Design and Performance of Flexible Pavements in the Tropics

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A procedure is presented for flexible pavement design in the tropics along with deflection criteria for flexible pavements. The deflection data were obtained during a research program that included pavement evaluation of over 200 sections in Africa and South America. Maximum permissible deflections were established for various ranges of traffic and are given in terms of average deflections plus two standard deviations. For the selection of a design deflection, emphasis is placed on the degree of uniformity in construction that is generally obtained by local construction practices. The flexible pavement design procedure is based on two relations: The first is between deflection and performance, and the second is between deflection and pavement strength. The structural evaluations were conducted on 170 test sections where deflections had been measured. Index properties and California bearing ratio density-moisture relations were determined for each soil layer within the excavated depth of 90 cm (36 in). The thickness and density of each structural course was measured. Structural coefficients were developed for various depths beneath the pavement surface rather than by layer description because of the multiple-layer systems encountered. A minimum thickness of cover for various California bearing ratio values was established to provide adequate support. A minimum thickness was also established to prevent excessive pavement cracking. Structural design curves were developed that provide a relation between design traffic and pavement structural index for 3 degrees of pavement uniformity. Design curves were also developed that provide a measure of the subgrade support and show minimum thickness of surface, base, and subbase that is required.

The pavement design procedures used in most tropical countries have been adopted from those developed in temperate climates. Because such procedures take into account the characteristics of the climate and the materials that prevail in the location where the design was developed, they do not really apply to the tropics. The design procedure described in this paper was developed from the analysis of pavement sections in South America (1) and Africa (2). The procedure was primarily derived from the establishment of relations between performance and deflection and between deflection and the structural strength of each component layer within the pavement structure.

The design procedure has been termed tropical design procedure for flexible pavements because it was developed principally for red, tropical, residual soils that form the basic layers of most pavement structures in the tropics. It is also considered applicable to all other tropical or subtropical soils that are residual or transported.

PAVEMENT PERFORMANCE EVALUATION

Pavement deflection measurements have been used to evaluate the performance of flexible pavements for over 20 years. Recently, several investigators have established relations between pavement strength and deflection (3, 4, 5, 6). A relation between deflection and the combined effect of California bearing ratio (CBR) and thickness was used to establish the relative strength coefficients of flexible pavement components in a study of pavements in Africa (2).

Deflection measurements also allow an evaluation of the structural uniformity of pavement sections. In this study, a coefficient of variation of 35 percent was selected to define the maximum tolerable variation when generally accepted quality control is exercised during construction.

Deflection tests were conducted on more than 200 test sections throughout Brazil. Deflections were measured at six stations, 30 m (98 ft) apart, within each 150-m (492-ft) test section. Measurements were obtained in both inside and outside wheel paths (IWP and OWP) and at various distances from the point of loading. The latter values provided data to define the deflection basin. The rebound deflection was obtained at each of the six stations within the test section. The slope of the deflection basin was determined by using Kung's description (3) in which the slope is defined by the maximum tan value. Both rebound deflection and the slope of the deflection basin were evaluated to establish the maximum value of each that allows satisfactory pavement performance. Vehicles with two axles were used and were loaded to provide an 8165-kg (18-kip) rear-axle loading. Tire pressures were maintained between 583 and 617 kPa (85 and 90 lbf/in^2). All deflection measurements were corrected to a standard temperature of 21°C (66°F).

Traffic Analysis and Present Serviceability Rating

The traffic data available included traffic counts by Departamento Nacional de Estradas de Rodagem (DNER) and various Departamento de Estradas de Rodagem (DER). The total number of vehicles that traversed the test sections since construction, or last overlay, was determined from these data and classified according to vehicle type. A loadometer survey, conducted in the state of Minas Gerais, was analyzed to establish the loading patterns of commercial vehicles, which was needed to determine the traffic equivalence factors (TEF) for each truck-unit classification.

TEFs were calculated in accordance with the interim guide (8) by the American Association of State and Highway Officials (AASHO) for each truck classification. TEFs for triple axles were extrapolated from the relation of single- and tandem-axle equivalencies. Unit equivalencies for the various truck classifications were based on the percentage of loaded and unloaded trucks and the loaded and curb weight of each unit. Unit equivalents for vehicles not included in the loadometer survey were estimated from information obtained from manufacturers and commercial agencies. For convenience, the 8165-kg (18-kip) single-axle loading is referred to as the standard load.

The traffic analysis and the loadmeter survey were used to determine the accumulated equivalent standard axle-load applications experienced by each test section. The average daily percentage of each group was multiplied by the applicable equivalent factor and summed according to the following:

$$\mathrm{AE18KSAL} = 365(\mathrm{N})(\mathrm{ADT})\Sigma(\mathrm{n})(\mathrm{UE18KSAL}) \qquad (1)$$

where

AE18KSAL = the accumulated equivalent standard single-axle load,
N = the age of the pavement in years,

ADT = the mean daily traffic,
(n) = the percentage of ADT for each group, and
UE18KSAL = the unit equivalent standard axle load.

Pavements were evaluated by means of a subjective rating of the riding quality while a standard vehicle traversed the test section at a constant speed of 80 km/h (48 mph). A mean value was selected from a minimum of two independent ratings but usually from three or more ratings. This rating, called the present serviceability index (PSI), ranged from 1 (excessive deterioration) to 9 (excellent). Pavements with ratings above 5 were considered as performing satisfactorily, regardless of intended life, while those with ratings of 5 or less were considered as terminated or in need of major repair. Variations in assigned ratings were usually not large, seldom varying from the mean by more than one rating point.

