
ENHANCING THE THERMAL PROPERTIES OF ASPHALT PAVEMENT FOR ENERGY GENERATION USING THERMOELECTRIC GENERATORS

Farouk Shehu Yakasai¹, Aminu Suleiman^{1,*}

¹Bayero University Kano

Email: faroukshehuyakasai@yahoo.com, asuleiman.civ@buk.edu.ng*

*Corresponding author: Aminu Suleiman

DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Asphalt pavements absorb substantial amounts of solar heat, much of which remains unutilized despite its potential for renewable electricity generation through thermoelectric generators (TEGs), making the enhancement of asphalt thermal properties essential for improving temperature gradients and energy harvesting efficiency. This study evaluates the use of steel slag, an industrial by-product, as a partial replacement for natural coarse aggregates to enhance the thermal performance of asphalt concrete, with mixtures designed using the Marshall Mix method at steel slag replacement levels ranging from 0% to 25%. Laboratory tests measuring thermal conductivity, specific heat capacity, and thermal diffusivity were performed and evaluated using a three-dimensional transient heat transfer model in Abaqus, and the Marshall properties were evaluated against the applicable ASTM D6927 criteria, resulting in an optimum binder content of 6.0%. The results show that the incorporation of steel slag influenced the thermal properties of the asphalt concrete. Among the mixtures investigated, the 5% steel slag replacement produced the highest thermal conductivity of 3.0421 W/m·K and the lowest specific heat capacity of 794.5 J/kg·K. It also recorded the highest thermal diffusivity of $1.58 \times 10^{-6} \text{ m}^2/\text{s}$. These findings suggest that a limited proportion of steel slag, particularly at 5% replacement, can improve the thermal response of asphalt concrete. The enhanced thermal properties may provide favourable conditions for future application in pavement-integrated thermoelectric energy harvesting systems. However, the present study focused on the thermal characteristics of the asphalt mixtures, and direct integration of thermoelectric generators (TEGs) and measurement of electrical power output were not undertaken.

Keywords: Asphalt concrete; thermoelectric generators; energy harvesting; thermal properties; steel slag; 3D finite element

1. INTRODUCTION

Nigeria continues to face challenges in providing reliable and affordable electricity, with significant dependence on fossil fuels for buildings, industries, and infrastructure. Rising energy costs and inadequate power supply have increased the need for sustainable renewable energy alternatives. Asphalt pavements, which dominate urban road networks, absorb substantial solar radiation due to their dark surfaces and can reach temperatures of up to 70 °C Chen et al., (2009). Although this heat contributes to the Urban Heat Island (UHI) effect and can accelerate pavement deterioration, it also represents a potential source of renewable thermal energy.

The rapid growth of urbanization and Information and Communication Technology (ICT) has encouraged the development of smart cities, integrating intelligent infrastructure to improve efficiency, safety, and sustainability (Marsal-Llacuna et al., 2015). One emerging technology is the integration of thermoelectric generators (TEGs) into pavement structures to convert temperature gradients into electrical energy through the Seebeck effect (Jiang et al., 2017). Such energy can potentially support low-power applications, including street lighting, traffic signals, and infrastructure monitoring, while requiring relatively low maintenance (Islam & Tarefder, 2014).

The efficiency of pavement-based thermoelectric energy harvesting depends largely on the temperature gradient and heat transfer within the pavement. Therefore, enhancing the thermal conductivity of asphalt concrete is important for improving heat transfer and maximizing TEG performance (J. Chen et al., 2015). Recent studies have investigated industrial and recycled materials,

including steel slag, crumb rubber, and recycled aggregates, as alternatives for improving asphalt pavement performance Hasita et al., 2020; Ding et al., 2019.

Among these materials, steel slag has attracted considerable interest because of its availability and favourable mechanical and thermal properties (Rondón-Quintana et al., 2018; Sabapathy et al., 2017). Its incorporation into asphalt mixtures has been reported to improve mechanical strength, fatigue performance, and thermal characteristics (Hainin et al., 2014; Kavussi et al., 2015; Fang et al., 2013).

