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Influence of Filler Type on Hot Mix Asphalt Properties: Performance Assessment of Bajil Limestone and Sana'a Basalt

Salman Al-Nuwairah [1*], Abdlsalam AL-Thawr[1] and Ali Rajeh[2]

[1]**Department of Civil Engineering, Faculty of Engineering, Sana'a University, Sana'a, Yemen,**
[2]**Director of the Laboratory and Quality Control Department, Road Maintenance Fund, Sana'a, Yemen.**

*Corresponding author: slman.alnoira@su.edu.ye

Abstract

Mineral filler selection significantly influences the mechanical performance and economic efficiency of Hot Mix Asphalt (HMA). This study evaluates two locally available Yemeni fillers, Bajil limestone and Sana'a basalt, to identify a technically and economically optimal alternative for pavement construction. Marshall mix design and standardized laboratory tests were conducted to assess stability, flow, volumetric properties, optimum asphalt content (OAC), and moisture susceptibility.

Results indicate that the limestone mixture achieved an OAC of (3.8%), compared to (4.8%) for the basalt mixture, representing a 21% reduction in asphalt binder demand and substantial cost savings. Although basalt provided slightly higher Marshall stability, both mixtures satisfied specification requirements. The limestone mix demonstrated superior moisture resistance, achieving a tensile strength ratio of (90.7%) compared to (82.6%) for basalt.

Overall, Bajil limestone provides adequate mechanical performance, improved durability, and enhanced economic efficiency, making it a practical and sustainable alternative filler for asphalt pavement applications in Yemen.

Article Info

Keywords:
Hot mix asphalt (HMA), Marshall properties, Moisture susceptibility (TSR), Limestone mineral filler, Asphalt mixture performance

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1. INTRODUCTION

The development of durable and cost-effective road infrastructure is a fundamental requirement for economic growth and social development, particularly in developing countries such as Yemen. Flexible pavements constructed with Hot Mix Asphalt (HMA) are widely used due to their adaptability, ease of construction, and relatively low maintenance cost. However, premature pavement distresses including rutting, moisture damage, and fatigue cracking remain common, leading to increased maintenance expenses and reduced service life. [1, 2]

The engineering performance of HMA is strongly influenced by the characteristics of its constituent materials, particularly the mineral filler. Although mineral filler constitutes a small fraction of the total mixture, it plays a critical role in modifying asphalt mastic properties, controlling volumetric characteristics, and affecting stiffness, durability, and optimum asphalt content (OAC). Consequently, appropriate filler selection can significantly improve both technical performance and construction economics.[3]

In Yemen, basalt dust is traditionally used as the primary filler source. While basalt generally provides acceptable mechanical strength, its production involves higher crushing energy and associated costs. In contrast, limestone deposits are abundant, easily accessible, and require lower processing energy. Despite this availability, limestone filler remains underutilized due to the lack of systematic local studies evaluating its suitability relative to conventional basalt filler. This represents a clear research gap in current Yemeni pavement engineering practice.[4]

Beyond the local economic benefits, the use of locally sourced limestone also supports global sustainability objectives by reducing transportation distances, lowering fuel consumption and associated carbon emissions, and promoting circular and resource-efficient construction practices. Therefore, adopting indigenous materials can contribute not only to cost reduction but also to environmentally responsible pavement engineering. This clear geological differentiation provides a rational basis for selecting representative sources of basalt and limestone fillers for comparative evaluation as shown in Figure 1. [5, 6]

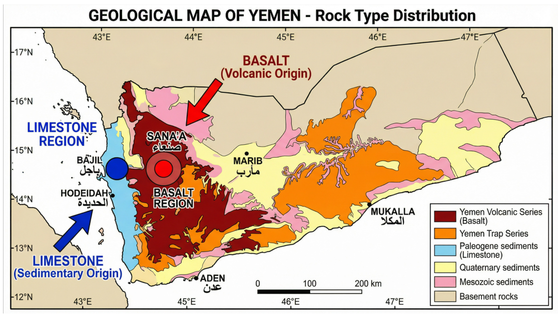


Figure 1. Geological Map of Yemen

Accordingly, this study aims to experimentally compare the performance of HMA mixtures prepared with Bajil limestone and Sana'a basalt fillers using standardized Marshall mix design and moisture susceptibility testing. It is hypothesized that Bajil limestone filler will provide comparable or superior mechanical performance at a lower optimum asphalt content than basalt filler, resulting in significant economic savings without compromising durability. [7, 8]

The findings of this research are expected to provide practical guidance for material selection in Yemen and similar developing regions while promoting sustainable and economical pavement construction practices.

