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Effect of Aggregate Gradation on Design Mix Using Modified Bitumen

Biswajit Das[1], Krushna Chandra Sethi[2], Jyoti Prakash Giri[3]
[1]PG Student, [2]Assistant Professor, [3]Associate Professor, Department of Civil Engineering, Centurion University of Technology and Management, Bhubaneswar, Khurda, Odisha, India–752050

Abstract: This study evaluates the influence of aggregate gradation and modified binders on the performance characteristics of Dense Bituminous Macadam (DBM) mixes, employing the Marshall mix design method in accordance with ASTM D1559. The investigation compares two aggregate gradation types—dense-graded and open-graded—and two binder types: conventional bitumen (VG-40) and crumb rubber modified bitumen (CRMB-60). A comprehensive suite of laboratory tests was performed, including Marshall Stability, flow value, bulk density, and volumetric properties such as Voids in Mineral Aggregate (VMA), Voids Filled with Bitumen (VFB), and air voids. Additional evaluations included Indirect Tensile Strength (ITS) and the Texas Boiling Test to assess moisture susceptibility. The findings indicate that open-graded mixes exhibit enhanced strength and stability performance relative to dense-graded counterparts. Moreover, CRMB-60 outperformed VG-40 in terms of Marshall Stability, tensile strength, and resistance to moisture-induced stripping. The optimum binder content (OBC) was identified based on an optimal balance of maximum stability, bulk density, 4% air voids, and 80% VFB.Overall, the synergy of an open-graded aggregate structure with CRMB binder resulted in the most durable and high-performing bituminous mix. These results underscore the critical role of aggregate gradation and binder modification in improving pavement performance, suggesting their suitability for high-traffic roadways and long-term infrastructure sustainability.

Keywords: Dense Bituminous Macadam (DBM), Aggregate Gradation, Modified Bitumen, Marshall Stability, CRMB, Neat Bitumen (VG-40), VMA, VFB, Indirect Tensile Strength (ITS), Moisture Susceptibility

I. INTRODUCTION

Bituminous pavements are extensively utilized in road construction owing to their cost-efficiency, structural flexibility, and ease of maintenance. The performance of Dense Bituminous Macadam (DBM) mixes is predominantly governed by two key parameters: aggregate gradation and binder type. Aggregates, constituting the majority of the mix volume, significantly influence the structural integrity, load-bearing capacity, and durability of the pavement. Concurrently, the type and quality of binder determine the cohesive and adhesive characteristics of the mixture. With escalating traffic demands and growing environmental concerns, optimizing these two components has become crucial for achieving high-performance asphalt pavements.Aggregate gradation refers to the distribution of particle sizes within the mix and plays a pivotal role in determining internal friction, void structure, and overall workability. Dense-graded mixes incorporate a full spectrum of aggregate sizes, facilitating better interlocking and load distribution, whereas open-graded mixes promote higher air voids, enhancing drainage and minimizing the risk of hydroplaning. Extensive research has confirmed that aggregate gradation significantly affects critical performance attributes such as rutting resistance, fatigue life, and volumetric stability [12], [13]. Golalipour et al. [12] demonstrated that poor gradation can elevate rutting potential, particularly in high-temperature regions with heavy traffic. Sridhar et al. [13] further emphasized that gradation and compaction effort directly impact the mechanical behavior and stability of dense bituminous macadam.Parallel to aggregate considerations, the selection of binder type profoundly influences the overall performance of DBM mixes. Conventional binders like VG-40 are widely used in Indian pavement construction due to their compliance with standard specifications. However, their limitations under extreme temperature variations and high-load conditions have prompted the adoption of modified binders. Crumb Rubber Modified Bitumen (CRMB), incorporating recycled rubber, improves elasticity, resistance to aging, and moisture susceptibility, while contributing to sustainable construction practices [1], [6]. Khan and Singh [1] noted that CRMB significantly enhances Marshall Stability and durability when paired with appropriate gradation. The Indian Roads Congress [6] has also endorsed the use of modified binders to improve pavement performance in stress-intensive and high-temperature environments.Aggregate gradation also affects binder-aggregate interaction. Open-graded mixes, with higher void content, tend to absorb more binder and may necessitate the use of higher-viscosity or modified binders to mitigate binder drain-down and stripping. Alvarez et al.

[10] compared surface friction course mixtures using asphalt rubber and performance-grade binders, concluding that modified binders enhance cohesion and minimize binder runoff. Afaf [11] further demonstrated that aggregate type and gradation influence air voids and flow characteristics—critical factors in determining optimum binder content.The Marshall mix design method, as per ASTM D1559 [8], remains a standard approach to evaluate the mechanical and volumetric properties of DBM mixes. This procedure helps determine the Optimum Binder Content (OBC) through the analysis of parameters like stability, flow, bulk density, air voids, and Voids Filled with Bitumen (VFB). Sharma and Jain [3] utilized this method to assess modified binders, finding that CRMB contributes to higher stiffness and improved resistance to repeated loading. Priyadharshini et al. [14] added that mixing and compaction temperatures significantly affect the dynamic modulus of modified mixes, thereby influencing the design output.In addition to the Marshall test, supplementary performance tests such as Indirect Tensile Strength (ITS) and the Texas Boiling Test are employed to assess tensile strength and moisture susceptibility. These tests are critical in evaluating the resilience of DBM mixes under environmental and hydraulic stresses. Reddy and Ransinchung [2] reported that CRMB exhibits superior bonding with aggregates, resulting in elevated ITS values and reduced moisture damage. Patil and Deshmukh [5] corroborated these findings, highlighting CRMB's effectiveness in minimizing stripping and enhancing pavement longevity.

II. LITERATURE REVIEW

The performance of bituminous mixtures is significantly influenced by aggregate gradation and the type of binder employed. Golalipour et al. [12] examined the impact of aggregate gradation on rutting behavior in asphalt pavements and found that coarser gradations generally exhibit superior rutting resistance, attributed to increased internal friction and enhanced load-bearing capability. Similarly, Sridhar et al. [13] reported that both aggregate gradation and compaction effort substantially affect the Marshall characteristics and mechanical integrity of dense bituminous macadam (DBM).

The incorporation of modified binders, particularly Crumb Rubber Modified Bitumen (CRMB), has shown considerable promise in improving pavement performance and durability. Khan and Singh [1] demonstrated that CRMB significantly enhances Marshall Stability and moisture resistance in Dense Bituminous Macadam compared to conventional VG-40 binders. Supporting this, Reddy and Ransinchung [2] highlighted the improved tensile strength and reduced stripping potential of CRMB, making it a suitable binder for heavily trafficked roads.

Alvarez et al. [10] conducted a comparative evaluation of asphalt rubber and performance-grade binders, revealing that rubber-modified mixes offer enhanced resistance to deformation and binder draindown, particularly in permeable friction course (PFC) applications. In a related study, Afaf [11] explored the influence of aggregate gradation and type on hot mix asphalt (HMA), concluding that finer gradations tend to increase the flow value and decrease air voids, thereby affecting key volumetric properties.

