Pavement Design of Unsurfaced Roads

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In some tropical countries, such as Thailand and Ecuador, unpaved soil-aggregate roads are normally constructed when the average daily traffic is less than 300. These pavements are generally constructed of a single layer of subbase, which varies in depth from 5 to 14 in. Currently, various empirical models give different results for the pavement design of unsurfaced roads. This study presents a design model that has been developed to provide a rational design methodology for low-volume unsurfaced roads. This methodology is based on the theory of plasticity. It has been found to be computable with the up-to-date experience in Ecuador and Thailand, according to which 8 in of gravel and 6 in of laterite carried about 25 000 and 5000 equivalent standard axles per lane in Ecuador and Thailand on silty sand and silty subgrade, respectively.

The pavement design for low-volume unsurfaced roads, particularly in tropical areas, has not received the benefit of the detailed research and studies that have been carried out to provide design methodologies for high-volume roads. In Thailand, unpaved (soil-aggregate) roads are normally constructed when the average daily traffic (ADT) is less than 300. These pavements are generally constructed of a single layer of laterite, which varies in depth from 5 to 14 in and has a California bearing ratio (CBR) that ranges between 7 and 60 percent (1). The local experience with laterite roads and other experience with unpaved roads (2,3) has shown that maintenance is difficult when an inappropriate design method is used, which indicates the necessity of the development of a rational model for unsurfaced roads. This necessity is illustrated by the different results obtained by the application of various empirical models available (4-6). These results are indicated in Figure 1, which shows the relationship between subgrade CBR and the number of coverages to failure of given equivalent single-wheel load (ESWL) and tire pressure. The data given in Figure 1 are restricted to equivalent wheel loads of 28 and 40 kips and tire pressures of 65 and 97 lbf/in², respectively. Figure 1 shows that for a subgrade CBR of 8 percent (typical local plastic laterite in Thailand) and an ESWL of 28 kips, the number of coverages to failure are 25, 40, and 500 (4-6). Similar results that show a meaningful difference exist for other values of subgrade CBR and wheel load. Therefore, this study presents a design model developed to provide a rational design methodology for low-volume unsurfaced roads. This methodology is based on the following parameters:

1. Traffic (ranging from 10 to 300 ADT),
2. CBR design of the subgrade, and
3. CBR design of the subbase material.

BASIC ASSUMPTIONS

Design thickness of flexible pavements is usually based on the theory of elasticity. However, for low-cost structures that have a permissible rut depth of more than 3 in, the theory of plasticity seems to be a more-compatible choice (7) and is therefore the one chosen for this study. The assumptions behind the theoretical model are delineated in Equations 1-3.

A rational model for unsurfaced roads must represent the relationship among wheel load, engineering properties of the soil and materials, and the number of coverages to failure. The general definition of such a model is given in the following equation:

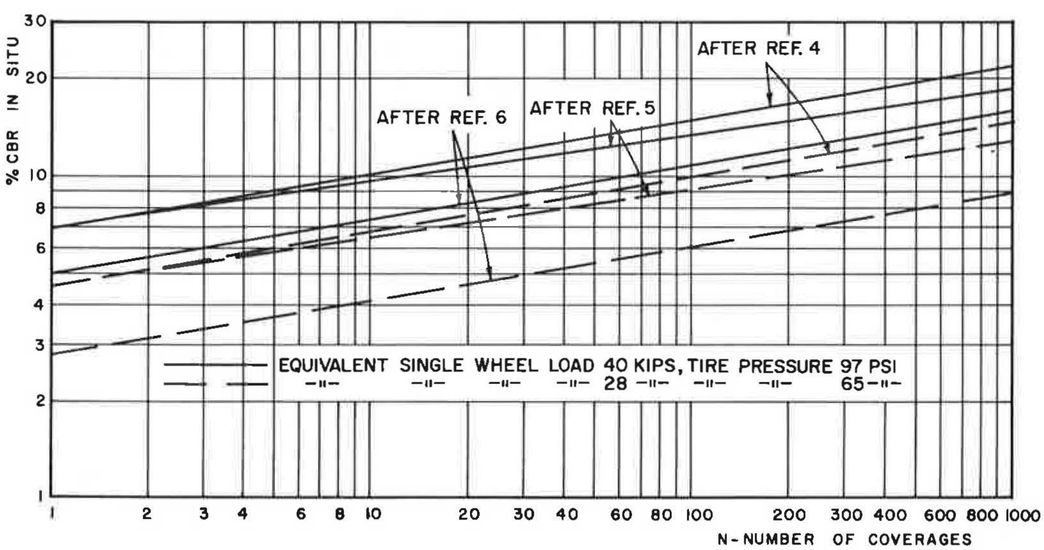
$$f(\underline{P}; p; CBR_s; CBR_L; N; H) = 0 \quad (1)$$

