
THERMAL EVALUATION OF ASPHALT CONCRETE FOR PAVEMENT-BASED THERMOELECTRIC ENERGY GENERATION: INFLUENCE OF AGGREGATE TYPE AND GRADATION

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ABSTRACT

Asphalt pavements absorb large amounts of solar radiation and develop pronounced through-thickness temperature gradients that thermoelectric generators (TEGs) can, in principle, convert into electricity. The magnitude of the recoverable heat depends on the thermal properties of the asphalt concrete, which are in turn governed by mixture composition. This study evaluates the mechanical and thermal behaviour of asphalt concrete for pavement thermoelectric energy harvesting and examines the influence of aggregate type and gradation. Four mixtures were produced from basalt and granite aggregates in wearing-course (WC) and binder-course (BC) gradations: BWC, BBC, GWC and GBC. Marshall mix design (ASTM D6927) established optimum bitumen contents of 5.0–5.5%. Mechanical performance was assessed through Marshall stability, flow and indirect tensile strength (ITS) tests; the apparent thermal conductivity (k_{app}) and specific heat capacity were measured using a steady-state electrical (Searle-type) apparatus. A three-dimensional transient heat-transfer model was built in Abaqus to compare the relative thermal response of the mixtures. Basalt mixtures gave the highest stability (BBC = 7.83kN) and ITS (BBC = 493kPa). The measured k_{app} values (2.90–4.03W/m·K) lie above the range normally reported for asphalt concrete and are treated here as relative, comparative indicators rather than absolute material constants. Within this comparative framing, GWC exhibited the highest apparent conductivity and the largest simulated heat flux (2371W/m²), indicating the greatest thermal potential for subsequent thermoelectric generator integration among the mixtures studied. Electrical power output was not directly evaluated; the thermal characterisation provides a basis for subsequent assessment of TEG integration and power generation. The finite-element results were internally consistent with the analytical Fourier solution to within 13%. Aggregate type and gradation significantly influenced both mechanical and thermal behaviour, providing guidance for material selection in TEG-integrated pavements.

Keywords: Asphalt concrete; thermoelectric generators; energy harvesting; apparent thermal conductivity; aggregate type

1. INTRODUCTION

Rising global energy demand, the depletion of fossil resources and the environmental burden of conventional generation have intensified interest in renewable and waste-energy technologies (Gholikhani et al., 2020; Pei et al., 2021). Road networks are attractive in this context because their surfaces are continuously exposed to solar radiation and traffic loading, storing large quantities of thermal and mechanical energy that is otherwise dissipated to the environment (Zhu et al., 2019). Recovering even a fraction of this energy could power road lighting, sensors and monitoring devices while reducing the surface temperatures associated with the urban heat island effect.

Among pavement energy-harvesting approaches, piezoelectric, photovoltaic and thermoelectric generation is well suited to asphalt because the material routinely develops the temperature differentials on which the technology relies. TEGs are solid-state devices that convert a temperature difference directly into electricity through the Seebeck effect, and can operate wherever a gradient exists (Champier, 2017; Shaaban et al., 2019). Experimental and prototype studies have demonstrated combined power-generation and pavement-cooling functions, with cold-side (heat-sink) design frequently controlling field performance (Jiang et al., 2018; Zhu et al., 2019).

The efficiency of a pavement TEG system depends on the available temperature gradient and on the thermal properties of the surrounding asphalt concrete-principally its thermal conductivity and

specific heat capacity (Aridi et al., 2021). These properties are, in turn, governed by mixture composition. Because aggregate typically constitutes the majority of the mixture by volume, aggregate mineralogy and gradation exert a strong influence on heat transfer, whereas the binder-present in small proportion-has a comparatively minor effect (Mrawira & Luca, 2006; Demirtürk et al., 2024; Pasetto et al., 2025). Much of the existing literature focuses on enhancing conductivity through conductive additives such as graphite, steel fibres or slag (Abbas & Alhamdo, 2023), while the comparative effect of conventional aggregate type and gradation on the thermal response relevant to TEG applications has received less systematic attention.