Discussion of Results

Deflection and Performance

The relation between performance and deflection was established for the OWP because this path, being the weakest zone of the pavement structure, usually controls the performance of the pavement.

Pavement performance is usually correlated with representative deflection, or the mean deflection plus two standard deviations. This correlation defines a deflection level that is exceeded by 2 percent of the length of the test section (9). The weaker sections, although limited in area, control the performance of the pavement. The relation between the representative deflection and performance is shown in Figure 1 in which data from Africa (2) were added. The recommended criterion represents a confidence level of about 95 percent; therefore, only 5 percent of the pavements meeting the deflection criterion were rated unsatisfactory.

The deflection testing in Brazil was conducted during the rainy season, but, since seasonal variations in moisture content beneath pavements are usually slight, seasonal variations in deflection are far less than those in temperate regions.

Permissible Deflection and Design Deflection

The design deflection is governed by the degree of uniformity obtained in the final pavement structure that is dependent on variations in the subgrade, borrow materials, construction practices, and the effectiveness of quality control. Variations in the test sections were examined and the mean coefficient of variation was found to be 25 percent. The maximum coefficient of variation was as high as 83 percent. A coefficient of variation of 35 percent is believed to indicate adequate quality control during construction. Accordingly, a maximum variation of 35 percent was selected in determining the recommended deflection criterion.

The relation between the coefficient of variation and design deflections is shown by the design curves in Figure 2. These curves demonstrate the importance of uniformity with relation to performance. For example, if two pavements had a mean deflection after construction of 0.864 mm (0.034 in) but different standard deviations (0.2 and 0.4), the performance of the two pavements would be different. The pavement with the lower standard deviation (0.2) would have an expected life of 350 000 standard, axle-load applications while the other pavement would have an expected life of only 100 000 standard axle-load applications and would require an overlay to extend its life.

DEFLECTION AND PAVEMENT STRENGTH

A relation between deflection and pavement strength provides the basic requirement for a structural design procedure for flexible pavements. The measurement of the thickness of individual structural layers and the evaluation of the strength of each component layer are required to establish such a relation. The measurement of the individual structural layers is straightforward. The evaluation of the strength of the individual layers is accomplished by one of several methods (CBR, R-value, triaxial compression, or others). The strength parameter is an index of the ability of the layer to transfer the vehicle load to the underlying layer at a lower stress level. The lateral distribution of the vertical load (load-spreading characteristic) of each soil layer depends on the magnitude and concentration of the applied stress, the shear resistance of the material, and the position of the layers within the pavement structure.

The most common method for determining the relative strength of soils in pavement design is CBR. This method is used more than any other combined methods in tropical countries. Pavement evaluations in Brazil were based on CBR tests on unbound soil layers within the pavement structures. Bound or chemically stabilized soil layers were excluded.

Structural Evaluation of the Test Sections

A total of 170 test pits, selected through analysis of the deflection results, were excavated at the stations where the deflections most nearly approached the mean value for the entire section. The test pits were excavated to the full width of one traffic lane and were 90 cm (36 in) deep. Excavation to this depth allows examination of the structural layers that are affected by vehicle loadings. The distributed vehicle load at a depth of 90 cm (36 in) is less than 1 percent of the applied vehicle load. The thickness of each structural course was measured at both the IWP and OWP. In some sections, as many as six layers were encountered; the thickness of each was measured. Density determinations were conducted in both wheel paths for each structural layer. When layer thicknesses exceeded 20 cm (8 in), a density determination was made in the top half of the layer and again in the bottom half of the layer.

Samples for laboratory testing were obtained from each of the soil layers. A CBR moisture-density relation was established for each soil layer component of the pavement structure. CBR was determined from three samples compacted at the field moisture content and at three compactive efforts: AASHTO standard T99-70, AASHTO modified T180-70, and the Brazilian standard that is about midway in compactive effort between the other two. For each layer, CBR was selected to correspond to the in situ density determined in the field test.

Structural Coefficients

A simple CBR-coefficient relation could not be used because the performance of a given layer depends not only on the material properties (shear resistance) but also on the magnitude of stress imposed. A material with CBR of 70, for example, will not be subjected to the same stress level when used as subbase as when it is used as a base course nor will it have the same load-spreading characteristics. The structural coefficients were developed to relate both CBR load-spreading characteristics and position of the layers within the pavement structure.

Structural coefficients were initially estimated from those developed in Africa (1, 2). These coefficients were later modified for various depths beneath the pavement surface, as given in Table 1. The basic structural equation in which the coefficients are used follows.

Figure 1. Relation between deflection and performance.

