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ASSESSMENT OF THE THERMAL CONDUCTIVITY OF SUSTAINABLE ASPHALT MIXTURES INCORPORATING CRUMB RUBBER VIA THE DRY PROCESS

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Abstract

Hot weather conditions increase the thermal conductivity of asphalt pavements, causing heat-related damages. Reducing thermal accumulation in pavement structures is essential to improve durability and service life. This study examines the thermal and mechanical performance of asphalt mixtures modified with crumb rubber (CR) via the dry process. Twelve modified mixtures with 1%, 3%, and 5% CR were prepared using four particle sizes (0.3 mm, 2.36 mm, 4.75 mm, and blended), along with an unmodified control mix. Thermal conductivity was measured using the QTM-500 device, while mechanical properties were evaluated via the Marshall method, including stability, flow, air voids, and voids filled with asphalt (VFA). Statistical analysis using ANOVA and Tukey HSD validated the results. Thermal conductivity decreased with higher CR content, reaching 0.4619 W/m.K at 5% CR with blended gradation – a 59.4% reduction from the baseline of 1.1389 W/m.K. Marshall stability peaked at 1% CR (14.446 kN) but declined at higher CR levels due to increased air voids, affecting compatibility. With blended gradation and 2%–3% CR, both insulation and mechanical integrity improved. In hot climates, CR use enhances thermal performance, promotes tire recycling, and offers cost-efficient pavement solutions.

Keywords:

Asphalt mixture;
Thermal conductivity;
Crumb rubber;
Dry process;
Pavement engineering.

1 Introduction

Asphalt concrete is a predominant material in road building, significantly influencing pavement performance. The temperature distributions inside the asphalt pavement structure are significantly impacted by the thermal characteristics of asphalt concrete, which in turn has a significant impact on the pavement's lifespan [1]. Thermal conductivity is essential for examining the thermal properties of pavement in engineering applications. It assesses a material's thermal conductivity, defined as the heat flux per unit area traversing a unit thickness of the material at a temperature differential of 1 °C [2]. Asphalt's thermal conductivity is key to heat transfer and temperature distribution in pavement layers' Various elements influence the variability in thermal conductivity, including the binder, aggregate, filler, and air void ratio. Table 1 delineates several asphalt classifications along with their respective estimated thermal conductivity values [18]. High thermal conductivity accelerates heat disposal, minimizing thermal stress. Reduced thermal conductivity improves thermal insulation, preventing temperature-induced failures such as cracking and thermal fatigue in cold areas. To lengthen pavement life, decrease care expenses, promote riding comfort, and improve heat conductivity [3]. Thermal conductivity in asphalt pavements is influenced by various factors, including material composition and compaction. Studies have shown that thermal conductivity values for asphalt mixtures typically range from 1.7 to 2.1 W/m·K [10]. Crumb rubber modification (CRM) has proved to be a feasible solution for boosting asphalt performance and sustainability. This method mixes asphalt with recycled tire rubber, providing several benefits. Rubber's elasticity boosts flexibility and fatigue resistance. Better thermal insulation by decreasing pavement heat transmission [4]. Using crumb rubber is a sustainable and economical method to enhance the performance and longevity of asphalt pavements while facilitating the recycling and repurposing of waste materials [5] [9]. Researchers in [21] found that adding 10%–20% RAP to base layers lowers costs and environmental impact, supporting the use of recycled materials like crumb rubber in surface mixtures. Two methods exist for the preparation of CR the dry process and the wet procedure. The dry technique is eco-friendly and involves mixing crumb rubber (CR) with heated aggregate and then adding warmed liquid bitumen. The result is a rubber-modified asphalt concrete mixture. This technology was initially devised and accomplished in Sweden, then patented in the USA in 1978 as Plus Ride [6]. In the dry process, 1% to 3% of the aggregate's weight is replaced with rubber crumb particles smaller than sieve No. 8, which are incorporated into the pavement concrete's fine aggregate. The dry process method needs high manufacturing temperatures to integrate rubber particles. The FHWA suggests a manufacturing temperature of 149 to 177 °C (300-350 °F) [6][7]. This study uses a dry method to examine the thermal conductivity characteristics of asphalt mixes enhanced with crumb rubber. The main goals are to evaluate the impact of crumb rubber concentration on thermal conductivity, examine the influence of mass gradation on heat transfer qualities, and compare the thermal performance of rubber mixes with traditional asphalt. The idea posits that augmenting crumb rubber content will diminish the thermal conductivity of asphalt mixes, hence improving insulating qualities and alleviating temperature-related pavement deterioration. This research offers significant insights for the design of sustainable asphalt pavements that enhance thermal performance and durability, hence extending road lifespan and minimizing environmental effects and resource consumption.

Table 1**:** The thermal conductivity values of asphalt category [18].

Asphalt category	**Description**	**Thermal conductivity range [W/m.K]***
Asphalt binder	Pure asphalt binder, typically derived from petroleum refining or natural sources	0.6 - 1.0
Dense graded asphalt	Asphalt mixture with well-graded aggregate and low air void content, providing a smooth and durable surface	1.5 - 2.5
Porous asphalt	Asphalt mixture aimed to allow water to trough done the pavement, featuring higher air void	0.7 - 1.5
Stone Matrix Asphalt	Gap-graded asphalt mixture with a significant percentage of coarse aggregate and substantial binder and filler material	1.5 - 2.5

W/m.K: Watts per meter per Kelvin, a unit of thermal conductivity indicating the material's ability to conduct heat.

2 Experimental works

2.1 Overview

In this study, 13 asphalt mixture samples were prepared, including a control mix (without rubber) and modified mixtures incorporating crumb rubber (CR) at different percentages (1%, 3%, 5%) with varying gradations (0.3 mm, 2.36 mm, 4.75 mm, and a blended gradation), where the rubber replaced the remaining aggregate retained on sieves No. 4, 8, and 50, and was mixed accordingly, as shown in the table. The mixtures were mechanically evaluated using the Marshall test to measure stability, deformation, bulk density, air voids, voids filled with asphalt, and voids in mineral aggregate. Subsequently, thermal conductivity was measured using the QTM-500 device via the transient hot-wire method, with samples thermally conditioned at 14°C before testing. The categorization of specimens within each category is presented in Table 2.

Table 2: Details of type mixtures.

