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Performance of Bituminous Mixes with Different Aggregate Gradations and Binders

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ABSTRACT

A bituminous mixture is composed of approximately 95% by weight, or 80% by volume, mineral aggregate. Therefore it is important to see how aggregate gradation affects the performance of bituminous mixes. The present study was taken up with the objectives of evaluating the effect of aggregate gradation on indirect tensile strength, shear strength and rutting behaviour of bituminous mixes and thereby to establish the relationship between some aggregate gradation parameters and tensile strength, shear strength, horizontal tensile strain and rutting values. Three aggregate gradations, two types of binder; VG-30 and PMB-40 and two types of mixes, Bituminous Concrete (BC) and Dense Bituminous Macadam (DBM) are used. The results indicate that the performance of mixes made with PMB-40 is better than that of the mixes made with VG-30 for both BC and DBM. In general, the BC mix is better than DBM mix in term of indirect tensile strength (ITS), horizontal tensile strain (HTS), and the compressive strength, while DBM mix is better in terms of shear strength and rut resistance. A parameter called gradation ratio is defined in this paper and is correlated with strength and performance parameters of a mix to predict later from aggregate gradation curve alone.

Keywords: *Performance, Aggregate gradation, Tensile strength, Shear strength, Rutting behavior.*

1. INTRODUCTION

Bituminous mixes are used as base and wearing courses in a pavement structure to distribute stresses caused by loading and to protect underlying unbound layers from the effects of water (Baha and Necati, 2007). A bituminous mixes have different types of distresses like: fatigue cracking, rutting, thermal cracking, friction, and moisture susceptibility. Out of these rutting is the one that is most likely to be a sudden failure, rutting in a pavement may occur due to poor design of hot mix asphalt. Other distresses are typically long term failures that show up after a few years of traffic (Brown et al., 2001). Some of the factors causing distresses in bituminous pavements are high pavement temperature, heavy axle loads, high tyre pressure and possibly inadequate binder and mix specification. Performance of bituminous mixes can be defined by their ability to resist permanent deformation, fatigue cracking, moisture induced damage, thermal cracking, and the mixture's overall stiffness. Aggregate gradation can affect all these and other properties such as skid resistance, field constructability, and the asphalt binder aging characteristics. Designing a bituminous mixture to meet the needs of a particular paving project requires careful selection of the aggregate and bitumen to be used. An appropriate bitumen grade and content must be selected. A compatible aggregate source and gradation must also be chosen to meet the needs of the project. All four properties will affect the overall performance of the bituminous mixture. Bituminous mixture is composed of approximately 95%, by weight, or 80%, by volume, mineral aggregate. Therefore it is important to see how aggregate gradation can affect the fundamental properties of bituminous mixture.

The present study was taken up with the objective of evaluating the effect of aggregate gradation on indirect tensile strength (ITS), shear strength and rutting behaviour of bituminous mixes and thereby to establish the relationship of these properties with aggregate gradation parameters.

2. BACKGROUND LITERATURE

The performance of a bituminous mixture depends on external and internal conditions; the external conditions being traffic load and environmental and the internal conditions being properties of the materials, structure of the mixture, design of the mixture, and process of the construction (Chowdhury et al., 2001). Bituminous mixture consists of bitumen binder, aggregates and air voids. The properties of a bituminous mixture depend on the quality of its components, the construction process, and the mix design proportions (Coree and Hislop, 2000). Gradation is defined as the distribution of particle sizes expressed as a percent of the total weight. If the specific gravities of the aggregates used are similar, the gradation in volume will be similar to the gradation in weight. Roberts et al. (1996) suggested that gradation is perhaps the most important property which affects almost all the important properties of a bituminous mixture, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. Permanent deformation in bituminous pavements, commonly referred to rutting, usually consists of longitudinal depressions in the wheel paths, which are an accumulation of small amounts of unrecoverable deformation caused by each load application (Sousa et al., 1991). Two mechanisms are involved in the formation of rutting: traffic densification and material lateral movement. Densification in a layer occurs in the first few summers after opening to traffic and the degree of densification depends on the initial compaction level. The lateral movement of material is related to the shear resistance of a bituminous mixture material. The aggregate angularity and binder content are both crucial in the mixture shear property (Carpenter, 1993). The rutting performance of a bituminous mixture depends not only on the properties of the aggregates and binder, but also on how these materials interact in the mixture. Rutting in bituminous mixes is controlled by the characteristics of the binder and aggregates and their interaction. According to Roberts et al. (1996), rutting can be reduced by increasing the voids in the mineral aggregate, establishing minimum and maximum air voids contents, limiting the amount of natural sand, establishing a minimum percentage of crushed coarse and fine aggregates, using stiffer binder, or by the use of coarser mixture gradations. Fred (1967) reported that aggregate gradation appeared to have more influence than aggregate type. He also concluded that the temperature susceptibility characteristics of the asphalt appear to have more influence at longer time of loading.