This study therefore evaluates the mechanical and thermal behaviour of asphalt concrete produced from two common aggregate sources (basalt and granite) in two standard gradations (wearing and binder course) and assesses their relative suitability for pavement thermoelectric energy harvesting using combined laboratory testing and three-dimensional finite-element (FE) simulation. The work is framed around locally sourced Nigerian materials, for which such thermal characterisation is currently limited. The use of locally sourced Nigerian aggregates also supports the development of sustainable and locally adaptable pavement materials, while the thermal characterisation provides a basis for future pavement-based energy-harvesting applications relevant to Nigeria's infrastructure and energy needs.

2. MATERIAL AND METHODS

2.1 Materials and mix design

Crushed basalt (Kore quarry) and granite (Barawa quarry), both from Batagarawa LGA, Katsina State, and 80/100-grade bitumen sourced in Kano State were used. Aggregate and bitumen properties were verified against the Federal Ministry of Works (FMW) general specification and the relevant ASTM/BS standards (Tables 1 and 2). Four mixtures were designed-Basalt Wearing Course (BWC), Basalt Binder Course (BBC), Granite Wearing Course (GWC) and Granite Binder Course (GBC)-using the Marshall method in accordance with ASTM D6927. Optimum bitumen contents, obtained from stability, flow, unit-weight and voids plots following the Asphalt Institute procedure, were 5.5% for BBC and 5.0% for GBC, BWC and GWC.

2.2 Mechanical testing

Marshall stability and flow were determined on compacted cylindrical specimens (101.6mm diameter×63.5mm height) at 60°C, and indirect tensile strength (ITS) was measured to assess cracking resistance. Three replicates were tested per mixture and the mean reported.

2.3 Thermal property determination

Thermal conductivity was measured in the laboratory on Marshall-derived sub-specimens using a steady-state electrical (Searle-type) apparatus (this steady-state, effectively one-dimensional test relates only to the laboratory measurement of the material properties, and is distinct from the transient three-dimensional finite-element model of Section 2.4), with the conductivity computed as $k = VIL/(A \cdot \Delta T)$, where V and I are the applied voltage and current, L the specimen thickness, A the cross-sectional area and ΔT the temperature difference across the specimen. Three replicates were averaged for each mixture. Specific heat capacity was determined by the method of mixtures using a copper calorimeter,

It should be noted that this formulation attributes the full electrical power ($V \cdot I$) to one-dimensional conduction through the specimen and neglects lateral and convective heat losses. For a comparatively low-conductivity, heterogeneous material such as asphalt concrete, these losses are not negligible, so the method tends to over-estimate the absolute conductivity. The values reported here are therefore designated apparent thermal conductivity (k_{app}) and are used primarily as relative indicators for comparing mixtures and as comparative inputs to the FE model, rather than as absolute material constants. Because the FE simulations use these apparent conductivities as material inputs, the calculated heat-flux and reaction-heat-flow magnitudes inherit the uncertainty and possible systematic bias of the conductivity measurements. Therefore, these numerical quantities are interpreted comparatively rather than as independently validated absolute heat-transfer values.

Three replicate measurements were conducted for each asphalt mixture, and the mean, standard deviation (SD) and coefficient of variation (CV) were used to assess measurement repeatability. The SD was calculated as the sample standard deviation, $s = \sqrt{\frac{\sum (ki - \bar{k})^2}{n-1}}$ while the CV was calculated as: $CV = (s / \bar{k}) \times 100$. The resulting CV values ranged from 0.63% to 2.70%, indicating relatively low within-mixture variability. However, the observed repeatability does not eliminate possible systematic bias associated with the steady-state Searle-type method. Therefore, independent testing using a transient method (e.g., transient plane source) or a guarded steady-state cell would be required to establish absolute thermal conductivity values (Demirtürk et al., 2024). This limitation is revisited in Section 3.3.

2.4 Finite element model and Mesh Sensitivity Analysis

A three-dimensional transient heat-transfer model of the Marshall specimen (101.6mm × 63.5mm) was developed in Abaqus/CAE using DC3D8 eight-node linear heat-transfer elements. The measured density, apparent thermal conductivity and specific heat capacity of each mixture were assigned as isotropic and homogeneous properties. An initial temperature of 298.15K was applied, while fixed temperatures of 335K at the upper face and 310K at the lower face were prescribed for BBC, BWC and GWC. For GBC, 334K and 310K were prescribed at the upper and lower faces, respectively, corresponding to the measured temperature difference. A surface film condition with a film coefficient of 10W/m²·K and an ambient temperature of 298.15K was applied to the lateral surface to account for heat loss to the surroundings. Temperature (NT11), heat flux (HFL3), and reaction heat flow (RFL11) were extracted for analysis.