Sharma and Jain [3] assessed the Marshall properties of Dense Bituminous Macadam mixes incorporating modified binders and observed improvements in mix stability and stiffness under high-load conditions. Priyadharshini et al. [14] emphasized the critical role of temperature during mixing and compaction when using modified binders, noting its influence on the dynamic modulus and overall workability of the mix.

With regard to moisture susceptibility, Patil and Deshmukh [5] found that CRMB substantially reduces stripping in bituminous mixtures. These findings were validated through the Texas Boiling Test, which indicated improved binder-aggregate adhesion in CRMB mixes. Additionally, Das and Chakroborty [4] underscored the importance of volumetric parameters—specifically Voids in Mineral Aggregate (VMA) and Voids Filled with Bitumen (VFB)—in designing durable and high-performance pavement layers.

III. METHODOLOGY

This study utilized the Marshall mix design procedure, as outlined in ASTM D1559, to assess the effects of aggregate gradation and binder type on the performance of Dense Bituminous Macadam (DBM). Two types of binders were evaluated: VG-40 (conventional bitumen) and CRMB-60 (modified binder). Aggregates were classified into dense and open-graded systems in accordance with the Ministry of Road Transport and Highways (MoRTH) specifications, with coarse and fine fractions combined to prepare a total mix weight of 1200 g per specimen.

Aggregates were heated to a temperature range of 160–170°C and mixed with bitumen preheated to 135°C. Binder content varied from 5.5% to 7.5% for VG-40 and from 5.0% to 7.0% for CRMB, in 0.5% increments. Each mix was compacted using a Marshall hammer (4.5 kg) delivering 75 blows per face at 160°C, followed by a 24-hour cooling period at ambient conditions.

The primary tests conducted included Marshall Stability and Flow, Volumetric Analysis (comprising VMA, VFB, and air voids Va), Indirect Tensile Strength (ITS), and the Texas Boiling Test for assessing moisture susceptibility.

The Optimum Binder Content (OBC) was determined by averaging the binder contents corresponding to maximum stability, maximum bulk density, 4% air voids, and 80% VFB. Comparative analysis was performed across different binder types and gradation patterns to quantify performance improvements attributable to binder modification and aggregate structure.

IV. RESULTS

This study analyzes experimental data to gain insights into the influence of aggregate gradation and binder type on the performance characteristics of Dense Bituminous Macadam (DBM) mixes. Key performance indicators include Marshall Stability, Flow Value, Bulk Density, Voids in Mineral Aggregate (VMA), Voids Filled with Bitumen (VFB), and Indirect Tensile Strength (ITS). A comparative evaluation is conducted between VG 40 and CRMB 60 (a modified bitumen) under two distinct aggregate gradation conditions: dense gradation and open gradation.

Parameters:

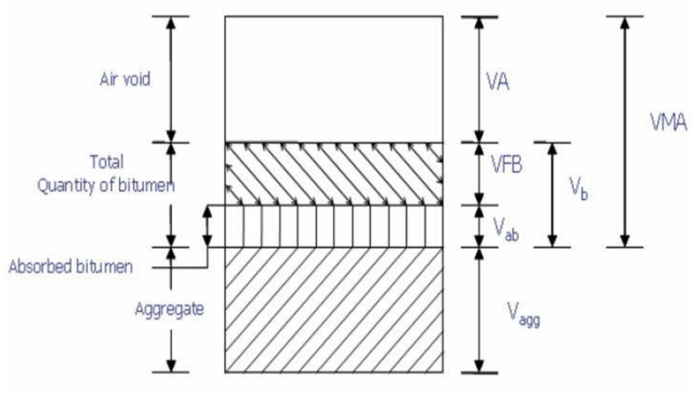

Fig1:PhaseDiagramofbituminousmix

To determine the Optimum Bitumen Content (OBC) of a mix, various parameters must be taken into account. Primarily, the calculation is predominantly influenced by the volumetric properties of the mix. Based on the work of Das A. and Chakraborty P. (2010), the following definitions and formulas are employed in the subsequent calculationshereafter are as follows:

- BulkDensityofMix:

$$\rho = \frac{weight\ of\ specimen in air}{Volume of the\ specimen}$$

Where,volumeofspecimen=weightofspecimeninair-weightinwater
ρ=bulkdensityofspecimen

- VolumeofAggregate:

$$\frac{Weight of Aggregate}{Specific Gravity of Aggregate}$$

- VolumeofBitumen:

$$\frac{Weight\ of Bitumen}{Specific\ Gravity of Bitumen}$$

- TotalVolume:

$$Volume of\ Aggregate + Volume of Bitumen$$

- VolumeofAirVoid:

$$Volume of Specimen - Total volume$$

- PercentofAirVoids (V_a):

$$\frac{Volume of Air\ Void}{Volume\ of Specimen} \times 100$$

- PercentofBitumenVolume(V_b):

$$\frac{Volume\ of\ Bitumen}{Volume\ of\ Specimen}\times 100$$

- VoidsinMineralAggregate(VMA):

$$Percent\ of\ Air\ Voids + Percent\ of\ Bitumen\ Volume$$

- VoidsFilledwithBitumen(VFB):

$$\frac{Percent\ of\ Bitumen\ Volume}{Voids\ in\ Mineral\ Aggregate}\times 100$$

A. *Influence of Aggregate Gradation on Mix Design Parameters:*

1) *Gradation (Open Graded Mix):*

Sieve size (mm)	% PASSING								
	20mm	10mm	6mm	F.Agg. (C. Dust)	20mm	10mm	6mm	F.Agg. (C. Dust)	MIX BLEND
					32.00%	25.00%	23.00%	20.00%	100.00%
37.5	100.0	100.0	100.0	100.0	32.0	25.0	23.0	20.0	100.0
26.5	100.0	100.0	100.0	100.0	32.0	25.0	23.0	20.0	100.0
19	33.11	100.00	100.0	100.0	10.6	25.0	23.0	20.0	78.6
13.2	15.72	99.82	100.0	100.0	5.0	25.0	23.0	20.0	73.0
4.75	0.00	42.08	61.11	91.7	0.0	10.5	14.1	18.3	42.9
2.36	0.00	33.62	50.96	88.9	0.0	8.4	11.7	17.8	37.9
0.300	0.00	0.00	15.84	40.2	0.0	0.0	3.6	8.0	11.7
0.075	0.00	0.00	6.88	28.6	0.0	0.0	1.6	5.7	7.3