Bitumen binders are visco-elastic materials whose resistance to deformation under load is very sensitive to loading time and temperature (Ramond et al., 1999). The bitumen viscosity directly affects the strength of bituminous concrete in compression (rutting) for the practical range of temperatures. The log of pavement resistance and of cohesion varies directly with the log of asphalt viscosity. Modulus of elasticity in compression was influenced by the type of asphalt, temperature and amount of lateral confinement (William et al., 1967). Brown and Snaith (1974) suggested that the increase in deformation is related to the decrease in binder viscosity at high temperatures (40^{o}C), thereby leading to a lower interlock between the aggregates. The contribution of the aggregate skeleton towards the behaviour of the mixture becomes more significant at higher temperatures.

3. EXPERIMENTAL PROGRAMME

One type of aggregate, two types of binders and two types of mixes (Bituminous Concrete (BC) and Dense Bituminous Macadam (DBM)) are used in this study. The DBM and BC layers are extensively used as base course and wearing course layers respectively on all major highways in India.

3.1 Materials

Two types of binders (VG-30 and PMB-40) are used to prepare the bituminous mixture specimens. These were tested for their physical properties and test values satisfied all the requirements of paving grade bitumen specified in IS: 73 -2006 and IS: 15462 -2004.

Crushed stone aggregates (coarse, fine and filler) from Ganga basin of Hardwar district in the state of Uttarakhand were used to prepare the bituminous mixture specimens. Maximum size and aggregate grading are directly controlled by the specification s (MORTH - 2001). Three aggregate gradations for each mix as described below were selected:

- Gradation U: Upper limit of gradation range. The nominal size of this gradation is 9.5 mm for BC and 19 mm for DBM mix.
- Gradation M: Midpoint of gradation range. The nominal size of this gradation is 13 mm for BC and 26.5 mm for DBM mix.
- Gradation L: The lower limits of gradation range. The nominal size of this gradation is 13 mm for BC and 26.5 mm for DBM mix.

Figs. 1 and 2 show the aggregate size distribution of three grading for two mixes used in the present study. The notation B and D are used to describe BC and DBM mixes and U, M and L describe upper, middle and lower gradation in a mix respectively.

