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Interactive Effects of Limestone/Basalt Mineral Fillers and Dry-Processed Crumb Rubber on Hot Mix Asphalt Performance

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ABSTRACT

Road networks in developing regions such as Yemen suffer from premature deterioration for many reasons, including the use of basalt asphalt mixtures in the design of pavement layers; however, these mixtures exhibit poor resistance to rutting and moisture damage, particularly under excessive axle loads. This study investigates the performance of hot mix asphalt (HMA) modified with crumb rubber (CR) from scrap tires using the dry mixing technique, with a focus on the influence of mineral filler type and rubber gradation. Two locally sourced fillers-limestone and basalt-were evaluated using three CR gradations (coarse, fine, and powder) at concentrations of 0%, 5%, 10%, 15%, 20%, and 25% by weight of the asphalt binder. A total of 210 Marshall specimens were tested. The results showed that the limestone reference mixture exhibited critically low voids in mineral aggregate (VMA=12.40%), below the 13% specification requirement, while excessive stability suggested susceptibility to premature aging. The addition of 15% fine crumb rubber to the limestone mixture yielded optimal performance: a stability of 14.7 kN, a VMA of 14.8%, and an optimum asphalt content of 4.0% at 4% air voids, satisfying the Marshall mix design criteria for a heavy-traffic wearing course. In contrast, the basalt mixture showed continuous performance degradation upon crumb rubber addition. A two-way ANOVA confirmed a significant interaction between filler type and rubber content ($p < 0.001$). The study concludes that the optimal formulation-limestone filler with 15% fine crumb rubber -offers a practical solution for sustainable pavement infrastructure development in Yemen.

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1. INTRODUCTION

Yemen's road network is facing accelerated deterioration owing to increasing traffic loads, excessive axle weights, and the use of traditional asphalt mixtures with inherent performance limitations. This deterioration has reached an advanced stage, necessitating extensive reconstruction and rehabilitation efforts at increasing maintenance costs. The disposal of end-of-life tires (ELTs) presents a formidable global waste management challenge, with an estimated 1.5 billion tires discarded annually [1] [2] In developing nations, such as Yemen, this problem is amplified by the absence of formal recycling infrastructure, leading to the accumulation of millions of tires in uncontrolled dumpsites that pose significant environmental and public health risks [3, 4]. A promising solution to both challenges is the incorporation of crumb rubber (CR) from ELTs into hot mix asphalt (HMA), which offers the dual benefit of improving pavement performance while addressing waste management concerns [5, 6].

The mineral filler, defined as the fraction of aggregate passing the 1.18 mm sieve, represents a critical factor influencing the mixture performance. Mineral fillers play a pivotal role in stiffening the asphalt-filler mastic and dictating the volumetric properties of the composite [7].

The surface chemistry and physical properties of the filler determine its interaction with the polar components of asphalt binder [8]. In Yemen, basalt is the most abundant aggregate and mineral filler in hot-mix asphalt owing to its local availability. However, basalt-based mixtures exhibit poor resistance to rutting and moisture damage, particularly under excessive axle loads. These performance limitations have prompted investigations into alternative filler materials, as illustrated in Figure 1

Figure 1. Sanaa - AL-Hudeida highway road

Materials engineers at the Road Maintenance Fund have explored the potential of limestone powder as a mineral filler to improve the properties of hot-mix asphalt (HMA) mixtures with basalt aggregates. Limestone-modified mixtures have demonstrated enhanced moisture resistance and high stability [9]. Nevertheless, these basalt mixtures with limestone filler failed to meet the minimum voids in mineral aggregate (VMA-the minimum air void space required for adequate asphalt film thickness) requirement according to Marshall properties [10]**.** This volumetric deficiency is a significant bar rier to the adoption of limestone-modified basalt mixtures for pavement construction.

The modification of asphalt with CR can be achieved through two primary methods: the wet process and the dry process. In the wet process, CR is pre-blended with the binder at elevated temperatures, allowing for intimate interaction between the rubber and asphalt components [11]. Conversely, the dry process involves adding CR directly to the heated aggregate before binder injection, eliminating the need for specialized plant modifications [12]. The dry process offers significant logistical and economic advantages, making it particularly suitable for regions with limited technological capacity and infrastructure. This characteristic renders it the most practical choice for implementation in Yemen's current context. However, the performance of dry-processed mixtures is notoriously variable and highly sensitive to complex interactions between CR particles, the aggregate skeleton, and mineral filler [13, 14].

Crumb rubber offers a viable remedy for this volumetric problem, as it is known to increase VMA and improve mixture elasticity. However, a crucial knowledge gap exists: although the general advantages of CR modification are well established, the precise interaction between various CR gradations in a dry-process system and locally accessible Yemeni fillers (limestone and basalt) remains insufficiently studied. The hypothesis that the type of mineral filler utilized has a fundamental impact on the efficacy of dry-process CR modification has not been rigorously tested. This study seeks to bridge this gap by systematically investigating the synergistic effects of filler type and rubber gradation on mixture performance.

The primary objectives of this research are:

- To assess how CR can improve mixture flexibility and increase VMA in hot mix asphalt with limestone powder filler and basalt aggregates.

- To evaluate the performance of HMA modified with three distinct CR gradations (coarse, fine, and powder) using a dry-process approach. - To determine how rubberized combinations perform when limestone or basalt fillers are employed.

- To identify the optimal, context-appropriate formulation for Yemen's sustainable pavement infrastructure development.

2. MATERIALS AND METHODOLOGY:

2.1. MATERIALS

All the materials were sourced locally within Yemen to ensure the practical relevance of the findings. The materials were characterized according to the American Society for Testing and Materials **(ASTM)** and American Association of State Highway and Transportation Officials **(AASHTO)** standards. [15].

2.1.1. Asphalt Binder:

A standard 60/70 penetration grade asphalt binder, commonly used for pavement construction in Yemen, was used for all mixtures. The physical properties of the resin are presented in Table 1.

2.1.2. Coarse and Fine Aggregates

Crushed basalt aggregates were obtained from a quarry in the Sarif area of Sana'a and were used as both coarse and fine fractions. The aggregates were washed, dried, and sieved to meet the gradation requirements for a dense-graded wearing course mixture according to the Yemeni Road Maintenance Fund (RMF) specifications, which align with the AASHTO M323 and ASTM D3515 gradation requirements for a 19 mm nominal maximum aggregate size (NMAS) wearing course mixture. The resulting gradation ensured proper particle packing and consistent volumetric properties of the mixture. The Bulk Specific Gravity (S.S.D) for the basalt aggregate was (2.902) for the coarse aggregate and (2.869) for the fine aggregate [13]. The final blend proportions are listed in

Table 1. Physical Properties of Asphalt Binder

No	Name Of Test	According to	Trials		AV.	Spec.
			1	2		
1	Penetration (at 25°C)	ASTM D5	67	66	67	60–70
2	Softening Point (Ring & Ball)	ASTM D36	53	53.5	53	46–56
3	Flash point (Cleveland Open Cup) °C	ASTM D92	305		305	≥ 230°C
4	Fire point (Cleveland Open Cup) °C		320		320	$>$ Flash point
5	Specific Gravity (g/cm^3)	ASTM D70	1.020	1.018	1.019	
6	Ductility Test (at 25°C) cm	ASTM D113	$>$100	$>$100	$>$100	≥ 100 CM
7	Saybolt-Viscosity Sec (at 135°C)	ASTM E102	174		174	150 Sec min
8	Color		dark black			

Table 2. Representative photographs of the materials are provided in Figure 2 for illustration. [16]

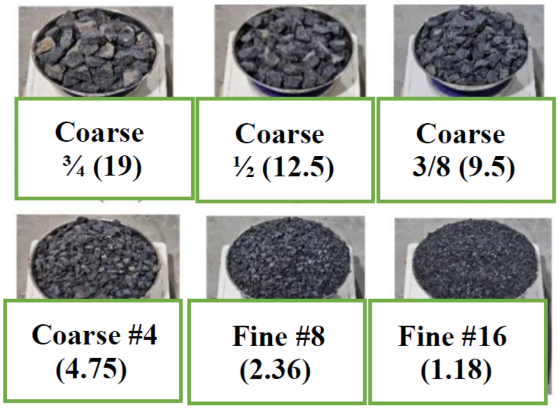

Figure 2. Coarse and Fine Aggregates retained on sieve number

Table 2. Resulting Aggregate Gradation (ASTM D3515)

Resulting Blend	Specification D4 ASTM 3515		
	Min	Max	Avg.
100	100	100	100
95.0	90	100	95
78.0	68	88	78
68.0	56	80	68
50.0	35	65	50
36.0	23	49	36
25.5	14	37	25.5
12.0	5	19	12
5.0	2	8	5

2.1.3. Mineral Fillers:

Two mineral fillers were investigated in this study. The basalt powder consisted of basalt dust collected from the fine fraction of crushed basalt (<1.18 mm). The limestone powder was sourced from Madinat Al-Sharq -Dhamar deposits and processed to satisfy standard mineral filler

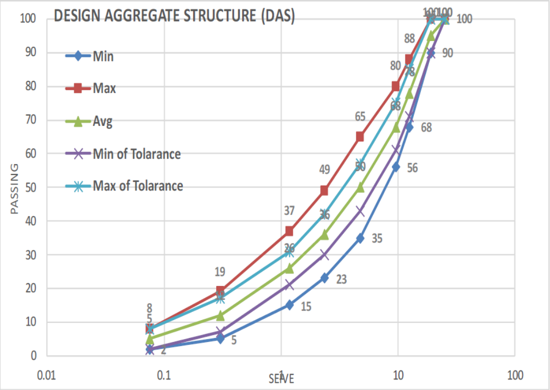

Figure 3. Aggregate Gradation Curve Used in Marshall Mix Design

gradation requirements. Both fillers were oven-dried and sieved prior to mixing to ensure a consistent reference.

particle size distribution. Images of the fillers are presented in Figure 4 and Figure 5 for visual reference [17].

