

LABORATORY EVALUATION OF FLY ASH CENOSPHERE-MODIFIED ASPHALT BINDERS AND ASPHALT MIXTURE THERMAL RESPONSE UNDER CONTROLLED IRRADIATION

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Abstract

Asphalt binders are highly temperature-sensitive materials, and excessive heat accumulation can accelerate softening and reduce pavement service performance in hot climatic regions. This study evaluates the use of fly ash cenospheres (FAC), an industrial by-product with lightweight hollow morphology, as a potential waste-derived modifier for asphalt binders and examines its influence on laboratory-scale thermal response under controlled irradiation. Four binder formulations were prepared: virgin 60/70 penetration-grade binder and binders modified with 5%, 10%, and 15% FAC by binder weight. Conventional binder properties were assessed through penetration, softening point, ductility, flash point, fire point, specific gravity, and rotational viscosity tests. Asphalt mixture slabs prepared with the corresponding binders were then exposed to a controlled irradiation system, and peak temperature and time to peak temperature were recorded. The results showed that FAC modification progressively reduced penetration and ductility while increasing softening point, viscosity, flash point, and fire point, indicating a stiffer and more binder system with improved high-temperature consistency. Under irradiation, the peak temperature decreased from 67.0°C for the control mixture to 59.8°C at 15% FAC, corresponding to a 10.75% reduction. The time to peak temperature increased from 3588 s to 3700 s, indicating delayed heat buildup. These findings suggest that FAC can improve the laboratory thermal response of asphalt mixtures while providing a potential waste-utilization pathway. However, field validation is required before pavement-scale heat-mitigation claims can be made.

1. INTRODUCTION

Flexible pavements are widely used because of their cost effectiveness, ease of construction, and adaptability to different traffic and environmental conditions [1]. In asphalt pavements, the binder strongly controls the temperature-dependent behaviour of the mixture because it governs stiffness, flow resistance, and viscoelastic response [2]. At elevated temperature, asphalt binder

becomes softer and more susceptible to deformation, which may accelerate heat-related pavement distress in hot climatic regions [3]. Therefore, improving the thermal response of asphalt binders and mixtures remains an important objective in pavement material design. Binder modification is a common method for improving the engineering response of asphalt materials. Polymer modifiers, mineral fillers, nanomaterials, and industrial by-products have

been used to improve stiffness, temperature susceptibility, high-temperature resistance, and durability-related properties [4], [5], [6]. Recently, waste-derived and mineral-based modifiers have received increasing attention because they can provide technical benefits while supporting material reuse [7], [8]. These modifiers may alter binder consistency, flow resistance, and thermal stability through filler effects, particle-binder interaction, and changes in the internal structure of the asphalt binder system.

Fly ash cenospheres (FACs) are lightweight, hollow, aluminosilicate-rich particles generated as a by-product of coal combustion. Their low density, spherical morphology, and thermal insulation-related characteristics make them potentially useful as functional mineral modifiers in asphalt materials [9], [10], [11], [12]. Compared with conventional dense mineral fillers, FACs may influence the physical and thermal response of asphalt binder because of their hollow structure and particle morphology [10], [13]. These characteristics make FACs relevant for asphalt applications where temperature sensitivity and heat buildup are major concerns.

Previous studies have examined different modifiers for improving asphalt binder and mixture performance, including polymers, nanomaterials, fly ash, and mineral fillers. However, the use of fly ash cenospheres in asphalt remains comparatively limited. Existing FAC-related studies have mainly focused on asphalt mastic thermal conductivity, high-temperature rheological response, fatigue behaviour, mixture thermal conductivity, and mixture-scale mechanical performance [10], [13], [14]. Some studies reported that FAC can reduce thermal conductivity and internal temperature, although possible reductions in rutting, fatigue, or shear performance have also been noted [10], [13]. Recent work on nanocensospheres has mainly emphasized binder-scale physical and rheological properties, including softening point, recovery, rutting resistance, fatigue life, storage stability, and aging resistance [7], [14]. However, fewer studies have directly connected FAC-modified binder properties with mixture-level heat buildup under controlled laboratory irradiation. This gap is

important because improved binder properties alone do not necessarily confirm improved mixture-level thermal response.

Controlled irradiation and laboratory heating tests provide repeatable methods for comparing the heat-buildup behaviour of asphalt mixtures under identical thermal exposure. Previous studies have used small-scale slabs, solar-simulation heating, infrared-radiation systems, and laboratory cooling-performance tests to evaluate temperature development in asphalt materials [15], [16], [17]. Although such tests cannot directly represent field-scale pavement heat-island behaviour, they can provide useful comparative indicators, including peak temperature, temperature reduction, heating rate, and time-dependent temperature response. In this study, peak temperature and time to peak temperature were selected as laboratory indicators to evaluate whether FAC-modified asphalt mixtures accumulate less heat or delay heat buildup under the same controlled irradiation condition.

In this study, FACs were incorporated into a 60/70 penetration-grade asphalt binder at 5%, 10%, and 15% by binder weight. The unmodified and modified binders were evaluated using penetration, softening point, ductility, flash point, fire point, specific gravity, and rotational viscosity tests. Asphalt mixture slabs prepared with the corresponding binders were then exposed to controlled laboratory irradiation. Peak temperature and time to peak temperature were recorded to assess the effect of FAC dosage on laboratory-scale heat buildup. The main objective was to determine whether FAC modification improves binder-level thermal stability and produces a measurable improvement in mixture-level thermal response under controlled irradiation.