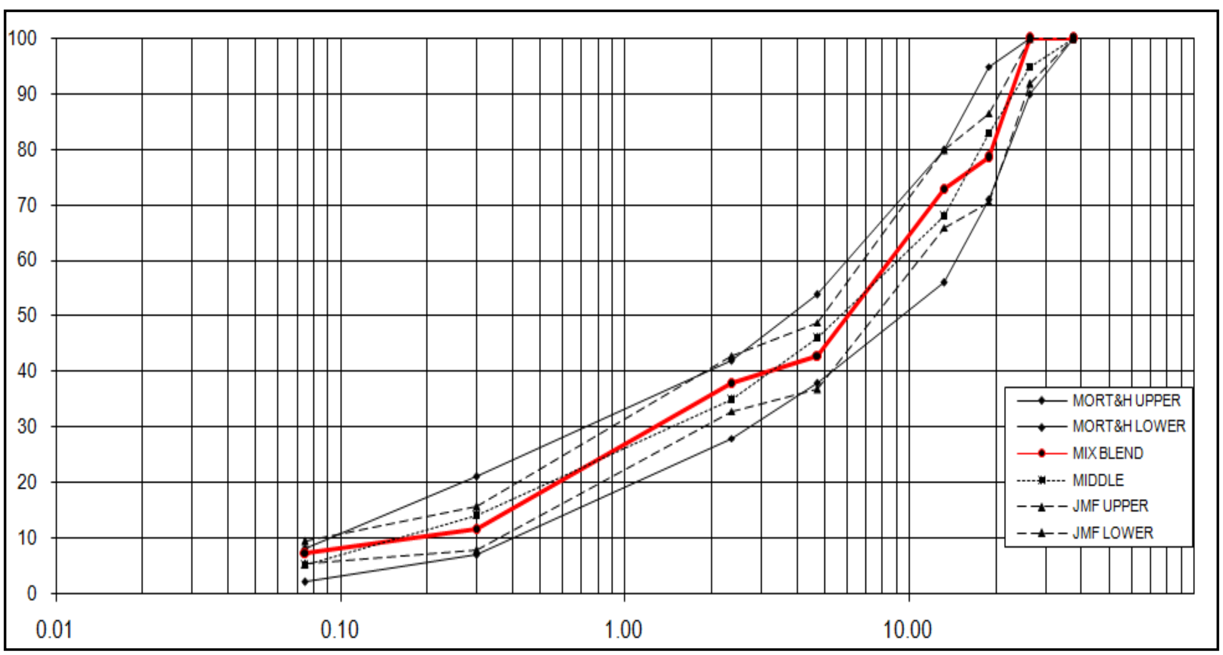

Fig2: Gradation Curve (Open Graded Mix)

2) Gradation (Dense Graded Mix):

Sieve size (mm)	% BY WEIGHT OF PASSING								
	20mm	10mm	6mm	F.Agg. (C. Dust)	20mm 32.00%	10mm 20.00%	6mm 18.00%	F.Agg. (C. Dust) 30.00%	MIX BLEND 100.00%
37.5	100.0	100.0	100.0	100.0	32.0	20.0	18.0	30.0	100.0
26.5	100.0	100.0	100.0	100.0	32.0	20.0	18.0	30.0	100.0
19	47.04	100.00	100.0	100.0	15.1	20.0	18.0	30.0	83.1
13.2	2.70	100.00	100.0	100.0	0.9	20.0	18.0	30.0	68.9
4.75	0.00	44.62	40.45	100.0	0.0	8.9	7.3	30.0	46.2
2.36	0.00	10.15	25.80	94.6	0.0	2.0	4.6	28.4	35.1
0.300	0.00	0.00	11.70	41.8	0.0	0.0	2.1	12.5	14.6
0.075	0.00	0.00	4.80	16.2	0.0	0.0	0.9	4.9	5.7

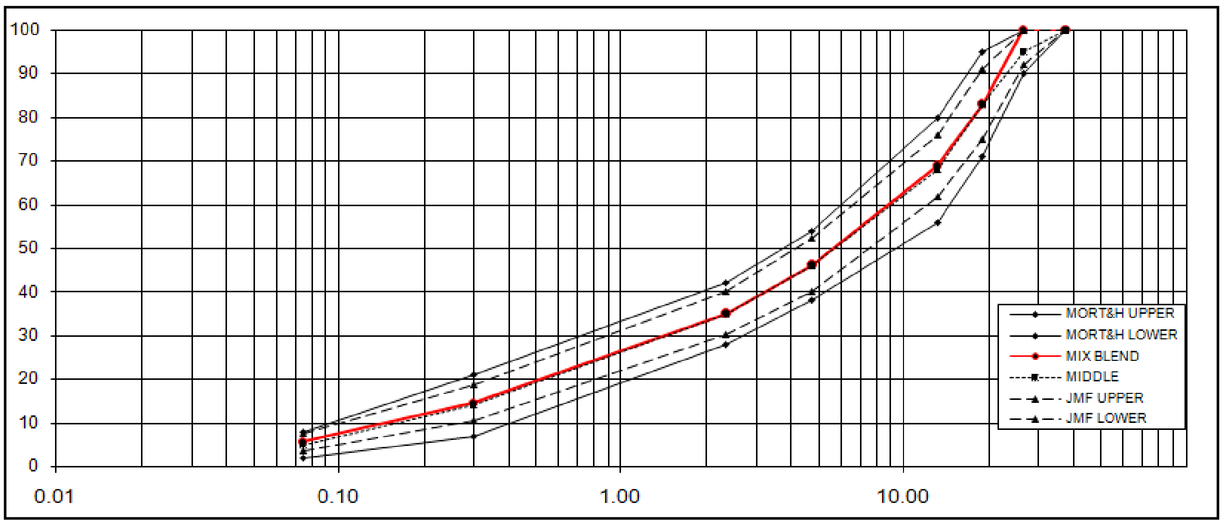

Fig3: Gradation Curve (Well Graded Mix)

3) MarshallStability:

Open-graded asphalt mixtures demonstrated superior stability compared to dense-graded counterparts, with CRMB 60 further enhancing performance relative to VG 40. This variation is illustrated in Figures 2 and 3 for VG 40 and CRMB 60, respectively:

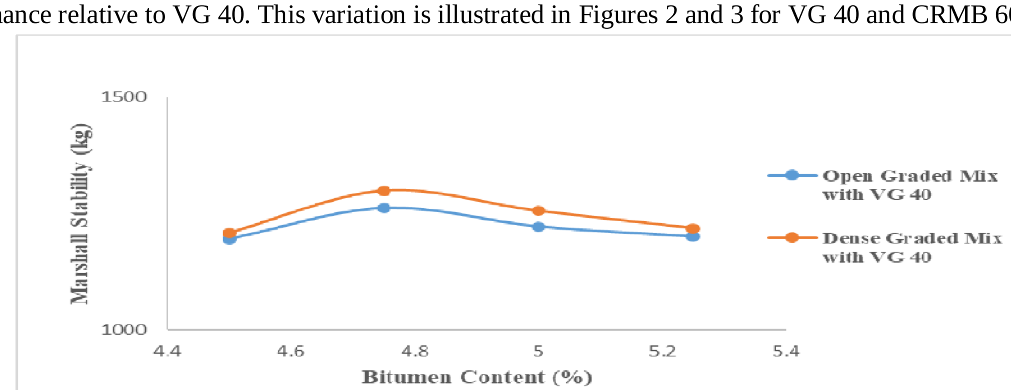

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Fig4:Marshall Stability Variation of Dense Bituminous Macadam (DBM) with Different Aggregate Gradations Using Neat Binder (VG 40)

