Research Article

Performance Evaluation of Porous Asphalt Mixtures Modified with Crumb Rubber

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Abstract

The objective of this study was to evaluate the mechanical and hydraulic behavior of porous asphalt containing crumb rubber (CR) as a dry-process replacement for the filler. Using 40–50 penetration-grade binders from Lanaz (Source A) in Erbil city and Phonix (Source B) in Slemani city, a constant asphalt content of 4.5%, and CR contents of 0%, 1.5%, 3%, and 4.5%, the mixtures were prepared. The laboratory program included falling-head permeability, Marshall stability and flow, volumetric analysis and indirect tensile strength at 25 and 60°C. With the CR content, the Marshall stability increased for both binders. Stability was 7.3 and 6.9 KN for sources A and B respectively at 4.5% CR compared with 5.4 and 3.5 kN for the controls. Nevertheless, the permeability of Source A decreased from approximately 0.41 to 0.11 cm/s, while Source B decreased from 0.50 to 0.08 cm/s.

Additionally, Marshall flow was approximately 5.0–5.1 mm at the highest dosage. Tensile strength at 60°C was increased by 35.3% and 69.1% at 4.5% CR, but tensile strength at 25°C was decreased by 11.4% and 17.4% for Sources A and B, respectively. This led to a reduction in the reported temperature-susceptibility index of about 25.8% and 34.1%. Overall, CR improved Marshall stability and high-temperature tensile strength while decreasing permeability and tensile strength at 25°C at the maximum dosage, altering the mechanical and hydraulic characteristics of porous asphalt.

Keywords: Porous asphalt; crumb rubber; permeability; Marshall stability; rutting; durability.

1. Introduction

Porous asphalt is a permeable pavement composition characterized by its interconnecting voids that facilitate the passage of water through the material. It is a friction layer added to a non-permeable pavement to increase lateral drainage and to improve the surface grip and visibility in bad weather. An aggregate composition must have enough porosity after compaction and during its service life to preserve this drainage capability. Hence, the mixture design should consider not only hydraulic efficiency but also the ability of the binder-aggregate framework to withstand stresses and prevent particle disintegration [1, 2].

The formulation of porous asphalt is greatly influenced by the balance between permeability and structural integrity. [3] revealed that aggregates with bigger vacancy ratios led to augmented porosity and permeability, while often exhibiting poorer indirect tensile strength and resistance to Cantabro abrasion. An additive that transforms the internal arrangement can consequently boost one reaction while hindering another. Measuring its performance merely by augmented strength or Marshall stability would disregard the drainage properties that characterize porous asphalt in contrast to traditional dense-graded mixtures.

Crumb rubber (CR) from used tires is a way to include recycled substance into asphalt mixes. It is reliant

upon how it is introduced. In wet processing rubber is added to the binder before the combination is manufactured, while in dry processing rubber is added straight to the mixture components. Researches on porous asphalt have shown either positive or negative impacts based on the rubber percentage, particle size and binder composition. In the work of Shirini and Imaninasab (2016), the wet-process modification improved the rutting resistance and reduced the permeability. Studies using the dry technique similarly reported changes in tensile behavior, water susceptibility, and drainage, but did not show a consistent improvement in all characteristics [4, 5].

These implications make a material-specific examination important. A dosage considered appropriate for a rubber-modified binder is not necessarily transferable to CR used as a dry-process filler substitute. Documented percentages may also correspond to different reference masses, because the research used different aggregate gradations, binder amounts and compaction procedures. Recent study on modified OGFC mixes suggests that a number of performance criteria should be considered together and not just accept a single mechanical outcome as an appropriate indicator of fitness [6, 7]. The critical question about the materials available is if CR leads to an improved measured mechanical response with sufficient drainage, and if this compromise is influenced by other binder sources.

This study investigates porous asphalt containing 0%, 1.5%, 3%, and 4.5% CR, which is injected using the dry method as a replacement for mineral filler. Two locally sourced binders with a penetration grade of 40–50, Lanaz and Phonix, are evaluated at a fixed asphalt content of 4.5%. The experimental strategy is similar to that of the previous two-binder fly-ash study [8], while researching a different additive and range of dose. Evaluation involves falling head permeability, Marshall stability and flow, mixture volumetrics, and indirect tensile strength at 25- and 60-degrees C. The purpose is to identify the dose and binder source trade-offs that impact drainage and mechanical response, and thereby justify the future selection of an acceptable CR content according to stated performance parameters.

2. Literature review

2.1 Hydraulic performance and aggregate structure

Hydraulic efficiency depends not only on the total air content in a compacted sample, but also on the void network that provides pathways for water transport. [1] evaluated many approaches for assessing the drainability of permeable friction courses and found water-accessible air gaps as a useful statistic. Their study shown that there are limitations to depending entirely on typical lab assessments to assure field drainage. This distinction is especially important when evaluating CR mixtures since a measured change in total air voids does not necessarily reflect a change in interconnected flow paths.

[3] tested ten aggregate gradations for permeability, draindown, tensile strength, Cantabro abrasion, and rutting. The overall void ratio is greater, the permeability and porosity are greater, and the tensile strength and abrasion resistance are lower. But the rutting reaction is not the same simple relation to porosity. Their findings underscore the need of controlling gradation and compaction when assessing additives. The present study shows that permeability, volumetric features and mechanical results in combination rather than a single attribute are more informative.

2.2 Crumb rubber introduced through the dry process

[4] examined three particle-size groups of CR with mass ratios of 10%, 15%, and 20% of bitumen. Fine rubber reduced the size of air spaces and permeability. At 25°C, the best quality rubber at the lowest

dosage improved the indirect tensile strength by 12%, but most of the other compounds decreased it. Moisture susceptibility was not generally increased with the addition of rubber. The results indicate that the reaction is dependent on particle size and dose and that a positive tensile result for one mixture should not be extrapolated to higher doses.

[5] researched the dry method of fine CR inclusion in porous asphalt using SBS-modified binder. Their test program included of tensile strength, stiffness, moisture sensitivity, permeability, Cantabro loss, draindown and creep. The rubberized composites showed better binder-aggregate adhesion, better control of draindown and better resistance to raveling, but lower vertical permeability and lower resistance to permanent deformation. This broad response is especially relevant to the evaluation of Marshall results, since an increased peak load capacity cannot be used to validate improved rutting resistance without an appropriate repeated-load evaluation. Because of the presence of SBS in the base binder of the present penetration grade binders, the results are not quantitatively applicable for them.