Number	**Type of asphalt mixtures**
1	Control + 0% CR
2	Aggregate + % CR with 0.3 mm gradation
3	Aggregate + % CR with 2.36 mm gradation
4	Aggregate + % CR with 4.75 mm gradation

2.2 Materials used

2.2.1 Asphalt binder filler

The asphalt binder used was penetration grade (40-50) asphalt cement, sourced from Al-Dura Refinery, south of Baghdad. Test results confirm compliance with SCRB specifications [11]. Table 3 presents its physical characteristics.

Table 3: Asphalt binder characteristics.

`	Test condition	ASTM	Units	Test results	Specification
Penetration	5 sec,100gm, 25˚c, 0.1mm	D5	1/10 mm	45	(40 – 50)
Ductility	25˚c,5cm/min	D 113	Cm	135	100 (Min)
Flash Point	Cleave land open cup	D 92	˚c	263	230 (Min)
Softening Point	(ring &ball)	D 36	˚c	57	---
Specific Gravity	25 ˚c	D 70	gm /cm3	1.04	---

2.2.2 Coarse and fine aggregates

Crushed quartz aggregate from the Al-Nibaie quarry was used, meeting Type IIIA surface course gradation per SCRB standards [11]. Standard tests assessed aggregate properties, with results and SCRB limits presented in Table 4.

Table 4: Physical properties of 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

2.2.3 Filler

The filler used was Ordinary Portland Cement from Mass Company, Al-Sulaymaniyah City. Its physical properties and gradation are detailed in Table 5.

Table 5: Filler gradation and physical properties.

U.S. sieve size [mm]	Percentage passing by weight [%]	SCRB specification R9, [2003]
0.3 (No.50)	98	95-100
0.075 (No.200)	97	70-100
Physical properties		
Specific gravity		3.1

2.2.4 Crumb rubber

The crumb rubber (CR) modifier was sourced from Al-Kut Towers Tires Factory, Al-Diwaniyah City, 180 km south of Baghdad. CR consists of black particles of varying sizes and shapes. Table 6 details its properties. Waste tires, collected from roadsides and disposal sites, were sorted by size, with fiber and steel reinforcements removed before shredding. Rubber particles were classified by sieve dimensions and termed rubber aggregate.

Table 6: Crumb rubber properties [9].

Property		Unit	Value	ASTM Specifications
Sp.gravity		gm\cm3	%	(D297)
Ash content		%	15-Jan	(D297)
Heating loss		%	1	(D1509)
sieve anylasis		%	90	(D5603)
fiber content		%	0.5	(D5603)
steel content		%	0	(D5603)

2.3 Selection of aggregate

The gradation used for this investigation has a nominal maximum size of 12.5 mm and complies with the SCRB 2003 wearing course criteria. Fig. 1 shows the selected aggregate gradation, which is also presented in Table 7.

Table 7: 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

2.4 Methods of mixing

CR may be produced using either the dry or wet approach [6]. The green dry method uses crumb rubber (CR), heated aggregate, and heated liquid bitumen. The result is rubber-modified asphalt concrete composite.

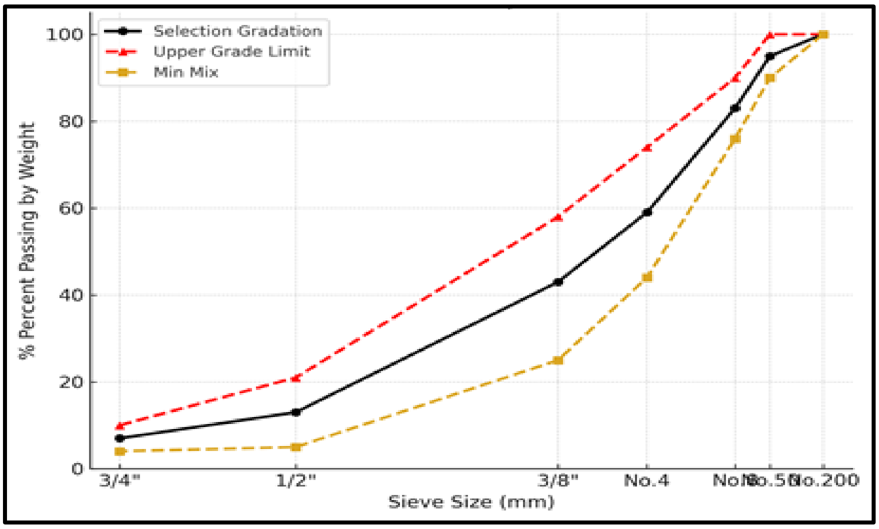

Fig. 1: Selection gradation.

In 1978, the US copyrighted Swedish Invention Plus Ride [13]. Dry technique replaces 1 % to 3 % of aggregate weight with rubber crumb particles smaller than sieve No. 8, adding them to pavement concrete's fine aggregate. In dry processes, rubber particles must be mixed at high temperatures. The FHWA advises 149–177 °C (300-350 °F) manufacturing. [6, 7]. Open-graded, dense-graded, and gap-graded Hot Mix Asphalt (HMA) pavement incorporates crumb rubber particles as elastic aggregates in the dry technique. The Hydrous Method: America's first wet process, the 1960s 'McDonald process,' began [6, 14]. Wet rubber modification includes mixing tire rubber with a binder and reacting at 175-200 °C (350-400 °F) for 45–60 minutes [14]. GTR-modified binders absorb asphalt binders and expand rubber at high temperatures [6, 15, 16]. Rubber can increase binder viscosity, boost stiffness and rut resistance. The binder system is stronger and crack-resistant with softened rubber particles [17].

2.5 Preparation of mixtures

Marshall mix was utilized for ordinary and rubber crumb-modified asphalt in this investigation. Marshall mix asphalt is common in Iraq. We choose coarse and fine aggregates and analyze their physical attributes and composite grades in the lab to meet asphalt mix specifications. Phase followed SCRB standards [11]. Stage two has two parts. Conventional asphalt mixes have 4, 4.4, 4.8, 5.2, and 5.6 percent binder asphalt without crumb rubber. Flow value, Marshall stability, bulk density, total air voids, and 5% binder by weight make the ideal asphalt mix. Pictured are Marshall sample preparation and asphalt mixture volumetric parameters for optimal binder content (OBC) evaluation with different binder percentages. Check how heating the right amount of asphalt cement with different CR ratios effects the mixture. We sampled each formulation three times, as presented in Fig. 2.

Fig. 2: Group of optimum asphalt content.

