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PROGRESS REPORT OF SUBCOMMITTEE ON METHODS OF MEASURING STRENGTH OF SUBGRADE SOIL—REVIEW OF METHODS OF DESIGN OF FLEXIBLE PAVEMENTS

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SYNOPSIS

A review of 22 methods of design of flexible pavements is presented and the particular type of test advocated for the measurement of the strength of the subgrade is noted for each method

A large number of the methods specify a plate bearing test for the subgrade test, several advocate a triaxial compression or some type of shear test, in two a penetration test is used Two of the methods merely give the range of support values for use with certain types of soils and in some of the methods the means of strength determination is not specified It would be desirable to know the exact manner in which a subgrade soil acts in supporting wheel loads so that a strength test could be selected which would measure the property of the soil which is most effective in this support

The condition of the soil, particularly as to moisture content, advocated at that time of testing is also noted for the various methods This item is not strictly a part of the test procedure, but since it has such an important effect on the results, its consideration is deemed worthwhile Only a relatively few of the methods specify the test condition exactly, but several advocate a consideration of surrounding conditions to guide its selection

To ascertain the different methods of measuring the strength of the subgrade for use in the design of flexible pavements, a review has been made of a number of the methods of designing such pavements It is not the intent here to present the complete derivations and explanations of the many methods of design It is merely intended to explain the methods to an extent sufficient to portray the means of determining the subgrade support The design formulas in which the strength factors are substituted are presented, in-so-far as possible, so that the importance of variations in this factor may be visualized

The order of presentation of the methods is largely chronological The terminology is not necessarily that of the original, since it has been attempted to unify it as nearly as possible A glossary of terms used in the formulas is included

It is probable that some methods have been omitted, since many agencies may be using methods or formulas which are their own development and have not been published. Certain others may have been published but have escaped the authors' attention. The number of methods given below should be sufficient however to give a general cross-section of the type of tests used in measuring subgrade strengths.

The Massachusetts Rule

The first published method of calculating the thickness of flexible pavements is the so-called Massachusetts Rule given in the 1901 Report of the Massachusetts Highway Commission (1) [1] A statement of this report reads: "On a road built of fragments of broken stone, the downward pressure takes a line at an angle of 45 deg from the horizontal, and is distributed over an area equal to the square of twice the depth of the broken

[1] Numbers in parentheses refer to the list of references at the end of the paper.

stone." Algebraically this would be written

$$t = 5\sqrt{\frac{P}{q}}$$

in which t = thickness of pavement, in
P = wheel load, lb.
q = bearing strength of subgrade, psi

The range in supportabilities of soils was given (non-porous soils, drained of ground water, at their worst, about 4 psi and sand and gravel, 20 psi) but the method of determination was not mentioned

Lelievre and Pons

Lelievre and Pons, in a paper at the 1913 International Road Congress in London presented a method of calculating the stresses transmitted through a macadam surface to the subgrade soil (2) Their deductions, rearranged to the form of equations for thickness, are

For surface courses

$$t = 0.45\sqrt{\frac{P}{q}} - 0.4b$$

For base courses

$$t = 0.75\sqrt{\frac{P}{q}} - 0.67b$$

in which t = thickness, in
P = wheel load, lb
q = bearing strength of subgrade, psi
b = diameter of loaded area, in

No means of determining the bearing value of the soil are given. They do mention the differences, however, in firm ground, compressible subsoils, and very bad ground, noting the loads which can be supported and the necessary thicknesses of stone

Harger and Bonney

The Harger and Bonney formula for depth of macadam is given in their 1927 Handbook (3) and is of the form

$$t = \sqrt{\frac{P}{3q} + \frac{w^2}{9}} - \frac{w}{3}$$

in which t = thickness of pavement, in.
P = wheel load, lb.
q = bearing strength of subgrade, psi
w = width of tire, in.