2.3 Wet-process and hybrid binder modification

[9] conducted a comparison of porous asphalt utilizing 10%, 15%, and 20% CR-modified binder with unmodified and SBS-modified mixes. Rubber enhanced resistance to rutting but diminished permeability, with the minimal rubber dosage yielding the most effective overall performance in their assessment. Supplementary rubber did not consistently enhance resilient modulus, skid resistance, or moisture resistance. The research endorses evaluation across several attributes; nevertheless, the dosage in the wet process cannot be directly compared to the filler-replacement % in the dry process.

[10] shown that the expansion and deterioration condition of CR influenced the efficacy of CR/SBS-modified porous-asphalt binders and mixtures. Completely swelled systems exhibited enhanced resistance to rutting, whereas heightened rubber degradation positively influenced several other responses, such as workability and low-temperature binder performance. Their results show that the condition of the modified material is not well characterized by the nominal rubber content alone. In research of the dry process, it is vital to document the mixing conditions and qualities of the rubber; one should not assume that the mechanisms identified for their hybrid binders are relevant to the present mixes without clear evidence.

2.4 Recent evidence and the role of binder formulation

[11] the production, compaction and service performance tests were utilized to examine eight OGFC formulations with binder additives and industrial fillers. CR, Portland cement and fly ash were able to boost durability and preserve good functional performance in that initiative. Assessment included testing for abrasion, wheel tracking, cracking and moisture-related issues. The large amount of data supports the potential use of CR, but also suggests that decisions on durability require evaluation beyond Marshall stability and temperature-sensitive tensile strength.

[12] Comparison of regular SBS, high-SBS, hybrid SBS-CR and epoxy-enhanced binders was done in OGFC mixtures. The hybrid SBS-CR blend demonstrated comparable permeability to the classic SBS control with increased wheel-tracking performance following moisture conditioning. The Cantabro performance, aged, was equal to the control, whereas the high-SBS and 50% epoxy systems showed more significant improvements in this respect. This result differs from the permeability reductions reported in many previous CR studies. All in all, the evidence indicates that a drainage penalty is not an inherent outcome

of every rubber-containing recipe; it is dependent on the overall recipe mix and the method of modification.

2.5 Regional context and contribution of the present study

[8] The Lanaz and Phonix binders were used to study the possibility of using fly ash as a substitute filler. The results suggested that the additions might improve Marshall stability, reduce permeability and modify volumetric properties. The research gives a relevant spatial and experimental comparison. However, one cannot assume that a mineral addition and CR produce the same tensile or thermal effects. Rubber is used in place of fly ash and requires a new examination of quantifiable features instead of the dosage which was favored previously.

The literature indicates good experience with rubberized porous asphalt however the proper CR content for the particular binder sources and dry-process combination used in this investigation was not determined. The importance of this finding is the direct comparison of two local binders in a homogeneous CR dose range and experimental setting. It examines if the optimum Marshall stability dose maintains permeability and tensile strength at both temperature conditions. This strategy resolves a practical mixture-selection dilemma while maintaining that conclusions are limited to the scope of the experiments performed. The aspects of long-term durability, moisture resistance, and field rutting performance are independent inquiries that demand thorough investigation [13].

3. Materials and Methods

3.1 Materials

In this investigation, the following sections describe the various asphalt binder from the Kurdistan region-Iraq that were employed locally:

3.1.2 Asphalt binder

According to the data and findings of prior research [14], the performance of open-graded asphalt is significantly influenced by the asphalt binder [15, 16]. Two penetration-graded asphalt binder sources (40-50) were implemented in this investigation. The Lanaz refinery was acquired from Erbil city, while the Phoenix refinery was acquired from Slemani city. Table (1) illustrates the asphalt cement's physical attributes.

Table 1 : Physical characteristics of the asphalt binder sources (A and B)

Property	Unit	Source A*	Source B**	Spec.
Penetration (25°C, 0.1 mm)	0.1 mm	43	47	40–50
Ductility (5°C, cm)	cm	>150	>150	>100
Softening Point—Ring and Ball Test	°C	53	50	49–60
Viscosity at 135°C	—	0.448	0.437	—
Flash and Fire Point Test	°C	250	265	>230
Loss on Heating	%	0.30	0.42	—
Specific Gravity	kg/cm³	1.0604	1.0550	—

* Source A: Lanaz Refinery, Erbil.

** Source B: Phonix Refinery, Suleimani.
Note: The heating temperature for mixing is 163°C.

3.1.2 Sample preparation (Preparation of Mixtures)

Three compacted specimens were prepared for the additive content in accordance with [14]. which is the conventional Marshall Test method employed in this investigation. Specimens with identical gradations are manufactured for porous bitumen.

The aggregate (coarse and fine) and additive materials were proportioned to meet the final requirements gradation (Job-mix formula) for the mixtures. The total weight of materials was 1200g, as illustrated in tables 2. Aggregates were elevated to a temperature of 175 °C to 190 °C, while the asphalt binder was heated to a temperature of approximately 120 °C to 135 °C. Then, the heated aggregates were thoroughly mixed by hand until all aggregate particles were coated with asphalt cement and the mixture temperature reached approximately 160°C. The aggregates were then added the required amount of asphalt binder (4.5% by total mix weight) for all trials and additive contents. The mixture was promptly compacted with 75 blows (double side) in a Marshall mold. The specimen was extracted from the mold using a specimen extractor after 24 hours as shown in the Figure 1.

Table 2. Final Job-mix formula for filler-limestone (control point zero additives)

Sieve size (mm)	Retained percentage (%)	Weight (gm)
12.5 mm	0%	0
9.5 mm	32%	384
4.75 mm	40%	480
2.36 mm	13%	156
1.70 mm	3%	36
0.075 mm	2%	24
Filler- limestone (zero additives)	5.5%	66
Asphalt Content	4.5%	54
Total	100%	1200 gm



Figure 1. Sets of Marshall specimens

3.1.3 Aggregate

The coarse aggregate is pulverized and transported from the Salaye quarry in Erbil. Consisting of durable, hard, and robust components that are devoid of coherent coatings. The physical characteristics of the coarse aggregate are illustrated in Table 3.