Accordingly, this study investigates the use of steel slag as a partial replacement for conventional coarse aggregate in asphalt concrete, with particular emphasis on its effects on thermal conductivity, specific heat capacity, and thermal diffusivity. The thermal response of the modified asphalt mixtures is further evaluated using three-dimensional finite element analysis in Abaqus. The study focuses on characterizing the thermal behavior of the mixtures and assessing their potential for future application in pavement-integrated thermoelectric energy harvesting systems. Direct integration of thermoelectric generators and evaluation of their electrical performance are beyond the scope of the present study.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this study comprised asphalt binder, natural limestone aggregates, and steel slag. The asphalt binder and natural aggregates were sourced locally within Kano State, Nigeria, while the steel slag was obtained from a rolling steel mill in Katsina State. The binder was characterized using standard consistency tests to determine its suitability for high-performance asphalt pavement applications. The natural aggregate was limestone with a nominal maximum particle size of 20 mm, and its physical and mechanical properties were evaluated in accordance with relevant standard specifications.

The steel slag was obtained from an electric arc furnace and air-aged for a minimum of 12 months prior to use to minimize potential volumetric expansion associated with free lime (CaO) and magnesia (MgO). The steel slag was subjected to the same physical and mechanical characterization tests as the natural aggregate to facilitate direct comparison and assess its suitability as a partial replacement for conventional coarse aggregate in asphalt mixtures.

Table 2.1: Physical properties of natural aggregate and steel slag.

PROPERTY	UNIT	VALUE	REQUIREMENT
Penetration (25°C,100g,5s)	0.1mm	60.19	60-80
Softening Point	°C	47	≥45
Flash Point	°C	273	≥260
Fire point	°C	281	
Density	g/cm ³	1.03	—

The results presented in Table 2.1 indicate that steel slag possesses superior mechanical properties compared with natural limestone aggregate, particularly in terms of strength, wear resistance,

and bulk density. These characteristics suggest its potential to improve the structural integrity and deformation resistance of asphalt mixtures when used as a partial coarse aggregate replacement. The bitumen properties presented in Table 2.2 show a penetration value of 60.17, corresponding to a 60/70 penetration grade, with flash and fire points of 273 °C and 281 °C, respectively. These results indicate adequate binder consistency and thermal stability, confirming its suitability for asphalt mixture production.

Table 2.2: Physical properties of bitumen

PROPERTY	Density	Water Absorption %	Crushing Value %	Impact Value %	Abrasion Value %	Flakiness & Elongation %
LIMESTONE	2.69	1.08	15.6	7.7	23	7.5
STEEL SLAG	3.5	1.29	12.1	14.5	13.2	2.2

2.2 Mix design

Aggregate gradation was conducted in accordance with the specifications of the Federal Ministry of Works, Nigeria, for a wearing course mixture, with the selected sieve sizes and percentage passing presented in Table 2.3. The aggregates were sieved and proportioned to achieve the specified gradation for asphalt specimen preparation. The Marshall Mix Design method (ASTM D6927) was employed to determine the Optimum Binder Content (OBC), with three specimens prepared at binder contents ranging from 5.0% to 8.0%. The OBC was determined based on the mixture's Marshall Stability, flow, air voids, and volumetric properties, as presented in Table 2.4, in accordance with the relevant Marshall design criteria.

Table 2.3: Design gradation adopted in the research

Sieve size (mm)	% passing	% retained
19	100	0
12.5	92.5	7.5
9.5	83.5	9
6.3	73.5	10
2.36	57.5	16
1.18	43.5	14
600 µ	33	10.5
300 µ	24	9
150 µ	18.5	5.5
75 µ	10.5	8
pan		10.5

Table 2.4: Marshall results for different binder content percentages

BINDER CONTENT	GMM	GMB	VTM %	VMA %	VFA %	STABILITY (KN)	FLOW (MM)
5	2.3	2.43	5.35	19.5	72.56	14.01	12.25
5.5	2.31	2.48	6.9	19.15	63.97	13.61	14.23
6	2.31	2.41	4.14	19.58	78.86	12.09	11.55
6.5	2.36	2.44	3.28	18.27	82.05	10.72	19.54
7	2.31	2.42	4.55	20.43	77.73	10.7	26.25
7.5	2.31	2.43	4.94	21.15	76.64	6.52	30.09
8	2.37	2.39	0.84	6.02	86.05	7.82	31.58

The optimum binder content (OBC) was selected as 6.0% based on the combined Marshall mix design parameters, including stability, flow, voids in total mix (VTM), and voids filled with asphalt (VFA). Although Marshall stability decreased with increasing binder content, the 6.0% binder content provided a suitable balance among strength, deformation, and volumetric properties. At 6.0% binder content, the mixture recorded a stability of 12.09 kN, flow of 11.55 mm, VTM of 4.14%, and VFA of 78.86%. At higher binder contents, the continued reduction in stability accompanied by an increase in flow indicated a progressively softer mixture. Therefore, 6.0% was selected as the OBC for the subsequent mixture preparation.

