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Effect of FAA and BBA Aggregate Gradations on the Marshall Performance of Asphalt Concrete Mixtures for Airport Runway Applications

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ABSTRACT

Runway pavements are subjected to heavy and repetitive aircraft loads, requiring asphalt mixtures with high stability and deformation resistance. Aggregate gradation plays a critical role in controlling the mechanical performance of Asphalt Concrete (AC) mixtures. This study investigates the effect of FAA dense-graded and BBA open-graded aggregate gradations on the Marshall characteristics of AC mixtures for airport runway applications. Laboratory Marshall testing with 75 blows of compaction was conducted to evaluate stability, flow, Marshall Quotient (MQ), voids in mix (VIM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). The results show that the optimum asphalt content (OAC) of the FAA mixture is 5.0%, while the BBA mixture requires a higher OAC of 5.6%. Under optimal conditions, the BBA mixture achieved a higher stability value (2270 kg) than the FAA mixture (2120 kg), indicating superior load-bearing capacity. The BBA mixture also exhibited higher VMA (15.82%) and VFA (77.38%), reflecting a stronger aggregate interlocking structure combined with higher asphalt content. These findings demonstrate that aggregate gradation philosophy significantly influences the mechanical performance of runway asphalt mixtures. The BBA gradation shows greater potential for use as a runway wearing course where high stability and resistance to deformation are required.

Keywords: *BBA; FAA; Gradation, Marshall Test, Optimum Bitumen Content*

Introduction

Runway

According to [1], the Runway is the most critical component because it affects flight safety. The Runway is the area where the aircraft takes off, according to data from the Central Statistics Agency [1]. The number of domestic air passengers at Juanda Airport in 2023 is projected to reach 5.2 million. This represents a 20.5% increase from 4.3 million passengers in 2022. This increase indicates increased air travel activity. In recent years, aircraft weight has increased, placing greater demands on airport pavements [2].

Due to the numerous takeoff and landing activities at airports with repeated loads, this causes damage to the runway condition such as cracking, rutting and even peeling [3]. In this case, the physical characteristics of runways [4]. Under these provisions, the asphalt surface of an airport must be smooth and free of irregularities, exhibit resistance to deformation under load and friction, provide adequate skid resistance under wet conditions through sufficient surface texture, and be free of loose materials to ensure aircraft safety.

Therefore, it is imperative to prioritize flight safety. One standard that can be implemented is the use of asphalt material in flexible pavement [5]. aggregates arranged and interlocked produce the quality of Asphalt Concrete (AC) pavement [6]. Under these conditions, a comparative evaluation of Asphalt Concrete (AC) gradation based on FAA (Federal Aviation Administration) and BBA (Beton Bitumineux pour chausées Aéronautiques) standards is required for pavement components. This evaluation aims to identify the values of stability, durability, and resistance to deformation to obtain a mixture with optimal performance.

Aggregate Gradation

Aggregate gradation is a key component of asphalt mixtures [7]. Mixture characteristics such as stability, stiffness, workability, permeability, durability, fatigue resistance, slip resistance, and resistance to water effects are strongly influenced by the aggregate size distribution [8]. Gradation is the most crucial factor in the marshalling characteristics of Asphalt Concrete (AC) mixtures, so it is necessary to select the aggregate gradation that provides the best performance [9].

In this study, 2 gradation types are used: BBA gradation (Beton Bitumineux pour chausées Aéronautiques), which is classified as an Open-Graded gradation. This gradation is widely used for the standard pavement layer on runways in France [10]. BBA includes four categories of asphalt mixtures: densely graded and gap-graded mixtures, each available with a maximum aggregate size of 10 mm or 14 mm. When a gap-graded mixture with a 14 mm size is used, the surface texture generally reaches 1.2–1.3 mm after construction, thereby minimizing the formation of surface grooves [11]. Meanwhile, the FAA (Federal Aviation Administration) gradation, classified as Dense Graded, is a gradation used by civil aviation in the United States and is also referenced by the Directorate General of Civil Aviation [12]. The differences between the two are as follows:

Dense Gradation

Continuous gradation, often referred to as well-graded, is a condition in which the aggregate composition has a complete and proportional distribution of grain sizes. In this type of gradation, all fractions starting from coarse aggregate, medium-sized aggregate, to fine aggregate are available in complementary amounts. This even particle-size distribution allows aggregates to be packed more tightly and efficiently, resulting in a more stable mixture with minimal voids [13].

