Optimizing the Bituminous Concrete Mixes for Fatigue Performance

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Abstract: The objective of the present research work is to study the influence of aggregate gradation on fatigue performance and of Bituminous Concrete (BC) mixes, and to optimize the bituminous concrete mix for fatigue performance of within the specification band which offers longer fatigue life. Five aggregate gradations for an bituminous concrete mix falling within the specification band limit for bituminous surface course are considered. Repeated load indirect tensile fatigue test is carried out at 30, 35 and 40 °C using gyratory compacted cylindrical specimens. Laboratory fatigue test results are used for developing the optimization model considering stiffness modulus, horizontal tensile strain and air void as the constraints. Sensitivity analysis is also carried out to study the effect of variation in constraints values on fatigue life.

INTRODUCTION

Bituminous Concrete (BC) mix is a combination of aggregate and bitumen binder. The aggregate acts as the structural skeleton of the pavement and the bitumen binder as the glue of the mixture. As a construction material asphalt concrete is much more complicated than it appears. It is a composite material consisting of aggregate particles (hard pieces of rock) of different sizes; a bitumen binder that is much softer than the aggregate, and air voids Roberts *et al.* (1996) [1]. The response of this mix to traffic and environmental loads depends on the properties of the constituents and the proportion (by volume) of each. In turn, the performance of the BC mix in rutting, cracking, and durability is directly related to the mixture response to loads Deacon *et al.* (1994) [2]. The mineral aggregate matrix, including coarse and fine particles in asphalt concrete paving mixtures, encompasses approximately 90 to 95 percent of mix volume. The properties of the aggregate have direct and significant effect on the performance of bituminous concrete pavements. Research work has been dedicated to characterizing the physical properties of aggregate (strength, shape, texture) and their relationship to the behavior of asphalt concrete mix for pavement construction Sousa *et al.* (1998) [3].

Highway engineers often refer to an aggregate skeleton in the mixture when discussing the role of aggregate. Indeed, most of the compressive strength and resistance to movement under truck loads are offered by the aggregate. Properties of the skeleton are related directly to the hardness, shape, texture, and gradation of the aggregates. Of these properties, gradation is the most unstructured.

Theoretically, it would seem reasonable that the best gradation for asphalt concrete mix is the one that results in the densest particle packing. The gradation resulting maximum theoretical density provides increased stability through increased interparticle contacts and reduced voids in the mineral aggregate Huang *et al.* (1970) [4]. However, sufficient air void space is required to permit enough binder cement to be incorporated to ensure durability, while still leaving some air space in the mixture to avoid bleeding. A tightly packed aggregates (low voids in mineral aggregate) also results in a mixture that is more sensitive to slight changes in asphalt content.

The performance of bituminous concrete mix is related to particle size distribution, which affects the most important properties of the mix, such as cracking resistance, rutting resistance, durability, permeability, and workability. Therefore, having a proper aggregate particle distribution is a very important factor for satisfactory field performance Roque *et al.* (2006) [5]. Typically the selection of aggregate gradation is based on specification bands within control points, but the main question is how to choose the best possible blend within the specified band to achieve better performance?.

The specific objective of this research work is to study the effect of aggregate gradation on fatigue performance of bituminous concrete mixes and to select the optimum aggregate gradation within the specification band limit which offers better fatigue performance. The selected gradations for surface course bituminous concrete mix, fall within the specification band limit of the Ministry of Road Transport and Highways, Government of India MoRTH (2001) [6].

MATERIALS, TEST METHODS AND RESULTS

Bitumen Binder

Bitumen of 60/70 penetration grade is used for this investigation.

Aggregates

Crushed granite of coarse and fine aggregates is obtained by crushing of aggregates obtained from a quarry near Chennai, Tamil Nadu, India. The crushed stone is sieved into various fractions after washing and drying. Ordinary Portland cement is used as filler material. The properties of the selected aggregates are within the requirements as specified by the Ministry of Road Transport and Highways (MORTH 2001).

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Table 1. Physical Properties of Binder

Physical Property	Test Method	Binder Grade 60/70
Penetration at 25^0C(100g,5s),1/10^{th} of mm.	ASTM D5-05a	66
Softening point(Ring and Ball),^{0}C,minimum	ASTM D 36	44
Ductility at 27^0C(5cm/min pull),minimum	ASTM D 113-99	79
Specific gravity	ASTM D 70	1.01

Table 2. Properties of Aggregate Tested

Properties Tested	Test Results	MoRTH Specification
Crushing Value	33%	45 % Max
Aggregate Impact Value	28%	30 % Max
LosAngeles Abrasion Value	14%	30 % Max
Water Absorption Value	0.85%	2 % Max
Specific Gravity	2.65%	2.5 - 3.0
Combined (EI + FI) Index	20%	30 % Max

Aggregate Gradation

Five aggregate gradations for a Bituminous Concrete (BC) mix falling within the specification band limit for application of surface course are considered. The gradations and mix designations considered in the present study are presented in Table **1**. The gradation curve is shown in Fig. (**1**).