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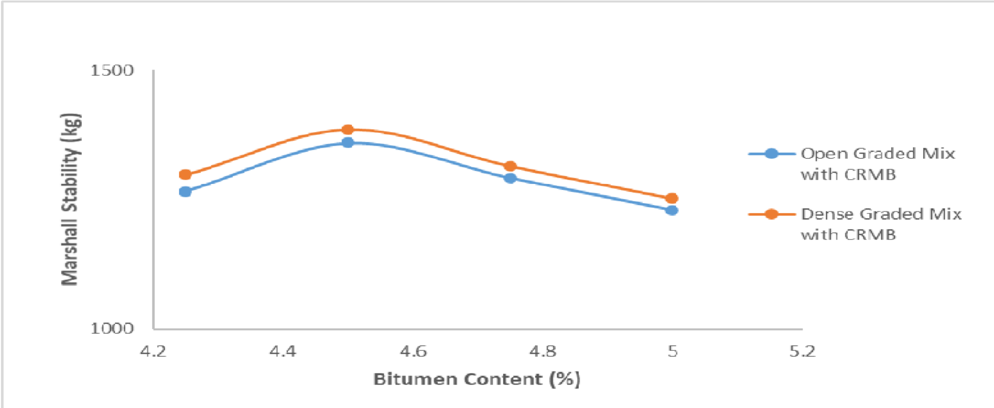

Fig5:Marshall Stability Variation of Bituminous Macadam (DBM) with Different Aggregate Gradations Using CRMB

B. 4FlowValue:

Higherflowvalueswererealizedwithelevatedbindercontentbutopengradedmixesweremoreflexible because of greater void content.

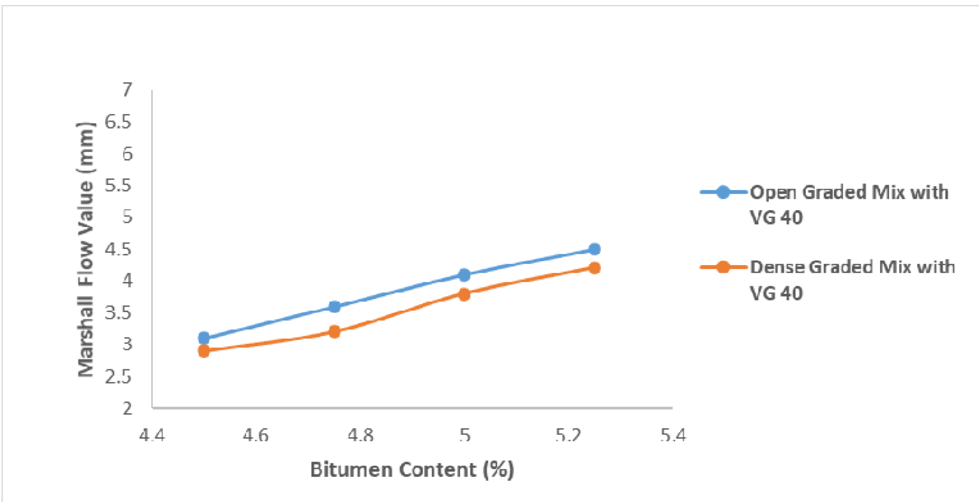

Fig6:Variation in Flow Values of Bituminous Macadam (DBM) with Different Aggregate Gradations Using VG-40

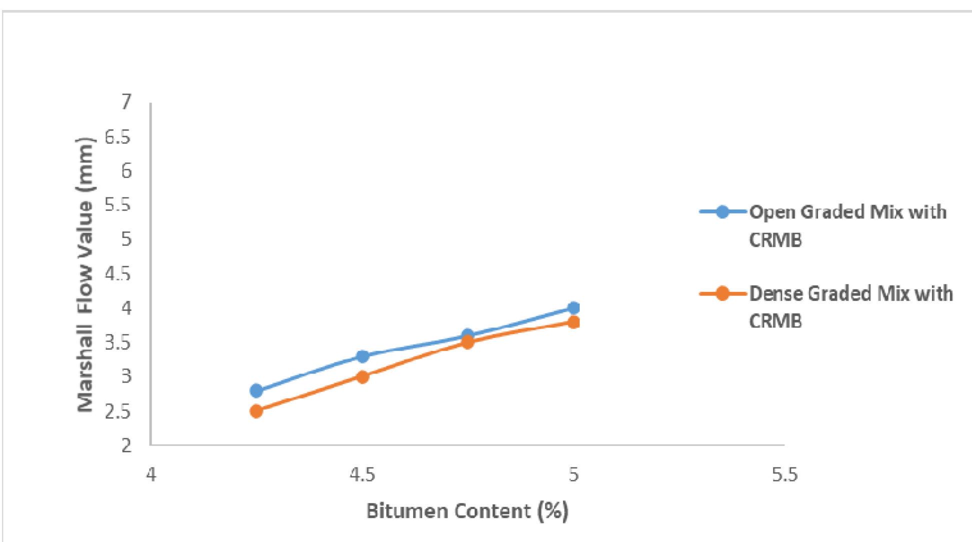

Fig7:Variation in Flow Values of Bituminous Macadam (DBM) with Different Aggregate Gradations Using CRMB

1) UnitWeight:

An observation is made that unit weight increases with an increase in the binder content up, to some point, and that it depreciates. The fig 8 and 9 shows the variations.

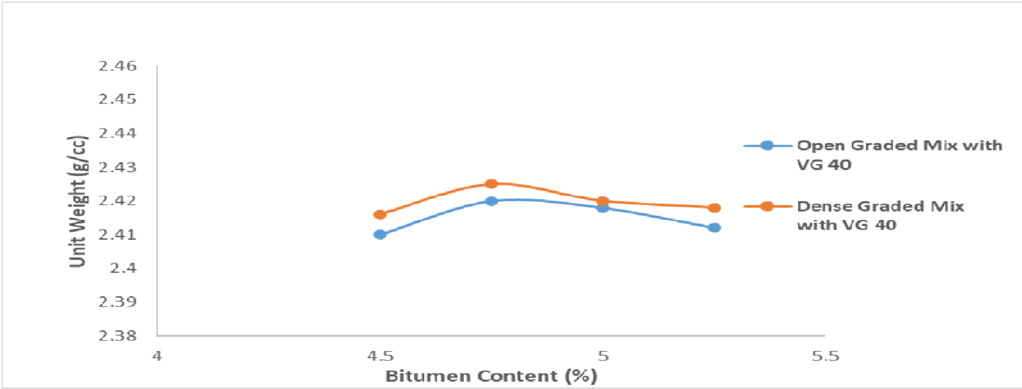

Fig8:Variation in the unit weight of Bituminous Macadam (DBM) with different binder contents of VG 40 and varying aggregate gradation

