STRUCTURAL DESIGN OF CONCRETE PAVEMENTS WITH LEAN CONCRETE LOWER COURSE

Robert G. Packard, Paving and Transportation Department, Portland Cement Association

A procedure is presented for the structural design of concrete pavements incorporating a lower layer of lean concrete, either as a subbase constructed separately or as a lower layer in monolithic construction. An analysis of flexural stresses is used to recognize the strength and elastic properties of the materials and the layer thicknesses. Modifications of conventional linear elastic theory are made based on the properties of concretes at low cement contents and on experimental and performance data. Because these data are limited, the design procedure is suggested as a preliminary guide. Simplified design charts are presented for conventional highway truck loadings; design data are also given that may be used for aircraft and other loadings.

In recent years in the United States, there has been a substantial increase in the use of lean concrete in pavement structures (1). These uses are:

1. Lower course of composite (monolithic) concrete pavement.
2. Subbase under concrete pavement.
3. Base course under asphalt surface.
4. Shoulders adjacent to concrete pavement.

Rational approaches to structural design are not yet well established and need to be developed to optimize the economics and performance of such pavements.

This report suggests a structural design approach for the first two applications listed above.

Design

This section presents design charts and procedures for:

1. Composite (monolithic) concrete pavement with lean concrete lower layer.
2. Concrete pavement with lean concrete subbase (unbonded).

These will be referred to as "monolithic" and "non-monolithic" pavements, respectively. The development of the design procedures, discussion of experimental data, and application to pavement loadings other than conventional trucks are given in later sections.

Although the design procedures discussed in this paper are based on flexural stresses, it is of interest to compare designs based on experimental tests and theoretical deflections. Relationships developed in 1974 (2) (similar comparisons were made by T. J. Larsen (3) at about the same time) served as the first guidelines for composite design. These give equivalent thickness factors for lean concrete based on elasticity properties. The following table shows some of the equivalency factors determined from these references for use in the equation:

$$h_e = h_1 + Ch_2$$

where h_e = thickness of an equivalent single-layer pavement

h_1 = thickness of surface layer of two-layer pavement

h_2 = thickness of lower layer of two-layer pavement

C = equivalence factor

E_2, Modulus of elasticity of lower layer

10^6 psi	GPa	C-values Ref. 2	C-values Ref. 3
1	7	0.53	0.50
2	14	0.68	0.66
3	21	0.77	0.78

Based on $E_1 = 5.6 \times 10^6$ psi (39 GPa) of surface layer

These values are for monolithic pavements. Corresponding values for non-monolithic pavements would be somewhat lower.

These early guides have the drawback of not recognizing the flexural strengths of surface and base concrete. Also, the use of equivalency factors in design may not give equivalent pavement sections over a wide range of material properties and pavement thicknesses. In spite of these limitations, the relationships are useful in an approximate way for comparing different pavement sections.

To recognize the structural properties of the surface and base concretes, a design procedure for composite pavement was developed based on flexural stresses in a two-layer system.

In this report, the composite design thickness is set equivalent to the thickness of a single slab of conventional concrete so that the design is directly related to established design or performance experience. In this way, the design can be used with whatever methodology is deemed appropriate in the user's experience -- PCA method, AASHTO method, a given state highway department's method, or an established airport pavement design procedure.

Monolithic Pavement

In monolithic construction, the practice has been to use a minimum surface course thickness -- about 25 to 30% of the total composite pavement thickness. This results in economy in cost and conservation of high-quality aggregates. Fig. 1 illustrates that this is also a good practice based on design considerations. For typical relationships between E (modulus of elasticity) and MR (modulus of rupture) for normal and lean concretes, the stresses in the bottom layer control the pavement thickness requirements up to h_1/T ratios (ratio of surface layer thickness to total thickness) of 60% or more. At higher h_1/T ratios, stresses in the surface layer may be excessive, especially at low E_2 values, even though stresses in the lower layer are safe.

As the thickness of the surface layer is increased in relation to total thickness, Fig. 1 shows that tensile stresses in the bottom of the lower layer are reduced at first, then level off at values up to about 50%, then are reduced again at higher values of h_1/T. Thus, from an economic viewpoint, there is no advantage in selecting a surface thickness greater than the range of 20 to 40% of the total thickness.

As a result of these considerations, design tables and charts have been prepared for monolithic slab design showing surface layer thicknesses that are less than the bottom course thicknesses. (This is not the case for non-monolithic design as discussed later.)

Fig. 2 for monolithic pavements and Fig. 4 for non-monolithic pavments have been prepared as practical guidelines for the design of composite pavements under loadings of conventional highway trucks. In these simplified charts, values for the moduli of elasticity do not appear but have been preselected to correspond with average relationships to moduli of rupture as discussed later in the section "Material Properties." Where aggregates in the lean concrete are unusual, soft, or contain substantially more fines than normal, the relationship between E and MR may differ appreciably from that built into Figs. 2 and 4. Design tables which include E-values as well as

Figure 1. Stresses in top and bottom layers of a monolithic pavement.

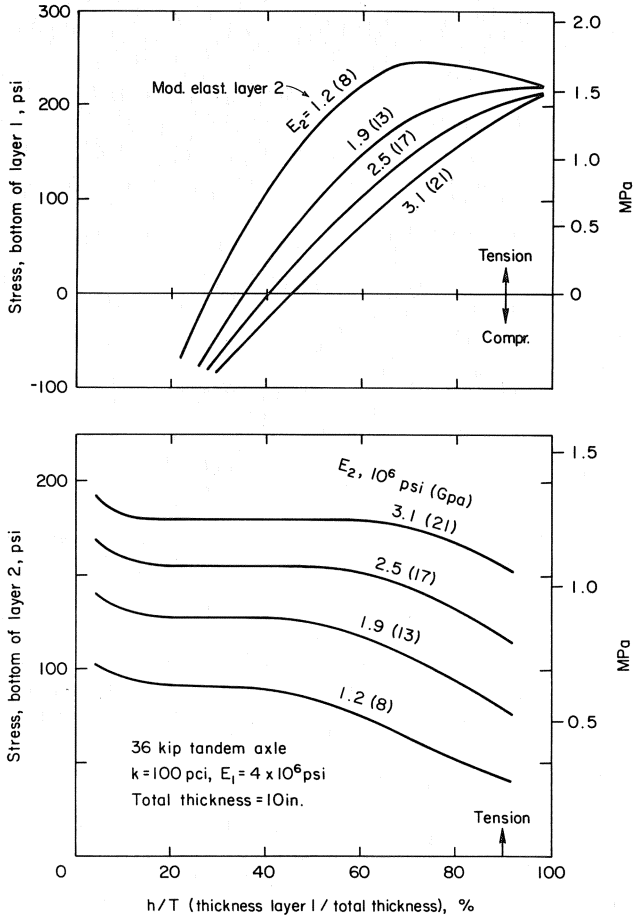
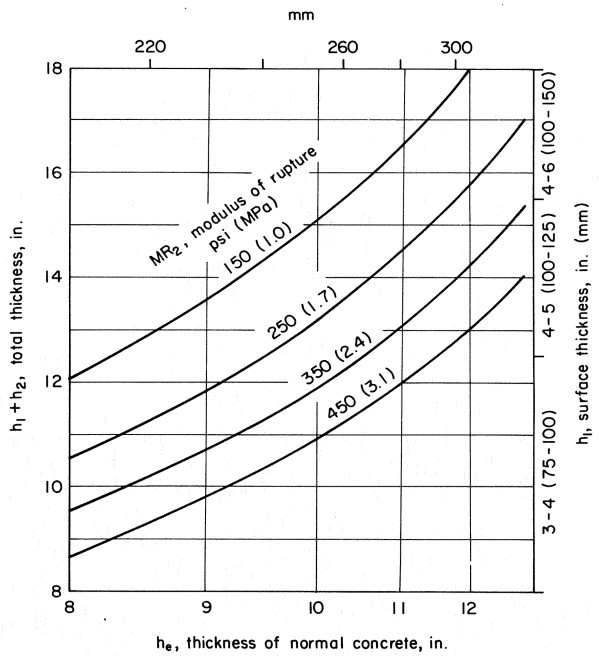


Figure 2. Design chart for monolithic pavement.