Accordingly, this study aims to experimentally evaluate and compare the performance of HMA mixtures prepared with Bajil limestone and Sana'a basalt fillers. It is hypothesized that Bajil limestone filler will provide comparable or superior mechanical performance while requiring a significantly lower optimum asphalt content than conventional basalt filler, resulting in improved economic efficiency without compromising durability.

2. METHODOLOGY

This study was conducted through a systematic laboratory investigation to evaluate and compare the performance of Hot Mix Asphalt (HMA) prepared with two different mineral fillers. The experimental program was designed to adhere to internationally recognized standards to ensure the validity and reliability of the results. The methodology encompassed material characterization, mix design, and a series of performance tests.

2.1. Materials

The constituent materials for the HMA mixtures were sourced locally in Yemen to reflect standard construction practices in the region.

2.1.1. Asphalt Binder

A standard 60/70 penetration grade asphalt binder, sourced from a Bahraini refinery, was used for all mixtures.The fundamental properties of the binder were verified through comprehensive testing as summarized in Table 1. The binder meets all requirements of both Yemeni and international specifications, ensuring its suitability for pavement applications in the local climate. The fundamental physical and rheological properties of the binder, such as penetration, softening point, and ductility, were tested and confirmed to meet the requirements of the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). [9, 10]

2.1.2. Coarse and Fine Aggregates

Crushed basalt aggregates were obtained from a quarry in the Saref area of Sana'a and used as both coarse and fine fractions. The aggregates were dried, sieved, and recombined to meet the 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. The Bulk Specific Gravity (S.S.D) for the basalt aggregate is **(2.924)** for the coarse aggregate and **(2.888)** for the fine aggregate. The final blend proportions are summarized in Table 1. Representative photographs of the materials are provided in **Figure** for illustration purposes only. [11]

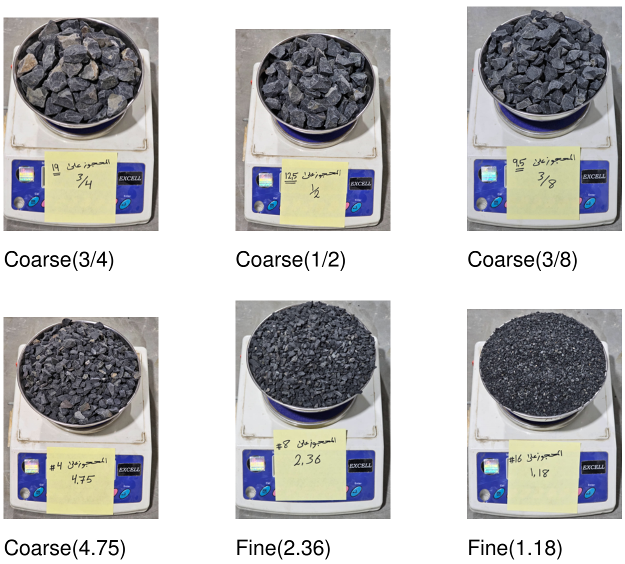


Figure 2. Coarse and Fine Aggregates retained on sieve number

Table 1. Properties and Test Results of the 60/70 Penetration Grade Asphalt Binder

Serial No.	Name of Test	According To	Trials 1	Trials 2	Average (AV.)	Specifications
1	Penetration (at 25A°C)	AASHTO T49 / ASTM D5	68	70	69	60 - 70
2	Softening Point (Ring & Ball)	AASHTO T53 / ASTM D36	53	54	53.5	46 min
3	Flash Point (Cleveland Open Cup)	AASHTO T48 / ASTM D92	315	315	315	232 min
4	Fire Point (Cleveland Open Cup)	AASHTO T48 / ASTM D92	340	340	340	-
5	Specific Gravity	AASHTO T228 / ASTM D70	1.021	1.023	1.022	-
6	Ductility Test (at 25A°C) cm	AASHTO T51 / ASTM D113	> 100	> 100	> 100	≥ 100 cm
7	Saybolt Viscosity (at 135A°C)	AASHTO T72 / ASTM E102	165	165	165	150 min
8	color		Dark			

