



Optimization of Thermal Conductivity in Asphalt Mixtures Through Fly Ash Utilization

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Abstract

Urban Heat Island (UHI) phenomena lead to elevated surface temperatures, increased energy consumption, and accelerated pavement degradation. This study aims to enhance the thermal and mechanical performance of asphalt mixtures by incorporating fly ash (FA), a byproduct of coal combustion, as a partial replacement for cement. Asphalt mixtures were prepared using various FA contents (0%, 2%, 4%, 6%) through the dry mixing method. Thermal conductivity was evaluated using the QTM-500 device, while Marshall tests assessed mechanical stability. Results showed that 6% FA reduced thermal conductivity by 20.13%, whereas 4% FA provided the best balance between thermal insulation and structural stability. A clear inverse relationship was observed between thermal conductivity and properties such as bulk density, Marshall stability, and air voids, indicating that FA can enhance insulation without compromising durability. The study focused on the surface asphalt layer, as it serves as the primary interface for solar radiation and heat exchange. Improving its thermal behavior reduces heat transfer to underlying layers, thereby extending pavement lifespan. Moreover, these improvements contribute to mitigating UHI effects, by lowering heat absorption during the day and minimizing heat retention at night supporting sustainable urban development.

Keywords: *Fly Ash, Asphalt Mixtures, Urban Heat Island, Thermal Conductivity, Marshall Stability, Sustainable Pavement Solutions.*

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1. Introduction

Energy consumption for cooling increases as an effect that will continue to raise its significance. The adoption of energy-intensive cooling methods requires more than just the raised amount of energy use. There is a rapid deterioration process that starts because of asphalt pavements exposure to heat owing to thermal expansion. To minimize this issue, the thermal performance of asphalt mixtures receives enhancement through its improvement. The search for sustainable infrastructure now focuses on enhancing asphalt mixture thermal properties. Fly ash (FA), a by-product of coal combustion serves as an effective material for enhancing thermal defenses in asphalt mixtures. The objective is to improve asphalt mixture thermal insulation properties. This material has established its reputation for The thermal conductive properties of this material remain lower than typical filler materials such as cement. Fly ash stands out because of its much lower thermal conductivity compared to cement-based fillers so it represents a superb choice [1, 15]. The material establishes itself as an efficient thermal resistance enhancer. pavement. The research which examined FA for asphalt mixtures demonstrated this material can enhance pavement thermal insulation. The use of fly ash provides asphalt mixtures with important added value. Additions of fly ash create a potential for lower heat absorption resulting in better cooling effects for pavements [2, 5, 7, 16]. Pavement cooling occurs simultaneously with extended surface survival times due to its

incorporation. Road surface lifespans increase in hot climates because of fly ash usage [17]. experience high temperatures [1, 2]. The primary This research aims to determine how fly ash affects various characteristics of asphalt mixtures. The effects of fly ash cause measurable changes in the thermal conductivity properties. mechanical properties of asphalt mixtures, with a The study centers its analysis on the surface layer because it functions as the main exposure to solar radiation. to solar radiation. During the process of heat transfer occurs between the pavement structure and atmospheric elements. Asphalt mixtures depend heavily on this topmost layer to fulfill their functions. component. This research aims to determine the effects of fly ash on asphalt mixture characteristics and mechanical properties. The research must identify the best amount of fly ash which improves thermal insulation capabilities. improve thermal insulation without compromising the mechanical performance of the mixture [3]. Different fly ash levels will be integrated into asphalt to fulfill the objective. Different percentages of fly ash acted as filler rather than cement according to the dry mix method for the combination production. The QTM-500 Quick Thermal Conductivity Meter serves as the instrument for thermal conductivity evaluation since it delivers swift accurate measurements. Selective tests for mechanical stability evaluation included Marshall stability tests together with flow measurements and air voids measurements. The purpose of this investigation explores how fly ash between 0% and 6% levels affect thermal

conductivity together with mechanical properties including density and structural stability and flow movement. (4) and (5)? Research about fly ash incorporation exists in abundance yet science lacks an understanding of how fly ash affects both thermal properties and mechanical performance of asphalt materials. Fly ash effectiveness for urban pavements needs special evaluation because they experience heavy usage alongside dramatic changes in temperature. The existing knowledge gap about fly ash effects on asphalt pavement thermal performance and durability profiles becomes addressed through this research by conducting an extensive analysis. The research will focus on inspecting the surface asphalt layer exposed to solar irradiation [6, 7].