2.6 Preparation of CR-modified asphalt mixture samples

The dry mixing approach was employed to produce modified asphalt concrete samples using crumb rubber after the aggregate preparation process was finalized and the aggregate was prepared for sample fabrication. The modification involves substituting a portion of the natural aggregates with crumb rubber of identical size fraction. Different percentages and gradations of crumb rubber (CR) were utilized, including a uniform mix size including equal amounts from three sizes: 4.76 mm, 2.36 mm, and 0.3 mm. The exact ratios of aggregates and crumb rubber modifier were blended prior to the application of asphalt binder. For an optimal mixing method of the asphalt binder combination, the quantity of crumb rubber was integrated with the aggregate and asphalt binder at a temperature ranging from 160 to 170 degrees Celsius.

2.7 Thermal conductivity measurement using QTM-500

The thermal conductivity of asphalt mixes was assessed using the QTM-500 Quick Thermal Conductivity Meter (Kyoto Electronics), utilizing the transient hot-wire method, which is recognized for its accuracy, rapidity, and non-destructive capability in measuring the thermal characteristics of solid materials. As shown in Fig. 3.

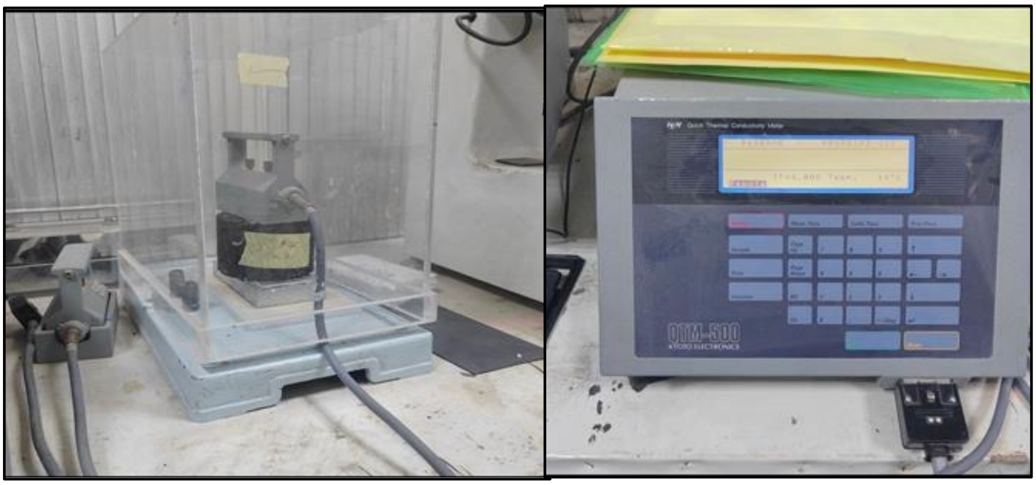

Fig. 3: The QTM-500 Quick Thermal Conductivity Meter used for measuring the thermal conductivity of materials.

2.7.1 Sample preparation and dimensions

Specimens were compacted utilizing the Marshall technique, guaranteeing consistent density and compaction. Each cylindrical sample had a diameter of 100 mm and height of 50 mm, meeting the optimal size requirements for accurate probe contact and minimal edge effects.

2.7.2 Testing procedure

3.1 Optimum binder content for virgin mixture

The Marshall test determined the optimal binder content for the surface layer in the virgin (control) mixture. Virgin mixtures were prepared and analysed 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. Table 8 presents the characteristics of the virgin mixture with the optimal binder, while Fig. 2 illustrates the specimen preparation for testing, showing the results of the optimal percentage in Table 9.

Table 8: Marshall characteristics at optimum (40/50) binder contents.

AC [%]	Density [g/cm^3]	Stability [KN]*	Flow [mm]	Air voids [%]	VMA [%]	VFA [%]
4	2.218	8.327	2.607	5.525934	18.576	56.9
4.4	2.273	9.1	3	4.608621	17.83	63.03
4.8	2.34	9.897	3.2	4.286345	15.64	69.43
5.2	2.345	8.852	3.933	3.898632	15.98	76.5
5.6	2.244	7.775	4.8	3.12673	19.24	78.29

KN: Kilonewton, a unit of force equal to 1,000 newtons.

Table 9: The result of optimal percentage.

Parameter	Stability [kN]	Flow [mm]	Air voids [%]	VMA [%]	VFA [%]	Density [g/cm^3]
Value at OBC (5.0 %)	9.3745	3.5665	4.09245	15.81	72.965	2.3425

3.2 Marshall properties and thermal conductivity of asphalt cement modification with C

This section comprehensively assesses the mechanical and thermal characteristics of asphalt mixes enhanced with crumb rubber via the dry process. The impact of several rubber gradations (0.3 mm, 2.36 mm, 4.75 mm, and a composite gradation of 4.75 + 2.36 + 0.3 mm) is examined concerning stability, flow, air spaces, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), bulk density. Table 10 summarizes the experimental result.

3.2.1 Influence gradation of CR on mechanical properties and thermal conductivity

1. Effect of Crumb Rubber (CR) content on stability

Marshall stability test results for asphalt mixtures with varying CR content and different gradations indicate a clear influence on mixture stability Fig. 4.

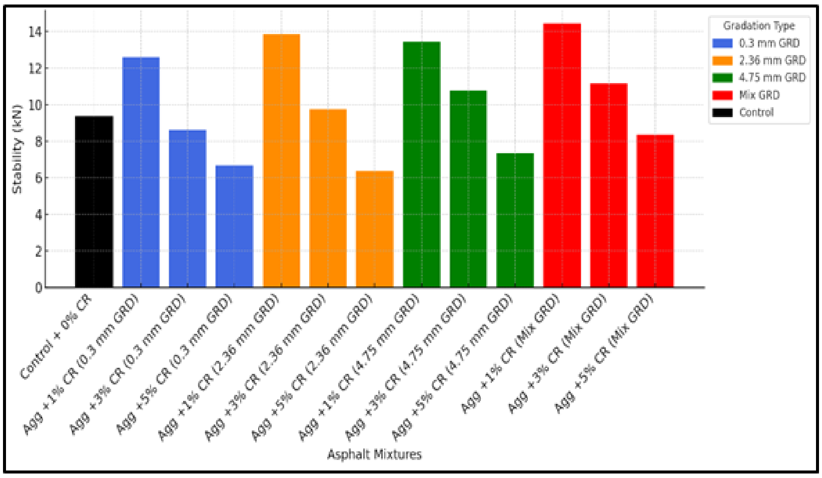

Fig. 4: The Marshall stability of varying CR content.

