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Effect of Aggregate Gradation on Rutting of Asphalt Pavements

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Abstract

Permanent deformation (i.e. rutting) of asphalt pavements is one of major types of distress modes experienced in the service life of pavements. Aggregates are one of the key building materials used in the construction industry and the largest portion of an asphalt pavement. Therefore, aggregate characteristics impressively affect the performance of asphalt pavements. Gradation is one of the important characteristics of aggregates affecting permanent deformation of hot mix asphalt. The objective of this research is to investigate the impact of aggregate gradation variations on rutting characteristics of asphalt concrete mixtures.

Keywords: Rutting, Hot Mix Asphalt, Aggregate Gradation, Marshal Test, Dynamic Creep Test.

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1. Introduction

Rutting has always considered as a matter of concern of hot mix asphalt (HMA) pavements' performance due to repeated loadings (Marks et al, 1990). The rate and depth of rutting depend on external and internal factors. External factors include load and volume of truck traffic, tire pressure, temperature and construction practices. Internal factors include thickness of pavement, bitumen, aggregate and mixture properties (Zaniewski and Srinivasan, 2004).

The factor that is usually noticed as the most effective parameter causing rutting is the characteristics of aggregates. Ahlrich (1996) also mentioned that HMA properties are highly affected by their aggregate characteristics. Button et al. (1990) have found nine possible factors cause rutting, but stated that the aggregate characteristics is the primary material quality factor influencing rut susceptibility. Stakston and Bahia (2003) also have indicated that rut resistance is "highly dependent on aggregate grading", and that mixes made with the best possible materials would fail without a proper gradation.

Experimental works and numerical modeling show that shear stresses caused by vehicle tire loading introduce significant amount of external energy to the mixture which is lead to the permanent deformations. There are three different mechanism caused these deformations. The first one is to reduce the friction between aggregates coated with bitumen. Friction resistance in these aggregates like all granular materials is related to their mineral components, roughness and also bitumen properties. The second mechanism is defeating the interlock between aggregates that it pushes the aggregates away from each other. Increasing air-void in asphalt mixture is the result of this kind of dilatory behavior. Quantity of expansion depends on gradation, angularity and the shape of the aggregates. The third mechanism is the loss of adhesion between aggregate and bitumen in asphalt mixture. It is expected that the effect of each mechanism depends on mix design and pavement layer thickness. For a thin pavement layer, stone-on-stone friction and interlock between aggregates are the principal mechanisms against rutting. Increasing the thickness of pavement layer would reduce the effect of friction and interlock between aggregate and therefore binder deformation properties has the most effect on the resistance against failure in cohesion and continuity between binder and aggregates (Jung and Young, 1998).

The internal resistance of HMA is affected directly by mix properties. However, there is often a lack of consistency between the aggregate specification and mixture performance. It seems that there is an appropriate internal strength range for materials for a defined maximum nominal size. Also internal resistance of HMA is increased by stone-on-stone contact (aggregate interlock). The internal contact of coarse aggregate is considered to be the main source for the internal resistance; thus, it is imperative that the mixture is placed with a strong coarse-aggregate skeleton. Changing the fine aggregate volume (large-stone asphalt mixes, (LSAMs)) would have effect on the internal resistance and load-carrying capacity of HMA as well. Stone-on-stone contact is started while aggregate skeleton is getting to a constant condition. Results to date have indicated that susceptibility to plastic deformation increases dramatically when natural fine aggregate particles replace crushed particles in a given aggregate gradation.(Chen and Liao, 2002; Krutz and Sebaaly, 1993; Elliot et al., 1991; Button et al., 1990; Mahboub and Allen, 1990; Brown and Bassett, 1990).

Therefore, this study focuses on the effect of gradation more in detail and investigates the effect of coarse and fine aggregate gradation on rutting mechanisms by dividing the gradation limits into different parts (upper, middle and lower gradation).

2. Materials and Methods

2.1. Materials

Bitumen properties

Asphalt bitumen 60/70 commonly used in the region was selected for this research. The bitumen properties were evaluated by laboratory tests, which are demonstrated in the Table1.