LL-Lower limit (Lowest gradation line (coarse graded)), OF-One fourth (between LL and MP (coarse graded)), MP-Mid point (Middle most gradation line), TF-Three fourth (between MP and UL (fine graded)), UL-Upper limit (upper most gradation line above TF).

Specimen Preparation

Bituminous Concrete (BC) mix specimens are prepared at optimum binder content, by mixing the aggregates and binder at desired mixing temperatures, and compacted using gyratory compactor for high traffic level (N_{ini}=9, N_{des}=125, and N_{max}=205 AASHTO *TP4*, (1999) [7] at desired compact-

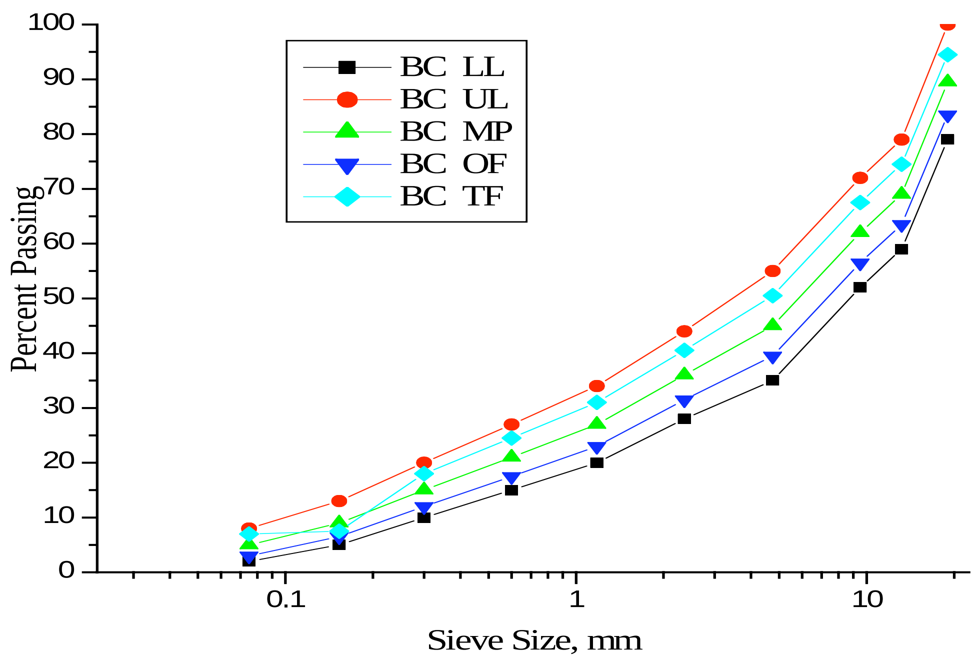

Fig. (1). Aggregate Gradation used in the Study (0.45 power curve).

Table 3. Aggregate Gradation Considered in the Present Investigation

BITUMINOUS CONCRETE (BC) GRADE - I						
Sieve Size, mm	Cumulative % by weight of Total Aggregate Passing					
	Specification limit	BC-LL	BC-OF	BC-MP	BC-TF	BC-UL
26.5	100	100	100	100	100	100
19	79-100	79	83.5	89.5	94.5	100
13.2	59-79	59	63.5	69	74.5	79
9.5	52-72	52	56.5	62	67.5	72
4.75	35-55	35	39.5	45	50.5	55
2.36	28-44	28	31.5	36	40.5	44
1.18	20-34	20	23	27	31	34
0.6	15-27	15	17.5	21	24.5	27
0.3	10-20	10	12	15	18	20
0.15	5-13	5	6.5	9	7.5	13
0.075	2-8	2	3	5	7	8

ing temperatures. The specimen after conditioning for two hours at desired temperature is placed between two steel strips so that the central axes of the strips, specimen and piston are in the same vertical plane. A constant repeated load is applied at a loading frequency of 5 hertz with a desired loading period of 0.2 second and rest period of 0.8 second. Haversine type of loading waveform is used, as this is the closest waveform that experienced in the field, since the loading pulse is followed by a rest period. The load repetitions are continued till the specimen failed. When the permanent horizontal deformation in the specimen is 5 mm, the tensile crack is about 0.8 mm wide and is found to be adequate to describe the fatigue life for a given mix Gilmore *et al.* (2007) [8]. Fatigue life of the BC mix is the number of load repetitions to cause failure of the specimen as above. The specimens are tested at two test temperatures viz., 30, 35 and 40 °C.