A mesh-sensitivity analysis was performed (Table 5) using nominal mesh sizes of 2, 3, and 4mm. For the representative BWC specimen, the corresponding HFL3 values were approximately 1351.55, 1312.95, and 1293.70W/m², respectively. The 3mm mesh differed by approximately 2.94% from the 2mm mesh and 1.47% from the 4mm mesh, indicating that further mesh refinement caused only minor changes in the calculated heat flux. Therefore, the 3mm mesh was adopted as a suitable balance between numerical accuracy and computational efficiency.

3. RESULT AND DISCUSSION

3.1 Material properties

Both aggregates satisfied the specification limits (Table 1). Basalt showed a higher specific gravity (2.82 vs 2.64), while granite recorded lower impact, abrasion and crushing values, indicating marginally greater resistance to mechanical degradation; both had acceptable flakiness and elongation indices. The bitumen properties (Table 2) were consistent with a 80/100 paving-grade binder.

Table 1: *Physical properties of basalt and granite aggregates*

Property	Basalt	Granite	Specification
Specific gravity (coarse)	2.82	2.64	2.5–3.0
Aggregate impact value (%)	11.1	7.7	30 max
LA abrasion (%)	24.3	20.0	30 max
Aggregate crushing value (%)	20.0	16.6	45 max
Flakiness index (%)	17.0	21.0	30 max
Elongation index (%)	15.0	25.0	30 max

Table 2: *Physical properties of the bitumen*

Test	Result	Standard
Penetration (0.1mm)	89	ASTM D5
Softening point (°C)	54	ASTM D36
Flash point (°C)	239	ASTM D92
Fire point (°C)	319	ASTM D92

Note: Values in the Specification column are presented as either permissible ranges or limiting requirements (minimum/maximum), as indicated.

3.2 Mechanical properties

Marshall stability, flow and ITS varied systematically with aggregate type and gradation (Table 3, Figure 1). The basalt mixtures outperformed the granite mixtures: BBC recorded the highest stability (7.83kN) and ITS (493.2kPa), followed by BWC, while GBC gave the lowest stability (3.86kN). The superior performance of the basalt mixtures is consistent with their higher specific gravity and better aggregate-bitumen interlock. The Marshall stability values of all four mixtures exceeded the minimum 3.5kN requirement specified for asphalt concrete in the Nigerian General Specifications for Roads and Bridges. GWC and GBC recorded 4.66kN and 3.86kN, respectively, and therefore satisfied the minimum stability requirement, although further optimisation may be required for higher traffic demands.

Table 3: *Marshall stability, flow and indirect tensile strength of the mixtures*

Mixture	Stability (kN)				Flow (mm)				ITS (kPa)			
	Replicate value (n = 3)	Mean	SD	CV (%)	Replicate value (n = 3)	Mean	SD	CV (%)	Replicate value (n = 3)	Mean	SD	CV (%)
BWC	6.56	6.56	0.27	4.04	3.40	3.40	0.00	0.00	485.60	475.90	10.18	2.14
	6.83				3.40				465.30			
	6.30				3.40				476.80			
BBC	7.83	7.83	0.17	2.17	3.80	4.03	0.21	5.16	531.10	493.20	34.09	6.91
	8.00				4.10				483.60			
	7.66				4.20				465.00			
GBC	3.90	3.86	0.24	6.28	3.40	3.47	0.12	3.33	445.30	466.10	29.69	6.37
	3.60				3.40				500.10			
	4.08				3.60				452.90			
GWC	4.58	4.66	0.20	4.26	2.40	2.77	0.51	18.36	460.60	439.30	22.25	5.07
	4.89				3.35				416.20			
	4.52				2.56				441.10			

Note: The values under the ‘Replicate value’ represent three independent measurements, SD = standard deviation; CV = coefficient of variation