The novelty of this work lies in the combined evaluation of FAC-modified asphalt binders and asphalt mixture thermal response under controlled irradiation. Rather than examining binder properties or mixture thermal behaviour separately, this study links conventional binder characterization with mixture-level heat-buildup indicators. The study does not claim direct field-scale pavement cooling or urban heat-island

mitigation. Instead, it provides preliminary laboratory evidence on how FAC dosage affects binder consistency, thermal stability, peak temperature, and time to peak temperature. The findings support the initial evaluation of FAC as a waste-derived mineral modifier for thermally responsive asphalt materials.

2. Methodology

2.1 Materials

A 60/70 penetration-grade asphalt binder was used as the base binder in this study. The binder was supplied by Attock Refinery, Pakistan. Limestone aggregate was obtained from the HDC

asphalt plant located in the Margalla Hills region, Islamabad, Pakistan. Fly ash cenospheres (FACs) were used as the binder modifier and were supplied by HEBEI Otesi New Material Technology Co. Ltd.

The FAC was selected because of its lightweight hollow morphology and potential insulating behaviour. The modifier was incorporated into the asphalt binder at 5%, 10%, and 15% by weight of binder. The unmodified 60/70 binder was used as the control. The materials used in the study are summarized in Table 1. While FAC properties are listed in Table 2 and 3.

Table 1. Materials used in the study

Material	Source	Description / role in study
Asphalt binder	Attock Refinery, Pakistan	60/70 penetration-grade base binder
Limestone aggregate	HDC asphalt plant, Margalla Hills, Islamabad, Pakistan	Aggregate used for asphalt mixture preparation
Fly ash cenospheres	HEBEI Otesi New Material Technology Co. Ltd.	Waste-derived hollow mineral modifier added by binder weight
FAC dosage	-	0%, 5%, 10%, and 15% by weight of binder

Table 2. Physical properties of fly ash cenospheres

Test Item	Units	Testing Standard	Test Results
Particle Size (60 mesh passing)	%	GB/T 21524-2008	100
Average particle density	g/cm ³	GB/T 4472-2011	0.89
Average packing density	g/cm ³	GB/T 23771-2009	0.45
Melting point (refractory)	°C	GB/T 7322-2017	1642
Thermal expansion coefficient (30-300°C)	X10 ⁻⁶ °C ⁻¹	GB/T 7320-2018	2.14

Table 3. Oxide composition of fly ash cenospheres

Test Item	Units	Testing Standard	Test Results
SiO ₂	%	GB/T 21114-2019	61.92
Al ₂ O ₃	%	GB/T 21114-2019	30.84
Fe ₂ O ₃	%	GB/T 21114-2019	1.34
CaO	%	GB/T 21114-2019	0.93
MgO	%	GB/T 21114-2019	0.40
Na ₂ O	%	GB/T 21114-2019	0.69
K ₂ O	%	GB/T 21114-2019	0.8
Other oxides	%	GB/T 21114-2019	3.08

2.2 Experimental matrix

Four asphalt binder formulations were prepared: virgin binder, 5% FAC-modified binder, 10% FAC-modified binder, and 15% FAC-modified binder. For each group, three replicate specimens were considered. The experimental programme was designed to evaluate both binder-level properties and mixture-level thermal response.

At the binder level, penetration, softening point, ductility, flash point, fire point, specific gravity, and rotational viscosity were measured. At the mixture level, asphalt slabs prepared using the corresponding binder formulations were subjected to controlled irradiation, and two thermal-response indicators were recorded: peak temperature and time to peak temperature [15], [16].

Table 4. Experimental matrix

Mix ID	Binder type	FAC content by binder weight	Controlled irradiation test	Replicates
Virgin	Unmodified binder	60/70 0%	Yes	3
FAC-5	FAC-modified binder	5%	Yes	3
FAC-10	FAC-modified binder	10%	Yes	3
FAC-15	FAC-modified binder	15%	Yes	3

2.3 Sample preparation and testing framework

The 60/70 penetration-grade asphalt binder was heated in a thermostatically controlled container until it became sufficiently fluid for modifier incorporation. The blending temperature was maintained at $160 \pm 5^\circ\text{C}$ throughout the preparation process to reduce binder viscosity and allow uniform dispersion of the fly ash cenospheres (FACs). Before blending, the FAC powder was kept in dry condition and preheated at $105 \pm 5^\circ\text{C}$ for 1 h to remove surface moisture and reduce the temperature difference between the modifier and the hot binder.

FAC was added to the hot binder gradually at dosages of 5%, 10%, and 15% by weight of binder. The modifier was introduced in small portions rather than all at once to reduce particle agglomeration and to improve dispersion within the binder matrix. After complete addition of

FAC, the binder-FAC blend was mixed using a laboratory high-shear mixer at 3000 rpm for 45 min. During mixing, the temperature was continuously monitored and maintained within $160 \pm 5^\circ\text{C}$. The sides of the mixing container were scraped periodically to prevent FAC accumulation along the container wall and to improve blending uniformity.

After mixing, the modified binder was visually inspected to confirm that no visible FAC clusters or dry powder pockets remained. The prepared binders were then poured into clean metal containers, labelled according to FAC dosage, and allowed to cool at room temperature before further testing. The same heating and handling procedure was followed for the virgin binder to maintain consistency among all binder groups.