Volumetric Analysis

Volumetric analysis is carried out as per AASHTO: T 166 [9] and the results are tabulated in Table **2**. It can be observed that the bulk specific gravity and the Voids in Mineral Aggregate (VMA) of the BC mix increases with increase in finer particles, while the air voids decreases.

Repeated Load Indirect Tensile Fatigue Test

The pavement materials are subjected to cyclic stresses due to repeated application of loads by fast moving vehicles. In view of this, it is decided to carry out repeated load indirect tensile test to determine fatigue life and other resilient characteristics of paving mixes. This test is similar to static indirect tensile test, but in this case, repeated loads are applied and resulting horizontal and vertical deformation measurements are made. Literature review is carried out to identify the available methods of fatigue testing. It is concluded that a study should be conducted using indirect tensile mode of testing as it presented a simple and inexpensive test method utilizing cylindrical specimens that could also be cored from a pavement if needed. The specimens are subjected to repeated diametric line loading along the vertical diameter which generates an indirect tensile stress on the horizontal diameter. This vertical loading produces both vertical compressive stress and horizontal tensile stress on the diameters of the specimen. The magnitudes of the stresses

Table 4. Results of Volumetric Analysis and Resilient Modulus

Mix Type	Bulk Specific Gravity	Air Voids, %	Voids in Mineral Aggregate, %	Resilient Modulus (M_R), MPa
BC-LL	2.382	4.5	15.2	1989
BC-OF	2.388	4.2	15.5	2266
BC-MP	2.387	4	15.9	2410
BC-TF	2.39	3.8	16.4	2600
BC-UL	2.393	3.6	16.8	2505

vary along the diameters, but are maximum at the center of the specimen Deacon *et al.* (1967) [10].

It can be observed from Table **3** that the laboratory fatigue life for asphalt concrete mix is found to be optimum for BC-TF mix at all the temperature and stress level.

Optimizing the Bituminous Concrete mix for Fatigue Performance

The main objective of this research work is to optimize the bituminous concrete mixes for fatigue performance. In order to do this, BC-Grade I as specified in the Ministry of Road Transport and Highways (MORTH), is selected. Five aggregate gradations for a BC mix falling within the specification band limit for application of surface course are considered. The volumetric analysis and the indirect tensile fatigue test results of all the five mixes studied are used for developing optimization model.

Formulating the Objective Function and Constraints

Objective is to maximize the fatigue life, subjected to the constraints of air voids, stiffness modulus and horizontal tensile strain.

Micromath scientific software [11] is used for developing the objective function equation.

Objective function is obtained by inputting the dependent (Fatigue life) and the independent variables (air voids, stiffness modulus, and horizontal tensile strain). Following is the objective function equation.

Maximize Y=1.8+ (2.9*x1) + (4.56*x2) + (2.5*x3) eqn …1

Subjected to constraints at bounds;

3.6, x1, 4.5;

1989, x2, 2600;

75, x3, 125;

Where

Y=Fatigue life,

x1=Air Voids (%),

x1=Stiffness modulus (MPa)

x1=Horizontal Tensile Strain (Microstrain).

The optimization solution is obtained by inputting the above objective function equation and the constraints in the LINGO software [12], which solves the optimization problem by simplex method. Following is the output from the software.

Global optimization solution found at iteration: 8

Objective value: 9625

Variable	Value
X1	3.9
X1	2630
X1	85

The above results are compared with the Table **4** and **5**, it can be observed that at 30 ^{0} C and 20 per cent stress level the BC-TF very closely matches with the output obtained.

Sensitivity Analysis

Sensitivity analysis is the study of how model output varies with changes in model inputs. A model is said to be sensitive to an input if changing that input variable changes the model output. This output variability can be apportioned,

Table 5. Indirect Tensile Fatigue Test Results

Stress level	Type of Asphalt Concrete Mix				
	BC-LL	BC-OF	BC-MP	BC-TF	BC-UL
	Number of Repetitions to Failure				
	Temperature = 30^0 C				
20	6655	7762	8010	9465	8720
30	2988	3125	3990	4935	4305
40	1208	1422	1649	2376	1939
	Temperature = 35 ^{0}C				
20	5986	6329	6885	7566	7135
30	2366	2855	3265	4725	3782
40	1092	1328	1562	1925	1766
	Temperature = 40 ^{0}C				
20	3965	4302	4885	5685	5228
30	2242	2600	3008	3755	3388
40	535	756	855	1465	1085

Table 6. Input Variables for Sensitivity Analysis

Fatigue Life	Air Voids	Stiffness	Horizontal Tensile Strain
6655	3.6	1989	75
7762	3.8	2266	82
8010	4	2410	95
9465	4.2	2600	113
8720	4.5	2505	125

qualitatively or quantitatively, to different sources of variation in the inputs Cacuci *et al.* (2003) [13].