Open Gradation.

Uniformly graded is a condition of aggregate composition in which the majority of the grains have very similar or nearly similar dimensions. Open gradation has a coarser mixture than dense gradation [14]. Because the grain distribution is not diverse, this gradation is also known as open gradation [15]. The gradation is illustrated in Figure 1.

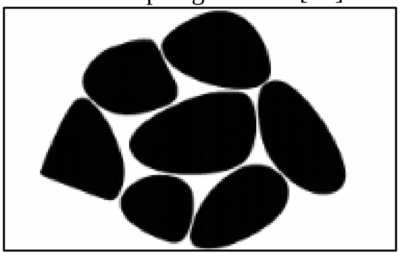

Figure 1. Illustration of Open Graded

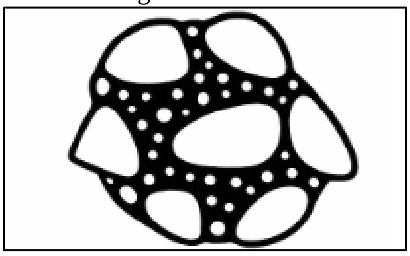

Figure 2. Illustration of Dense Graded

From a mechanical perspective, the FAA dense-graded mixture provides a compact aggregate structure with lower interconnected voids, thereby improving mixture stiffness but potentially limiting aggregate interlocking. In contrast, the BBA open-graded mixture is dominated by coarse aggregates, forming a stone-on-stone skeleton that enhances interlocking and load transfer. This structural difference is expected to significantly influence the Marshall stability and deformation resistance of the mixtures.

Asphalt

Asphalt is an adhesive material composed mainly of bitumen, a natural petroleum product [16]. Asphalt is used on road pavements to provide a layer that is resistant to vehicle loads and environmental factors [17]. In this study, Pertamina Pen 60/70 asphalt was used. Pertamina Penetration 60/70 asphalt is a variation of asphalt characterized by specific properties based on the penetration level at a temperature of 25°C. Penetration is the depth to which a standard penetration tool can penetrate the asphalt at that temperature. At the same time, the 60/70 range represents the range of penetration values for this type of asphalt (Pertamina Bitumen) [18]. In flexible pavements, 60/70 pen asphalt is often used because it is compatible with various additives and maintains good performance at lower production temperatures [19].

Marshall Performance

The Marshall Design Method began to be developed in the late 1950s to early 1960s [20]. In the specifications, the current asphalt mixture design concept uses the Marshall Method to determine the air content that meets the performance requirements under standard, uniform compaction conditions and within the specified compaction temperature range [21]. Furthermore, the Federal Aviation Administration (FAA) continues to recommend the Marshall Method for quality control of runway pavement due to its relatively fast testing procedure and simplicity in laboratory implementation [15].

Previous studies have mainly compared different asphalt mixture types for airside pavements rather than the underlying aggregate gradation philosophy. Direct laboratory comparisons between the

FAA Dense Graded and BBA Open Graded gradation approaches under identical conditions remain very limited. Therefore, this study explicitly compares these two gradation philosophies to evaluate their effects on the Marshall characteristics of runway asphalt mixtures.

Research Method

This study employed a controlled laboratory experimental approach to evaluate the effect of aggregate gradation on the Marshall performance of asphalt concrete mixtures using 60/70 penetration asphalt. All variables other than aggregate gradation were kept constant, and the evaluation was limited to laboratory-scale Marshall parameters without conducting further performance tests such as rutting or fatigue.

In this study, data were collected through a series of experiments conducted at the Transportation and Road Construction Materials Laboratory of the Sepuluh Nopember Institute of Technology. The research process will be outlined in sequence as follows:

Aggregate Testing

The aggregates used in this study came from PT. Tripalindo, one of the primary sources of material. To ensure their quality and compliance with the required specifications for the asphalt mixture, a series of tests was conducted on the aggregates. The test specifications are used as the basis for evaluating the quality of aggregates in asphalt mixtures, as shown in Tables 1 and 2.

