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Asphalt pavement resilience under wildfire: an experimental observation and numerical analysis

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ABSTRACT

Asphalt pavements are critical infrastructure components during wildfires, ensuring evacuation, emergency response, and access to essential services. Understanding asphalt deterioration under extreme heat is therefore vital. This study examines the thermal and mechanical responses of asphalt pavements subjected to wildfire-induced temperatures, focusing on structural and service performance. An integrated experimental/computational framework was developed to assess the wildfire resilience of three hot mix asphalt (HMA) types: conventional, boron-surrogated and wood sawdust-surrogated mixtures. Mechanical behaviour was evaluated through Marshall stability and flow tests after controlled thermal exposure. Transient thermal conductivity measurements and finite element simulations were conducted to analyse heat transfer, while skid resistance and scanning electron microscopy tests assessed surface texture, microstructure, and bitumen-aggregate interactions. Results indicate that wildfire exposure severely affects the upper 10 cm of pavement. Wood sawdust surrogated mixtures improved post-fire performance, highlighting the potential of sustainable, low-cost materials for wildfire-resilient pavement design.

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transient thermal
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1. Introduction

Wildfires represent a globally significant environmental phenomenon, contributing to substantial economic losses and ecological degradation. The impacts of these events have been further intensified by the ongoing effects of climate change. Consequently, wildfire regimes are undergoing notable transformations, with extended fire seasons, increased average fire sizes across many regions, and the emergence of wildfires in areas previously unaffected by such events (Artés et al., 2019). The concurrent effects of global climate alteration and the expansion of human settlements within wildland–urban interface zones have substantially increased the likelihood of large-scale and destructive wildfire events across numerous regions of the world. Climate change has markedly intensified the frequency

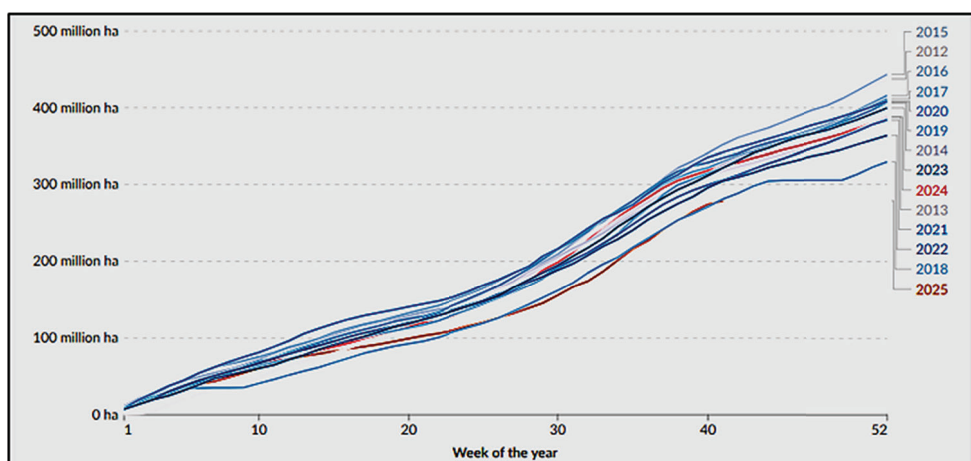


Figure 1. Global cumulative area burnt by wildfires (Our World in Data, 2025).

and magnitude of extreme wildfire events on a global scale. In recent years, extensive fires across South American rainforests, dry forests, and wetland ecosystems, together with large-scale burnings in Canada's boreal forests, have resulted in profound ecological and infrastructural consequences. These events have contributed to severe degradation of forest and wildlife habitats, accelerated deterioration of built infrastructure, and heightened carbon emissions in several regions, including Los Angeles, California, Canada, Brazil, Bolivia, India, Portugal, and Türkiye (Kelley et al., 2025). Global forest losses reached nearly 10 million hectares in 2023 due to wildfires and have tended to increase year by year from 2001 to 2023 (Statista, 2025). Additionally, fire danger indicators have recorded the highest values during the last 37 years in many European countries (Artés et al., 2019).

Figure 1 illustrates the increasing amounts of global wildfires from 2021 to 2025. The chart presents the cumulative weekly burned area caused by wildfires throughout the year (Our World in Data, 2025). The collected evidence highlights that wildfires are no longer isolated or exceptional events but an emerging global challenge with a high likelihood of affecting numerous regions in the foreseeable future. This reality necessitates comprehensive investigation into their underlying climatic, ecological, and anthropogenic drivers, alongside the development of both proactive (active) and preventive (passive) countermeasures. Such an integrated approach is essential not only to mitigate the adverse environmental and socio-economic impacts of wildfires but also to accelerate the rehabilitation of affected ecosystems and the restoration of critical infrastructure to sustainable and resilient conditions.

Wildfire events are getting more extreme in terms of acres burned, duration and intensity, and they can disrupt transportation, communications, water supply, and power and gas services (WHO, 2025). Road infrastructure plays a critical role in ensuring the safety, durability, and functionality of modern transportation facilities. Their thermal and mechanical performance under extreme conditions, particularly fire and high-temperature exposure, has attracted growing scientific attention. Recent research has examined various aspects of asphalt materials, including their fire performance, flame-retardant additives,

nanotechnology-based modifications, environmental impacts, climate resilience, and non-destructive testing approaches. Asphalt pavements have an indispensable importance during wildfire incidents by facilitating evacuation processes, emergency response operations, the movement of essential goods, and access to vital services (Fraser et al., 2022). Resilience to excessive heat exposure and performance reduction of the pavements (especially flexible ones) due to wildfires should be handled thoroughly to organise the post-wildfire rehabilitation and repair process. Consequently, a comprehensive understanding of the immediate and direct effects of fire exposure on asphalt pavement infrastructure is of paramount importance.

The design of climate-resilient asphalt pavement structures is essential to adapt to changing environmental conditions. Comprehensive literature reviews have discussed adaptation measures for designing climate-change-resilient asphalt pavements, including the use of binder modifiers, cooling coatings, and drainage systems (Duque et al., 2024). Studies have systematically examined the flammability and rheological behaviour of mixed flame-retardant-modified asphalt binders, demonstrating synergistic improvements in the flame-retardant performance (Wu et al., 2008). Research has focused on improving the road pavement performance using fibre-reinforced hot and cold asphaltic mixes, demonstrating significant enhancements in stability, flexibility, and resistance to rutting and cracking (Salahuddin et al., 2023). Barzegar and Wen (2023) investigated the effects of wildfire-induced temperature on evacuation route pavements through numerical modelling of the 2018 Camp Fire, analysing thermal distributions along Highway 70 while accounting for vegetation, topography, and material properties. Results demonstrate extreme thermal loading (3–297°C within 5 h post-ignition, peaking at 20 h), with proximity (5 m vs. 10 m) critically influencing pavement response. These findings emphasise the role of vegetation management in heat mitigation and reveal the vulnerability of asphalt pavement under such conditions, underscoring the need for resilient infrastructure design in wildfire-prone regions.

Recent scholarly literature on wildfires highlights the complex impacts of such events on pavement and road infrastructure, which are further intensified by climate change-induced increases in fire frequency, intensity, and duration (Ram et al., 2025). Direct consequences, such as thermal damage to asphalt and related structures, along with indirect effects, such as erosion, flooding, and debris-related traffic loads, significantly impair pavement performance. Post-wildfire debris hauling operations have been documented to drastically reduce fatigue life, as exemplified by the case of Skyway in Paradise, California, where pavement failure was accelerated by over 14 years (Zarei et al., 2025). The resilience of bridge piers to multi-hazard scenarios, including fire, vehicular impact, and air blast, has also been examined, highlighting the necessity for advanced structural modelling and mitigation strategies (Alomari et al., 2024). Furthermore, wildfires exacerbate surface erosion and road–stream connectivity, necessitating drainage upgrades following fires (Sosa-Pérez & MacDonald, 2017). In fire-prone regions, such as Arizona, modelling indicates a high probability of debris flows post-fire, with over 50% likelihood under moderate rainfall in recently burned watersheds, posing significant threats to road systems (Fraser et al., 2022). The adequacy of rural road networks is also critical for evacuation and emergency response, with studies confirming that inadequate infrastructure increases wildfire vulnerability (Dye et al., 2021; Thompson et al., 2021). This has spurred innovation in flame-retardant asphalt technologies, where nanoporous and composite retardants have been shown to reduce

flammability and smoke emission, while enhancing rutting resistance (Bi et al., 2024; Xia et al., 2024). Similarly, the integration of basalt fibres in asphalt mixtures improves fire resistance, skid resistance, and noise reduction, promoting safer and more durable pavements for tunnels (Xie et al., 2025). Ram et al. (2025) provided a comprehensive review of the impacts of wildfires on pavement systems, highlighting both direct thermal effects and secondary consequences, such as structural fatigue and hydrological damage. This study emphasises that extreme heat can lead to binder aging, surface deformation, and cracking, while post-fire erosion and heavy emergency vehicle traffic further accelerate pavement deterioration. However, environmental concerns and economic feasibility continue to develop widespread fire-resistant asphalt pavement applications (He et al., 2024; Xiao et al., 2019).

Since yet, no research has been conducted to observe the wild-fire resilience of asphalt pavements and to analyse the deterioration mechanism of various asphalt pavements (boron and sawdust surrogated) and of multiple asphalt layers. The authors synthesised the current research, identified methodological gaps, and recommended integrating wild-fire risk into pavement design and asset management practices to enhance infrastructure resilience. This gap highlights a critical opportunity for future studies, particularly given Turkey's unique boron resource advantage and wood sawdust as a byproduct of biomass material.