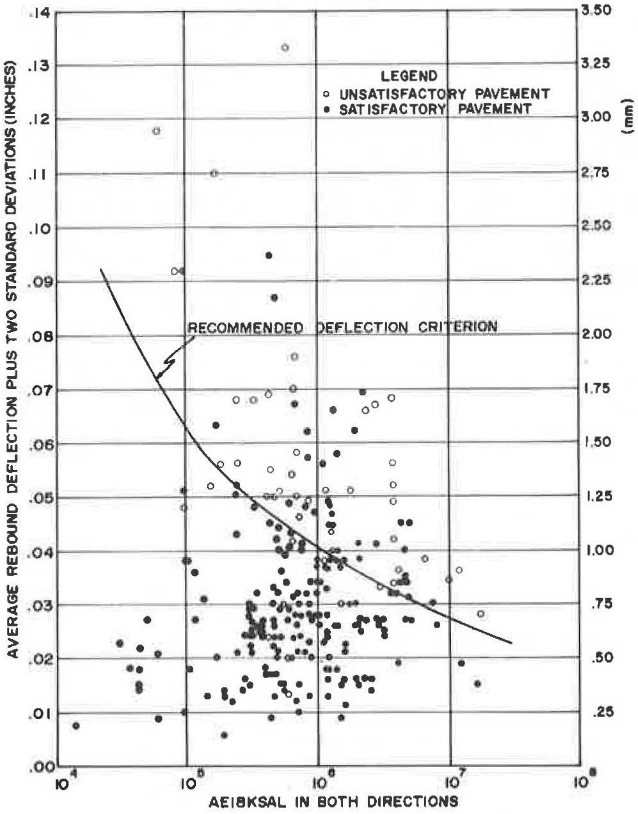
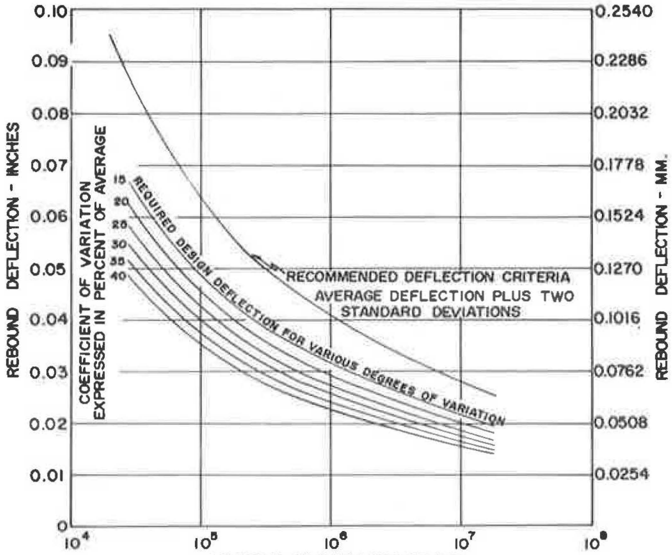


Figure 2. Relation between design deflection and traffic for practical range of coefficients of variation.



$$\text{Pavement structural index (SI)} = a_1 t_1 + a_2 t_2 + \ldots a_n t_n \qquad (2)$$

where

$a_1, a_2, \ldots a_n$ = the structural coefficients in dimensionless units per cm; and
$t_1, t_2, \ldots t_n$ = the thicknesses of the component layers in cm.

The surface course is referred to by a_1t_1, the base course is referred to by a_2t_2, and so on. SI is computed to a depth of 90 cm (36 in).

SI is related to the pavement deflection by the following equations:

$$SI = (0.039\ RD)^{-1} \qquad (3)$$

where RD = the measured Benkelman beam deflection in mm. For the corresponding U.S. customary unit in inches, the following equation is used.

$$SI = (RD)^{-1} \qquad (4)$$

Maximum and Minimum Structural Coefficients

The maximum and minimum structural coefficients given in Table 1 represent the two extremes in stress distribution beneath flexible pavements. The maximum structural coefficient represents the maximum angle of lateral distribution beyond which there is no vertical stress

Table 1. Pavement coefficients for flexible pavement design.

Pavement Component	Strength Coefficient
Base course	
Crushed stone (Macadam hydraulic)	
Open graded	1.037
Graded	1.394
Cement treated (compressive strength 7 d)	
4500 MPa or more	2.400[b]
2750 MPa to 4500 MPa	2.100[b]
2750 MPa or less	1.600[b]
Lime treated	1.4 to 1.6[b]
Concretionary gravels	
CBR (design)	
+100	1.394
90	1.232
85	1.167
80	1.102
75	1.037
70	0.940
60	0.552
50 (min)[a]	0.383
Subbase course	
CBR (design)	
+40	0.576
35	0.290
30	0.205
25 (min)	0.075
Subgrade layer	
CBR (design)	
+20	0.481
15	0.357
10	0.212
9	0.183
8	0.133
7	0.084
6	0.053
5	0.033
4	0.020
3	0.015
2 (min)	0.010

Notes: 1 Pa = 0.000 145 lbf/in^2.
Design coefficient limits: Base course refers to materials to a depth of 25 cm, subbase course refers to material layers between 25 to 50 cm, and subgrade layer refers to material layer between 50 to 90 cm.

[a] Material with a CBR of 40 can be used between the depth intervals of 10 and 25 cm and assigned the same coefficient.

[b] Values estimated from structural coefficient relations given in the 1972 AASHO Interim Guide for Design of Pavement Structures.

while the minimum coefficient represents the case in which the increased load exceeds the shearing resistance of the soil that results in a concentration of the vertical stress in the central cone, i.e., perimeter shear (10). The maximum and minimum coefficients in Table 1 were initially estimated and then modified by trial and error computations, using the sections that displayed the lower extremes of CBR values.

The results of the analyses of test sections with CBR values below the minimum value are shown in Figure 3. Deflections of these sections were calculated by using Equations 2 and 3 or 4, but without assigning structural coefficients to the layers with low CBR values. The solid points represent the sections where the calculated values of deflection were equal to or near the measured deflection. The open circles represent the sections where the calculated values of deflection were much less than the measured deflections. Thus, the solid points represent those layers that had poor load-distribution qualities but did not cause excessive elastic deflection in the pavement system. On the other hand, the open circles represent those layers that had poor load-

Figure 3. Critical CBR values with depth below pavement surface based on field analysis.