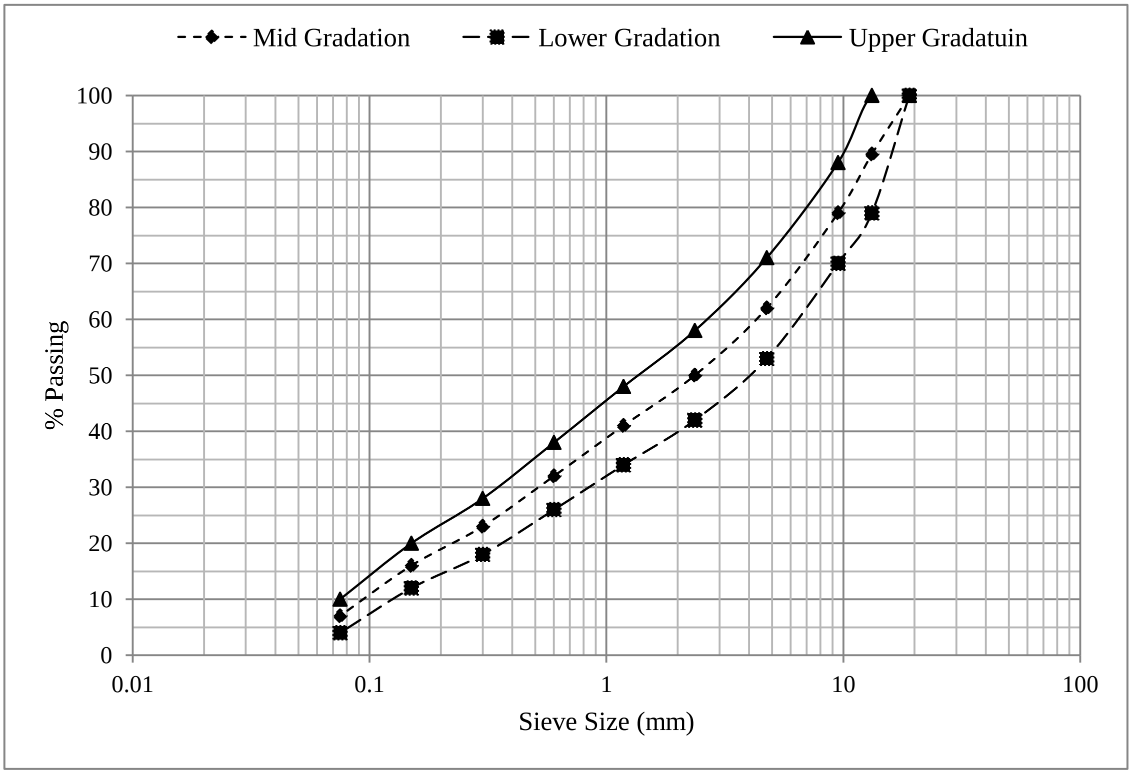

Fig.1: Aggregate Gradation of Bituminous Concrete (BC) mix

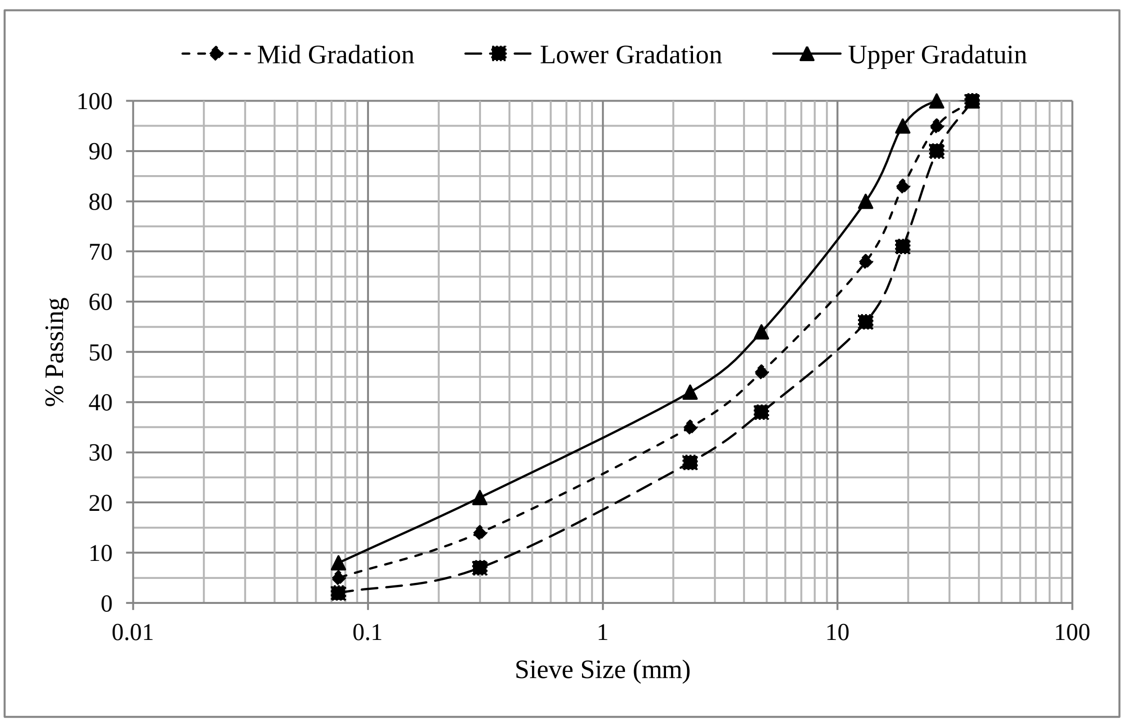

Fig.2: Aggregate Gradation of Dense Bituminous Macadam (DBM) Mix

3.2 Optimum Binder Content (OBC)

The Marshall method of mix design as laid in ASTM D 1559 was followed to determine optimum binder content (OBC) of different mixes. Three specimens were prepared at 5%, 5.5%, 6.0%, and 6.5% for BC mixes and 4%, 4.5%, 5.0%, and 5.5% for DBM mixes, and these were tested for stability, flow, air voids, unit weight and voids in mineral aggregate (VMA). The OBC was calculated as the average of asphalt content for maximum stability, maximum unit weight, and 4.0% air voids. Table 1 shows the results of OBC for twelve mixes.

Table 1: Marshall Parameters for Different Bituminous Mixes

Type of Mix	Mix ID	OBC %	Bulk Density	VMA %	VFB %	Stability kN	Flow mm
BC	BLV	5.2	2.365	14.0	75	21.43	2.8
	BMV	5.5	2.390	14.3	75	22.25	3.0
	BUV	5.7	2.386	15.0	75	20.55	3.3
	BLP	5.2	2.370	14.4	74	22.75	3.4
	BMP	5.5	2.377	14.4	75	23.85	3.7
	BUP	5.7	2.371	15.3	75	22.0	4.0
DBM	DLV	4.65	2.360	12.5	68	20.0	2.2
	DMV	4.80	2.395	13.0	74	18.67	2.9
	DUV	5.0	2.367	14.0	73	17.18	3.2
	DLP	4.60	2.335	13.1	65	21.52	2.8
	DMP	4.75	2.380	13.3	70	20.11	3.5
	DUP	4.9	2.387	14.0	74	18.92	3.9

3.3 Indirect Tensile Strength (ITS) Test

This test was performed by loading a Marshall specimen with a single load parallel to the vertical diametral plane and conducted as per ASTM D 6931-07. The horizontal deformation at peak load was measured during the test by using strain gauges. The test is conducted at 25°C to evaluate mix properties at low temperature. The equation for tensile strength and tensile strain at failure are given below:

$$S_T = \frac{2000P}{\pi dt} \quad (1)$$

$$\varepsilon_t = 13.2 * X_t \quad (2)$$

where S_T is ITS (kPa), ε_t is horizontal tensile strain at failure (mm/mm), P is applied load (N), D is diameter of specimen (mm), t is thickness of specimen (mm), and x_t is horizontal deformation at peak load (mm).