The objective of this study is to determine the potential deterioration/deformation that the excessive heat effect triggered by wildfire in existing asphalt pavements and to predict the possible disruptions to the service capability of the asphalt pavement.

This study constitutes a novel experimental-computational framework to evaluate wildfire-resilient asphalt mixtures by systematically investigating three modified HMA formulations: control (conventional), boron-surrogated, and wood sawdust-surrogated. The experimental data directly inform a validated finite element model (FEM) that simulates coupled thermal-mechanical performance under wildfire conditions, addressing the limitations of prior simulation-only approaches. This study investigated the mechanical performance of various HMA samples exposed to excessive heating conditions due to wildfire via Marshall tests, attaining stability and flow values. Transient thermal conductivity measurements were performed to understand the heat transfer mechanism of the asphalt concrete samples built upon Barzegar and Wen's (2023) numerical simulations of wildfire thermal exposure (297°C threshold). The surface texture and skid resistance performance of the HMA samples were evaluated by skid resistance tests following the EN 13036-4 (Road and airfield surface characteristics – test method for measurement of slip/skid resistance of a surface: The pendulum test) standard. Additionally, scanning electron microscopy (SEM) tests were conducted to observe the microstructure, surface morphology, bitumen-aggregate interaction, adhesion capabilities, and deterioration mechanism of the bitumen in the mixtures subjected to excessive heat conditions.

Thermal conditioning is a critical degradation mechanism in asphalt pavement materials, particularly under extreme temperature scenarios such as fire exposure or prolonged solar radiation. While traditional conditioning studies focus primarily on long-term oxidative aging, this experimental setup was designed to simulate accelerated thermal exposure in a controlled environment, simulating the conditions of excessive heating potentially encountered during fire events. The goal was to observe the visual and internal thermal

Table 1. Characteristic properties of the bitumen.

Experiment	Unit	Limits	Results	Standard
Penetration	mm	50 - 70	59	EN 1426
Softening point	°C	46 - 54	48.8	EN 1427
Flash point	°C	≤ 230	338	EN ISO 2592
Solubility	%	99	99.85	EN 12592
Specific gravity			1.03	TS-1087

responses of various asphalt mixtures under increasing temperature conditions and to record the surface and core temperature gradients in real time using thermocouple data.

2. Experimental methodology

In order to reach the aim of this study, the answers to the following research questions will be sought through various experimental observations and numerical analyses:

The amount of influence on the stability and flow values of asphalt pavements exposed to excessive heating conditions owing to wildfire and the capability of various types of aggregate replacements to boost the resilience to excessive heat conditions will be attained by Marshall tests following the EN 12697 (bituminous mixtures) standard. The variations in the thermal conductivity behaviour of asphalt pavements incorporating different aggregate replacement types were investigated through the transient thermal conductivity method. This method was deliberately employed in lieu of the EN 12939 and EN 12664 standard procedures, which are primarily designed for steady-state conditions and therefore inadequate for capturing the dynamic variations in thermal conductivity under progressively elevated temperature environments. The alterations in the surface characteristics (skid resistance) of asphalt pavements subjected to excessive heating will be evaluated using the British Pendulum Test, conducted in accordance with the EN 13036-4 standard (Method for the measurement of the slip/skid resistance of a surface). Finally, the morphological characteristics of the asphalt pavement exposed to excessive heating were examined using Scanning Electron Microscopy (SEM), and the obtained microstructural observations were critically interpreted to elucidate the heat-induced alterations in the material structure. Figure 2 depicts the flow chart of the experimental process used in this study.

Test materials (bitumen, aggregate, boron, and sawdust) were procured to produce HMA samples (conventional, boron-surrogated, wood sawdust surrogated) in accordance with the EN 12697 bituminous mixture standard. Bitumen with AC50/70 penetration value and a density of 1.03 g/cm³ were supplied by the Karabuk Provincial Road Authority asphalt plant in Türkiye. The characteristic properties of the bitumen used in the experiments are presented in Table 1.

HMA mixtures were made from the limestone aggregate which includes coarse aggregate (4.75–25 mm), fine aggregate (0.075–4.75 mm), and filler (0.075 and < 0.075 mm). Table 2 presents the aggregate particle size distribution and characteristic properties of the aggregates were tabulated in Table 3.

Boron is abundantly found in the Earth's crust with approximately 230 mineral forms, predominantly alkali and alkaline-earth borates such as tincal, kernite, colemanite, and

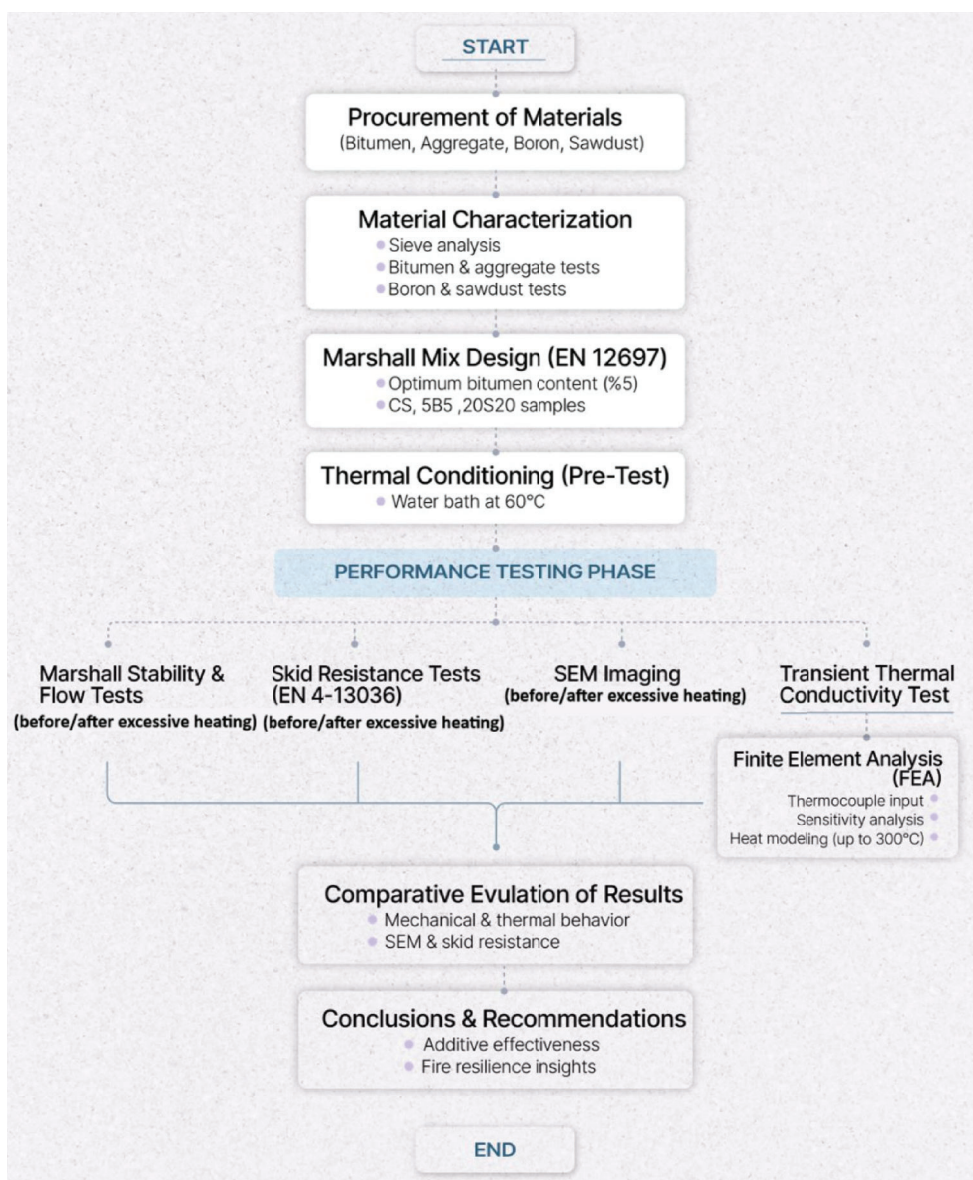


Figure 2. Flow chart of the research.

ulexite. Turkey has the world's largest boron reserves, including nearly all global colemanite deposits (BOREN (Bor Araştırma Enstitüsü), 2024). Boron minerals are widely utilised in defense, chemical, nuclear, and aerospace industries for thermal insulation, flame retardation, and wear-resistant materials (TMMOB, 2003). The use of boron in asphalt mixtures has gained attention in construction. Studies have shown that boron additives improve the rheological properties of bitumen and reduce thermal cracking (Oruç & Yılmaz, 2016), although its incorporation as an aggregate or filler presents challenges. Colemanite waste increases bitumen demand and reduces Marshall stability (Morova & Terzi, 2015), whereas

Table 2. Aggregate particle size distribution.

	Sieve dimensions (mm)	Passing amount (%)	Limits	
			Min (%)	Max (%)
Coarse aggregate	25	100.0	100	100
	19	92.7	80	100
	12.5	70.0	58	80
	9.5	57.1	48	70
Fine aggregate	4.75	42.2	30	52
	2	25.5	20	40
	0.425	10.2	8	22
	0.18	7.0	5	14
Filler	0.075	4.7	2	7
	<0.075	0.0	0	0

Table 3. Characteristic properties of the aggregates.