MR-values are presented later.

Fig. 2 shows the required total thickness and surface thickness of a composite pavement equivalent to a given thickness of normal concrete. It is based on limiting the stress in the lower layer to safe values relative to allowable stress in a single slab of normal concrete under the same loading condition. At the indicated surface thicknesses, stresses in the upper layer are quite low.

Non-Monolithic Pavement

The largest paving use of lean concrete in recent years has been as a subbase under a conventional concrete pavement. This is a non-monolithic construction where the surface course of normal concrete is later placed on a hardened lean concrete subbase.

In highway construction, the lean concrete subbase is built at least 2 ft (0.6 m) wider on each side, than the mainline pavement to support the tracks of the slipform paver. This extra width is structurally beneficial for wheel loads applied at pavement edge.

The usual practice in selecting relative thicknesses for surface and subbase layers is just the opposite of that for monolithic composite pavements. Surface thickness is generally about twice the total thickness; for example, 9 in. (229 mm) of concrete on a 5 in. (127 mm) subbase for a highway and 14 in. (356 mm) concrete on 7 or 8 in. (178 or 203 mm) of subbase for an airport with fairly heavy loads.

Fig. 3 indicates that optimum conditions occur when the surface thickness to total thickness ratio, h_1/T, is 60% to 70%. For example, at an E_2-value of 1.2 x 10^6 psi (8 GPa), assume that it is necessary to limit stress in the lower layer to about half of the strength of the material -- assume that this is 75 psi (520 kPa). This requires an h_1/T ratio of at least 60%. At 60%, stresses in the upper layer are safe because they are less than the specified ratio (half, in this case) of the strength of normal concrete. On the other hand, at an h_1/T ratio as high as 80%, stress-strength ratio in the top layer exceeds that in the bottom, controls the design, and annuls the effect of decreased stress in the lower layer. As a result, design charts and tables for non-monolithic slabs show surface thicknesses greater than subbase layer thicknesses.

Fig. 4 is the design chart for non-monolithic pavements (concrete on lean concrete subbase). It shows the required surface and subbase thicknesses equivalent to a specified thickness of normal concrete.

Basis for Design

As in conventional concrete pavement design methods, the design of layered concrete pavements in this paper is based on the concept of limiting the flexural stresses due to vehicle loads to safe values in terms of the flexural strength of the

Figure 3. Stresses in top and bottom layers of a non-monolithic pavement.

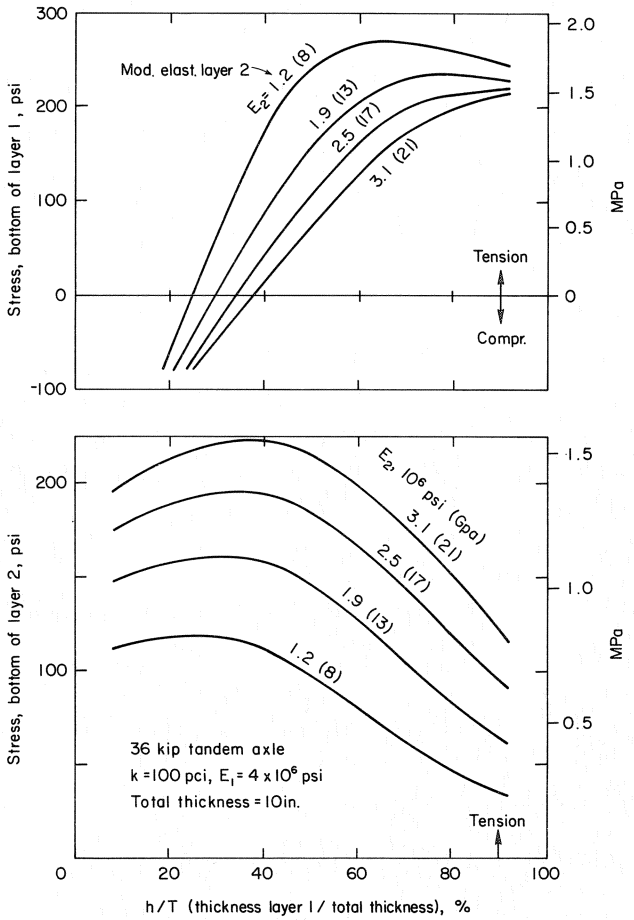
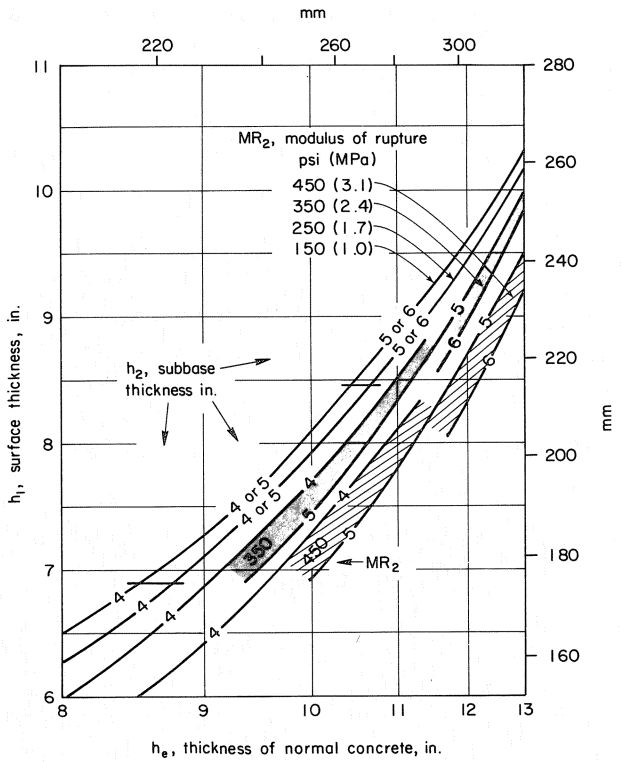


Figure 4. Design chart for non-monolithic pavement.



materials used. The design method described here indicates the thickness of a two-layer pavement that will have the same margin of safety, or stress ratio (ratio of flexural stress to flexural strength), as a single-layer pavement of normal concrete of a thickness established by appropriate design considerations.

Logical modifications of conventional theory and material properties have been used so that the results appear to be reasonably consistent with experimental test results, properties of materials with normal and low cement contents, and the limited performance data available.

Material Properties

The physical properties of concrete affecting a pavement's load-carrying capacity are its flexural strength (modulus of rupture), modulus of elasticity, and fatigue characteristics.

In the design of pavements of normal concrete, the modulus of elasticity is usually assumed to be about 4 or 5 million psi (30 or 35 GPa) and, in this narrow range, the thickness requirement is not significantly affected. The flexural strength, however, has a strong influence on the thickness requirement. For lean concretes, these properties may be considerably less and cover a greater range: MR values from 150 to 500 psi and E-values from 1 to 4 million psi (MR, 1-4 MPa; E, 7-30 GPa). As a result, both of these properties have a pronounced effect on the design of pavements incorporating lean concrete.

Strength and Elastic Properties. The strength and elastic properties of lean concretes covering a range of quality are bounded between those of conventional, full-strength concrete on the high side and become similar to those of good cement-treated aggregate (high-quality granular soil-cement) on the low side.

Figure 5. Modulus of rupture vs. compressive strength.