Table 2. Properties and Test Results of the 60/70 Penetration Grade Asphalt Binder

Resultin 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

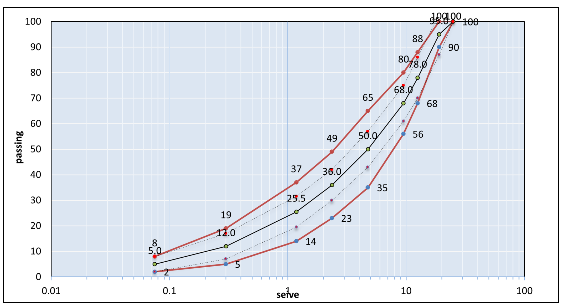
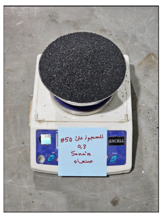


Figure 3. Aggregate Gradation Curve Used in Marshall Mix Design

2.1.3. Mineral Fillers

Two mineral fillers were investigated. The control filler consisted of basalt dust collected from the fine fraction of crushed basalt (< 1.18 mm). The alternative filler was limestone powder sourced from Bajil deposits and processed to satisfy standard mineral filler gradation requirements. Both fillers were oven-dried and sieved prior to mixing to ensure consistent particle size distribution. Images of the fillers are presented in Figure and Figure for visual reference.

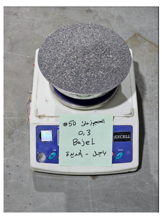


Filler #50 (0.3) Sana'a (S)

Filler #200 (0.075) Sana'a (S)

Filler (The Pan) Sana'a (S)

Figure 4. Basalt Mineral Filler from Sana'a retained on sieve number



Filler #50 (0.3) Bajil (B)

Filler #200 (0.075) Bajil (B)

Filler (The Pan) Bajil (B)

Figure 5. Limestone mineral filler from Bajil retained on sieve numbers

2.2. Experimental Program

The experimental work was centered on the Marshall mix design method, a widely accepted procedure for determining the Optimum Asphalt Content (OAC) and evaluating the performance of HMA. The Marshall mix design method was selected because it remains the most widely adopted and standardized procedure for asphalt mixture design in Yemen and many developing regions. This method provides reliable evaluation of stability, volumetric properties, and moisture resistance while ensuring practical applicability under local construction conditions. Therefore, it was considered appropriate and sufficient for the objectives of this comparative study.[12]

2.2.1. Marshall Mix Design and Specimen Preparation

The Marshall mix design was performed in accordance with ASTM D6926 and ASTM D6927. For each filler type, a series of trial mixtures was prepared with varying asphalt contents (ranging from 3% to 6% by weight of the total mix).

The aggregates were heated to $170°$C and the asphalt binder to $160°$C. The materials were then thoroughly mixed at $160°$C to ensure uniform coating. Cylindrical specimens (101.6 mm in diameter and approximately 63.5 mm in height) were prepared by compacting approximately 1200g of the loose HMA in a preheated mold at a temperature of $140°$C. Compaction was achieved by applying 75 blows to each face of the specimen using a standard Marshall compaction hammer.

To ensure experimental repeatability and reliability, all Marshall and volumetric tests were conducted on three replicate specimens for each asphalt content. The reported values represent the average of the measurements. The variability between specimens was minimal, with deviations typically within ± 5%, indicating good consistency of the experimental results.

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

Table 3. Geochemical and Physical Properties of Mineral Samples

Property	Test Method / Standard	Limestone (Bajil)	Basalt (Sana'a)
Chemical Analysis			
Major Oxides (%)			
CaO		52.12	1.38
SiO_2		2.25	59.20
Al_2O_3		0.85	27.41
Fe_2O_3 (Total Iron)		0.71	3.92
MgO		1.14	0.43
K_2O		0.11	0.51
Na_2O		0.18	3.43
MnO		0.03	1.38
L.O.I (Loss on Ignition)		42.61	2.34
Physical Properties			
Specific Gravity	ASTM C128	**2.672 (Measured)**	**2.838 (Measured)**
Color	Visual Inspection	Light Gray to Off-White	Dark Gray to Black
Hardness (Mohs Scale)	Scratch Test	~3	~6

2.2.2. Volumetric and Marshall Property Testing

After compaction and cooling, each set of specimens was subjected to a series of tests to determine their physical and mechanical properties:

•Bulk Specific Gravity (Gmb): Determined according to ASTM D2726.