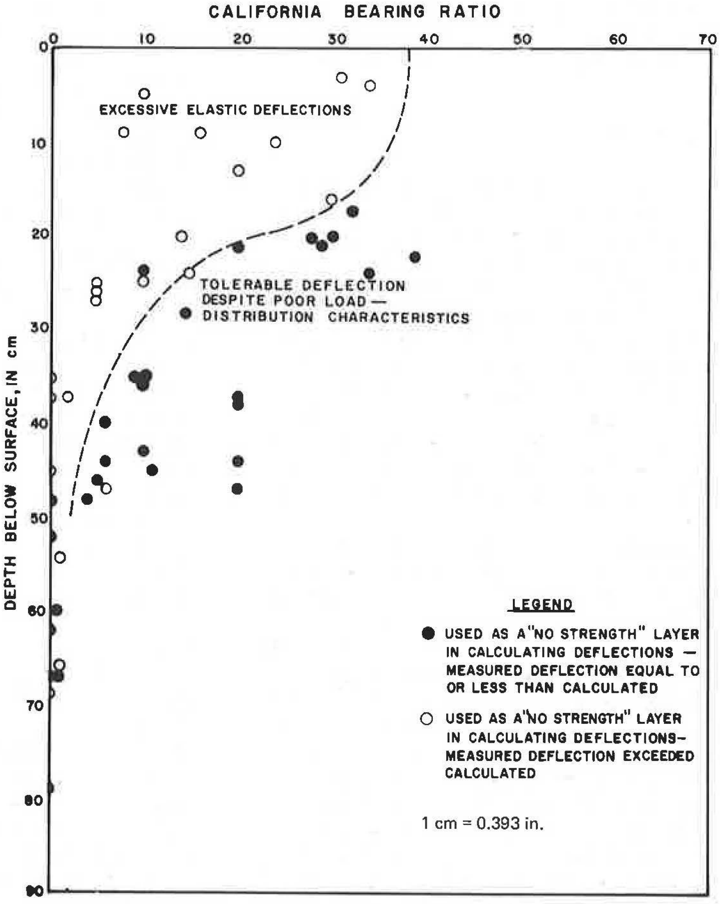
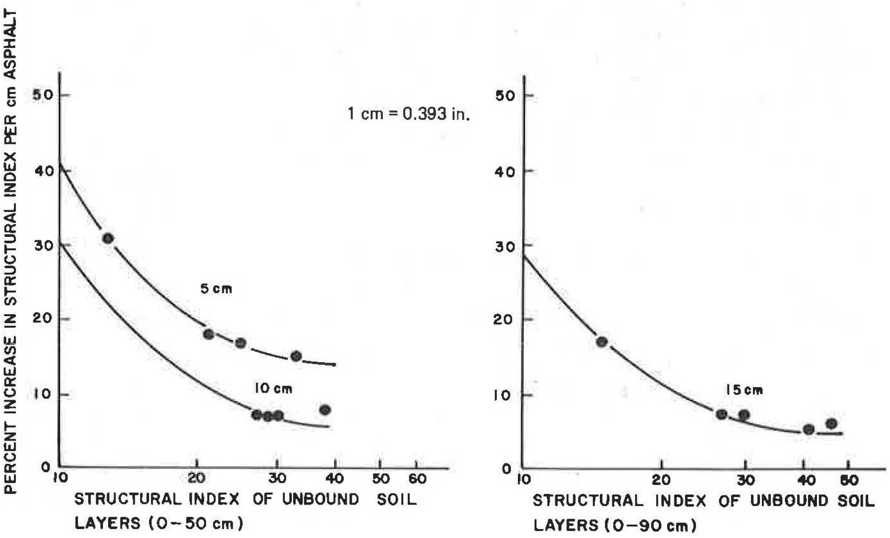


Figure 4. Effect of asphalt on pavement strength for various thicknesses of asphalt and unbound soil layer strengths.



spreading qualities and allowed excessive elastic deflection. The minimum thicknesses of cover for various CBR values were based on this analysis.

Calculated Deflections and Benkelman Beam Deflections

Surface Treatment Pavements

The measured deflections of single and double bituminous-surface treatments (SBST and DBST) pavements were compared with calculated deflections from Equations 2 and 3 or 4. After sections with low CBR or density values were eliminated, there were 55 test sections available that displayed good correlation when the precision of the field measurements was taken into account. The structural error of estimate was ±0.0739 mm (0.00291 in).

Asphalt-Concrete Pavements

An asphalt layer provides two benefits to the pavement system: It increases the strength and load-spreading characteristics of the layer itself, and it increases the load-spreading characteristics of the underlying unbound layers. This second benefit was substantiated by comparing the strengths of the unbound underlying soil layers, computed from Equation 2, with the composite strength determined from measured deflections and Equations 3 or 4. In the first analysis, the difference in these strengths was attributed to the asphalt layer and was considered residual strength. However, when the difference in strength was converted to structural coefficients, the results were unsatisfactory for use in the design procedure.

In the second analysis, it was assumed that the load-spreading characteristics of the soil layers beneath the asphalt layer increase with depth. This assumption was verified by separating the test sections into groups with mean asphalt thicknesses of 5, 10, and 15 cm (2, 4, and 6 in). The curves that are shown in Figure 4 display a relation between the strength increases of the unbound materials down to a depth of about 50 cm (20 in) for the 5-cm (2-in) asphalt group and also for the 15-cm (6-in) asphalt group. The latter group is based on a depth of 90 cm (36 in). The curve for the 10-cm (4-in) asphalt group was extrapolated to parallel the 5-cm (2-in) curve. It appears reasonable that the residual strength is partially attributable to the asphalt layer and partially attributable to the increase in the load-spreading characteristics of the underlying soil layer.