Figure 4. Limestone Mineral Filler from Madinat Al-Sharq retained on sieve number

The physical and chemical properties of the fillers were characterized before the mixture preparation. The chemical composition was determined using X-ray fluorescence (XRF) analysis at the Geological Survey Center in Yemen, whereas the physical properties, such as specific gravity, fineness, and absorption, were measured according to the relevant ASTM standards. The results are presented in **Table** 3.

Table 3. Geochemical and Physical Properties of Mineral Samples

Property	Test Method / Standard	Madinat Al-Sharq (Limestone)	Basalt (Sana'a)
Chemical Analysis			
Major Oxides (%)			
CaO	XRF Analysis	51.08	1.37
SiO_2	XRF Analysis	2.25	59.20
Al_2O_3	XRF Analysis	0.85	27.38
Fe_2O_3 (Total Iron)	XRF Analysis	0.70	3.92
MgO	XRF Analysis	1.14	0.43
K_2O	XRF Analysis	0.11	0.51
Na_2O	XRF Analysis	0.18	3.43
MnO	XRF Analysis	0.03	1.38
L.O.I (Loss on Ignition)	ASTM D7348	42.66	2.33
Physical Properties			
Specific Gravity	ASTM C128	2.607 (Measured)	2.803 (Measured)
Color	Visual Inspection	Light Gray to Off-White	Dark Gray to Black
Hardness (Mohs Scale)	Scratch Test	∼3	∼6

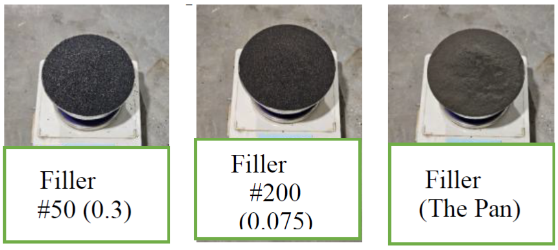

Figure 5. Basalt Mineral Filler from Sanaa retained on sieve number

Table 4. Properties of crumb rubber

Physical Properties	Results	Specifications	Standards
Specific gravity	1.16	1.15 ± 0.05	-
Metal content	None	Max. 0.01%	ASTM D5603-19a
Textile Content	0.15%	Max. 0.5 %	ASTM D5603-19a
Foreign Material	0.1%	Max. 0.25 %	
Color and form	Black fine		

2.1.4. Crumb Rubber (CR):

Crumb rubber, derived from scrap tires, was procured from Free Recycle Limited, a recycling company in Sanaa, Yemen.(as shown in **Figure 6**). was used as an additional aggregate fraction in this study. To investigate the effect of particle size on the performance of asphalt mixtures, three distinct gradations of ambient-ground crumb rubber were selected for this study: coarse, fine, and powder (**Figure 7**). The selection and classification of these rubber types were based on their particle size distribution, in accordance with established international standards, primarily ASTM D6114 / D6114M-19: Standard Specification for Asphalt-Rubber Binder [18].

Figure 6. Tire recycling facility in Sanaa

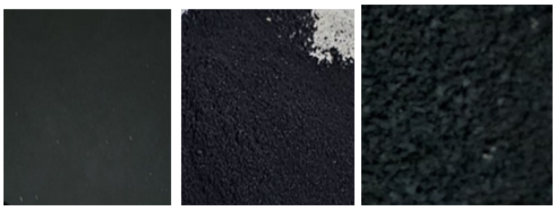

Figure 7. Powder , Fine, and Coarse Rubber

The physical properties of crumb rubber are presented in Tables 4:

The particle size distribution of each rubber type was determined using sieve analysis. The results are summarized in **Table 5** and **Figure 8**, which show the percentage of material passing through a series of standard sieves.

While **ASTM D6114** provides gradation requirements for crumb rubber used in the **wet process** (asphalt-rubber binder production), no equivalent ASTM standard exists specifically for **dry process** applications. In the dry

Table 5. Particle Size Distribution of Crumb Rubber Types

Sieve No.	Sieve Size (mm)	Coarse Rubber (% Passing)	Fine Rubber (% Passing)	Powder Rubber (% Passing)
#8	2.36	68.6	100.0	100.0
#16	1.18	31.4	93.0	100.0
#30	0.595	-	63.0	100.0
#50	0.297	-	32.0	92.1
#100	0.15	-	1.0	49.7
#200	0.075	-	-	20.4
Pan	<0.075	-	-	0.03

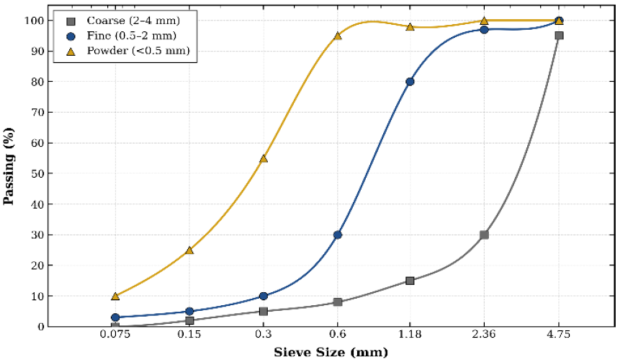

Figure 8. Particle Size Distribution of Crumb Rubber Types

process, crumb rubber is incorporated directly into the aggregate blend rather than being pre-reacted with the binder, allowing for a wider range of particle sizes to be investigated. This study intentionally selected three distinct gradations-coarse (2-4 mm), fine (0.5-2 mm), and powder (<0.5 mm)to systematically evaluate the full spectrum of particle size effects on HMA performance. This approach is consistent with previous dry process research by **Soto & Calabi (2018)**, **Tahami et al. (2019)**, and **Vignali et al. (2016)**, who successfully utilized similar non-standard gradations to advance the understanding of rubber-aggregate interaction mechanisms.

2.2. METHODOLOGY

The experimental program was designed as a two-phase, multi-factorial study to systematically evaluate the effects of the filler type, crumb rubber content, and crumb rubber gradation. A total of 210 Marshall specimens were prepared and tested in this study.

- **Phase 1 (Full Marshall Design)**:

This phase focused on materials with anticipated high interaction with the binder (fine powder rubber with limestone filler). Full Marshall mix designs were conducted, varying the asphalt content in 0.5% increments to determine the Optimum Asphalt Content (OAC) for each of the 12 unique mixtures (two control + five fine rubber contents + five powder rubber contents).

- **Phase 2 (Screening Test):**

This phase focused on materials with lower anticipated binder interactions (coarse rubber) or for comparative purposes (basalt filler). These mixtures were prepared only at the predetermined OAC of their respective control mixes to efficiently screen the performance trends.

Table 5 present comprehensive experimental design allows for a systematic evaluation of both main effects and interactions between filler type, rubber type, rubber content, and asphalt content. The large number of specimens ensures statistical reliability and enables the identification of optimal combinations with confidence.

Table 6. Summary of Experimental Program

Filler Type	**Rubber Type**	**Rubber Content (%)**	**Asphalt Content (%)**	**Total Specimens**
Limestone	**None**	**0**	**3.0, 3.5, 4.0, 4.5, 5.0**	**3*5=15**
Limestone	**Fine**	**5, 10, 15, 20, 25**	**3.0, 3.5, 4.0, 4.5, 5.0**	**3*5*5=75**
Limestone	**Powder**	**5, 10, 15, 20, 25**	**3.0, 3.5, 4.0, 4.5, 5.0**	**3*5*5=75**
Basalt	**None**	**0**	**3.5, 4.0, 4.5, 5.0, 5.5**	**3*5=15**
Basalt	**Fine**	**5, 10, 15, 20, 25**	**5.0 (OAC)**	**3*5=15**
Limestone	**Coarse**	**5, 10, 15, 20, 25**	**3.6 (OAC)**	**3*5=15**
Total				≈ 21

2.2.1. Determination of Optimum Asphalt Content (OAC)

Jane AUTEUR, Institute of Published Science, University of Examples, Singapore, and John WRIGHT, Institute of Submissions, School of Technicalities, USA.

Abstract: Academic manuscripts should include an abstract that describes the hypothesis, the methods proposed to validate or invalidate the hypothesis, and a brief summary of the results of investigation.