Experiment	Unit	Coarse aggregate	Fine aggregate	Filler	Standard
Volume specific gravity	g/cm ³	2.696	2.649	–	EN 1097-6
Apparent specific gravity	g/cm ³	2.737	2.745	2.756	
Water Absorption	%	0.5	1.3	–	
Effective specific gravity	g/cm ³	–	–	2.711	ASTM D-2041
MgSO ₄ Freezing loss	%	–	–	18	EN 1367-2
Resistance to fragmentation	%	–	–	21	EN 1097-2
Flakiness Index	%			12.7	BS 812

Table 4. Physical characteristics of boron (colemanite).

Experiment	Unit	Results
Specific gravity	g/cm ³	2.50
Bulk density	g/cm ³	1.00
Molecular weight	g/mol	411.08
Heat capacity	J/kg*K	15.4
Heat conductivity	W/m*K	0.526
Specific surface area	m ² /g	3.30
Surface tension	mN/m	64.78
Colour scale	–	88.53

boron filler is suitable only for low/medium-traffic wearing courses (Gürer & Selman, 2016). The boron (colemanite) material was supplied from ETİ Mining Operations General Directorate, Türkiye. The physical characteristics of boron (colemanite) used in the experiments are presented in Table 4.

A wide variety of tree species exist in global scale, and sawdust derived from these trees commonly emerges as a waste or by-product material. In this study, the sawdust to be utilised was selected based on its local availability and prevalence as a by-product in the region where the experimental work was conducted. In this context, two tree species, beech (*Fagus orientalis*) and pine (*Pinus* spp.), were identified as the most suitable candidates. Accordingly, an initial investigation was carried out to examine the interaction between bitumen and sawdust obtained from these two species, with the aim of determining which type would be more suitable for incorporation into the asphalt mixture. To address this preliminary research question, Fourier Transform Infrared Spectroscopy (FTIR) tests were

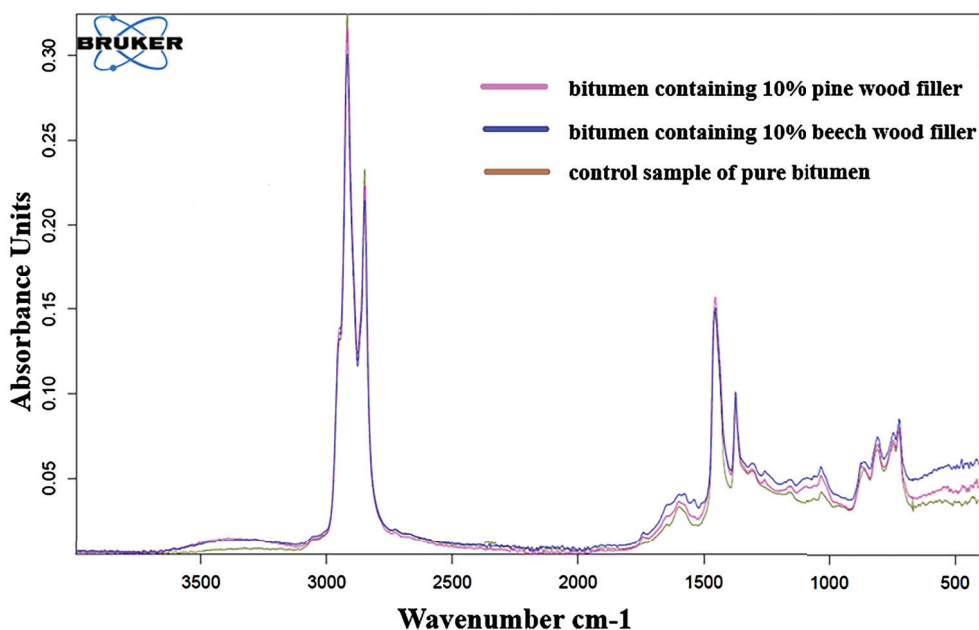


Figure 3. FTIR test results on multiple bitumen samples.

performed on three bitumen samples: one containing 10% beech wood filler, another containing 10% pine wood filler, and a control sample of pure bitumen. The comparative FTIR spectra obtained from these tests are presented in Figure 3.

Accordingly, the functional groups contained in the wood sawdust at filler size (such as -OH , C-O , and related groups) possess the potential to establish physical or chemical interactions with bitumen. Although all three materials exhibited generally similar spectral patterns, certain differences in peak intensities should be noted. The absence of significant spectral mismatches indicates that a stable mixture was obtained. In particular, the more pronounced peak observed around $1020\text{--}1050\text{ cm}^{-1}$ in the beech-containing sample reflects its higher cellulose content. Conversely, the more prominent peaks in the aromatic region ($1260\text{--}1270$ and $1510\text{--}1600\text{ cm}^{-1}$) in the pine-containing sample suggest a higher lignin content. The higher cellulose content of the beech-modified sample implies dominant hydrophilic characteristics, meaning it has an affinity for water, which may adversely affect viscosity and adhesion performance. In contrast, the higher lignin content in the pine-modified sample indicates more hydrophobic behaviour, implying improved stripping resistance and water damage resistance in the asphalt mixture. Moreover, lignin is a natural polymer known to enhance the elasticity and deformation resistance of bitumen, as reported in the literature (Gürer & Selman, 2016; Oruç & Yılmaz, 2016). Based on these findings, the use of wood sawdust derived from pine was selected for the subsequent stages of this study.

Pine wood sawdust with particle sizes ranging from 25 mm to 0.075 mm and exhibiting fibrous morphology was obtained from Sevingen Forest Products Company. The sawdust was oven-dried at $60\text{ }^{\circ}\text{C}$ for three days until a constant mass was achieved to ensure the

Table 5. Chemical and thermal degradation properties of pinewood (Tutuş et al., 2010).

	Chemical compounds (%)	Degradation temperature (°C)
Holocellulose	73.67	310
Cellulose	46.85	340
Alphacellulose	68.19	–
Lignin	28.57	360
Ash	0.45	–
Alcohol-benzene solubility	6.71	–
1% NaOH solubility	16.28	–
Hot water solubility	3.82	–
Cold water solubility	3.42	–

complete removal of residual moisture. The oven-dry bulk density of the material was measured as 360 kg/m³. All sawdust samples were subjected to sieve analysis to determine their particle size distribution. Pine wood sawdust, representing the most common and readily available wood species in the regional market, was selected as the replacement material. The chemical composition and thermal degradation properties of the pine wood sawdust are presented in Table 5.

2.1. Marshall tests

As the initial step following material procurement, efforts were focused on determining the optimal bitumen content. Sieve analyses were conducted to prepare aggregates (limestone, colemanite, and sawdust) in compliance with the sieve sizes specified in the standards (Figure 2). Then, Marshall design procedures were followed to identify the optimum bitumen content for the control samples and to establish design-based quantities. Marshall samples were prepared with 4% to 7% bitumen in 0.5% increments, and the optimum bitumen content was determined to be 5%. Properties of the Marshall samples were tabulated in Table 6. The same amount of the bitumen content was used in the mix design for all samples to observe the various aggregate replacement effects.

In the preliminary stage of the study, it was intended to produce asphalt concrete specimens containing 30% and 40% wood sawdust by weight as aggregate replacement and to evaluate their performance through various testing procedures. However, several specimens disintegrated before demoulding, while others could be removed from their moulds but failed during heating in the Marshall water bath, rendering the stability tests impossible

Table 6. Properties of Marshall Samples.

Properties	Values
Coarse aggregate (g)	307.1
Fine aggregate (g)	791.2
Filler (g)	51.8
Bitumen (%)	5
Specific gravity	2.372
Voids (%)	4.7
Voids filled with asphalt (VFA) (%)	72.63
Voids in mineral aggregate (VMA) (%)	14.27
Marshall stability (kN)	12.31
Flow (mm)	3.88

Table 7. Experiment matrix.

Replacement amount		Samples
Type	Particle sizes	Code
100% limestone aggregate	25 mm to 0.075 mm	CS
20% boron	< 2 mm	5B20
20% sawdust	< 2 mm	5S20

*Three samples were produced for each type.

to perform. These observations indicated that excessive wood sawdust content significantly weakened the internal cohesion and structural integrity of the mixtures. Similarly, in the case of boron-modified asphalt mixtures, substitution levels of 30% and above were also found to be unsuitable based on the Marshall test results. Specimens containing such high boron content exhibited noticeably reduced stability and increased flow values, failing to satisfy the minimum requirements specified by the relevant standards. This deterioration in mechanical performance was attributed to the excessive presence of boron particles, which likely disrupted the aggregate skeleton and hindered proper bitumen adhesion. Consequently, it was concluded that both sawdust and boron replacement ratio should be less than 30% by weight, and that substitution levels of 5%, 10%, and 20% would be more suitable for subsequent experimental evaluation.

Boron (colemanite) and sawdust passing through 2 mm sieves were replaced with aggregates at ratios of 5%, 10%, and 20%. Hot mix asphalt samples with 5% bitumen content were produced in accordance with the EN 12697 Marshall Test standard, and 20% replacement was found to be the optimum amount in terms of Marshall stability, flow, and bitumen amount for both boron and sawdust samples. These samples were used to evaluate the performance of the wildfire under excessive heating conditions, and the experimental matrix is outlined in Table 7.