The strength increase factors were used to calculate the deflection in 65 out of 87 test sections with asphalt surfacing. Twelve sections were eliminated because of surface deterioration, low CBR or density values, and other obvious discrepancies. The remaining data displayed good correlation with measured deflection when the precision of the field measurements was considered.

Natural Cementing or Slab Action

There were 20 test sections that exhibited deflections significantly lower than the deflections calculated by Equations 2 and 3 or 4. The values for CBR were no higher than those encountered in the other sections; therefore, the test did not measure the actual strength these layers exhibited in the field.

The majority of these sections were located in northeastern Brazil. This area is subject to long, dry periods that allow for a natural hardening of certain types of red tropical soils. During excavation of the test sections, one or more of the layers were naturally cemented. These layers were a part of an older pavement structure or were part of a newer pavement that had been unsurfaced for a period of time. Data from these sections could not be included in the design analysis; therefore, further study is required for effective utilization of these soils.

Slope of the Deflection Basin and Structural Strength

A pavement design procedure should include minimum thickness requirements for asphalt that will reduce pavement cracking to tolerable limits for a given design period. It was felt that these requirements should be based on a relation between the thickness of the asphalt layer and the slope of the deflection basin (slope index). However, it was found that a suitable relation could not be established without indicating CBR of the base material. Figure 5 shows the minimum slope indexes for given thicknesses of asphalt after base CBR values have been grouped into appropriate ranges. These curves were used to establish minimum thicknesses of asphalt to prevent excessive cracking.

STRUCTURAL DESIGN CURVES AND DESIGN PROCESS

The structural design curves were developed from the relations between design deflection and traffic that were established for selected coefficients of variation, and from the relation between deflection and SI. The relation between calculated deflection and measured deflection is shown in Figure 6 in which the standard error of estimate is ±0.081 mm (0.003 in). Because that portion of the error attributable to the structural coefficient affects the development of the design curves, the design deflection data were adjusted during the translation of deflection to SI to account for the errors. The adjusted values provide a more conservative relation for design purposes.

The structural design curves are shown in Figure 7. These curves illustrate the relation between design traffic, given in terms of standard axle applications in both directions, and SI. The coefficient of variation is a reflection of local construction practices and should be determined for each general design area by analyzing deflections in existing roads. SI obtained from Figure 8 represents the minimum required strength for a standard 90-cm (36-in) pavement section. This SI forms the basis for a flexible pavement design.

The objective of the structural design process is to use SI to determine the thickness of each pavement layer, i.e., the surface (t_1), the base (t_2), and so on. Design traffic, CBR of each structural layer, and applicable coefficient of variation are required to use this procedure. Thus, SI is determined by assuming SIs for each layer in a standard 90-cm (36-in) pavement section by using Equation 2. In that equation, a_1 is the structural coefficient of the surface material, a_2 is the coefficient of the base material, and so on. Also, $t_1 + t_2 + \ldots t_n$ is 90 cm (36 in).

Structural coefficients for various soils are given in Table 1 that also provides structural coefficients for crushed stone, and cement- and lime-treated soils. The coefficient for crushed stone was determined from test sections that have macadam base courses. The structural coefficient of open-graded crushed stone is less than the higher quality concretionary gravels because of cohesion in the concretionary material. The structural coefficients for cement- and lime-treated soils are estimated from relations given in the interim guide by AASHO (8).

The strength of the subgrade, or the subgrade CBR, is a key element in the design of the overlying structural layers and is shown in Figure 8, which was partially replotted from Figure 3. The minimum thickness of cover varies inversely with the value of the subgrade CBR. Figure 8 also shows the relation between subgrade CBR and SI. Because SI of the subgrade influences the design thickness of the structural layers, it is referred to as the subgrade support. Higher strength subgrades furnish greater support and permit the use of thinner structural layers. The combined SI for the structural layers (surface, base, and subbase) is equivalent to the required SI (from Figure 7) less the subgrade support.

Flexible Pavement Design

More than one trial may be required to design a flexible pavement. The first trial begins with the selection of a surface type and concludes with the determination of the base and subbase thickness. The surface type and thickness are determined from Table 2 and is based on the base-course CBR value and the design traffic.

The minimum design thickness of the unbound structural layers (base and subbase) in a surface treatment (ST) pavement design is equal to the minimum thickness of cover as derived from Figure 8. The thickness of ST is not considered because it does not contribute signifi-

Figure 5. Relation between slope index and thickness of asphalt concrete for the practical range of base-course CBR values.