where

$\underline{P}$ = ESWL,
p = tire pressure,
CBR_S = CBR of subgrade,
CBR_L = CBR of subbase (generally laterite in Thailand),
N = number of coverages to failure, and
H = depth of subbase.

According to Foster's observations (8), the in situ CBR values of a single granular layer vary with depth; there are high values on the surface and low

Figure 1. Relationship between subgrade CBR and number of coverages to failure.



values at the bottom. Similar results were obtained from existing single-layered pavements (H = 6-8 in) in service (7). Table 1 presents these in situ CBR results (7).

It should be noted that Foster's finding and the results of Greenstein and Livneh (7) are compatible with the variation of the ratio E_G/E_S with depth, where E_G is the resilient modulus of the granular material and E_S is the resilient modulus of the subgrade material. This variation of E_G/E_S with depth is taken into consideration when the theory of elasticity is used to determine the thickness of flexible pavements.

Summing up, the variation in in situ CBR with depth is given according to the following expression (see Figure 2):

$$\log CBR_Y = \Big(\log CBR_L \,\{1 - [(20 + y - H)/20]\}\,[\log(CBR_L/CBR_S)] + \log CBR_S\Big) \rightarrow H - 20 > Y > 0 \quad \rightarrow H \geqslant Y \geqslant (H - 20) \qquad (2)$$

where

- CBR_Y = in situ CBR of laterite subbase as a function of depth Y;
- CBR_L = CBR on surface of laterite subbase material, i.e., for Y = 0 (or over an 8-in single layer of subbase, as shown in Figure 2);
- CBR_S = CBR of subgrade; and
- H = thickness of laterite subbase, which is thickness of pavement (see Figure 2).

Equation 2 is valid only for 0 < Y < H. When Y > H, CBR_Y is actually equal to CBR_S.

Finally, the results by Wiseman and Zeitlen (9) are expressed by the following equation:

$$S = \lambda \cdot CBR \qquad (3)$$

where S is the shear strength of the material and λ is the material constant.

DEVELOPMENT OF DESIGN CRITERIA FOR EARTH PAVEMENT

The models from material cited for pavement design of unsurfaced roads are empirical. Such a model (10), is given below:

$$\text{Log } CBR_S = -1.574\,55 + 0.581\,14 \log \underline{P} + 0.490\,26 \log p + 0.171\,90 \log N - 0.001\,23 \log CBR_L - 0.654\,71 \log H - 0.382\,51 \log SN \qquad (4)$$

where SN denotes the "shape number," i.e., the geometric dimensions and deflection of the tires, and the other variables are as previously described. For this case--a single-layer earth road without a subbase cover--the design model must include the following design parameters: $\underline{P}$; p; N, where $CBR_S = CBR_L$ = CBR.

For a given wheel size (a given contact area), the following relationship can be obtained by partial differentiation of Equation 4 between the CBR and the tire pressure (which is, in the first approximation, equal to the contact pressure between the tire and the earth):

$$[(\partial \log CBR)/(\partial \log p)] = \{[(\partial \log CBR)/(\partial \log p)]\} + \{[(\partial \log CBR) \div (\partial \log \underline{P})]/[(\partial \log P)/(\partial \log p)]\} = 0.580\,426 + 0.489\,66 = 1.07 \qquad (5)$$

Equation 5 indicates that an approximate linear relationship exists between the CBR and the tire pressure given by the following:

$$CBR \approxeq Cp \qquad (6)$$

where C is a constant obtained by integration of Equation 5.

Equation 5 is equivalent to Equation 3 and is compatible with the plastic theory of cohesive medium, which was used successfully by Greenstein and Livneh (7) for pavement design of a base course covered by surface treatment. Therefore, the conclusion under discussion is that it is possible to adopt Equation 5 as a submodel.