In line with the Marshall standard (EN 12697), aggregates shall be dried and heated in an oven at $110 \pm 5^\circ\text{C}$ for at least one hour, and bitumen shall be heated in an oven at $150 \pm 5^\circ\text{C}$ for 3-5 h. Considering the instructions, all mixture materials, including sawdust and boron, were conditioned in an oven for specified durations and temperatures. After heating process, bitumen, aggregates, and wood sawdust/boron were mixed in a heated mixer to achieve a uniform blend at a compaction temperature of 150°C . The temperature of the mixtures was monitored using a digital probe thermometer. The prepared mixture was promptly poured into pre-heated Marshall moulds, ensuring homogeneity through tamping with a rod, and compacted by applying 75 blows to each side as specified by the standard. Three samples were prepared for each experiment. The compacted samples were left to cool at room temperature and demoulded within the standard-defined period using a mould extractor. The dimensions of the samples were measured using digital callipers. Subsequently, the samples were conditioned in a 60°C water bath for 45 min to prepare for the Marshall test. Finally, stability and flow values were obtained using the Marshall device. These procedures were applied to all samples in the experimental matrix outlined in Table 6 before and after the excessive heat treatment. In this way, pre-excessive heat treatment and post-excessive heat treatment values in terms of Marshall stability and flow were observed.

2.2. Transient thermal conductivity measurement

The thermal conductivity of asphalt concrete is a critical material property that significantly influences pavement performance, particularly under extreme temperature conditions. The accurate prediction of this property is essential for designing durable roadways and optimising energy-efficient infrastructure systems. Chen et al. (2015) developed a finite element model to predict the thermal conductivity of asphalt concrete by analysing its three-phase microstructure (binder, aggregate, and air voids), demonstrating superior accuracy over conventional analytical methods. The results showed that thermal conductivity depends critically on the air void distribution, aggregate arrangement, and particle orientation, while the model enables optimisation through material modifications, such as thermal-enhanced binders. This approach provides engineers with an improved tool for designing pavements with tailored thermal performances. To complement these advances, Vo et al. (2016) demonstrated that incorporating conductive fillers (e.g. graphite and carbon fibres) enhances the thermal conductivity while maintaining mechanical integrity, as validated through microstructure analysis and 2D simulations. Their work underscores the potential of material engineering to achieve climate-adaptive pavements, bridging predictive modelling with practical mix design innovations. Zhao et al. (2020) evaluated the thermal behaviour of porous asphalt concrete (PAC) using a finite element model reflecting its heterogeneous mesostructure, integrating simulations with laboratory tests to assess temperature-dependent variations in thermal conductivity and specific heat. Results indicated that both parameters slightly increased with temperature, while air voids notably reduced conductivity. Similarly, Górszczyk and Malicki (2025) compared steady-state and transient laboratory methods for measuring the thermal conductivity of asphalt mixtures composed mainly of limestone aggregates. They reported higher conductivity in mixtures with coarser aggregates and lower bitumen content. Although the transient method was faster, it exhibited greater variability. Thermal conductivity values ranged from 1.73 to 2.20 W/m*K, and a conversion factor was proposed to reconcile both methods.

Thermal conditioning is a critical degradation mechanism in asphalt pavement materials, particularly under extreme temperature scenarios such as fire exposure or prolonged solar radiation. While traditional conditioning studies focus primarily on long-term oxidative aging, this experimental setup was designed to simulate accelerated thermal exposure in a controlled environment, simulating the conditions of excessive heating potentially encountered during fire events. The goal was to observe the visual and internal thermal responses of various asphalt mixtures under increasing temperature conditions and to record the surface and core temperature gradients in real time using thermocouple data.

The experimental setup employed a precisely instrumented oven environment with K-type thermocouples positioned at both the upper and lower surfaces of cylindrical Marshall specimens. The samples were circumferentially insulated with ceramic wool 10 mm in thickness, exhibiting a thermal conductivity below 0.04 W/m*K at 300 °C. This insulation ensured unidirectional heat flow and enabled accurate assessment of vertical thermal gradients during transient analysis, as might be observed during a vertical flame exposure scenario in fire events. A stepwise heating protocol was implemented in 50°C increments. The thermal changes on the surface and underneath the test samples, as well as inside the oven, were recorded, and with Finite Element Analysis (FEA), the transient thermal conductivity value was obtained by modelling the temperature and time curves.

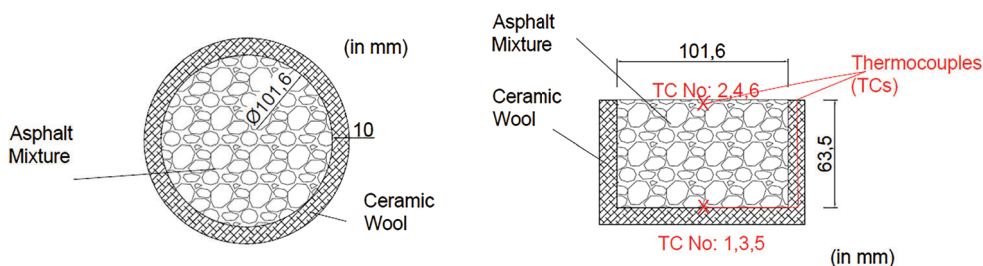


Figure 4. Thermocouple placement plan on test samples.

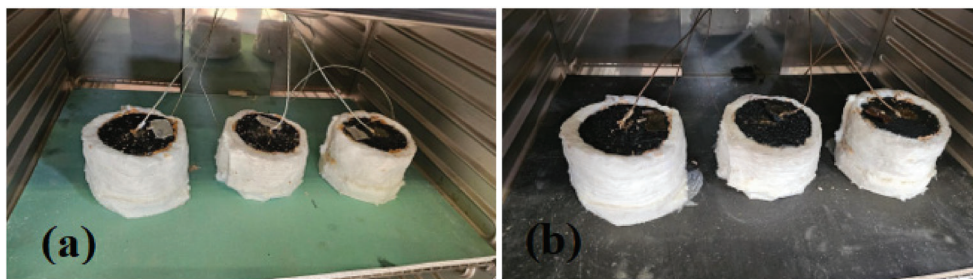


Figure 5. Test samples in heating oven (a) before, (b) after test.

To accurately assess the temperature distribution within each sample, two K-type thermocouples were embedded in each asphalt cylinder. Additionally, the ambient temperature within the oven chamber was recorded using an external ambient thermocouple, whereas the internal control thermocouple (sensor) provided reference data on the chamber's temperature regulation. Figure 4 illustrates the thermocouple placement plan.

A thermal conditioning experiment was conducted using a laboratory-grade programmable heating oven. The procedure involved subjecting the samples to a stepwise thermal exposure protocol, gradually increasing the oven temperature from 50°C to 300°C with 50°C increments. The total testing process lasted about in 3 h. The complete procedure for each temperature increment involves a systematic sequence of steps to provide consistency and data reliability. Initially, the oven was pre-programmed to reach the designated target temperature. Once the set point was achieved, as confirmed by the oven's internal sensor, the samples underwent a brief thermal stabilisation phase to promote uniform heat distribution. This phase was minimal in duration and did not significantly contribute to the total testing time. Subsequently, real-time temperature readings were collected from all thermocouples to monitor the internal thermal responses. This protocol ensured that both internal temperature gradients and surface condition changes were precisely monitored. Thermocouples affixed to the test samples were secured using high-temperature-resistant adhesives, which provided effective thermal contact and prevented displacement during exposure to elevated temperatures to provide accurate and stable thermal measurements. The initial positions of the samples within the oven and their conditions after heating are shown in Figure 5.

Temperature deviations in critical points (the oven set temperature, oven's internal temperature, ambient temperature within the chamber, internal temperatures at the top and



Figure 6. SEM analysis samples.

bottom of the test samples) were measured with thermocouples installed on suitable points during the experimental process. The most important discrepancy was identified between the set temperature of the oven, which was regulated by its internal control thermocouple, and the ambient temperature within the chamber, as recorded by an additional internal thermocouple (TC10). Despite this deviation, the oven set temperature was adopted as the official reference for each thermal phase because it defines the boundary condition imposed on the system.

2.3. Scanning electron microscopy (SEM) tests

Scanning electron microscopy (SEM) is employed to visualise the surface morphology, microstructural characteristics, and, in some cases, compositional features of the materials at high resolution. This technique enables the observation of fine details at the nano and microscales. In this study, SEM imaging was used to evaluate the air voids, bitumen-aggregate interaction, and adhesion capabilities of the mixture by presenting a comparative analysis before and after excessive heat conditions. Broken Marshall samples exposed to stability and flow tests were used to produce SEM test samples, and two samples were selected to best represent the full mixture. Figure 6 indicates the samples used in the test.