Table 1 Binder Properties

Experiment	Value	Standard No.
Penetration Grade at 25 C, 1/10 mm	64	ASTM D5
Softening point (°C)	61	ASTM D36
Specific Gravity	1.013	ASTM D70
Kinematic Viscosity (centi Stokes) 60°C	422	ASTM D2170

Aggregate Gradation

Aggregate is the major structural framework of asphalt mixture to absorb and control different stresses on the pavement. Aggregates for this study were brought from the local region of the project in order to simulate the real technical experience (near north-east of Iran). Table 2 shows different properties of these aggregates which are crushed limestone with two broken faces. The sieve diagram for wearing course is also presented in Figure 1.

Table 2 Aggregate properties

Type of Aggregates	Water Absorption (%)	apparent specific gravity (gr/cm^3)	specific gravity (gr/cm^3)	Standard No.
Coarse (retained on No.8 sieve)	0.58	2.70	2.65	ASTM C27
Fine (passing through No.8 and retained on No.200 sieve)	0.63	2.72	2.67	ASTM C28
Aggregate mixture		specific gravity : 2.68		ASTM C29

Aggregate gradations were selected with a nominal size of 19mm based on The Asphalt Institute Manual Series "Principles of Construction of Hot-Mix Asphalt Pavements "No.22 MS-22 (1983). According to the failure mechanisms (Rutting), the gradations should be limited between upper limit and lower limit based on the 19 mm nominal maximum aggregate size. In this study the gradation range divided into three variations that form a band (Figure 1).

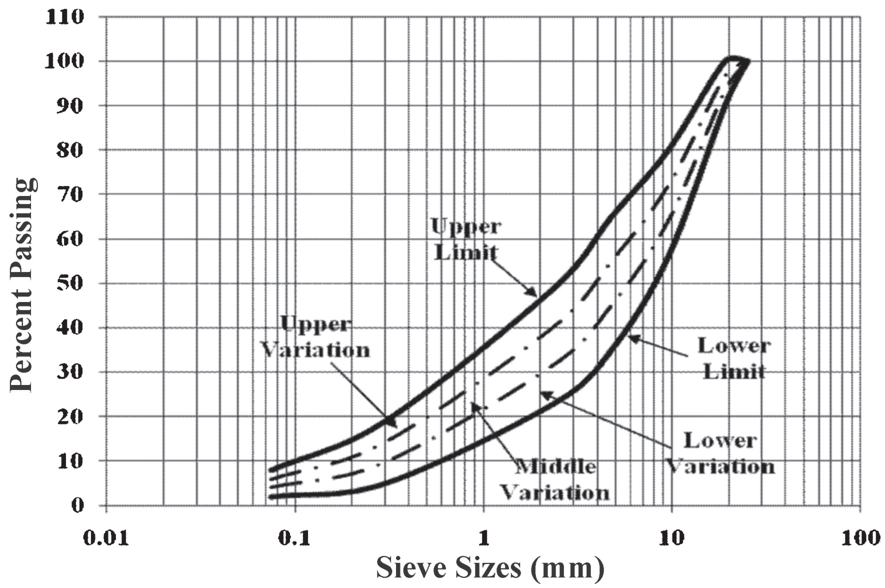

Figure 1 Upper and lower limit, and three different variations for gradation for 19 mm nominal maximum aggregate size.

In order to compare each of variations, the medium gradation of each variation were chosen from sieve diagram. Table 3 shows the percentage of passing for each variation (upper limit, middle limit and lower limit gradation bands).

Table 3 Passing Percentage for the upper limit, middle limits and lower limits gradation bands

Sieve Size	lower limit gradation band	middle limit gradation band	upper limit gradation band
25 mm (1 in.)	100	100	100.0
19 mm (0.75 in.)	91.7	95.0	98.3
9 mm (0.375 in.)	60	68.0	76.0
4.75 mm (# 4)	40	50	60.0
2.36 mm (# 8)	27.3	36.0	44.7
0.3 mm (# 50)	7.3	12.0	16.7
0.075 mm (# 200)	3.0	5.0	7.0
Under sieves	0.0	0.0	0.0

2.2. Test Methods

Marshal test

It is well known that the optimum bitumen content is highly dependent on the type and the gradation of aggregates. Therefore, the optimum bitumen content was defined by Marshall Stability curves, specific gravity, air voids (%), Marshall Flow curves and VMA (%) according to the Asphalt Institute manual. In this study, three Marshall Specimens for each gradation were prepared in the laboratory condition according to ASTM D1559-76 assuming high traffic volume area. Afterwards, the air voids, voids in mineral aggregate (VMA), Marshall Stability, Marshall Flow and resilient modulus were evaluated. Table 4 shows the summary of Marshall Test results for each gradation.