The relationship between CBR and N (coverages to failure) is obtained by partial derivation of Equation 4, i.e.,

$$(\partial \log CBR)/(\partial \log N) = 0.1716 \qquad (7)$$

According to Womack (4) and Brabston and Hammitt (5), the values of this factor $[(\partial \log CBR)/\partial \log N)]$ are 0.17 and 0.14, respectively. Brabston and Hammitt (5) deal with a subbase pavement covered by a thin asphalt membrane. Therefore, for unsurfaced pavement, the CBR is expected to have higher sensitivity to N. In other words, $[(\partial \log CBR)/(\partial \log N)] > 0.14$. Thus, for this study, Equation 7 is compatible with the empirical results found by Womack (4).

Table 1. In situ CBR results.

Thickness of Granular Layer (cm)	CBR of Subgrade (%)	CBR in Middle of Granular Layer (%)	CBR on Surface of Granular Layer (%)
15.0-17.0	9	25-40	>80
14.5-16.0	12	28-44	>80

Note: 1 cm = 0.39 in.

Figure 2. Variation in CBR value with depth.

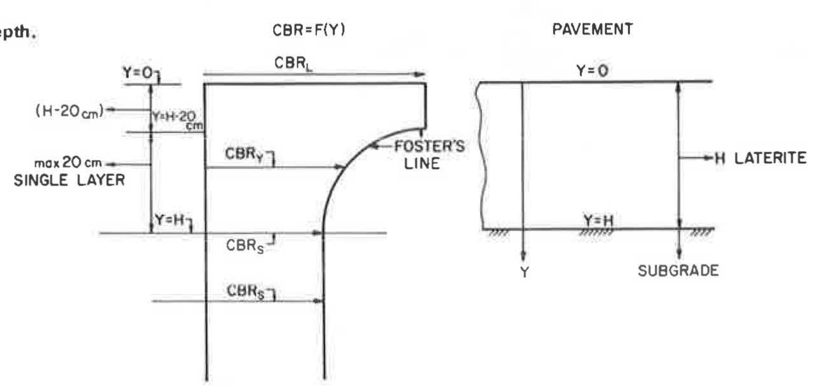


Table 2. Test results on earth pavement.

Source	In Situ Test Results: CBR In Situ (%)	ESWL (lbf 000s)	Tire Pressure (lbf/in^2)	No. of Coverages to Failure	Calculated Values from Equation 6: K	CBR	N[a]
Unpublished data from Livneh and Greenstein	6.3[b]	27	70	8	-2.831	6.6	6.0
	7.9	36	90	11	-2.882	9.3	4.2
	7.9[c]	27	70	21	-2.804	7.8	22.6
	7.9[c]	27	70	18	-2.793	7.6	22.6
Womack (4)	3.7	23	60	1	-2.834	3.9	0.7
	7.5	23	60	40	-2.802	7.4	44.6
	3.7	29	40	1	-2.806	3.7	1.0
	7.5	29	40	70	-2.816	7.6	64.7
	7.5	29	60	16	-2.792	7.2	20.3
	3.7	23	40	3	-2.830	3.9	2.3
Turnbull and Burns (11)	4.0	10	40	40	-2.780	3.7	60.8
	4.5	10	100	3	-2.730	3.7	8.8
	8.3	10	100	27	-2.628	5.5	313.0
	7.5	10	200	2	-2.625	4.9	24.0
	15.5	10	300	30	-2.600	9.5	519.0
	4.0	25	40	10	-2.906	5.0	2.7
	4.5	25	100	2	-2.930	5.9	0.4
	10.5	25	100	40	-2.930	9.9	55.6
	11.5	25	200	20	-2.842	12.4	13.1
	18.3	25	200	147	-2.789	17.4	195.8
	17.0	25	300	75	-2.857	18.9	40.1
	12.5	50	100	30	-2.863	14.1	14.7
	19.5	50	200	120	-2.921	25.1	27.2
	22.5	50	300	35	-2.853	24.8	19.6

[a]K = -2.8102. [b]Site 1. [c]Site 2.

Figure 3. Distribution of in situ CBR.