3.4 Static Triaxial Test

The static triaxial test is used to determine the shear strength of bituminous mixes under confining pressure. AASHTO T 167 is the standard test typically used to measure a mixture's confined compressive strength. The test was carried out on cylindrical specimen of 100 mm diameter and 200 mm height. Two confining pressures 1.5 kg/cm^2 (147 kPa) and 3.0 kg/cm^2 (294 kPa) were used for each mix. The samples are loaded axially to failure, at the selected constant confining pressure at a strain rate of 1.25 per min., at a temperature of 25°C. The shear strength of the mix is developed principally from the cohesion (c) of the binder and angle of internal friction (φ) for aggregates, and it is represented by the general Mohr-Coulomb equation as follows:

$$\tau = c + \sigma \tan \varphi \quad (3)$$

where τ is shear strength (kg/cm^2) at failure, σ is maximum normal stress (kg/cm^2), c is intercept parameter, cohesion (kg/cm^2), and φ is slope of the failure envelope or the angle of internal friction (°).

3.5 Rut Wheel Test

This test is used to determine the resistance of bituminous mixes to rutting. The test is conducted on confined mould in which slab specimen of dimensions (260 x 320 x 40) mm is rigidly restrained on its four sides. The wheel tracking apparatus consists of a loaded wheel which bears on a sample held on moving table. The table moves in backward and forward motion with respect to the centre of the top surface of the specimen. The test was conducted at 60 °C at a load frequency of 106 passes per minute. The steel wheel with solid rubber tire is applied with a load of 72 kg (63 psi) and indents a straight path in specimen. Each specimen was tested for 10000 passes.

4. RESULTS AND DISCUSSION

4.1 Indirect Tensile Strength (ITS)

The tensile strain at failure determined from ITS tests is useful in predicting the cracking potential of mixes. Mixes that can tolerate high strains prior to failure are more likely to resist cracking than the mixtures that cannot tolerate high strains. Tensile stress and strain at failure for bituminous mixes is shown in Fig. 3. The results indicate that the tensile strength of mixes made with PMB-40 is higher (2.24% - 19.0%) than that of mixes made with VG-30. It is primarily due to higher viscosity of PMB-40 as compared to VG-30. It also indicates that the tensile strength for BC mixes is higher (7.86% - 35.46%) than DBM mixes. The mix prepared with upper gradation of aggregates (finer) has higher tensile strength ((2.65%-19.34%) in BC and (10.58% - 33.27%) in DBM mixes) than mixes prepared with mid gradation lower gradation (coarser) for both types of binder. Also, the horizontal tensile strain at failure for mixes made with VG-30 is higher (7.05% - 32.3%) than mixes made with PMB-40 and horizontal tensile strain for DBM mixes higher (55.41% - 79.45%) than BC mixes. In both types of mixes (BC and DBM), the horizontal tensile strain reduces as one moves from lower to upper aggregate gradation for both types of binder.