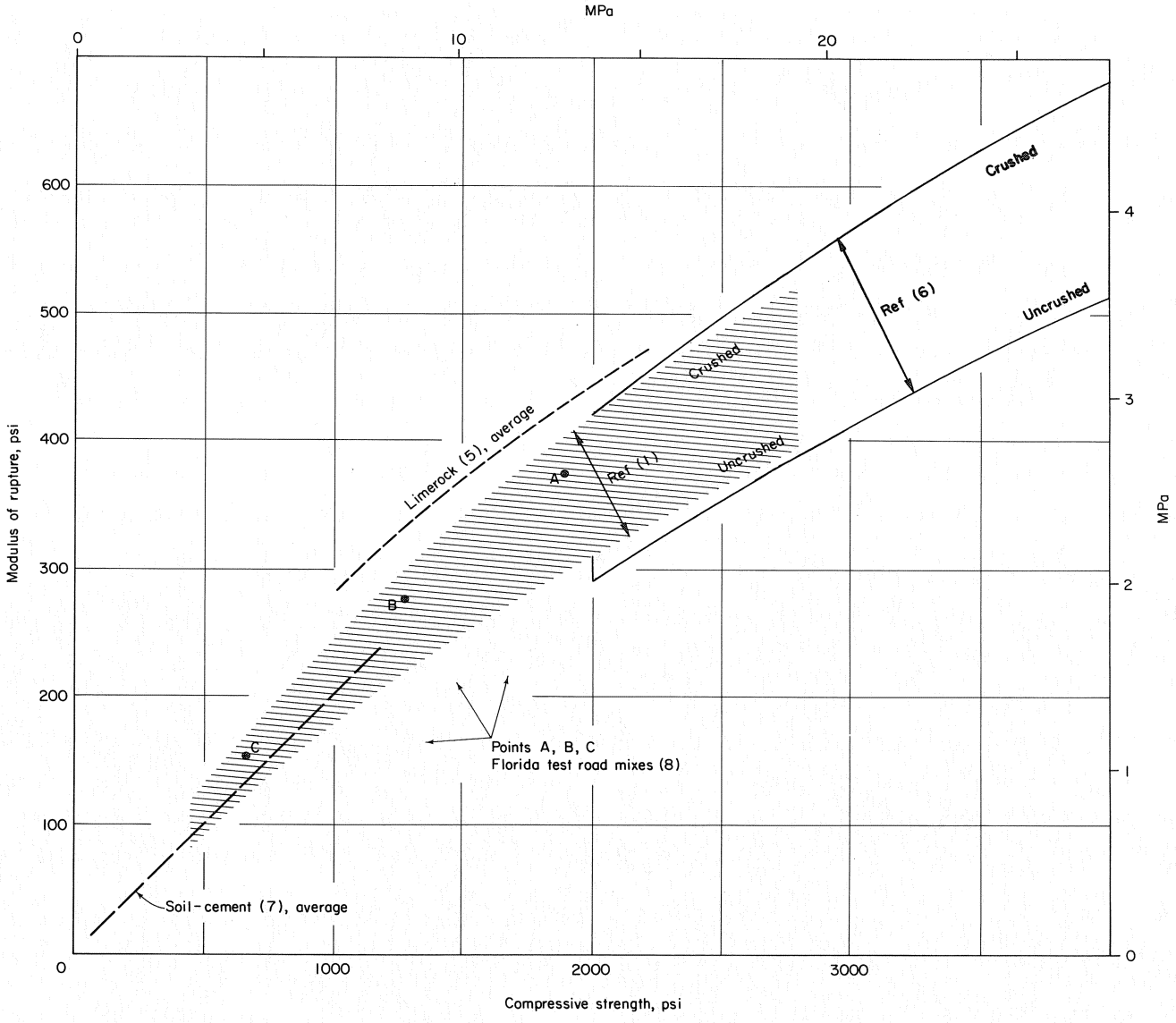
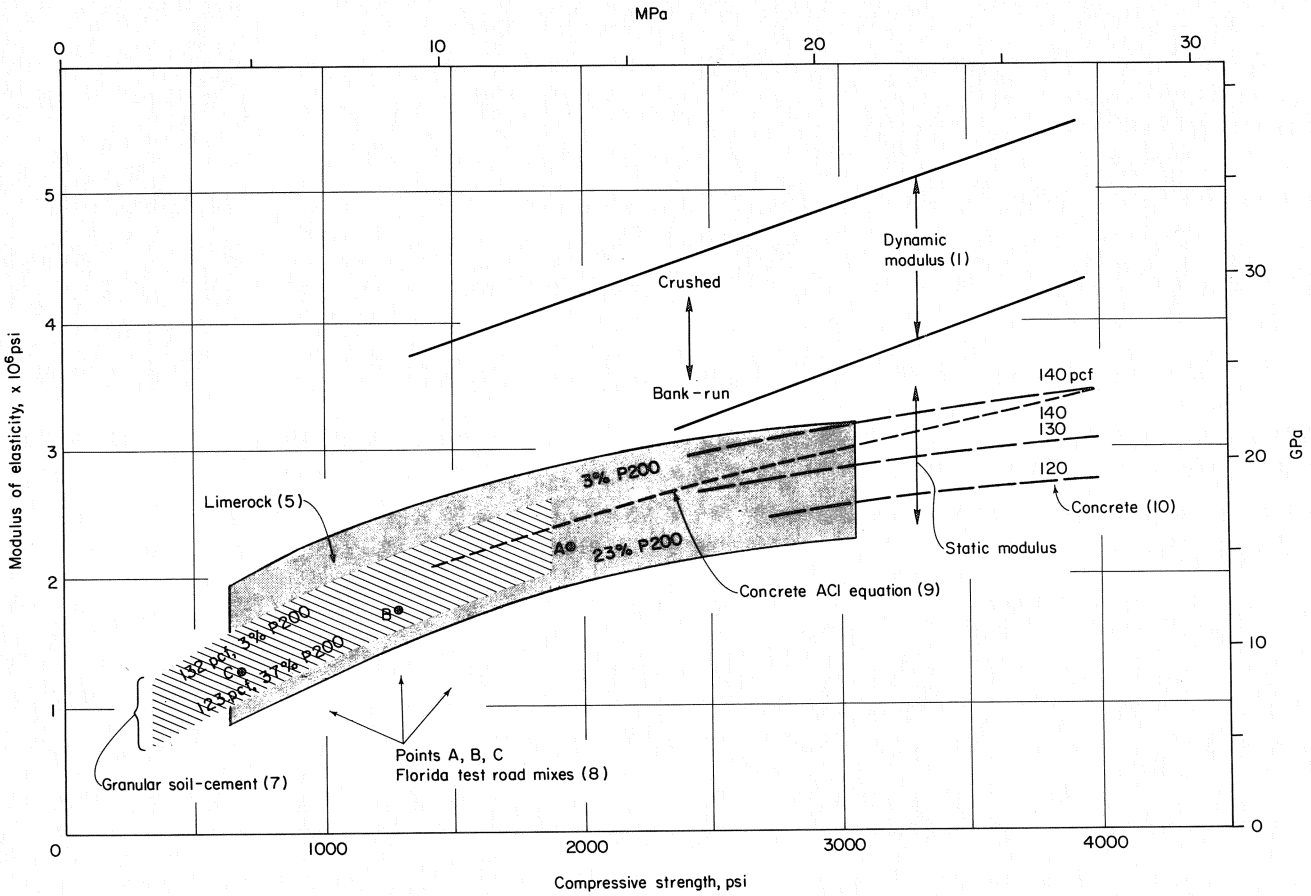


Figure 6. Modulus of elasticity vs. compressive strength.



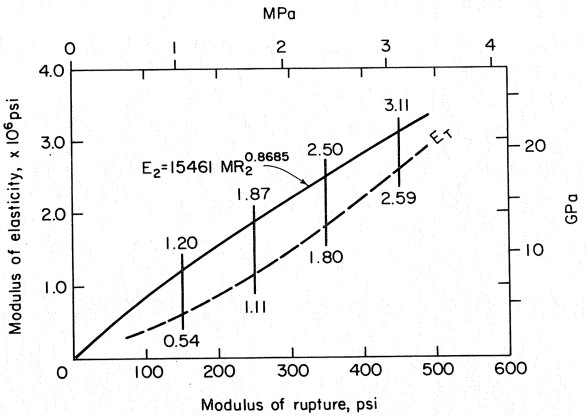
To define the lower boundary of quality, experience with soil-cement is considered in this design procedure. A substantial amount of research on soil-cement design has been performed by PCA (4) as well as other agencies.

Figs. 5 and 6 shows the relationship of flexural strength (MR) and modulus of elasticity to compressive strength for cement-bound materials. In general, for a given compressive strength, the flexural strength will be somewhat higher for crushed materials than for rounded aggregates; modulus of elasticity may be higher for cleaner aggregates and for concretes with higher densities. Static modulus (ASTM C469) values generally range from 70% to 80% of dynamic modulus (ASTM C215) values.