Following the determination of the OBC, asphalt concrete mixtures were prepared by partially replacing the natural coarse aggregate with steel slag at replacement levels of 5%, 10%, 15%, 20%, and 25%. Three specimens were prepared for each replacement level using the Marshall mix design procedure. The resulting mixtures were evaluated in terms of density, volumetric properties, Marshall stability, and flow to assess their performance and determine the effects of steel slag incorporation.

The thermal properties of the control and steel slag-modified mixtures were also determined at the Physics Laboratory, Ahmadu Bello University, Zaria. As shown in Table 2.5, all mixtures satisfied the specified Marshall criteria, indicating that steel slag can be used as a partial replacement for natural coarse aggregate without compromising the overall performance of the asphalt mixtures.

Table 2.5: Marshal results for different steel slag percentages

STEEL SLAG %	GMM	GMB	VTM %	VMA %	VFA %	STABILITY (KN)	FLOW (MM)
5	2.34	2.42	3.3	21.4	84.6	12.37	15.22
10	2.31	2.43	4.9	22.45	78	11.28	9.84
15	2.35	2.44	3.7	21.11	82.5	11.93	9.62
20	2.36	2.45	3.7	20.8	82.2	11.4	10.53
25	2.36	2.46	4.1	20.77	80.26	11.2	9.13

2.3 Determination of thermal properties

The thermal conductivity was determined experimentally using Marshall-derived sub-specimens and a steady-state electrical Searle-type apparatus. The method assumes one-dimensional heat conduction, with the apparent thermal conductivity calculated as: $k = VIL/(A \cdot \Delta T)$, where (V) and (I) are the applied voltage and current, respectively, (L) is the specimen thickness, (A) is the cross-sectional area, and (ΔT) is the temperature difference across the specimen. Three replicate measurements were conducted for each mixture and their mean values reported. Specific heat capacity was determined using the method of mixtures with a copper calorimeter, also based on three replicate measurements.

The measured conductivity is reported as apparent thermal conductivity (K_{app}), since its determination assumes that the applied electrical power is transferred through the specimen

predominantly by one-dimensional conduction and does not explicitly account for lateral or convective heat losses. These factors may affect the measured conductivity and potentially lead to an overestimation of its absolute value. Therefore, the measured conductivity values are used primarily for comparative assessment of the asphalt mixtures and as material-property inputs for the finite element model. No correction factor was applied to account for the potential experimental bias before the values were incorporated into the Abaqus model. Consequently, the agreement between the experimental and numerical results is interpreted as consistency under the adopted experimental and modelling assumptions rather than as independent validation of the absolute thermal conductivity.

2.4 Finite element model

A three-dimensional finite element thermal analysis was conducted using Abaqus to simulate the transient thermal response of the cylindrical asphalt specimens investigated experimentally. The specimen geometry was modelled using the actual laboratory dimensions as a three-dimensional deformable solid. Separate models were developed for the control mixture and the mixtures containing 5%, 10%, 15%, 20%, and 25% steel slag replacement.

The experimentally determined apparent thermal conductivity, specific heat capacity, and density of each mixture were assigned as the thermal material properties in the corresponding Abaqus models. Consistent with the experimental methodology described in Section 2.3, the measured apparent thermal conductivity values were used directly without applying a correction factor for the potential overestimation associated with the laboratory measurement method.

The specimens were discretized using three-dimensional, eight-node linear heat-transfer brick elements (DC3D8). Mesh refinement was applied to obtain an adequately resolved temperature and heat-flux distribution within the specimens. A transient heat-transfer analysis was performed to capture the time-dependent thermal response. The thermal loading and boundary conditions were defined to represent the heat-transfer conditions of the laboratory thermal testing, with heat applied through the heated surface and the resulting thermal response evaluated throughout the specimen.

The numerical analysis was conducted over a simulation period of 3600 s. Temperature, heat flux, and reaction heat flux distributions were extracted from the Abaqus results to assess the thermal response of the asphalt mixtures. Particular attention was given to the 5% steel slag mixture because it exhibited the highest experimentally determined thermal conductivity and thermal diffusivity.