- The control mixture (**0% CR**) exhibited a stability of **9.374 kN**, serving as a baseline for comparison.
- Adding **1 % CR** resulted in a significant increase in stability, reaching its highest value of **14.446 kN** with the mixed gradation (**4.75 + 2.36 + 0.3 mm**).
- As the CR content increased to **3 % and 5 %**, stability values declined, suggesting that excessive rubber content may reduce load-bearing capacity.

Table 10: Summary of the experimental result of CR.

Type of asphalt mixtures	Stability [kN]	Flow [mm]	Air void [%]	VMA [%]	V.F.A [%]	Bulk density	Thermal conductivity [w/m.k]	Reduction thermal conductivity compared to control [%]
Control + 0% CR	9.374	3.566	4.092	15.81	72.965	2.3425	1.1389	-
*Agg +1% CR with 0.3 mm *GRD	12.6	3.1	3.702	18.129	79.58	2.263	1	12.2
Agg +3% CR with 0.3 mm GRD	8.632	4	5.729	19.1703	70.116	2.234	0.77	32.4
Agg +5% CR with 0.3 mm GRD	6.67	7	8.335	20.742	59.815	2.191	0.75	34.1
Agg +1% CR with 2.36 mm GRD gradation	13.853	3.28	4.104	19.859	79.333	2.215	1	12.2
Agg +3% CR with 2.36 mm GRD gradation	9.747	4.1	6.644	18.266	63.628	2.259	0.86	24.5
Agg +5% CR with 2.36 mm GRD gradation	6.365	7.5	7.277	19.156	62.01	2.235	0.73	35.9
Agg +1% CR with 4.75 mm GRD gradation	13.432	4.2	4.366	23.191	81.175	2.123	0,9878	13.3
Agg +3% CR with 4.75 mm GRD gradation	10.782	5.3	6.78	19.734	65.643	2.219	0.7553	33.7
Agg +5% CR with 4.75 mm GRD	7.356	8	8.792	20.476	57.065	2.198	0.766	32.7
Agg +1% CR with mix (4.75 +2.36 +0.3) mm GRD	14.446	3.8	4.52	18.824	75.99	2.244	0.8955	21.4
Agg +3% CR with mix (4.75 +2.36 +0.3) mm GRD	11.154	4.1	5.257	21.508	75.558	2.17	0.6361	44.1
Agg +5% CR with mix (4.75 +2.36 +0.3) mm GRD	8.338	6.9	6.445	23.846	72.971	2.105	0.4619	59.4

Agg: Refer to the aggregate used in asphalt mixtures, GRD: Rerfer to the gradation of aggregate.

Effect of gradation on stability

The performance of asphalt mixtures varied based on the CR gradation used:

- Fine gradation (0.3 mm CR): Maximum stability of 12.6 kN at 1 % CR, decreasing to 8.632 kN at 3 % CR and 6.67 kN at 5 % CR.
- Medium gradation (2.36 mm CR): Highest stability of 13.853 kN at 1 % CR, slightly higher than the fine gradation. Stability decreased to 9.747 kN at 3 % CR and 6.365 kN at 5 % CR.
- Coarse gradation (4.75 mm CR): Stability values were 13.432 kN at 1 % CR, decreasing to 10.782 kN at 3 % CR and 7.356 kN at 5 % CR.
- Mixed gradation (4.75 + 2.36 + 0.3 mm CR): This combination exhibited the highest stability values at all CR levels, with 14.446 kN at 1 % CR, 11.154 kN at 3 % CR, and 8.338 kN at 5 % CR.

2. Effect of CR content on flow

The flow values of asphalt mixtures provide insights into their deformation characteristics under load. Fig. 5 shows the results indicating a direct correlation between CR content and the flow properties of asphalt mixtures. The control mixture (0 % CR) had a flow value of 3.566 mm. With 1 % CR, flow remained within an acceptable range (3.1–4.2 mm), preserving integrity and flexibility. Increasing CR to 3% and 5% raised flow values, peaking at 8 mm for 5 % CR (4.75 mm gradation), indicating excessive CR softens the mixture and increases deformation risk.

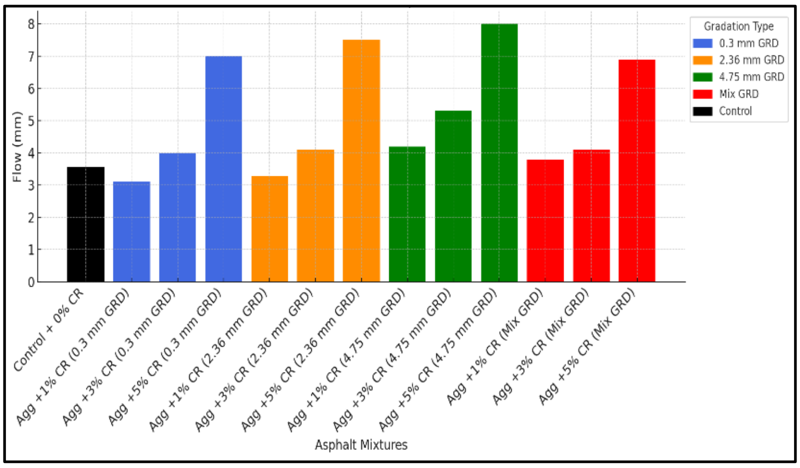

Fig. 5: Flow values of various asphalt mixtures.

Effect of gradation on flow

The flow properties varied depending on the CR gradation used:

• Fine gradation (0.3 mm GRD): Flow increased from 3.1 mm at 1 % CR to 7 mm at 5 % CR, indicating a loss of stability at higher CR content.

• Medium gradation (2.36 mm GRD): Flow values followed a similar pattern, increasing from 3.28 mm at 1 % CR to 7.5 mm at 5 % CR.

• Coarse gradation (4.75 mm GRD): Flow values were higher than those observed in fine and medium gradations, reaching 8 mm at 5 % CR.

• Mixed gradation (4.75 + 2.36 + 0.3 mm GRD): Flow values were well-controlled, with 3.8 mm at 1 % CR, 4.1 mm at 3 % CR, and 6.9 mm at 5 % CR. This suggests that a balanced combination of different particle sizes helps maintain mixture resistance to deformation.