Table 1. Coarse Aggregate Specifications

Types of Material Testing	Condition	Standard
Resistance to degradation	Maximum: 40%	ASTM C131
Aggregate durability with Sodium Sulfate / Magnesium Sulfate	Maximum 12% with sodium sulfate, 18% magnesium sulfate	ASTM C88
Clay grains and brittle particles	Maximum 0.3%	ASTM C142
Percentage of broken particles	Minimum 90%	ASTM D5821
Flat, oval particles	Maximum 8%	ASTM D4791

Table 2. Specifications for Coarse and Fine Aggregates

Laboratory test	Condition		Standard
Liquid limit	Max	25	ASTM D4318
Plasticity Index	Max	4	ASTM D4318
Clay Clumps and Friable Grains in Aggregates	Max	1 %	ASTM C88
Sand equivalence value	M in	45	ASTM D2419

Asphalt Testing

The selection of asphalt should consider local conditions, especially climate and temperature. In areas with air temperatures below 25 °C, asphalt with a penetration value higher than Pen 60/70 can be selected [22]. In accordance with the climatic conditions in Indonesia, which have an average annual temperature of > 25 °C, the type of asphalt used for runway, taxiway, and apron work is AC 60/70. For asphalt testing, the specifications are shown in Table 3.

Table 3. Coarse and Fine Aggregate Specifications

Types of Testing	Specification	Testing Method
Penetration at 25 °C (0.1 mm)	60-70	ASTM D 5-95
Softening point (°C)	≥ 48	ASTM D 36-86
Ductility at 25 °C, (cm)	≥ 100	ASTM D 113-86
Flash point (°C)	≥ 232	ASTM D 92-90
Solubility in Trichloroethylene (%)	≥ 99	ASTM D 2042
Specific gravity	≥ 1.0	ASTM D 70-82

Mixed Planning

Asphalt mix design plays an essential role in ensuring pavements have long-term durability and optimal structural performance [23]. The gradations used are BBA and FAA gradations. To meet pavement specifications, all aggregate particles must be within a specified size range and used in a specified proportional ratio. This distribution pattern of various aggregate grain sizes is defined as aggregate gradation [24]. The gradation to be used in this research is shown in Figures 3 and 4.

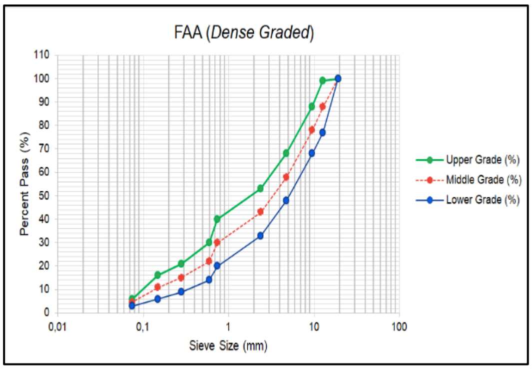

Figure 3. FAA Gradation (Dense Graded)

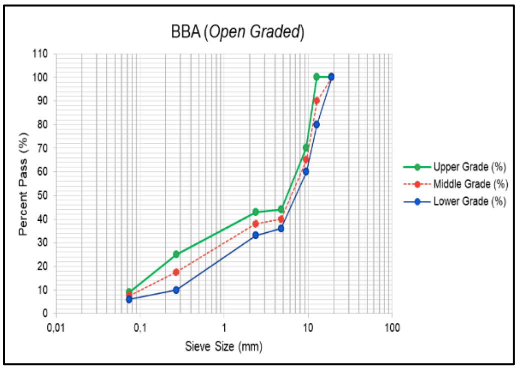

Figure 4. BBA Gradation (Open Graded)

Before mixing, determining the optimal asphalt content is crucial to ensuring the asphalt mixture has adequate structural performance and durability. Determining the optimum asphalt content usually begins with selecting the initial asphalt content, which serves as an initial estimate in the mix design process [8]. This value is generally referred to as the middle asphalt content or ideal asphalt content because it falls within the middle range of asphalt content theoretically expected to produce a mixture with the best volumetric characteristics and stability.

$$Pb = 0.035\ (\%CA) + 0.045(\%FA) + 0.18\ (\%\ Filler) + Constant \quad (1)$$

Using the equation for the middle asphalt content, the estimated asphalt content (Pb) is 5.7% for the Dense-Graded mixture. Meanwhile, for the Open Graded mixture, the resulting value is slightly higher, namely 5.9%, in line with the characteristics of open gradation, which has larger aggregate-to-aggregate spacing and requires relatively more asphalt to achieve adequate bonding and stability.