Table 3. Physical Properties of Aggregate

Test	Test Value	Standard	Specification
Bulk Specific Gravity	2.652	ASTM C127-04	—
Apparent Specific Gravity	2.784	ASTM C127-04	—
Los Angeles Abrasion	22%	ASTM C131	≤ 40%
Impact Value	6%	ASTM D5874	≤ 30%
Water Absorption	1.75%	ASTM C127	≤ 3%

3.1.4 Crumb rubber (Additive) Replacing Filler

Porous asphalt mixtures were prepared by using crumb rubber (CR) as a partial substitution of standard mineral filler. The CR was made from recycled scrap tires and processed into a fine powder form for incorporation into the aggregate structure the final form of CR is illustrated in Figure 2. The dry process was adopted in this inquiry instead of the wet process in which the crumb rubber is directly mixed with the asphalt binder. The pre-determined amount of CR was added to the heated aggregates and stirred thoroughly for uniform dispersion before the asphalt binder was added. This approach allowed CR ions to be considered as components of the solid aggregate–filler system, and at the same time simplified the mixture creation procedure.

The inclusion of CR as a filler replacement was to improve the durability, resilience and flexibility of the porous asphalt mixture, as well as to promote the beneficial use of waste-tire materials. CR may influence the internal aggregate structure, binder absorption, air-void characteristics, and resistance to permanent deformation and cracking as a result of its relatively low density and elastic characteristic. Consequently, the volumetric and mechanical performance of the CR-modified mixtures were assessed and contrasted with that of the conventional control mixture in order to ascertain the impact of filler replacement. The interconnected void structure necessary for adequate drainage was maintained with a focus on achieving sufficient stability and resistance to moisture-related damage.



Figure 2. Sample of prepared CR

3.1.5 The Selection of Gradation

The gradation of porous asphalt utilized in various countries and agencies is depicted in Figure 3, with varying degrees of gradation. Occasionally, it is feasible to achieve discrepancies of approximately 5% in the vacancies in the total mix VTM for two gradation conditions that are comparable [15, 16]. Table 4 illustrated the aggregates' physical attributes. The selection of aggregate gradation was determined by conducting over 40 trials that were compared to the gradations of NAPA and other countries, as illustrated in Table 4.

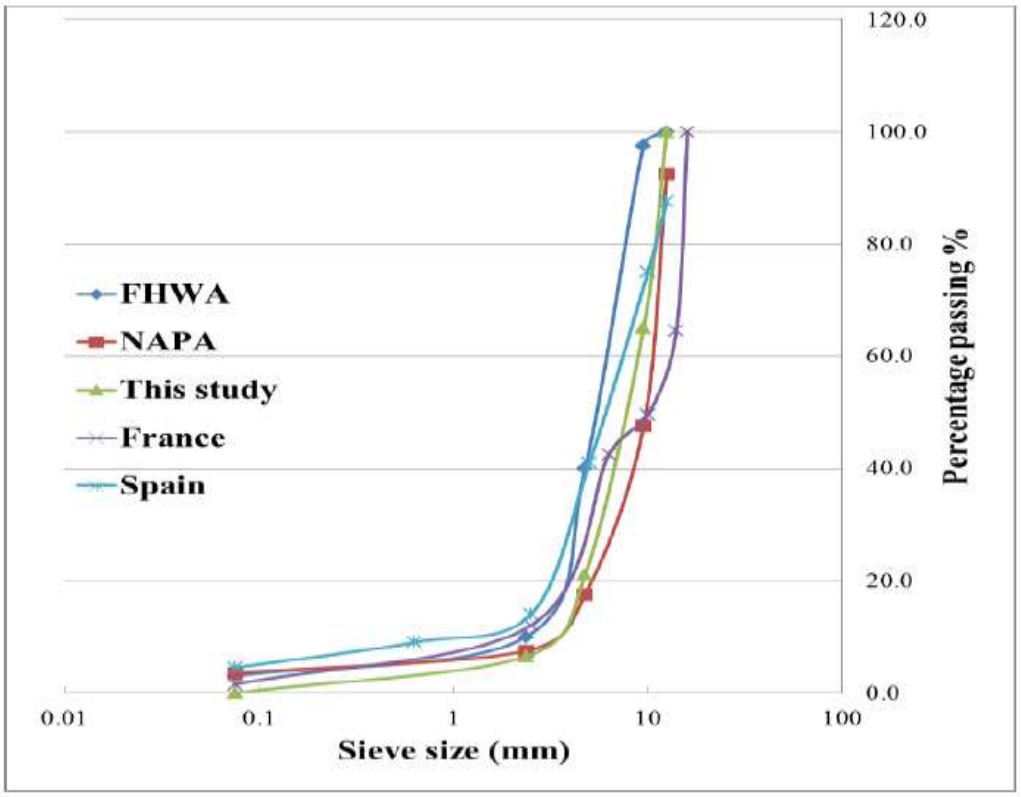


Figure 3. Aggregate gradations for porous asphalt mixtures between some countries and agencies

Table 4. Aggregate gradation evaluated in this study

sieve size (mm)	% passing
12.5	100
9.5	65
4.75	21
2.36	6
1.7	3
0.075	0

3.2 The Porous Asphalt Study Testing Program (Study Tests)

The optimal binder content is typically determined by the asphalt content range of 3.5 to 6.5% in the gradation [17]. More than 40 trials were conducted in this study to optimize the results of bitumen content and aggregate gradation. The entire testing program was conducted on specimens that were prepared with a 4.5% asphalt binder content. The following is the schedule for the preparation of the bituminous concrete mixture:

1. Choosing appropriate aggregate gradation.
2. Preparation of optimize asphalt concrete mixtures with asphalt content of 4.5%.
3. The preparation of asphalt concrete mixtures, with a content of 4.5 percent asphalt and CR consisting of 1.5, 3, and 4.5 percent of the total weight of filler displaced by CR.
4. Using the falling head permeability test, prepare three samples for each of the twenty-four cases in order to estimate the permeability efficiency (K value).
5. Preparation of three groups of Marshall Specimens. In each of the groups, there were three samples that were used for the Marshall Stability-flow test. The CR additive was used at 1.5, 3, and 4.5 % for each of the binder sources.
6. The preparation of two groups of Marshall specimens for the purpose of analyzing the impact of cracking at low temperatures and applying an indirect tensile test to the samples. At two distinct temperatures, namely 25 and 60 degrees Celsius, three specimens were prepared for each case, resulting in a total of forty-eight samples being prepared.

3.2.1 Permeability Test

The falling head method, which had been utilized in the past for the purpose of determining the permeability coefficient of porous asphalt mixes [3, 18], was utilized in order to measure the permeability of each and every specimen.