2.4. Skid resistance tests

The surface characteristics are highly significant for the safety performance of road pavements. Microstructures under dry conditions and macrostructures under wet conditions are regarded as acceptable indicators. In this regard, Skid Resistance (British pendulum) tests following EN 13036-4 (Method for measurement of slip/skid resistance of a surface) standard were applied to CS and surface characteristics (skid resistance) alteration of the asphalt pavement for pre-excessive heating and post-excessive heating conditions were observed as an additional test. Excessive heating may highly be supposed to affect the skid-resistance characteristics of asphalt surfaces. The reduction in the Pendulum Test

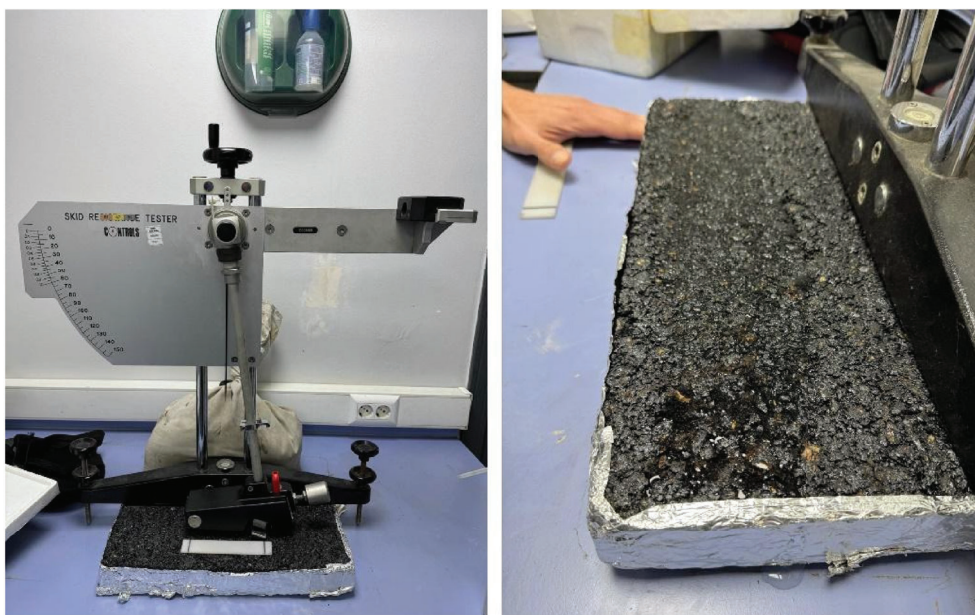


Figure 7. A snapshot during the skid resistance test process.

Values (PTV) suggests that the surface may exhibit increased slipperiness under wet conditions subsequent to excessive heating, which could consequently diminish road safety and increase pavement repair and rehabilitation needs earlier.

In compliance with EN 13036-4, skid resistance tests were performed in a controlled laboratory environment using a British Pendulum Tester fitted with a standard rubber slider No. 57, which is recommended for assessing surfaces under vehicular traffic in wet conditions. Asphalt concrete specimens incorporating limestone aggregates were prepared in accordance with a previously established Marshall mix design. Laboratory-compacted rectangular slabs measuring 410 mm × 260 mm × 50 mm in dimensions were produced, and their upper surfaces were finished to provide a smooth and uniform texture suitable for British Pendulum skid resistance testing. During testing, the asphalt surface, the water used for wetting, and the surrounding air exhibited temperatures of approximately 25 °C, 25 °C, and 24.4 °C, respectively, with a recorded relative humidity of 74%. The pendulum device was calibrated before each test, and the sliding length was set to 126 ± 1 mm. Each specimen was moistened to simulate wet pavement conditions, and five valid swings were conducted to determine the average Pendulum Test Value (PTV). This methodology ensured a reliable assessment of microstructural surface friction under thermal and environmental variations. Figure 7 shows a snapshot of the experimental process.

3. Results and discussion

This section presents empirical findings and subsequent analyses derived from a comprehensive experimental program. The results were systematically organised to address the central research questions concerning the thermal and mechanical resilience as well as surface and morphological properties of various asphalt mixtures under simulated wildfire

conditions. Each subsection details the outcomes of the Marshall stability and flow tests, transient thermal conductivity measurements, skid resistance evaluations, and Scanning Electron Microscopy (SEM) analysis.

3.1. Marshall test results

Marshall tests were conducted considering the experimental matrix in Table 6. The results are presented in Figure 8.

The stability values revealed divergent responses among sample types when subjected to excessive heating. The control sample (CS) exhibited a notable decrease (46.6%) in stability, dropping from 963.48 kg to 514.40 kg, underscoring the vulnerability of conventional asphalt mixtures to thermal degradation. The boron-surrogated mixture (5B20) also experienced a 34% reduction, from 885.73 kg to 582.96 kg, which can be expressed as a better resilience capability to thermal degradation than the conventional asphalt mixture. In contrast, the wood sawdust-surrogated sample (5S20) demonstrated a remarkable 18.8% increase in stability, rising from 961.20 kg to 1142.24 kg, indicating enhanced mechanical performance post-heating. This behaviour may be linked to the thermal decomposition and partial carbonisation of the lignocellulosic content in sawdust, which can act as a micro reinforcement within the asphalt matrix. Several studies (Rowell, 2012; Sjöström, 1993; Yang et al., 2007) have demonstrated that the high lignin content in wood sawdust and the fact that lignin is a natural polymer can enhance the elasticity and deformation resistance of bitumen. The findings obtained in this study are consistent with those reported in the literature.

The flow values demonstrate a significant increase for all sample types following exposure to excessive heating. The control sample (CS) exhibited an increase in flow from 3.62 mm to 9.35 mm, indicating a 158% rise, which reflects a substantial loss of structural stiffness under high temperatures. The boron-surrogated mixture (5B20) experienced an even greater proportional increase in flow, from 2.56 mm to 8.79 mm (243% rise), suggesting that boron incorporation may not provide sufficient resistance to thermal softening. Conversely, the wood sawdust-surrogated mixture (5S20) showed the lowest increase in flow, from 3.11 mm to 5.52 mm (77.8% rise), implying improved resistance to plastic

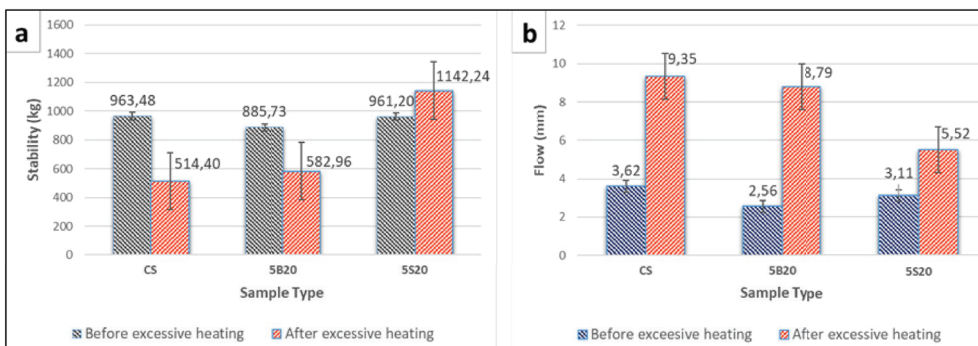


Figure 8. Marshall test results (a) Stability values (b) Flow values.

deformation under heat exposure. These findings align with those of previous studies, indicating that elevated temperatures reduce the viscosity and stiffness of bitumen, thereby increasing the susceptibility to rutting and permanent deformation. The relatively superior performance of 5S20 may be attributed to the fibrous and porous nature of wood sawdust, which can enhance internal friction and binder absorption.

3.2. Transient thermal conductivity test results

The ambient-temperature specific heat capacity was 900 J/kg*K value applied to the model, and slight increase applied at 100°C and 200°C for sensitivity analysis with thermal conductivity values to validate actual transient thermal tests measured with thermocouples fixed to the bottom of the specimen. The limited increase in the specific heat capacity of asphalt mixtures with temperature is primarily attributed to the temperature-dependent molecular mobility of bitumen and the relatively low heat capacity of mineral aggregates. Moreover, the absence of moisture which possesses a considerably higher specific heat further constrains the variation once evaporation occurs. Conversely, the thermal conductivity of asphalt mixtures generally decreases with moisture loss, as evaporated water with higher conductivity is replaced by air of much lower thermal conductivity within the voids. The density of the materials was calculated to be 2230 kg/m³ for the model because of the low water content, and it was assumed that the value was constant at elevated temperatures.

Sensitivity analysis was performed for thermal conductivity for ambient temperature starting from 1.50 to 2.50 W/m*K with slight decrease with 100°C and 200°C were evaluated and reported below (Table 8 and Figure 9). The temperature-dependent material properties were input at elevated temperatures 100°C and 200°C with reduction 0.1 W/m*K for thermal conductivity. Similarly, the specific heat capacity value started at 900 J/kg*K with slight increases at 100°C and 200°C, were evaluated and reported below. Results indicated that Model 5 with 2.1 W/m*K thermal conductivity for ambient temperature and 900 J/kg*K specific heat capacity for the ambient temperature were close to the testing results. Before the analysis, the top side surface thermocouple temperature values were applied to the model, and the remaining surface was assumed to be adiabatic to simulate the actual testing condition and to precisely calculate the transient thermal properties of the material. A convection coefficient of 25 W/m²*K was applied to the top surface of the specimen for the finite element analysis. The temperature measurements in the actual test for the three samples were close to each other and are reported in Figure 8 as TC1, TC3, and TC5.

Table 8 presents the thermal conductivity and specific heat values used to validate the finite element model (FEM) against the experimental results. The thermal conductivity values were iteratively adjusted for three temperatures (20°C, 100°C, and 200°C), with a general trend of decreasing conductivity with increasing temperature. This is consistent with the expected physical behaviour under elevated thermal loads. Similarly, the specific heat was incrementally increased from 900 J/kg*K at room temperature up to 1300 J/kg*K at 200°C, reflecting the increased heat storage capacity of materials at high temperatures.