Marshall Testing

This Marshall test is used to evaluate the performance of the mixture design created. Flow, stability, Marshall Quotient, VIM, VMA, and VFA can be determined after Marshall testing for each gradation. The test specimen is compacted 75 times on each side using an automatic tamper [27] and then left at room temperature for 24 hours. To determine the VIM, VMA, and VFA values, the test specimens were weighed to determine the dry weight, then soaked for 24 hours. Next, the test specimens were weighed in water, and then drained and dried using a damp cloth for the SSD condition weighing process. Before testing, the Marshall test specimens were soaked in water at 60 °C for approximately 30 minutes. After the soaking stage was complete, each test specimen was then tested using a Marshall machine to obtain stability and flow values. The characteristics of the asphalt concrete mixture for both types of gradation in this study are in accordance with the technical specifications set out in the 1 2012 Federal Aviation Administration guidelines. These guidelines specifically regulate the mixture requirements used in the surface course of airport runway pavements. Details of these provisions are presented in Table 4.

Table 4. Asphalt Concrete Requirements for Airport Paving

Testing Properties	Pavement Design
Number of Collisions	75
Stability, pounds (kg) minimum	2150 (975)
Flow	10–16
Target air voids	3.5
VMA	15%

Result and Discussion

Material Quality Test Results

This study focused on evaluating the quality of the two principal constituents of asphalt mixtures, namely aggregates (coarse and fine) and asphalt binder. The aggregate tests comprised measurements of specific gravity, water absorption, abrasion resistance, and other properties associated with aggregate strength and particle integrity, which are essential to ensuring adequate mechanical performance of the mixture.

The asphalt binder was characterized through penetration, ductility, softening point, flash point, and specific gravity tests. These parameters were used to assess the binder's consistency, flexibility, temperature susceptibility, and thermal stability, thereby confirming its suitability for pavement applications.

The complete results of the material quality evaluations for coarse aggregates, fine aggregates, and asphalt binder are presented in Tables 5, 6, and 7, respectively. These results serve as the fundamental basis for assessing the appropriateness of the materials before their application in the asphalt mix design process.

Table 5. Coarse Aggregate Test Results

Type	Standard	Condition		Test Results
		Min	Max	
Bulk Specific Gravity	-	2.5	-	2.65
SSD Specific Gravity	-	2.5	-	2.69
Apparent Specific Gravity	-	2.5	-	2.75
Absorption	SNI-03-1969-2008	-	3%	1.40%
Aggregate Wear	ASTM C131	-	30%	28.55%

Table 6. Results of Fine Aggregate Testing

Type	Standard	Condition		Test Results
		Min	**Max**	
Bulk Specific Gravity	-	2.5	-	2.52
SSD Specific Gravity	-	2.5	-	2.57
Apparent Specific Gravity	-	2.5	-	2.64
Absorption	SNI-03-1969-2008	-	3%	1.8%

Table 7. Results of Asphalt Pen 60/70 Testing

No	Types of Testing	Testing Method	Unit	Mark	Specification*)
1	Penetration 25 ˚C	ASTM D 5-95	0.1 mm	64.5	60-70
2	Ductility 25 ˚C	ASTM D 113-86	cm	132	≥ 100
3	Softening Point	ASTM D 36-86	˚C	52	≥ 48
4	Flash point	ASTM D 92-90	˚C	315	≥ 232
5	Burn Point	ASTM D 92-90	˚C	319	-
6	Specific gravity	ASTM D 70-82	gr/cm ^{3}	1.08	≥ 1.0

Characteristics of an asphalt mixture

The Marshall test primarily provides two fundamental parameters, namely stability and flow. After applying the necessary corrections to the measured stability values, the mixture performance index, the Marshall Quotient (MQ), is calculated. The Marshall Quotient is defined as the ratio between the corrected stability and the corresponding flow value, expressed as:

$$MQ = Stability / Flow \quad (2)$$

This parameter represents the mixture's stiffness and its resistance to permanent deformation. The complete results of the Marshall characteristics, including Stability, Flow, and Marshall Quotient, are summarized in Tables 8 and 9 for the FAA and BBA gradations, respectively.