To begin the process of preparing a sample, the first thing that was done was to wrap the specimen in plastic wrap around the sides. This was done in order to ensure that the water would depart the specimen at the bottom rather than through the outermost part of the specimen. Following that, a strip of transparent tape was positioned along the top of the specimen and then folded over with the sticky side facing outward. This was done to ensure that water would not be able to pass between the specimen and the standpipe once the specimen was placed within the standpipe. In light of this, the specimen was inserted into the standpipe in the manner seen in Figures 4, and 5, and plumber's putty was added to the perimeter of the tape in order to prevent any water from escaping between the standpipe and the specimen [19].

In addition to the permeameter arrangement being leveled, the water exit was situated at the same elevation as the top of the specimen. The specimen was initially soaked with water by filling the output pipe until it was completely saturated. This was done after the specimen had been secured in the standpipe. According to Lyons and Putman (2013), the standpipe was then filled with water to a level that was approximately 300 millimeters above the top of the specimen. After that, the valve that was located at the bottom of the specimen was opened so that the water could flow through the specimen.

Using a stopwatch, the amount of time that was required for water to descend from a level that was 200 millimeters above the specimen (h1) to a level that was 50 millimeters above the specimen (h2) was

recorded and repeated four times for each specimen. The permeability of each Marshall sample was then determined by using Equation (1), where A is the cross-sectional area of the specimen in centimeters, an is the cross-sectional area of the stand pipe, and L is the height of the specimen. The average time, "t," was then used to determine the permeability of each Marshall sample.

$$\text{Permeability (K value)} \qquad K = \frac{aL}{At}\ln\left(\frac{h1}{h2}\right) \qquad [1]$$

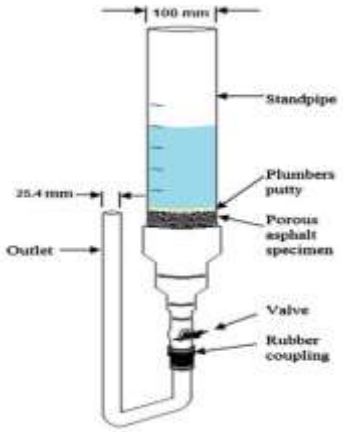


Figure 4. Illustration of the permeability test schematic (fallen head procedure) (Lyons & Putman 2013)



Figure 5. Permeability falling head test

3.2.2 Resistance to Plastic Flow of Asphaltic Mixtures (Marshall Method)

The Marshall apparatus was employed to measure the resistance to phasic flow of cylindrical specimens of asphalt paving mixture deposited on the lateral surface using the ASTM, D-1559 method. The prepared mixture is placed in a preheated mold that is (4) in. (101.6mm) in diameter and (3) in. (76.2 mm) in height.

The mold is compacted with 75 blows per side using a hammer with a sliding weight of 10 Lb. (4.536 Kg) and a free fall of 18 in. (457.2 mm) on the top and bottom of each specimen. This is followed by a 24-hour period of cooling at ambient temperature for the specimens.
The Marshall Stability and flow tests were carried out on every specimen in accordance with the procedure outlined in ASTM, D-1559. The specimen is immersed in a water bath at a temperature of sixty degrees Celsius for thirty to forty minutes. After that, it is subjected to compression on the lateral surface at a rate of two inches per minute (or fifty-eight millimeters per minute) until the failure point is achieved. The findings of the preparation of three specimens for each percentage of CR for two different binder sources are provided, with the averages being reported.

3.2.3 Resistance to Low-Temperature Cracking & Temp Susceptibility of Asphalt Mixture
This objective was accomplished by the utilization of the ASTM D-4123 method, which is a technique that determines the indirect tensile strength of asphalt concrete mixture. Following the preparation of the specimens in accordance with ASTM-D-1559, they were allowed to cool at room temperature for a period of twenty-four hours. Following this, they were immersed in a water bath at the precise test temperature for fifteen minutes before to the testing. Following the placement of the loading strips on the specimens, the specimens were subjected to an indirect tensile strength test at a rate of 2 inches per minute (50.8 millimeters per minute) until the maximum load resistance was recorded. A total of three specimens were made for each mix combination, and the findings were obtained and reported on average. An examination temperature of 25 degrees Celsius was acquired for the purpose of cracking at low temperatures. For the purpose of determining the degree or value of temperature susceptibility, a different test temperature of sixty degrees Celsius was observed; the outcome of this experiment is presented in Table 5.
The tensile strength St was calculated as follows:

$$St = \frac{2Pulti.}{\pi\, tD} \quad (Kg/cm2) \qquad [2]$$

Where Pulti. =Ultimate applied load (Kg); t=thickness of the specimen (cm); D=diameter of the specimen (cm), The temperature susceptibility T.S. was determined as:

$$T.S = \frac{STi - STj}{j - i} \qquad \left(\frac{Kg/cm2}{^{\circ}C}\right) \qquad [3]$$

Where STi= Tensile strength at (i ˚C) temperature, in this work i= 25 ˚C; STj= Tensile strength at (j ˚C) temperature, in this work j= 60 ˚C

3. Result and Discussion

3.1 Permeability

The permeability reaction to crumb rubber (CR) was shown to be dependent on the binder source at the lowest addition level, as demonstrated in Figure 6. However, the permeability response was lowered for both sources when the CR concentration was increased. According to the approximate values that were read from the figure, the coefficient of permeability for Source A (Lanaz) increased from 0.41 cm/s in the control mixture to 0.45 cm/s at 1.5% CR. After that, it decreased to 0.23 cm/s at 3% CR and 0.11 cm/s at 4.5% CR, respectively. With each subsequent addition of CR, Source B (Phonix) demonstrated a steady decline in velocity, going from roughly 0.50 cm/s in the control to 0.27, 0.16, and 0.08 cm/s when the CR was added. Consequently, the highest dosage resulted in the lowest permeability for both of the binders considered. Despite the fact that the initial increase for Source A demonstrates that total void content alone does not explain water transport, this overall drop occurs concurrently with the decrease in total air voids. It is also possible that variations in pore connectivity and the size of flow channels are contributing factors. Because of this, the findings indicate that there is a drainage penalty at greater CR contents, which is something that needs to be taken into consideration with any improvement in mechanical performance.