2. Experimental Work

The dry mix method helped prepare samples through which asphalt mixtures received partial cement replacement by fly ash for property evaluation. Applied weight ratios between fly ash and cement formed different mixtures in the asphalt compositions.

- 0% Fly Ash + 7% Cement: Serves as the control mixture.
- 2% Fly Ash + 5% Cement: Introduces a small amount of fly ash.
- 4% Fly Ash + 3% Cement: Increases the proportion of fly ash to further reduce cement content.
- 6% Fly Ash + 1% Cement: Maximizes fly ash content to assess its impact at high substitution levels.

Each mixture was thoroughly mixed to ensure uniform distribution of materials. This setup allows for an assessment of the optimal fly ash content that improves the mechanical and thermal properties of. A total of four asphalt mix designs were developed using different fly ash (FA) contents: 0% (reference), 2%, 4%, and 6% by weight of total aggregates, using the dry mixing method. The total number of Marshall specimens was 33, including 15 specimens for the reference mix. For each modified mix, six specimens were prepared, divided into three for thermal conductivity testing and three for mechanical property evaluation (stability, flow, density, and air voids).

3. Methodology

3.1 Asphalt Binder:

This research utilized a penetration grade (40-50) asphalt cement as the virgin binder, sourced from the Al-Dura refinery located south of Baghdad. The selected asphalt cement is in compliance with the specifications outlined by the State Corporation of Roads and Bridges (SCR B). Physical characteristics of the asphalt binder were tested to ensure conformity with standard requirements, with results summarized in Table 1.

Table 1. Asphalt binder characteristics

Test Condition	AST M	Units	Test Results	Specificati on
Penetration (5 sec, 100 gm, 25°C, 0.1 mm)	D5	1/10 mm	45	40 – 50
Ductility (25°C, 5 cm/min)	D113	cm	135	100 (Min)
Flash Point (Cleveland open cup)	D92	°C	263	230 (Min)

Softening Point (Ring & Ball)	D36	°C	57	---
Specific Gravity (25°C)	D70	gm/c m ³	1.04	---

3.2 Coarse and Fine Aggregates:

The aggregates used in this study were crushed quartz sourced from the Al-Nibaie quarry. Both fine and coarse aggregates were tested to ensure they meet the Type IIIA surface course gradation standards as per SCR B rules. Physical properties of the aggregates are detailed in Table 2.

Table 2. Physical properties of Coarse and Fine Aggregate.

Property	Value	ASTM Designation No.
Coarse aggregate		
Bulk specific gravity	2.584	ASTM C 127
Apparent specific gravity	2.608	ASTM C 127
Water absorption %	0.57%	ASTM C 127
Wear % (Los Angeles)	13.08%	ASTM C 131
Fine aggregates		
Bulk specific gravity	2.646	ASTM C 128
Apparent specific gravity	2.687	ASTM C 128
% water absorption	1.42%	ASTM C 128

3.3 Filler:

The filler used in this research was Ordinary Portland cement, procured from Mass Company in Al-Sulaymaniyah City. The physical parameters and gradation of the cement filler were thoroughly examined, as shown in Tables 3.

Table 3. Filler Gradation and Physical Properties

U.S. Sieve Size (Mm)	Percentage Weight (%)	Passing by SCR B Specification R9, (2003)
0.3(No.50)	98	95-100
0.075 (No.200)	97	70-100
Physical properties		
Specific Gravity	3.1	

3.4 Fly Ash (FA):

Fly ash, a byproduct from the combustion of pulverized coal in electric and steam generating plants, is extensively used in engineering applications due to its beneficial properties. In 2001, over 61 million metric tons were produced, with significant portions utilized in applications such as portland cement concrete, soil stabilization, and as an asphalt filler.