The Optimum Asphalt Content for each reference mixture (L-R0) Limestone - Reference and (B-R0) Basalt - Reference were determined using the Marshall mix design method ASTM D6926 [18]. Although this method is considered a volumetric-empirical approach, it remains widely used internationally and is the standard method specified in Yemen's national specifications [19].

For the limestone filler, specimens were prepared at five trial asphalt contents: 3.0%, 3.5%, 4.0%, 4.5%, and 5.0% by the total weight of the mixture. For the basalt filler, specimens were prepared at five trial asphalt contents: 3.5%, 4.0%, 4.5%, 5.0%, and 5.5% of the total weight of the mixture. Three replicate specimens were compacted for each asphalt content. The OAC was determined as the asphalt content corresponding to a target air void content of 4.0%, which is the midpoint of the acceptable range (3-5%) for mixtures under heavy traffic [20]. Additionally, the selected OAC was verified to ensure that all other volumetric and mechanical properties (VMA, VFB, stability, and flow) met the specification requirements outlined in **Table 7**.

Table 7. Marshall Mix Design Criteria (ASTM D3515 for Heavy Traffic)

Property	Specification Range	Reference
Air Voids (%)	3.0–5.0	ASTM D3515
VMA (%)	≥ 13.0 (for 19 mm NMAS)	
VFB (%)	65–75	
Marshall Stability (kN)	≥ 8.0	
Flow (mm)	2.0–3.5	

2.3. LABORATORY PROCEDURES

2.3.1. Mix Preparation: The Dry Process

The dry process for incorporating crumb rubber into asphalt mixtures involves adding rubber directly to the heated aggregate before introducing the asphalt binder [15]. This is fundamentally different from the wet process, in which rubber is first blended with the binder. In the dry process, the rubber particles primarily function as elastic aggregate particles rather than as binder modifier [21].

The specific mixing procedure used in this study was developed based on a comprehensive review of the best practices documented in the literature [22] and is detailed below.

2.3.1.1 Heating Phase.

Aggregate Heating: The batched aggregates (coarse, fine, and filler) were placed in a forced-draft oven and heated to a temperature of 160-170℃. This temperature range is recommended by the **Asphalt Institute (MS-2)** for conventional HMA and has been validated for dry-process rubberized mixtures in several studies [23]. The aggregates were maintained at this temperature for a minimum of 4 hours to ensure uniform heat distribution throughout the mass, as shown in Figure 9.

Figure 9. Kiln for heating aggregate

Asphalt Binder Heating: The asphalt binder was heated in a separate temperature-controlled container to 155-160℃. This temperature is within the recommended range for 60/70 penetration grade asphalt to achieve a viscosity suitable for adequate coating (approximately 0.17 ± 0.02 Pa·s) [23]. Overheating was avoided to prevent the oxidative aging of the binder.

Crumb Rubber Preheating (Optional): While some researchers recommend preheating crumb rubber [24], in this study, the rubber was stored at room temperature and added directly to the hot aggregate. This approach is supported by studies showing that the rubber particles rapidly equilibrate to the aggregate temperature during the initial dry-mixing phase [25].

2.3.1.2 Mixing Sequence.

The mixing sequence is critical in the dry process and directly affects the distribution of rubber particles and the final properties [26].

Step 1 - Dry Mixing of Rubber and Aggregate (60 seconds): The pre-weighed crumb rubber was added to the heated aggregate (at 165-170℃) and mixed manually for approximately 60 seconds **Figure 10**. This dry mixing step is essential to ensure the uniform distribution of the rubber particles throughout the aggregate mass before the binder is introduced [27]. During this phase, the manual mixing process allowed for thorough and controlled blending, ensuring that the rubber particles were evenly dispersed among the aggregate particles. Some researchers have reported that a limited amount of binder absorption into the rubber particles may begin during subsequent stages, causing slight swelling [28].

Figure 10. Dry Mixing of Rubber and Aggregate (60 seconds)

Step 2 - Addition of Asphalt Binder: After dry mixing phase, the heated asphalt binder (at 155-160℃) was poured over the rubber-aggregate blend, as shown in **Figure 11**.

Step 3 - Wet Mixing (90-120 seconds): The mixer was restarted, and the entire mixture was blended for

Figure 11. Addition of Asphalt Binder

90-120 seconds until all aggregates and rubber particles were uniformly coated with asphalt **(Figure 12).** Visual inspection was performed to confirm complete coating. The mixing time was based on the recommendations from **ASTM D6926** [29] and has been validated for dry-process mixtures in studies by **Abusharar et al. [30] and Tan et al. [31]**.

Figure 12. Wet Mixing (90-120 seconds)

2.3.2. *Specimen Compaction*

Immediately after mixing, the hot mixture was transferred to preheated cylindrical Marshall molds (internal diameter: 101.6 mm, height: approximately 63.5 mm after compaction). The compaction procedure followed **ASTM D6926** [29] and Marshall method specified in ASTM D6927 [17].

Compaction Temperature

The mixture was compacted at a temperature–140-145℃. This temperature is consistent with the Marshall method requirements, which specify that compaction should be performed at a temperature that allows adequate densification of the asphalt concrete mixture without causing excessive damage to the aggregate particles or the premature aging of the binder [17]. The selected temperature range ensured the proper workability of the mixture during the compaction process, facilitating the achievement of the target bulk density [32].

Compaction Procedure

The specimens were compacted using the Marshall compaction method, which involves applying a series of controlled hammer blows to the top and bottom surfaces of each specimen. For this study, a standard Marshall hammer (mass: 4.54 kg, drop height: 457.2 mm) was used to apply **75 blows** on each face of the specimen, following the standard Marshall design procedure [17]. This compaction approach ensures a uniform density distribution throughout the specimen and is widely accepted in asphalt pavement design and research [32].

2.3.3. *Testing Procedures*

After compaction and cooling, each set of specimens was subjected to a series of tests to determine their physical and mechanical properties according to the Marshall method (ASTM D6927-17) [11]. The following properties were determined.

Marshall Stability: The maximum load (in kN) that the specimen can withstand before failure. This represents the strength of the HMA [23].

Marshall Flow: The total deformation (in mm) of the specimen at the point of the maximum load. This indicates the plasticity and flexibility of the HMA [23].

Volumetric Properties: Bulk specific gravity, theoretical maximum density (Gmb), air voids (AV), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) were calculated to show the relationship between the percentage of rubber content and the volumetric characteristics of the mixture [33].

The OAC for each filler type was determined by analyzing the graphical plots of these properties versus asphalt content and selecting the binder content that provided the best balance of properties [34, 35].

The presentation of detailed numerical results

The corresponding plots ensure transparency and allow the reproducibility of the experimental procedure in accordance with the ASTM and AASHTO standards.

2.3.4. *Moisture Susceptibility Testing*

To evaluate the durability of the optimized mixtures (at their respective OACs) and their resistance to moisture-induced damage, the Tensile Strength Ratio (TSR) was determined in accordance with AASHTO T283. Six specimens were prepared for each mix type. Three specimens were tested for Indirect Tensile Strength (ITS) in a dry (unconditioned) state. The other three were subjected to moisture conditioning (partial vacuum saturation followed by a freeze-thaw cycle) before testing for their conditioned ITS. The TSR was then calculated as the ratio of the average conditioned ITS to the average dry ITS, expressed as a percentage [36].

2.4. STATISTICAL ANALYSIS

Analysis of Variance (ANOVA) will be employed by the SPSS statistical program to determine whether the observed differences in mixture properties were statistically significant or could be attributed to random experimental variability. Post-hoc pairwise comparisons (Tukey's Honest Significant Difference test) were conducted to identify the specific mix combinations that differed significantly from one another. A significance level (α) of 0.05 was used for all statistical tests, consistent with the standard practice in engineering research [37].

3. RESULTS AND ANALYSIS

3.1. RESULTS TEST

3.1.1. Test results for the Control Hot Mix Asphalt

In this study, two types of reference Hot Mix Asphalt (HMA) mixtures were used.

3.1.1.1 Limestone Reference Hot Mix Asphalt (L-R0)

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Table 8 presents the Marshall test results for the limestone reference mix (L-R0) at various asphalt contents (3.0%, 3.5%, 4.0%, 4.5%, and 5.0%). The properties include bulk specific gravity (Gmb), maximum theoretical specific gravity (Gmm), percent air voids, percent voids in mineral aggregate (VMA), percent voids filled with asphalt (VFA), stability, and flow. For each asphalt content, three specimens were tested. The reported values represent the average after removing any outliers based on statistical criteria.

Table 8. Marshall Test Results for (L-R0)

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.492	2.666	6.54	13.39	51.2	16.58	2.08
3.5	2.537	2.648	4.19	12.26	65.9	18.77	2.53
4.0	2.535	2.623	3.35	12.78	73.8	16.15	3.23
4.5	2.546	2.600	2.08	12.87	83.8	15.99	3.43
5.0	2.544	2.567	0.92	13.41	93.2	13.71	3.84

🟥 **Out of criteria**

At an air voids ratio of 4%,, the optimum asphalt content (OAC) values for the limestone reference mix were selected based on the asphalt content trends illustrated in **Figures 13** and are listed in **Table 9**

Table 9. OAC (optimum asphalt content) at AV=4% in Limestone Reference Mix (L-R0)

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.6	2.53	2.63	**4.00**	12.40	67.0	17.55	2.7

3.1.1.2 Basalt Reference Mix (B-R0). **Table 10** presents the Marshall test results for the basalt reference mix (B-R0) at various asphalt contents (3.5%, 4.0%, 4.5%, 5.0%, and 5.5%). The properties include bulk specific gravity (Gmb), maximum theoretical specific gravity (Gmm), percentage of air voids, percentage of voids in mineral aggregate (VMA), percentage of voids filled with asphalt (VFA), stability, and flow. Three specimens were tested for each asphalt content. The reported values represent the average after removing outliers based on statistical criteria.