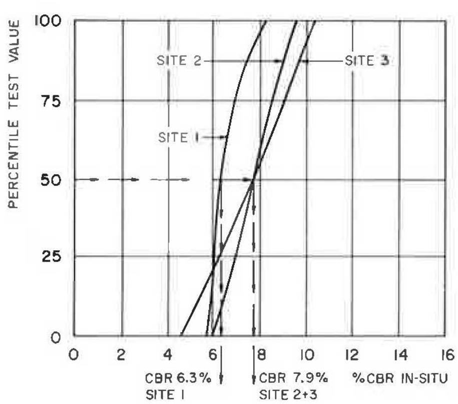
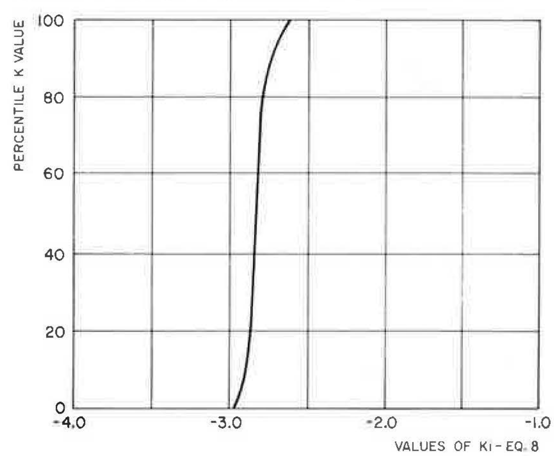


Figure 4. Distribution of K_i-values (according to Equation 8).



In conclusion, the solution of Equations 5 and 7 is given in the following:

$$0.489\,66 \log p + 0.580\,426 \log \underline{P} + 0.1716 \log N - \log CBR + K = 0 \qquad (8)$$

where K is a constant parameter determined by the site investigation presented in the following section.

EVALUATION OF IN SITU INVESTIGATION (EARTH PAVEMENT)

A summary of empirical in situ test results is given in Table 2 (4,11). The parameters included in Table 2 are subgrade CBR, ESWL ($\underline{P}$), tire pressure (p), and number of coverages to failure (N). For example, tests were run on three sites that had a silty-sand subgrade classified A-2-4 by the American Association of State Highway and Transportation Officials (AASHTO). The distribution of the in situ CBR for the three sites is shown in Figure 3. This figure shows that in situ CBR corresponds to the 50th percentile, is 6.3 percent on site 1, and 7.9 percent on sites 2 and 3. The earth pavement failed after N = 8, 21, and 18 coverages on sites 1, 2, and 3, respectively. The ESWL was 27 kips and the tire pressure was 70 lbf/in^2 (see Table 2). Another study (4) was carried out on uncompacted sandy subgrade (CBR = 3.7 percent) and on silty subgrade (CBR = 7.5 percent). In this case, the earth pavement failed after N = 1 and 40 coverages (by ESWL = 23 kips and p = 60 lbf/in^2), respectively.

The experimental data given in Table 2 enabled us to study the reliability of the model developed in the previous section (Equation 8) and to determine the K-values. The results of this computation are given in Table 2. For example, in the experiment carried out on site 1 with a subgrade CBR of 6.3 percent, the calculated K-value is $K_i = -2.831$. The distribution of K_i (according to Equation 8) is given in Figure 4. This distribution has a standard deviation of 0.0879, which is an indication of the reliability of the developed model. Finally, the value of K in Equation 8 is based on the K_i-values given in Table 2, i.e.,

$$K = \sum_{0}^{24} K_i / 24 = \sum_{0}^{24} (\log CBR_i - 0.489\,66 \log p_i - 0.580\,426 \log \underline{P}_i - 0.1716 \log N_i)/24 \quad (9)$$

where

CBR_i = in situ CBR of each study i (according to Table 2, 24 studies exist),
$\underline{P}_i$, p_i = ESWL and tire pressure in each study i, and
N_i = number of coverages to failure in each study i.

Substituting the calculated K_i-values (shown in Table 2) into Equation 9 gives K = -2.8102. Substituting this value into Equation 8 enables the determination of the required CBR (or coverages for a given ESWL, p, and N or CBR). The results of this calculation are given in Table 2. For example, in the investigation carried out on site 1 (subgrade CBR = 6.3 percent; ESWL = 27.000 lb; p = 70 lbf/in²; N = 8), the calculated CBR (by using Equation 8) is 6.6 percent. The relationship between the in situ measured subgrade CBR and calculated CBR by the model developed in this study is a statistical test of this model's reliability. This statistical correlation (linear regression) is given in the following:

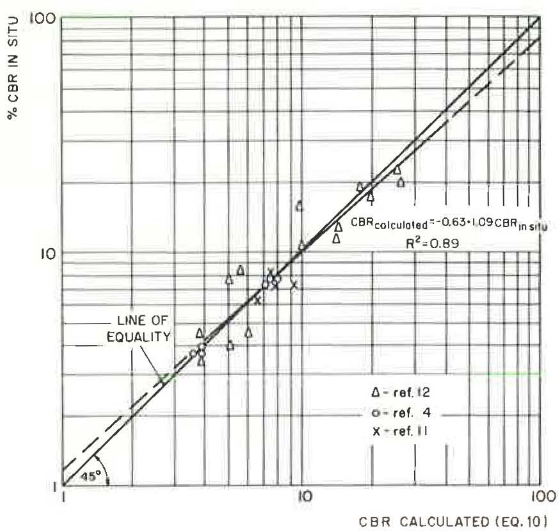
$$\text{Calculated CBR} = -0.63 + 1.09\text{CBR in situ} \quad R^2 = 0.89 \quad (10)$$

Equation 10 is plotted in Figure 5, which contains the measured and calculated CBR values. The important conclusion derived from Figure 5 is that in the practical range of the in situ CBR (3-30 percent), Equation 10 coincides with the line of equality of in situ CBR and calculated CBR. This is additional proof of the validity of the model developed for this study.

Relative lower correlation (which is expected for the number of coverages to failure, $R^2 = 0.77$) is obtained for the calculated and measured coverages (Figure 6). In this case also, the correlation line (Equation 11) coincides with the line of equality (calculated log N = in situ log N):

$$\log N\ (\text{calculated}) = 0.95 \log N \text{ in situ} + 0.0688 \quad (11)$$

Figure 5. Relationship between calculated CBR (Equation 10) and measured CBR in situ.



DEFINITION OF METHODOLOGY FOR LATERITE SURFACE PAVEMENT

Studies by the U.S. Army Corps of Engineers and others (3,6,12) have shown that the maximum practical coverages per lane to failure for a soil-aggregate surface are in the region of 10×10^3 to 15×10^3 equivalent standard axles (ESA), which is equivalent to approximately 25 000 applications of ESA. Therefore, since it is normal practice in Thailand to reconstruct the surface annually or every two years, the most economical pavement section should have the minimum thickness required to carry the estimated traffic through this period and

Figure 6. Relationship between calculated N (Equation 8) and N measured in situ.

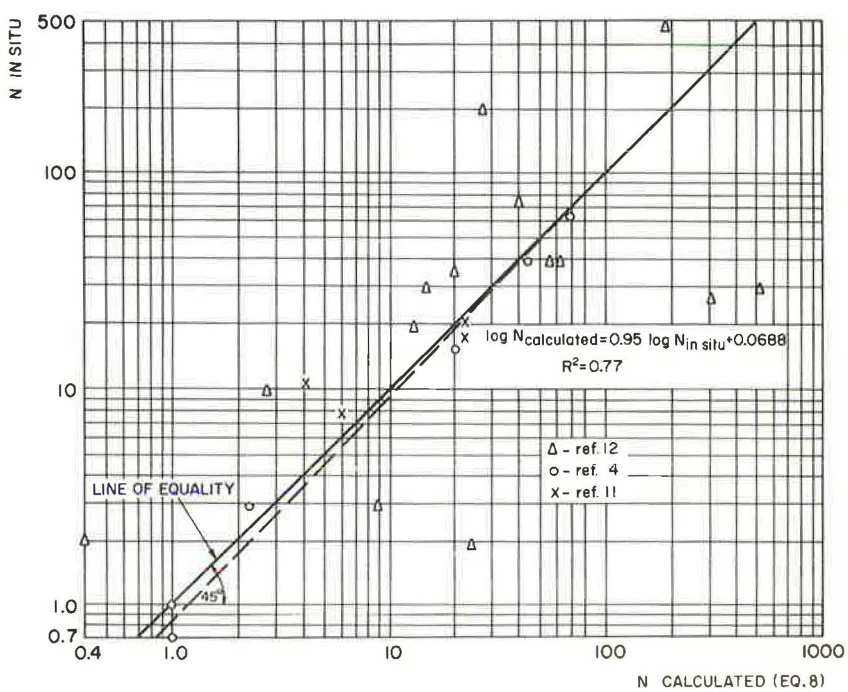


Figure 7. Stress distribution beneath surface of flexible pavement.