This material is particularly valued for its high specific gravity of 2.645 and a specific surface area of 650 m²/kg, enhancing the mechanical properties of construction materials. The detailed physical characteristics of the fly ash used in this study are presented in Table 4, and a visual representation of the fly ash is provided in Figure 1, illustrating its fine particulate nature.

Table 4. Physical properties of FA

Maximum Sieve size (micron)	%pass ing	Specific gravity	Specific surface area (m ² /kg) kg)
0.075	98	2.645	650



Figure 1. Fly Ash specimen (AF)

3.5. Selection of Aggregate Gradation

The gradation used for this investigation has a nominal maximum size of 12.5 mm and complies with the SCRB 2003 wearing course criteria. Figure 1 shows the selected aggregate gradation, which is also shown in Table 5.

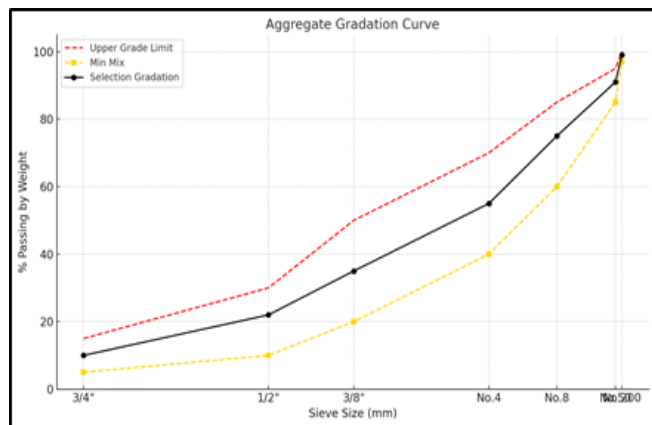


Figure 2. Gradation curve with specific limit

Table 5. Selected Gradation for Aggregate

Sieve Size		% Passing by Weight	
Standard sieves (mm)	English Sieves (in)	Selected limit	Specification Range (SCRB 2003)
19	3/4"	100	100
12.5	1/2"	95	90-100
9.5	3/8"	83	76-90
4.75	No.4	59	44-74
2.36	No.8	43	25-58
0.3	No.50	13	21-May
0.075	No.200	7	10-Apr

3.6. Experimental Design

This study adopted the Marshall mix design method, a standard approach widely utilized in Iraq for both conventional and modified asphalt mixes. The methodology involved several key laboratory assessments aligned with the General Standards of the State Corporation of Roads and Bridges (SCRB) [8].

3.6.1 Aggregate Selection and Analysis:

Aggregates selection began the initial process since appropriate coarse and fine aggregates needed to be selected. Researchers

carefully analyzed the aggregates to validate their physical standards along with composite grades which met SCRB standards.

3.6.2 Mix Formulation and Optimization:

The research involved creating conventional asphalt mixes through binder asphalt additions of 4%, 4.4%, 4.8%, 5.2% and 5.6% weights in relation to aggregate components. The experimental range allowed researchers to identify the correct asphalt content that combined excellent flow value with Marshall stability as well as bulk density and total air voids performance. A binder content of 4.8% was selected as the ideal level because it produced the best mix qualities.

3.6.3 Fly Ash Integration and Evaluation:

Different amounts of fly ash (FA) entered the mixtures for testing the asphalt property changes. The experimental team heated asphalt cement and combined it with different FA ratios before making three specimens for each formulation mix to validate the research findings.

3.6.4 Volumetric and Stability Analysis:

The article features an illustration which outlines the Marshall sample manufacturing steps and various volumetric measurements taken while evaluating optimal binder contents. The graphic presents practical steps involved in sample preparation and use of fractional approaches to evaluate mix characteristics across different binder content levels.