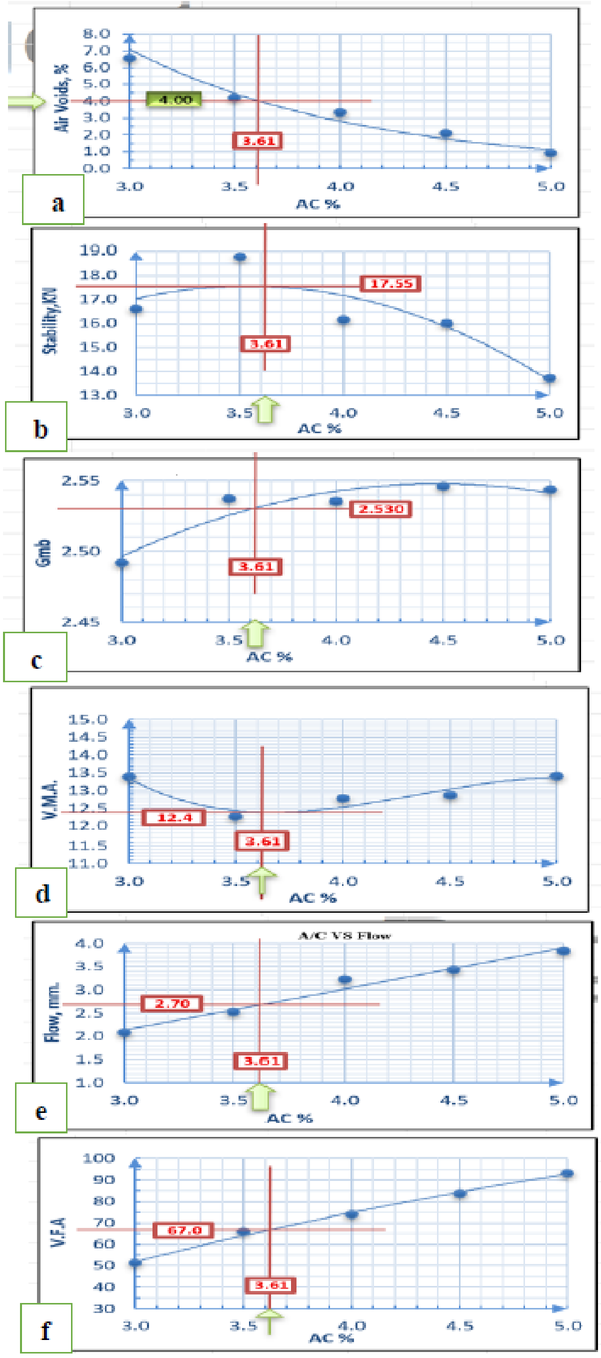

Figure 13. (a,b,c,d,e, and f) Performance criteria for Limestone Reference Mix (a=Air Voids , b=Stability , c=Gmb ,d=VMA ,e=Flow, and f= VFA)

At an air voids ratio of 4%,, the Optimum Asphalt Content (OAC) values for the Limestone Reference Mix were selected based on the asphalt content property trends illustrated in **Figures 14**, as shown in **Table 11**

Table 10. Marshall Test Results for Basalt Reference Mix (B-R0)

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.5	2.471	2.718	9.10	16.01	43.2	15.67	2.53
4.0	2.488	2.693	7.62	15.87	52.0	15.45	2.77
4.5	2.524	2.666	5.34	15.10	64.7	15.02	2.77
5.0	2.541	2.652	4.18	14.96	72.1	15.66	3.07
5.5	2.550	2.624	2.84	15.13	81.3	16.08	3.63

🟥 **Out of criteria**

Table 11. Optimum asphalt content at AV=4% in Basalt Reference Mix (B-R0)

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
5.07	2.53	2.63	4.00	14.85	73.5	15.51	3.3

3.1.1.3 Moisture Susceptibility Results.

The durability of the two optimized mixes was assessed by evaluating their resistance to moisture-induced damage using the Tensile Strength Ratio (TSR) test (AASHTO T283). The results, shown in **Table 12**, indicate the percentage of tensile strength retained by the mix after the moisture conditioning.

Table 12. Moisture Susceptibility (TSR) Results

Filler Type	Tensile Strength Ratio (TSR) (%)	Minimum Specification (%)
Basalt (B-R0)	82.20	> 80
Limestone (L-R0)	88.20	> 80
Limestone (L-15F)	84.40	> 80

3.1.2. Test results for the addition of crumb rubber to hot mix asphalt with limestone mineral filler (full marshal design) :

for reference, it was explained in paragraph 2.2

3.1.2.1 Test results for the addition of fine rubber to hot mix asphalt with limestone mineral filler: .

Five HMA experiments were completed with the addition of fine rubber at ratios (5%, 10%, 15%, 20%, and 25%) as following:

- **At 5% fine rubber:**

Table 13. Marshall Test Results for HMA with Limestone-5% Fine Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.486	2.658	6.47	13.58	52.4	13.49	2.25
3.5	2.513	2.646	5.03	13.10	61.6	13.11	3.03
4.0	2.513	2.615	3.90	13.55	71.2	13.46	2.67
4.5	2.535	2.601	2.53	13.23	80.9	13.23	3.00
5.0	2.543	2.584	1.60	13.44	88.1	13.35	3.93

3.1.2.2 Test results for the addition of powder rubber to Hot Mix Asphalt with limestone mineral filler: .

Five HMA experiments were completed with the addition of powder rubber at ratios (5%, 10%, 15%, 20%, and 25%) as following:

3.1.2.3 Optimum Asphalt Content for Hot Mix Asphalt with limestone mineral filler modified with crumb rubber: .

1. The optimum asphalt content for hot mix asphalt with fine rubber Table 23 presents the Marshall mix design properties at the optimum asphalt content (OAC) for the limestone-filler hot mix asphalt incorporating fine

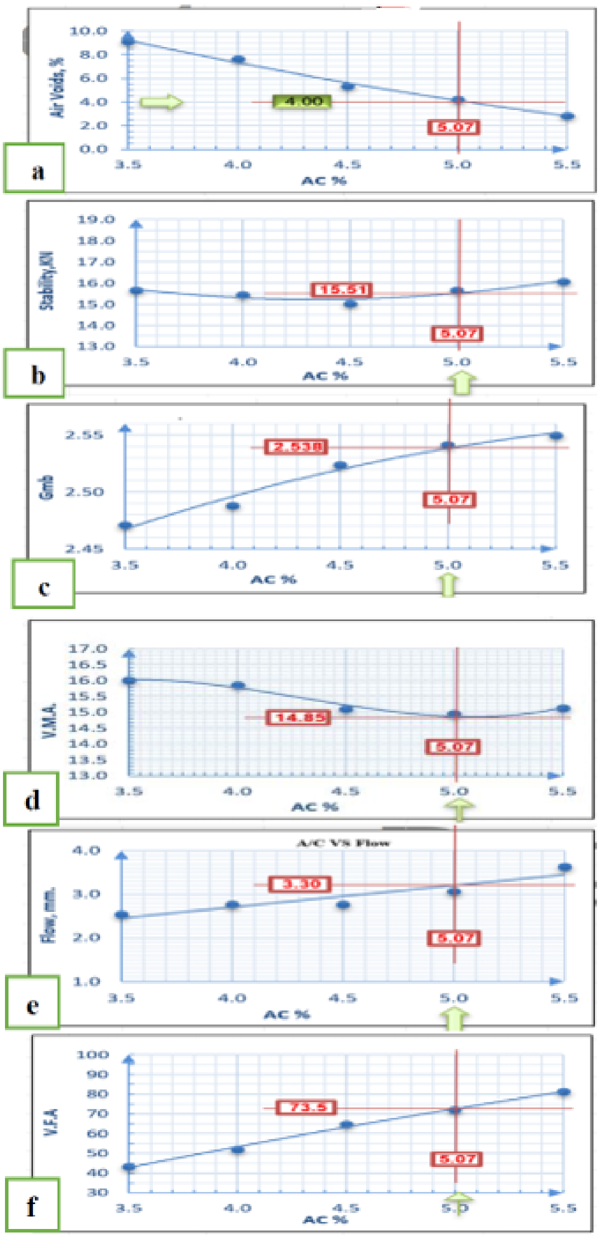

Figure 14. (a,b,c,d,e, and f) Performance criteria for Basalt Reference Mix (B-R0) (a=Air Voids , b=Stability , c=Gmb ,d=VMA ,e=Flow, and f= VFA)

rubber (FR) at replacement levels of (5%, 10%, 15%, 20%, and 25%) by weight of the total aggregate. The OAC for each rubber content level was determined at a fixed air void ratio of 4%, in accordance with the Marshall mix design method.