Table 4 Marshall Results for all gradations

	Lower limit band	Middle limit band	Upper limit band
Optimum binder content (%)	4.30	4.35	4.40
Marshall stability (kgf) (defining the optimum binder content)	1150	1380	1400
Specific gravity (gr/cm^3) (defining the optimum binder content)	2.384	2.415	2.399
Air voids (%) (defining the optimum binder content)	4.5	3.5	4
Marshall flow (mm) (controlling the optimum binder content)	2.94	3.56	3.88
Voids in mineral aggregates (%)(controlling the optimum binder content)	14.7	13.45	14.2

Dynamic Creep Test

Dynamic creep test samples were made with 100 mm diameter and 150 mm height. Gyratory Compactor was used to compact three cylindrical samples for each of three gradation bands with the optimum bitumen content (Table 4). The Dynamic Creep tests were tested by using UTM14P to apply repeated axial load pulse on the specimens. This machine can measure the vertical deformation with the Linear Variable Displacement Transducer (LVDTs). By entering the sample diameter and height as an input, the software will control the preload stress, deviator stress, frequency of stress application and contact stress during testing period. In this research, dynamic creep test conditions were chosen according to British standard (BS DD226). The tangential stress applied to sample was 2 kPa and the axial stress was 100±2 kPa. Prior to testing, a preload was added to the testing sequence with magnitude of 10 kPa. Preload application time was 600 (s) which can assure us about the complete contact between load bar to the sample. A square pulse wave was used and the experiment was finished after 1800 cycles of loading and unloading. In each cycle, the pulse width and the rest period were the same as 1000±10 (ms). Table 5 shows the average results of Dynamic Creep Test.

Table 5 Average Dynamic Creep test results

Gradation	Average creep stiffness (MPa)	Average resilient modulus (MPa)	Average recoverable strain (%)	Average cumulative strain (%)	Average recoverable deformation (mm)	Average permanent deformation (mm)
Upper Gradation band	22.4	554.7	0.0505	1.251	0.0749	1.8750
Middle gradation band	17.7	576.0	0.0490	1.592	0.0719	2.3858
Lower Gradation band	13.15	526.1	0.0540	2.167	0.0786	3.2478

3. Results and Discussions

3.1. Analysis of Marshall Test results

The test data from Marshal Test were analyzed to identify the effect of gradation variation. Analysis examines the variation of the different mixture parameter (i.e., air voids, VMA, stability, flow, and resilient modulus). Figures 2 to 5 were prepared to compare the results of mixture parameters for all three gradation bands.

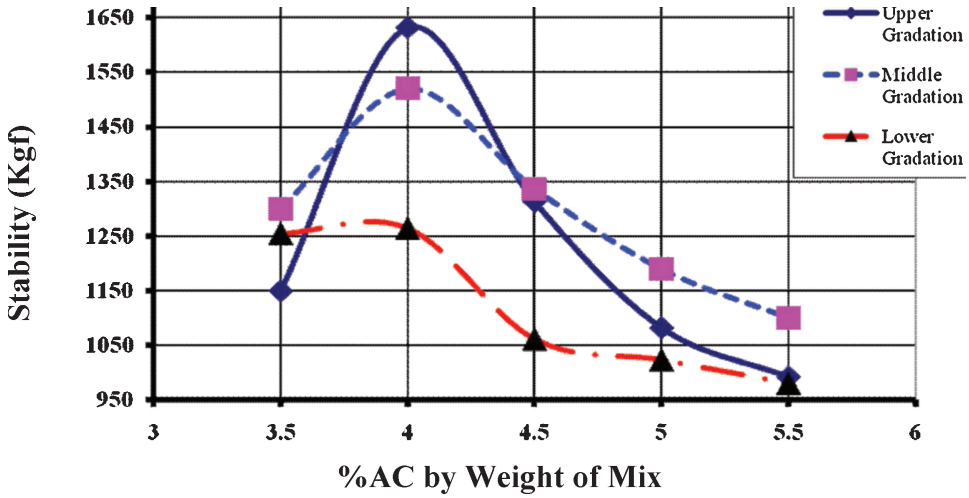

Figure 2 Asphalt Mixtures Stability Curves.