For design purposes, it is suggested that static modulus of elasticity values be used because of better agreement with experimentally measured values of deflections and strains. However, similar thickness design relationships will be obtained when dynamic values are used because the ratio of E_1 to E_2 will be approximately the same for static or dynamic values.

The upper curve in Fig. 7 shows the average relationship between modulus of elasticity and flexural strength on which the design charts, Figs. 2 and 4, are based. This relationship is suggested for design purposes because of possible variations among users in the determination of E-values by different test methods and the

Figure 7. Relationship between modulus of elasticity and modulus of rupture used for design charts.



difficulties of measuring very small strains in the tests. When considering the effects of changes in E or MR on design results, it should be remembered that they are not independent variables but are fairly closely related to one another for concretes of a given aggregate.

Fatigue. The fatigue properties of concretes at various strength levels are reported to be similar when stress is expressed as a ratio to strength. This is shown in Fig. 8 (11) for concrete beams of various strengths and in Fig. 9 (12) for composite pavement sections (concrete on soil-cement).

The similarity of fatigue characteristics of these materials is a fundamental basis in this report for relating thickness of pavements with lean concrete to the thickness of a normal concrete pavement.

Figure 8. Fatigue curves for normal and lean concretes.

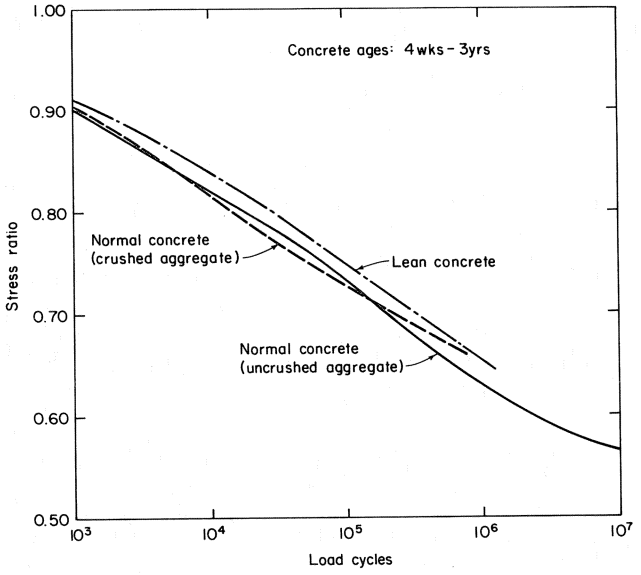
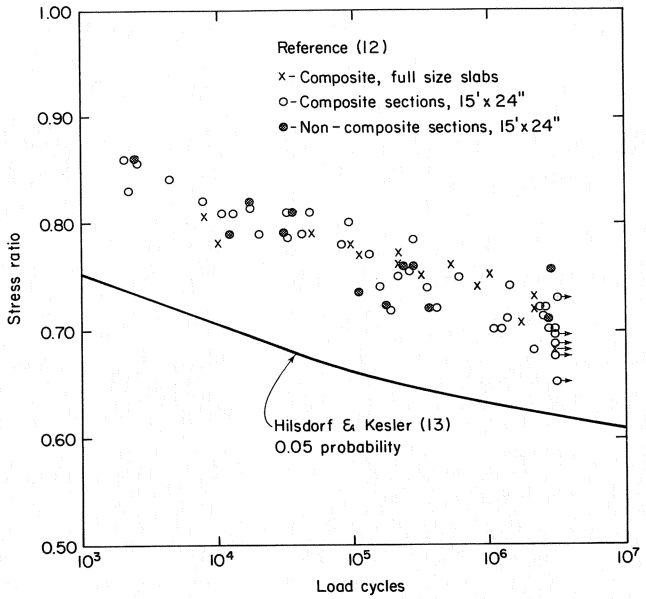


Figure 9. Fatigue relationships for composite slabs.



Non-Linearity. The stress-strain behavior of stronger lean concretes is expected to be fairly linear, similar to normal full-strength concrete. However, for weaker lean concretes, the behavior in flexure is somewhat more complex. As concrete becomes leaner, it may exhibit more non-linear and bi-modular elastic effects (the modulus in tension is less than in compression). The leaner the concrete, the more these effects appear at a lesser degree of loading (ratio of load stress to ultimate strength). That is, a redistribution of stress in the tensile zone takes place, with the result that the higher tensile stress at the extreme fiber is relieved to some extent by the less-strained material located closer to the neutral axis.

Fig. 10 shows stress-strain curves for normal and lean concretes (14) and the increasing degree of non-linearity as the concrete becomes leaner.

After several analyses with the computation methods discussed in the next section, a degree of non-linearity was incorporated into the bottom layer of the pavement so that the stress-strain curves are almost linear for strong lean concretes and progressively develop more non-linearity for weaker concretes.

The initial degree of non-linearity used in the computer analysis with E_2-values less than 4,000,000 psi (28 GPa) is set to the values shown in Fig. 7 where E_T and E_C (E_2) are moduli in tension and compression, respectively.

In the computer analysis, these values are then iterated so that the E_T value is dependent on the position of the neutral axis and the E_C value is dependent on the position of the centroid of the lower layer. An example of the curvilinearity introduced for a low modulus material is shown on the left in Fig. 11 in the stress curves of the lower layers.

The non-linear modification is necessary because comparisons of flexural stresses computed by conventional linear elastic theory to flexural strengths are not valid for materials with significant non-linearity; the stresses are substantially overestimated.

Figure 10. Non-linearity of stress-strain curves for normal and lean concretes.

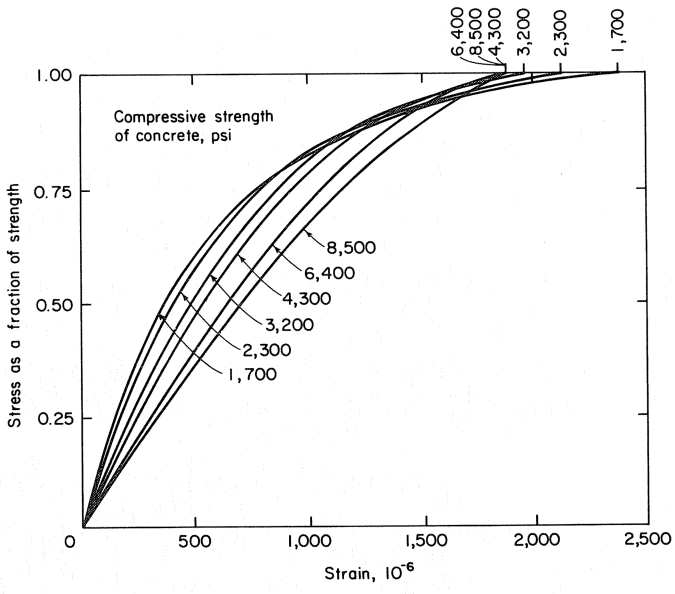
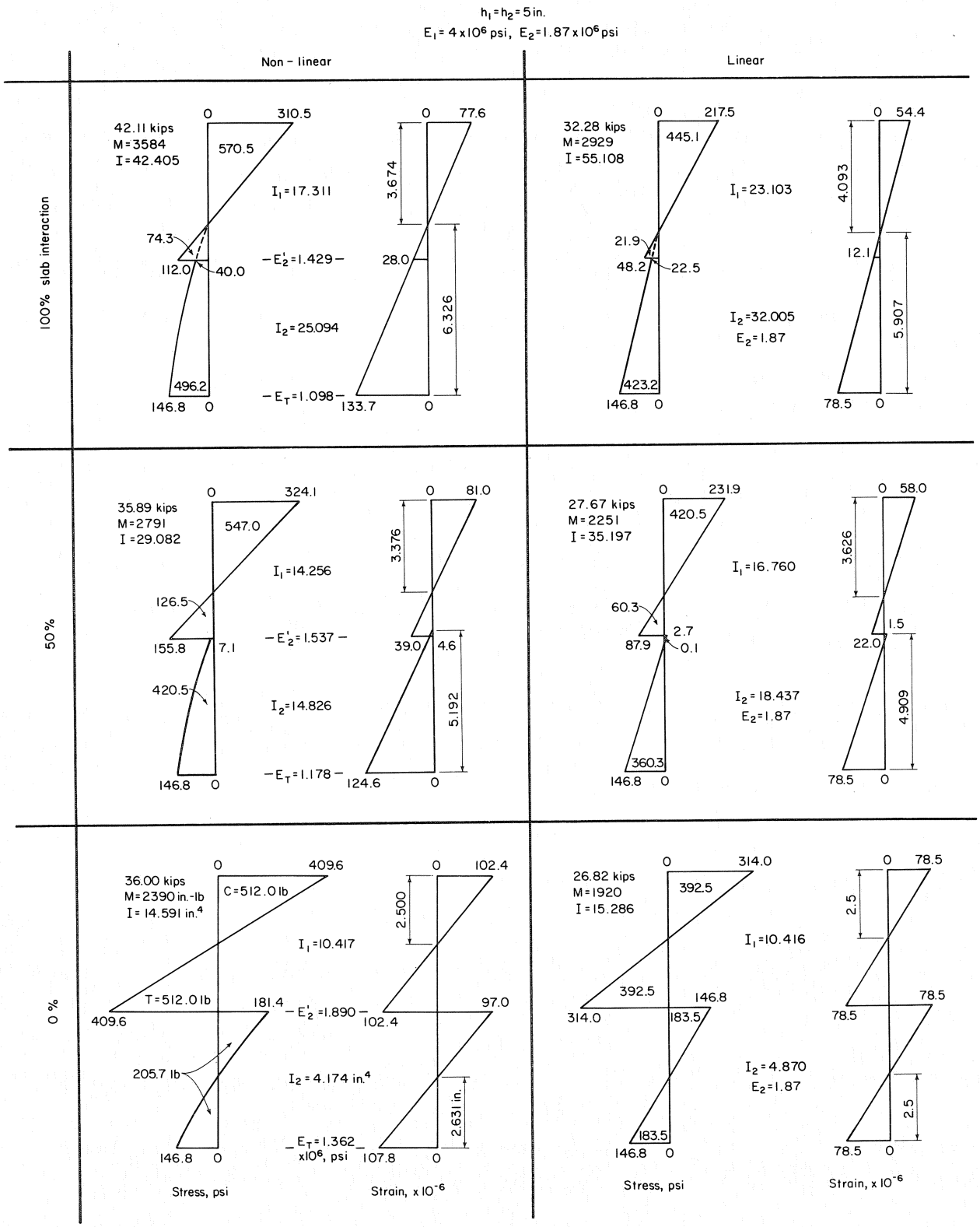