2. The optimum asphalt content for hot mix asphalt with powder rubber Table 24 presents the Marshall mix design properties at the (OAC) for the limestone-filler HMA incorporating powder rubber (PR) at replacement levels of 5%, 10%, 15%, 20%, and 25% by weight of the total aggregate. The OAC for each rubber content level was determined at a fixed air void ratio of 4%, in accordance with the Marshall mix design method.

- **At 10% fine rubber:**

Table 14. Marshall test results for HMA with limestone-10% Fine Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.449	2.67	8.29	14.88	44.3	15.43	1.95
3.5	2.473	2.647	6.56	14.47	54.6	14.42	2.33
4.0	2.491	2.609	4.53	14.31	68.4	13.71	2.40
4.5	2.503	2.595	3.55	14.34	75.3	12.94	2.40
5.0	2.532	2.576	1.70	13.79	87.7	12.80	3.63

- **At 15% fine rubber:**

Table 15. Marshall Test Results for HMA with Limestone-15% Fine Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.438	2.651	8.03	15.26	47.3	16.59	2.05
3.5	2.462	2.612	5.75	14.86	61.3	15.43	2.80
4.0	2.474	2.586	4.33	14.88	70.9	14.89	2.48
4.5	2.486	2.551	2.54	14.93	83.0	14.21	2.80
5.0	2.501	2.538	1.44	14.85	90.3	14.07	3.73

- **At 20% fine rubber:**

Table 16. Marshall Test Results for HMA with Limestone-15% Fine Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.436	2.630	7.38	15.32	51.8	14.87	2.12
3.5	2.440	2.598	6.10	15.63	60.9	13.67	2.68
4.0	2.470	2.588	4.58	15.04	69.5	13.23	2.33
4.5	2.471	2.518	1.85	15.43	88.0	12.47	2.83
5.0	2.477	2.500	0.93	15.67	94.1	12.26	3.42

3.1.2.4 Test results for the addition of Coarse rubber to Hot Mix Asphalt with limestone mineral filler: .

The optimum asphalt content of 3.6% of reference hot

· **At 25% fine rubber:**

Table 17. Marshall Test Results for HMA wit Limestone-25% Fine Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.414	2.617	7.76	16.09	51.8	14.55	2.17
3.5	2.415	2.582	6.46	16.48	60.8	13.38	2.47
4.0	2.453	2.575	4.74	15.62	69.6	12.68	2.13
4.5	2.451	2.492	1.65	16.12	89.8	13.62	2.83
5.0	2.454	2.477	0.92	16.45	94.4	14.63	3.10

- **At 5% powder rubber:**

Table 18. Marshall Test Results for HMA wit Limestone-25% Fine Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.496	2.658	6.08	13.22	54.0	16.81	2.05
3.5	2.533	2.646	4.28	12.41	65.5	20.76	2.80
4.0	2.533	2.615	3.12	12.84	75.7	15.13	2.50
4.5	2.535	2.601	2.53	13.23	80.9	15.39	2.80
5.0	2.543	2.584	1.60	13.44	88.1	15.25	3.73

- **At 10% powder rubber:**

Table 19. Marshall Test Results for HMA with Limestone 10% powder Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.488	2.658	6.41	13.53	52.6	17.15	2.68
3.5	2.520	2.646	4.74	12.84	63.1	19.87	2.88
4.0	2.526	2.615	3.41	13.11	74.0	16.46	2.73
4.5	2.537	2.601	2.44	13.16	81.4	16.27	3.28
5.0	2.538	2.584	1.77	13.59	87.0	14.94	3.70

🟥 **Out of criteria**

- **At 15% powder rubber:**

Table 20. Marshall Test Results for HMA with Limestone15% powder Rubber

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.480	2.667	7.00	13.78	49.2	16.99	3.20
3.5	2.520	2.638	4.48	12.86	65.2	18.51	2.97
4.0	2.529	2.613	3.20	12.98	75.4	17.15	3.15
4.5	2.536	2.587	1.95	13.20	85.2	15.90	3.77
5.0	2.535	2.567	1.25	13.70	90.9	14.62	3.93

🟥 **Out of criteria**

- **At 20% powder rubber:**

Table 21. Marshall Test Results for HMA with Limestone 20% powder Rubberr

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.484	2.655	6.46	13.67	52.8	16.17	1.57
3.5	2.522	2.634	4.27	12.80	66.7	18.68	2.17
4.0	2.532	2.611	3.04	12.91	76.5	16.58	2.63
4.5	2.546	2.579	1.29	12.87	90.0	14.98	3.03
5.0	2.537	2.551	0.56	13.64	95.9	14.17	3.87

🟥 **Out of criteria**

mix asphalt with limestone as mineral filler (L-R0) with the addition of coarse rubber at ratios (5%, 10%, 15%, 20%, and 25%) as shown in **Table 25**.

3.1.2.4 Test results for the addition of fine rubber to hot mix asphalt with limestone mineral filler: .

The optimum asphalt 5.0% of reference hot mix asphalt with basalt as mineral filler (B-R0) with addition of fine rubber ratio (5%, 10%, 15%, 20%, and 25%) as shown in **Table 26**:

- **At 20% powder rubber:**

Table 22. Marshall Test Results for HMA with Limestone 20% powder Rubberr

AC %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.0	2.489	2.655	6.27	13.50	53.5	16.38	1.83
3.5	2.526	2.634	4.10	12.65	67.6	18.72	2.35
4.0	2.533	2.611	2.97	12.84	76.9	16.35	2.76
4.5	2.546	2.579	1.28	12.87	90.0	15.51	3.15
5.0	2.542	2.551	0.36	13.47	97.3	13.90	3.65

3.2. ANALYSIS

3.2.1. Experimental / Laboratory Analysis

3.2.1.1 Performance of Control Mixtures .

- Basalt Reference Mix (B-R0)

The basalt reference mix (B-R0) achieved an OAC of 5.0%, representing a 38.8% increase in binder content compared with the limestone-based mix (3.61%). This significant increase is consistent with the established literature, which attributes this behavior to the higher specific surface area, porosity, and absorption capacity of basalt aggregates and fillers [38]. The resulting VMA of 14.8% provides a larger internal void space to accommodate the binder and potentially facilitate the rubber modification. This higher binder demand reflects the inherent physical and chemical characteristics of basalt, which influence its interaction with asphalt binder [38]. This reference mix serves as a comparative baseline to evaluate the extent of performance changes when crumb rubber is incorporated into a basalt-aggregate matrix, despite the anticipated challenges related to the material's surface properties.

- The **Limestone Reference Mix (L-R0)**

The limestone reference mix (L-R0) at 3.61% OAC exhibited a high stability of 17.55 kN, which, coupled with a critically low VMA of 12.40%, indicated an overly stiff and brittle aggregate-binder matrix. According to the Asphalt Institute standards, insufficient VMA restricts the binder film thickness, leading to premature fatigue cracking [23]. This baseline performance suggests a lack of necessary viscoelastic flexibility. Furthermore, the sharp decline in stability with incremental binder increases confirms the high sensitivity and narrow design tolerance of the mix. These findings justify the necessity of crumb rubber to optimize the void structure and enhance the long-term durability [39].

- **Moisture Susceptibility (TSR)**

The durability of an asphalt pavement, particularly in regions with seasonal rainfall, is critically dependent on its resistance to moisture-induced damage. The tensile strength ratio (TSR) results, presented in **Table 12**, demonstrate that both filler types successfully meet the minimum standard requirement of 80%. The limestone reference mix (L-R0) exhibited a high moisture resistance with a TSR value of 88.2%. limestone exhibited a 7.3% higher TSR value. Meanwhile, the basalt reference mix (B-R0) also demonstrated satisfactory performance, retaining 82.2% of its original tensile strength. The variation in TSR values between the two mixtures can be attributed to their distinct chemical compositions. Limestone, being calcareous (calcium carbonate), naturally possesses a strong chemical affinity with the acidic asphalt binder. Conversely, basalt is more siliceous in nature, which typically results in a relatively lower, yet still acceptable, adhesive bond with the binder [40, 41]. Ultimately, both mixtures prove to be durable and structurally sound against moisture damage, as shown in **Figure 15**

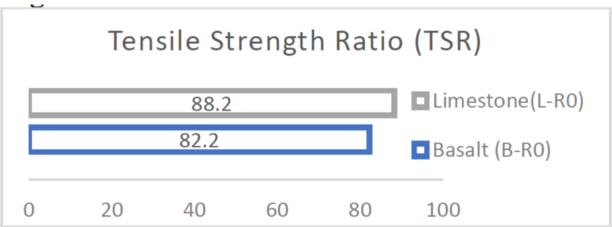

Figure 15. Tensile Strength Ratio (TSR)

3.2.1.2 Effect of Crumb Rubber on Limestone Mixtures .

o Fine Rubber (0.5-2.0 mm):

The experimental results for the limestone-based HMA modified with fine rubber provide a definitive solution to the core research problem identified in this study. Unlike the reference mix (L-R0), which exhibited an excessively high and brittle stability of 17.55 kN, the incorporation of fine rubber successfully moderated this stiffness. At the optimal dosage range of 10% to 15%, the Marshall stability was strategically reduced to a more resilient range of 13.3–14.7 kN. Crucially, this modification addressed the primary performance gap by significantly increasing the VMA from 12.40% to over 14.89%, thereby providing the necessary internal space for the binder film thickness and viscoelastic flexibility [23], as shown in **Figure 16** and 17.