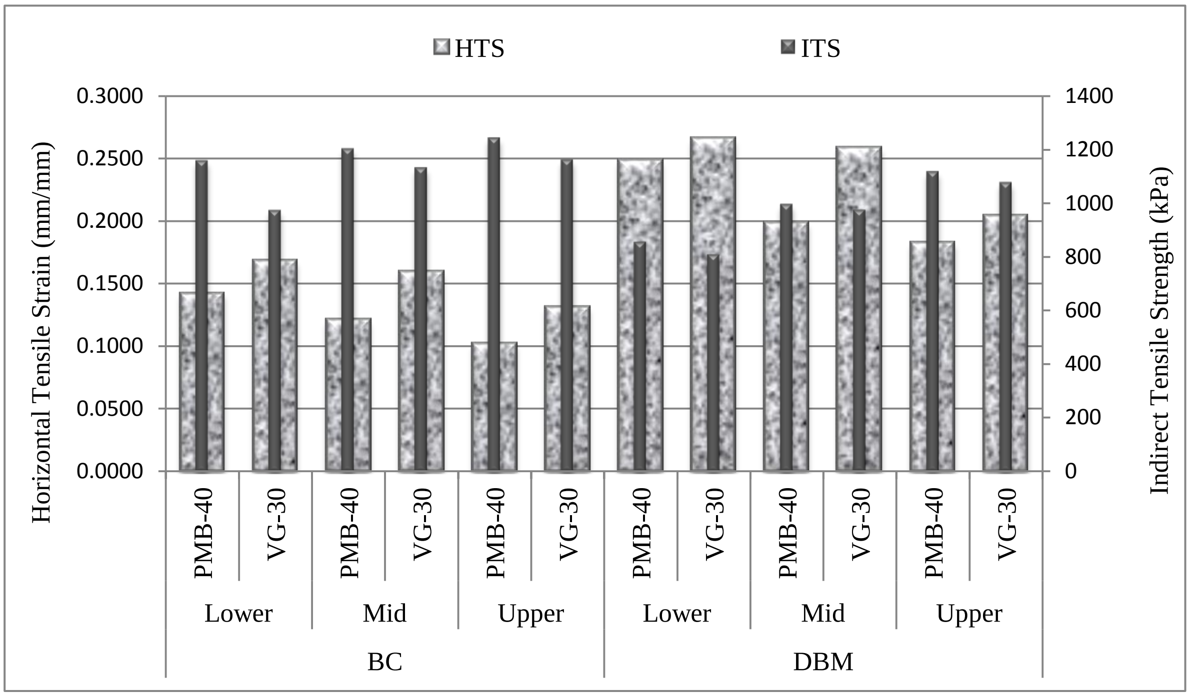

Fig.3: ITS and Horizontal Tensile Strain for Different Mixes

4.2 Shear Strength of Mixes

The shear strength and related parameters for bituminous mixes with two types of binders and different aggregate gradations are shown in Table 2. The results indicate that the maximum shear strength for mixes made with PMB-40 is higher (16.40% - 35.32%) than mixes made with VG-30. It is due to higher viscosity of modified binder which improved the cohesion between the particles. The shear strength for lower gradation mix (coarser) is higher ((10.51% - 38.37%) in BC mix and (5.08% - 19.91%) in DBM mix) than mid gradation mix and upper gradation mix (finer) in both types of binder. It is due to higher angle of internal friction (φ) in coarser mix and is related to size and surface area of aggregate particles. As the size increases, the surface area will also increase resulting in increase in the friction between the particles in the mix. As may be seen, the shear strength for DBM mixes is higher than that for BC mixes. It indicates that the DBM mixes are more resistant to permanent deformation.

The stress-strain plots for different mixes and the modulus of elasticity was calculated from initial tangent drawn to the curve. These values for different mixes are given in Table 3. The results show that the mixes made with PMB-40 have higher E-value (9.19% - 27.75%) than mixes made with VG-30 for both types of mixes. In both types of mixture (DBM and BC), The mix with lower gradation (coarser) has higher E-value and failure stress and lower failure strain, while the mix with upper gradation (finer) has lower E-value and failure stress and higher strain value. Further, the BC mixes have higher strength (32.03% - 56.28%) than DBM mixes for both types of binders.

4.3 Wheel Tracking Test

The rut depth after 10,000 passes for bituminous mixes with different type of binders and different aggregate gradations is shown in Table 4. The results show that the mixes made with PMB-40 have less rut depth (31.28% - 46.84%) than mixes made with VG-30 in both types of mixes. Also, the performance of DBM mixes is higher (37.78% - 55.11%) than BC mixes in rutting test. In both types of mixes, the mix prepared with lower gradation and PMB-40 has less rut depth, while the mix prepared upper gradation and VG-30 has higher rut depth. The rutting resistance increases with two important parameters. First, the increase in percent of coarser aggregate materials in a mix, which improves the interlocking between the aggregate particles. Second, the increase in viscosity and hardness of bitumen binder. Fig. 4 shows a plot between shear strength and rut depth. Rut depth decreases as the shear strength increases. The following relations are developed.

- For BC mixture:

$$RD = 12.111 - 0.503\,(SS) \quad (4)$$

(R^2 = 0.99)

- For DBM mixture:

$$RD = 8.8009 - 0.3835\,(SS) \quad (5)$$

(R^2 = 0.89)

where *RD* is rut depth in mm at 60°C, and *SS* is shear strength value (kg/cm^2) at confining pressure of 1.5 kg/cm^2 at 25°C. The above empirical relations can be used to predict rut depth in a mix without actually doing the rutting test and will be extremely helpful when performance of 2 or more mixes is to be compared.

Table 2: Summary of Results from Static Triaxial Tests

Type of Mix	Mix ID	Confining Pressure (σ_3) (kg/cm^2)	Principal Stress (σ_1) (kg/cm^2)	Deviator Stress (σ_d) (kg/cm^2)	*c* (kg/cm^2)	φ (°)	Max. Shear Strength (τ) (kg/cm^2)
BC	BLP	1.5	23.41	21.91	5.53	29.38	18.71
		3	23.81	24.81			21.19
	BLV	1.5	22.16	20.66	4.19	26.98	15.47
		3	26.16	23.16			17.51
	BMP	1.5	22.31	20.81	6.16	25.77	16.93
		3	26.11	23.11			18.77
	BMV	1.5	20.5	19.0	4.66	22.02	12.95
		3	23.8	20.8			14.29
	BUP	1.5	21.18	19.68	6.87	21.19	15.08
		3	24.38	21.38			16.32
	BUV	1.5	18.96	17.46	5.17	17.58	11.18
		3	21.76	18.76			12.06
DBM	DLP	1.5	20.83	19.33	4.10	36.09	19.28
		3	26.63	23.63			23.51
	DLV	1.5	19.28	17.78	3.21	33.85	16.14
		3	24.58	21.58			19.70
	DMP	1.5	19.14	17.64	5.20	33.52	17.88
		3	24.34	21.34			21.32
	DMV	1.5	18.25	16.75	4.15	31.55	15.36
		3	23.05	20.05			18.30
	DUP	1.5	18.05	16.55	5.82	30.54	16.47
		3	22.65	19.65			19.18
	DUV	1.5	17.11	15.61	4.52	27.59	13.46
		3	21.21	18.21			15.60