Figure 11. Stress and strain distribution in composite slabs (tandem axle loads for equal stress in lower layer).



Interaction Between Slabs

For a monolithic slab, the surface layer of normal concrete and the lower layer of lean concrete are assumed to act as one slab. Upon bending under a load, there is no slippage at the interface and complete continuity of the strain distribution exists through the cross section. This condition is described as 100% interaction and is illustrated at the top of Fig. 11.

Unbonded slabs are assumed to act as separate slabs with slippage at the interface. The condition of a perfectly smooth, frictionless interface is described as 0% interaction as shown at the bottom of Fig. 11. The real situation for unbonded slabs is that the interaction is probably somewhere between the two extremes. The only information available on this is from research (15) of concrete pavements on cement-treated subbases where three conditions of interface treatment were used: (1) bonded with grout, (2) separated with a thin layer of bituminous curing material, and (3) separated with polyethylene film. Measurements of stresses and deflections under load indicated that the bonded condition was only slightly better than the separated conditions. This showed that there is considerably more interaction between unbonded slabs than is indicated by an assumed frictionless condition.

Accordingly, for the computer analysis of the unbonded condition, several levels of interaction factors were investigated: 0, 25, 50, and 75%. A factor of 50% fit the measured deflections well; approximated stresses only fairly, but as well as other values of interaction factors; and, most importantly, was in agreement with the research conclusions regarding the degree of slab interaction. As a result, an interaction factor of 50% was selected as a reasonable design value for the non-monolithic condition.

The technical definition of the interaction factor is explained by stating that a factor of 50% gives a combined moment of inertia of the two slabs that is half way between the moments of inertia of the full-bond condition and the frictionless condition. In the computer analysis, this concept is introduced before the non-linear iteration routine which changes the situation slightly.

Computation of Stresses in Two-Layer Pavement

Flexural stresses in a two-layer pavement can be computed when the bending moment and the radius of relative stiffness (ℓ, see equation below) of the pavement system are known. The first step is to determine the M-ℓ relationship for a single layer slab for a given loading configuration. The moment may be determined by the use of published design charts, influence charts, or computer programs. The selected design situation may be for a single or tandem axle load, or an aircraft or other vehicle, at pavement edge, joint, or interior load position.

Fig. 12 illustrates M-ℓ curves determined for single and tandem axle loads at pavement edge computed by a finite element program (16) and at pavement interior by another program (17). (The charts and tables in this paper for highway trucks are based on the M-ℓ curve for the edge loading condition for a pavement with a 15-ft (4.6m) joint spacing.)

The ℓ-value of a two-layer pavement section is determined as follows:

$$\ell = \sqrt[4]{\frac{12\ E_1 I}{11.73k}}$$

where ℓ = radius of relative stiffness, in.

E_1 = modulus of elasticity, psi

I = moment of inertia, in.^{4}

k = modulus of subgrade reaction, pci

I-values computed for a two-layer system based on a transformed section analogy are listed in tables presented later. The moment is determined from the selected M-ℓ relationship and, in turn, the tensile stresses in the two layers are computed as explained below.

This procedure was verified for a two-layer slab by a finite element computer program (18) for both monolithic and unbonded slabs. Table 1 shows stresses derived from a one-layer slab, and converted to the two-layer monolithic situation, and stresses from the computer program for a two-layer slab. Table 1 also shows the same for non-monolithic pavement. (For these verifications, linear elastic properties were used.)

Computation of the stresses for one slab on top of another with non-linearity is more complex. The parameters listed in Tables 2 and 3 are used to compute these stresses by the following equations:

$$S_1 = \frac{M\bar{y}}{I} \quad \text{and} \quad S_2 = \frac{MB}{I}$$

where: S_1 = stress at bottom of layer 1, psi

S_2 = stress at bottom of layer 2, psi

(Multiply stress by 6.895 to obtain stress in kPa units.)

M = bending moment determined from M-ℓ relation for a one-layer slab, in.-lb.

I = moment of inertia (Table 2 or 3), in.^{4}

$\bar{y}$ = distance from bottom of top slab to neutral axis (Table 2 or 3), in.

B = a parameter used to calculate S_2 (Table 2 or 3), in.

These tables are presented as an aid to users who wish to determine stresses for other vehicles (aircraft, for example) or other load positions. The tabulated parameters from which stress is computed as described above, are properties of the pavement system independent of the load configuration and load position. They can therefore be used for any load configuration and position.

In this report, tandem axles are taken as the critical loading. This is because fatigue consumption computations usually show that the tandem axles are critical for typical axle-load distribution data obtained from loadometer tables. Also, as shown in Fig. 12, curves for tandem-axle loading are steeper than those for single-axle; when comparing a one-layer pavement (smaller ℓ-value) to an equivalent two-layer

pavement (larger ℓ-value) the ratios of bending moments for tandem-axles will be greater than those for single-axles. The M-ℓ relationship for tandem axle loadings is:

$$M = 1854 - 1564 \log \ell + 100.54$$

It is noted from Fig. 12 that the ratios of the moment for the interior load position to that for the edge position are almost constant across the range of ℓ-values. This means that the same design thickness for two layer pavement will be obtained for either load position because the concept in this report is to compare relative stresses, not absolute stress values.