It is based on an assumption of a 45-deg. angle of distribution of a load applied on a length w equal to the width of tire A uniform pressure distribution is assumed on the subgrade The authors give a table of recommended safe supporting power of subgrade soils for different textural grades of soil for use in the formula, the values vary from a low of 4 to 8 psi for fine sands and heavy clay to 25 to 30 psi for coarse sand and fine gravel

Downs

W S Downs (4), Professor of Railway and Highway Engineering at West Virginia University, proposed in 1933 the following equation for the thickness of flexible pavements

$$t = \sqrt{\frac{P}{\pi q}} = 0.564\sqrt{\frac{P}{q}}$$

in which t = thickness of pavement, in
P = wheel load, lb
q = the safe bearing power of the subgrade, psi

This equation is based on a point loading and an angle of distribution of the load through the pavement of 45 deg The formula is offered as a determination of relative thicknesses required for different wheel loads and no consideration is given to the determination of the bearing power of the subgrade

Gray

B E Gray suggested a formula in 1934 of the same general form as Downs but considered the load distributed on a circular area of radius, a (5) The equation is of the form

$$t = 0.564\sqrt{\frac{P}{q}} - a$$

Terms other than the radius, a, in inches, are identical to those of Downs' formula

No mention is made of how the subgrade bearing value should be determined.

Hawthorn

Prof G. E Hawthorn has developed formulas for the thickness of flexible pavements based on the wheel load, area of wheel contact, shearing angles in the surfacing, and the supporting strength of the subgrade (6). The design is rather involved and consists of solution of simultaneous equations for t, the thickness. One equation is an expression of the pressure transmitted to the subgrade, the other the bearing value of the subgrade The first is

$$q = \frac{P}{(t \tan \theta + a)^2}$$

and the second, too involved for presentation here, may be written

$$q = f\,(t, D_p, D_s, \phi, c)$$

in which t = thickness of pavement, in
q = bearing strength of subgrade; also stress transmitted to subgrade, psi
θ = angle of load distribution.
a = radius of loaded area, in.
ϕ = angle of internal friction of subgrade
c = cohesion.
D_p = density of pavement, lb. per cu ft
D_s = density of subgrade, lb per cu ft.

Solution of the two equations is most easily accomplished by plotting curves of q vs. t and obtaining an intersection

The expression for the subgrade support is theoretical and is based on the resistance of the soil to sliding according to its angle of internal friction and cohesion. A laboratory shear test is advocated for the determination of these two items

Housel

Prof W S Housel of the University of Michigan presented in 1937 a formula of design on cohesive soils in which the vertical resistance of the pavement to punching shear is considered in calculating the stress on the subgrade and the supporting power of the subgrade is evaluated in terms of its ultimate shearing resistance (7) The design equation is

$$t = \frac{(p - 4m_2)b}{4m_1} + \frac{m_2 b}{p}$$

in which t = thickness of pavement, in
p = load applied, psi, assumed equal to inflation pressure of tire
b = diameter of contact area, in.
m_1 = shearing resistance of surface, psi.
m_2 = shearing resistance of subgrade, psi.

The supporting value of the subgrade in this equation is $4m_2$, m_2 being the ultimate shearing resistance of the subgrade.

Goldbeck

The method of design advanced in 1938 by A. T Goldbeck of the National Crushed Stone Association considers an elliptical contact area of load and also dual tire loadings (8) (9) The simplified equation for single truck tires is

$$t = \sqrt{\frac{2P}{\pi q}} - \frac{3L_2}{2}$$

in which t = thickness of nonrigid pavement required, in
P = maximum wheel load, lb.
L_2 = $\frac{1}{2}$ minor axis of ellipse of tire contact area, in.
q = subgrade supporting value, psi.

For dual tires, the formula is

$$t = \sqrt{\left(\frac{B}{2\pi}\right)^2 + H} - \frac{B}{2\pi}$$

in which t = thickness of nonrigid pavement required, in.
B = $2S + (L_1 + L_2)$
H = $\frac{2P}{q} - \frac{2SL_1}{\pi} - L_1L_2$
P = maximum wheel load supported on dual tires, lb.
q = subgrade supporting value, psi
L_1 = $\frac{1}{2}$ major axis of ellipse of tire contact area, in
L_2 = $\frac{1}{2}$ minor axis of ellipse of tire contact area, in.
S = center to center spacing of tires, in

The subgrade supporting value is determined by a laboratory plate bearing test using a 100-sq in round plate The bearing capacity is taken as the unit load at the point of $\frac{1}{2}$-in indentation or at a lesser indentation determined at the point at which the ratio of pressure increase to indentation increase is equal to 100

Palmer and Barber

In 1940, E S Barber presented in a discussion of a paper by himself and L A Palmer a design formula making use of triaxial compression test data and taking into consideration the deflection permissible in the subgrade soil (10). The formula may be written

$$t = \frac{a}{\sqrt[3]{C_p/C_s}} \sqrt{(p/q)^2 - 1}$$

in which t = thickness of pavement, in

a = radius of circular loaded area, in.