Table 3: Elastic Modulus for Different Mixes at Confining Pressure of 1.5 kg/cm^2

Type of Mix	Mix ID	Failure Stress Kg/cm^2	Failure Strain (%)	E-value MPa
BC	BLP	21.91	2.35	168.0
	BLV	20.66	2.50	131.5
	BMP	20.81	2.60	125.3
	BMV	19.0	2.75	108.5
	BUP	19.68	2.90	101.0
	BUV	17.46	3.10	92.5
DBM	DLP	19.33	1.70	107.5
	DLV	17.78	2.0	98.1
	DMP	17.64	2.05	89.5
	DMV	16.75	2.30	77.6
	DUP	16.55	2.40	76.5
	DUV	15.61	2.60	66.9

Table 4: Rut Depth after10,000 Passes for Different Mixes

Type of Mix	Aggregate Gradation	Binder Type	Mix ID	Rut Depth (mm)
BC	Lower	PMB-40	BLP	2.70
		VG-30	BLV	4.10
	Mid	PMB-40	BMP	3.80
		VG-30	BMV	5.53
	Upper	PMB-40	BUP	4.50
		VG-30	BUV	6.60
DBM	Lower	PMB-40	DLP	1.68
		VG-30	DLV	2.50
	Mid	PMB-40	DMP	1.88
		VG-30	DMV	3.12
	Upper	PMB-40	DUP	2.02
		VG-30	DUV	3.80

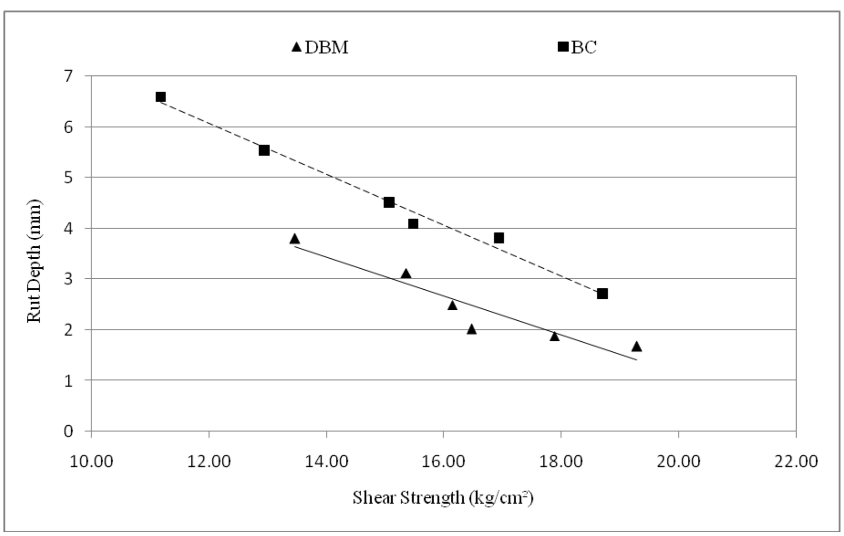

Fig.4: The Relation between Rut Depth and Shear Strength

4.4 Effect of Aggregate Gradation

The particle size distribution of aggregates for two types of mixes is identified by the gradation curves. From the gradation curve there parameters that have relation with shape of the curve are D_{15}, D_{50}, and D_{85}, where D_x is the size of sieve through which x percent of the total material would pass. These sizes are used to define the Gradation Ratio (*GR*) as by following equation:

$$GR = \frac{D_{85} - D_{50}}{D_{50} - D_{15}} \quad (6)$$

Gradation ratio (*GR*) will indicate the type of aggregate grading. Larger the value of GR, denser will be the gradation. Values of percent passing of particle size (D_{85}, D_{50}, and D_{15}) and value of *GR* for two mixes (BC and DBM) are given in Table 5.

An attempt is made to correlate the performance properties of the bituminous mixes with aggregate gradation parameter as defined above. Figs. 5 to 7 show the effect of *GR* on performance tests results of different mixes. The correlation between *GR* and the performance properties is very significant. These relations are found to be either linear (Eq. 7) or second degree polynomial (Eq. 8).

$$Y = a + b\,x \quad (7)$$

$$Y = a + b\,x + c\,x^2 \quad (8)$$

where Y is the performance property of a mix, x is the gradation parameter (*GR*), and a, b, c are constants.

