Analytical Evaluation of Bituminous Overlays on Flexible Pavements

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Criteria were developed to predict the performance of bituminous overlays on flexible pavements considering fatigue and modes of distress. Data collected on several pavement sections on national highways in India were correlated to the mechanistic response of the pavement to develop the performance criteria. The theoretical responses of the pavement were calculated by using a computer program developed to solve elastic layered systems. Design charts were prepared to assist field engineers in designing pavement sections that can be expected to perform satisfactorily during the design period without developing excessive fatigue cracking and rutting.

In India flexible pavements are designed by using the subgrade CBR value according to the guidelines of Indian Roads Congress (*1*), with no consideration given to cracking or rutting. The CBR method (*1*), which was developed about 20 years ago, has little relevance for the present-day high volume of traffic coupled with heavy axle loads. It is therefore essential that analytical design methods based on the stress-strain behavior of the pavement materials be developed by correlating the mechanistic response of the pavement with the performance of pavements in the field. The two most important forms of pavement distress that lead to the functional failure of the pavement are fatigue cracking of bituminous and other bound layers and rutting along wheelpaths. Repeated applications of wheel loads, which cause excess tensile strain in the bituminous layer and excess vertical compressive strain on the subgrade, are identified as major reasons for fatigue cracking and rutting, respectively. Hence, to preclude the two modes of distress in a pavement during its design life, any rational design method for flexible pavements must aim at keeping these two strain values within the limits that the pavement materials can withstand. These limits must be determined from laboratory and field tests. Mechanistic design methods with either fatigue cracking or rutting as design criteria have already found application in the United States and several countries in Europe (*2–6*). Efforts have also been made in India in recent years to reduce the empirical content of the pavement design by studying and analyzing the performance of in-service pavements (*7–10*).

As a result of exhaustive research on the fatigue of the bituminous mixes commonly used in India, Pandey (*7,11*) developed performance-based fatigue criteria by calibrating laboratory fatigue results from the field performance of the bituminous pavements. A rutting criterion was developed by the authors (*8*) from the analysis of several in-service pavements that showed failure caused by rutting ranging from 20 to 25 mm along wheelpaths. On the basis of these two criteria, the authors presented charts for the design of flexible pavements with bituminous overlays to preclude the development of excessive cracking and rutting in the pavement within the design period (*10*).

In the present paper several additional pavement sections are considered in developing performance-based fatigue criteria in place of the earlier criteria (*7,10*), which were developed by calibrating a laboratory fatigue curve with limited field performance data. Field engineers in India usually consider a pavement to have failed if the area of cracked surface amounts to about 20 to 30 percent of the total pavement area. Hence, in the present investigation the failure condition considered for fatigue criteria is the development of surface cracking (mean + standard deviation) in excess of 20 percent of the paved area. Similarly, for rutting criteria, development of a rut depth in excess of 20 mm is taken as a failure condition.

Field data collected for several pavement sections on National Highway 5 (NH5) in Orissa, NH2, NH6, and NH41 in West Bengal, NH2 in Bihar, and NH4 in Karnataka states in India were utilized in developing the performance criteria. Structural analysis of the pavements was carried out by using the ELAYER computer program (*12*), which was developed to solve elastic layered pavement systems. Results from laboratory tests conducted on bituminous mixes (*13*) and granular materials and subgrade soils (*14*) and the studies conducted on the lateral placement and axle load characteristics of commercial vehicles (*15–17*) were used in the development of performance criteria. Design charts were developed on the basis of fatigue and rutting criteria to enable field engineers to design pavements to serve during the life period satisfactorily without developing excessive fatigue cracking or rutting.

STRUCTURAL ANALYSIS OF FLEXIBLE PAVEMENTS

The flexible pavement system was idealized as a linear elastic layered system to compute stresses, strains, and deflections in the pavement. Each layer in the pavement is characterized by its elastic modulus (E) and Poisson's ratio (μ). Several field studies (*18–26*) indicated that the use of elastic theory provided a reasonable estimate of pavement response to fast-moving wheel loads if appropriate values of elastic parameters are used in the analysis. Although the behavior of the pavement materials is not linearly elastic in general, this approach can be used by assigning elastic modulus and Poisson's ratio values corresponding to appropriate loading time, pavement temperature, and other field conditions. A computer program, ELAYER, was developed (*12*) on the basis of the solutions presented by Burmister (*27,28*) for elastic layered system. Rough interfaces between layers are assumed in the analysis, which is appropriate for most construction practices. Figure

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1 shows the cross section of a typical three-layer pavement system considered for analysis. As shown in Figure 1 the loading configuration consists of dual wheel loads, each being 20 kN, that are assumed to act over circular areas at 550 kPa of tire pressure. Average center-to-center spacing between the dual wheels was 310 mm.

ELASTIC PROPERTIES OF PAVEMENT MATERIALS

Elastic Modulus Value

Subgrade Soil

The elastic modulus value of subgrade soil (E_3) was estimated from its CBR by using the relationship (*29,30*)

$$E_3 = 10.0 \cdot \text{CBR} \quad (1)$$

where E_3 is in megapascals.