A formal mesh-convergence analysis and complete records of the apparatus-level electrical settings used during the laboratory test were not available from the original experimental programme. Therefore, numerical values for these parameters are not reported retrospectively. This limitation is acknowledged because complete reproduction of the laboratory conditions would require detailed information on the applied electrical input, thermal losses, insulation and contact conditions, together with a formal mesh-independence assessment. These aspects are recommended for consideration in future experimental–numerical studies.

3. RESULTS AND DISCUSSION

3.1 Thermal Properties of Modified Asphalt Mixtures

This section presents the experimental thermal properties of asphalt mixtures containing 0%, 5%, 10%, 15%, 20%, and 25% steel slag as partial replacement for natural coarse aggregate. The measured thermal conductivity, specific heat capacity, and calculated thermal diffusivity are summarized in Table 3.1.

Table 3.1: Summary of thermal properties

SN	Concentration of steel slag	Apparent Thermal conductivity (W/mk)	Specific heat capacity (J/KgK)	Thermal diffusivity (m ² /s)
1	0%	2.0598	1207.98	7.08x10 ⁻⁷
2	5%	3.0421	794.5	1.58x10 ⁻⁶
3	10%	2.689	842.89	1.31x10 ⁻⁶
4	15%	2.5072	861.51	1.19x10 ⁻⁶
5	20%	2.3615	928.54	1.04x10 ⁻⁶
6	25%	2.1683	1010.51	8.72x10 ⁻⁷

The incorporation of steel slag influenced the thermal conductivity of the asphalt mixtures. At lower replacement levels, thermal conductivity increased compared with the control mixture. The highest value was recorded at 5% steel slag replacement, with a thermal conductivity of 3.0421 W/m·K, compared with 2.0598 W/m·K for the control mixture. This increase may be associated with the relatively high density and thermal conductivity of steel slag compared with the conventional coarse aggregate. The measured volumetric properties also showed variations in mixture structure with increasing steel slag content. For example, the 5% mixture recorded a VTM of 3.3%, compared with 4.9% for the 10% mixture, while the 15%, 20%, and 25% mixtures recorded VTM values of 3.7%, 3.7%, and 4.1%, respectively. These differences in volumetric characteristics may affect the continuity of solid heat-transfer paths within the asphalt mixture.

Beyond the 5% replacement level, thermal conductivity decreased progressively, with values of 2.6890, 2.5072, 2.3615, and 2.1683 W/m·K recorded at 10%, 15%, 20%, and 25% steel slag replacement, respectively. The reduction may be related to changes in aggregate–binder configuration and the distribution of solid and void phases as the steel slag content increases. Such changes may influence the continuity of heat-transfer pathways within the mixture. However, direct microstructural characterization was not conducted in this study; therefore, this explanation should be regarded as a possible interpretation rather than a confirmed mechanism. Further investigation using microscopic analysis or three-dimensional aggregate-packing analysis would be required to establish the specific microstructural factors responsible for the observed trend.

Overall, the 5% steel slag mixture exhibited the highest measured thermal conductivity among the mixtures investigated, indicating the most favourable thermal conductivity under the conditions of the present experimental programme.

Specific heat capacity also varied with steel slag incorporation. The control mixture recorded the highest value of 1207.98 J/kg·K, whereas the 5% steel slag mixture recorded the lowest value of 794.50 J/kg·K. With further increases in steel slag content, the specific heat capacity increased to 842.89, 861.51, 928.54, and 1010.51 J/kg·K at 10%, 15%, 20%, and 25% replacements respectively.

The distinct reduction at 5% replacement, followed by the gradual increase observed from 10% to 25%, indicates a non-monotonic variation in specific heat capacity. Based on the measurements available in this study, the specific mechanism responsible for the low value at 5% cannot be established conclusively. The variation may be influenced by differences in mixture composition and volumetric characteristics associated with steel slag incorporation, as well as experimental variability in determining the thermal properties of a heterogeneous asphalt mixture. Therefore, the 5% result is considered an observed experimental response rather than evidence of a specific material mechanism. Further studies involving repeated measurements, constituent-level thermal characterization, and microstructural analysis would be useful for explaining this behaviour.