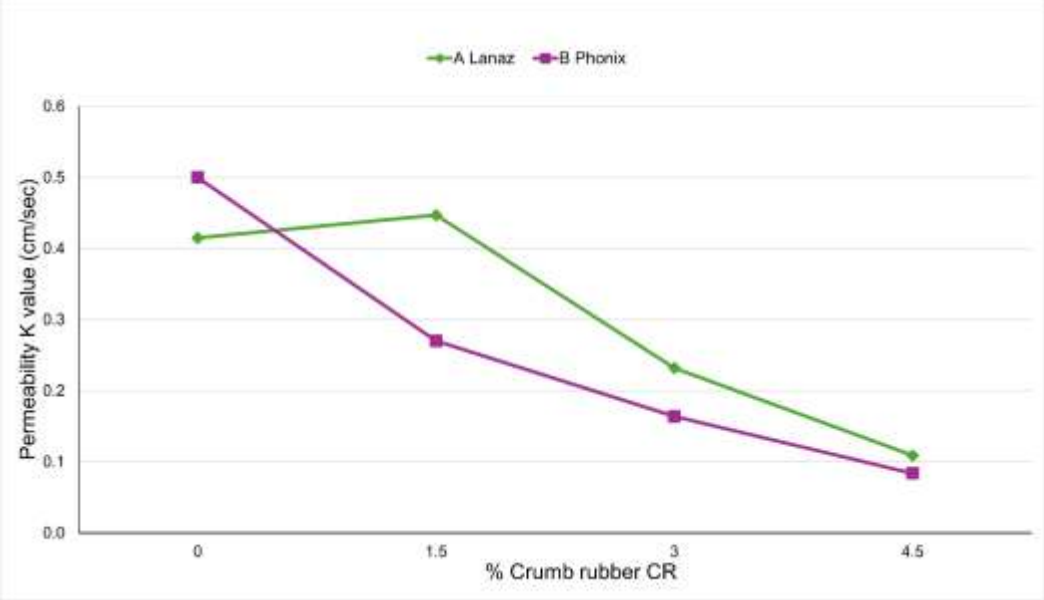


Figure 6. Percentage of Crumb rubber versus Permeability value (K)

3.2 Indirect Tensile Strength and Moisture Susceptibility (Indirect tensile strength Method)

Figure 7 demonstrates how CR concentration affects the temperature-susceptibility index, which is computed as the difference in tensile strengths at 25 and 60°C divided by the 35°C temperature span. Initially, Source A ascended from 0.458 to 0.478 (kg/cm²)/°C, before falling to 0.463 at 3% CR and 0.340 at 4.5% CR. Source B experienced a steady decline from 0.469 to 0.461, 0.340, and 0.309 (kg/cm²)/°C. As per the indicated indices, the decreases at 4.5% CR in relation to the respective controls were about 25.8% for Source A and 34.1% for Source B. Thus, the peak CR dosage led to a lesser absolute reduction in tensile strength per degree of temperature elevation for both binders. This indicator relies on the strength at

each test temperature: a lower number can occur due to heightened strength at 60°C, decreased strength at 25°C, or both factors. Thus, the reduction ought to be considered with the individual strength values in Table 5, instead than being viewed as an indication of superior performance at every temperature.

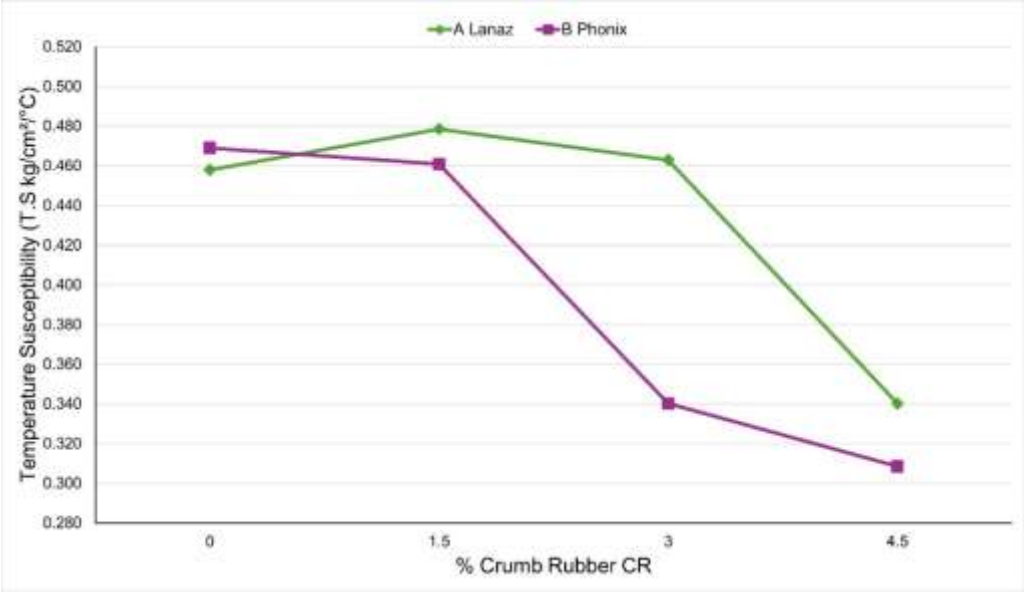


Figure 7. Crumb Rubber content versus Temperature susceptibility

Table 5. Effect of Crumb Rubber as additive using two sources of binder on indirect tensile strength test, according ASTM (D4123)

additive	%	Source (A) Lanaz			Source (B) Phonix		
		ST j=60 °C (Kg/cm²)	ST i=25 °C (Kg/cm²)	T.S (A) (Kg/cm²)/°C	ST j=60 °C (Kg/cm²)	ST i=25 °C (Kg/cm²)	T.S (B) (Kg/cm²)/°C
Crumb Rubber	0%	4.947	20.994	0.458	3.195	19.625	0.469
	1.5%	4.817	21.564	0.478	3.724	19.853	0.461
	3%	5.477	21.678	0.463	4.637	16.544	0.340
	4.5%	6.691	18.598	0.340	5.404	16.202	0.309

Various tensile-strength responses are illustrated in Table 4 at temperatures of 25°C and 60°C. The control's Source A increased from 20.994 kg/cm² to a maximum of 21.678 kg/cm² at 3% CR at 25°C, and then decreased to 18.598 kg/cm² at 4.5% CR. At 3% and 4.5% CR, Source B exhibited a slight initial increase

from 19.625 to 19.853 kg/cm², which was subsequently followed by decreases to 16.544 and 16.202 kg/cm². Source A began with a modest decrease from 4.947 to 4.817 kg/cm² at 60°C, which was subsequently followed by increases to 5.477 and 6.691 kg/cm². Source B experienced a continuous increase from 3.195 to 5.404 kg/cm². In comparison to the controls, the strength of Sources A and B was increased by approximately 35.3% and 69.1% at 60°C, respectively, when 4.5% CR was applied. However, the strength was reduced by 11.4% and 17.4% at 25°C. Therefore, the lower temperature-susceptibility indices at this dosage indicate a stronger high-temperature response and a weaker response at 25°C. These measurements delineate temperature-dependent tensile strength; however, they do not establish moisture resistance, which necessitates a distinct comparison of moisture-conditioned and unconditioned specimens at a shared test temperature.