3. Effect of CR content on air voids

Air voids in asphalt mixtures impact durability, permeability, and performance. Results show a strong link between CR content and air voids Fig. 6. The control mixture (0% CR) had 4.092 % air voids as a benchmark. With 1 % CR, air voids stayed within an acceptable range (3.702 %-4.52 %), ensuring compaction and durability. Increasing CR to 3 % and 5 % raised air voids, peaking at 8.792 % for 5 % CR (4.75 mm gradation), indicating reduced compatibility and higher porosity.

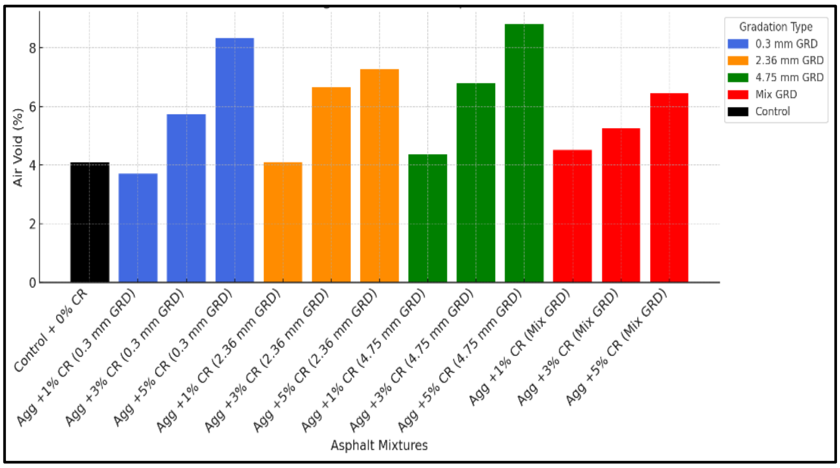

Fig 6: Air voids with various asphalt mixtures.

Effect of gradation on air voids

The variation in air voids across different gradations indicates the influence of particle size distribution:

• Fine gradation (0.3 mm GRD): Air voids increased from 3.702 % at 1 % CR to 8.335 % at 5 % CR, suggesting that higher CR content results in reduced compaction.

• Medium gradation (2.36 mm GRD): Air voids increased from 4.104 % at 1 % CR to 7.277% at 5 % CR, showing a similar trend.

• Coarse gradation (4.75 mm GRD): Air voids were generally higher, increasing from 4.366 % at 1 % CR to 8.792 % at 5 % CR, indicating excessive voids at higher CR content.

• Mixed gradation (4.75 + 2.36 + 0.3 mm GRD): This gradation exhibited a more balanced air void distribution, with values ranging from 4.52 % at 1 % CR to 6.445 % at 5 % CR, suggesting improved compaction and better aggregate packing.

4.Effect of CR content on VMA

Voids in Mineral Aggregate (VMA) indicate the void volume between aggregates filled with binder and air. Results Fig. 7 show VMA varies with CR content. The control mixture (0 % CR) had a VMA of 15.81 %. Adding 1 % CR increased VMA across all gradations, enhancing asphalt absorption and flexibility. Higher CR content (3 % and 5 %) further raised VMA, peaking at 23.846 % for 5 % CR (mixed gradation), suggesting excessive CR increases porosity, potentially reducing durability and cohesion.

Effect of gradation on VMA

Gradation significantly influenced the VMA values:

• Fine gradation (0.3 mm GRD): VMA increased from 18.129 % at 1% CR to 20.742 % at 5 % CR, showing a steady rise.

• Medium gradation (2.36 mm GRD): VMA fluctuated slightly but remained high, with a peak of 19.859 % at 1% CR and 19.156 % at 5% CR.

• Coarse gradation (4.75 mm GRD): The highest VMA values were observed at 23.191% at 1% CR, followed by 20.476% at 5% CR, indicating a looser aggregate structure.

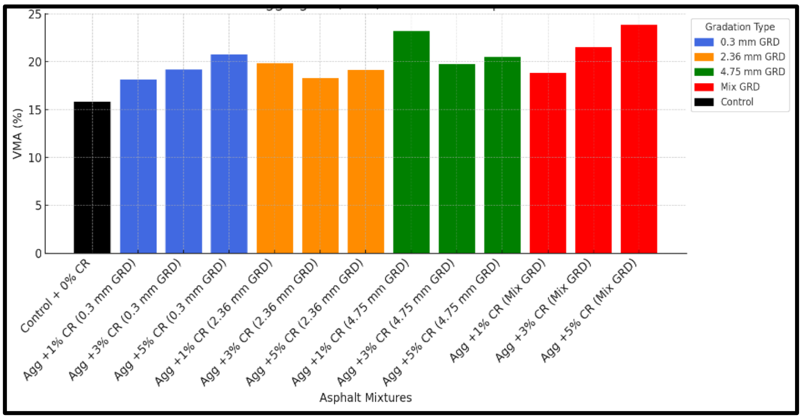

Fig. 8: VMA of various asphalt mixtures.

• Mixed gradation (4.75 + 2.36 + 0.3 mm GRD): This gradation exhibited a progressive increase, with values ranging from 18.824 % at 1 % CR to 23.846 % at 5 % CR, confirming that combining different particle sizes enhances asphalt absorption.

5.Effect of CR content on VFA

Voids Filled with Asphalt (VFA) indicate the portion of VMA filled with binder, affecting mixture density and permeability Fig. 8. The control mixture (0 % CR) had a VFA of 72.965 %. Adding 1 % CR increased VFA, peaking at 81.175 % for 4.75 mm gradation, enhancing absorption and durability. With 3% and 5% CR, VFA generally declined, reaching a low of 57.065% at 5% CR (4.75 mm gradation), indicating excessive air voids and reduced binder effectiveness.

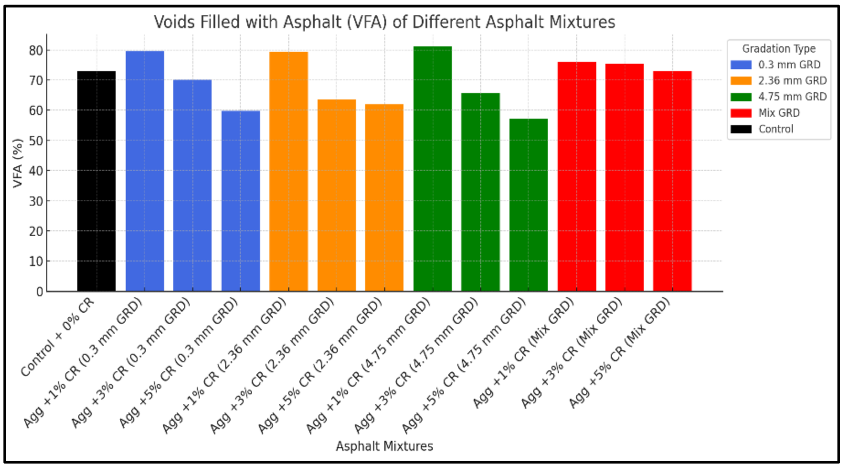

Fig. 8: Voids Filled with Asphalt (VFA) of different asphalt mixture.