The bulk specific gravity (Gmb) of the limestone-based mixtures demonstrated a consistent declining trend with increasing fine rubber content, decreasing from approximately 2.49 g/cm³ in the reference mix to 2.41–2.46 g/cm^3) at 15% rubber content. This reduction is attributed

Table 23. The all-optimum asphalt content for Each hot mix asphalt at different fine rubber content

OAC (%)	Fine rubber (%)	Gmb	Gmm	AV (%)	VMA (%)	VFA (%)	Stability (kN)	Flow (mm)
3.95	5.0	2.520	2.619	4.00	13.50	70.0	13.40	3.00
4.25	**10.0**	**2.499**	**2.600**	**4.00**	**14.40**	**72.9**	**13.30**	**2.75**
4.09	**15.0**	**2.475**	**2.580**	**4.00**	**14.89**	**73.5**	**14.70**	**2.81**
4.10	20.0	2.465	2.573	4.00	15.40	74.0	13.00	2.65
4.12	25.0	2.445	2.555	4.00	15.90	75.0	12.90	2.60

🟥 **Out of criteria**

Table 24. The all-optimum asphalt content for Each hot mix asphalt at different powder rubber content

OAC %	Powder rubber %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.62	5.00	2.53	2.64	4.00	12.51	67.9	17.40	2.60
3.78	10.0	2.52	2.62	4.00	12.98	69.1	17.96	2.80
3.68	15.0	2.52	2.62	4.00	12.90	68.5	17.80	3.03
3.61	20.0	2.52	2.62	4.00	12.82	68.9	17.70	2.42
3.55	25.0	2.53	2.63	4.00	12.75	68.0	17.50	2.35

🟥 **Out of criteria**

Table 25. OAC 3.6% with limestone mineral filler with addition of coarse rubber

OAC %	Coarse rubber %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
3.6	5.00	2.49	2.619	4.93	14.7	66.46	14.0	4.5
3.6	10.0	2.44	2.616	6.73	15.0	55.13	13.0	5.0
3.6	15.0	2.4	2.608	7.98	17.0	53.06	12.0	5.0
3.6	20.0	2.37	2.612	9.26	17.8	47.98	8.50	4.5
3.6	25.0	2.34	2.61	10.34	18.5	44.11	7.00	4.0

🟥 **Out of criteria**

to the lower density of crumb rubber (1.1–1.2 g/cm^3) compared with that of mineral aggregates, which displace denser components and create additional air voids within the mixture structure, as illustrated in Figure 18

- Tensile Strength Ratio (TSR) with CR

Upon the addition of 15% fine crumb rubber (by weight of the asphalt binder) to the limestone mixture, the moisture resistance decreased to 84.4% of the TSR. This 3.8

Table 26. OAC 5.0% with Basalt mineral filler with addition of fine Rubber

OAC %	fine rubber %	Gmb	Gmm	AV%	VMA%	VFA%	Stability (KN)	Flow (mm)
5.0	5.00	2.454	2.678	8.36	17.50	52.2	17.84	2.53
5.0	10.0	2.474	2.618	5.52	16.85	67.2	14.69	2.93
5.0	15.0	2.437	2.584	5.69	18.08	68.5	13.81	3.63
5.0	20.0	2.429	2.564	5.25	18.33	71.4	14.20	3.50
5.0	25.0	2.440	2.524	3.32	17.97	81.5	13.05	2.97

🟥 **Out of criteria**

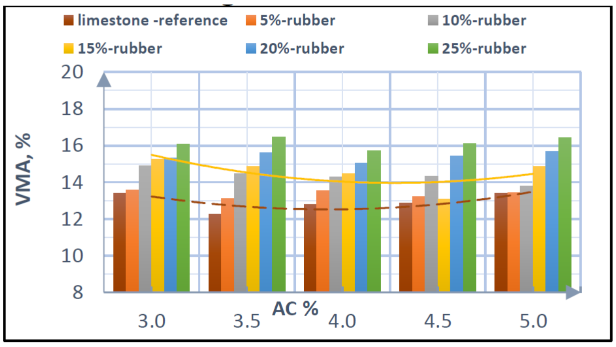

Figure 16. Effect of Fine Rubber Content on Air Voids in Mineral Aggregate at Different Asphalt Contents

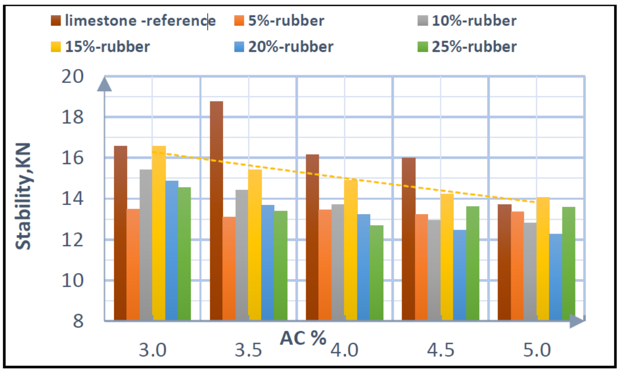

Figure 17. Effect of Fine Rubber Content on Marshall Stability at Different Asphalt Contents

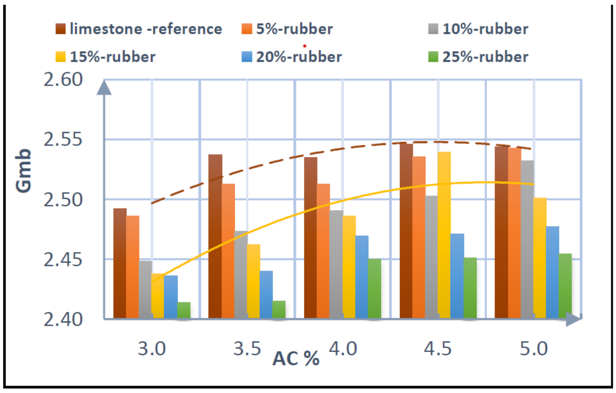

Figure 18. Effect of Fine Rubber Content on bulk specific gravity (Gmb)

pp reduction, while still exceeding the minimum specification requirement of 80%, indicates that the incorporation of fine crumb rubber slightly compromises the moisture durability of the limestone-based composite. This phenomenon can be attributed to the reduced contact between the limestone filler and asphalt binder due to the physical displacement caused by rubber particles, which may diminish the chemical bonding at the filler-binder interface. Despite this marginal decrease, the modified limestone mixture (L-15F) maintained adequate moisture resistance, demonstrating that the benefits of improved volumetric properties and elasticity do not come at the cost of unacceptable durability loss. Ultimately, both the reference mixtures and the optimized limestone-rubber composite proved to be durable and structurally sound against moisture damage, as shown in Figure 19

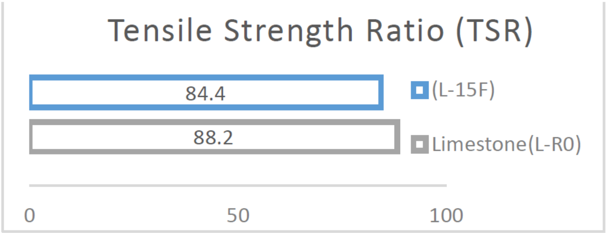

Figure 19. Tensile Strength Ratio (TSR) with 15%CR

These findings align with the research objective of transforming a brittle, high-stability baseline into a durable, fatigue-resistant pavement. According to recent literature, fine rubber particles act as an elastic "cushioning agent" within the aggregate matrix, redistributing internal stresses, and preventing premature cracking [39].

By effectively resolving the ‘high stability/low VMA’ conflict, a fine rubber content of 10–15% was identified as the optimal modification range. This balance ensures that the mixture maintains sufficient structural integrity while gaining the essential ductility required for long-term performance under cyclic loadings.

- Powder Rubber (<0.5 mm):

The experimental results for the limestone-based hot mix asphalt (HMA) modified with crumb rubber powder (CPR) had a minimal effect on VMA (Figure 20. The VMA remained relatively flat as the powder rubber content increased. This critical finding suggests a different mechanism of action; the much smaller particles of powder rubber appear to act more as a void filler or binder extender, integrating into the asphalt mastic rather than physically expanding the aggregate structure. This aligns with the findings of **Almusawi et al. (2020)** [42], who noted that the rubber particle size significantly influenced the Marshall parameters.