Repeated load triaxial test of various soils indicated that Equation 1 is reasonably correct for CBR values of about 5.0. For stronger subgrades the following relationship, which was found to be closer to the triaxial test results (*6*), was used to estimate the elastic modulus values of subgrade (E_3).

$$E_3 = 17.6 \cdot (\text{CBR})^{0.64} \quad (2)$$

Granular Base Course

A granular layer in a flexible pavement is difficult to characterize. It is a no-tension material, and nonlinear iterative analysis (*31*) is required to determine the stress distribution in such a layer. In the absence of simple mathematical solutions for such granular materials, the Shell relationship (*2*) for the modular ratio given by Equation 3 was used for estimating the elastic modulus value (E_2) of granular base course.

$$E_2 = 0.2(H_2)^{0.45} \cdot E_3 \quad (3)$$

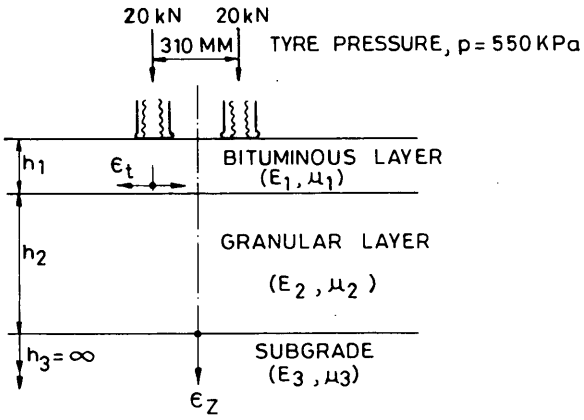

FIGURE 1 Typical three-layer pavement section.

where H_2 is the thickness of granular base (in millimeters). The modular ratio (E_2/E_3) has limits of from 2 to 4.

Bituminous Materials

Bituminous macadam (BM) (*32*), with a wearing course of thin premix bituminous carpet and seal coat (*33*), is the most common type of bituminous construction adopted in India. The gradation of aggregates in BM is close to mix IIe of the Asphalt Institute (*34*). The open-graded mix has a bituminous content of 4-percent by weight of the total mix, and the air void after 6 months of traffic is about 15 percent. All of the pavement sections discussed in this paper contain BM construction with a bituminous wearing surface. The average annual air temperature (AAAT) for the region in which the majority of the pavement sections under consideration are situated was found to range from 27°C to 29°C. In the absence of any data for average annual pavement temperature (AAPT) of bituminous pavements in India, the relationship developed by Brunton et al. (*35*) was used to determine the AAPT from the AAAT. For an AAAT of 28°C, the AAPT was found to be 35°C.

A repeated load test at a rate of 120 repetitions per minute on the open-graded BM specimens 100 mm in diameter and 200 mm in height containing 80/100 bitumen and cast according to the grading of the Ministry of Surface Transport (*32*) resulted in a resilient modulus value of about 200 MPa for a test temperature of 30°C and a loading time of 0.12 sec. Although references on such open-graded materials are scarce, Claessen et al. (*2*) have reported similar values of elastic modulus for lean bituminous macadam. By using Shell's nomograph (*36*), the experimental dynamic modulus value was corrected for a loading time of 0.02 sec and an AAPT of 35°C, and the modified value was 500 MPa. For dense asphalt concrete under similar conditions, the elastic modulus is almost 1000 MPa (*36*) for 80/100 bitumen, with the air void being 3 to 5 percent.

Poisson's Ratio

For the bituminous mix, Poisson's ratio was taken as 0.5, which was considered appropriate for the range of temperatures under consideration (*37,38*). The value of Poission's ratio was taken as 0.40 for granular materials and subgrade soils (*39*).

FIELD PERFORMANCE STUDIES

Performance data collected over several pavement sections on NH2, NH6, and NH41 in West Bengal, NH5 in Orissa, NH2 in Bihar, NH4 in Karnataka, and State Highway 9 in Uttar Pradesh were used in the development of the performance criteria. Tables 1 and 2 show the details for pavement sections considered in developing the fatigue and rutting criteria, respectively. The CBR values were determined after 4 days of soaking of soil specimens cast at the in situ dry density and moisture content. These sections are situated in areas with annual rainfall in the range of 1000 to 1600 mm. Many of the sections considered are part of Research Scheme R-6 sponsored by the Ministry of Surface Transport, Government of India. Performance data on several of the remaining pavement sections were collected as part of a consultancy project

TABLE 1 Details for Pavement Sections Considered for Fatigue Criteria

S NO	LOCATION NH/SH	KM	TRAFFIC (CVPD)	SUBGRADE CBR (%)	LAYER THICKNESS (mm) BITUMINOUS MACADAM	GRANULAR BASE	MAX. HORIZONTAL TENSILE STRAIN (ϵ_t x 10^{-6})	OVERLAY LIFE MONTHS	CSA 10^6
1	4	41.43	3000	30.0	70	320	306.0	36	7.70
2	4	41.50	3000	30.0	95	320	318.3	54	12.1
3	4	41.60	3000	30.0	120	320	297.9	72	16.9
4	2	283.0	3800	3.5	100	540	361.0	18	4.11
5	2	595.3	3650	4.8	95	340	752.7	5	1.07
6	2	607.1	3650	5.5	95	380	659.6	13	2.90
7	2	607.2	3650	5.5	170	380	445.1	21	4.90
8	2	657.7	3650	2.9	150	265	794.4	4	0.86
9	5	256.8	3500	6.7	70	680	493.3	20	4.5
10	5	256.9	3500	6.7	95	680	482.6	20	4.5
11	5	81.60	2280	3.8	95	500	783.7	16	2.0
12	6	128.8	2800	9.8	70	320	465.1	12	2.58
13	6	128.9	2800	9.8	110	320	441.6	11	2.16
14	6	130.0	2800	5.2	70	340	772.8	8	1.98
15	6	131.0	2800	8.9	100	325	572.4	11	2.72
16	9	198.0	1180	5.0	70	600	648.3	50	3.91

CVPD: Commercial vehicles per day in both traffic directions
CSA: Cumulative standard axle repetitions

carried out by the Transportation Engineering Section of the Indian Institute of Technology (IIT), Kharagpur, India (*40,41*). The length of each of the pavement sections of the Research Scheme, which is about 300 m, was subdivided into three parts on which different overlay thicknesses were used. All of the pavement sections have two-lane carriageways 7.0 m in width with two-way traffic.