The relatively high thermal conductivity and low specific heat capacity recorded at 5% steel slag replacement contributed to its highest calculated thermal diffusivity. This indicates that the SS-05% mixture had a greater capacity for transmitting thermal energy through the specimen under the conditions investigated.

Thermal diffusivity was calculated from the measured thermal conductivity, density, and specific heat capacity using:

$$\alpha = K / \rho C_p$$

Where α is the thermal diffusivity (m^2/s), K is the thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$), ρ is the density (kg/m^3), and C_p is the specific heat capacity ($\text{J}/\text{kg}\cdot\text{K}$). The 5% steel slag mixture recorded the highest thermal diffusivity of $1.58 \times 10^{-6} \text{ m}^2/\text{s}$, reflecting its combination of relatively high thermal conductivity and low specific heat capacity and, consequently, a greater rate of heat propagation through the mixture.

Overall, the results demonstrate that steel slag content influences the thermal properties of the asphalt mixtures. Among the mixtures investigated, the 5% replacement level produced the highest thermal conductivity and thermal diffusivity, indicating an enhanced thermal response under the conditions of the present study. This improvement may be beneficial for pavement applications where enhanced heat transfer is desirable, including potential future integration with pavement-based thermoelectric energy harvesting systems. However, the present study was limited to the thermal characterization and numerical evaluation of the asphalt mixtures; direct integration of a thermoelectric generator and assessment of its electrical performance were not undertaken.

3.2 Verification of Thermal Results Using 3d Finite Element Simulation In Abaqus

THERMAL RESPONSE OF THE 5% STEEL SLAG MIXTURE

The figures below present the heat flux, temperature, and reaction heat flux distributions of the asphalt specimen containing 5% steel slag (SS-05%) after 3600 s of transient thermal simulation. The heat flux distribution (HFL) was relatively uniform across the SS-05% specimen, with a magnitude of approximately $1242 \text{ W}/\text{m}^2$. The narrow range displayed in the contour legend is consistent with the predominantly conductive and relatively uniform thermal loading adopted in the numerical model, resulting in only small spatial variations in heat flux across the specimen. Therefore, the closely spaced values in the legend do not indicate an absence of heat transfer; rather, they reflect the relatively uniform heat-flux distribution under the applied boundary conditions. The thermal response of the SS-05% mixture was therefore assessed in conjunction with its measured thermal conductivity and thermal diffusivity, as well as the simulated temperature distribution, rather than being inferred from the HFL contour alone.

The temperature distribution ranged from approximately 38.0°C at the edges to 62.5°C at the core, indicating a clear temperature gradient within the simulated specimen. The combination of the observed heat flux and relatively high thermal diffusivity indicates effective heat propagation through the SS-05% mixture under the simulated conditions. Such temperature gradients are relevant to the concept of pavement-integrated thermoelectric energy harvesting because a temperature difference across a thermoelectric generator is required for thermoelectric conversion. However, no TEG device was incorporated into the present finite element model, and electrical voltage, power output, or conversion efficiency was not calculated. Therefore, the simulated thermal response should be regarded as an indication of the potential thermal suitability of the SS-05% mixture for future TEG integration rather than a demonstration of thermoelectric energy generation.

The reaction heat flux distribution (RFL11) shown ranged from $+2.810 \times 10^{-2}$ to $-2.810 \times 10^{-2} \text{ W}/\text{m}^2$, compared with approximately $\pm 1.982 \times 10^{-2} \text{ W}/\text{m}^2$ for the control mixture. The increased reaction flux magnitude indicates greater thermal exchange at the specimen surfaces. Collectively, the numerical results indicate that the 5% steel slag mixture exhibited favourable thermal behaviour under the simulated conditions, including relatively effective heat propagation and surface heat exchange. These characteristics support further investigation of the mixture for potential application in pavement-integrated thermoelectric energy harvesting. However, the present study did not evaluate the performance of an integrated TEG, including the temperature difference across the device, voltage generation, electrical power output, or thermoelectric conversion efficiency. Therefore, the numerical results should be interpreted as an assessment of the thermal characteristics of the asphalt mixture rather than a direct demonstration of thermoelectric energy generation.