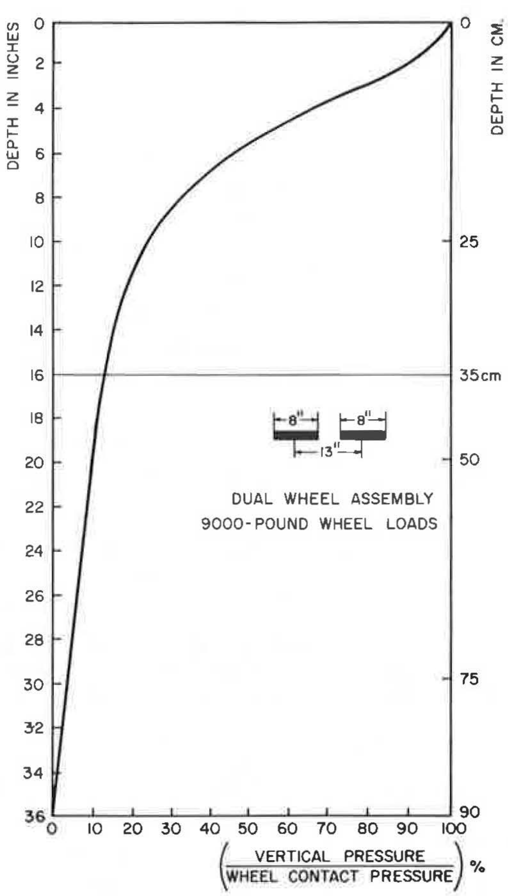
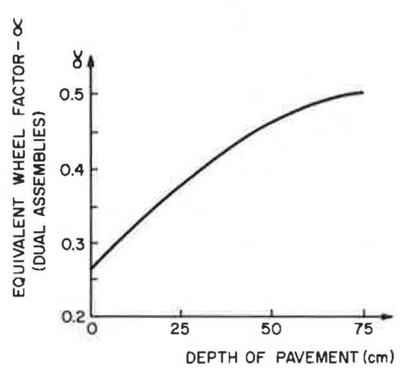


Figure 8. Equivalent wheel factor (α) versus depth of pavement.



less than 25 000 applications of ESA per lane.

As stated in the section on basic assumptions, the plastic theory was adopted for this study for the analysis of the pavement design. In other words, Equations 2 and 8 (with K = -2.8102) are the basic equations that govern the pavement design for laterite roads. Therefore, in this case (two-layer analysis), an equivalent CBR of the two-layer system must replace the CBR of the one-layer system given in Equation 8. This equivalent CBR is defined in the following equation:

$$CBR_{eq} = (1/h) \int_0^h CBR_y dy \qquad (12)$$

where

CBR_{eq} = equivalent CBR of two-layer system (subgrade and subbase), which replaces subgrade CBR of one-layer analysis in Equation 8;

CBR_y = in situ CBR of pavement system as a function of depth y (see Figure 2 and Equation 2); and

h = depth of pavement that supports standard axle load (9000 lb, dual-wheel assembly).

In this study, it is assumed that h is the depth beneath which the vertical stress is less than 15 percent of the tire contact pressure. Therefore, based on Figure 7 [adapted from Martin and Wallace (13)], h = 14 in.

Finally, the use of Equations 8 and 12 for the 18 000-lb axle load (p = 70 lbf/in^2) yields the following equation for the pavement design of unsurfaced subbase roads:

$$-2.8102 + 0.489\,66 \log(70) + 0.580\,426 \log(\alpha \times 18\,000) + 0.1716 \log(N) = \log CBR_{eq} = \log[(1/35)\int_0^{35} CBR_y dy] \qquad (13)$$

where α denotes ESWL, i.e., α (axle load) = ESWL, and α is a function of the type of axle and pavement depth. For the dual assembly, the values of α are given as a function of the depth of pavement in Figure 8 [modified from Livneh, Ishai, and Uzan (14)].

APPLICATION

Earth Roads

The nomogram shown in Figure 9 is used for the application to earth roads of the model (Equation 8 with K = -2.8102) developed in this study. In this figure, Equation 8 has been solved for a range of values of ESWL, tire pressure, subgrade CBR, and number of coverages to failure.

Figure 9. Design charts for earth roads.