A thin bituminous wearing course of 20-mm Premix Carpet with a seal coat over a granular base was considered as part of the granular base because the structural strength provided by this layer is negligible. Boulder and brick soling were not considered in the structural layer thicknesses because of their poor load-spreading behaviors, as found by Sivaguru et al. (*42*). The badly cracked bituminous layer on which the overlay was placed was considered part of the granular layer.

Measurement of rut depth along the wheelpaths was made by using a 3-m straight edge at regular intervals in both directions of traffic. The percentage of the area of cracked surface because of fatigue was estimated by visual observation.

TABLE 2 Details for Pavement Sections Considered for Rutting Criteria

S NO	LOCATION NH/SH	KM	TRAFFIC (CVPD)	SUBGRADE CBR (%)	LAYER THICKNESS (mm) BITUMINOUS MACADAM	GRANULAR BASE	MAX. VERTICAL TENSILE STRAIN (ϵ_z x 10^{-6})	OVERLAY LIFE MONTHS	CSA 10^6
1	2	595.1	3650	4.8	--	340	1302.0	16	3.65
2	2	607.0	3650	5.5	--	380	974.30	13	2.90
3	5	81.70	2280	3.8	--	595	667.70	46	6.64
4	6	99.00	2800	4.5	--	200	2368.0	4	0.75
5	6	100.0	2800	3.0	--	395	1668.0	4	0.75
6	6	135.0	2800	1.4	120	560	1257.0	25	5.33
7	6	137.0	2800	4.2	35	425	985.80	48	8.06
8	6	138.0	2800	5.5	30	95	2321.0	4	0.75
9	6	148.0	2800	4.7	80	270	1341.0	48	8.06
10	6	149.0	2800	5.3	45	455	683.3	48	8.06
11	6	150.0	2800	9.7	40	365	707.8	48	8.06
12	6	153.0	2800	10.0	--	390	686.7	4	0.75
13	6	160.0	2800	8.0	--	130	1880.0	4	0.75
14	6	179.0	2800	3.7	50	520	767.40	48	8.06
15	41	46.00	1520	5.0	130	65	1846.0	60	5.26
16	41	48.00	1520	4.0	150	230	1182.0	60	5.26
17	41	49.0	1520	4.0	170	225	1079.0	60	5.26
18	41	50.0	1520	4.5	155	50	1729.0	60	5.26
19	41	51.0	1620	3.2	--	270	2759.0	4	0.43
20	41	52.0	1620	3.6	--	240	2749.0	4	0.43

-- Thin bituminous overlay considered as part of granular base

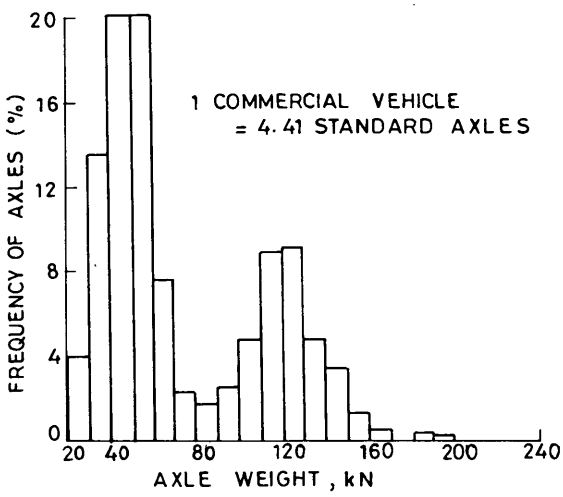

FIGURE 2 Distribution of axle weights (combined data for NH2, NH5, and NH6).

CALCULATION OF EQUIVALENT STANDARD AXLE REPETITIONS

It is necessary to estimate the number of repetitions of 80-kN loads [equivalent single axle loads (ESALs)] from measurements of the axle loads of commercial vehicles. A portable weigh bridge was designed and fabricated by the authors (*16*), and field studies were conducted on NH2, NH5, and NH6 to find the axle load spectrum on the various national highways (*17*) under study. Repetitions of ESAL were determined for different pavement sections by using AASHTO equivalency factors. The average value of the truck factor was found to be 4.40, whereas the value recommended by the Indian Roads Congress (IRC) is 3.0 (*1*). The high truck factor is due to the fact that a very large percentage of commercial vehicles have rear axle loads exceeding 102 kN, which is the legal axle load in India. A typical distribution of axle weights on the national highways under study is shown in Figure 2.

Studies of the lateral placement characteristics of wheel loads of commercial vehicles (*15*) indicated that the inner wheelpaths of commercial vehicles in either direction keep close to the centerline of the two-lane road, and about 50 percent of the wheelpaths of the total two-way commercial vehicles lie within a 1.00-m band. Figure 3 presents a typical distributon of the inner wheelpaths of the rear axles of commercial vehicles on two-lane Indian national highways.