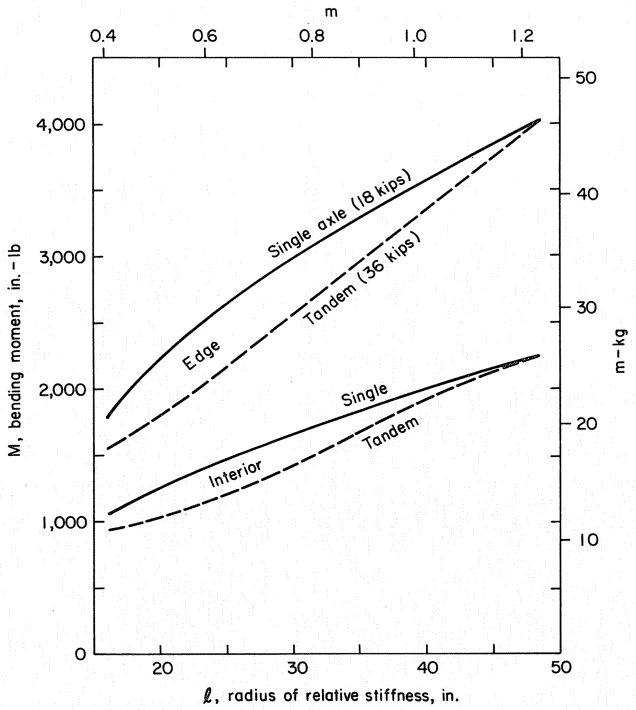
Use of the procedure for determining stresses described here is illustrated by the example in the next section.

Research Data and Performance Experience

In this report, an attempt has been made to relate the design to the limited research and performance data available.

In previous sections several aspects of pertinent research have been discussed. Data on research of concrete on cement-treated subbases (15) have been discussed to show the relative structural effects of the subbases and the effects of bonding and unbonding on interaction at slab interface. Data from repeated load tests (12) show the fatigue characteristics of composite slabs. (Fig. 9) This research also indicates that performance is better than conventional linear-theory stress/fatigue analysis would predict, and that considerable additional pavement serviceability is obtained after the actual occurrence of first crack in the lower layer.

Figure 12. M-ℓ relationships for edge and interior load positions, highway truck loadings.



For roads in service, the only information available at this time is the excellent performance of composite pavements at the Florida Econocrete Test Road (8). These test sections consist of 3 in. (76 mm) of strong concrete constructed monolithically on 9 in. (229 mm) of lean concrete at three different levels of strength. It is of interest to compare this performance with the design analysis given in this report. The material properties are tabulated as follows:

Layer	Mix	Compressive strength, psi	MR, psi	Static E, 10^6 psi
Top	-	5111	735	5.75
Bottom	A	1955	380	2.21
Bottom	B	1278	279	1.73
Bottom	C	675	158	1.29

By the analysis described in this report, the composite sections are equivalent to the range of normal concrete pavement thicknesses as follows:

Section	Equivalent Thickness, in. (mm) Case 1	Case 2	Case 3
3 in. on 9 in. Mix A	10.9 (277)	10.8 (274)	9.3 (236)
3 in. on 9 in. Mix B	9.8 (249)	9.7 (246)	7.8 (198)
3 in. on 9 in. Mix C	7.5 (191)	7.5 (191)	5.4 (137)

where Case 1 - Represents the material properties of the surface concrete at the road test--a very strong paving concrete.

Table 1. Verification of stress values for two-layer pavement computed from M-ℓ curves for one-layer pavement.

Subgrade Modulus, pci	Layer Thickness, in.		Stress, psi* 100% Interact. Bottom Layer		0% Interact. Bottom Layer		0% Interact. Top Layer	
	h_1	h_2	(1)	(2)	(1)	(2)	(1)	(2)
100	2	4	326	326	492	492	984	985
		6	214	214	347	348	463	464
		8	154	154	246	246	246	246
	4	4	206	205	189	189	754	756
		6	155	154	207	207	551	551
		8	120	119	186	185	371	370
	6	4	136	135	80	79	478	476
		6	114	114	105	105	422	420
		8	94	94	115	115	346	345
300	2	4	261	262	385	378	770	756
		6	174	174	277	277	369	369
		8	126	126	198	199	198	199
	4	4	167	167	151	151	604	605
		6	127	126	166	167	444	445
		8	98	98	150	151	301	302
	6	4	111	111	65	65	387	388
		6	93	93	86	86	343	343
		8	77	77	94	94	282	282

* (1) Stress determined from 1-layer system as described in text.
(2) Stress computed by 2-layer finite element program.

18 kip single-axle load, 20' joint spacing.

$E_1 = 5 \times 10^6$, $E_2 = 1.25 \times 10^6$ psi.

1 in. = 25.4 mm, 1 psi = 6.8 kPa, 100 pci = 27.1 N/cm^3

Table 2. Parameters for computing stresses in monolithic pavements (100% slab interaction).

	Inches		E_2 = 1.20x10^6 psi			E_2 = 1.87x10^6 psi			E_2 = 2.50x10^6 psi			E_2 = 3.11x10^6 psi		
	h_1	h_2	I	$\bar{y}$	B	I	$\bar{y}$	B	I	$\bar{y}$	B	I	$\bar{y}$	B
E_1 = 4 x 10^6 psi	3	6	18.6	0.442	0.771	30.4	-0.216	1.578	40.5	-0.710	2.398	48.9	-1.073	3.190
		8	33.8	-0.100	0.943	55.4	-0.976	1.921	73.5	-1.585	2.911	88.8	-2.012	3.877
		10	55.9	-0.704	1.116	91.0	-1.779	2.258	120.3	-2.483	3.416	145.6	-2.961	4.558
		12	85.8	-1.355	1.287	138.6	-2.609	2.589	183.0	-3.394	3.916	222.1	-3.916	5.235
	4	6	26.0	1.063	0.855	41.7	0.420	1.752	55.6	-0.102	2.671	67.2	-0.506	3.557
		8	44.0	0.589	1.028	72.0	-0.287	2.104	95.9	-0.946	3.198	115.9	-1.430	4.254
		10	69.7	0.056	1.199	114.3	-1.042	2.449	151.8	-1.819	3.712	183.3	-2.368	4.942
		12	104.1	-0.527	1.373	170.1	-1.832	2.787	225.3	-2.710	4.219	272.3	-3.314	5.624
	5	8	56.7	1.217	1.112	91.6	0.354	2.279	122.0	-0.335	3.473	147.6	-0.861	4.622
		10	86.0	0.736	1.285	140.7	-0.359	2.630	187.3	-1.183	3.997	226.4	-1.788	5.317
		12	124.8	0.208	1.458	204.7	-1.110	2.975	272.0	-2.053	4.512	328.6	-2.724	6.006
		14	174.2	-0.361	1.630	285.3	-1.890	3.315	378.1	-2.939	5.022	456.9	-3.668	6.690
	6	10	105.3	1.368	1.369	170.8	0.286	2.806	227.5	-0.569	4.274	275.2	-1.218	5.687
		12	148.5	0.883	1.542	243.1	-0.431	3.156	323.7	-1.419	4.796	391.2	-2.145	6.381
		14	203.2	0.359	1.714	333.4	-1.179	3.502	443.1	-2.288	5.312	535.3	-3.081	7.070
		16	270.4	-0.200	1.887	443.3	-1.953	3.843	587.9	-3.171	5.823	710.4	-4.024	7.755
	7	10	128.4	1.969	1.452	205.1	0.904	2.977	272.9	0.027	4.530	330.3	-0.656	6.049
		12	176.0	1.519	1.626	285.9	0.217	3.331	381.0	-0.804	5.073	460.8	-1.574	6.750
		14	235.8	1.030	1.799	386.1	-0.503	3.682	514.0	-1.656	5.596	621.2	-2.503	7.445
		16	309.1	0.509	1.972	507.1	-1.249	4.028	674.1	-2.524	6.112	814.5	-3.438	8.134
	8	10	155.6	2.549	1.535	244.3	1.501	3.145	324.0	0.610	4.808	392.1	-0.102	6.408
		12	207.8	2.126	1.709	333.7	0.841	3.504	444.4	-0.204	5.343	537.7	-1.011	7.115
		14	272.8	1.668	1.883	443.9	0.147	3.858	591.5	-1.040	5.873	715.2	-1.931	7.814
		16	352.1	1.178	2.056	576.3	-0.574	4.208	767.3	-1.893	6.395	927.3	-2.860	8.508
E_1 = 5 x 10^6 psi	3	6	15.6	0.625	0.617	26.0	0.026	1.292	35.2	-0.456	1.996	43.1	-0.826	2.680
		8	28.2	0.160	0.756	47.5	-0.664	1.577	64.1	-1.279	2.423	78.2	-1.727	3.249
		10	46.7	-0.367	0.894	78.1	-1.407	1.854	104.9	-2.135	2.840	127.9	-2.647	3.809
		12	71.8	-0.945	1.032	119.1	-2.186	2.127	159.4	-3.013	3.250	194.5	-3.580	4.362
	4	6	22.1	1.232	0.684	35.8	0.663	1.432	48.4	0.171	2.221	59.3	-0.228	2.989
		8	37.0	0.833	0.823	61.6	0.035	1.723	83.5	-0.608	2.661	102.1	-1.101	3.573
		10	58.2	0.377	0.961	97.9	-0.648	2.008	132.3	-1.426	3.089	161.6	-2.000	4.144
		12	86.9	-0.128	1.100	145.9	-1.373	2.288	196.5	-2.272	3.510	239.7	-2.913	4.707
	5	8	48.1	1.446	0.890	79.8	0.647	1.920	106.3	0.023	2.883	130.2	-0.501	3.884
		10	72.2	1.041	1.028	120.4	0.044	2.153	163.2	-0.760	3.326	199.7	-1.377	4.467
		12	104.4	0.590	1.167	175.3	-0.635	2.440	237.1	-1.575	3.756	289.7	-2.273	5.038
		14	145.5	0.099	1.305	244.5	-1.349	2.721	329.8	-2.413	4.178	402.4	-3.183	5.603
	6	10	89.2	1.659	1.096	146.3	0.691	2.295	198.1	-0.125	3.552	242.7	-0.774	4.779
		12	124.8	1.249	1.234	208.0	0.052	2.584	282.0	-0.912	3.992	345.0	-1.652	5.360
		14	170.1	0.802	1.373	285.4	-0.623	2.871	386.2	-1.725	4.422	472.0	-2.547	5.933
		16	225.9	0.320	1.511	379.7	-1.329	3.153	512.7	-2.558	4.846	625.8	-3.454	6.499
	7	10	109.8	2.247	1.163	176.1	1.308	2.432	237.6	0.486	3.774	291.2	-0.186	5.082
		12	148.9	1.870	1.301	244.8	0.703	2.726	331.7	-0.275	4.220	406.4	-1.048	5.673
		14	198.2	1.457	1.440	330.3	0.061	3.015	447.8	-1.064	4.657	547.9	-1.927	6.253
		16	258.8	1.012	1.578	434.0	-0.612	3.303	587.6	-1.875	5.088	718.2	-2.821	6.827
	8	10	134.4	2.816	1.229	210.5	1.902	2.567	282.4	1.079	3.989	345.6	0.389	5.381
		12	177.1	2.464	1.368	286.3	1.326	2.864	386.9	0.341	4.441	474.1	-0.457	5.979
		14	230.6	2.080	1.507	380.0	0.714	3.158	515.0	-0.426	4.885	630.8	-1.322	6.567
		16	295.9	1.666	1.646	493.0	0.070	3.444	668.4	-1.216	5.322	817.9	-2.203	7.147