Table 8. FAA Marshall Gradation Properties Results (Dense Graded)

Properties Testing	Asphalt Content (%)					Standard
	4.7	**5.2**	**5.7**	**6.2**	**6.7**	
Stability	1820.98	2319.51	2121.08	1844.43	1764.86	Min. 800 kg
Flow	3.37	3.35	3.47	3.89	3.92	2-4 mm
MQ	541.45	698.1	610.94	476.23	449.82	Min. 250 kg/mm
VIM	5.07	3.74	2.16	1.18	1.08	3-5%
VMA	15.18	15.01	14.64	14.8	15.72	Min. 15%
VFA	66.69	75.07	85.31	92.07	93.15	Min. 65%

The data from Table 8 will be used to create a graph showing the relationship between each Marshall parameter (such as stability, flow, VIM, VMA, and VF A) and the asphalt content in the mixture listed in Figure 5.

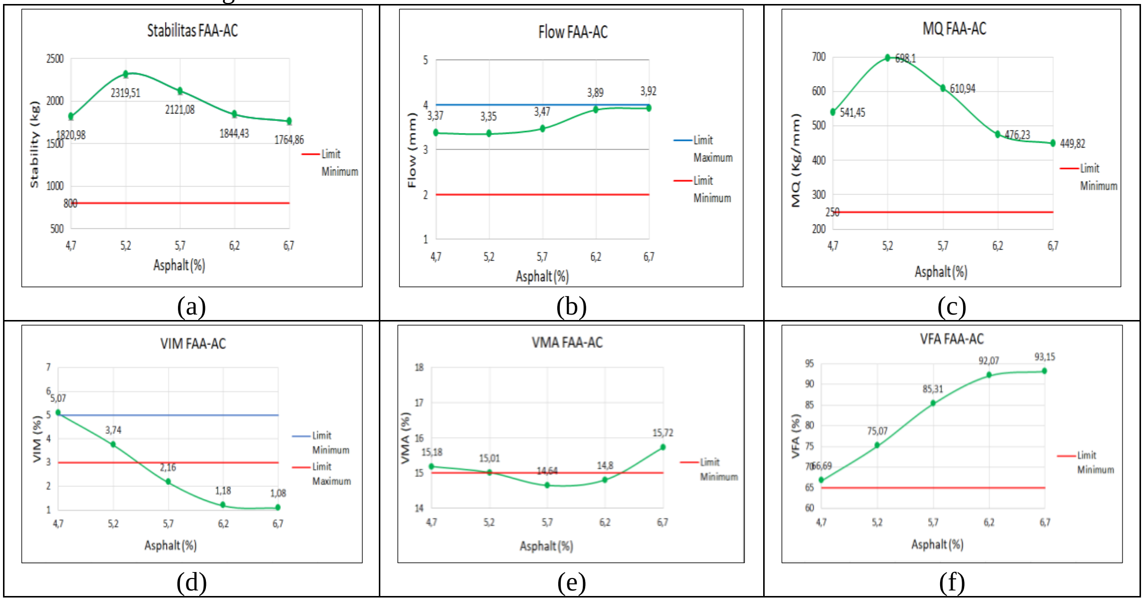

Figure 5. (a) FAA stability; (b) FAA Flow; (c) FAA MQ; (d) FAA VIM; (e) FAA VMA; (f) FAA VFA

Figure 5 shows a systematic variation of the Marshall parameters with increasing asphalt content. Stability and Marshall Quotient (MQ) exhibit a decreasing trend, indicating a reduction in the mixture's load-bearing capacity and stiffness as the asphalt content increases. This behavior reflects the transition of the mixture toward a more ductile, less structurally rigid state.

Conversely, the flow value and the Volume of Filler Asphalt (VFA) tend to increase with higher asphalt content, demonstrating that the mixture becomes more flexible and more susceptible to deformation under loading. This increase is associated with the greater proportion of asphalt binder within the mixture, which enhances plasticity.

Meanwhile, the Volume of Interconnected Voids (VIM) and the Voids in Mineral Aggregate (VMA) both show a decreasing trend. This occurs because additional asphalt progressively fills the voids between aggregates, thereby reducing the amount of air voids and inter-aggregate spaces within the mixture.

Based on the combined trends of these Marshall parameters (Stability, flow, VIM, VMA, VFA), the optimum asphalt content for the FAA (Dense Graded) mixture can be determined, as illustrated in Figure 6.