A traffic growth rate of 7.5 percent, as suggested by IRC (*1*), was considered whenever necessary to compute the cumulative standard axle load repetitions.

DEVELOPMENT OF FATIGUE FAILURE CRITERIA

Laboratory Fatigue Relationship

Laboratory investigations of the fatigue behaviors of bituminous mixes were reported elsewhere (*7*). Third-point repeated loading was applied on beams of bituminous mix at a temperature of 20°C. The fatigue relationship for bituminous mixes with 80/100 grade bitumen and 7 percent air voids at a test temperature of 20°C was obtained as

$$N = 7.1140 \cdot 10^{-10} \cdot (1/\epsilon_t)^{3.99} \quad (4)$$

where N is the number of repetitions to fatigue and ϵ_t is the tensile strain.

Bituminous mixtures have longer fatigue lives at higher temperatures because of greater flexibility. Equation 4 was therefore modified to obtain a fatigue relationship for an AAPT of 35°C by using the equations of Rauhut and Kennedy (*43*). The equation is given as

$$N = 1.7564 \cdot 10^{-7} \cdot (1/\epsilon_t)^{3.89} \quad (5)$$

Since fatigue data for bituminous mixes for air voids of 15 percent are not available, the research work of Pell and Taylor (*44*) on the effects of air voids on fatigue life was used in the

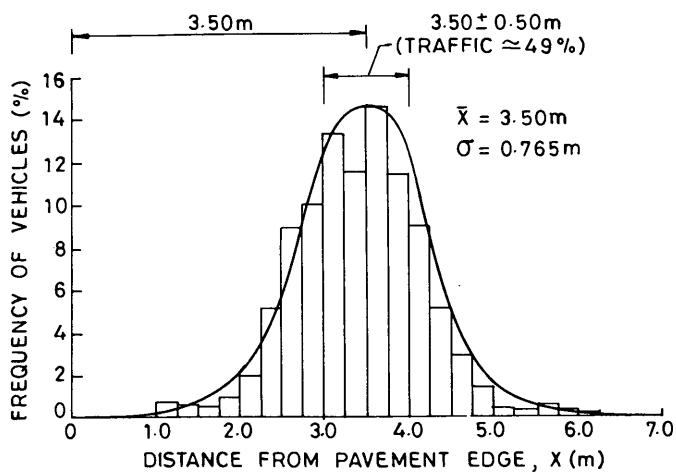

FIGURE 3 Distribution of inner wheelpaths on two-lane roads.

investigation described here. It was found that the fatigue lives of bituminous mixes decreased with an increase in the air voids. Equation 5 was therefore modified to obtain a fatigue curve for BM with 15 percent air void and is shown as line 2 in Figure 4.

Laboratory fatigue relationships do not take into account (a) the healing of the mixes due to the rest periods available in the field because of intermittent traffic, (b) the lateral wander of wheel loads, or (c) changes in the properties of the mixes because of weathering. It is thus necessary to calibrate a laboratory fatigue line with the performance of BM overlays that failed because of fatigue cracking during service.

Calibration of Laboratory Fatigue Relationship

Several pavement sections that failed because of fatigue cracking were analyzed by using the ELAYER program to compute the maximum horizontal tensile strain (ϵ_t) in the bituminous layer. The lives of the bituminous overlays corresponding to the failure of the pavements due to the development of fatigue cracking were computed in terms of cumulative standard axles (CSAs). It was found that the fatigue life computed from the laboratory relationship must be multiplied by an average shift factor of 15.0 to get an estimate of field fatigue life. The laboratory fatigue line (20°C, 7 percent air voids), the extrapolated relationship (35°C, 15 percent air voids), and the fatigue relationship calibrated from field performance are shown in Figure 4. The calibrated fatigue line shown in Figure 4 can be represented by the following relationship.

$$N = 6.6277 \cdot 10^{-7} \cdot (1/\epsilon_t)^{3.89} \quad (6)$$

Errors, if any, introduced while applying corrections for air voids and temperatures are eliminated to a large extent during the calibration.

The authors' fatigue relationship is shown in Figure 5 in comparison with some other fatigue criteria developed elsewhere. The fatigue line developed by the authors is positioned higher on the plot compared with those developed by others mainly because of (a) the higher temperatures in the study area and (b) the lower level of serviceability tolerated before rehabilitation measures are taken.

DEVELOPMENT OF RUTTING FAILURE CRITERIA

Correlation of the computed vertical subgrade strain (ϵ_z) values with observed pavement lives in the rutting mode of failure (N) resulted in the following relationship

$$N = 2.0567 \cdot 10^{-4} \cdot (1/\epsilon_z)^{3.5062} \quad (7)$$

where ϵ_z is the vertical subgrade strain and N is the number of standard axle repetitions.