The preparation parameters used for the modified binders are summarized in Table 5.

Table 5. Preparation parameters for FAC-modified asphalt binders

Parameter	Value used in this study
Base binder	60/70 penetration-grade asphalt binder
FAC dosages	0%, 5%, 10%, and 15% by binder weight
Binder heating temperature	$160 \pm 5^\circ\text{C}$
FAC preheating condition	$105 \pm 5^\circ\text{C}$ for 1 h
FAC addition method	Gradual addition into hot binder
Mixer type	Laboratory high-shear mixer

Mixing speed	3000 rpm
Mixing duration	45 min
Temperature control during mixing	160 ± 5°C
Storage after blending	Clean labelled metal containers

2.4 Asphalt mixture slab preparation

Asphalt mixture slabs were prepared using limestone aggregates and the corresponding unmodified or FAC-modified asphalt binders. The same aggregate source, aggregate gradation, binder content, mixing procedure, compaction method, and slab dimensions were maintained for all mixtures so that the thermal response could be compared mainly as a function of binder modification. Four mixture groups were prepared using the virgin binder, 5% FAC-modified binder, 10% FAC-modified binder, and 15% FAC-modified binder.

Before mixing, the aggregates were heated to 100°C, and the asphalt binder was heated to 160 ± 5°C to achieve sufficient coating and workability. The heated binder was then added to the heated aggregates and mixed until a visually

uniform asphalt mixture was obtained. The prepared mixtures were placed into slab moulds measuring 12 in × 12 in × 2 in and compacted using a gyratory compactor. The same compaction procedure was applied to all slabs to minimize differences in density and internal structure among mixtures.

After compaction, the asphalt slabs were allowed to cool at room temperature before irradiation testing. Three replicate slabs were prepared for each mixture group. The prepared slabs were labelled according to FAC dosage and stored under laboratory conditions until testing. The main purpose of preparing mixture slabs was to evaluate whether binders modified with different FAC contents produced measurable differences in heat buildup behaviour under controlled irradiation.

Table 6: Asphalt mixture slab preparation parameters.

Parameter	Value used in this study
Aggregate type	Limestone aggregate
Aggregate source	HDC asphalt plant, Margalla Hills, Islamabad
Binder type	60/70 penetration-grade asphalt binder
FAC contents	0%, 5%, 10%, and 15% by binder weight
Binder content	5%
Aggregate heating temperature	100°C
Binder heating temperature	160 ± 5°C.
Slab dimensions	12 x 12 x 2 in
Compaction method	Gyratory Compactor
Replicates	3 slabs per mixture

2.5 Controlled irradiation test setup

The thermal response of the asphalt mixture slabs was evaluated using a controlled laboratory irradiation setup. The irradiation chamber consisted of a glass enclosure measuring 35 cm × 35 cm × 35 cm. The inner sides of the chamber were lined with aluminium foil to improve reflection of incident radiation, while a

polystyrene layer was placed at the base to reduce heat loss from the bottom of the slab. Asphalt slabs measuring 12 in × 12 in × 2 in were placed inside the chamber and exposed to a constant irradiation source under identical laboratory conditions.

Heating was provided using four 100 W incandescent bulbs positioned above the asphalt

slab surface. The same bulb arrangement, lamp-to-slab distance, exposure duration, and initial laboratory condition were maintained for all mixtures to ensure direct comparison among the virgin, 5% FAC, 10% FAC, and 15% FAC asphalt slabs. Temperature was recorded using thermocouples inserted at depths of 1 cm and 3 cm from the slab surface. The thermocouples were connected to a digital data logger, and temperature readings were recorded throughout the irradiation period.

For each mixture group, three replicate slabs were tested. The temperature-time data were used to determine the peak temperature and the time required to reach peak temperature. Peak temperature was used as an indicator of maximum heat buildup, while time to peak temperature was used as an indicator of delayed thermal response under the imposed irradiation condition. The same testing procedure was followed for all slabs to minimize experimental variability.

Table 7: Controlled irradiation setup and temperature-measurement parameters used for asphalt mixture thermal-response testing.

Parameter	Value used in this study
Irradiation chamber	Glass enclosure
Chamber size	35 cm × 35 cm × 35 cm
Internal lining	Aluminium foil
Base insulation	Polystyrene layer
Slab size	12 in × 12 in × 2 in
Heat source	Four 100 W incandescent bulbs
Temperature sensor	Thermocouples
Sensor depths	1 cm and 3 cm
Recorded outputs	Peak temperature and time to peak temperature
Replicates	3 slabs per mixture

2.6 Data Analysis

The experimental data were analysed at the replicate level. For each binder formulation, the mean and standard deviation were calculated for the measured binder properties and irradiation-response parameters. The two main thermal-response indicators were peak temperature and time to peak temperature. Percentage changes in these indicators were calculated relative to the virgin mixture to quantify the effect of FAC dosage.

For peak temperature, percentage reduction was calculated by comparing each FAC-modified mixture with the virgin mixture. For time to peak temperature, percentage increase was calculated using the same reference mixture. The relationship between FAC dosage and thermal response was evaluated by comparing the mean

values of the virgin, 5% FAC, 10% FAC, and 15% FAC mixtures.