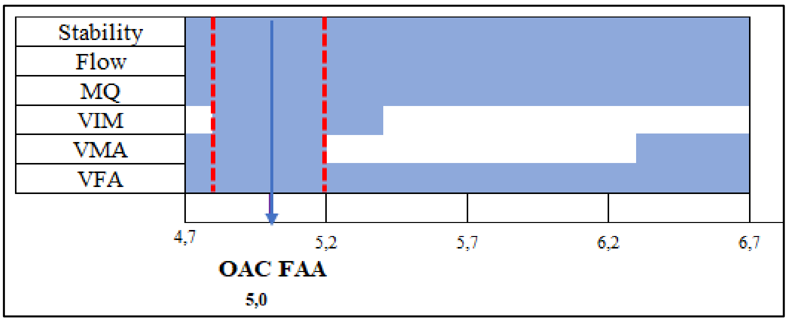

Figure 6. Optimum Asphalt Content FAA Gradation (Dense Graded)

Similarly, the Optimum Asphalt Content for the BBA (Open-Graded) mixture was determined using the same procedure. The results of the Marshall parameters and the corresponding OAC determination for the BBA gradation are presented in Table 9.

Table 9. Marshall Properties Results of BBA Gradation (Open Graded)

Testing Properties	Asphalt Content (%)					Standard
	4.9	5.4	5.9	6.4	6.9	

Stability	1849.46	2168.8	2421.18	1712	1624.44	Min. 800 kg
Flow	3.29	3.64	4.03	4.16	4.68	2-4 mm
MQ	562.54	595.74	602.41	412.36	348.71	Min. 250 kg/mm
VIM	6.28	4.08	2.86	1.26	1.04	3-5%
VMA	16.77	15.84	15.78	15.41	16.22	Min. 15%
VFA	62.6	74.35	81.92	91.93	93.68	Min. 65%

Based on the Marshall Properties of BBA Gradation in Table 9, a graph of the relationship between the Marshall parameters and asphalt content is shown in Figure 7.

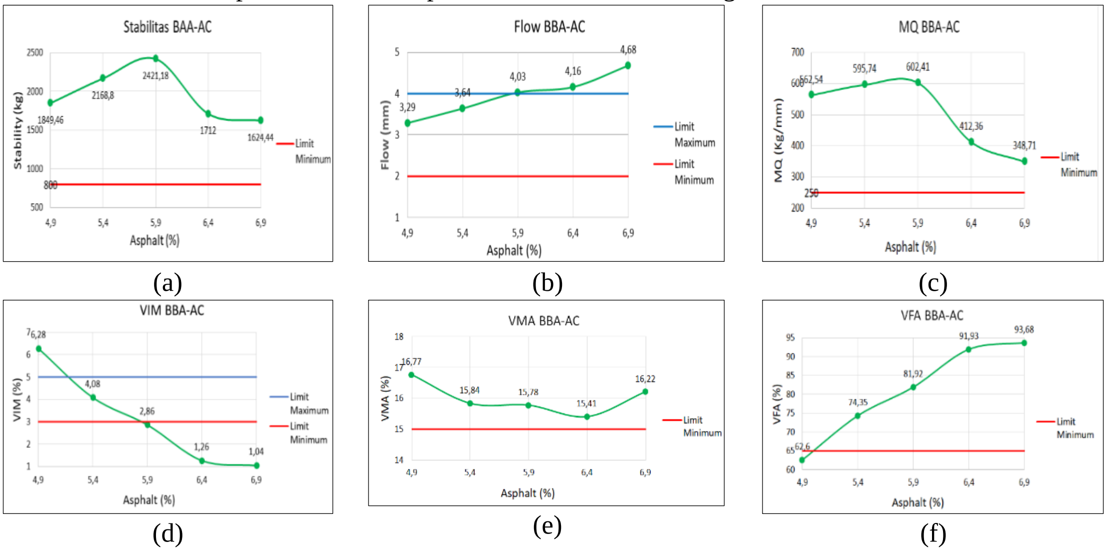

Figure 7. (a) BBA stability; (b) Flow BBA; (c) MQ BBA; (d) VIM BBA; (e) VMA BBA; (f) BBA FAA

Based on the combined behavior of these Marshall and volumetric parameters (Stability, Flow, VIM, VMA, VFA), the Optimum Asphalt Content (OAC) for the BBA (Open Graded) gradation can be determined, as it represents the asphalt content at which the mixture achieves a balanced performance in terms of stability, deformation resistance, and volumetric requirements.