For 85 percent one-sided confidence limits, the relationship is

$$N = 5.7316 \cdot 10^{-5} \cdot (1/\epsilon_z)^{3.5062} \quad (8)$$

The coefficient of determination (R^2) for these relationships is 0.45. The rutting criterion for an 85 percent one-sided confidence limit was adopted in this paper for developing design charts for BM overlays over flexible pavements. The rutting criterion suggested by the authors is shown in Figure 6 along with some other criteria developed elsewhere. Although the authors' criterion for

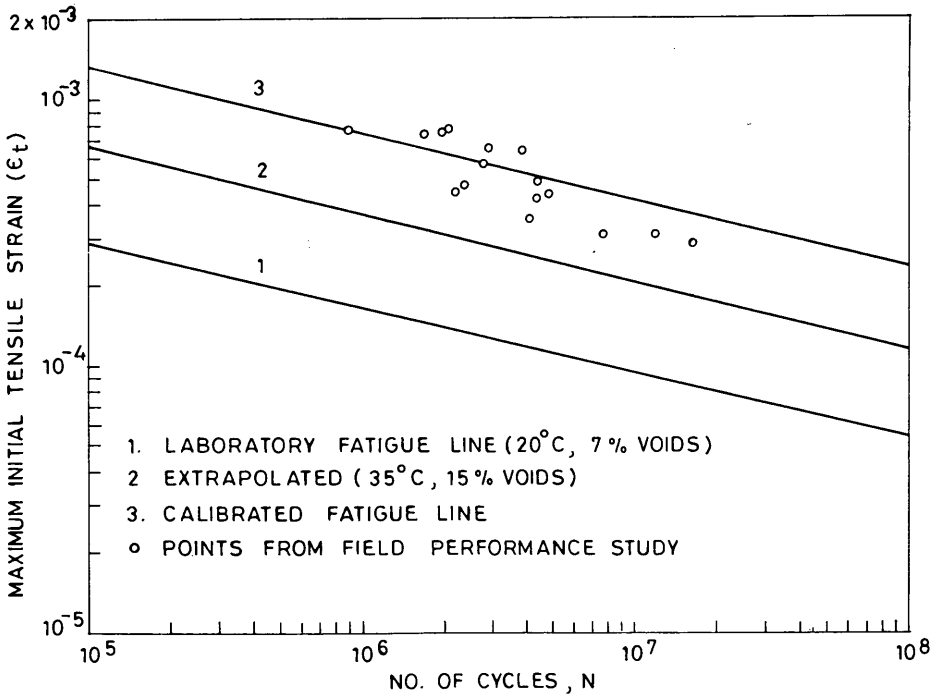

FIGURE 4 Calibration of laboratory fatigue criteria.

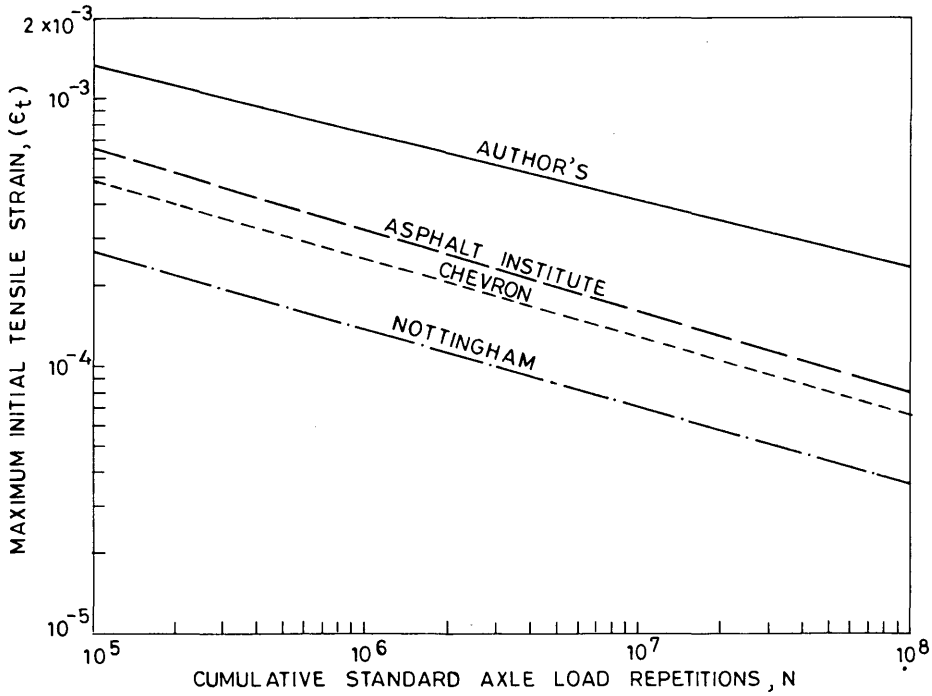

FIGURE 5 Comparison of fatigue criteria.

the 85 percent confidence limit is closer to that of Shell (*2*), it is liberal in comparison with the other two criteria. This is because (a) the allowable rut depth is 20 mm for India in comparison with 10 to 15 mm in, for example, the United Kingdom, the United States, and The Netherlands, and (b) diverse climate and traffic conditions.