3.7 Testing Methods

3.7.1 Thermal Conductivity

Measurement Using QTM-500

The thermal conductivity of the asphalt mixes was measured using the QTM-500 Quick Thermal Conductivity Meter (Kyoto Electronics). This device employs the transient hot-wire method, which is renowned for its precision, speed, and non-destructive evaluation of the thermal properties of solid materials. as show in figure 3.



Figure 3. The QTM-500 Quick Thermal Conductivity Meter used for measuring the thermal conductivity of materials.

3.7.2 Sample Preparation and Dimensions

The Marshall compaction method provided many specifications to achieve identical compaction density and uniformity in all samples. Special attention was given to making cylindrical samples with a 100 mm diameter and 50 mm height. The particular measurements were selected to enhance probe accuracy and reduce edge effects that could affect thermal conductivity data collection.

3.7.8 Testing Procedure

1. The test samples reached thermal equilibrium at 14°C controlled room temperature prior to testing so all experimental conditions remained stable.
2. During the measurement process the PD-31 probe was directly applied to the surface of the asphalt specimen. After placing the QTM-500 in remote mode the device activated its testing sequence automatically.
3. Over the duration of testing the QTM-500 used short heating pulses against the specimen after which it tracked how temperature fluctuations developed. The W/m·K watt measurement data for thermal conductivity was automatically generated within the QTM-500 system. The experiment required multiple result measurements to confirm the reliability of the obtained data through repeated procedures.

4. Result

4.1 Determination of Optimum Binder Content

The Marshall test determined the optimal binder content for the surface layer in the virgin (control) mixture. Virgin mixtures were prepared and analyzed with five binder percentages (4%, 4.4%, 4.8%, 5.2%, 5.6%), with three specimens for each percentage. The average value for each binder content was calculated, revealing that the optimal binder percentage for the virgin mixture was 5% by weight of the mixture. This optimal percentage was used in preparing the recycled mixtures in the study. Table (8) presents the characteristics of the virgin mixture with the optimal binder, while Figure (2) illustrates the specimen preparation for testing, showing the final results of the optimal percentage in Table 6.

Table 6. Marshall characteristics at optimum (40/50) binder contents.

AC %	Density (g/cm ³)	Stability (kN)	Flow (mm)	Air Voids (%)	VMA (%)
4	2.218	8.3	2.60	5.52	18.5
4.4	2.273	9.1	3	4.60	17.8
4.8	2.34	9.8	3.2	4.28	15.6
5.2	2.345	8.8	3.93	3.89	15.9
5.6	2.244	7.7	4.8	3.12	19.2
Value at OBC (5.0%)	9.374	3.5	4.09	15.8	72.9

4.2 Thermal conductivity

This section presents a detailed comparison of the thermal conductivity results for asphalt mixtures modified with varying percentages of (FA), relative to the control mixture (0% FA + 7% Cement). As illustrated in Figure 4, the results demonstrate the effectiveness of FA in enhancing thermal insulation and contributing to more thermally stable pavement structures.

4.2.1 Control Mixture (0% Fly Ash + 7% Cement)

This mixture serves as the basis for evaluating the effect of fly ash addition. The thermal conductivity of this mixture was measured for comparison with modified mixtures. The thermal conductivity is 1.1389 W/m·K. Its relatively high thermal conductivity indicates a greater susceptibility to heat accumulation, especially in warm climates [18]. This behavior can accelerate surface temperature rise,

leading to thermal cracking, creases, and premature aging of the asphalt surface. High thermal conductivity also means poor thermal insulation [19], which can transfer excess heat to the underlying pavement layers, potentially reducing the life of the entire structure.