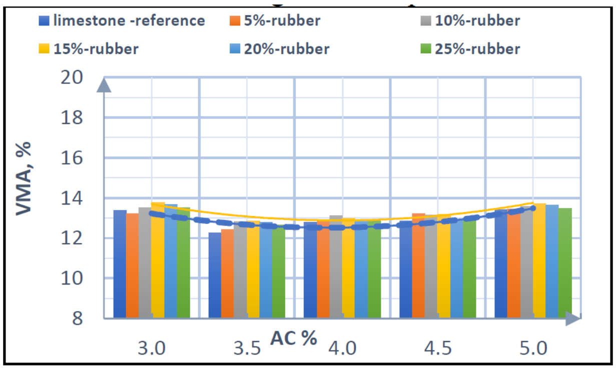

Figure 20. Effect of Powder Rubber Content on Air Voids in Mineral Aggregate at Different Asphalt Contents

Peak stability was achieved at a much lower content of 5% (Figure 21). Beyond this concentration, stability either decreased or plateaued. This strongly suggests that the primary benefit of powder rubber comes from modifying the asphalt binder itself, likely by absorbing the lighter oil fractions and increasing its viscosity. This stiffening effect appears to be maximized at a low concentration, with additional rubber providing no further benefits. This again underscores the findings of **Almusawi et al. (2020)** [42],that particle size dictates the interaction.

However, the design window becomes progressively narrower at higher rubber contents, indicating high sensitivity to small variations in asphalt content, which could pose a quality control challenge during production.

These findings are consistent with those of previous studies, which suggest that the dry method often results in poor interactions between the rubber particles and asphalt binder. Unlike the wet method, the dry process treats rubber as a part of the aggregate, leading to the ’swelling’ of the rubber particles during mixing and compaction. This swelling disrupts the internal aggregate packing skeleton and creates excessive air voids [43, 44]. Consequently, the use of crumb rubber powder via the dry method in this study was deemed unsuitable for enhancing the performance of limestone-based HMA.

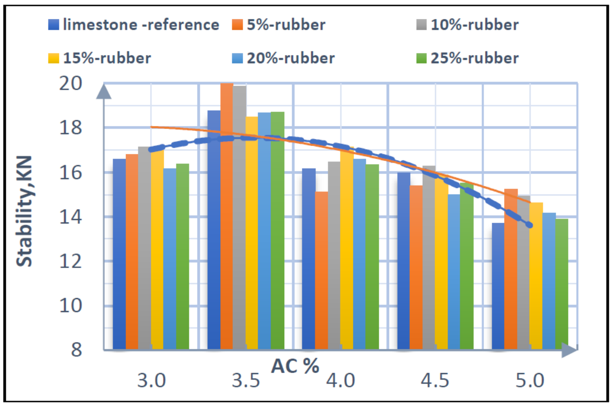

Figure 21. Effect of Powder Rubber Content on Air Voids in Mineral Aggregate at Different Asphalt Contents

- Coarse Rubber (2.0–4.0 mm):

Coarse rubber (2-4 mm) demonstrated the poorest performance among all rubber types. Large particles severely disrupt the aggregate skeleton, creating excessive voids and reducing aggregate interlock [43]. At 25%, the mixture failed to meet the minimum stability requirements for heavy traffic (7.0 kN < 8.0 kN) (Figure 17) as specified by the standard mix design criteria [23], confirming that coarse rubber is unsuitable for high-content dry process modification(Fig 22).

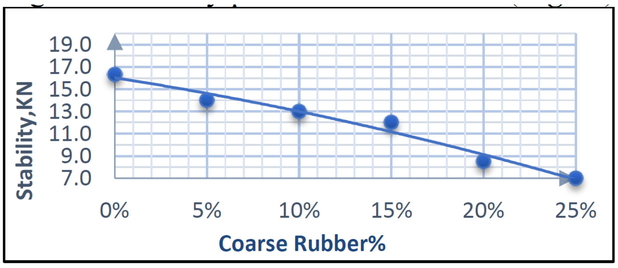

Figure 22. Effect of Different Coarse Rubber Content on Stability at (OAC for L-R0) = 3.6%

3.2.1.3 Effect of Crumb Rubber on Basalt Mixtures .

- Fine Rubber (0.5-2.0 mm):

The basalt filler mixes exhibited different rubber tolerances compared to the limestone. The higher VMA of the basalt mixes (14.85% reference vs. 12.40% limestone) provides more space to accommodate rubber particles without excessive disruption. The basalt mix, which already had a high binder demand (OAC = 5.0%) [38], became rich and unstable. The CR particles disrupted the already well-balanced basalt-binder system, leading to a loss of stability and cohesion. However, the stability at (25% RC) (13.05 kN) was lower than that of the basalt reference (15.51 kN), indicating an 11.8% reduction (Figure 23).

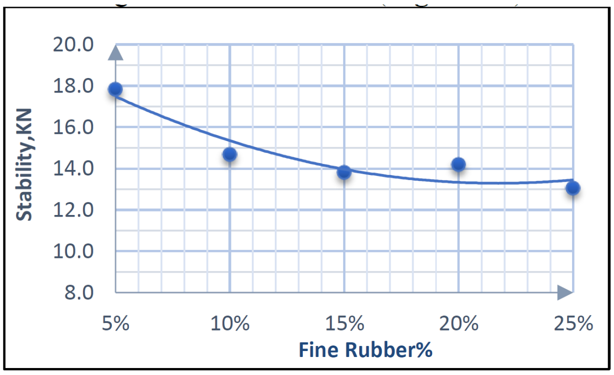

Figure 23. Effect of Different Fine Rubber Content on Stability at (OAC for B-R0) = 5.0%

3.2.2. *Statistical Analysis*

A comprehensive statistical analysis was performed using IBM SPSS Statistics (v.26) on 210 Marshall specimens to validate the results. The analysis employed a systematic progression from descriptive statistics through inferential testing (ANOVA) to predictive modeling (GLM), ensuring both statistical rigor and practical applicability.

3.2.2.1 Descriptive Statistics .

Table 27 presents the descriptive statistics for all investigated Marshall properties for the 210 specimens. The standard errors remained below 2% of the mean for all properties, confirming high measurement precision and experimental consistency.

Table 27. the descriptive statistics

Property	Unit	n	Mean	Std. Dev.	Min.	Max.
Marshall Stability	kN	210	15.02	2.38	8.45	20.12
Marshall Flow	mm	210	2.98	0.79	1.23	5.12
VMA	%	210	10.87	2.18	7.23	16.45
VFB	%	210	60.37	17.18	22.10	93.20
Air Voids	%	210	4.47	2.40	0.92	12.34

Prior to inferential analysis, the Shapiro-Wilk normality test confirmed that all primary variables followed a normal distribution ($p > 0.05$), except for VFB, which showed a minor deviation ($p = 0.002$) that did not substantially affect ANOVA robustness. Levene's test verified homogeneity of variance across groups for all variables ($p > 0.05$), and the Durbin-Watson statistic (DW = 1.87) confirmed independence of observations.

3.2.2.2 Two-Way ANOVA: Filler Type, Rubber Content, and Their Interaction .

A two-way ANOVA was employed to evaluate the individual and interactive effects of filler type and rubber content on Marshall stability. The results are presented in Table 28.

Table 28. Two-way ANOVA

Source of Variation	*SS*	Df	MS	F	p-value	η^2
Filler Type	512.34	1	512.34	174.23	< 0.001	0.459
Rubber Content	287.56	5	57.51	19.56	< 0.001	0.257
Filler × Rubber Interaction	156.78	5	31.36	10.67	< 0.001	0.140
Error	602.64	205	2.94	-	-	-

All three effects were highly significant ($P < 0.001$). Filler type emerged as the dominant factor, explaining 45.9% of the total variance in stability (η^2= 0.459), followed by rubber content (η^2 = 0.257). The Filler × rubber interaction effect (η^2 = 0.140) constitutes the most critical finding of this analysis: the effectiveness of rubber modification is not universal but depends fundamentally on the mineral filler type. The limestone filler exhibited a synergistic response to rubber addition, whereas the basalt filler exhibited an antagonistic response.

Tukey HSD post-hoc analysis revealed that the most significant pairwise difference occurred between 0% and 15% rubber content (mean difference = 2.52, $p < 0.001$), whereas the difference between 10% and 15% was not statistically significant ($p = 0.081$), indicating a performance plateau in this range.

3.2.2.3 Regression Analysis and Predictive Modeling .

Simple Linear Regression (SLR) analysis identified the dominant predictors for each Marshall property. The key findings are presented in Table 29.

Table 29. Simple Linear Regression (SLR)

Dependent Variable	Dominant Predictor	Regression Equation	R^2	p-value	β (Std.)
Stability (kN)	Rubber Type (RT)	ST = 19.219 − 1.709 × RT	0.370	< 0.001	-0.609
Flow (mm)	Asphalt Content (AC)	FL = 0.927 + 0.508 × AC	0.221	< 0.001	$+0.470$
VMA (%)	Rubber Type (RT)	VMA = 11.288 + 1.224 × RT	0.485	< 0.001	$+0.696$
VFB (%)	Asphalt Content (AC)	VFB = -4.791 + 17.994 × AC	0.696	< 0.001	$+0.834$
Air Voids (%)	Asphalt Content (AC)	AV = 14.817 − 2.521 × AC	0.563	< 0.001	-0.750

Rubber Type was the strongest predictor of both stability (R^2 = 0.370) and VMA (R^2 = 0.485), confirming its central role in addressing the research problem. Transitioning from coarse rubber (RT = 1) to fine rubber (RT = 3) increased the predicted VMA from 12.40% to 14.7%, directly resolving the low VMA deficiency of the reference limestone mix. Asphalt content dominated the volumetric properties (VFB: R^2 = 0.696; air voids: R^2 = 0.563), consistent with the established mix design theory.