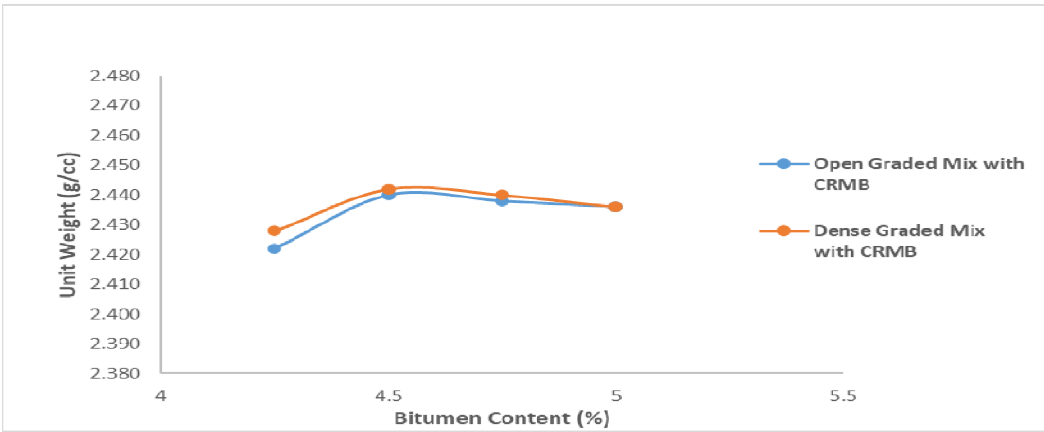

Fig9:Variation in the unit weight of Bituminous Macadam (DBM) with varying binder contents of CRMB and different aggregate gradations

2) VMA:

Theresultofthisstudyshowsthattheairvoidvaluegoestodownwithincreasebindercontent.Fig10and11 gives the variation of air void with different binder content.

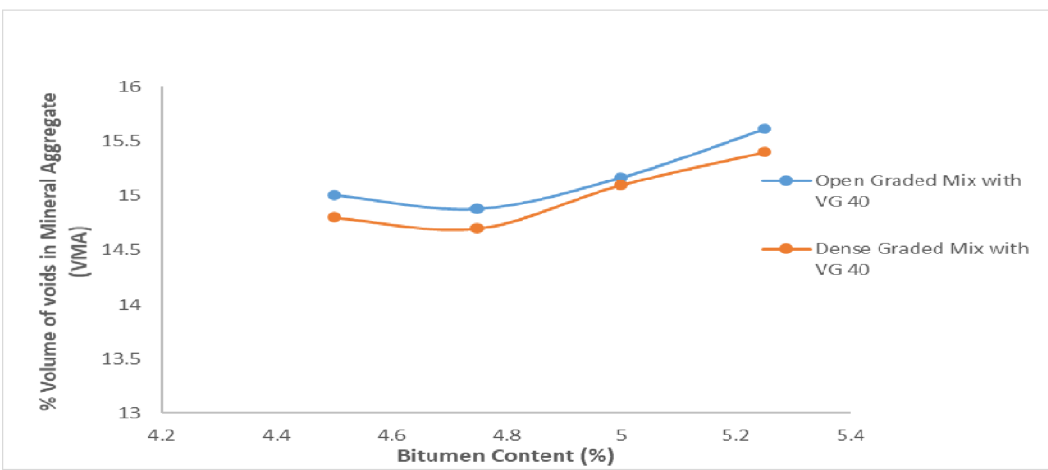

Fig10:VariationofVMAofBituminous Macadam (DBM)withdifferentaggregategradation (With VG 40)

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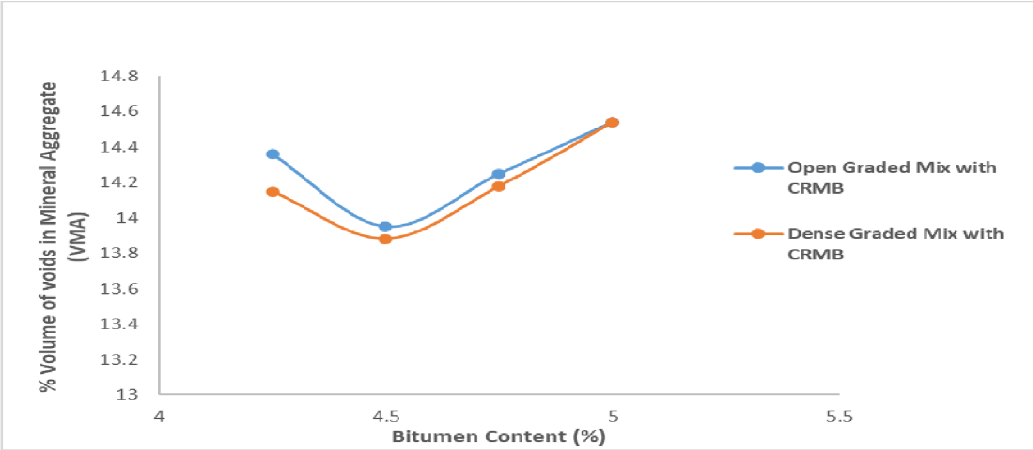

Fig11:VariationofVMAofDBMwithaggregategradation (With CRMB)

3) VFB:

Whenthebindercontentisincreased,theVFBalsorises.BothFigure12andFigure13illustratethedifference in VFB that occurs with varying binder contents.

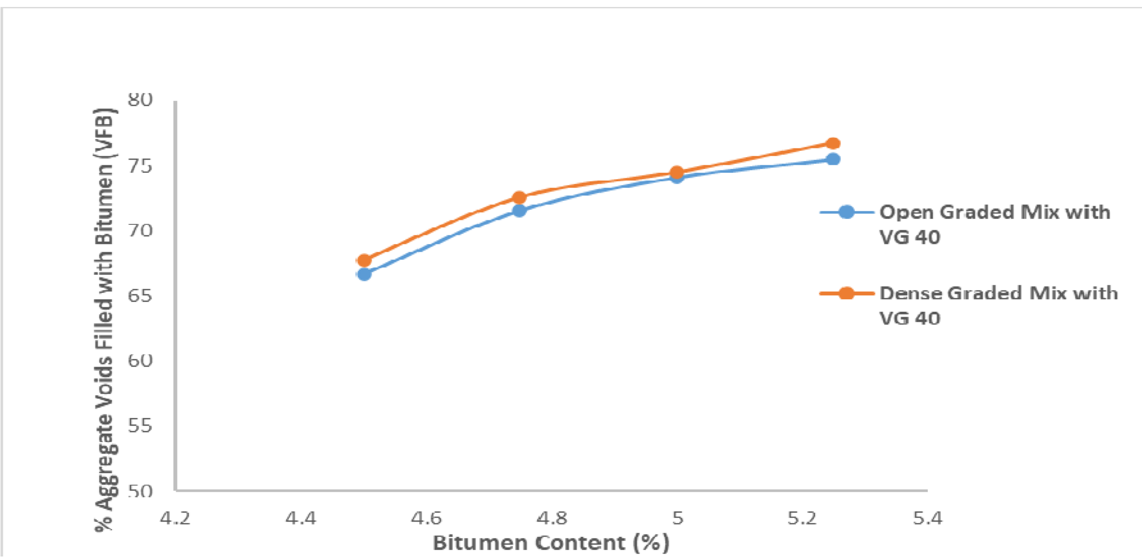

Fig12:VariationofVFBofDBMwithdifferentaggregategradation (With VG 40)