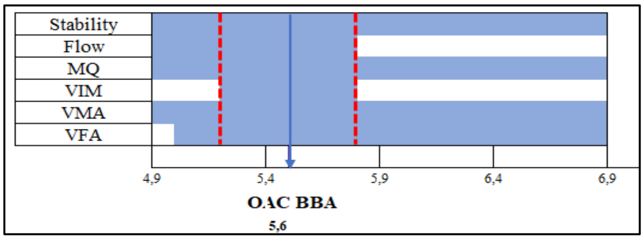

Figure 8. Optimum Asphalt Content for BBA Gradation (Open Graded)

The Optimum Asphalt Content (OAC) for both gradations were determined using a bar-chart analysis that graphically compares all Marshall parameters, including Stability, Flow, VIM (Voids in Mix), VMA (Voids in Mineral Aggregate), and VFA (Voids Filled with Asphalt), across asphalt content variations. Based on the combined trends and compliance of each parameter with the specified criteria, the OAC was determined to be 5.0% for the FAA (dense-graded) mixture and 5.6% for the BBA (open-graded) mixture.

Marshall Test Data Analysis

After the Optimum Asphalt Content (OAC) for each gradation was established, asphalt mixture specimens were prepared using the respective optimum values. These specimens were then subjected to laboratory testing to evaluate their mechanical performance. The FAA and BBA mixtures, produced at their respective OACs, were tested to determine the main Marshall parameters: stability, flow, and the Marshall Quotient (MQ).

These parameters reflect the mixture's resistance to deformation, workability, and overall structural capacity under loading conditions. A comparison between the optimum asphalt content and the corresponding stability values for each gradation is presented in Figure 9.

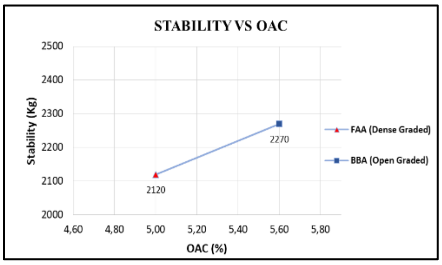

Figure 9. Stability vs. Optimum Asphalt Content

The higher stability obtained by the BBA mixture (2270 kg) compared to the FAA mixture (2120 kg) can be attributed to the open-graded structure of BBA, which promotes stronger stone-on-stone contact and aggregate interlocking. This interlocking mechanism improves load transfer efficiency and enhances resistance to shear deformation. In contrast, the dense-graded FAA mixture relies more on asphalt mortar for load distribution, which reduces its maximum achievable stability. For Optimum Asphalt Content and flow can be seen in Figure 10

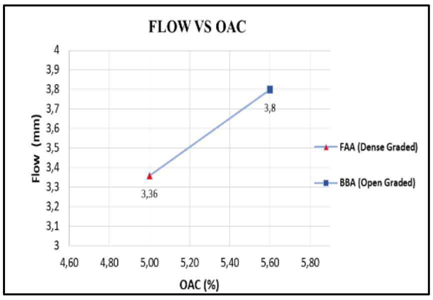

Figure 10. Stability vs. Optimum Asphalt Content

Figure 9 indicates that the flow value is strongly influenced by the asphalt content in the mixture. As the asphalt content increases, the mixture becomes more plastic and more susceptible to deformation under applied loads. This effect is more pronounced in the BBA (Open Graded) mixture, which consistently exhibits higher flow values than the FAA (Dense Graded) mixture.

At its optimum asphalt content of 5.6%, the BBA mixture produces a flow value of 3.8 mm, whereas the FAA mixture, at its optimum asphalt content of 5.0%, shows a lower flow value of 3.36 mm. This difference suggests that the open-graded aggregate structure of the BBA mixture, which contains larger inter-aggregate voids, allows a greater proportion of asphalt binder to dominate the mixture behavior, thereby increasing its plasticity and tendency to flow.

In contrast, the denser aggregate arrangement in the FAA mixture provides stronger internal confinement of the binder, resulting in lower flow values and improved resistance to plastic deformation. The relationship between the Optimum Asphalt Content and the VIM value is further illustrated in Figure 11.