C_p and C_s = stress-strain moduli of the pavement and subgrade, psi.

p = average pressure on loaded area, psi.

q = allowable bearing pressure on subgrade, psi. $= \frac{C_s d_s}{1.5a}$

d_s = allowable displacement of subgrade, in.

The moduli C_p and C_s are determined by the triaxial compression test.

A design method making use of this formula has been used by the Kansas Highway Department (11) The modulus of the subgrade soil is taken as the average of those in two tests with different lateral pressures, the stress range for which the modulus is selected is dependent upon the wheel load and the depth to the soil. A permissible deflection of 0 1 in is used for design purposes

Barber

Mr Barber, in another article, has presented a design method basing the required thickness on the permissible shear in the subgrade (12). A design chart is given from which the thickness may be determined when the unit load, the radius of the loaded area, and the cohesion and angle of internal friction are known. The later two items are determined by a triaxial compression test

Hubbard and Field

In 1940 Prevost Hubbard and Frederick C. Field of the Asphalt Institute presented a series of curves giving the required thickness of asphaltic concrete for given unit wheel load pressures for subgrade ratings varying from 15 to 70 psi (13). The subgrade rating is determined by a plate bearing test using a plate of the same size as that of the design load and is the load sustained for a deflection of ½ in The design curves were based on a series of laboratory tests on soils and various thicknesses of asphaltic pavements placed on the soils, in which tests it was noted that the pavements were able to withstand a deflection of 0 5 in with no evidence of failure, irrespective of variations in size of the bearing plate.

The method of determining the subgrade bearing power is described

Spangler

Prof M G Spangler of Iowa State College presented in 1942 a formula for design of flexible pavements based on an equating of the safe allowable deflection to the theoretical maximum deflection of the subgrade for an empirical expression of the pressures transmitted through the pavement (14). The equation is of the form:

$$d_p = \frac{0\ 9P\sqrt{\frac{F}{t}}}{C_s}$$

in which d_p = safe allowable deflection of pavement, in

P = wheel load, lb

t = pavement thickness, in

C_s = the modulus of compressions of the subgrade soil, psi.

F = the "subgrade stress factor" $= \frac{0070 + 0000068\, C_s}{\sqrt[3]{P/1000}}$

Solution for t requires an expression for the safe allowable deflection, d_p, which is a function of the pavement thickness Spangler discusses means of determining this item.

The strength of the subgrade is provided for by the modulus, C_s. Spangler recommends that the value be determined by laboratory triaxial compression tests or by such field tests as the California bearing ratio or North Dakota cone tests The latter two would require correlation work which has not been done as yet. A method of determining C_s by measuring deflections of a pavement under an actual wheel load is also suggested.

W. H. Campen and J. R. Smith

W. H. Campen and J. R. Smith of the Omaha Testing Laboratories presented in 1942 a design method based on determination of the strength imparting characteristics of superimposed subbase or base materials as determined by plate bearing tests (15). The bearing value of the subgrade is that load which a rigid plate of the specified size will sustain at $\frac{1}{2}$-in. deformation. Tests are also made with at least 6 in. of selected subbase or base material in place on the subgrade. The increase in bearing strength per inch of material is calculated from the results and a computation made of the necessary thicknesses to sustain the design loading.

North Dakota Cone

Keith Boyd presented in 1942 a design curve for pavement thickness according to the bearing value of the subgrade as determined by a cone penetration apparatus, commonly called the North Dakota cone (16). The curve can be expressed by the formula

$$t = \frac{65.7}{q^{0.388}}$$

in which t = total base and mat thickness, in.
q = cone bearing value, psi

The curve was determined by testing both good and failed areas in the road, plotting the thicknesses versus bearing value with designation of the point as good or failed, and drawing the curve to separate the two types of points.

Highway Research Board Committee on Flexible Design

A method of designing the thickness of runway pavements was presented in a Report of the Committee on Flexible Pavement Design, A. C. Benkelman, Chairman, in 1943 (17). The method is based on large-scale loading tests of trial pavement sections.