•Theoretical Maximum Specific Gravity (Gmm): Determined according to ASTM D2041.

•Volumetric Analysis: Using the Gmb and Gmm values, the key volumetric properties were calculated: Air Voids (Va), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA).

•Marshall Stability and Flow: The specimens were immersed in a water bath at $60°$C for 30-40 minutes and then tested for Marshall stability (maximum load resistance, in kN) and flow (deformation at maximum load, in mm) as per ASTM D6927.

The OAC for each filler type was determined by analyzing the graphical plots of these properties versus asphalt content, selecting the binder content that provided the best balance of properties.[13, 14]

The presentation of detailed numerical results and corresponding plots ensures transparency and allows reproducibility of the experimental procedure in accordance with ASTM and AASHTO standards.

2.2.3. 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**. For each mix type, six specimens were prepared. 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 being tested for their conditioned ITS. The TSR was then calculated as the ratio of the average conditioned ITS to the average

Table 4. Marshall Test Results for HMA with Sana'a Basalt Filler

AC %	Gmb	Gmm	Va %	VMA %	VFA %	Stability (KN)	Flow (mm)
4.0	2.508	2.668	5.99	15.88	62.2	16.53	2.93
4.5	2.521	2.652	4.93	15.87	69.0	16.41	2.90
5.0	2.532	2.63	3.73	15.96	76.7	17.16	2.90
5.5	2.534	2.605	2.74	16.35	83.3	15.39	3.20
6.0	2.517	2.587	2.59	17.33	85.1	12.80	3.20

Table 5. Marshall Test Results for HMA with Bajil Limestone Filler

AC %	Gmb	Gmm	Va %	VMA %	VFA %	Stability (KN)	Flow (mm)
3.0	2.493	2.69	7.33	14.16	48.3	20.67	2.00
3.5	2.543	2.665	4.57	12.89	64.5	18.06	2.60
4.0	2.552	2.64	3.32	13.03	74.5	17.28	2.55
4.5	2.561	2.618	2.19	13.20	83.4	16.24	2.75
5.0	2.554	2.590	1.38	13.86	90.1	14.73	4.03

dry ITS, expressed as a percentage.[15]

3. DATA COLLECTION

This section presents the comprehensive data collected from the laboratory experimental program. The results are organized to show the influence of varying asphalt content on the properties of the Hot Mix Asphalt (HMA) for both the Bajil limestone and Sana'a basalt fillers, leading to the determination of the Optimum Asphalt Content (OAC) and the final performance characteristics of each mix.

3.1. Marshall Mix Design Results

The Marshall mix design procedure was conducted on a series of specimens for each filler type, with asphalt content varying from 3% to 6%, Asphalt content ranged from 3.0% to 5.0% for Bajil limestone and from 4.0% to 6.0% for Sana'a basalt, in 0.5% increments, based on regional experience to bracket the expected optimum. The key volumetric and mechanical properties were measured for each specimen. **Tables 4 and 5** provide the complete Marshall test data, including bulk specific gravity (Gmb), theoretical maximum specific gravity (Gmm), air voids, VMA, VFA, stability, and flow for each asphalt content level. The average results are summarized in **Table 4** for Sana'a basalt mix and **Table 5** for Bajil limestone mix.

3.2. Optimum Asphalt Content (OAC) and Final Mix Properties

The Optimum Asphalt Content (OAC) for each mix was determined as the asphalt percentage that corresponds to a target air void level between (3% - 5%), while also ensuring that all other parameters (Stability, Flow, VMA, VFA) met the standard Marshall design criteria. Based on the data from **Table 4 and 5**, the OAC and the corresponding properties for each mix were established.

The summarized results presented in **Table 6** were directly derived from the complete Marshall design data shown in **Tables 4 and 5** . The Optimum Asphalt Content (OAC) values were selected based on the property asphalt content trends illustrated in **Figures 6 and 7** , ensuring a clear and traceable link between the raw measurements and the final performance comparison.