Negative value of $\bar{y}$ indicates bottom of top slab is in compression

1 in. = 25.4mm, 1.0x10^6 psi = 6.9 GPa

Table 3. Parameters for computing stresses in non-monolithic pavements (50% slab interaction).

Inches		E_2 = 1.20x10^6 psi			E_2 = 1.87x10^6 psi			E_2 = 2.50x10^6 psi			E_2 = 3.11x10^6 psi		
h_1	h_2	I	$\bar{y}$	B	I	$\bar{y}$	B	I	$\bar{y}$	B	I	$\bar{y}$	B
$E_1 = \overline{4}$ x 10^6 psi													
7	4	39.1	3.141	0.849	47.0	2.882	1.596	54.5	2.641	2.364	61.4	2.422	3.121
	5	44.3	3.023	0.942	55.7	2.690	1.780	66.5	2.388	2.640	76.3	2.123	3.482
8	4	55.2	3.652	0.916	64.6	3.398	1.717	73.7	3.157	2.542	82.2	2.936	3.358
	5	61.1	3.540	1.010	74.7	3.214	1.903	87.6	2.911	2.820	99.4	2.641	3.722
	6	68.3	3.420	1.103	87.0	3.018	2.087	104.4	2.655	3.095	120.2	2.340	4.081
9	4	75.5	4.162	0.982	86.6	3.912	1.836	97.5	3.671	2.719	107.7	3.447	3.594
	5	82.1	4.054	1.078	98.0	3.732	2.024	113.3	3.430	3.000	127.3	3.156	3.960
	6	90.2	3.939	1.171	111.8	3.543	2.210	132.2	3.180	3.276	150.8	2.859	4.322
10	4	100.5	4.669	1.048	113.5	4.422	1.956	126.2	4.182	2.894	138.4	3.957	3.829
	5	107.9	4.566	1.144	126.3	4.248	2.146	144.0	3.946	3.177	160.6	3.670	4.197
	6	116.8	4.454	1.239	141.6	4.064	2.333	165.2	3.701	3.456	186.9	3.376	4.562
11	5	138.8	5.075	1.211	159.9	4.761	2.266	180.4	4.460	3.354	199.7	4.181	4.433
	6	148.7	4.968	1.307	176.9	4.582	2.454	203.9	4.220	3.635	229.0	3.890	4.800
	7	160.3	4.853	1.401	196.8	4.395	2.640	231.3	3.971	3.913	262.9	3.594	5.163
12	6	186.4	5.479	1.373	218.2	5.098	2.575	248.9	4.736	3.813	277.5	4.403	5.037
	7	199.1	5.368	1.468	240.0	4.915	2.762	279.0	4.491	4.092	314.9	4.110	5.401
	8	213.7	5.252	1.562	265.0	4.724	2.947	313.4	4.240	4.368	357.4	3.812	5.763
14	6	281.0	6.497	1.506	320.7	6.123	2.814	359.5	5.762	4.166	396.0	5.426	5.508
	8	313.1	6.282	1.697	375.8	5.765	3.191	435.7	5.281	4.728	491.0	4.844	6.241
	10	354.1	6.046	1.884	445.9	5.381	3.561	532.1	4.776	5.279	610.2	4.247	6.963
16	6	404.8	7.511	1.637	453.2	7.143	3.052	500.9	6.784	4.517	546.5	6.444	5.977
	8	441.8	7.305	1.831	517.2	6.797	3.433	590.0	6.314	5.084	657.8	5.871	6.716
	10	488.6	7.081	2.020	597.4	6.427	3.807	700.7	5.822	5.641	795.2	5.282	7.443
$E_1 = \overline{5}$ x 10^6 psi													
7	4	37.1	3.209	0.683	43.7	2.992	1.296	50.1	2.783	1.938	56.2	2.588	2.582
	5	41.3	3.112	0.758	50.9	2.830	1.447	60.3	2.564	2.169	69.0	2.323	2.889
8	4	52.8	3.719	0.737	60.6	3.507	1.392	68.4	3.300	2.081	75.8	3.104	2.773
	5	57.6	3.627	0.813	68.9	3.352	1.546	80.1	3.088	2.315	90.5	2.845	3.083
	6	63.5	3.527	0.888	79.2	3.186	1.698	94.3	2.866	2.545	108.4	2.577	3.388
9	4	72.7	4.226	0.790	81.9	4.019	1.488	91.1	3.814	2.223	100.0	3.618	2.963
	5	78.0	4.139	0.867	91.3	3.869	1.644	104.3	3.608	2.458	116.7	3.364	3.276
	6	84.6	4.044	0.943	102.7	3.710	1.797	120.3	3.392	2.691	136.9	3.101	3.583
10	4	97.2	4.733	0.843	107.9	4.529	1.584	118.7	4.325	2.363	129.2	4.129	3.152
	5	103.2	4.648	0.921	118.4	4.384	1.740	133.6	4.125	2.601	148.1	3.880	3.467
	6	110.4	4.557	0.997	131.1	4.230	1.895	151.4	3.914	2.835	170.6	3.622	3.777
11	5	133.5	5.156	0.974	150.9	4.896	1.837	168.3	4.639	2.743	185.1	4.394	3.657
	6	141.5	5.069	1.051	165.0	4.746	1.992	188.1	4.433	2.979	210.1	4.140	3.969
	7	151.0	4.975	1.128	181.4	4.589	2.145	211.2	4.219	3.212	239.2	3.879	4.277
12	6	178.3	5.578	1.105	204.7	5.261	2.089	230.8	4.950	3.121	255.9	4.656	4.160
	7	188.6	5.487	1.182	222.7	5.107	2.243	256.2	4.740	3.356	287.8	4.399	4.470
	8	200.5	5.392	1.257	243.4	4.947	2.396	285.3	4.523	3.588	324.4	4.135	4.778
14	6	271.0	6.593	1.211	303.8	6.284	2.280	336.6	5.977	3.404	368.3	5.683	4.540
	8	297.0	6.418	1.366	349.3	5.984	2.591	400.7	5.566	3.876	449.4	5.175	5.164
	10	330.4	6.224	1.517	407.5	5.660	2.896	482.2	5.128	4.339	551.8	4.646	5.777
16	6	392.5	7.605	1.317	432.4	7.302	2.471	472.6	6.998	3.685	511.8	6.704	4.916
	8	422.6	7.437	1.473	485.1	7.014	2.785	547.2	6.600	4.162	606.5	6.208	5.547
	10	460.7	7.254	1.626	551.6	6.704	3.093	640.5	6.176	4.629	724.2	5.690	6.166