Effect of gradation on VFA

Different gradations had distinct effects on the ability of asphalt to fill aggregate voids:

• Fine gradation (0.3 mm GRD): VFA values ranged from 79.58 % at 1% CR to 59.815% at 5% CR, indicating that excessive CR leads to a more porous structure.

• Medium gradation (2.36 mm GRD): The trend was similar, with values declining from 79.333 % at 1 % CR to 62.01 % at 5 % CR.

• Coarse gradation (4.75 mm GRD): The highest VFA was 81.175 % at 1 % CR, but it dropped significantly to 57.065 % at 5 % CR, suggesting that excessive CR compromises asphalt film coverage.

• Mixed gradation (4.75 + 2.36 + 0.3 mm GRD): This gradation exhibited more stable VFA values, with 75.99 % at 1 % CR and a moderate decline to 72.971 % at 5 % CR, indicating that a well-graded mixture better retains the asphalt binder.

6. Effect of CR Content on Bulk Density

Bulk density, a key indicator of compactness in asphalt mix design, shows a decreasing trend with increasing CR content Fig. 9. The control mixture (0 % CR) had the highest bulk density at 2.3425 g/cm³. With 1 % CR, bulk density slightly decreased but remained relatively high (2.123–2.263 g/cm³). Higher CR content (3 % and 5 %) further reduced bulk density, reaching a low of 2.105 g/cm³ at 5% CR (mixed gradation), indicating increased voids and reduced compactness.

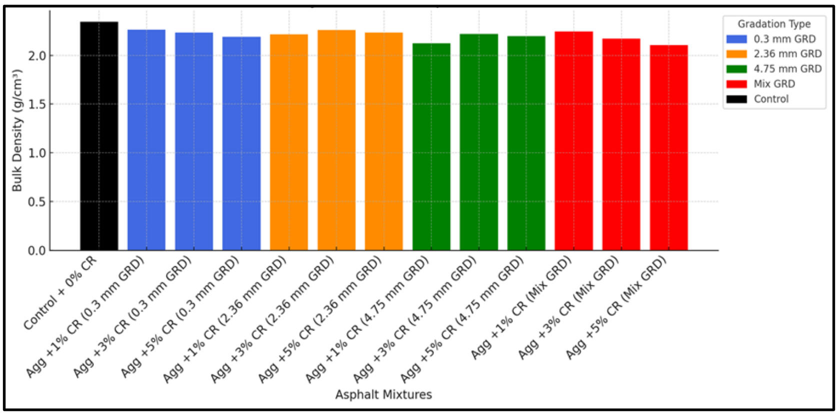

Fig 9: Bulk density of various asphalt mixtures.

Effect of gradation on bulk density

Different gradations exhibited varying bulk density trends:

• Fine gradation (0.3 mm GRD): Bulk density decreased from 2.263 g/cm³ at 1 % CR to 2.191 g/cm³ at 5 % CR, showing a steady reduction.

• Medium gradation (2.36 mm GRD): The values remained relatively stable, with the highest at 2.259 g/cm³ (1 % CR) and a drop to 2.235 g/cm³ (5 % CR).

• Coarse gradation (4.75 mm GRD): The density values were lower than in the fine and medium gradations, with 2.123 g/cm³ at 1 % CR and 2.198 g/cm³ at 5 % CR, indicating increased voids at higher CR content.

• Mixed gradation (4.75 + 2.36 + 0.3 mm GRD): This gradation exhibited a more balanced bulk density trend, with values decreasing from 2.244 g/cm³ at 1 % CR to 2.105 g/cm³ at 5 % CR, suggesting better overall compaction control.

3.2.2 Influence of gradation of CR on thermal conductivity

Thermal conductivity is a crucial property of asphalt mixtures, influencing their ability to dissipate heat and resist temperature-related distress. Fig. 10 illustrates the effect of crumb rubber (CR) content and different gradations on thermal conductivity compared to the reference mix. The results indicate a significant decrease in thermal conductivity with increasing CR content. The incorporation of crumb rubber led to increased air voids which would contribute to decreased thermal conductivity. Studies on rubberized T-beams confirmed better ductility performance with lower weight which indicates its potential use as a sustainable insulation additive [22] as shown in Table 6.

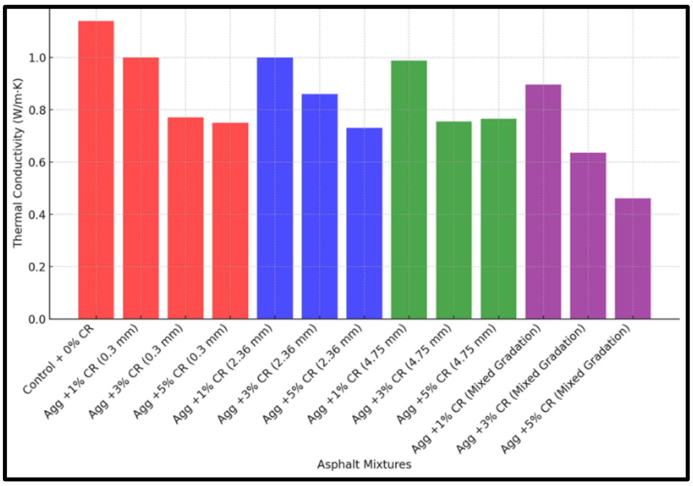

Fig. 10: Thermal conductivity of various asphalt mixtures with gradation categories.

• The control mixture (0 % CR) had the highest thermal conductivity at 1.1389 W/m.K, reflecting its higher density and compactness.

• As CR content increased, thermal conductivity decreased significantly. For example:

- 1 % CR (various gradations): Values ranged from 1.0 to 0.9878 W/m.K, showing a slight reduction.
- 3 % CR (various gradations): Thermal conductivity further dropped to 0.77 to 0.7553 W/m.K.
- 5 % CR (various gradations): The lowest thermal conductivity was recorded, with values ranging from 0.75 to 0.4619 W/m.K.