3.2.2.4 Full Factorial General Linear Model (GLM) .

Multiple Linear Regression (MLR) models demonstrated adequate predictive power for volumetric properties (Adj. R^2 up to 0.878 for VFB) but weak performance for mechanical properties (Adj.R^2 = 0.445 for stability; 0.323 for flow). This indicates the presence of significant non-additive interaction effects. Therefore, a Full factorial GLM was implemented, yielding substantial improvements in model accuracy, as shown in Table 30.

Table 30. Multiple Linear Regression (MLR)

Property	MLR Adj. R^2	GLM Adj. R^2	Improvement
Stability (kN)	0.445	0.747	+0.302
Flow (mm)	0.323	0.783	+0.460
VMA (%)	0.677	0.900	+0.223
VFB (%)	0.878	0.967	+0.089
Air Voids (%)	0.832	0.950	+0.118

The most dramatic improvements were observed for Flow (+0.460) and Stability (+0.302), attributed to the significant interaction terms RC × RT (significant for all five properties) and FT × RC (significant for four of the five properties). These interactions confirm that the effects of rubber modification are interdependent, and the impact of rubber content is moderated by both rubber gradation and filler type. This finding explains the contradictory results reported in previous single-factor studies and constitutes a novel contribution to this field.

3.2.2.5 Summary of Statistical Findings .

The statistical analysis provides three principal conclusions:

First, Filler Type was the dominant factor controlling stability (η^2= 0.459), and the filler × rubber interaction was statistically significant (p < 0.001), confirming that the effectiveness of dry-process rubber modification is context-dependent rather than universal.

Second, Fine Rubber ((0.5–2 mm) mm) is the most effective gradation for simultaneously reducing excessive stability ($\beta = -0.609$) and increasing VMA ($\beta = +0.696$), with an optimal rubber content range of 10–15% validated by both ANOVA and post-hoc testing.

Third, the Full Factorial GLM demonstrates that interaction effects are essential for the accurate prediction of mechanical properties, with R^2 improvements of up to +0.460 over additive linear models, resolving contradictions in the existing literature.

4. DISCUSSION

4.1. LIMESTONE FILLER MIXTURES: HIGH MOISTURE RESISTANCE VERSUS STRUCTURAL BRITTLENESS – THE ROLE OF VMA

The limestone reference mixture exhibited a higher tensile strength ratio (88.2%) than the basalt reference mixture (82.2%), primarily owing to the superior chemical affinity of the calcareous limestone filler with the acidic asphalt binder, which promotes stronger adhesion. However, despite their higher moisture resistance, limestone-based mixtures are known to suffer from premature cracking and reduced service life. This apparent contradiction is explained by the critically low voids in the mineral aggregate (VMA = 12.40%) observed in the limestone reference mix, which falls below the minimum specification of 13.0%. Such a low VMA results in an excessively thin binder film thickness, accelerating oxidative aging and leading to a brittle mixture with high Marshall stability (17.55 kN) but limited flexibility. In contrast, the basalt reference mix, with a VMA of 14.89%, accommodated a thicker binder film that enhanced flexibility and fatigue resistance, albeit with slightly lower moisture resistance.

The incorporation of 15% fine crumb rubber into the limestone mixture successfully addressed this structural deficiency, while maintaining acceptable moisture durability. The modified limestone-rubber composite (L-15F) achieved a VMA of 14.89%, comparable to that of the basalt reference mix, and a reduced Marshall stability of 14.7 kN, indicating improved elasticity and reduced brittleness. While the tensile strength ratio decreased slightly to 84.4% from the reference value of 88.2%, this 3.8 percentage point reduction remained well above the minimum specification requirement of 80%, confirming that the moisture resistance of the modified mixture was adequate for long-term durability. This trade-off between marginally reduced moisture resistance and substantially improved structural flexibility and volumetric properties represents an optimal balance for pavement performance under Yemen's climate and traffic conditions.

Thus, TSR alone is an insufficient indicator of overall durability; the VMA-related structural deficiencies in limestone mixtures necessitate modification, such as the incorporation of fine crumb rubber, to expand the internal void structure, improve the long-term performance, and achieve a balanced combination of moisture resistance and mechanical resilience.

4.2. MECHANISMS OF FILLER-RUBBER INTERACTION

The contrasting behaviors of the limestone and basalt fillers can be explained by differences in their surface chemistry, particle morphology, and mineralogical composition.

Limestone (calcite,$CaCO_3$) is a basic calcite material with a high surface energy and strong affinity for polar compounds, such as asphaltenes in asphalt binders. This promotes strong adhesive bonding at the filler–binder interface [25]. Additionally, limestone particles tend to have a flaky or blocky morphology with a high specific surface area, providing abundant contact points for mechanical interlocking with the rubber particles. The relatively low specific gravity of the limestone powder (2.607) further facilitates its dispersion within the mastic, allowing the rubber particles to occupy strategic positions within the aggregate skeleton.

In contrast, basalt is an igneous siliceous rock primarily composed of plagioclase and pyroxene. Its surface is acidic to neutral and exhibits a lower chemical affinity for asphalt binders than limestone [24] Basalt particles are typically more angular and denser (specific gravity 2.803), which reduces the available void space for rubber integration. The inherently higher asphalt demand of basalt mixtures (OAC = 5.0% vs. 3.6% for limestone) means that any additional binder-modifying agent (such as rubber) creates an over-rich system in which excess binder displaces rubber particles from the aggregate–binder interface, leading to the observed monotonic decline in stability.

The results revealed a fundamental principle: the effectiveness of crumb rubber modification in asphalt mixtures is not universal but depends critically on the characteristics of the base mixture, particularly the mineral filler type [45]. The limestone-rubber system demonstrated synergistic benefits, whereas the basalt-rubber system showed antagonistic effects [46].

Why Limestone Responds Positively:

The fine particle size and high surface area of limestone powder create abundant contact points for rubber particles, facilitating mechanical interlocking and structural integration [47]. The low initial VMA (12.40%) provided space for rubber particles to fill voids and improve the aggregate skeleton without excessive binder demand. The fine rubber gradation proved to be optimal, balancing the structural contribution with binder compatibility.

Why Basalt Responds Negatively:

The denser, more angular particles and higher inherent VMA (14.8%) of basalt leave less room for rubber integration. The already high asphalt content requirement (5.0%) means that additional rubber creates an over-rich system prone to rutting. The basalt-binder-rubber combination lacks the synergistic benefits observed with the use of limestone.

4.3. COMPARISON WITH PREVIOUS STUDIES

Previous research on rubberized asphalt has primarily focused on wet-process modifications in developed countries using different aggregate types [4]. **Bahia et al. (2003)** reported improved fatigue resistance with rubber modification; however, their work did not address filler-rubber interactions [7]. **Kandhal et al. (1998)** noted that the effectiveness of the dry process varies with the mixture composition, which is consistent with our findings [13]. **Lo Presti (2013)** emphasized the importance of rubber particle size, which our results confirm through the superior performance of fine rubber [16].

5. CONCLUSION AND RECOMMENDATIONS

a. Conclusions

- **Filler Type** is Critical: The mineral filler type fundamentally determines the effectiveness of dry-process rubber modification. Limestone filler is highly compatible with crumb rubber, whereas basalt filler exhibits antagonistic effects.

- **Optimal** Formulation Identified: The limestone filler with 15% fine crumb rubber at 4.0% asphalt content achieved optimal performance, meeting all ASTM D6927-17 requirements while solving the original VMA deficiency.

- **Rubber Gradation** Matters: Fine rubber (0.5-2 mm) outperformed both coarse and powder gradations, providing an optimal balance between structural contribution and binder compatibility.

- **Filler-Rubber Interaction** is significant: Two-way Analysis of Variance (ANOVA) confirms that the interaction effect between filler type and rubber content is statistically significant ($p < 0.05$), indicating that the effectiveness of rubber modification is not universal but context-dependent.

b. Recommendations

For Implementation in Yemen:

- Conduct field trials to validate laboratory results under actual pavement conditions and traffic loads.

- Adopting the dry-process method in hot mix asphalt production in regions with available limestone can improve pavement infrastructure while solving the tire waste crisis.

- Standardize the optimal formulation: Limestone filler + 15% fine crumb rubber + 4.0% asphalt content should be adopted as a standard specification for sustainable pavement in Yemen.

- Establish tire recycling facilities to produce consistent, high-quality crumb rubber that meets fine gradation specifications.

For Future Research:

- The long-term performance was investigated through accelerated pavement testing and field monitoring of in-service pavements.

- Evaluate the moisture susceptibility and durability of limestone-rubber mixtures under Yemen's climate conditions.

- Optimize rubber content beyond 25% to identify potential upper limits for rubber incorporation.

- Study coarse-graded mixtures to determine if results apply to other pavement layers.

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