3.3. 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 6, indicate the percentage of tensile strength retained by the mix after moisture conditioning.

Table 7. Moisture Susceptibility (TSR) Results

These collected data form the basis for the analysis and discussion presented in the subsequent sections of this paper.

Table 6. Comparison of Properties at Optimum Asphalt Content (OAC)

Property	Bajil Limestone	Sana'a Basalt	Standard Specification
(OAC) (%)	3.8	4.8	-
Stability (kN)	15.05	17.84	> 8.0
Flow (mm)	2.85	2.20	2 - 4
(Va) (%)	4.68	3.67	3 - 5
(VMA) (%)	13.77	15.37	> 13
(VFA) (%)	66.03	76.1	65 - 75

Table 7. Moisture Susceptibility (TSR) Results

Filler Type	Tensile Strength Ratio (TSR) (%)	Minimum Specification (%)
Bajil Limestone	90.7	> 80
Sana'a Basalt	82.6	> 80

4. RESULTS AND DISCUSSION

This section provides a detailed analysis and interpretation of the experimental results presented in the previous section. The discussion focuses on comparing the effects of limestone and basalt fillers on the key engineering properties of the Hot Mix Asphalt (HMA), culminating in a holistic evaluation of their suitability for pavement construction in Yemen.

4.1. Influence of Filler Type on Optimum Asphalt Content (OAC)

The most significant finding of this study, from both an economic and engineering perspective, is the substantial difference in the Optimum Asphalt Content (OAC) required by the two fillers. As shown in Table 6 and Figures 6 and 7 , Bajil limestone mix achieved its optimal properties at an OAC of (3.8%), whereas Sana'a basalt mix required (4.8%) representing a (21%) reduction in binder content. This full percentage point reduction in binder content represents a direct and considerable cost saving, given that asphalt binder is the most expensive component of the HMA.

The lower asphalt demand of the limestone filler can be attributed to its distinct physical and chemical properties compared to basalt. Limestone particles generally have a lower surface area and lower absorption capacity than basalt fines. Consequently, less asphalt binder is needed to coat the aggregate particles and fill the interstitial voids, leading to a more economically efficient mixture.

4.2. Comparative Analysis of Mechanical Properties

4.2.1. Marshall Stability and Flow

The mechanical strength and deformation characteristics of the two mixes are summarized in Table 6. Sana'a basalt mix exhibited Marshall stability was approximately (18.5%) higher than limestone stability of (17.84 kN) compared to the (15.05 kN) for the Bajil limestone mix. This indicates that the basalt filler creates a stiffer, more rigid asphalt mastic but both of them Excellent.

However, it is crucial to interpret this result in a practical context. While the basalt mix is stronger, the stability of the limestone mix (15.05 kN) comfortably exceeds the typical minimum requirement of 8.0 kN for wearing course mixtures. This level of stability is more than adequate for the vast majority of traffic volume roads prevalent in Yemen. Therefore, the superior stability of the basalt mix may represent an over-engineering for many applications, achieved at the unnecessary cost of higher binder content.

Regarding deformation, the limestone mix showed a slightly higher flow value (2.85 mm) compared to the basalt mix (2.20 mm). Both values are well within the acceptable range of 2-3.5 mm. The higher flow of the limestone mix suggests a slightly more flexible pavement, which can be advantageous in resisting fatigue cracking over its service life.

4.2.2. 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 (stripping). The Tensile Strength Ratio (TSR) results, presented in Table 7, provide a clear distinction between the two fillers in this regard.

Bajil limestone mix demonstrated excellent moisture resistance, retaining (90.7%) of its original tensile strength after conditioning limestone exhibited a (9.8%) higher TSR value. In contrast, Sana'a basalt mix retained only (82.6%) of its strength. While both mixes pass the minimum requirement of 80%, the superior performance of the limestone is unequivocal. This enhanced durability is likely due to the better chemical affinity between the calcareous limestone (calcium carbonate) and the acidic asphalt binder, which promotes a stronger adhesive bond that is less susceptible to being stripped by water. Basalt, being more siliceous in nature, has a weaker natural adhesion to asphalt, making it more prone to moisture damage.[16, 17]