3. Results

3.1 Effect of FAC on conventional binder properties

The conventional binder test results are presented in Table 8. The addition of fly ash cenospheres (FACs) produced a clear dosage-dependent change in the physical properties of the asphalt binder. Penetration decreased from 62.7 mm for the virgin binder to 58.9 mm, 55.9 mm, and 48.5 mm for the 5%, 10%, and 15% FAC-modified binders, respectively. This reduction indicates that FAC increased binder stiffness and reduced binder softness at the tested condition.

Ductility also decreased with increasing FAC content, falling from 82.67 cm for the virgin binder to 76.33 cm, 70.00 cm, and 63.33 cm for

the 5%, 10%, and 15% FAC binders, respectively. This trend suggests that although FAC improved stiffness-related properties, higher FAC contents may reduce binder deformation capacity.

In contrast, softening point increased from 49.8°C for the virgin binder to 52.9°C, 57.2°C, and 60.4°C for the 5%, 10%, and 15% FAC binders, respectively. Rotational viscosity also increased from 485 cP for the virgin binder to 613 cP, 637 cP, and 652 cP for the corresponding FAC-modified binders. The increase in softening point and viscosity indicates improved high-temperature consistency and greater resistance to flow after FAC modification.

Flash point and fire point also increased with FAC addition. The flash point increased from 281°C for the virgin binder to 320°C, 330°C, and 340°C

for the 5%, 10%, and 15% FAC binders, respectively, while the fire point increased from 309°C to 329°C, 344°C, and 359°C. These results indicate improved thermal safety-related characteristics of the modified binders. The change in specific gravity was comparatively small, decreasing from 1.030 for the virgin binder to 1.003 for the 15% FAC binder.

Overall, FAC modification reduced penetration and ductility while increasing softening point, viscosity, flash point, and fire point. These results indicate that FAC produced a stiffer binder system with improved high-temperature consistency; however, the reduction in ductility should be considered when evaluating possible cracking-related concerns at higher FAC contents.

Table 8: Characterization properties of modified and unmodified binders

Tests	Test standard	Virgin	5%FAC	10%FAC	15%FAC
Penetration (mm)	ASTM D5	62.7	58.9	55.9	48.5
Flash point (°C)	ASTM D92	281	320	330	340
Fire point (°C)	ASTM D92	309	329	344	359
Softening point (°C)	ASTM D36	49.8	52.9	57.2	60.4
Specific gravity	ASTM D70	1.030	1.012	1.008	1.003
Ductility (cm)	ASTM D113	82.67	76.33	70.00	63.33
Viscosity (cpoise)	ASTM D4402	485	613	637	652

3.2 Peak temperature response under irradiation

The peak temperature response of the virgin and FAC-modified asphalt mixtures is shown in Figure 1. The virgin asphalt mixture reached the highest peak temperature of 67.0°C under controlled irradiation. With the incorporation of FAC, the peak temperature decreased progressively to 64.2°C, 61.13°C, and 59.8°C for the 5%, 10%, and 15% FAC mixtures, respectively.

Compared with the virgin mixture, the reduction in peak temperature was 4.18% for the 5% FAC mixture, 8.76% for the 10% FAC mixture, and 10.75% for the 15% FAC mixture, as shown in

Figure 2. This trend indicates that increasing FAC content reduced the maximum temperature reached by the asphalt mixtures under the same laboratory irradiation condition.

The reduction in peak temperature may be associated with the hollow morphology and low-density nature of FAC particles, which can influence heat buildup within the asphalt mixture. The trend is also consistent with the binder-property results, where FAC modification increased softening point and viscosity. However, these results should be interpreted as laboratory-scale thermal-response indicators rather than direct evidence of field-scale pavement cooling.

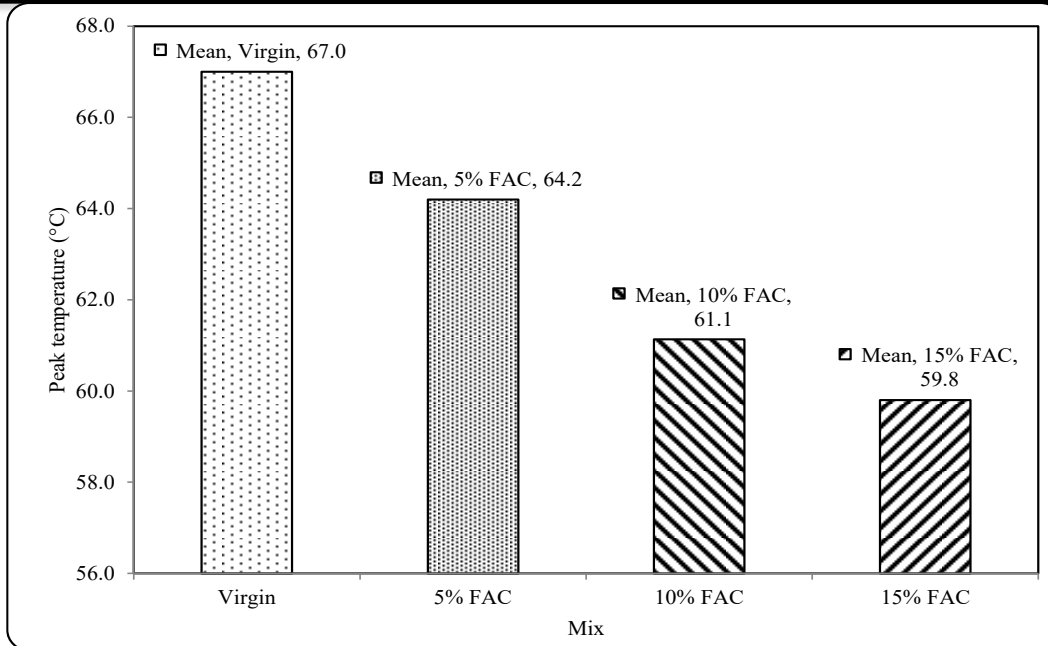


Figure 1: Peak temperature of virgin and FAC-modified asphalt mixtures under controlled irradiation.