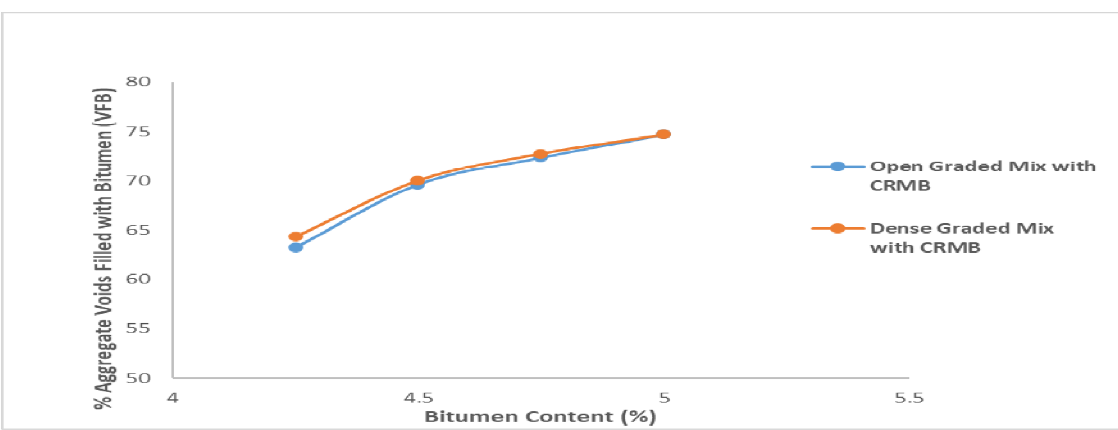

Fig13:VariationofVFBofDBMwithdifferentaggregategradation (With CRMB)

4) VA:

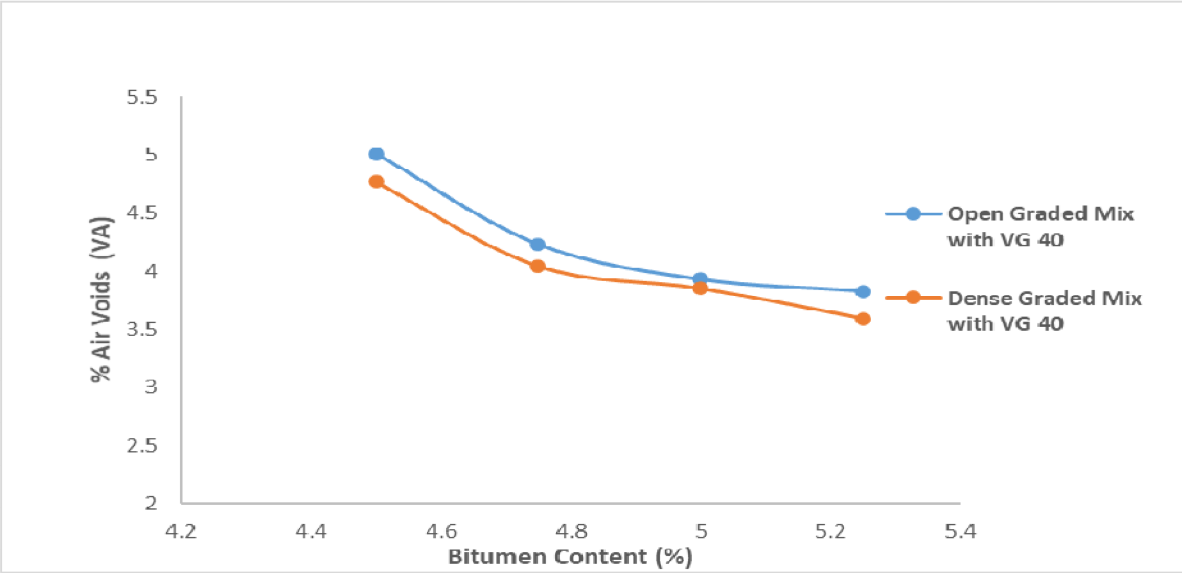

Fig14:VariationofVAof DBMwithdifferentaggregategradation (With VG 40)

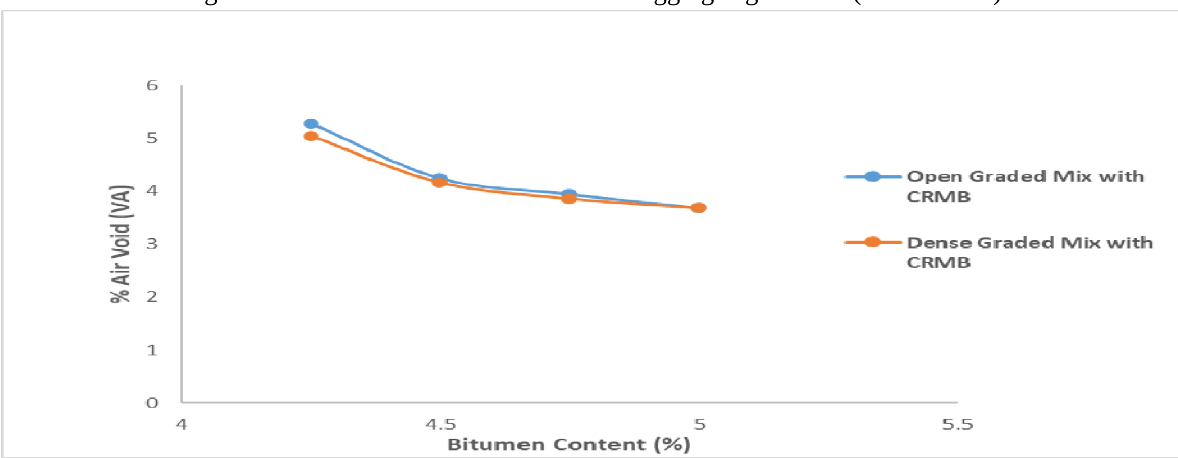

Fig15:VariationofVAofDBMwithdifferentaggregategradation (With CRMB)

C. Impact of Altered Binder on the Mix Design

1) MarshallStability:

The following figure (Figure 16) demonstrates the stability of the mix in relation to the optimal binder content. For both gradations, the CRMB binder exhibits superior performance compared to VG 40.