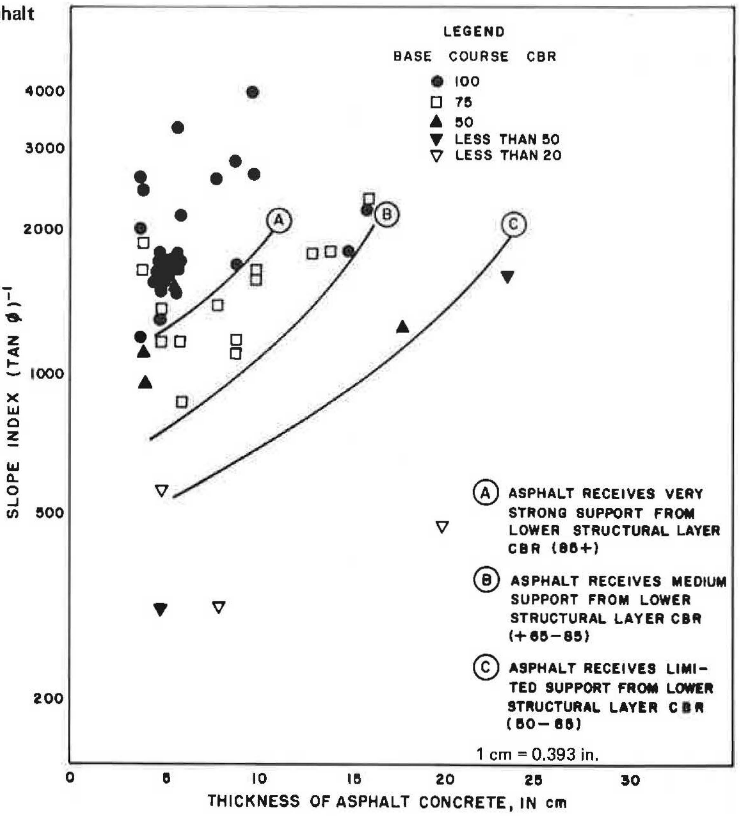
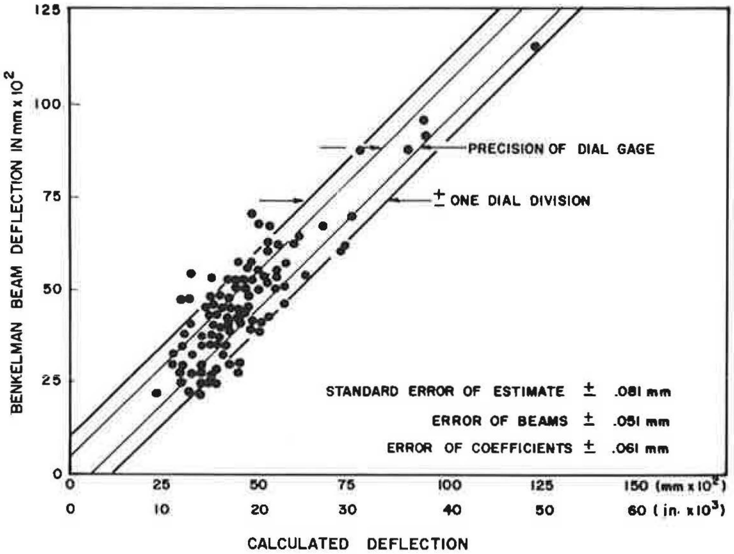


Figure 6. Comparison between measured deflections and calculated deflections.



cant strength to the pavement section. However, an asphalt-concrete (AC) surface does provide strength and consequently is considered part of the minimum thickness of cover. In an AC-pavement design, the minimum design thickness of the unbound structural layers equals the minimum thickness of cover less the thickness of AC.

The minimum base-course thickness is determined from Figure 8 and is based on the CBR of the subbase material. The subbase course is the remaining thickness of the cover. Finally, the subgrade thickness for design purposes is the difference between the standard 90-cm (36-in) design and the thickness of the cover.

The adequacy of this first trial design section to carry the design traffic is determined by summing SIs of each pavement layer (Equation 2) and comparing the summed SI to the required SI from the structural design curves shown in Figure 9. SI of each pavement layer is equivalent to the product of its thickness and its structural coefficient (Table 1) to the extent that its thickness or CBR value fall within the strength and design coefficient limits provided in the table. Those portions of the pavement section that do not fall within these limits do not provide strength to the pavement and therefore are excluded from the derivation of SI of the entire pavement section. However, the thickness of those portions is included as part of the standard 90-cm (36-in) section. ST pavement design is the least complex because ST does not impart any strength to the pavement structure.

The benefit of the AC load-spreading characteristic

Figure 7. Structural design curves for determining required structural index of the standard pavement section.

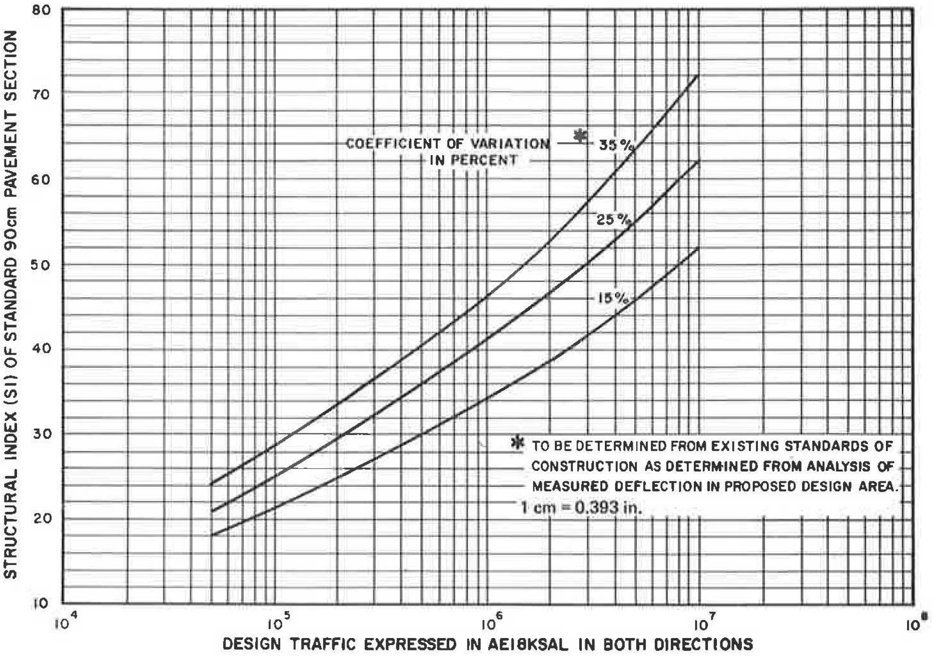


Figure 8. Subgrade support and minimum thickness of cover based on subgrade CBR values.