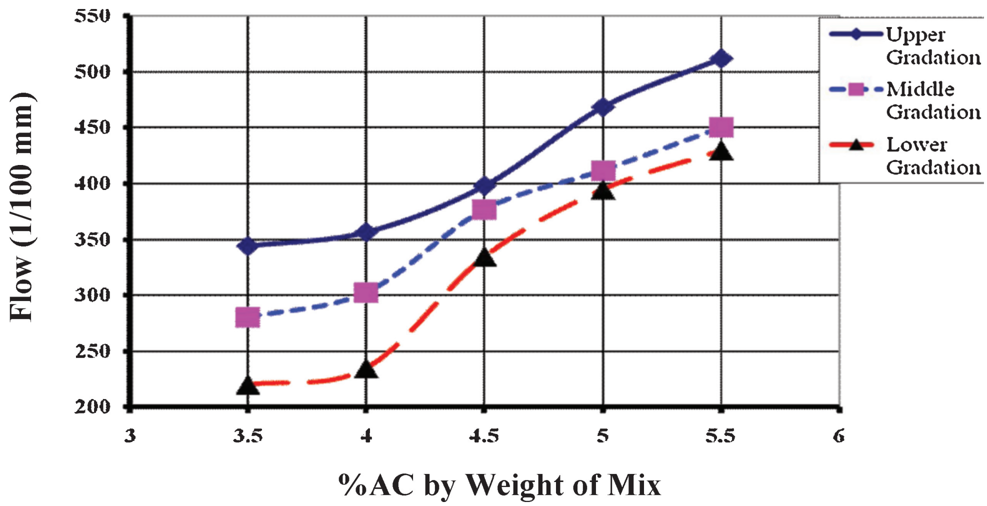

Figure 3 Asphalt Mixtures Flow Curves.

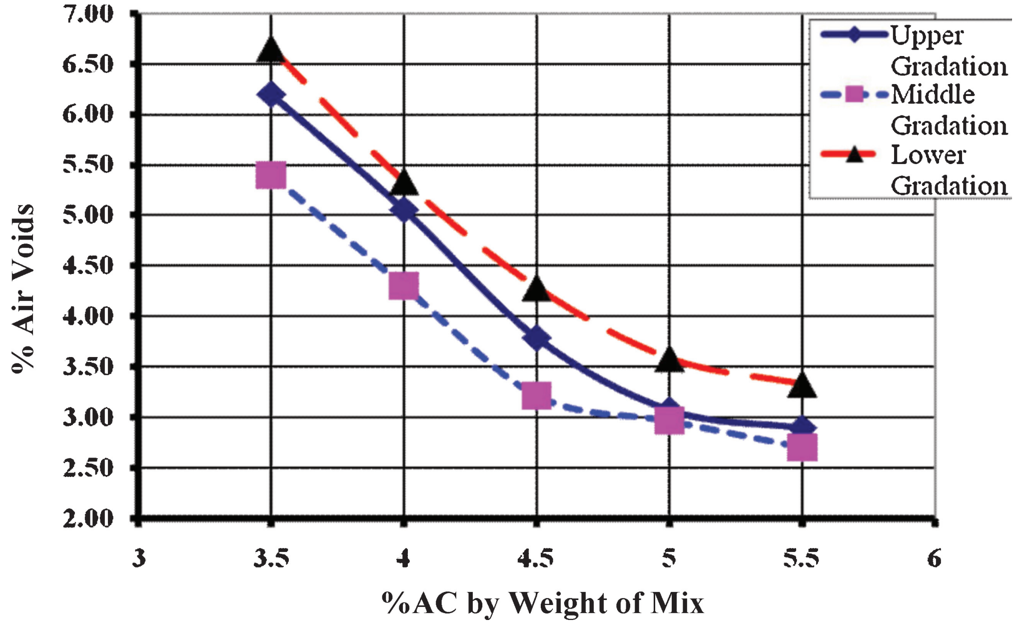

Figure 4 Asphalt Mixtures Air Voids Percentage Curves.