DEVELOPMENT OF DESIGN CHARTS

Design charts were developed by analyzing pavement sections for subgrade vertical strain (ϵ_z) and horizontal tensile strain (ϵ_t) under the standard loading conditions discussed earlier in the paper and finding the pavement composition (thickness and elastic proper-

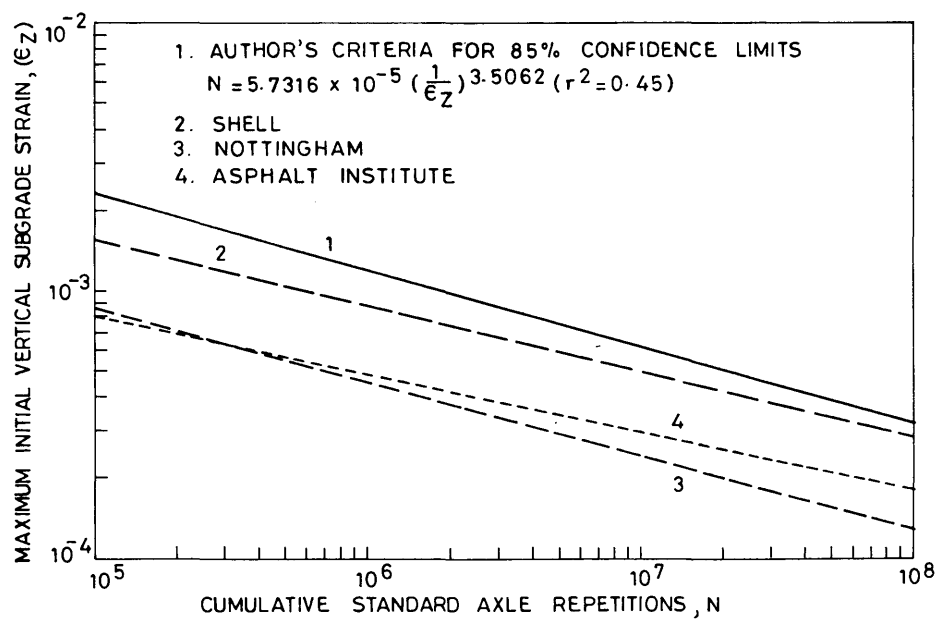

FIGURE 6 Rutting criteria.

ties) that can keep these strain values below the limiting values set by the performance criteria for different values of CSA load repetitions. Several combinations of pavement sections were selected by considering six values of subgrade modulus (30, 40, 50, 60, 100, and 170 MPa), a varying granular base thickness at 20-mm intervals ranging from 150 to 450 mm, and BM thickness ranging from 50 to 350 mm at intervals of 10 mm. Some of the design charts for different levels of traffic prepared for different subgrade modulus values are presented in Figures 7 to 10. These charts were developed to give design thicknesses that can satisfy both the fatigue and rutting failure criteria. The *R* and the *F* noted in Figures 7 to 10 indicate the portions of the curve that correspond to fatigue and rutting criteria, respectively.

By examining the design charts presented in Figures 7 to 10, the following inferences can be drawn with respect to the contribution of the major components of the pavement toward its performance:

1. With an increase in the subgrade modulus value the governing criterion shifts from the rutting to the fatigue mode of failure because pavements with stronger subgrades perform better against rutting failure.
2. Pavements with a lesser thickness of granular base course are likely to fail in rutting early. This in a way signifies the contribution of the granular layer in preventing rutting, as can be seen from the steeper slopes of the rutting criterion portions of the design curves.
3. As is evident from the flatter slopes of the design curves for fatigue criteria, the contribution of the granular base in preventing fatigue cracking is not substantial. Beyond the rutting portion of the design curves, the provision of additional thicknesses of the granular base serves little purpose because the reduction in the thickness of BM is only marginal.
4. The slopes of the design curves give an indication of the equivalence factors for the bituminous layer in terms of the granular base course. As seen from the plots the equivalency factor may vary from a value of as low as 1.2 (for the steepest curve) to a very large value, depending on the combination of subgrade strength and the thicknesses of the granular base course and bituminous layer.

COMPARISON WITH OTHER DESIGN PRACTICES

The design thicknesses obtained from the chart developed by the authors were compared with those obtained from other design methods such as the IRC design method (*1*), the Asphalt Institute method (*45*), the Shell method (*2*), and British practice (*46*). The comparison is shown in Table 3. Although the Asphalt Institute and Shell methods use analytical approaches, the IRC method and British practice are based mostly on field experience. A comparison of design thicknesses has been made for a range of subgrade modulus values, granular and bituminous layer thicknesses, and traffic levels. The IRC method suggests a larger thickness of the granular layer, whose contribution beyond a certain limit has been found to be insignificant. Thus, the pavement sections are in general underdesigned against fatigue cracking because of a low bituminous layer thickness. The suggested design thicknesses differ from others because of the construction practices, traffic, climate, and failure criterion adopted in the preparation of the charts.

CONCLUSIONS

The thickness design charts presented here on the basis of performance studies on several bituminous overlays in India can be