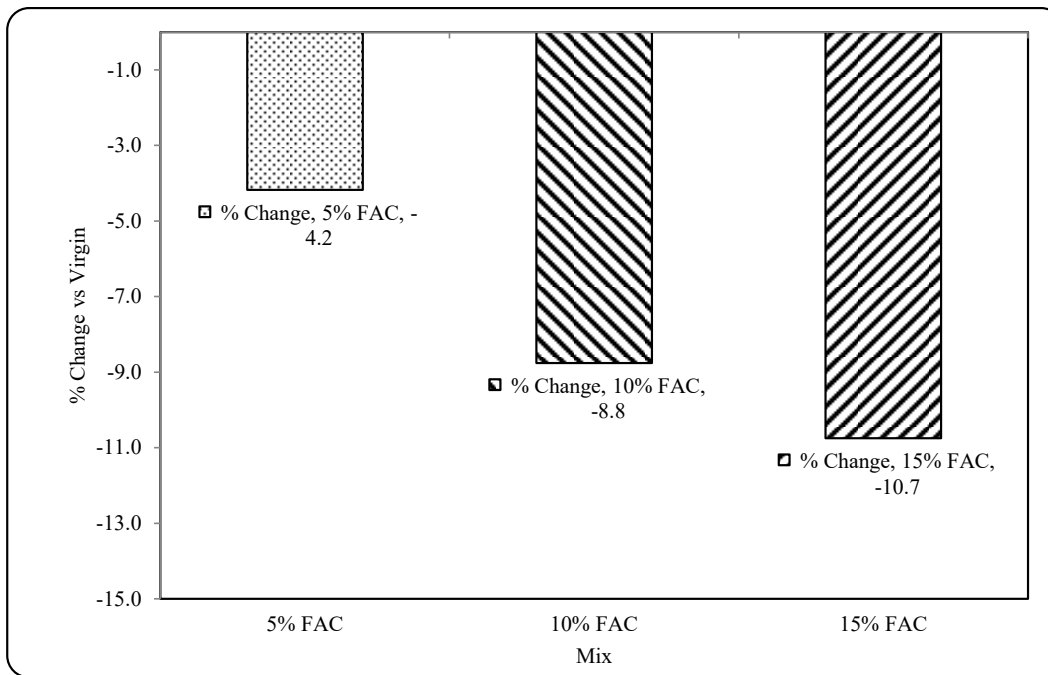


Figure 2: Percentage reduction in peak temperature of FAC-modified asphalt mixtures relative to the virgin mixture.

3.3 Time to peak temperature response

The time required to reach peak temperature is shown in Figure 3. The virgin asphalt mixture reached its peak temperature after 3588 s. With FAC modification, the time to peak temperature

increased to 3637 s, 3680 s, and 3700 s for the 5%, 10%, and 15% FAC mixtures, respectively.

Compared with the virgin mixture, the increase in time to peak temperature was 1.35% for the 5% FAC mixture, 2.55% for the 10% FAC mixture, and

3.11% for the 15% FAC mixture, as shown in Figure 4. This progressive increase indicates that FAC-modified mixtures required a longer time to reach their maximum temperature under the same controlled irradiation condition.

The delayed peak temperature response is consistent with the reduction in peak temperature reported in

Section 3.2. Together, these results suggest that FAC modification reduced the rate of heat buildup in the laboratory irradiation test. However, this interpretation is limited to the controlled experimental condition used in this study and should not be treated as direct evidence of field-scale cooling performance.