Three sections of pavement are constructed on a prepared subgrade. One is of a thickness estimated by any desired method, the second is 50 per cent greater and the third 30 per cent less. Tests are made by repetitional loading with a rigid bearing plate. The results are analyzed by a method similar to that advocated by Mr. Prevost Hubbard (18) taking into consideration the number of load applications to be expected on different pavements on an airport and deducting the settlement under initial load from the total to minimize the effects of unequal construction compaction. A net settlement value of 0.2 in. is used to determine the safe loading, except that the total deflection must not exceed 0.5 in. The thickness required to support the design load is obtained by plotting the thicknesses of the trial sections against the recorded deflections.

Vokac

Roland Vokac of the Berry Asphalt Company has developed design formulas based on a method in which the confining influence of the asphaltic surface is considered (19). The geometry of the pressure bulb is used in the derivation of the equations.

The fundamental equations may be written in the form

$$t_b = \frac{b}{4}\,\frac{(p - q)}{\sqrt{pq}}$$

and

$$t_s = \frac{\dfrac{p - P_s}{4m_3R}}{b}$$

in which t_b = thickness of base course, in.
b = diameter of bearing or contact area, in.
p = average unit stress on bearing area or tire inflation pressure, psi
q = bearing strength of subgrade, psi.
t_s = thickness of asphalt surface, in.
$P_s = \dfrac{(p+q)^2}{4p}$, required minimum bearing strength of base course, psi
m_3 = shear strength of asphalt surface, psi

$$R = \frac{1}{1 - \sqrt{\dfrac{q}{p}}}$$

It is advocated that the bearing strength of the subgrade be determined by rigid plate bearing tests, at deflections of about 0.1 to 0.2 in.

U S Navy Department, Bureau of Yards and Docks

A trial section method of determining flexible pavement thickness is outlined by the U S. Navy Department, Bureau of Yards and Docks, in Manual No 1, revised, dated June 1943 (20). The procedure is to construct a base of the estimated correct thickness and then incrementally load a circular rigid plate to the design load. The basis for design is a 0 2 in. deflection. If this value is not reached or exceeded by the first section an estimate is made for another one by the formula

$$d = \frac{pa}{C} G$$

in which d = pavement deflection, in
p = contact pressure, psi.
a = radius of contact area, in
C = modulus of vertical deformation, psi
G = settlement factor (dependent upon t, the pavement thickness and a) This value is read with a curve

C is calculated by the formula with the data of the first test. A new settlement factor, G, is then determined with this value of C and a deflection of 0 2 in ; the thickness is determined from a curve of G and t/a values. A second trial section is then built and loaded as before If the deflection for the design load varies too much from 0 2 in a third section may be necessary, using an average value of C.

Klinger

E. W. Klinger, on the basis of experimental work of Hubbard and Field, advocated the following equation for flexible pavement design (21) (22).

$$t = K_2 \sqrt{\frac{p}{q} - 1}$$

in which t = thickness, in
p = applied load, psi
q = subgrade support, psi
K_2 = constant for type of pavement

Neither Mr McLeod, in the original discussion of the formula, nor Mr. Klinger, in a later presentation, discuss the determination of q

California Bearing Ratio Method

The California bearing ratio method of flexible base design, originally developed by the California Department of Highways, has been adopted with modifications by the U. S. Engineer Department (23). The method is an empirical one, the ability of the subgrade to support loads is expressed by a soil bearing value determined in a laboratory test and expressed as a ratio to a standard value By field correlation, thicknesses of pavement required for different wheel loads were determined for the soil bearing ratios The U S Engineer Department extrapolated the curves up to wheel load values of 75,000 lb.

In application, the bearing ratio is determined for the subgrade soil and base materials and the required thickness taken from the design curve for the specified wheel load Areas subject to vibrations of slow moving or warming up planes, such as aprons and taxiways, are designed for wheel loads 25 per cent greater than the static load. For areas used only infrequently, the thickness is selected as 80 per cent of that given by the design curves

The bearing test is made either on laboratory prepared specimens or cores from the field which have been soaked, top and bottom, for 4 days and permitted to drain for 15 minutes

Glossop and Golder

R Glossop and H Q Golder presented a method of design of pavements on clay soils before the Institution of Civil Engineers in London in 1944 (24) The method is based on the criterion that the maximum pressure transmitted to the subgrade through the pavement (calculated by Boussinesq equations) must not exceed π times the shear strength of the subgrade

The shear strength of the subgrade is determined by unconfined compression tests made on samples taken immediately ahead of construction.