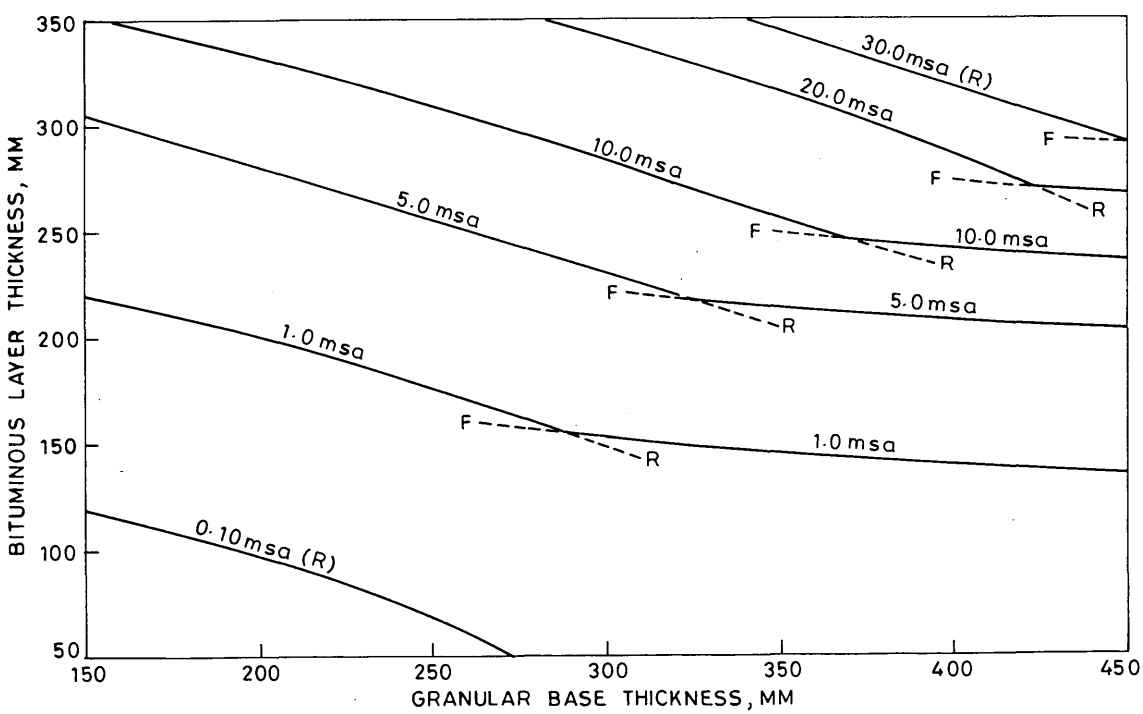

FIGURE 7 Design thickness for different traffic levels (subgrade modulus = 30 MPa).

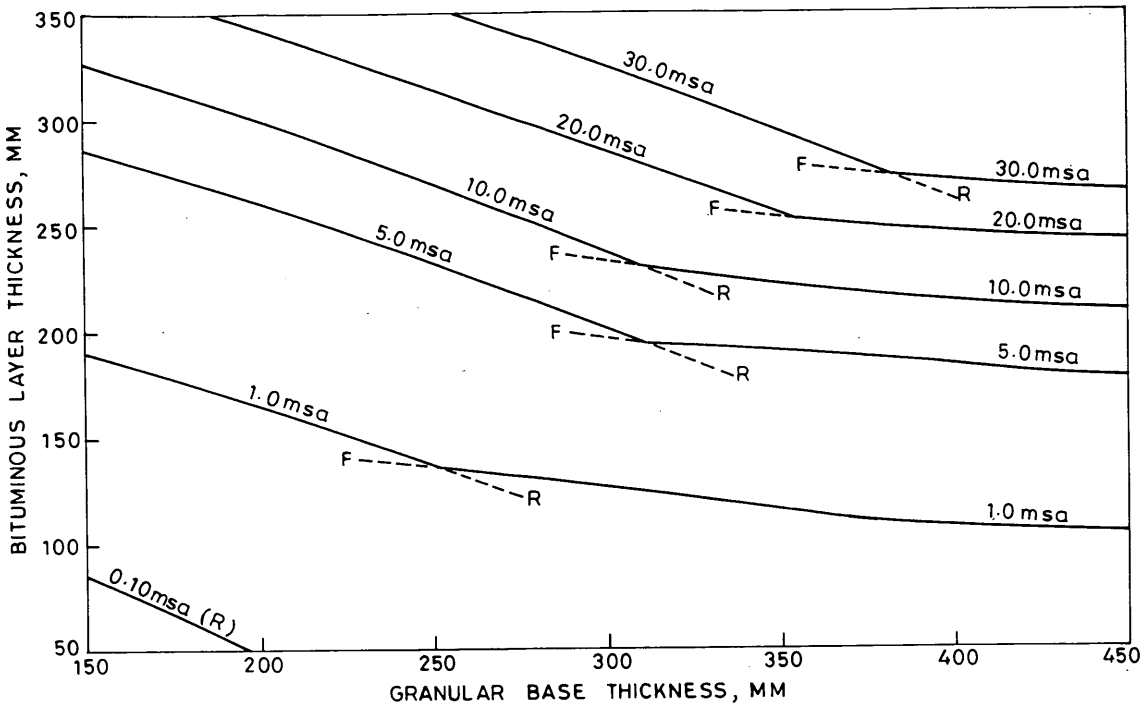

FIGURE 8 Design thickness for different traffic levels (subgrade modulus = 40 MPa).