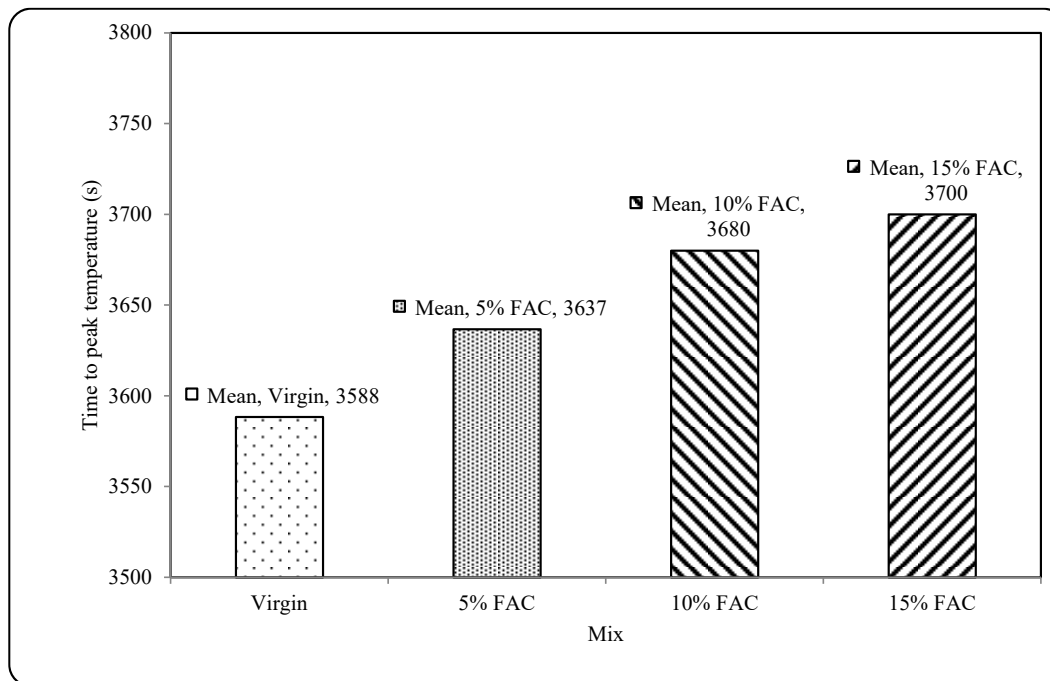


Figure 3: Time to peak temperature of virgin and FAC-modified asphalt mixtures under controlled irradiation.

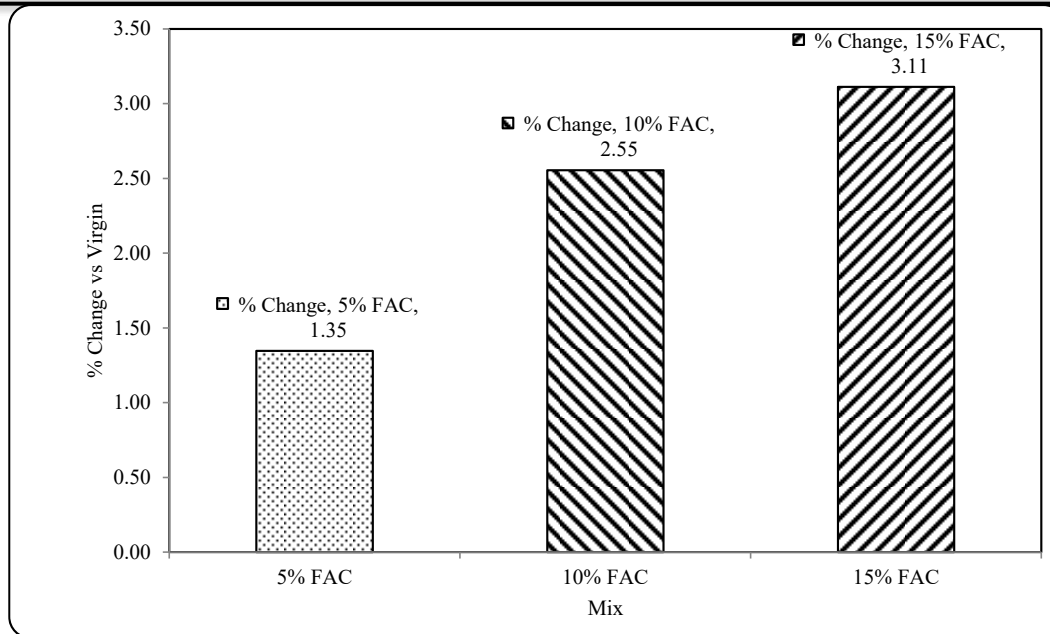


Figure 4: Percentage increase in time to peak temperature of FAC-modified asphalt mixtures relative to the virgin mixture.

3.4 Association of peak temperature with softening point and viscosity

The relationship between peak temperature and selected binder properties was examined to understand whether changes in binder consistency were associated with the thermal response of the asphalt mixtures. Figure 5 shows the relationship between binder softening point and peak temperature, while Figure 6 shows the relationship between binder viscosity and peak temperature.

A negative relationship was observed between softening point and peak temperature. Mixtures prepared with binders having higher softening points tended to reach lower peak temperatures under controlled irradiation. The relationship between softening point and peak temperature showed a coefficient of determination of $R^2 = 0.901$, indicating a strong inverse trend within the tested mixtures.

A similar negative relationship was observed between viscosity and peak temperature. As binder viscosity increased, the peak temperature of the corresponding asphalt mixture decreased. The viscosity–peak temperature relationship showed an R^2 value of 0.835, suggesting that higher binder flow resistance was associated with lower heat buildup under the adopted laboratory condition. These findings indicate that FAC-induced changes in binder properties were linked with the observed mixture-level thermal response. The increase in softening point and viscosity after FAC modification corresponded with lower peak temperature during irradiation. However, these relationships should be interpreted as exploratory correlations based on the tested mixtures only. They should not be considered proof of a universal causal relationship without additional mixtures, broader temperature conditions, and field validation.