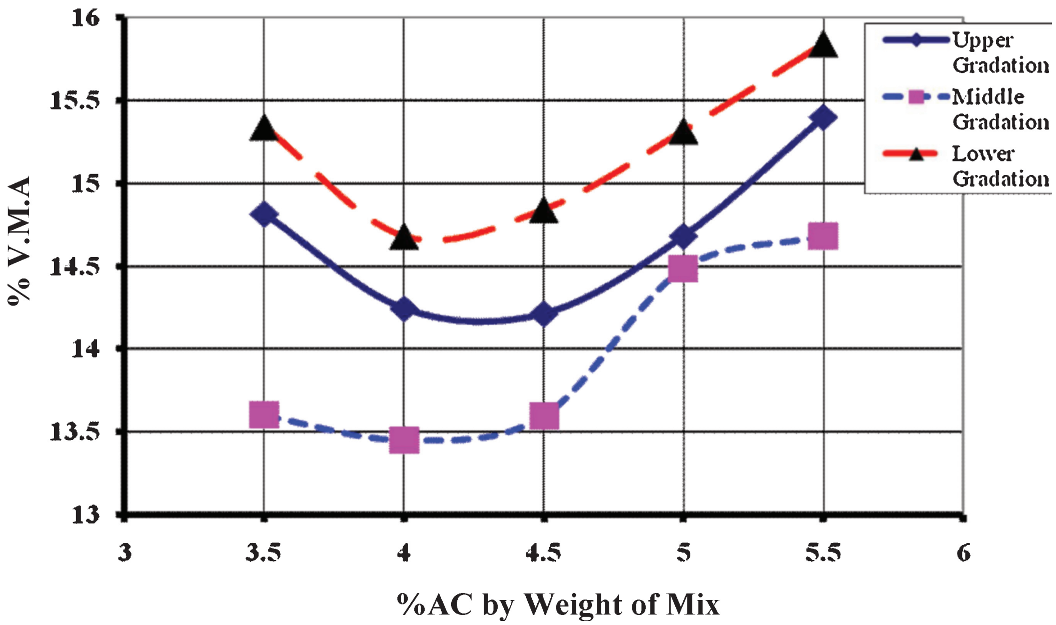

Figure 5 Asphalt Mixtures VMA Percentage Curves.

The mixture with upper gradation band has the highest stability and the lower one has the lowest. Also asphalt mixture with upper gradation band has the highest flow parameter and also the lower one has the minimum of flow parameter in three gradation bands. Furthermore, the mixture with lower gradation band has the lowest special gravity but it has the highest amount of air voids and VMA. The middle gradation mixture has the lowest air voids percentage and VMA but it has the highest special gravity (Krutz and Sebaaly, 1993). It can be said that the stability is a more representative parameter in marshal test which can be correlated with the findings from other statistical analyses involving APA measurements (Kim et al., 2009).

3.2. Dynamic Creep Behaviour of Mixtures

In this part the results of dynamic creep test for all three gradations are summarized in Figure 6 and 7.