3.3 Marshall Stability and Flow

3.3.1 Stability

The Marshall stability of both binder sources increased as the CR content increased, as illustrated in Figure 8. Source A's approximate stability values were 5.4, 5.8, 6.1, and 7.3 kN at 0%, 1.5%, 3%, and 4.5% CR, respectively. Approximately 3.5, 4.1, 5.1, and 6.9 kN were the corresponding values for Source B. The difference between the sources narrowed at the highest dosage, despite the fact that Source A maintained the higher stability throughout the investigated range. The increases at 4.5% CR were approximately 35% for Source A and 97% for Source B in comparison to the controls, as indicated by the plotted values. These results show that the peak load capacity increases with increasing CR content under the conditions of the Marshall test. The response may depend on the changes in mixture void structure that accompany them; however, the present results do not identify the underlying mechanism. The lowest permeability was observed for 4.5 % CR although it showed the highest measured stability. Thus, maximum stability is not the only factor to determine the optimal CR content for porous asphalt.

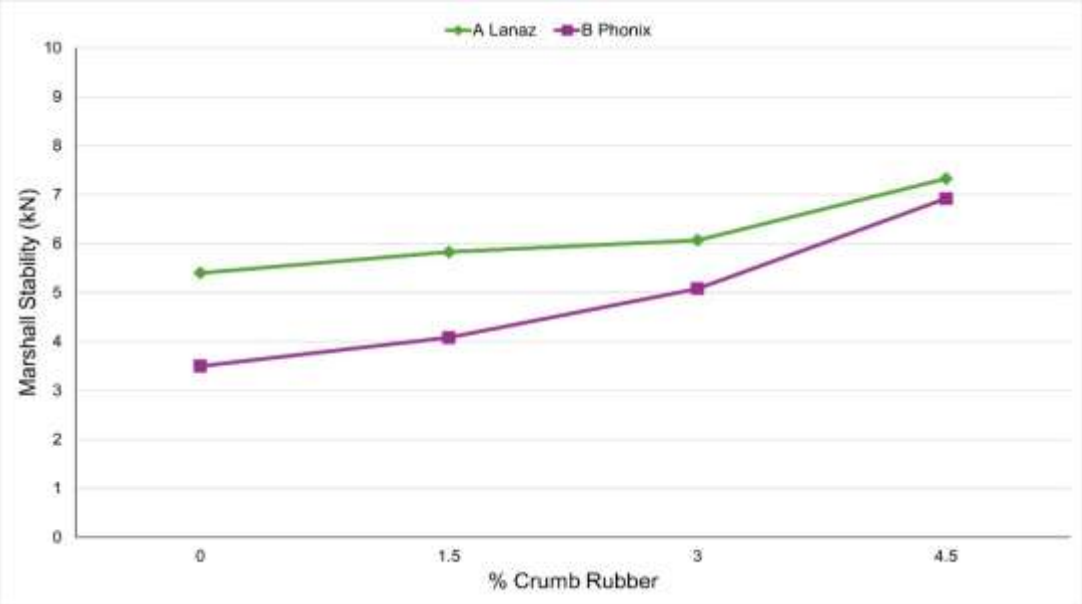


Figure 8. Marshall Stability versus % Crumb rubber

3.3.2 Flow

The Marshall flow of Source A is shown in Figure 9. A steady increase in the Marshall flow was observed from approximately 3.3 mm in the control mixture to 3.5, 4.1, and 5.0 mm with the addition of CR. Source B had a different initial response, the flow rate ranged from around 4.6 mm to 4 mm at 1.5% CR and then increased to around 4.4 mm at 3% CR and 5.1 mm at 4.5% CR. Although the difference between sources decreased with increasing CR content, Source B was the higher flow at each dosage. The simultaneous increase in flow and stability at the highest dosage indicates that the mixtures experienced a higher peak load with a larger amount of deformation at that load. A more deformable mixture response is compatible with higher flow but does not necessarily imply better elastic recovery or resistance to permanent deformation. Consequently, the flow and stability results need to be evaluated together, and repeated-load testing needs to be conducted before any conclusions can be drawn about the rutting performance.

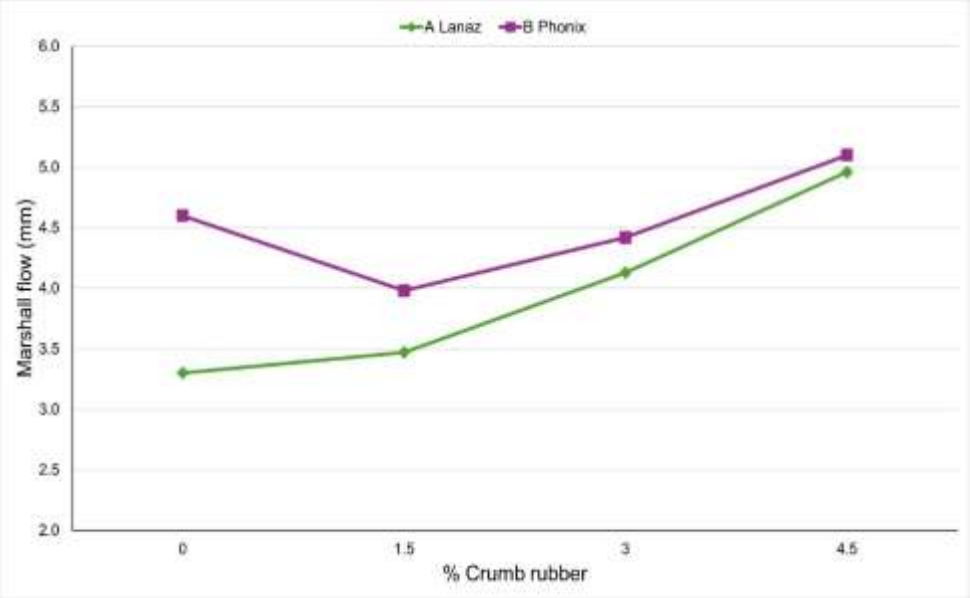


Figure 9. Marshall Flow versus % Crumb Rubber

3.4 Volumetric Calculation

3.4.1 Total Void in Mixture (VTM)

As shown in Figure 10, the number of voids in the total mixture (VTM) significantly decreased with the increase of CR content. The source assignments shown in the figure reveal that Source A decreased from ~20.4% in the control to 16.2%, 13.0%, and 9.2% with the addition of successive CRs. Source B decreased in proportion from about 19.4% to 15.6%, 13.9% and 10.4% respectively. Maximum reduction in air-void volume was observed at 4.5% CR for both sources. This decrease is consistent with the lower permeability obtained at the higher concentrations, showing that the modified mixtures left less space for water to move. However, VTM includes all air voids and does not differentiate between connected pores and