Tables 6 and 7 show the values of these coefficients and R^2 values of different models developed for mixes prepared with PMB-40 and VG-30 respectively. The results indicate that the parameter *GR* is significant to predict the performance property through a single relation for DBM and BC mixes.

Table 5: Gradation Ratio Parameter for Different Mixes

Type of Mix	Aggregate Gradation	%Passing Parameter			Gradation Ratio
		D_{15}	D_{50}	D_{85}	GR
BC	Upper	0.1	1.3	8.5	6.00
	Mid	0.13	2.3	11	4.01
	Lower	0.21	4	16	3.17
DBM	Upper	0.15	4	15	2.86
	Mid	0.33	6	20	2.47
	Lower	0.7	10	23	1.40

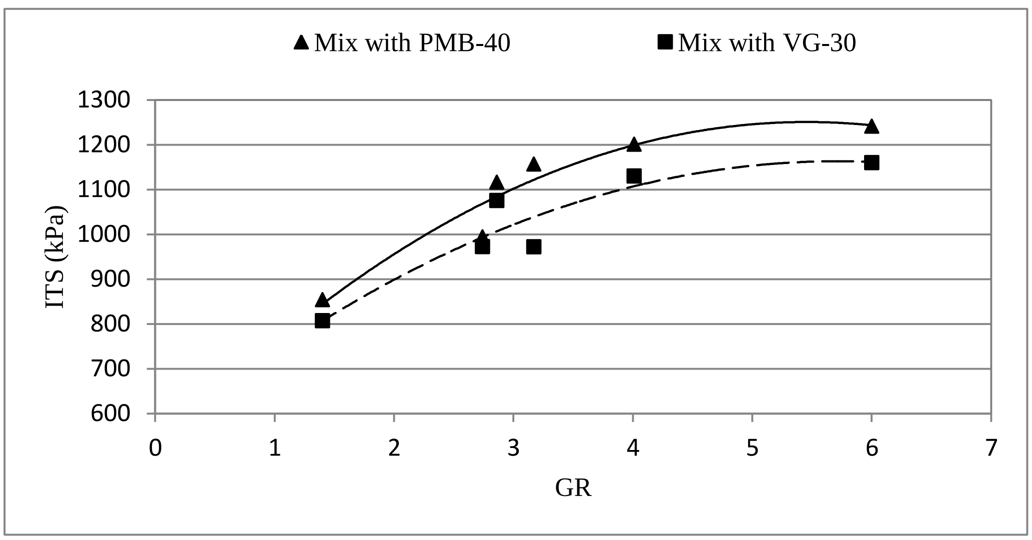

Fig.5: Relation of GR with Indirect Tensile Strength (ITS)

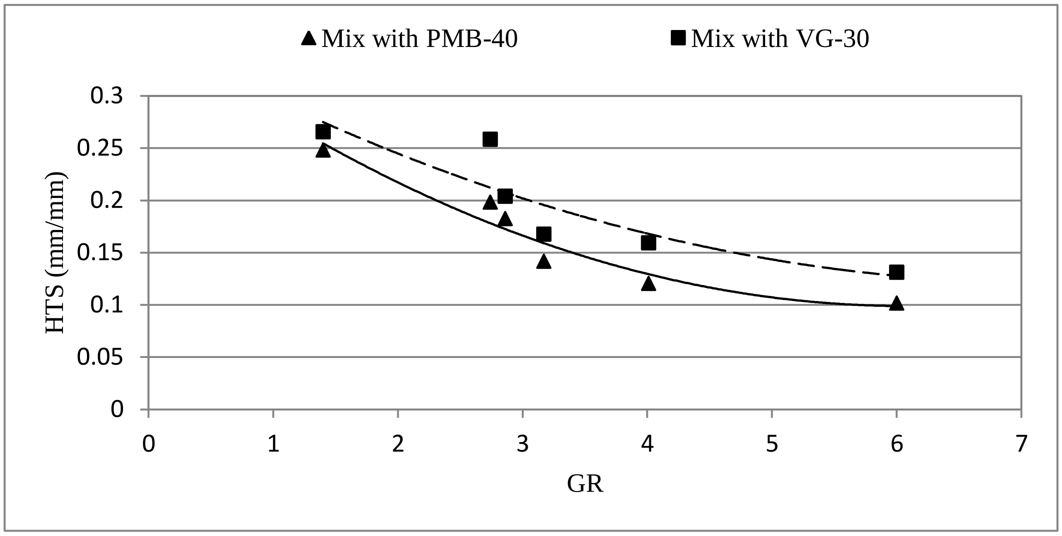

Fig.6: Relation of GR with Horizontal Tensile Strain (HTS)