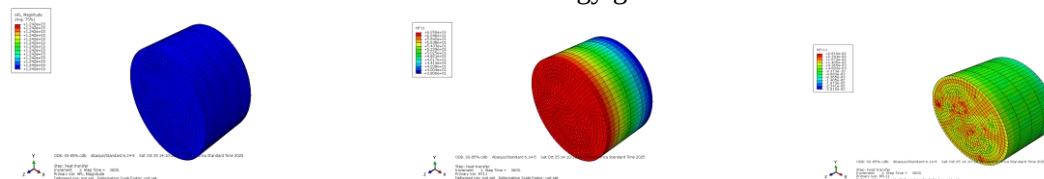


Figure 3.3: Simulated heat flux (HFL, Top left), temperature distribution (NT11, Top right) and reaction heat flux (RFL, bottom) for the optimum % of steel slag (5%)

3.3 Numerical Verification of the Abaqus Model Using Percentage Error Analysis

Table 3.2 presents the percentage differences between the experimental apparent thermal conductivity values and the corresponding Abaqus results. The percentage differences ranged from 4.52% for the control mixture to 5.84% for the mixture containing 25% steel slag. The relatively small differences indicate consistent agreement between the experimental measurements and the numerical results across the investigated replacement levels. However, since the experimental apparent thermal conductivity values were directly assigned as material inputs in the Abaqus models, these differences should be interpreted as a measure of numerical consistency under the adopted modelling assumptions rather than as independent validation of the absolute thermal conductivity.

ABAQUS consistently slightly overestimates the measured thermal conductivity, which may be attributed to idealized modelling assumptions, including homogeneous material properties, perfect aggregate–binder bonding, and the absence of air voids and material imperfections. In contrast, laboratory specimens exhibit inherent heterogeneity and voids that may reduce heat transfer.

The relatively narrow difference between the experimental and Abaqus results, ranging from 4.52% to 5.84%, indicates good numerical consistency across the investigated steel slag replacement levels. The slightly higher Abaqus values may be associated with the idealized representation of the asphalt mixture, including the use of homogeneous material properties and the omission of some physical heterogeneities and heat-loss mechanisms that may be present in the laboratory specimens. Since the experimental apparent thermal conductivity values were directly assigned as material-property inputs without applying a bias correction, the numerical results should be interpreted as verification of the thermal response under the adopted modelling assumptions rather than as independent validation of the absolute thermal conductivity. Nevertheless, the consistent agreement observed across the replacement levels supports the use of the model as a comparative tool for assessing the thermal behaviour of the investigated asphalt mixtures.

Table 3.2: Percentage error analysis

Steel percentages (%)	Slag	Experimental thermal conductivity (W/mk)	Abaqus thermal conductivity (W/mk)	Percenatge error
0		2.0598	2.153	4.52%
5		3.0421	3.219	5.82%
10		2.689	2.845	5.80%
15		2.5072	2.653	5.82%
20		2.3615	2.499	5.82%
25		2.1683	2.295	5.84%

4. CONCLUSIONS

The objective of the research is to determine the effect of partially substituting coarse aggregates with steel slag on the thermal properties of asphalt concrete using experiments and to also verify the laboratory results using finite element simulation technique on ABAQUS. The following conclusions are drawn from the study:

1. The physical and mechanical properties of the bitumen, natural aggregate, and steel slag satisfied the relevant specifications for asphalt concrete production. Steel slag exhibited higher density, strength, and abrasion resistance than the natural aggregate, indicating its suitability as a partial replacement material.
2. Partial replacement of conventional coarse aggregate with steel slag altered the thermal properties of the asphalt concrete mixtures. In particular, all steel slag-modified mixtures exhibited higher thermal conductivity and thermal diffusivity than the control mixture, indicating an overall improvement in heat-transfer and thermal-propagation characteristics with steel slag incorporation.
3. The optimum steel slag replacement level for the thermal properties investigated in this study was 5%, which produced the highest thermal conductivity of 3.0421 W/m·K and thermal diffusivity of $1.58 \times 10^{-6} \text{ m}^2/\text{s}$. These results indicate that the 5% steel slag mixture exhibits favorable thermal characteristics

that may support its potential application in pavement-integrated thermoelectric energy harvesting systems. However, the present study was limited to the thermal characterization of the asphalt mixtures, and direct integration and performance evaluation of a thermoelectric generator, including voltage and power output, were not undertaken.