As an initial boundary condition in the finite element analysis, a thermal conductivity value of 1.5 W/m*K was assigned to represent the lower bound case (Model A), incorporating a decrement of 0.1 W/m*K per 100°C rise in temperature. This assumption was based on the lowest-likelihood scenario derived from sensitivity analysis. In contrast, the upper bound condition (Model B) employed an initial thermal conductivity of 2.5 W/m*K,

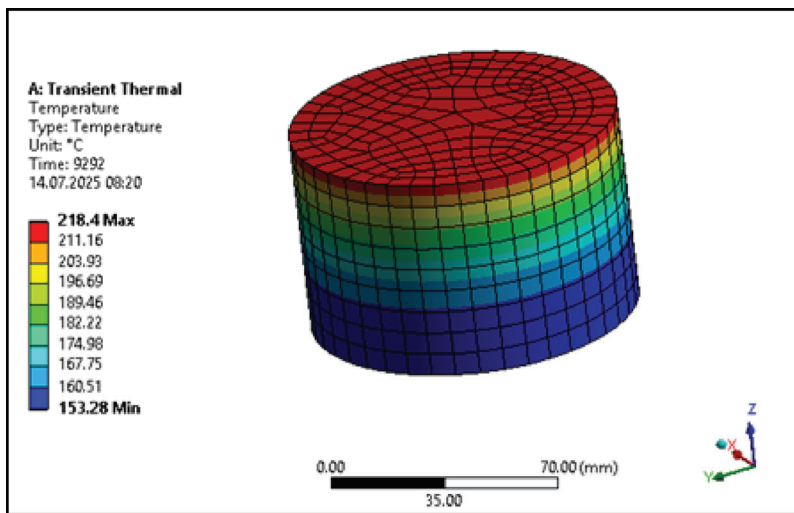


Figure 9. Transient finite element analysis to validate the test results (Model 5).

Table 8. Input values for validation of test results.

No	Thermal conductivity W/m*K			Specific Heat capacity J/kg*K		
	20 °C	100 °C	200 °C	20 °C	100 °C	200 °C
Model A	1.5	1.4	1.3	900	1000	1100
Model B	2.5	2.4	2.3	900	1000	1100
Model 1	2.2	2.1	2.0	900	1000	1100
Model 2	2.45	2.35	2.25	900	1000	1100
Model 3	1.9	1.8	1.7	900	1000	1100
Model 4	2.0	1.9	1.8	900	1000	1100
Model 5	2.1	2.0	1.9	900	1000	1100
Model 6	2.2	2.1	2.0	900	1100	1300
Model 7	2.45	2.35	2.25	900	1100	1300
Model 8	1.9	1.8	1.7	900	1100	1300
Model 9	2.0	1.9	1.8	900	1100	1300
Model 10	2.1	2.0	1.9	900	1100	1300

again adjusted with a decrement of 0.1 W/m*K per 100°C increase, as informed by the highest probability case in the material parameter range. As the simulated temperature profiles showed slight deviations from the empirical results, additional intermediate values were introduced through iterative adjustments to ensure convergence with the actual thermocouple data recorded during testing. Notably, Model 5, which performed best under thermal stress conditions in experimental testing, also exhibited a moderate thermal conductivity gradient (2.1 → 2.0 → 1.9 W/m*K) and a specific heat increase up to 1100 J/kg*K. This balance likely contributes to its thermal stability. In contrast, Model A, with the lowest conductivity profile, serves as the conservative case in the sensitivity analysis, whereas Model B, with the highest thermal conductivity values (2.5 → 2.4 → 2.3 W/m*K), represents the upper bound. These iterations were critical for matching the simulated thermal behaviour to the actual recorded thermocouple readings (TC1, TC3, and TC5), thereby ensuring that the model captured the transient heat transfer effects with higher fidelity (Figure 10).

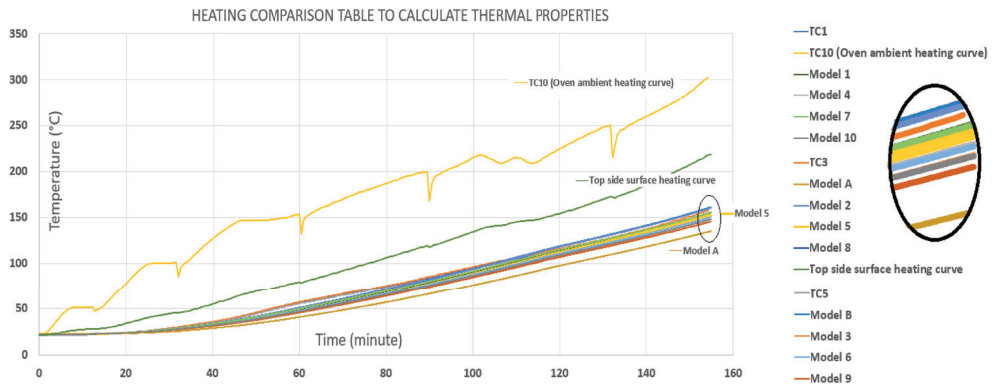


Figure 10. Comparison graph of test and numerical analysis (sensitivity analysis for thermal conductivity and specific heat determination).

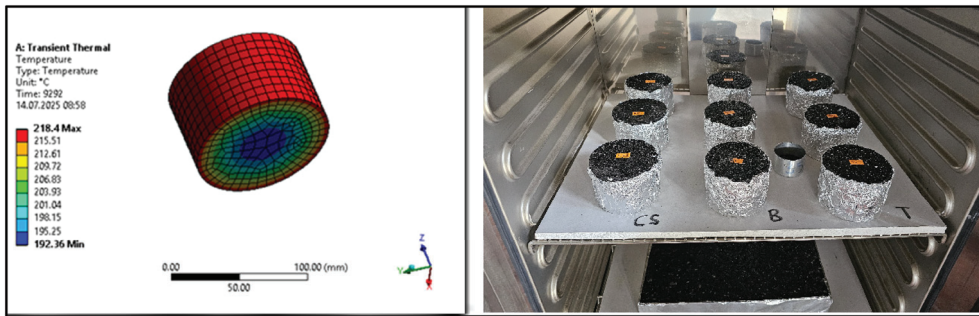


Figure 11. Oven exposure for the test samples.

The results of the sensitivity analysis show that the thermal conductivity of the asphalt pavement can be taken $2.1 \text{ W/m}\cdot\text{K}$ at ambient temperature, $2.0 \text{ W/m}\cdot\text{K}$ for 100°C and $1.9 \text{ W/m}\cdot\text{K}$ for 200°C . The specific heat of the asphalt pavement can be considered as $900 \text{ J/kg}\cdot\text{K}$ at an ambient temperature of $1000 \text{ J/kg}\cdot\text{K}$ for 100°C and $1100 \text{ J/kg}\cdot\text{K}$ for 200°C . The proposed values to be used for typical section FEA are described in the following sections.

Before the Marshall test, three sets of specimens were exposed to the same heating conditions from the top side and boundaries. After defining the temperature-dependent material properties, a thermal analysis was performed for the typical asphalt pavement material before the Marshall test specimen under the same heating conditions. Analysis performed for the specimen and threshold of the exposure can be taken 192.36°C for typical section asphalt pavement in order stay safe side (Figure 11). The skid resistance test samples were also exposed to the same and simultaneous heating conditions.

192.36°C temperature value was used for a typical section of the asphalt pavement resilience evaluation (Figure 12). Transient thermal analysis was conducted on a typical section of asphalt pavement, comprising a 5 cm upper layer surface course, a 5 cm binder course, and a 20 cm base layer. The analysis assumed fire exposure on the side of the asphalt pavement, with the section subjected to a temperature of 300°C , incrementally increased

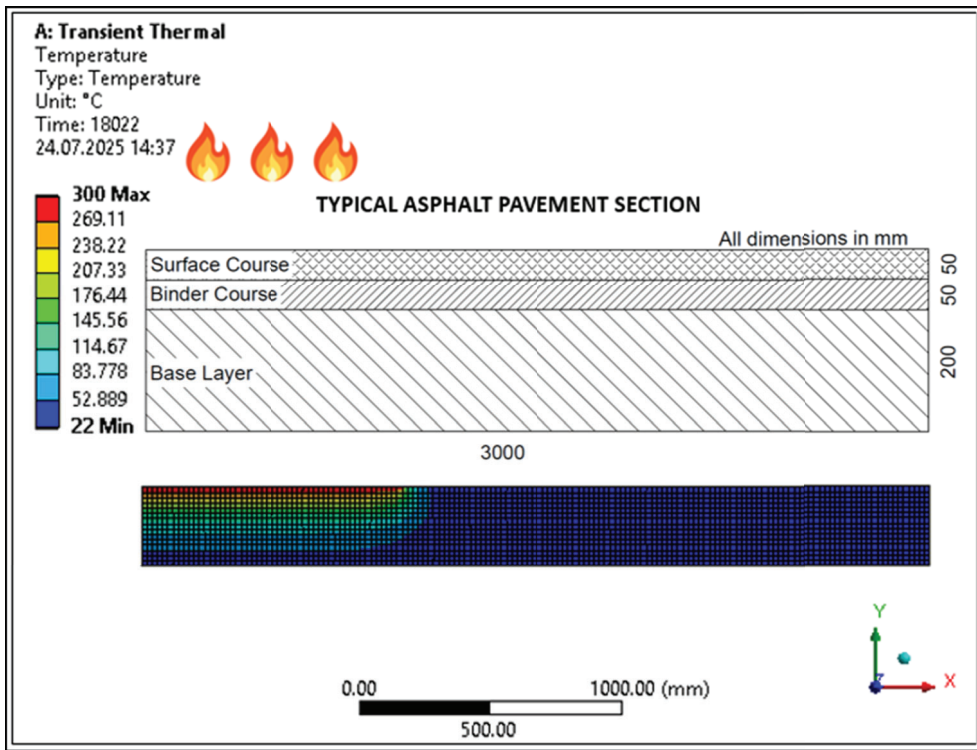


Figure 12. FEA transient thermal analysis for typical asphalt pavement section.

to simulate horizontal temperature movement in the oven test conditions. After reaching 300°C, the temperature was maintained for five hours.