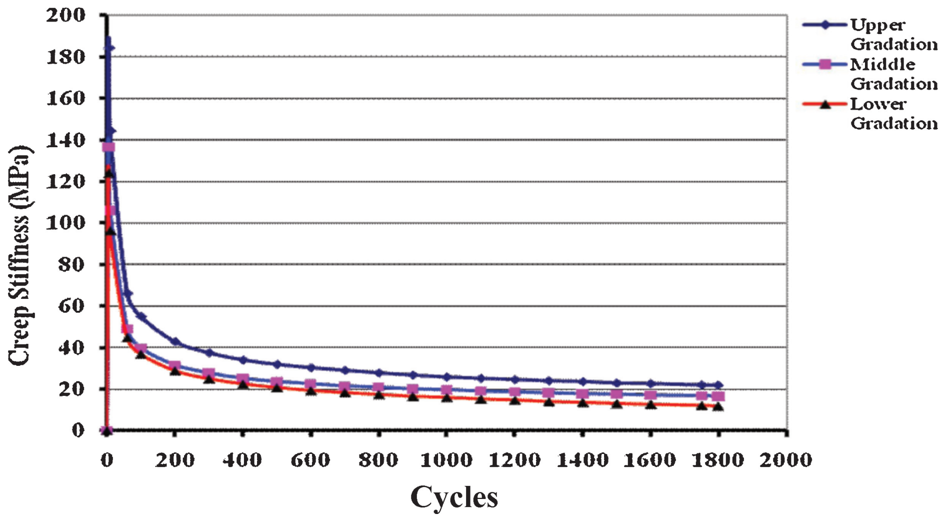

Figure 6 Creep Stiffness Curves

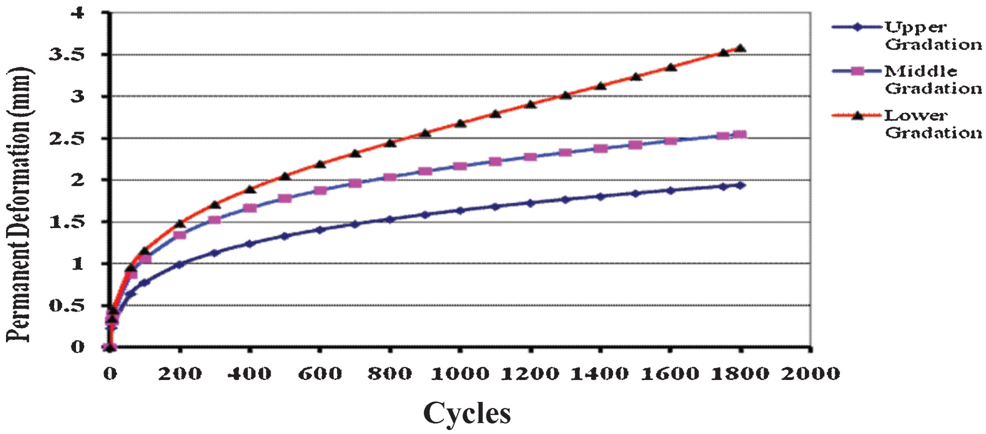

Figure 7 Permanent Deformation Curves

Dynamic creep test results showed that the mixture with upper gradation band limit has the lowest permanent deformation and cumulative strain while the mixture with the lower gradation band limit has the highest one. For creep stiffness, the upper gradation mixture has the highest amount and lower gradation mixture has the minimum amount among all. Also the middle gradation band mixture has the lowest deformation and recoverable strain but its resilient modulus is the highest. Also the mixture with lower gradation band showed the highest amount for deformation and recoverable strain and the lowest for resilient modulus. These results confirm that the lower limit graded mixture is more susceptible to rutting (Chowdhury et al., 2001; Hand et al., 2001; Sebaaly et al., 2004; Kim et al., 2009).

These results show that the load carrying capacity of the asphalt mixtures would depend on different factors related to the aggregate gradation and properties such as the friction of angular particles, aggregate interlock and bonding between bitumen and aggregates in addition to aggregate stiffness. As a result, it can be concluded that the aggregate gradation has a critical role in rutting resistance due to the fact that aggregate structure is the main load carrying component of mixtures. Two methods of dissecting an asphalt mixture structure is skeleton and void method (Coenen, 2011). Shashidhar et al. (2000) demonstrated a semi-granular load transition in asphalt mixture particles which make it appropriate to be dissected by skeleton method. Hence, the aggregate gradation plays significant role in shaping the skeleton to carry loads in mixtures. Consequently, the segregation within the specimen of coarse mixture would explain the reason why lower limit graded mix showed maximum deformation (Krutz and Sebaaly, 1993) while proper interlock between fine crushed aggregate make it more rut-resistance (Uge and Van de Loo,1974). Therefore, it can be said that aggregate structure and skeleton plays an operative role in permanent deformation resistance.

4. Summary of Findings

For the mixtures evaluated in this study, the following findings are derived:

- Comparison between permanent deformation and creep modulus curves from Dynamic Creep test and Marshall Stability curve respectively, shows that the result of Marshall Stability test can be a good and accessible predictor for permanent deformation of asphalt mixtures in addition to other tests performed specifically to evaluate the rutting performance of each mixture.
- Based on these gradations, it is found that by reducing the air voids percentage and voids in mineral aggregate up to the certain amount, resilient modulus of the mixture will be increased and therefore deformation and non-recoverable strain will reduce. However, for selected gradations in this study, air voids percentage and VMA could not give a good estimation of rutting.
- Gradation bands placed in the upper limit of asphalt mixture design gradation chart show the best performance against rutting while lower bands have the highest amount of permanent deformation.
- Whereas the selected gradations are almost parallel with the job mix formula, it can be concluded that for gradations parallel with job mix formula when it gets near to upper limit curve, permanent deformation is reduced and rutting resistance will be increased. Also this result seems to indicate that when the gradation is near to the lower limit curve, the permanent deformation is increased and the rutting resistance will be decreased.

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