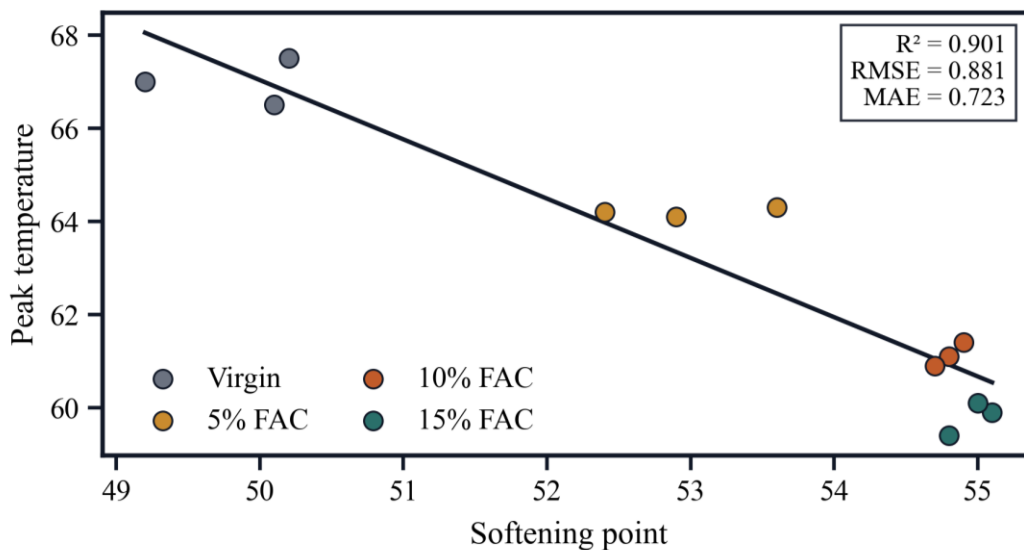


Figure 5: Relationship between binder softening point and peak temperature of virgin and FAC-modified asphalt mixtures.

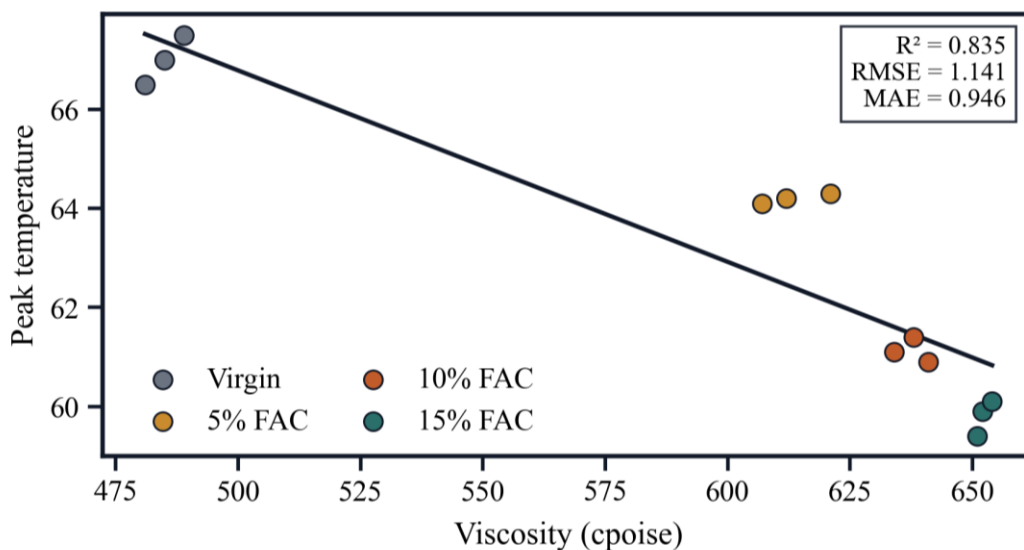


Figure 6: Relationship between binder viscosity and peak temperature of virgin and FAC-modified asphalt mixtures.

3.5 Sustainability relevance and implications for heat accumulation mitigation

The normalized laboratory thermal-response index is shown in Figure 7. This index was used as an internal comparative indicator to summarize the combined effect of reduced peak temperature and increased time to peak temperature. The index increased from 0.00 for the virgin mixture to 0.41, 0.82, and 1.00 for the

5%, 10%, and 15% FAC mixtures, respectively. This trend indicates a progressive improvement in the laboratory thermal-response behaviour of the mixtures with increasing FAC dosage. The increase in the index suggests that FAC-modified mixtures showed lower maximum temperature and delayed heat buildup under the adopted controlled irradiation condition. Among the tested mixtures, the 15% FAC

mixture showed the highest normalized thermal-response index. However, this index should be interpreted only as an internal laboratory comparison among the tested mixtures. It should not be considered a validated field-performance index or a direct measure of pavement cooling effectiveness.

From a sustainability perspective, the use of FAC may provide a waste-utilization pathway by

incorporating an industrial by-product into asphalt materials. The observed reduction in peak temperature and delay in heat buildup indicate that FAC has potential as a waste-derived modifier for improving laboratory thermal-response indicators. However, broader environmental benefits cannot be claimed without life-cycle assessment, field validation, and additional asphalt-mixture performance testing.

The normalized index was calculated using:

$$I = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}}$$

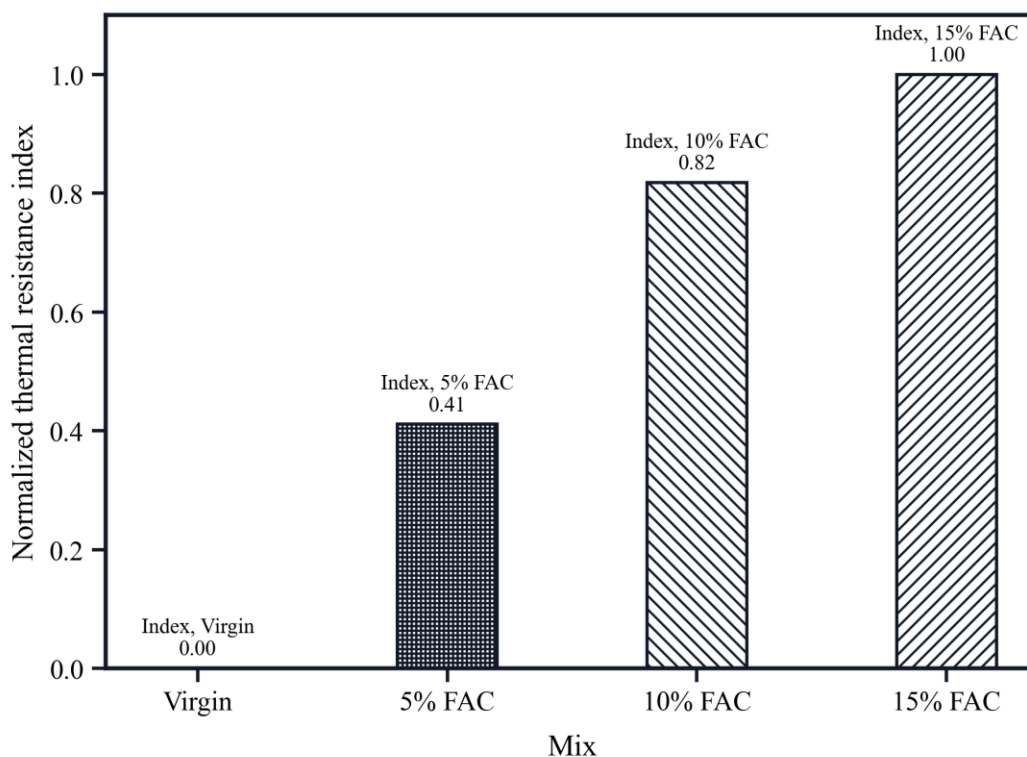


Figure 7: Normalized laboratory thermal-response index of virgin and FAC-modified asphalt mixtures based on peak temperature and time to peak temperature.

4. Discussion

The results indicate that fly ash cenospheres affected both the conventional binder properties and the laboratory thermal response of asphalt mixtures. Increasing FAC content reduced penetration and ductility while increasing softening point, viscosity, flash point, and fire point. These changes show that FAC

modification produced a stiffer binder system with improved high-temperature consistency. The reduction in penetration and increase in viscosity suggest greater resistance to flow, while the increase in softening point indicates improved resistance to temperature-induced softening.

The thermal-response results followed the same general dosage-dependent pattern. Peak temperature decreased from 67.0°C for the virgin mixture to 59.8°C for the 15% FAC mixture, corresponding to a 10.75% reduction. At the same time, the time to peak temperature increased from 3588 s to 3700 s, corresponding to a 3.11% increase. These results suggest that FAC-modified mixtures accumulated less heat and required more time to reach their maximum temperature under the controlled irradiation condition.

The association between binder properties and mixture thermal response provides additional explanation for this trend. The negative relationships between peak temperature and both softening point and viscosity indicate that mixtures prepared with binders of higher consistency tended to reach lower peak temperatures. This supports the interpretation that FAC-induced changes in binder properties were linked with the observed reduction in laboratory heat buildup. However, these relationships are based on a limited number of mixtures and should be interpreted as exploratory trends rather than universal causal relationships.

The normalized thermal-response index also showed a progressive increase with FAC dosage, with the 15% FAC mixture showing the highest index value. This confirms that, within the tested mixtures, higher FAC contents produced stronger laboratory thermal-response improvement. Nevertheless, the index is an internal comparative measure and should not be treated as a validated design parameter.

From a practical perspective, FAC modification appears useful for improving selected laboratory thermal-response indicators of asphalt mixtures while also supporting the reuse of an industrial by-product. However, the results must be interpreted with caution. The study did not directly measure field pavement temperature, urban heat-island mitigation, thermal conductivity, rutting resistance, fatigue performance, moisture susceptibility, or long-term aging resistance. In addition, the reduction in ductility suggests that excessive FAC content

may introduce stiffness-related cracking concerns. Therefore, FAC should be considered a promising waste-derived asphalt modifier for preliminary thermal-response improvement, but field validation and broader mechanical-performance testing are required before pavement-scale recommendations can be made.

5. Conclusions

This study evaluated the effect of fly ash cenospheres (FACs) on the conventional properties of 60/70 penetration-grade asphalt binder and the laboratory thermal response of asphalt mixtures under controlled irradiation. Based on the experimental results, the following conclusions can be drawn:

1. FAC modification reduced penetration and ductility while increasing softening point, rotational viscosity, flash point, and fire point. These changes indicate that FAC produced a stiffer binder system with improved high-temperature consistency.
2. Under controlled irradiation, the peak temperature decreased from 67.0°C for the virgin mixture to 59.8°C for the 15% FAC mixture. This corresponds to a 10.75% reduction in peak temperature relative to the control mixture.
3. The time to peak temperature increased from 3588 s for the virgin mixture to 3700 s for the 15% FAC mixture, representing a 3.11% increase. This indicates delayed heat buildup under the adopted laboratory irradiation condition.
4. Among the tested mixtures, the 15% FAC mixture showed the strongest laboratory thermal-response improvement. However, this should not be interpreted as a confirmed optimum dosage because rutting resistance, fatigue performance, moisture susceptibility, aging resistance, and field thermal performance were not evaluated.
5. FAC shows potential as a waste-derived asphalt modifier for improving selected laboratory thermal-response indicators. However, field validation and broader asphalt-mixture performance testing are required before pavement-scale cooling or long-term performance claims can be made.

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