isolated voids, which explains why permeability does not always vary directly with VTM variations. The results emphasize the need to balance the large decrease in the open structure that is required for drainage with the increase in Marshall stability. A lower VTM should not be assumed to improve the performance of porous-asphalt.

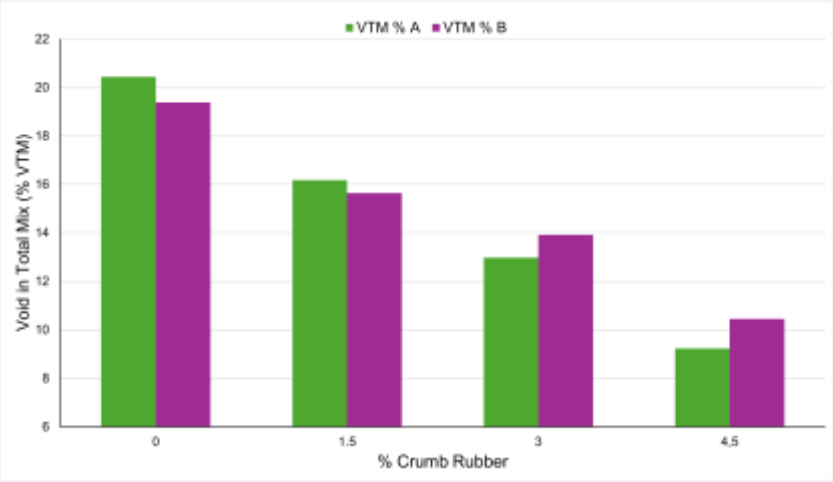


Figure 10. Void in Total Mix VTM versus % Crumb Rubber

3.4.2 Void in Mineral Aggregate (VMA)

Figure 11 shows that the voids in mineral aggregate (VMA) decreased with the increase of CR content for both binder sources. The values for Source A approximated a decreasing trend with each addition from 25.6% in the control mixture to 19.5%, 18.0% and 15.8%. Source B decreased from ~26.7% to 18.3%, 16.9% and 16.8%, with little further change between 3% and 4.5% CR. The most important reduction for both sources was the first one at 1.5% CR. The results showed in the plot indicate a reduction in the volume of air voids and effective binder available in the aggregate structure. The VTM and permeability results indicate that the less open mixture structure agrees with this observed trend with increasing CR content. However, VMA is a calculated volumetric property and its significance in a rubber-containing composition is dependent upon consistent treatment of constituent proportions and specific gravities. Therefore, the observed reduction should be evaluated together with the drainage performance and not used independently to decide an optimal dosage.

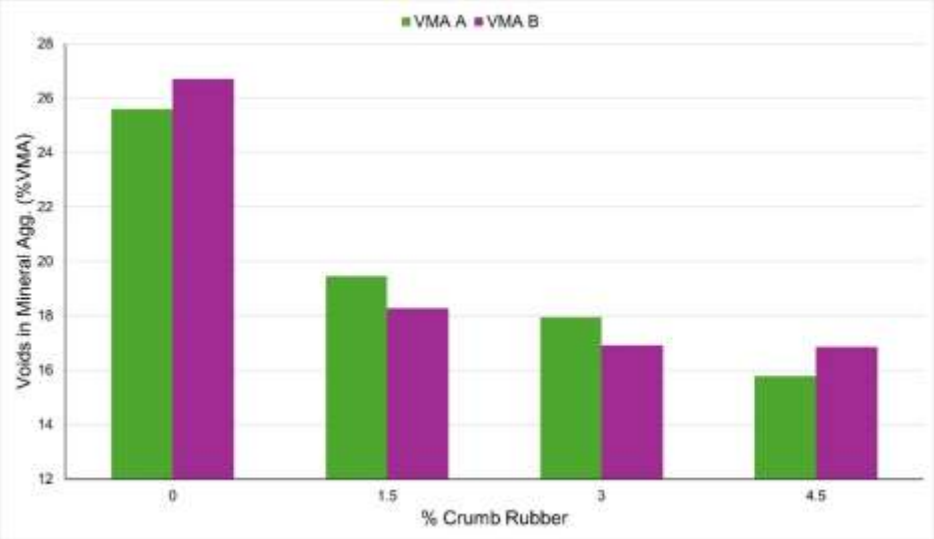


Figure 11. Voids in Mineral Agg. VMA versus % Crumb Rubber

3.4.3 Void Filled with Asphalt (VFA)

The VFA Figure 12 shows a non-monotonic response in relation to the CR content. For Source A, the percentage of voids filled with asphalt decreased from approximately 24.4% in the control to 17.8% at 1.5% CR. This was increased to 26.7% at 3% CR and 39.2% at 4.5% CR. Source B showed an overall pattern of decline consistently from about 23.6% to 16.4%, then an increase to 22.7% and 41.6%. Consequently, the greatest dosage resulted in the highest reported VFA for both binder sources, while the initial addition yielded the lowest values. The proportion of VMA occupied by effective asphalt is denoted by VFA, which is contingent upon the relationship between VMA and air-void content. An increase in VFA does not necessarily imply that additional binder was added. The competing mechanical and drainage responses are illustrated by the rise in CR at higher levels, which is accompanied by a decrease in permeability and an increase in stability. Rather than treating the largest VFA as the most favorable result, these trends endorse the joint consideration of permeability, VFA, VTM, and VMA when evaluating CR content.