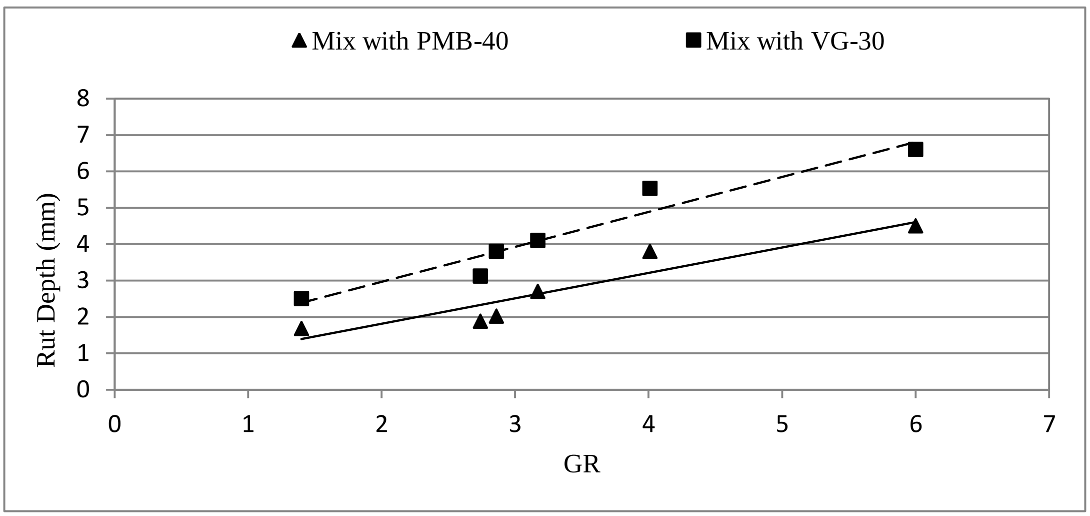

Fig.7: Relation of GR with Rut Depth

Table 6: Relations between Performance Property and GR for Mixes with PMB-40

Performance Property (Y)	*X*	Coefficient			R^2	Ratings*
		a	b	c		
ITS (kPa)	GR	515.11	269.77	-24.728	0.9251	Excellent
HTS (mm/mm)	GR	0.3616	-0.0864	0.0071	0.9372	Excellent
Shear Strength (C.F 1.5) (Kg/cm^2)	GR	20.273	-0.8565	---	0.7309	Good
Shear Strength (C.F 3.0) (Kg/cm^2)	GR	25.142	-1.5146	---	0.8755	V. good
Rut Depth (mm)	GR	0.4145	0.6984	---	0.8795	V. good

* Fair: (0.5 – 0.69), Good: (0.7 – 0.79), Very Good: (0.80 – 0.89), Excellent: (0.9 – 1.0)

Table 7: Relations between Performance Property and GR for Mixes with VG-30

Performance Property (Y)	*X*	Coefficient			R^2	Ratings*
		a	b	c		
ITS (kPa)	GR	538.24	218.39	-19.074	0.8803	V. good
HTS (mm/mm)	GR	0.3577	-0.0655	0.0045	0.7953	Good
Shear Strength (C.F 1.5) (Kg/cm^2)	GR	17.816	-1.1068	---	0.8155	V. good
Shear Strenght (C.F 3.0) (Kg/cm^2)	GR	21.974	-1.7039	---	0.8746	V. good
Rut Depth (mm)	GR	1.0486	0.9593	---	0.9346	Excellent

*Fair: (0.5 – 0.69), Good: (0.7 – 0.79), Very Good: (0.80 – 0.89), Excellent: (0.9 – 1.0)

5. CONCLUSIONS

The performance of two types of mixes with three types of aggregate gradations and two types of binders are evaluated using different tests. The results indicate that the performance of mixes made with PMB-40 is better than the mixes made with VG-30 for both types of layers. In general, the BC mixture is better than DBM in indirect tensile strength (ITS), horizontal tensile strain (HTS), and the compressive strength, while DBM mixture is better in shear strength and rut resistance. The upper gradation (finer) mix has higher ITS ((2.65% - 19.34%) in BC mix and (10.58% - 33.27%) in DBM mix) and less HTS ((4.95% - 28.23%) in BC mix and (2.71% - 26.44%) in DBM mix), less compressive strength ((14.75% - 39.88%) in BC mix and (13.79% - 31.80%) in DBM mix) than mid and lower (coarser) gradation mixes, while the lower (coarser) gradation mix has higher shear strength ((10.51% - 38.37%) in BC mix and (5.08% - 19.91%) in DBM mix) and less rut depth ((15.55% - 40.0%) in BC mix and (6.93% - 34.21%) in DBM mix) than mid and upper (finer) gradation mixes. The relation between shear strength and rut depth is found to be highly significant and can be used to predict rut in a mix from triaxial test data. Also, the performance parameters are correlated with gradation parameter like *GR* and good to excellent relations are obtained for different strength and performance characteristics of a mix. These relations are extremely useful when different mixes are to be compared for their performance in the field. The comparative performance can be predicted from aggregate gradation data alone without actually performing tests for rutting in laboratory.

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