The temperature-dependent thermal properties of the asphalt pavement were assigned, as detailed in Section 2.6, Transient Thermal Conductivity Measurement, and sensitivity analysis. A convection coefficient of 25 W/m²·°K was applied to the top surface of the specimen for finite element analysis, with a 20 mm mesh size applied to the entire section. The results indicated that the bottom side of the upper layer exceeded 200°C, the middle part of the binder course reached approximately 180°C, and the bottom part of the binder course reached approximately 140°C. Consequently, it is recommended that the 5 cm upper layer and 5 cm binder course be removed to ensure safety following wildfire exposure (Figure 14). Horizontally, no significant vertical spread was observed, suggesting that only 5-10 cm had to be removed.

These results were consistent with the typical thermal weakening trend observed in asphalt mixtures by Puente et al. (2016) and Toraldo (2013); however, suggests/encourages the potential of biomass-based additives to improve excessive heat resistance performance. Additionally, SEM analysis was conducted on the 5S20 sample, which indicated the best result in terms of flow and stability values to conceive the microstructural mechanism and to make accurate comments on the factors that cause performance enhancement.

3.3. Scanning electron microscopy (SEM) test results

The SEM investigation focused exclusively on the 5S20 sample, an asphalt composite containing 5% bitumen and 20% sawdust replacement, because the 5S20 sample exhibited better mechanical performance results than 5B20. Two sets of SEM images were captured, one prior to excessive heat exposure (SEM1B/SEM2B) and the other following excessive heating (SEM1A/SEM2A), simulating wildfire-like thermal loads. Observations at identical magnification levels (from 40x to 1000x) provided insights into the morphological and structural alterations caused by thermal degradation.

Figure 13 illustrates the 40x magnification of the samples before and after excessive heating. Both SEM1B and SEM2B (before excessive heating) exhibited a relatively homogeneous surface texture, with moderate porosity and continuous bitumen coating. Filler and surrogated sawdust particles are embedded in the matrix, showing clear bonding interfaces with the binder phase. The surface appeared mechanically stable with no signs of melting, flow, or charring.

Post-exposure samples (SEM1A and SEM2A) showed notable darkened zones and coarse surface roughening. Delamination and microfractures are evident, particularly around the sawdust–bitumen interface. These results suggest partial thermal decomposition of ligno-cellulosic structures (notably lignin and cellulose), as well as binder softening, consistent

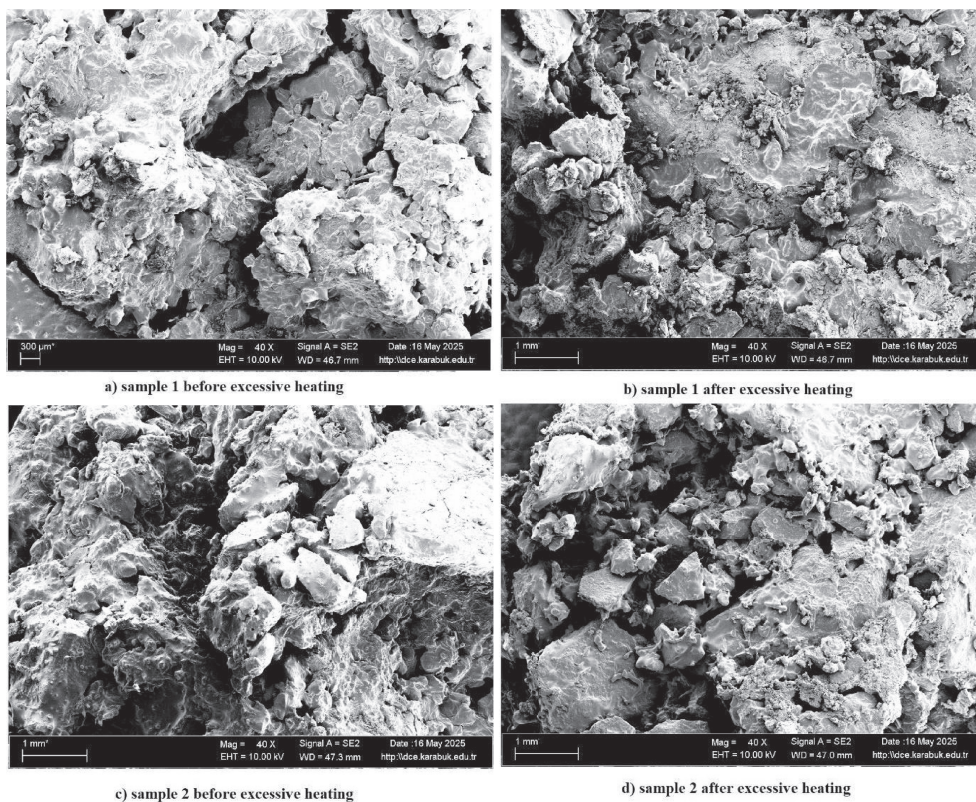


Figure 13. 40x images of SEM1-2B and SEM1-2A.

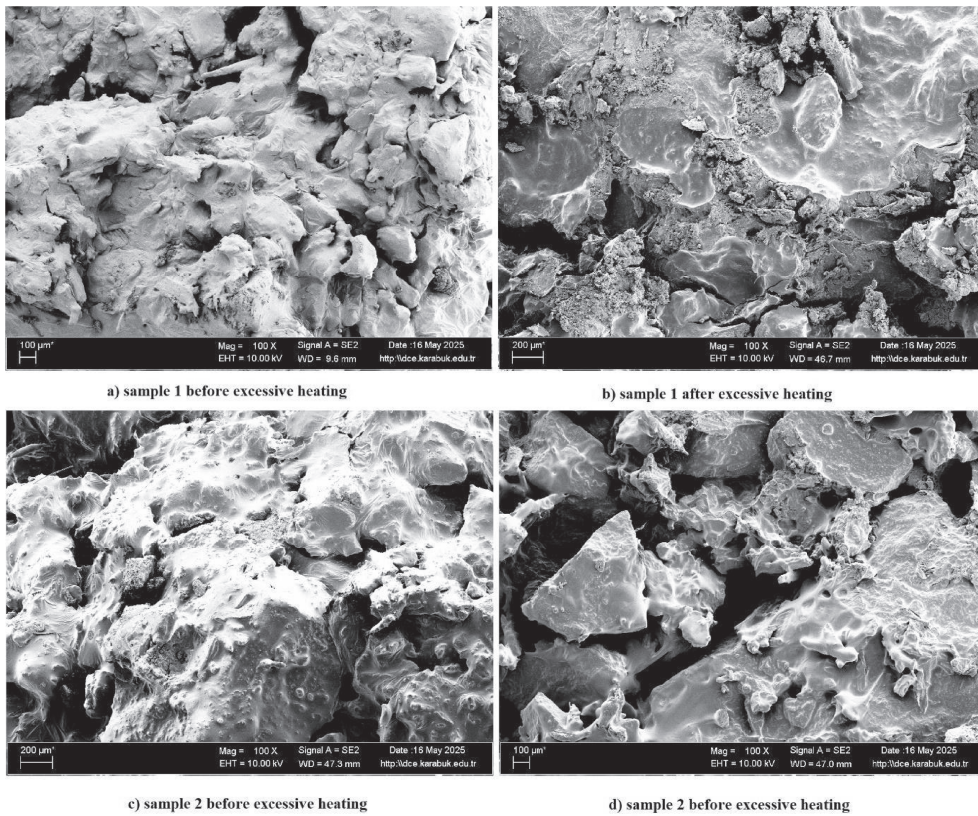


Figure 14. 100x images of SEM1-2B and SEM1-2A.

with lignin degradation onset temperatures ($\sim 360^{\circ}\text{C}$) reported by Tutuş et al. (2010) and by Zhu et al. (2021).

Figure 14 illustrates the 100x magnification of the samples before and after excessive heating. Well-dispersed sawdust fibres were visible and embedded within a continuous binder matrix before excessive heating. The texture of the bitumen phase was relatively smooth and exhibited plastic characteristics without crack propagation. However, after excessive heating, distinct signs of carbonisation and void formation were observed. The sawdust structure loses its integrity, with fibrous residues exhibiting shrinkage and charring. Bitumen exhibits surface blistering and detachment, likely driven by binder volatilisation and oxidative hardening, as reported by Puente et al. (2016).