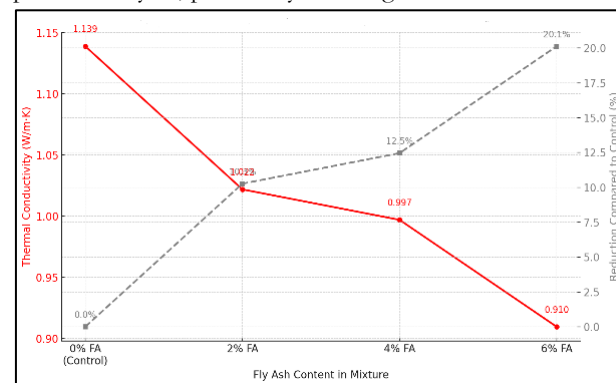


Figure 4. Effect FA content on thermal conductivity of on Asphalt mixture

4.2.2 2% Fly Ash + 5% Cement

The addition of 2% FA resulted in a significant 10.27% decrease in thermal conductivity, recording a reading of 1.0219 W/m·K, highlighting the positive role of fly ash in thermal insulation, even at low dosages. This effect is mainly attributed to the porous and irregular shape of the FA particles, which hinders heat transfer pathways within the asphalt matrix [20]. However, despite its thermal benefits, this mixture recorded the lowest Marshall stability (8.1 kN), indicating a trade-off between improved thermal insulation and reduced mechanical strength. The reduced stability may be due to the low cementitious binder content, indicating that while fly ash enhances thermal performance, it must be carefully balanced to avoid compromising structural reliability, especially in high-load traffic applications.

4.2.3 4% Fly Ash + 3% Cement

The asphalt mixture containing 4% fly ash showed a further reduction in thermal conductivity of 0.997 W/m·K, a decrease of 12.46% compared to the reference mixture. This mixture provides thermal insulation, making it particularly suitable for pavements exposed to high temperatures [22]. In support of this, [9,21] reported that replacing 60% of the cement with a mixture of fly ash and bottom ash resulted in a 15.6% reduction in thermal conductivity, as measured by ASTM D5334, reinforcing the role of fly ash in improving the thermal properties of asphalt compounds.

4.2.4 6% Fly Ash + 1% Cement

This mixture showed the greatest thermal improvement compared to previous addition ratios, reaching a reading of 0.9096 W/m·K, with a conductivity reduction of 20.13%. This result is consistent with [10], who reported a 20.9% conductivity reduction when replacing conventional fillers with FAC. The high FA content introduces more micro-voids and increases the internal porosity of the mixture, reducing thermal conductivity paths [23,24,25,26]. This makes the mixture particularly useful for mitigating surface heat, reducing thermal stress, and extending pavement life in hot climates.

4.3 Correlation between Thermal Conductivity and Mechanical Properties

For asphalt mixtures altered with different fly ash (FA) proportions, this section investigates the interactions between thermal

conductivity and important mechanical parameters namely, Marshall stability, flow, air voids, and bulk density.

4.3.1 Marshall Stability and thermal Conductivity

Figure 5 illustrates an inverse correlation between Marshall stability and thermal conductivity in asphalt mixtures with varying fly ash (FA) contents. As FA increases, thermal conductivity decreases while stability improves, indicating enhanced thermal insulation and mechanical strength.

- The control mix (0% FA) exhibited the highest thermal conductivity (1.1389 W/m·K) and moderate stability (9.374 kN).
- At 2% FA, conductivity dropped to 1.0219 W/m·K, while stability declined to 8.1 kN, likely due to reduced binder cohesion at lower cement content.
- At 4% FA, conductivity further decreased to 0.997 W/m·K, and stability increased to 10.1 kN, reflecting improved interaction between FA particles and the asphalt matrix.
- The 6% FA mix achieved the lowest conductivity (0.9096 W/m·K) and highest stability (11.1 kN), suggesting enhanced void filling and aggregate interlock.

These results are consistent with previous studies [11, 12], which demonstrated that increasing FA or porous fillers reduces thermal conductivity by increasing void content and reducing density, without significantly compromising strength.