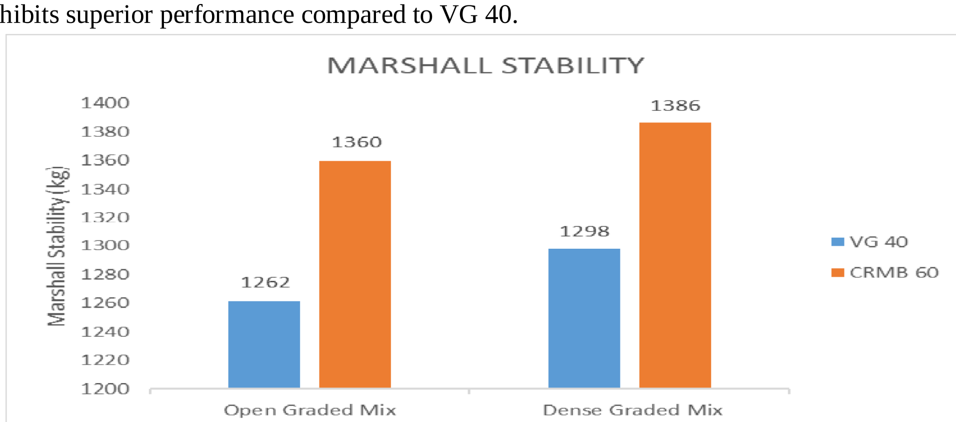

Fig16:EffectofCRMBonMarshallStability(withdifferenttypegradation)

2) FlowValue:

TheuseofbinderCRMBleadstothefollowingconsequencesattheexpenseoftheflowvalueinthegradation mix. This is illustrated by fig. 17

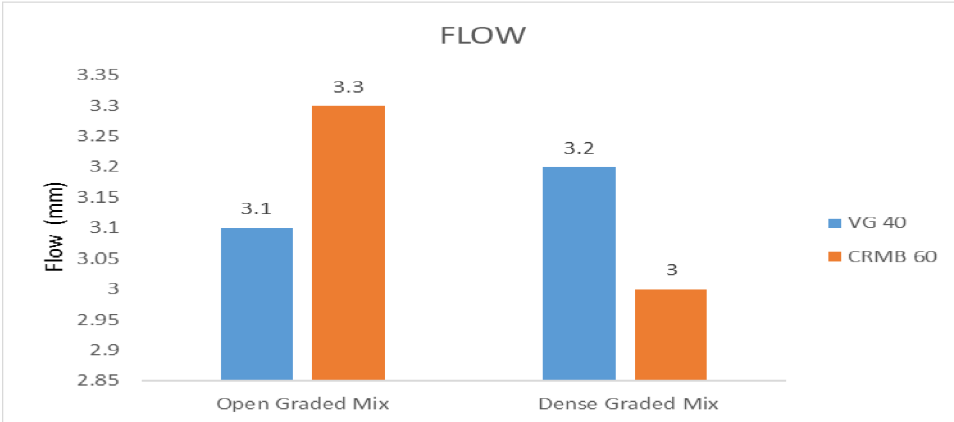

Fig17:EffectofCRMBonMarshallFlowValue(withdifferenttypegradation)

3) UnitWeight:

Theunitweightincreasesincaseofusemodifiedbinder.Itcanbeseeninthefig.18.

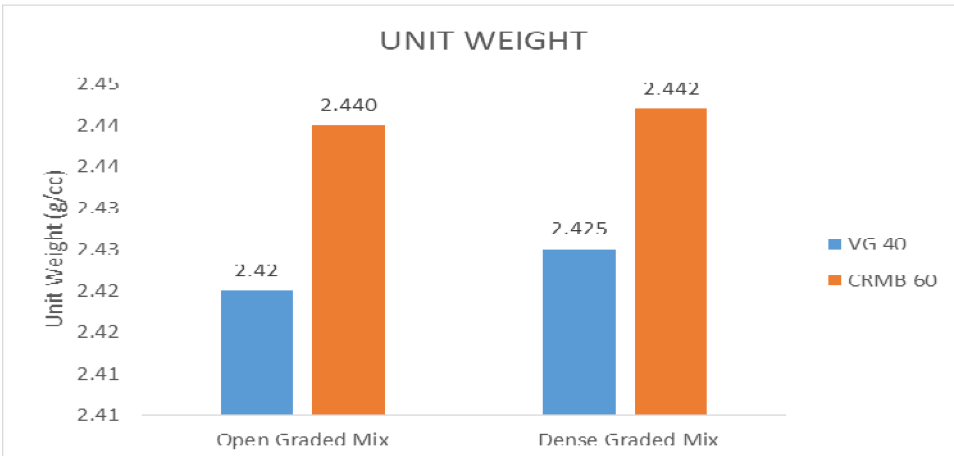

Fig18:EffectofCRMBonunitweight(withdifferenttypegradation)

4) VMA:

The result is less effective in the case of VMA, as the reduction of voids is not a relevant property for the analysis.

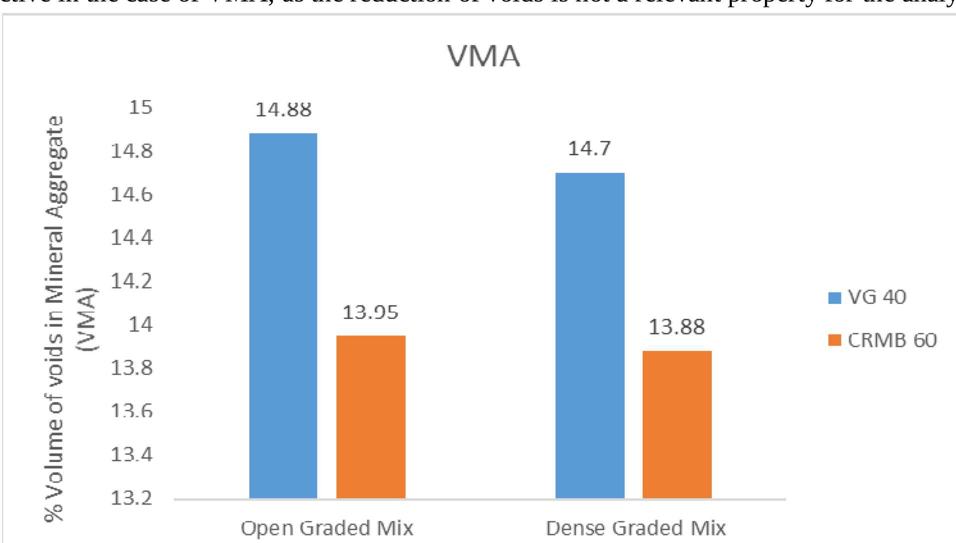

Fig19:EffectofCRMBonVMA(withdifferenttypegradation)

5) VFB:

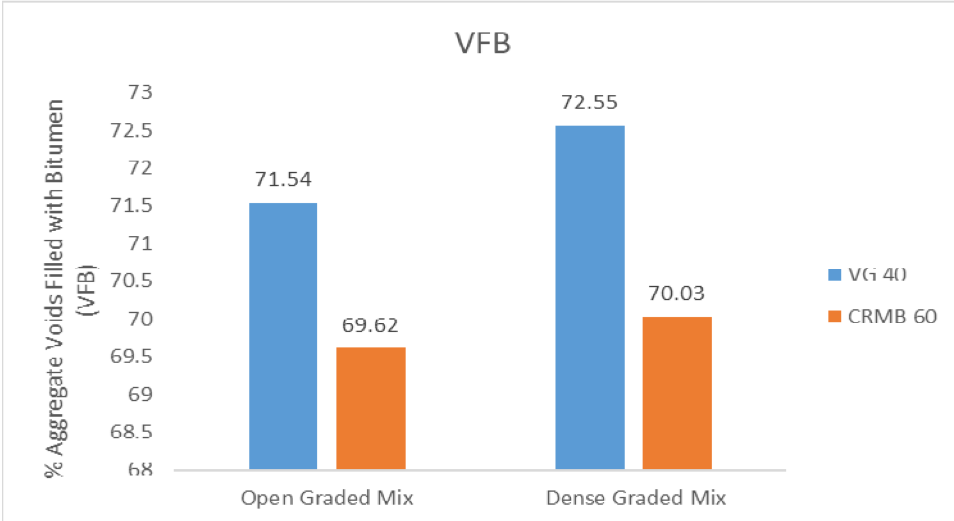

Fig20:EffectofCRMBonVFB(withdifferenttypegradation)