V R Smith

A method of design using a theoretical curve giving the required depth of pavement according to the radius of loaded area required to reduce the stress in the subgrade to a permissible value as determined by triaxial

TABLE 1

SUMMARY OF FORMULAS AND METHODS OF DESIGN OF FLEXIBLE PAVEMENTS

Name of Formula or Method	Basic Equation or Procedure	Type of Test to Determine Bearing Strength of Soil
Massachusetts Rule	$t = 0.5\sqrt{\frac{P}{q}}$	Not specified.
Lelievre and Pons	For surface courses $t = 0.45\sqrt{\frac{P}{q}} - 0.4b$ For base courses. $t = 0.75\sqrt{\frac{P}{q}} - 0.67b$	Not specified
Harger and Bonney	$t = \sqrt{\frac{P}{3q} + \frac{w^2}{9}} - \frac{w}{3}$	Recommended values given for soils of various textures
Downs	$t = 0.564\sqrt{\frac{P}{q}}$	Not specified
Gray	$t = 0.564\sqrt{\frac{P}{q}} - a$	Not specified
Hawthorn	$q = \frac{P}{(t \tan \theta + a)^2}$ $q = f(t, D_p, D_s, \phi, c)$	Shear test to determine φ and c
Housel	$t = \frac{(p - 4m_2)b}{4m_1} + \frac{m_2 b}{p}$	Shear test
Goldbeck	For single tires $t = \sqrt{\frac{2P}{\pi q}} - \frac{3L_2}{2}$ For dual tires $t = \sqrt{\left(\frac{B}{2\pi}\right)^2 + H} - \frac{B}{2\pi}$	Plate bearing test Load at ½ in indentation or at point at which ratio of pressure increase to indentation increase = 100
Palmer and Barber	$t = \frac{a}{\sqrt[3]{C_p/C_s}}\sqrt{\left(\frac{P}{q}\right)^2 - 1}$	Triaxial test
Barber	Design curves Unit load, radius of loaded area, and cohesion and angle of internal friction of subgrade soil required.	Triaxial test
Hubbard and Field	Design curves Unit load and subgrade rating required.	Plate bearing test Load at ½ in deflection
Spangler	$d_p = \frac{0.9P\sqrt{\frac{F}{t}}}{C_s}$	Triaxial test or other tests
Campen and Smith	Series of computations Bearing strength of subgrade, of 6 in sub-base in place, and/or of 6 in of base in place required	Plate bearing tests. Load at ½-in deflection
North Dakota Cone	Design curve Cone bearing value required	Bearing test with cone penetration apparatus
Committee on Flexible Pavement Design	Trial section method	Plate bearing tests. Load for 0.2 in. net deflection at required number of load applications
Vokac	$t_b = \frac{b}{4}\frac{(p - q)}{\sqrt{pq}}$ $t_s = \frac{P - p_s}{\frac{4m_2R}{b}}$	Plate bearing tests Load at 0.1 to 0.2 in. deflection
Navy	Trial section method	Plate bearing tests. Load at 0.2-in deflection
Klinger	$t = K_1\sqrt{\frac{p}{q} - 1}$	Not specified
C B R. Method	Design curves Bearing ratio and wheel load required	Bearing ratio tests
Glossop and Golder	Design curves Shear strength and total load required	Unconfined compression test on undisturbed sample
Smith	Design curves Radius of loaded area and principal stress difference of soil required	Triaxial test
Civil Aeronautics Administration	Design curves Soil class and load required	Classification tests, including grading, Atteberg constants, capillary rise, and California bearing ratio

testing was advanced by V R Smith of the Standard Oil Co of California in 1944 (25) The triaxial tests are made on soils which have been saturated by application of a head of water.

Civil Aeronautics Administration

The Civil Aeronautics Administration has prepared a series of design charts giving the required thicknesses of subbase, base, and surface for gross plane loads and for different classifications of material (26) A classification method has been set up giving the soil group according to sand, silt, and clay content; liquid limit, plastic limit, and volume change; and capillary rise and California bearing ratio The thickness classification is also based on frost and drainage conditions.