4. The three-dimensional (3D) transient heat-transfer simulation conducted in Abaqus demonstrated consistent thermal responses across the investigated asphalt mixtures. The differences between the experimental apparent thermal conductivity values and the corresponding Abaqus results ranged from 4.52% to 5.84%, indicating a relatively close numerical agreement across the steel slag replacement levels. However, since the experimentally determined apparent thermal conductivity values were directly assigned as material property inputs in the numerical model, the Abaqus results should be interpreted as demonstrating consistency with the experimental thermal response under the adopted modelling assumptions, rather than as an independent validation of the absolute thermal conductivity values.
5. Further research should investigate the direct integration of thermoelectric generators into steel-slag-modified asphalt pavement systems. Future studies should evaluate the temperature difference across the TEG, electrical voltage and power output, thermoelectric conversion efficiency, and long-term performance under field conditions. In addition, an economic assessment of steel slag sourcing, processing, transportation, and incorporation into asphalt mixtures should be conducted to determine the practical feasibility and scalability of the proposed application.

REFERENCES

1. Hasita, S., Rachan, R., Suddepong, A., Horpibulsuk, S., Arulrajah, A., Mohammadinia, A., & Nazir, R. (2020). Performance Improvement of Asphalt Concretes Using Steel Slag as a Replacement Material. *Journal of Materials in Civil Engineering*, 32(8), 04020227. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003306](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003306)
2. Chen, J., Wang, H., & Li, L. (2015). Determination of effective thermal conductivity of asphalt concrete with random aggregate microstructure. *Journal of Materials in Civil Engineering*, 27(12), 04015045.
3. Chen, M. Z., Wei, W., & Wu, S. P. (2009). On cold materials of pavement and high-temperature performance of asphalt concrete. *Materials Science Forum*, 620, 379–382.
4. Ding, X., Chen, L., Ma, T., Ma, H., Gu, L., Chen, T., & Ma, Y. (2019). Laboratory investigation of the recycled asphalt concrete with stable crumb rubber asphalt binder. *Construction and Building Materials*, 203, 552–557.
5. Fang, F. T., Chong, Y. C., Nyunt, T. T., & Loi, S. S. (2013). Development of environmentally sustainable pavement mix. *International Journal of Pavement Research and Technology*, 6(4), 440.
6. Hainin, M. R., Rusbintardjo, G., Hameed, M. A. S., Hassan, N. A., & Yusoff, N. I. M. (2014). Utilisation of steel slag as an aggregate replacement in porous asphalt mixtures. *Jurnal Teknologi (Sciences & Engineering)*, 69(1). <https://journals.utm.my/jurnalteknologi/article/view/2529>
7. Islam, M. R., & Tarefder, R. A. (2014). Determining thermal properties of asphalt concrete using field data and laboratory testing. *Construction and Building Materials*, 67, 297–306. <https://doi.org/10.1016/j.conbuildmat.2014.03.040>
8. Jiang, W., Yuan, D., Xu, S., Hu, H., Xiao, J., Sha, A., & Huang, Y. (2017). Energy harvesting from asphalt pavement using thermoelectric technology. *Applied Energy*, 205, 941–950. <https://doi.org/10.1016/j.apenergy.2017.08.091>
9. Kavussi, A., Jalili Qazizadeh, M., & Hassani, A. (2015). Fatigue behavior analysis of asphalt mixes containing electric arc furnace (EAF) steel slag. *Journal of Rehabilitation in Civil Engineering*, 3(1), 74–86.
10. Marsal-Llacuna, M.-L., Colomer-Llinàs, J., & Meléndez-Frigola, J. (2015). Lessons in urban monitoring taken from sustainable and livable cities to better address the Smart Cities initiative. *Technological Forecasting and Social Change*, 90, 611–622.
11. Rondón-Quintana, H. A., Ruge-Cárdenas, J. C., Patiño-Sánchez, D. F., Vacca-Gamez, H. A., Reyes-Lizcano, F. A., & Muniz De Farias, M. (2018). Blast Furnace Slag as a Substitute for the Fine Fraction

of Aggregates in an Asphalt Mixture. *Journal of Materials in Civil Engineering*, 30(10), 04018244. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002409](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002409)

12. Sabapathy, Y. K., Balasubramanian, V. B., Shankari, N. S., Kumar, A. Y., & Ravichandar, D. (2017). Experimental investigation of surface modified EOF steel slag as coarse aggregate in concrete. *Journal of King Saud University-Engineering Sciences*, 29(4), 388–393.