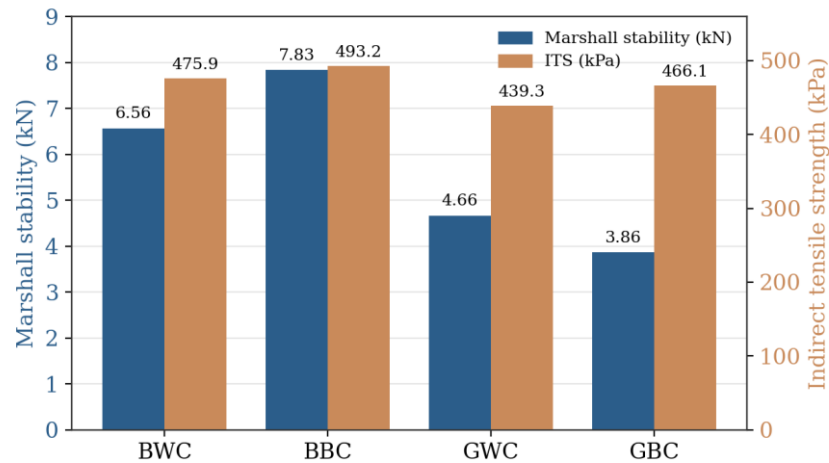


Figure 1: Marshall stability and indirect tensile strength of the four mixtures.

3.3 Thermal properties

The measured apparent thermal conductivity (k_{app}) ranged from 2.90W/m·K for BWC to 4.03W/m·K for GWC, with BBC and GBC recording 3.18 and 2.97W/m·K, respectively (Table 4, Figure 2). Specific heat capacity ranged from 765J/kg·K for GWC to 832J/kg·K for BWC. GWC therefore exhibited the highest apparent thermal conductivity and the lowest specific heat capacity, indicating a comparatively greater tendency for heat transfer through the mixture under the test conditions.

The measured k_{app} values should, however, be interpreted with caution. Reported thermal conductivities for conventional dense-graded asphalt concrete are typically around 1.7-2.1W/m·K (Mrawira & Luca, 2006) and rarely exceed 3W/m·K. The GWC value of 4.03W/m·K is therefore higher than expected for an asphalt concrete mixture containing binder and air voids. This overestimation is attributed to the steady-state electrical method, which assumes that the applied electrical power is transferred entirely by axial conduction while neglecting lateral and convective heat losses. These losses may be significant and may differ among mixtures, particularly for GWC, which exhibited the highest heat-transfer rate. Consequently, the measured values are treated as apparent thermal conductivities and are used primarily as comparative indicators and as inputs to the FE model rather than as absolute material constants.

Based on the measured values, the apparent thermal conductivity followed the order GWC > BBC > GBC > BWC. However, because lateral and convective heat losses may affect the mixtures to different degrees, this ranking should not be interpreted as an absolute ranking of intrinsic thermal conductivity. The mixture ranking is therefore considered a comparative indication of thermal response, and GWC's apparent advantage may be partly influenced by its greater unaccounted heat loss. The trend also indicates an interaction between aggregate type and gradation: for granite, the wearing-course mixture had a higher k_{app} than the binder-course mixture (GWC > GBC), whereas for basalt, the binder-course mixture was slightly higher than the wearing-course mixture (BBC > BWC). Thus, the effect of gradation on thermal response depends on the aggregate type.

Table 4: Apparent thermal conductivity and specific heat capacity of the mixtures

Mixture	Apparent thermal conductivity, k_{app} (W/m·K)				Specific heat capacity (J/kg·K)			
	Replicate value (n = 3)	Mean	SD	CV (%)	Replicate value (n = 3)	Mean	SD	CV (%)
BWC	2.9313	2.902	0.039	1.350	829.2175	832.240	7.550	0.910
	2.9167				841.0377			
	2.8571				827.0027			
BBC	3.2411	3.180	0.085	2.670	788.2649	793.310	4.970	0.630
	3.2174				793.4597			
	3.0819				798.2073			
GBC	2.952	2.972	0.029	0.630	792.7049	802.390	8.450	1.050
	2.9741				806.19			
	2.989				808.2716			
GWC	4.0783	4.026	0.050	1.240	781.4167	765.070	23.380	3.060
	3.9788				775.5046			
	4.0216				738.2893			