Figure 15 illustrates the 1000x magnification of the samples before and after excessive heating. A continuous phase of bitumen encapsulates both aggregate fines and organic filler (sawdust), with some micro-voids observed, indicative of the initial binder porosity. The interfaces appeared well bonded before excessive heating. Excessive heat-exposed micrographs show cohesive failure in the bitumen matrix, void coalescence, and significant microcracking, particularly along the sawdust boundaries. These disruptions correlate with the thermal expansion mismatch between the organic fillers and asphalt matrix, a mechanism discussed in asphalt-fibre studies by Guo et al. (2023b). Furthermore, partial pyrolysis

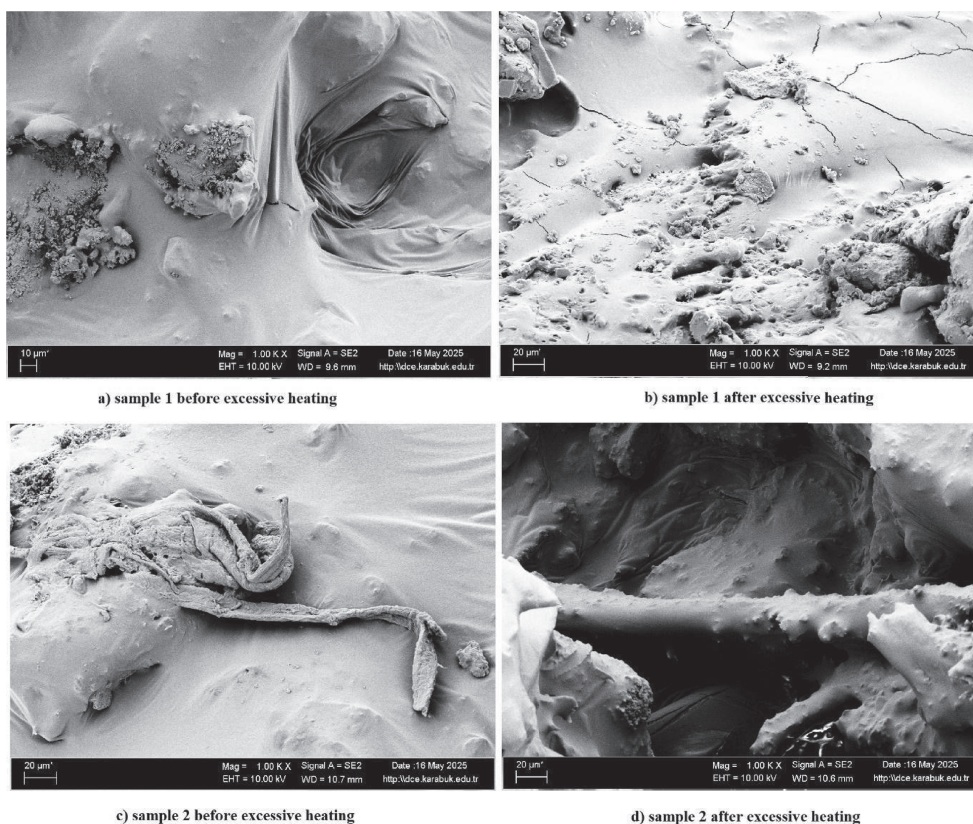


Figure 15. 1000x images of SEM1-2B and SEM1-2A.

of the lignocellulosic structure appears to have generated gas pockets that contribute to void enlargement.

As a result, the SEM images clearly illustrate the relatively superior thermal resilience of 5S20 compared to conventional mixtures (CS), as also evident from the Marshall stability and flow results. Heating induces visible morphological changes, such as porosity growth, binder degradation, and fibre charring. The overall structural framework remained more cohesive in the 5S20 than in the control samples. The thermal insulation effect of charred sawdust acted as a micro-barrier and delayed thermal propagation. Binder absorption by porous lignocellulose reduced the amount of free-flowing bitumen and mitigated softening. The increased internal friction owing to the fibrous structure contributed to the post-heating mechanical strength retention. These mechanisms are aligned with prior research, indicating that biomass additives improve asphalt thermal performance through a combination of physical and chemical parameters.

3.4. Skid resistance test results

Skid resistance testing was conducted exclusively on the control sample (CS) using a British Pendulum Tester in accordance with EN 13036-4, under standardised laboratory conditions

simulating wet pavement behaviour. The test provided a Pendulum Test Value (PTV) as an indicator of the surface friction before and after exposure to excessive heating. The results tabulated in Table 9 correspond to a reduction of approximately 6% in skid resistance.

The decline in surface friction can be attributed to multiple thermal degradation mechanisms, all of which are consistent with both SEM observations and findings from previous studies (Androjić & Dimter, 2022; Zhu et al., 2021). One is bitumen softening and reflow. At temperatures exceeding 200–250°C, bitumen underwent thermal softening, resulting in partial flow and surface smoothing (Puente et al., 2016; Zhu et al., 2021). This reduces the microtexture responsible for tire–pavement interaction, especially under wet conditions. The second is the loss of surface microtexture. The thermal expansion coefficient of bitumen is nearly 10 times higher than the aggregate (Behnia et al., 2018; Guo et al., 2023a), and this may be attributed to the divergent thermal behaviours causing bleeding on the surface during excessive heat exposure. SEM analysis showed delamination and minor flow traces after heating. The bitumen phase tends to cover finer surface roughness, reducing macro-roughness and micro-roughness. This is aligned with the observations in the literature, where flame-exposed asphalt samples demonstrated reduced skid performance owing to binder redistribution. The last is the binder hardening and brittleness mechanisms. Oxidative hardening and volatilisation of light bitumen components result in surface embrittlement. Over time, this not only reduced friction but also increased microcrack formation, as seen in the post-heating SEM images of the CS-equivalent control group. These results emphasise the critical need for thermally resilient pavement designs in fire-prone regions to ensure post-fire traffic safety.

4. Conclusion

This study addressed the critical vulnerability of asphalt pavements to extreme thermal events, particularly wildfires, by exploring the performance enhancement of Hot Mix Asphalt (HMA) with industrial by-products, such as boron and wood sawdust surrogation. The experimental and numerical findings clearly demonstrated that the incorporation of wood sawdust (5S20) significantly enhanced the thermal resilience of asphalt mixtures. After heating, this mixture exhibited a notable increase in Marshall stability and a comparatively moderate increase in flow within the standard limits, outperforming both the control and boron-modified (5B20) samples. These results underline the efficacy of sawdust as a functional replacement material in the development of wildfire-resilient pavement systems. In addition to improved mechanical and thermal-resilience performance, this study contributes to broader environmental efforts by creating new value-added applications for waste and industrial by-products, thereby supporting waste valorisation and circular economy initiatives. Moreover, the use of locally sourced biomass waste contributes to reduced production costs and offers an economically viable solution for climate-adaptive infrastructure.

Skid resistance tests conducted on the control sample revealed significant sensitivity of the asphalt surface to excessive thermal exposure. According to British Pendulum Test results, an approximately 6% reduction in the Pendulum Test Value (PTV) was observed following exposure to wildfire-simulated high temperatures. This decrease indicates that the surface may become slippery under wet conditions, thereby posing a risk to vehicular

Table 9. Skid resistance test results.

Thermal Cond.	Sample Description (Modified Abrasion)	Wet Asphalt Surface °C	Wet Slider Surface °C	Skid Resistance Values PTV				Average PTV	Average Corrected PTV (PTV Corr)	Environmental Conditions
Before	1 point	25	25	65	64	63	65	64	65*	Asphalt = 25 °C Water = 25 °C Air = 24,4 °C
After	1 point	20	20	62	62	60	60	61	61**	Humidity = 74% Asphalt = 25 °C Water-25 °C Air = 20 °C Humidity = 40,5%

* Adjustment for measured slider temperature between 23-29°C: +1

** Adjustment for measured slider temperature between 19-22°C: 0

safety. Moreover, the marked reduction in surface friction suggests that early maintenance and repair interventions are required for pavements subjected to such thermal effects.

Microscopic evaluation, employing SEM on sawdust-enhanced mixtures, provided compelling insights into the mechanisms underlying improved performance. The formation of char layers and fibrous reinforcement from the pyrolysed lignocellulosic sawdust appeared to act as a thermal barrier, reducing binder degradation and mitigating structural disintegration at high temperatures.

Results from finite element analyses and Marshall testing indicate that, following wildfire exposure, the surface and intermediate asphalt layers, amounting to approximately 10 cm of the upper pavement, should be milled and reconstructed to preserve structural integrity and performance. In contrast, pavements incorporating sawdust-replaced asphalt exhibited superior post-fire behaviour, suggesting that major maintenance and rehabilitation can be deferred and that functionality may be restored with limited surface treatments.

These findings have significant practical implications for infrastructure design, particularly in wildfire-prone regions. The use of wood sawdust not only improves the thermal performance and post-fire mechanical stability but also offers a sustainable pathway for valorising biomass waste. By integrating such low-cost, widely available materials into asphalt mixtures, transportation networks can be made more resilient, thereby ensuring safer evacuation routes and post-disaster accessibility. Furthermore, the demonstrated reduction in post-heating skid resistance in conventional mixtures highlights the safety-critical importance of such modifications. Notably, the findings also suggest that the extent of the required repair, specifically in terms of damage depth and lateral spread, can be pre-identified based on post-fire surface performance, allowing for more targeted and cost-efficient rehabilitation planning.

Despite the promising outcomes, this study was limited to laboratory-scale testing under controlled conditions. Future research should prioritise full-scale field validation to assess the long-term performance under realistic traffic and environmental scenarios. Additional investigations should include comprehensive life-cycle assessments, potential environmental impacts, and cost–benefit analyses to support widespread implementation. Expanding the scope to explore hybrid or multi-additive systems may further advance the development of next-generation climate-adaptive pavement solutions.

Another limitation of this study is that only a single mix type, defined by a specific aggregate and binder source, was considered. Future research should include a broader range of material sources and mix designs, together with field validation, to improve the robustness and applicability of the findings.

In addition, although the Marshall test provided a practical basis for comparative evaluation, it represents a relatively conventional approach. Therefore, future studies should incorporate advanced performance based methods such as dynamic modulus, rutting, and fatigue tests etc. to achieve a more comprehensive and mechanistic assessment of asphalt behaviour under extreme thermal conditions.

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Author contributions

CRedit: **Metehan Calis**: Conceptualization, Supervision, Writing – original draft; **Mustafa Yurdabal Apak**: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft; **Ahmet Fazıl Kara**: Investigation, Software, Validation, Visualization; **Halil Ibrahim Yumrutas**: Conceptualization, Data curation, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing; **Isxaq Osman Abdirahman**: Data curation, Investigation, Writing – original draft

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