6) VA:

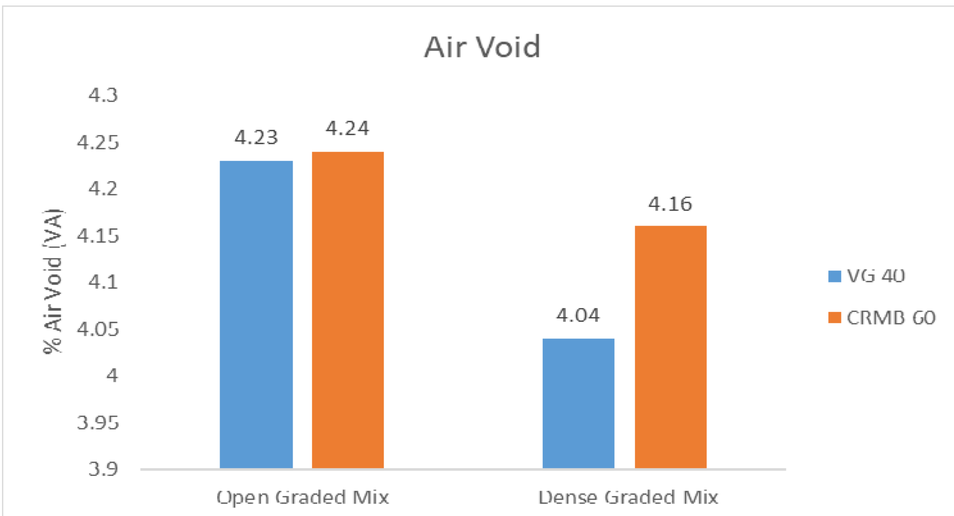

Fig21:EffectofCRMBonVA(withdifferenttypegradation)

7) Optimum Binder Content:

TheOptimumBinderContentisarrivedusinganaveragevalueofthefollowingthreebitumencontentasobtained from the above graph i.e.

1) Relationshipofbitumencontentwiththemaximumstability
2) There is a relationship between the bitumen content and maximum unit weight of the aggregate.
3) Thecontentofbitumenasonethatisequalto4percentairvoidinthemix
4) Bitumencontentequalto70percentofthepercentageofvoidsintheaggregatefilledbythebitumen in the mix.

V. CONCLUSION

The research highlights that both aggregate gradation and binder type play a crucial role in determining the performance of Dense Bituminous Macadam mixtures. Dense-graded mixtures exhibited superior stability and tensile strength compared to their Open-graded counterparts. Additionally, the incorporation of Crumb Rubber Modified Bitumen (CRMB) significantly improved the mixture's strength, moisture resistance, and overall durability when compared to the standard VG-40 binder. The synergy between CRMB and optimized aggregate gradation was found to be the most effective combination for producing high-performance bituminous pavements.

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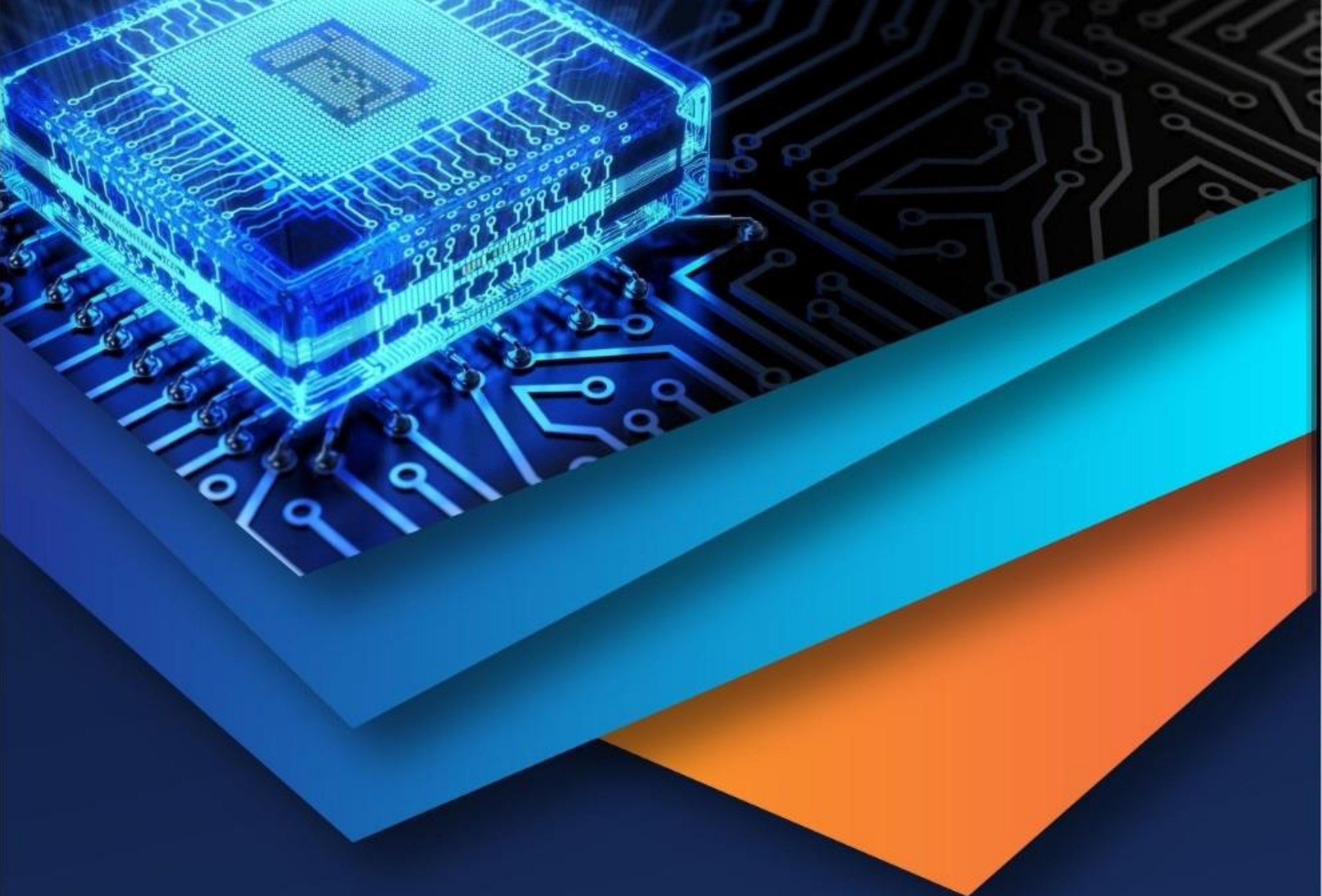

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