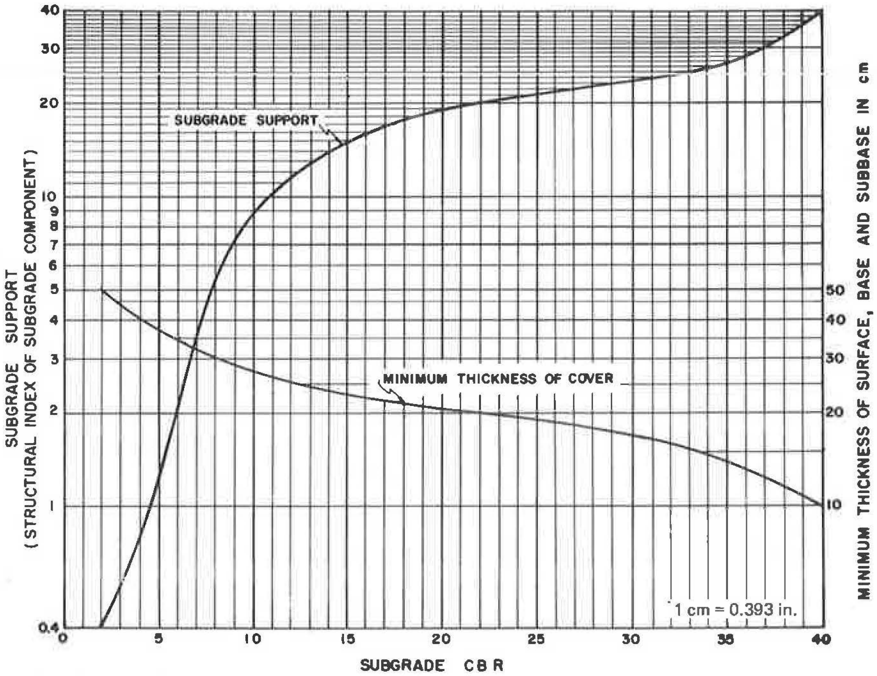


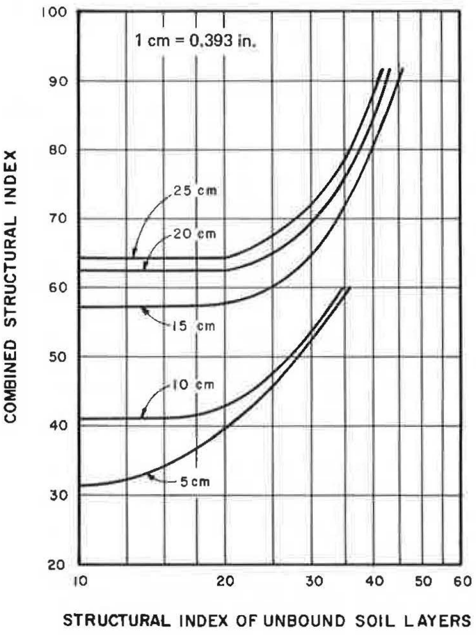
Table 2. Recommended type and thickness of surface courses.

Total Standard EAL Applications in Both Directions	Strength of Base Course (CBR)							
	+100	90	85	80	75	70	60	50
100 000	ST	ST	ST	ST	ST	ST	ST	ST
200 000	ST	ST	ST	ST	ST	ST	ST	5
300 000	ST	ST	ST	ST	ST	ST	5	5
400 000	ST	ST	ST	ST	ST	5	5	7.5
500 000	ST	ST	ST	ST	5	5	5	10
600 000	ST	ST	ST	5	5	5	5	10
700 000	ST	ST	5	5	5	5	7.5	15
800 000	ST	5	5	5	5	5	7.5	15
900 000	ST	5	5	5	5	5	10	15
1 000 000	ST	5	5	5	5	5	10	15
2 000 000	5	5	5	5	7.5	10	15	20
3 000 000	5	5	5	7.5	10	10	15	20
4 000 000	7.5	7.5	7.5	7.5	10	15	15	21
5 000 000	7.5	7.5	7.5	10	10	15	20	21
6 000 000	7.5	7.5	7.5	15	15	15	21	21
7 000 000	10	10	10	15	15	15	22	22
8 000 000	10	10	10	16	16	16	22	22
9 000 000	10	10	10	17	17	17	22	22
10 000 000	10	10	10	18	18	18	23	23

Notes: ST denotes a double bituminous-surface treatment.

☐ To be used only if higher quality base material is not available and stabilization or modification proves to be too expensive.

Figure 9. Combined strength of pavement section of asphalt and unbound soil layers for 5, 10, 15, 20, and 25 cm of asphalt concrete.



is shown in Figure 9 for 5, 10, 15, 20, and 25 cm (2, 4, 6, 8, and 10 in) of AC surfaces. The load-spreading benefit extends only 50 cm (20 in) below the surface for the 5 and 10-cm (2 and 4-in) AC surfaces whereas the load-spreading benefit extends throughout the entire 90-cm (36-in) design section for the 15, 20, and 25-cm (6, 8, and 10-in) AC surfaces.

If the computed SI is lower than the required SI, shown in Figure 7, then the strength of the pavement may be improved by

1. Increasing the subbase thickness, which increases the minimum thickness of cover but does not affect the surface and base courses;
2. Increasing the base thickness and reducing the subbase by a similar amount, which retains the minimum thickness cover;
3. Using an AC surface instead of ST or increasing the AC thickness and reducing the thickness of the base course; and
4. Any combination of the above.