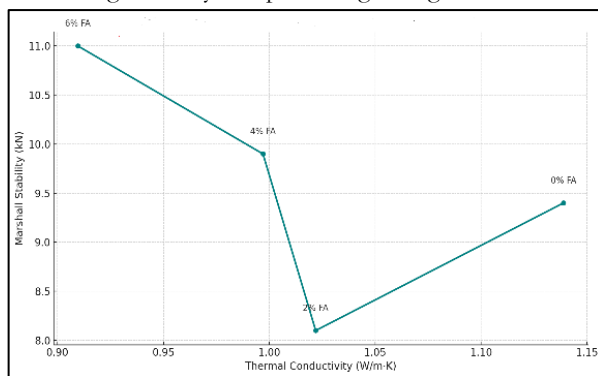


Figure 5. Relation between Marshall Stability and Thermal conductivity

4.3.2 Flow and Thermal Conductivity

Figure 6 shows that as fly ash (FA) content increases, thermal conductivity decreases, while flow values indicate a general increase in stiffness. This reflects the dual role of FA in reducing heat transfer and modifying mixture deformability.

- 0% FA: Highest flow (3.566 mm) and thermal conductivity (1.1389 W/m·K), indicating a soft, heat-sensitive mix prone to deformation.
- 2% FA: Flow reduced to 2.84 mm, and conductivity to 1.0219 W/m·K, suggesting improved stiffness but insufficient structural integrity (lowest stability: 8.1 kN).
- 4% FA: Flow at 3.0 mm with further conductivity reduction (0.997 W/m·K), balancing insulation and strength (stability: 10.1 kN).
- 6% FA: Slight flow increase (3.4 mm), but lowest conductivity (0.9096 W/m·K) and highest stability (11.1 kN), showing optimized stiffness and thermal performance.

The reduction in flow aligns with the increased internal porosity and reduced density caused by FA, which impedes heat transfer and restricts excessive deformation. This supports findings in [12], which confirmed that FA reduces thermal conductivity through structural modifications

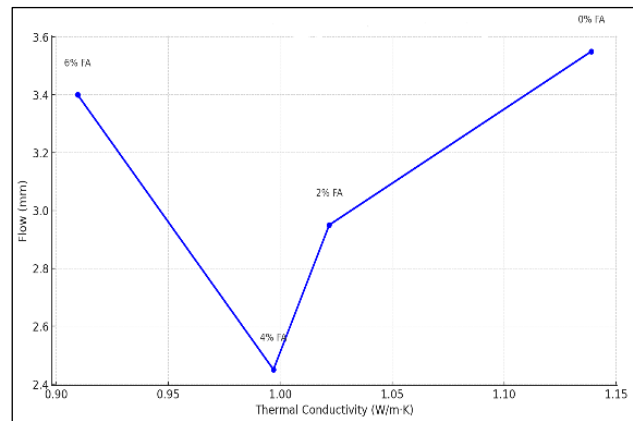


Figure 6. Relation between Flow and Thermal conductivity

4.3.3 Air Voids and Thermal conductivity

Figure 7. illustrates an inverse relationship between air voids and thermal conductivity in asphalt mixtures incorporating fly ash (FA). As FA content increases, air voids tend to rise, resulting in lower thermal conductivity due to the insulating effect of entrapped air.

- 0% FA: Lowest air voids (4.092%) and highest thermal conductivity (1.1389 W/m·K), reflecting dense compaction and greater heat transfer.
- 2% FA: Air voids increased to 7.726%, reducing conductivity to 1.0219 W/m·K, though associated with lower mechanical stability (8.1 kN).
- 4% FA: Moderate air voids (6.077%) and further conductivity reduction (0.997 W/m·K) reflect improved compaction and better thermal–structural balance.
- 6% FA: Air voids slightly decreased (5.672%) while conductivity reached its lowest (0.9096 W/m·K), with highest stability (11.1 kN), suggesting effective void distribution and matrix integrity.