This method of design is direct and requires only those tests sufficient to determine the soil classification.

Table 1 is a brief summary of the various methods. This table indicates that plate bearing tests are the most common type of test advocated for determining the strength of the subgrade Some type of shear test is also advocated in several of the methods. In Table 2 an attempt has been made to group the tests

The Spangler and Vokac methods could be listed in either the Plate Bearing Test or the Shear Test column as they did not strictly advocate any particular test procedure The North Dakota cone and the California bearing ratio tests are both, in a sense, shear tests. The California test is a measure of the shear resistance of a soil at a relatively low strain

Plate bearing tests are probably favored because of their previous use in the design of foundations for buildings and other structures. Also, the method is direct in that the test is usually made on an area similar to that through which the wheel load is applied, and corresponds in a sense to the action of the wheel load on the soil. Such items as rigidity of the plate, static loading, and incremental increases in load are phases of the procedure which differ from the actual loading in service but which are dictated for reasons of simplicity of testing.

One of the main objections to the use of plate bearing tests is the amount of equipment required, the load reaction necessary, particularly for large size plates, and the time required in testing Also, it is difficult to adjust the soil condition to that desired.

The use of such tests as direct shear and triaxial compression is an indirect method of determining the bearing strength of the subgrade; the results of such tests are substituted in theoretical or semi-empirical expressions for the supporting power of the soil. Such tests are advantageous in that they can be closely controlled and the effect of variations in such items as moisture content can be readily demonstrated The equipment required for such tests is not as massive as for plate bearing tests, although the set-up for such tests as the triaxial compression test is rather intricate.

In advocating any particular type of test for the measurement of the bearing strength of a soil one point which should be kept in mind is "How does the soil act when loaded and what property of the soil will portray its supportability?" The actual alterations in a soil under load are important We know that when a wheel load is applied deformations occur, these may consist of consolidation, elastic deformation, and plastic deformation. We must decide which of these movements we are interested in, and then decide how to determine the soils resistance to such strains.

It would be helpful if we could specify for soil bearing strength tests just what property of the soil is measured The various plate bearing tests listed in Table 1, for example, may not constitute measurements of the

TABLE 2

None Specified	Plate Bearing Test	Shear, Triaxial or Similar Test	Penetration Test	Values Given for Class of Soil
Mass Rule Lebevre & Pons Downs Gray Klinger	Goldbeck Hubbard & Field Campen & Smith Com Flex Pave Vokac Navy	Hawthorn Housel Palmer & Barber Barber Spangler Glossop & Golder	N Dak Cone C B R	Harger & Bonney C A A

same property. In a plate test, it would seem that for small deformations a high proportion of the movement might be consolidation of the soil under the plate, as the total deformation becomes greater, elastic deformation and also plastic deformation may occur in greater amounts. The separation of deformation due to plastic flow from simple vertical consolidation is difficult but such separation would aid in the interpretation of results. Plastic flow constitutes a shear action in the soil and plate bearing tests carried to this extent are in a sense a form of shear test.

In the various shear tests the strain at which the shear is measured is an important item. Whether to consider the shear strength of the soil at low strains or the ultimate value depends upon what assumption is made as to the soil action under the wheel load. It may be that the possibility of failures in the base courses or surface course may limit the permissible strain in the subgrade soil.

Although it may not necessarily be a part of the design method, in the application of any method the condition of the soil at the time of the test must be selected Table 3 indicates the conditions specified in some of the test procedures.

The Hubbard and Field, North Dakota cone, and Navy methods, although they are listed as "Condition Not Specified," would probably be run on the soil as it exists in the field.

The criterion of design for the C. B R. test, as used by the Office of Chief of Engineers, is that the samples shall be soaked, top and bottom, for 4 days and then permitted to drain for 15 min. before testing This may reduce the moisture content considerably in the lighter textured soils.

It may be that the condition of the soil at the time of test is something which must be determined independently for each location and hence is not a part of the bearing strength test. However, information as to what the general condition of the soil should be for either laboratory or field tests might be of help in the application of some strength tests.