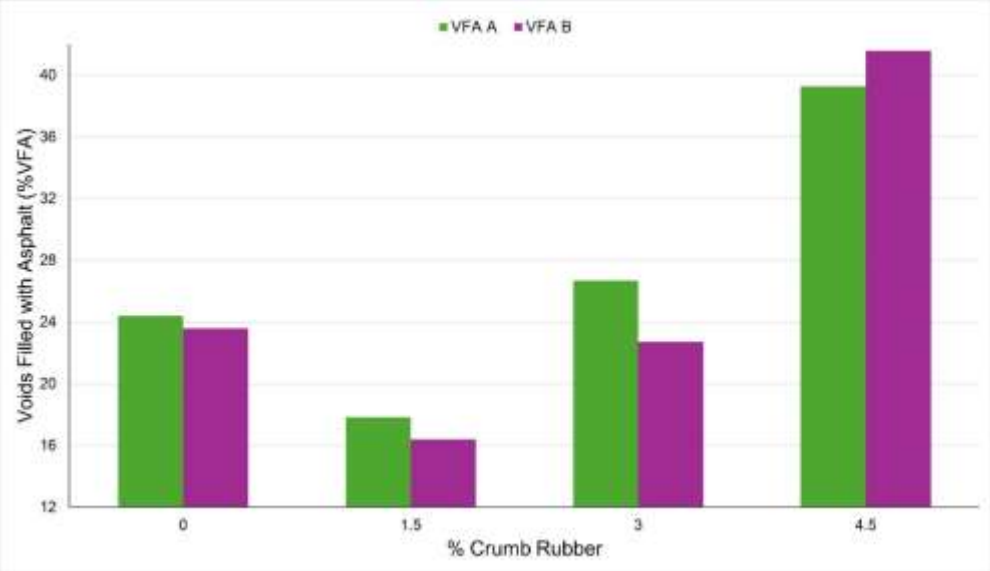


Figure 12. Void Filled with Asphalt (VFA) versus % Crumb Rubber

3.5 Comparison with previous studies

The decline in permeability with increased CR content is qualitatively consistent with the findings of [4], who investigated dry-process porous asphalt with three rubber size classifications and dosages of 10%, 15% and 20% by mass of bitumen. The investigation showed that fine rubber particles reduced air gaps and permeability, but tensile strength generally decreased, although the best rubber at minimum dosage increased strength at 25°C by 12%. In this analysis, Source A showed maximum strength at 3% CR, 25°C but both sources were inferior to their controls at 4.5% CR. Therefore, the consensus is not a single ideal but a dose dependent response and a possible decrease in tensile strength at higher levels. Differences in rubber size, binder amount, compaction methods and dose criteria prevent direct numerical comparison between the research.

[9] documented reduced permeability in rubberized porous asphalt with improved rutting resistance. They concluded that 10% CR dose was the most effective in their overall evaluation. The formulations were based on a wet-process rubber modified binder but in this study the CR was used through the dry method. The observed increase of Marshall stability and decrease of permeability are consistent with the general trade-off between mechanical properties and drainage; however, Marshall stability does not directly evaluate the resistance to rutting. The finding that additional rubber additions can negatively impact some characteristics also supports the necessity to evaluate several performance parameters, not just to select the maximum dosage. Due to the differences in the integration technique, dose parameters and mixture configuration, their ideal cannot be directly applied to the present mixes.

The investigation on fly ash conducted by [8], which set the experimental methodology, also observed the increase of Marshall stability as well as the decrease of permeability and air voids with the increase of the additive concentration. However, its tensile behavior depending on temperature was different from the present CR results. For both binder types, the tensile strength at 25°C increased at 8% fly ash concentration, with temperature susceptibility indices of 0.541 and 0.544 (kg/cm²)/°C. In the present

study, a 4.5% CR resulted in a reduction in strength at 25°C relative to the controls, with the indices reaching 0.340 and 0.309 (kg/cm^2)/°C. Thus, similar stability and drainage patterns may not lead to similar tensile properties. Analysis of the additives at a range of several dosages shows different trends and does not show superiority of one additive at a similar concentration.

5. Conclusions

Laboratory results indicate that replacing mineral filler with CR affected the load response and drainage of porous asphalt, with the magnitude and initial orientation of some modifications varying by binder source.

Conclusions below apply to the materials and test conditions investigated.

1. In both types of binders, stability of Marshall increased with increase of CR content. At 4.5% conversion rate the values obtained were 7.3 kN and 6.9 kN for Lanaz and Phonix, which were improvements of about 35% and 97% over the respective controls. Lanaz showed superior absolute stability, although Phonix had a larger relative improvement. The flow at this dosage increased to about 5.0 mm and 5.1 mm, demonstrating a better deformation at the maximum Marshall load.
2. The mechanical benefits seen at high levels of CR were associated with reduced drainage. For the 4.5% CR, the permeability dropped to about 0.11 cm/s for Lanaz and 0.08 cm/s for Phonix, compared to about 0.41 and 0.50 cm/s in the control group. The air voids and VMA decreased with increasing CR content while VFA decreased first and then increased. The trends suggest that hydraulic implications should be considered together with stability in the selection of CR content.
3. At the two testing temperatures, CR had different effects on tensile strength. At 4.5% CR, the strength at 60°C increased by 35.3% for Lanaz and 69.1% for Phonix, while the strength at 25°C decreased by 11.4% and 17.4%, respectively. The maximum strength was obtained at 3% CR for Lanaz and 1.5% CR for Phonix at 25°C, showing that the optimum dosage is determined by the particular reaction studied.
4. The temperature-susceptibility index decreased to 0.340 and 0.309 (kg/cm²)/°C at 4.5 % CR for Lanaz and Phonix, respectively. The drop indicates improved strength at 60°C and reduced strength at 25°C; it should not be interpreted as an improvement in tensile capabilities at all temperatures.
5. The highest dosage of CR provided the best Marshall stability, but resulted in the lowest permeability and reduced strength at 25°C. So, a 4.5% CR cannot be considered the best possible ideal. Selection requires clear standards for drainage and mechanical acceptability, validation of volumetric calculations, and variability at the specimen level. These results need to be moisture conditioned, abraded, and subjected to repeated-load testing before they can be used to assess moisture durability, raveling, or rutting resistance.

Abbreviations

The following abbreviations are used in this manuscript:

CR	**Crumb Rubber**
KN	**Kilonewton**

SBS	**Styrene– Butadiene–Styrene**
OGFC	**Open-Graded Friction Course**
ASTM	**American Society for Testing and Materials**
NAPA	**National Asphalt Pavement Association**
VTM	**Voids in Total Mix**
VMA	**Voids in Mineral Aggregate**
VFA	**Voids Filled with Asphalt**

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