These trends align with previous findings [13], which confirmed that FA enhances thermal insulation by increasing internal porosity and reducing mixture density, without significantly impairing strength when optimally proportioned

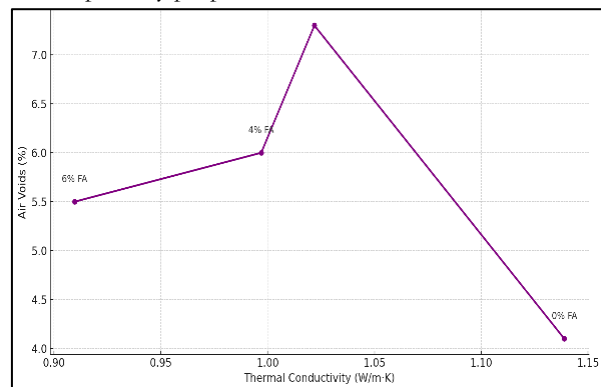


Figure 7. Relation between Air Voids and Thermal conductivity

4.3.4 Density and Thermal Conductivity

Figure 8 illustrates a direct relationship between bulk density and thermal conductivity in asphalt mixtures containing varying fly ash (FA) contents. As FA increases, bulk density decreases due to enhanced internal porosity, resulting in lower thermal conductivity and improved insulation performance.

- 0% FA: Exhibited the highest bulk density (2.3425 g/cm^3) and thermal conductivity ($1.1389 \text{ W/m}\cdot\text{K}$), indicating dense compaction and effective heat conduction.
- 2% FA: Density decreased to 2.284 g/cm^3 , with thermal conductivity reduced to $1.0219 \text{ W/m}\cdot\text{K}$. The added FA introduced microvoids that partially disrupted heat flow.
- 4% FA: Further reduction in density to 2.274 g/cm^3 and conductivity to $0.997 \text{ W/m}\cdot\text{K}$ reflected a better balance between compaction and insulation.
- 6% FA: Reached the lowest bulk density (2.262 g/cm^3) and thermal conductivity ($0.9096 \text{ W/m}\cdot\text{K}$), marking a 20.13% reduction compared to the control. Despite the lower density, the mix maintained the highest Marshall stability (11.1 kN), indicating sufficient structural integrity.

These results are consistent with previous studies. Ghosh et al. [13] reported that replacing sand with fly ash in mortar reduced both bulk density and thermal conductivity due to increased air voids. Similarly, Deng et al. [14] demonstrated that incorporating lightweight fillers such as fly ash cenosphere significantly enhanced the thermal resistance of asphalt mixtures by increasing porosity and interrupting conductive heat paths

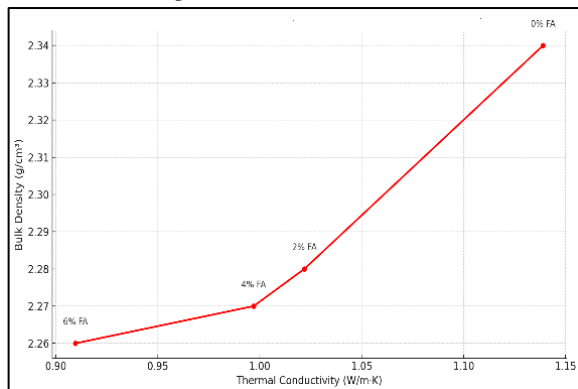


Figure 8. Relation between bulk Density and Thermal Conductivity

5. Conclusions and Recommendations:

This study confirmed that incorporating fly ash into asphalt mixtures effectively enhances thermal insulation performance. A 6% fly ash addition resulted in a 20.13% reduction in thermal conductivity, thereby contributing to surface cooling and the mitigation of urban heat island effects. Furthermore, the inclusion of fly ash positively impacted mechanical behavior, as demonstrated by improved Marshall stability and reduced air void content at higher dosages. From an environmental standpoint, fly ash promotes sustainable construction by reducing dependence on virgin materials and mitigating CO₂ emissions associated with cement production. It is worth noting that fly ash content beyond 6% was not tested in this study due to concerns regarding excessive filler content, which could adversely affect mixture workability, increase brittleness, and compromise mechanical integrity under heavy traffic loading.

6. Recommendation:

To maximize the practical adoption of fly ash in asphalt applications, it is recommended to develop unified performance-based specifications and conduct long-term field evaluations under various

traffic and climatic conditions. This will ensure that the material's benefits translate effectively into real-world durability and performance.

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