This trend suggests that CR-modified asphalt mixtures have improved insulation properties due to the lower thermal conductivity of rubber particles compared to conventional aggregates.

Effect of gradation on thermal conductivity:

The thermal conductivity values varied based on gradation:

• Fine gradation (0.3 mm GRD), thermal conductivity decreased with rising CR content, from 1.0 W/m·K at 1 % CR to 0.75 W/m·K at 5 % CR Fig. 11. This decline highlights rubber's insulating effect, reducing heat transfer in asphalt composites. Since thermal conductivity is inversely related to density, CR-modified asphalt is expected to have a lower k-value. Similarly, autoclaved aerated concrete panels (AACP) with densities of 400-800 kg/m³ have k-values of 0.08-0.19 W/m·K [19, 20]. Studies confirm that adding CR enhances thermal and acoustic insulation in concrete and asphalt, reducing heat transmission.

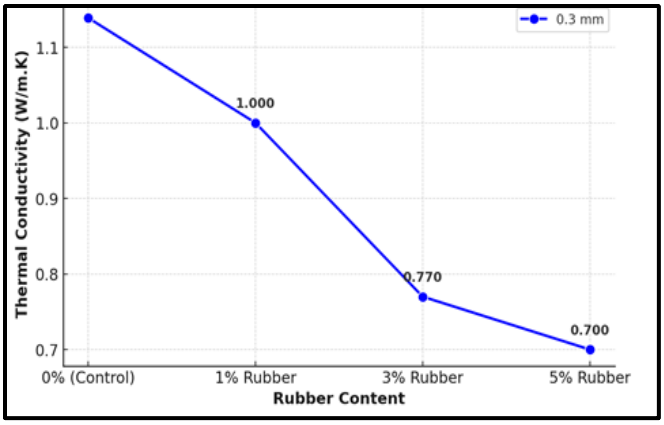

Fig. 11: Thermal conductivity vs. CR content for 0.3 mm grad.

• Medium gradation (2.36 mm GRD): Conductivity declined from 1.0 W/m.K at 1 % CR to 0.73 W/m.K at 5 % CR, indicating better insulation as CR content increased. As shown on Fig. 12.

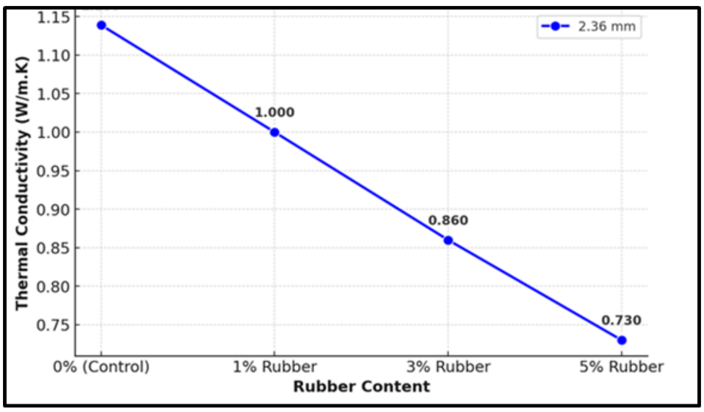

Fig. 12: Thermal conductivity vs. CR content for 2.36 mm grad.

• Coarse gradation (4.75 mm GRD): A notable drop was observed, with thermal conductivity reaching 0.6361 W/m.K at 5 % CR as shown in Fig.13.

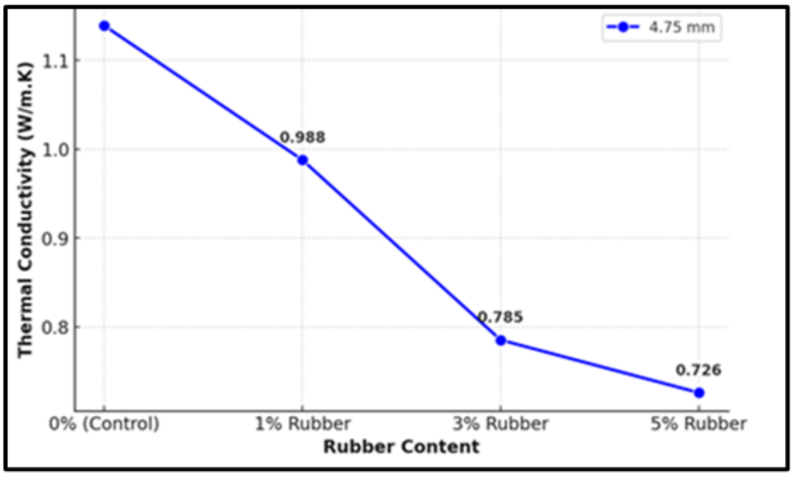

Fig. 13. Thermal conductivity vs. CR content for 4.75 mm grad.

• Mixed gradation (4.75 + 2.36 + 0.3 mm GRD): The lowest thermal conductivity values were recorded at higher CR content, with 0.4619 W/m.K at 5 % CR, suggesting superior thermal insulation as shown in Fig. 14.

4 Statistical analyses

4.1 Statistical methodology

To analyse the effect of crumb rubber (CR) content on mechanical and thermal properties of asphalt mixtures, the following statistical procedures were employed:

4.1.1 Data collection

Asphalt samples were prepared according to laboratory standards and measured for 0% (Control mixture), 1 %, 3 %, and 5 % CR.

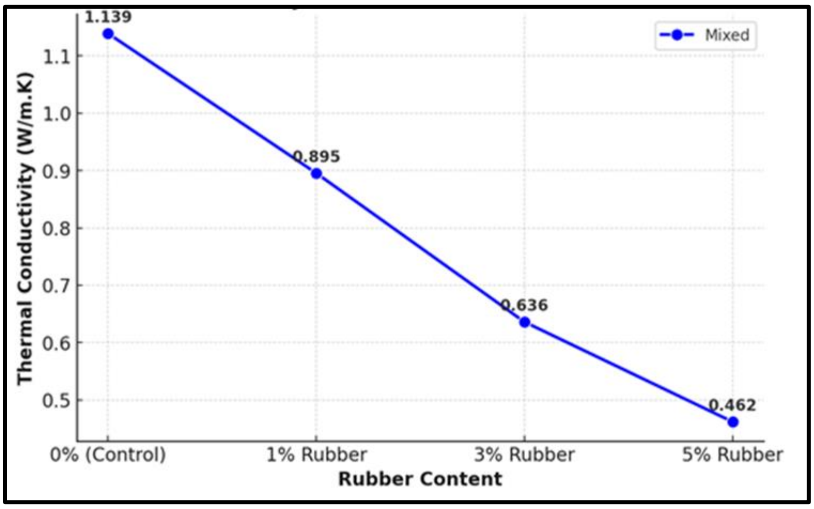

Fig. 14. Thermal conductivity vs. CR content for mix mm grad.