1 in. = 25.4mm, 1.0x10^6 psi = 6.9 GPa

Case 2 - Represents more typical values for paving concrete: E_1 = 4 x 10^6 psi (30 GPa) and MR = 650 psi (4.5 MPa).

Case 3 - Represents the same conditions as Case 2 except the values are computed by conventional linear theory.

These composite pavements, opened to traffic in March 1978, have carried approximately 2 million equivalent 18-kip (80 kN) single-axle loads. The condition of all the sections is excellent. Based on design procedures in current practice (AASHTO or PCA) it is indicated that the composite sections are at least equivalent to, and perhaps better than for Mix C, the thicknesses shown for Cases 1 and 2.

Case 3 for conventional linear elastic theory is listed to demonstrate that closer agreement to performance data is obtained by the non-linear elastic approach (Cases 1 and 2) suggested in this report.

More time and load repetitions on the Florida sections should reveal more detailed comparisons and show the effect of the three different qualities of lean concrete.

Design for Aircraft or Other Vehicles

Thickness requirements of composite pavements for vehicles other than highway trucks may be determined as described in the following example.

Assume that a composite design is required for a Boeing 767 aircraft for which it has been determined that a 12-in. (305 mm) thickness (h_e) of normal concrete is adequate. The assumptions are:

Boeing 767 maximum gear load = 143,000 lb (65 Mg).
Foundation support, k = 300 pci (81 N/cm^3)
Concrete modulus of rupture, MR = 650 psi (4.5 MPa)
Flexural stress for stated conditions, S = 347 psi (2.4 MPa)

The first step is to determine the M-ℓ relationship for the aircraft loading. The results, determined from a Boeing 767 design chart (19), are shown in Fig. 13.

The next step is to determine the modulus of rupture (MR_2) and modulus of elasticity (E_2) of the lean concrete to be used. For the example assume these values are close to:

MR_2 = 250 psi (1.7 MPa)
E_2 = 1.9 x 10^6 psi (13 GPa)

In this procedure the allowable stress ratio in the composite slabs must not exceed the stress ratio for the normal 12-in. slab assumed above. This stress ratio is 347/650 or 0.533. Therefore, the allowable stresses in the composite slabs are:

Top layer, S_1 = 0.533 x 650 = 347 psi (2.39 MPa)
Bottom layer, S_2 = 0.533 x 250 = 133 psi (0.92 MPa)

Trial sections of composite pavements are then selected and stresses are computed from the parameters listed in Table 2 or 3. Calculations are illustrated in Table 4 for a monolithic slab where the results indicate either a 5 in. on 12 in. section or a 6 in. on 11 in. (127 on 305 mm or 152 on 279 mm) section.

Figure 13. M-ℓ relationships for Boeing 767 aircraft.

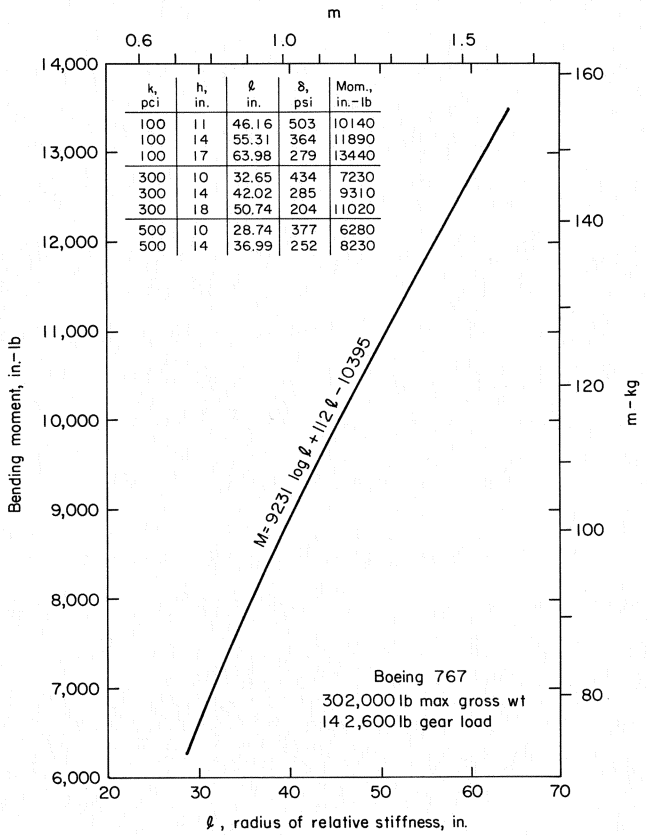


Table 4. Calculations used in composite pavement design for a Boeing 767 aircraft.

Layer Thickness, in.		Values from Table 2			ℓ, in. (computed from I)	M, in.-lb (from Fig. 13)	Stress, psi	
h_1	h_2	I	$\bar{Y}$	B			S_1	S_2
5	10	140.7	-0.359	2.630	37.22	8273	-21	155
5	12	204.7	-1.110	2.975	40.88	9059	-49	132
6	10	170.8	0.286	2.806	39.07	8675	15	143
6	12	243.1	-0.431	3.156	42.67	9432	-17	122

E_1 = 4 x 10^6 psi (28 GPa), E_2 = 1.87 x 10^6 psi (13 GPa), 1 inch = 25.4 mm.

Summary

Due to the recent increasing use of lean concrete in pavements there is a need to develop rational approaches to the structural design of such pavements.

This report reviews structural design concepts and material properties of cement-bound materials and suggests preliminary design procedures for pavement structures with lean concrete lower courses used as: (1) a subbase course under a normal concrete pavement, and (2) a lower layer in a composite (monolithic) pavement.

The design procedure indicates a thickness of a two-layer pavement equivalent to a given thickness of normal concrete. It assumes that the latter has been determined by an established design procedure (PCA, AASHTO, or other), or by experience that recognizes the appropriate design factors such as the magnitudes and numbers of truck loads, concrete properties, and subgrade-subbase strength. Analysis of flexural stresses serves as a way of incorporating the strength and elastic properties of the materials and the layer thicknesses into the design.

Logical modifications of conventional theory and material properties are suggested so that design results are reasonably consistent with experimental test results, properties of materials with low cement contents, and the performance data available. It is recognized that research and performance data are very limited so the procedure must be considered as a first-generation guide.

A method is given that is applicable to a range of design problems extending one-layer analysis to a two-layer analysis by a relatively simple process. It applies to any load position desired--load at pavement edge, pavement joint, or interior of slab.

The design charts presented are for conventional truck loadings; however, data are given that can be used to design for other types of loads--aircraft and special heavy vehicles.

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