This review of methods of design of flexible pavements has indicated a wide variety of types of tests for measuring the strength of subgrade soils. Not only is there a variety of methods, but for any one method there is a variety of procedures and interpretation of results. For example, in plate bearing tests there is little agreement on method of loading or the penetration for which a significant result is obtained

It is hoped that this review may emphasize the need of analysis of the mechanics of the support of wheel loads by flexible pavements and that in the design of such pavements consideration be made of what property of the subgrade is desired to be measured and a test selected which will yield this information

TABLE 3

Condition of Soil Not Specified	Condition Not Specified but Consideration of Climate Advocated	Condition to be "worst anticipated" or "as it will exist"	Soaked, Saturated or Nearly Saturated	Condition As it Exists at Construction
Mass Rule	Harger & Bonney	Goldbeck	C B R[a]	Glossop & Golder
Lelievre & Pons	Barber	Spangler	Smith	
Downs	C A A	Campen & Smith	Kansas adoption of Palmer and Barber	
Gray		Com Flex Pave		
Housel		Vokac		
Palmer & Barber				
Klinger				
Hubbard & Field				
North Dakota Cone				
Navy				

[a] 15 min. drainage after soaking

GLOSSARY OF TERMS USED IN FORMULAS AND METHODS OF DESIGN OF FLEXIBLE PAVEMENTS

t = total thickness of flexible pavement, in

t_s = thickness of asphaltic surface, in

t_b = thickness of base, in.

P = total load, lb

p = unit load, psi

a = radius of loaded area, in

b = diameter of loaded area, in

L_1 = ½ major axis of elliptical loaded area, in (Goldbeck)

L_2 = ½ minor axis of elliptical loaded area, in (Goldbeck)
w = width of tire, in. (Harger and Bonney)
S = center to center spacing of dual tires, in
q = bearing strength of subgrade, psi
ϕ = angle of internal friction of subgrade
c = cohesion of subgrade, psi
θ = angle of load distribution
m_1 = shear strength of base, psi (Housel)
m_2 = shear strength of subgrade, psi
m_3 = shear strength of asphaltic surface, psi (Vokac)
C_p = stress strain modulus of pavement, psi
C_s = stress strain modulus of subgrade, psi
F = subgrade stress factor (Spangler)
G = settlement factor (Navy)
d_p = allowable displacement in pavement, in
d_s = allowable displacement in subgrade, in
D_p = density of pavement, lb per cu ft
D_s = density of subgrade, lb per cu ft

The following factors are defined according to terms in the preceding tabulation.

$$B = 2S + (L_1 + L_2) \quad \text{(Goldbeck)}$$

$$H = \frac{2p}{\pi q} - \frac{2SL_1}{\pi} - L_1L_2 \quad \text{(Goldbeck)}$$

$$R = \frac{1}{1 - \sqrt{q/p}} = \text{load reaction coefficient (Vokac)}$$

$$p_s = \frac{(p+q)^2}{4p} = \text{average stress on base, also bearing strength of base (Vokac)}$$

$$F = \frac{.0070 + .0000068C_s}{\sqrt[3]{P/1000}} \quad \text{(Spangler)}$$

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COMMITTEE ON FLEXIBLE PAVEMENT DESIGN

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REPORT OF SUBCOMMITTEE ON METHODS OF SUBGRADE, SUBBASE, AND BASE PREPARATION FOR STRENGTH

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SYNOPSIS

Strength as used in this report is the resistance of compacted soil mixtures to plastic flow or consolidation and their ability to distribute load The report reviews methods for selecting, proportioning and mixing, control of water, compacting, making field control tests and preparing subgrade

The reviews led to the following conclusions and recommendations.

1. More soil surveys and their use to better advantage are needed
2 Mechanical mixing is recommended.
3 Equipment for compaction in one pass and for direct compaction of sandy soil is needed.
4 Drainage should receive more attention
5. Greater subgrade density and thickness should be required
6 In specifying density more attention should be given to strength of mixture
7 Laboratory tests for correlation with field tests of density are needed
8 Contracting and inspecting personnel should know more about basic principles of soil compaction
9. Attention should be given to possibility of frost damage.

The assignment of the subcommittee is: "Examination of all the present methods of construction procedure by means of which the inherent values of soils of any type may be developed to the greatest degree, with the view of making some recommendations in regard thereto and also indicating need of new types of equipment if any"

It is recognized that soil mixtures can be rendered more or less stable by a process of densification. The degree of stability can be measured by the resistance of the compacted