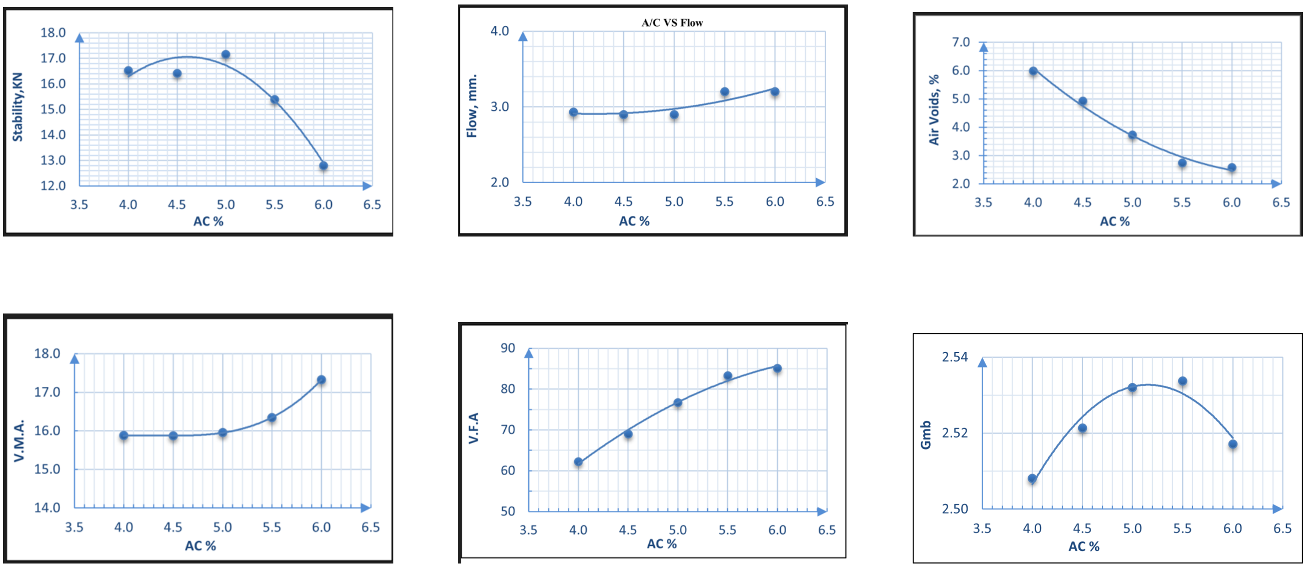


Figure 6. Performance criteria for Sana'a (Stability, Flow, Va, VMA, VFA, and Gmb)