Note: The values under the ‘Replicate Value’ represent three independent measurements, SD = standard deviation; CV = coefficient of variation

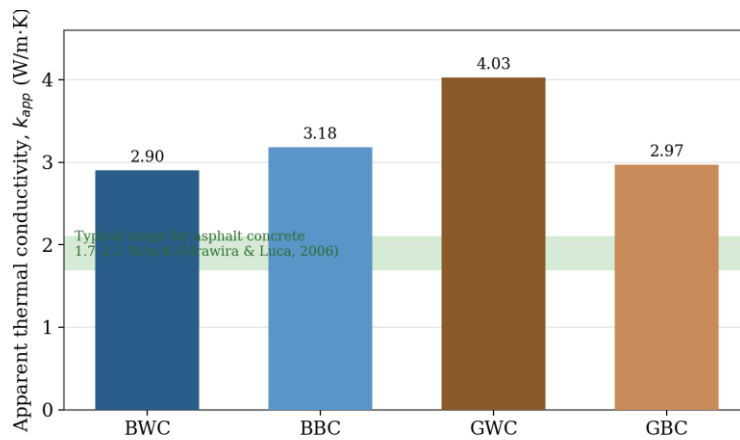


Figure 2: Apparent thermal conductivity of the mixtures relative to the range typically reported for asphalt concrete (Mrawira & Luca, 2006).

Table 5: Mesh-sensitivity check for BWC specimen

Mesh size (mm)	HFL3 (W/m ²)	Difference from 3mm (%)
2	1351.55	2.94
3	1312.95	Reference
4	1293.7	1.47

Note: HFL3 represents the numerical heat flux extracted from the central region of the specimen. The 3 mm mesh was selected for the FE simulations.

The trend also shows an interaction between aggregate type and gradation: for granite the wearing course exceeded the binder course ($GWC > GBC$), whereas for basalt the binder course slightly exceeded the wearing course ($BBC > BWC$). Gradation therefore does not act in a single consistent direction independent of aggregate source, which is relevant when selecting mixtures for thermal performance.

3.4 Numerical thermal response

The transient simulations produced comparable temperature differences across all specimens ($\Delta T \approx 24\text{--}25\text{K}$), confirming that the mixtures were subjected to similar thermal loading and that differences in heat transfer arise from material properties rather than boundary conditions. Representative contour plots for GWC are shown in Figure 3. Peak heat flux (HFL3) and reaction heat flow (RFL11) differed markedly between mixtures (Table 6, Figure 4): GWC gave the highest heat flux (2371W/m^2) and reaction heat flow (up to 263W), consistent with its higher apparent conductivity,

followed by BBC. This indicates that, among the mixtures studied, GWC offers the greatest capacity to transfer heat through the layer and therefore the greatest relative potential for thermoelectric harvesting.

GWC was selected for the representative contour plots because it exhibited the highest apparent thermal conductivity and the highest simulated thermal response among the four mixtures. The remaining mixtures showed the same general through-thickness heat-transfer pattern, with differences primarily in the magnitude of the heat flux.

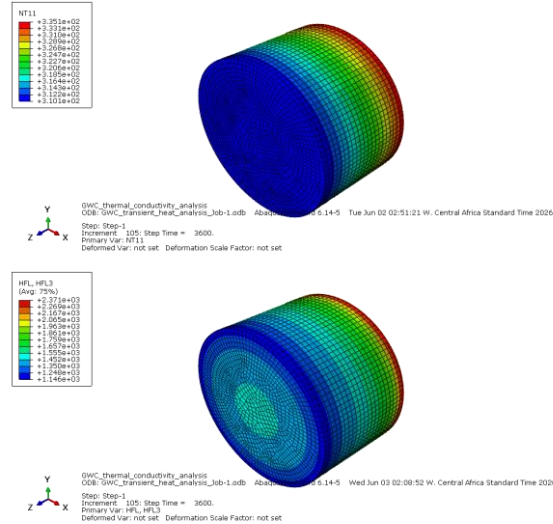


Figure 3: Simulated temperature distribution (NT11, top) and heat flux (HFL3, bottom) for the GWC mixture.