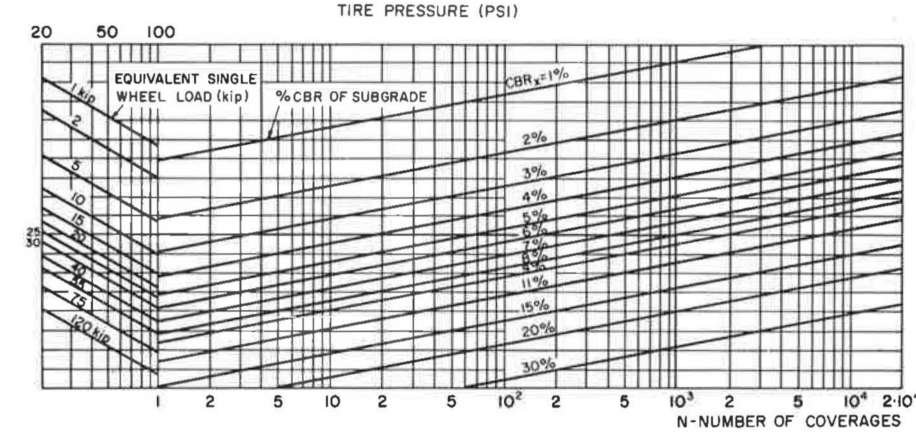
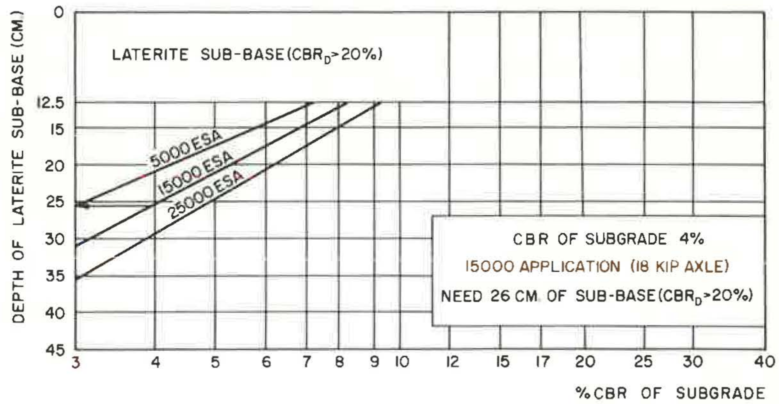


Figure 10. Pavement design of unsurfaced laterite roads.



By entering the tire pressure and ESWL (as shown by the arrows in Figure 3), the number of coverages to failure for any given subgrade CBR design value can be determined. The example in Figure 9 shows that a subgrade that has a CBR of 8 percent permits 1000 coverages of 9000-lb equivalent wheel loads with a tire pressure of 70 lbf/in^2.

Unsurfaced Subbase Roads

The nomogram shown in Figure 10 is used for the application of the model (Equation 13) developed in this study for unsurfaced subbase roads. In this figure, Equation 13 has been solved for a range of subbase thicknesses, subgrade CBR values, and number of applications (5000-25 000 applications of ESA, which is equivalent to 2500-12 500 coverages) for an 18 000-lb axle. Therefore, for a given subgrade CBR design value, the required subbase thickness can be determined. For example, for a CBR value of 4 and estimated loading of 15 000 ESAs, the required subbase thickness is 10 in (see Figure 10).

It is important to note that the conclusions from Figure 10 are compatible with the up-to-date experience in Ecuador (3). According to Greenstein and Garcia (3), an unpaved gravel road 8 in thick on a silty-sand subgrade (CBR 6-7 percent) carried about 25 000 ESAs (18 kips) per lane until reconstruction of the surface was required. This is an indication of the reliability of the developed model.

An additional indication of the validity of this model is the local experience in Thailand for rural roads, according to which a minimum pavement depth of 6 in is used over silty subgrade (CBR ≈ 5-6 percent) for approximately 5000 ESAs, which is nominally the minimum design traffic load.

The following three limitations should be observed when Figure 10 is used:

1. Figure 10 can be used for local laterite subbase with a CBR design value that ranges between 20 and 40 percent.
2. For subbase CBR values greater than 40 percent, the required thickness may be reduced by approximately 30 percent to a practical minimum of 5 in.
3. For subgrade CBR values greater than 15 percent, local subgrade can be used as the pavement layer.

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