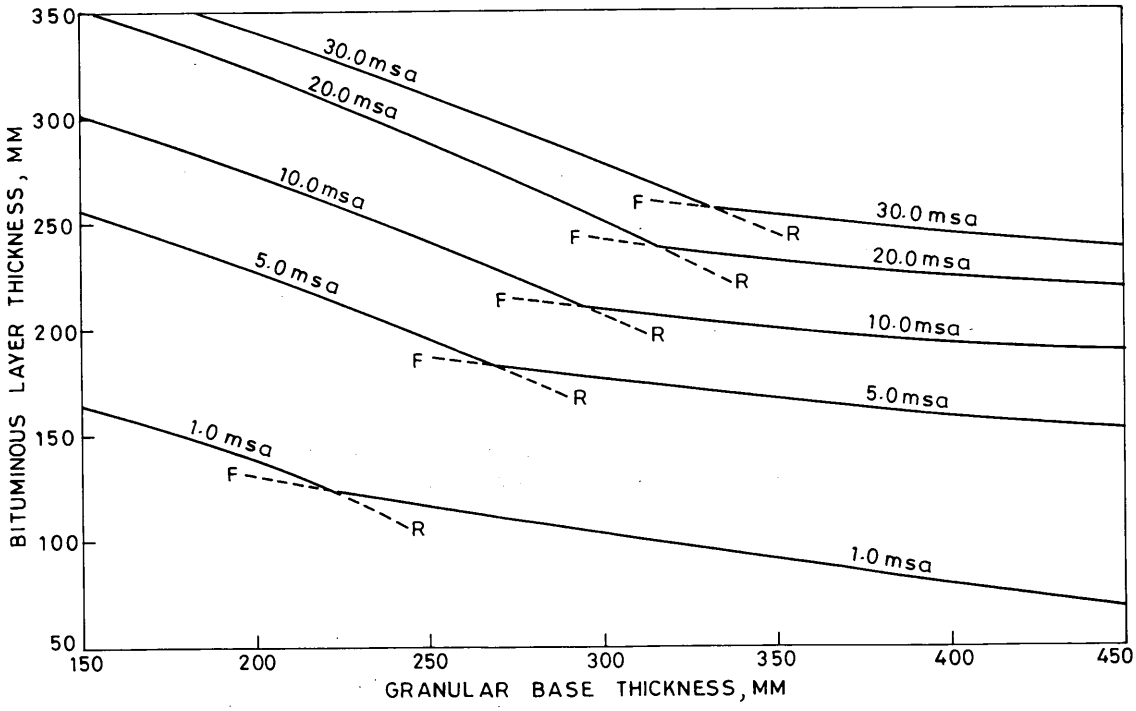

FIGURE 9 Design thickness for different traffic levels (subgrade modulus = 50 MPa).

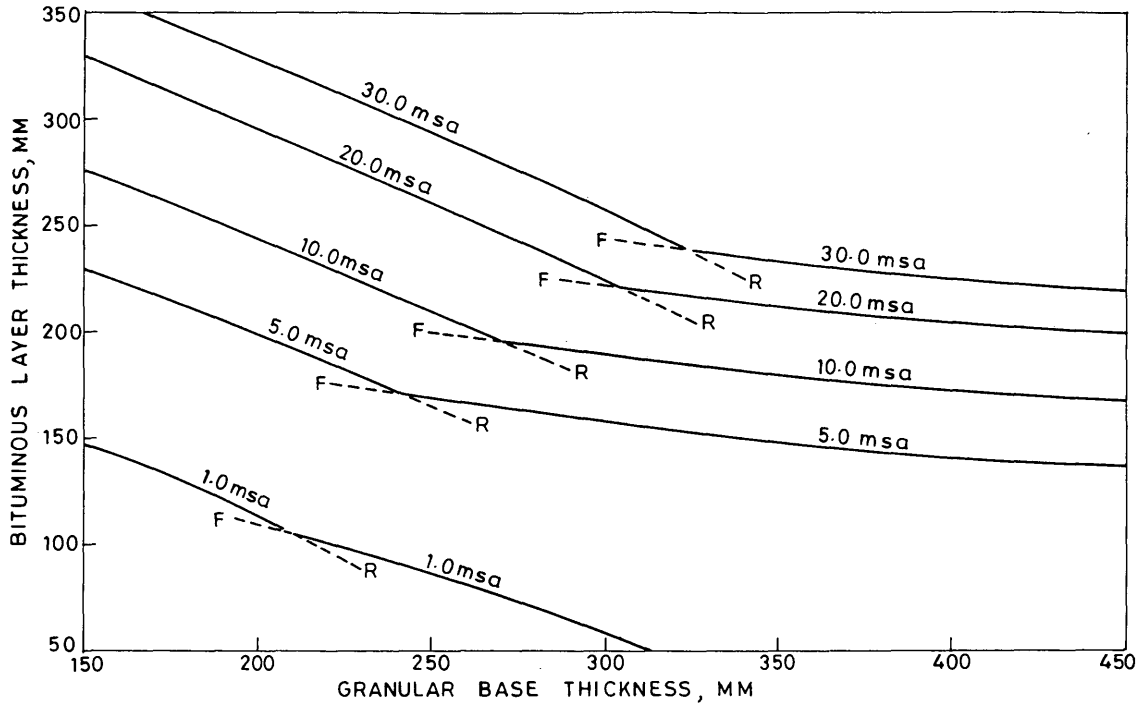

FIGURE 10 Design thickness for different traffic levels (subgrade modulus = 60 MPa).

TABLE 3 Comparison with Other Design Practices

SUBGRADE MODULUS (MPa)	DESIGN LIFE (CSA) (10^6)	GRANULAR BASE THICKNESS (mm)	BITUMINOUS LAYER THICKNESS (mm) ASPHALT INSTITUTE METHOD	SHELL METHOD	IRC METHOD	AUTHORS' CRITERIA
30	1.0	150	275	-	-	220
		300	225	-	-	155
		450	155	-	-	135
50	1.0	150	220	230	-	165
		300	165	150	-	105
		450	125	75	-	70
	10.0	150	350	350	-	300
		300	330	270	-	210
		450	300	180	-	190
60	1.0	370	-	-	20	50
	10.0	395	-	-	105	175
		420	-	-	140	205

- unavailable

used to design BM overlays for the traffic and climatic conditions described in this paper. The proposed fatigue and rutting criteria take into account the seasonal effects, and hence no adjustment to the thickness is necessary.

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