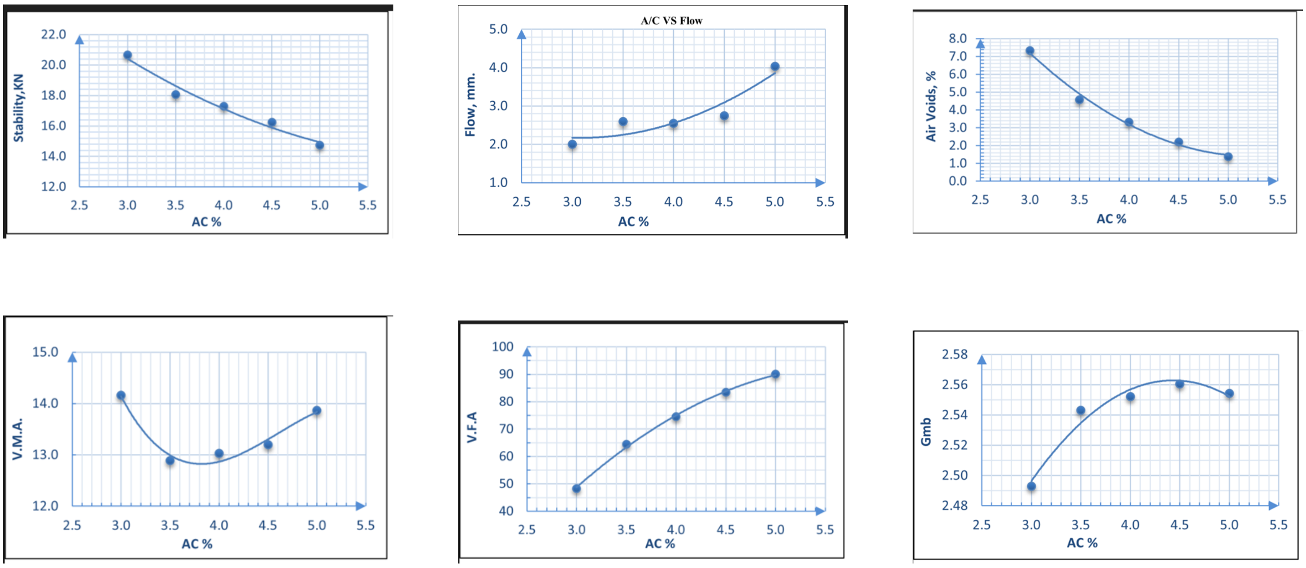


Figure 7. Performance criteria for Bajil (Stability, Flow, Va, VMA, VFA, and Gmb)

4.3. Volumetric Properties and Mix Characteristics

The volumetric properties detailed in Table 6 align with the findings for OAC and mechanical performance. The Sana'a basalt mix required a higher OAC because it exhibited a higher Voids in Mineral Aggregate (VMA) of 15.37% compared to the limestone mix's 13.77%. A higher VMA indicates more space between aggregate particles, which must be filled by asphalt binder. This confirms that the particle packing of the basalt aggregate and filler is less efficient than that of the limestone.

Both mixes achieved the target air void (Va) content of 3-5% at their respective OACs, ensuring a dense, impermeable structure. The Voids Filled with Asphalt (VFA) for both mixes also fell within the standard 65-75% range, indicating a proper balance between binder film thickness and rutting resistance. [18]

4.4. Overall Discussion and Implications

When synthesized, the results draw a clear and compelling picture. The Sana'a basalt filler produces a mechanically stronger and stiffer HMA, which may be desirable for high-stress locations like major intersections or heavily trafficked industrial routes. However, this superior strength comes at a significant economic cost due to a 26% higher asphalt binder requirement (4.8% vs. 3.8%). Furthermore, its lower TSR value indicates a higher inherent vulnerability to moisture damage, which could lead to a shorter service life without the use of expensive anti-stripping additives.

Conversely, the Bajil limestone filler emerges as a more strategic and economically rational choice for general-purpose road construction in Yemen. It produces a robust and durable HMA that meets all standard engineering specifications while requiring substantially less of the most expensive ingredient. Its superior moisture resistance (TSR of 90.7%) suggests a longer-lasting pavement with lower maintenance requirements. The combination of lower initial cost and enhanced durability makes Bajil limestone a highly attractive and sustainable alternative for the country's pavement infrastructure development.

5. CONCLUSION

This investigation undertook a thorough comparative analysis of two indigenous mineral fillers, Bajil limestone and Sana'a basalt, to evaluate their respective aptitudes for enhancing the performance and economic viability of Hot Mix Asphalt (HMA) in Yemen. The laboratory findings support several key determinations.

A primary conclusion of this research is the notable economic benefit associated with the use of limestone filler. The HMA mixture formulated with Bajil limestone necessitated a substantially lower optimum asphalt content in comparison to the mixture utilizing Sana'a basalt. This marked decrease in the required quantity of asphalt binder, the most costly constituent of HMA, signifies a clear potential for considerable cost reductions in pavement construction initiatives throughout Yemen.

Furthermore, the limestone-based mixture achieved a level of stability that comfortably surpasses the established requirements for roadways with traffic volumes, which are representative of the predominant road infrastructure in Yemen. Consequently, the limestone mixture provides ample strength for its designated use, obviating the expense associated with a higher binder content.

The study also revealed that the limestone mixture possesses superior durability and resistance to moisture. The mix with Bajil limestone showed a markedly greater resilience to moisture-induced damage, indicating a stronger adhesive bond between the limestone and the asphalt binder than that observed with the basalt filler. This enhanced adhesion suggests a longer potential service life for the pavement and a diminished susceptibility to stripping, a prevalent mode of pavement distress in the area.

In summation, although Sana'a basalt is capable of producing a good pavement, Bajil limestone stands out as the more strategically and economically sound material choice. It yields a cost-effective, durable, and adequately robust asphalt mixture that is highly suitable for the prevailing traffic conditions in Yemen.

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