987.21; 38 °C = 2016.18). The obtained result shows that by increasing the graphite contents in the asphalt concrete thermal effusively increased also increasing temperature resulted from higher effectivity of the asphalt concrete.

## 4. Discussion

Studies revealed the temperature over the asphalt concrete surface is up to 65-70°C which is significantly higher than the natural ground surface. The potential of high surface temperature has opened a new era for engineers and researchers to study the potential benefits of asphalt solar collectors. Thus, it is important to understand the asphalt concrete thermo-physical properties. This study mainly focuses on the thermo-physical properties of asphalt concrete by the addition of graphite by 2-6% respectively and polyethylene (PE) added by 9% to achieve high stability in asphalt concrete which is one of the lacking factors in the past studies. Thermo-physical properties mainly play role in the asphalt solar collector are the density of the asphalt concrete, thermal conductivity, specific heat capacity, thermal diffusivity, and thermal effusivity. The investigation of the thermo-physical properties using a unique and new method of two-point thermal conductivity of asphalt concrete using FOX-50 steady flow heat meter set up of 28 °C and 38 °C.

The density of the asphalt decreased as the addition of graphite content increased in the mix. The findings indicated that the average density of the graphite-modified asphalt is in the line with the past result. Incorporation of graphite and polymer the density of graphite polymer-modified asphalt concrete decreased where density has a strong relationship with the thermal conductivity, the lower is density higher will be the thermal conductivity.[23,42,53] The lower the density higher is the thermal conductivity of the asphalt concrete and for the improvement of solar asphalt concrete, it is necessary to utilize the material high in thermal and lower in density. Thus, graphite has the highest thermal conductivity and lower density significantly reduces the density of asphalt. The study observed that thermal conductivity has increased by almost 110% with the addition of 2-6% of graphite powder in comparison to the control asphalt. Asphalt concrete is a highly temperature-sensitive material. Thus, we cannot increase the temperature that of the bitumen softening point is the reason in past studies, most the researcher avoided the thermal conductivity at higher temperatures except at room temperature thermal conductivity was determined in the past.

The study found that by increasing the temperature from 28 °C – 38 °C thermal conductivity of graphite polymer asphalt concrete slightly increased. The thermal conductivity of the asphalt concrete increased with the addition of graphite powder.[13,42,56,57] Specific heat capacity or the heat storage capacity of the modified asphalt concrete has increased by increasing the graphite contents in the mixture. Moreover, higher temperature significantly increases the heat storage capacity of the asphalt concrete, specific heat capacity is temperature dependent and vary with temperature.[34] The thermal diffusivity of the modified asphalt concrete has increased with the addition of graphite polymer content in the asphalt. The thermal diffusivity of asphalt concrete increased by increasing the temperature and graphite contents.[23,35,42] The thermal effusivity of the asphalt concrete increased with the addition of graphite powder and temperature-dependent properties also increases by increasing the temperature from 28-38 °C.

## 5. Conclusion

Asphalt solar collector has opened a new era for researchers and it is important to understand the asphalt concrete thermo-physical properties. This study mainly focuses on the thermo-physical properties of asphalt concrete by the addition of graphite content as well polyethylene (PE). The reason for additive incorporation in asphalt has been drawn in the introduction. Thermo-physical properties mainly play role in the asphalt solar collector are the density of the asphalt concrete, thermal conductivity, specific heat capacity, thermal diffusivity, and thermal effusivity. The study has made the following conclusion by addition of Graphite-PE content in the asphalt density decreased, and ultimately thermal conductivity increased. In other words, supported by past studies lower the asphalt concrete density higher is the thermal conductivity. The key conclusion of the study is the addition of graphite content of 2-6% lower the density and enhances the thermal conductivity but bear in mind Marshall stability is very essential so the study has optimized the 4% addition of the graphite and 9% PE gives the highest Marshall stability and further addition of graphite reduce the Marshall stability despite density reduces and thermal properties increase but we have optimized Graphite 4% and PE-9% gives the best result. Thermal conductivity is the temperature-dependent thermal properties of the material, especially in the case of the solid (non-homogenous) study concluded that thermal conductivity increases with increasing temperature. Asphalt is a highly temperature-sensitive material so we did not have to increase the temperature more than the softening point of bitumen used in the asphalt. The result shows thermal conductivity of the asphalt concrete increased with the addition of graphite powder and by increasing the temperature from 28-38 °C. The study found that the specific heat capacity ($C_p$) of the graphite polymer asphalt concrete has improved and increased with the temperature. The thermal diffusivity of the graphite polymer asphalt concrete has improved and also increase with the temperature. The study concludes the Thermal effusivity of the graphite polymer asphalt concrete has increased.

**Conflict of interest**

There are no conflicts to declare.

**Supporting information**

Applicable.

**Nomenclature**

| | |
|---|---|
| $\lambda$ | Thermal conductivity (W/(m·K)) |
| $\lambda_{cal}$ | Known thermal conductivity for calibration (W/(m·K)) |
| $\rho$ | Density (kg/m$^3$) |
| $a$ | Thermal diffusivity (m$^2$/s) |
| $b$ | Thermal effusivity (J/m$^2$ K s$^{1/2}$) |
| $c_p$ | Specific heat capacity (J/(kg·K)) |
| d | thickness of specimen (m) |
| $d_{total}$ | thickness of both the rubber sheets and the specimen together (m) |
| Hhfm (T) | correction factor to remove the effect of the plates (J/(m$^2$·K)) |
| H | amount of heat energy per square meter (J/m$^2$) |
| m | mass (kg) |
| q | heat flux flowing through the specimen (W/m$^2$) |
| Q | heat energy (J) |
| Q1, Q2 | signal values of two separate tests (µV) |
| $QL_{equil}$ | Heat Flow Meter signal at the final steady-state, lower plate (µV) |
| QLi | Heat Flow Meter signal value of lower plate (µV) |
| $QU_{equil}$ | Heat Flow Meter signal at the final steady-state, upper plate (µV) |
| $QU_i$ | Heat Flow Meter signal value of upper plate (µV) |
| $S_{cal}$ | Temperature dependent calibration factor (W/(m$^2$·µV)) |
| $SL_{cal}$ | Calibration factor of lower plate (W/(m$^2$·µV)) |
| $SU_{cal}$ | Calibration factor of upper plate (W/(m$^2$·µV)) |
| T | Temperature (K) |
| $T_{cal}$ | Known temperature for calibration (K) |
| $T_m$ | Average test temperature (K) |
| $\Delta T_{ext}$ | Temperature difference between external thermocouples (K) |
| x | Thickness of specimen (m) |
| $\Delta x_1$ | Depth of the groove (mm) $\Delta x_1$ |
| $\Delta x_2$ | Thicknesses of two separate specimens (m) |

**Subscripts**

| | |
|---|---|
| GPAC | Graphite polymer asphalt concrete |
| PE | Polyethylene |
| r | rubber sheets |
| Cal | Known thermal properties for calibration |

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