Methodology

There are several possible procedures to perform sensitivity analysis (SA). The most common sensitivity analysis is sampling-based. A sampling-based sensitivity is one in which the model is executed repeatedly for combinations of values sampled from the distribution (assumed known) of the input factors. Other methods are based on the decomposition of the variance of the model output and are model independent Saltelli *et al.* (2004) [14].

Table 7. Results of Sensitivity Analysis

9270	9270	9270
10550	9288	10533
11239	9321	11191
12151	9366	12057
11748	9397	11625
9270	10533	9287
10551	10551	10551
11240	10584	11208
12151	10629	12075
11748	10660	11643
9271	11189	9320
10551	11207	10583
11241	11241	11241
12152	11286	12107
11749	11317	11675
9271	12056	9365
10552	12074	10628
11241	12107	11286
12152	12152	12152
11749	12183	11720
9272	11623	9395
10553	11641	10658
11242	11674	11316
12153	11719	12182
11750	11750	11750

The model is evaluated and the computed distribution of the target function (Objective function) is shown in Table **7**. It can be observed that the variation in the output of the sensitivity analysis is less than eighteen per cent compared to optimal value.

CONCLUSIONS

This paper presented an evaluation of fatigue performance and optimizing the bituminous concrete mixes with different aggregate gradations based on the ones proposed by the Ministry of Road Transport and Highways for surface courses. Based on results the following conclusions are drawn.

- Optimum aggregate gradation is found to be BC-TF which gives maximum fatigue life.
- The optimization model developed closely predicts the optimum fatigue life with less than five per cent variation.
- The result of the sensitivity analysis shows that the model output is having variation of less than eighteen per cent with changes in model inputs.

REFERENCES

[1] F.L. Roberts, P.S. Kandhal and E.R. Brown. *Hot Mix Asphalt Design and Construction*, Second Edition. NAPA Education Foundation, Lanham, Maryland. p. 156, 1996.

[2] J.A.Deacon, J. Tayebali, F. Finn. Coplantz, and C.L. Monismith.1994. Fatigue Response of Asphalt –Aggregate Mixes, *Strategic Highway Research Program* Report No. SHRP-A- 404, Part-III Mix Design and Analysis, National Research Council, Washington, D.C.

[3] Sousa, B. Jorge, Pais, C. Jorge, Prates, Manuel *et al*. 1998. Effect of Aggregate Gradation on Fatigue Life of Asphalt Concrete Mixes, *Transportation Research Record, Journal of Transportation Research Board*, n 1630, Washington, D.C. Sep. p 62-68.

[4] E.Y. Huang. A Study of Strength Characteristics of Asphalt-Aggregate Mixtures as Affected by the Geometric Characteristics and Gradation of Aggregate, *Journal of the Association of Asphalt Paving Technologists*, Vol. 39, p. 98-133, 1970.

[5] R.Roque, B. Birgisson and S. Kim. Development of Mix Design Guidelines for Improved Performance of Asphalt Mixtures, *Final Report Submitted to Department of Civil and Coastal Engineering*, College of Engineering, University of Florida. p. 1-16, 2006.

[6] Ministry of Road Transport and Highways (MoRT&H). 2001. *Specification for Roads and Bridge Works*, Government of India, Indian Roads Congress, New Delhi, India, 4th Revision.

[7] Method for Preparing and Determining the Density of HMA Specimens by Means of the SHRP Gyratory Compactor, *AASHTO TP 4*, 1999.

[8] Gilmore, D.W., R.P. Lottman, J.A. Scherocman. Use of Indirect Tension Measurements to Examine the Effect of Additives on As-

phalt Concrete Durability. *Journal of the Association of Asphalt Paving Technologists*, Vol. 53, p. 495, 2007.

[9] Standard Test Method for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens, AASHTO T 166.

[10] J.A. Deacon and C.L. Monismith. Fatigue of Asphalt Paving Mixtures, Highway Research Record (HRR), *Highway Research Board (HRB), National Research Council*, Washington, D.C, No 158, 1967.

[11] Micromath software www.micromath.com 14/11/07

[12] Lingo, Gloabal Optimization Solution. http://www.lindo.com/products/lingo/lingom.html 14/11/07

[13] Cacuci, Dan G. In Sensitivity & Uncertainty Analysis, Volume 1: Theory; Chapman & Hall, 2003.

[14] A. Saltelli, S. Tarantola, F. Campolongo and M. Ratto. 2004, Sensitivity Analysis in Practice. A Guide to Assessing Scientific Models, John Wiley & Sons publishers.

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