The engineering decision to undertake one of the above alternatives will be based on economic considerations, local conditions, and the availability of the materials required to increase SI.

DESIGN EXAMPLE

1. Given: Estimated daily traffic in both directions = 1 250 000 SAL; construction variations in nearby highways = 35 percent; and subgrade CBR = 9, base CBR = 80, and subbase CBR = 30.

2. Determine required SI from Figure 8: Enter horizontal axis at the 1 250 000 design traffic and turn to vertical axis after intersection with 35 percent curve. SI = 36.

3. Select surface type from Table 2: An AC surface, 10 cm (4 in) thick, is recommended for a base CBR of 80 and SAL of 1 250 000.

4. Determine pavement design thickness from Figure 9: Minimum cover over subgrade (surface, base, and subbase) = 30 cm (12 in) for subgrade CBR of 9; minimum cover over subbase = 17 cm (7 in) for subbase CBR of 30; and minimum cover over base = 0 for base CBR of 80. Therefore, for the first trial the thicknesses are 10 cm (4 in) of AC, 10-cm (4-in) base, 10-cm (4-in) subbase, and 60-cm (24-in) subgrade.

5. Determine a subgrade support index (SSI) from Figure 8 with a subgrade CBR of 9. SSI = 7.

6. Determine SI of unbound soil layers: SI = the summation of the products of the structural coefficients (Table 1) and the layer thicknesses. Base-course coefficients are applicable only between 0 and 25 cm (0 and 10 in) from the surface. Subbase coefficients are applicable only between 25 and 50 cm (10 and 20 in) below the surface. The base and subbase-course thicknesses used in determining the SI are referred to as standard base and subbase courses and are not to be confused with the actual base and subbase design thicknesses. Determine SI of unbound soil layers as follows (1 cm = 0.393 in):

$$\begin{aligned}\text{SI for unbound soil layer} &= \text{subbase-course SI (50-25 cm)}\\ &\quad + \text{base-course SI (25-10 cm)}\\ \text{SI} &= [(\text{Coeff. of CBR } 9 \times 20 \text{ cm})\\ &\quad + (\text{Coeff. of CBR } 30 \times 5 \text{ cm})]\\ &\quad + [(\text{Coeff. of CBR } 30 \times 5 \text{ cm})\\ &\quad + (\text{Coeff. of CBR } 80 \times 10 \text{ cm})]\\ \text{SI} &= [(0 \times 20) + (0.205 \times 5)]\\ &\quad + [(0 \times 5) + (1.10 \times 10)]\\ &= [(1.02) + (11.02)]\\ \text{SI} &= 12.04 \qquad (5)\end{aligned}$$

7. Determine combined SI of all structural layers: AC increases the strength of the pavement and reduces the stress on the unbound structural layer. The combined SI that accounts for this relation in a 10-cm AC is shown in Figure 9. Enter the SI compacted in step 6 (12.04) in the horizontal axis and turn to vertical axis upon intercepting the AC = 10 curve. The combined SI = 41.

8. Determine adequacy of first trial design:

$$\begin{aligned}&\text{Required SI} = 48 \text{ (step 2), and}\\ &\text{Calculated SI} = 9 \text{ (step 5)} + 41 \text{ (step 7)} = 48 \qquad (6)\end{aligned}$$

Therefore, the adequate design is 10-cm AC, 10-cm base, 10-cm subbase.

CONCLUSIONS

A new design procedure called the tropical design procedure for flexible pavements was developed for tropical regions through the analysis of over 200 test sections in Brazil and augmented by earlier studies in Africa. Relations were established between performance and deflection and between deflection and the structural strength of component layers in the pavement structure.

Deflection tests were conducted at six stations within each test section. Rebound deflection and the slope of the deflection basin were determined as well as the coefficient of variation within the test sections. Traffic data, compiled by the Brazilian State and National Highway Department, were classified and traffic equivalent factors and equivalent standard axle-load applications were calculated. A subjective pavement rating was applied to each test section, and pavement performance, which was determined by the rating, was related to representative deflections (mean deflection plus two standard deviations) to establish a deflection criterion for tropical conditions.

A design deflection was devised that incorporates an allowable degree of variation, recommended as 35 percent, to the deflection criterion. Maximum values of the slope of the deflection basin are also proposed that reduce pavement cracking to acceptable limits.

Structural coefficients were established and were based on the relations between deflection and strength of the pavement component layers. The structural coefficients were based on CBR of the unbound structural layers as well as the position of the layers in the pavement structure. A strength factor for asphalt layers was established and was based on the thickness of the asphalt layer and the strength of the underlying soil layers. A relation between the slope of the deflection basin, asphalt thickness, and base-course CBR was established. This relation defines the minimum thickness of asphalt required to prevent excessive pavement cracking within a given traffic period.

A flexible pavement design procedure is described. Structural design curves are provided for design traffic and various degrees of construction uniformities. A design equation is used in the basic design procedure to compute SI of trial sections. Structural coefficients are selected for unbound soil layers and are a function of CBR value of the layer and the position of the layer within the pavement structure. AC surfacing increases the strength of the pavement sections when it is used in the design. Asphalt-strength curves are given for five standard AC thicknesses of 5, 10, 15, 20, and 25 cm (2, 4, 6, 8, and 10 in). Suggested asphalt thicknesses are given for various ranges of traffic and base-course CBR values.

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