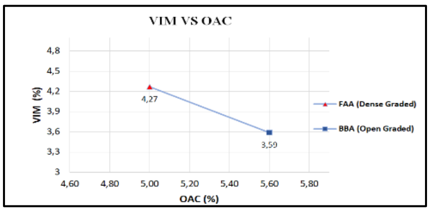

Figure 11. VIM vs. Optimum Asphalt Content

Figure 10 shows that, under optimum conditions, the dense-graded mixture contains a higher proportion of air voids than the open-graded mixture.

This phenomenon is primarily attributed to the higher Optimum Asphalt Content (OAC) required by the BBA mixture. The greater amount of asphalt binder in the BBA mixture more effectively fills the intergranular voids, thereby reducing the remaining air voids within the mixture. Although a more open aggregate structure generally characterizes open-graded mixtures, the increased asphalt content compensates for this condition by occupying a greater portion of the available voids.

Therefore, the asphalt content plays a dominant role in controlling the VIM, resulting in the BBA mixture exhibiting a lower VIM than the FAA mixture despite its open-graded nature. The relationship between Optimum Asphalt Content and VMA is further illustrated in Figure 12.

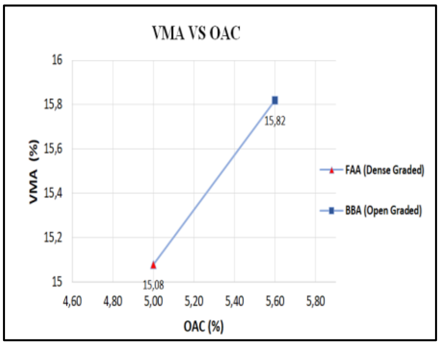

Figure 12. VMA vs. Optimum Asphalt Content

Figure 11 shows that the higher VMA in the BBA mixture is mainly attributed to its aggregate composition, which is dominated by coarse particles with a relatively smaller proportion of fine aggregates. As a result, the inter-granular voids cannot be filled optimally, leading to a looser aggregate skeleton and a larger volume of mineral voids. In contrast, the FAA dense-graded mixture has a more continuous, well-distributed particle-size gradation, allowing finer aggregates to effectively fill the spaces between coarse particles and producing a more compact structure with a lower VMA.

This behavior is consistent with the fundamental characteristics of open-graded mixtures, which are designed to form a stone-on-stone skeleton with relatively larger internal void spaces. The relationship between the Optimum Asphalt Content and the VFA value is further presented in Figure 13.

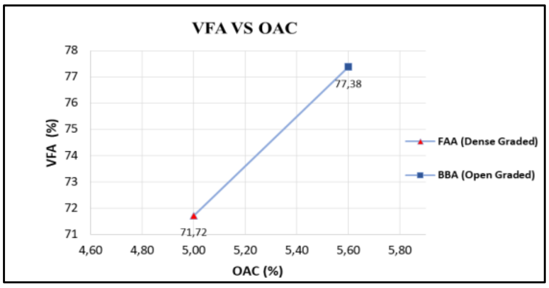

Figure 13. VFA vs. Optimum Asphalt Content

Figure 12 The results indicate that the BBA (open-graded) mixture exhibits a higher VFA value of 77.38% at an optimum asphalt content of 5.6%, compared to 71.72% for the FAA (dense-graded) mixture at 5.0%. This higher VFA is associated with the greater optimum asphalt content required by the BBA gradation and its inherently more open aggregate structure. Despite the higher asphalt content, the BBA mixture maintains effective *stone-on-stone contact* among coarse aggregates, allowing load transfer to be dominated by the aggregate skeleton rather than the asphalt binder, thereby enhancing resistance to permanent deformation (*rutting*). In contrast, the dense aggregate structure of the FAA mixture limits the increase in VFA and relies more on binder contribution for load distribution.

Conclusion

This study confirms that aggregate gradation philosophy significantly influences the Marshall performance of asphalt concrete mixtures for airport runways. The BBA open-graded mixture exhibited superior mechanical performance, achieving higher stability (2270 kg), greater VMA (15.82%), and higher VFA (77.38%) at an optimum asphalt content of 5.6%, compared to the FAA dense-graded mixture, which reached a stability of 2120 kg at 5.0%. From a practical runway perspective, these results indicate that the BBA gradation is better suited to surface layers subjected to high aircraft wheel loads and braking forces, where a strong aggregate skeleton and effective stone-on-stone contact are required to enhance load transfer and resistance to deformation. In contrast, the FAA gradation remains appropriate for general runway conditions that prioritize uniform compaction and volumetric control.

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