Three specimens were tested for accuracy at each CR content level, yielding 12 data sets per property.

4.1.2 ANOVA implementation

A one-way analysis of variance **(ANOVA)** was conducted using the following steps:

1) Data preparation: Organizing measured values for each property into a structured dataset.
2) Computing mean values: Calculating the mean for each CR content level.
3) Variance analysis: Determining the variance within and between groups using the formula: F=Between-group variance Within-group variance F = \ frac {\text {Between-group variance}} {\text {Within-group variance}}.
4) Significance Testing: Using P-values to assess statistical significance:
   - If P <0.05, the difference between groups is statistically significant.
   - If P> 0.05, no significant difference exists.

Table 1: ANOVA results for mechanical and Thermal Properties.

Property	F-Value	P-Value	Statistical significance
Stability [KN]	31.27	0.000043	Significant
Flow [mm]	37.76	0.00002	Significant
Air voids [%]	15.99	0.000597	Significant
Thermal conductivity [W/m·K]	9.14	0.00428	Significant

Findings:

• All P-values are below 0.05, confirming that variations in CR content significantly impact the mechanical and thermal properties of asphalt mixtures.

4.1.3 Tukey HSD test implementation

Following the identification of statistically significant differences via ANOVA, Tukey's Honest Significant Difference (HSD) test was performed to compare individual CR content levels.

1. **Computing pairwise differences**: Differences in mean values were calculated for each property across CR levels.
2. **Assessing statistical significance**: A critical Q-value was used to determine significant differences.
3. **Identifying significant pairs**: Pairs exhibiting substantial differences were highlighted.

Table 2: Summary of Tukey HSD test results.

Property	Statistical significance
Stability [KN]	Increased at **1 % CR**, then significantly decreased at **3 % and 5 % CR**.
Flow [mm]	Flow increased significantly as **CR content increased**, especially at **3 % and 5 % CR**.
Air voids [%]	Air voids increased with higher **CR content**, confirming its effect on mixture porosity.
Thermal conductivity [W/m·K]	Significant reduction in thermal conductivity at **3 % and 5 % CR**.

4.2 Interpretation of results

The research findings demonstrated that crumb rubber (CR) percentages directly affect asphalt mixture mechanical performance alongside thermal conductivity measurements. Phenomenal changes in Marshall stability, flow, air voids and thermal conductivity result from CR content variations according to one-way analysis of variance (ANOVA) results which present p-values below 0.05. The data fluctuations indicate that additional elements may need consideration in addition to crumb rubber content.

Post-analytical investigation employed the Tukey's Honest Significant Difference (HSD) test for identifying statistical differences between CR levels. Specific concentrations of CR produced measurable statistical variations based on the results of the conducted test. The mixture stability increased markedly with 1 % CR addition while the higher 3 % and 5 % levels produced denser mixtures. The HSD test resulted in more accurate research results while showing which CR levels optimized mechanical properties and thermal resistance. The findings from this research enable forward progress in sustainable pavements development.

5. Conclusions

• Research findings show that the dry process addition of crumb rubber (CR) to asphalt materials significantly impacts thermal and mechanical properties of the mixtures. Thermal conductivity decreased by 59.4 % when adding 5 % CR using mixed gradation (4.75 + 2.36 + 0.3 mm) during the dry processing method compared to the untreated mixture. Asphalt materials with limited thermal conductivity maintain better insulation abilities which decreases the chances of heat-based asphalt degradation. The dry process at 1 % CR produced mixes with the highest Marshall stability value of 14.446 kN but higher CR contents increased air voids which degraded mechanical properties yet enhanced insulation capabilities.

• The implementation of CR-modified asphalt brings forward an environmentally friendly yet economical solution for road infrastructure construction especially in regions enduring excessive heat. A mix gradation ratio of 2 %–3 % CR content creates the most suitable combination between roadway strength and heat resistance. Environmentally sustainable tire recycling on a large scale happens through the dry process. Results from testing justify the usage of CR-modified mixtures for pavement engineering since they combine enhanced performance with sustainability goals.

6. Recommendations

1. Practical applications in road construction

• **High-traffic roads (highways, airports, urban roads):** Use **1 % CR with mixed gradation (4.75 + 2.36 + 0.3 mm)** for optimal stability and flexibility.

• **Hot climate regions:** Apply **3 %–5 % CR** to enhance thermal insulation and mitigate temperature-induced distress, with mechanical reinforcement to prevent deformation.

• **Cost-effective pavement design:** A **2 % CR content** balances mechanical strength and thermal performance, ensuring long-term durability.

2. CR gradation and content optimization

• **Mixed gradation (4.75 + 2.36 + 0.3 mm)** delivers superior strength and insulation, making it preferable over single-size CR applications.

• Further studies should refine **CR particle size distribution** to maximize performance while minimizing segregation and production challenges.

3. Enhancing durability and performance

• **Optimize compaction** at higher CR content (3 %–5 %) by adjusting temperature and pressure to counteract excessive air voids.

• **Explore binder additives** (e.g., polymers, warm mix asphalt) to improve CR compatibility and performance.

• Conduct **moisture susceptibility and freeze-thaw resistance tests** to evaluate long-term durability in wet and cold climates.

4. Environmental and economic benefits

• Promote **the dry process** as an eco-friendly alternative, with policy incentives for recycled materials in road construction.

• Conduct **cost-benefit analyses** to quantify lifecycle savings through reduced maintenance and extended pavement lifespan.

• Expand **waste tire recycling programs** to ensure a sustainable CR supply chain.

5. Future research directions

• **Monitor field performance** under varying climates, traffic loads, and aging effects to validate laboratory findings.

• Utilize **advanced techniques** (e.g., DSC, DMA) to study the thermal and viscoelastic behaviour of CR-modified asphalt.

• Investigate **CR with other sustainable modifiers** (e.g., bio-binders, plastic waste) for enhanced eco-friendly performance.

• Develop **numerical models and simulations** to predict long-term behaviour under different service conditions.

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