Table 6: Summary of simulated thermal response of the mixtures

Mixture	ΔT (K)	Peak heat flux, HFL3 (W/m ²)	Peak reaction heat flow, RFL11 (W)
BWC	25.0	1912	178.3
BBC	25.0	2018	211.2
GWC	25.0	2371	263.1
GBC	24.1	1875	187.1

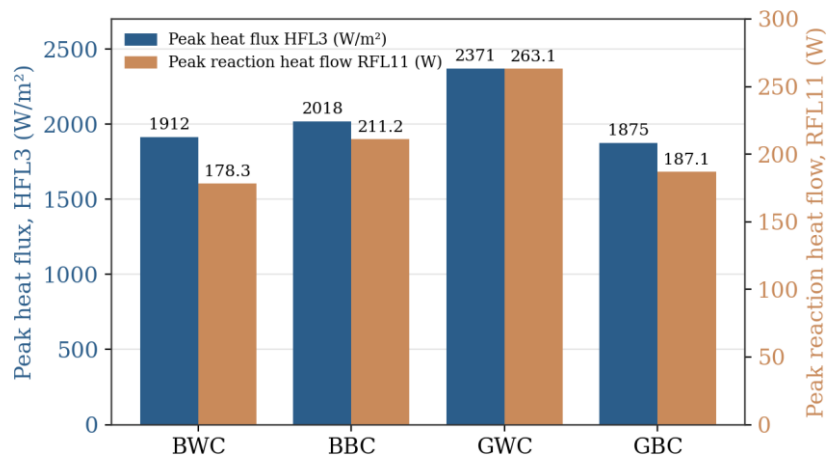


Figure 4: Simulated peak heat flux and reaction heat flow for the four mixtures.

3.5 Model verification

The FE model was checked against the analytical Fourier solution $q = k \cdot \Delta T / L$ using the same apparent conductivities, specimen thickness (0.0635m) and simulated temperature differences. Agreement was within 13% for all mixtures (Table 7). This confirms that the model correctly reproduces one-dimensional conduction and is internally consistent; it is a verification of the numerical

implementation rather than an independent experimental validation, since both the analytical and numerical fluxes derive from the same measured conductivity. What is reported here is a code verification of the numerical solution against the analytical (closed-form) Fourier result; independent experimental validation against measured heat-flux or temperature-field data was outside the present scope and is recommended for future work.

Table 7: *Verification of numerical against analytical heat flux*

Mixture	ΔT (K)	k_{app} (W/m·K)	Analytical flux (W/m ²)	Abaqus flux (W/m ²)	Difference (%)
BBC	25.00	3.18	1252	1425	12.11
BWC	25.00	2.90	1142	1313	12.98
GBC	24.10	2.97	1123	1287	12.74
GWC	25.00	4.03	1585	1759	9.86

4. CONCLUSION

The mechanical and thermal behaviour of four asphalt concrete mixtures, produced from basalt and granite aggregates in wearing- and binder-course gradations was evaluated for pavement thermoelectric energy harvesting through laboratory testing and three-dimensional transient FE simulation. The main findings are:

- Aggregate type strongly influenced mechanical performance: basalt mixtures gave higher Marshall stability and ITS than granite mixtures, with BBC the strongest (7.83kN; 493kPa).
- Aggregate type and gradation both affected thermal response, with an interaction between them; GWC showed the highest apparent conductivity and the largest simulated heat flux (2371W/m²), indicating the greatest relative thermal-harvesting potential.
- The mixture ranking is therefore considered a comparative indication of thermal response rather than an absolute ranking of intrinsic thermal conductivity, as heat losses may affect the mixtures differently.
- The FE model reproduced the analytical Fourier solution within 13%, providing internal verification of the numerical implementation; this should not be interpreted as independent experimental validation.
- The study provides thermal characterisation and numerical assessment relevant to TEG investigation; electrical power output was not directly evaluated. Future work should couple the thermal model with experimentally determined TEG/Seebeck parameters to quantify actual electrical generation.
- Future work should establish absolute thermal conductivities using a transient or guarded steady-state method, validate the model against independent measurements, and couple the thermal model to a Seebeck-based estimate of electrical output to quantify harvesting feasibility.

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