TEXAS TRANSPORTATION INSTITUTE

TEXAS HIGHWAY DEPARTMENT

COOPERATIVE RESEARCH

Bases for Flexible Pavements
2-8-54-1

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

BIBLIOGRAPHY No. 188

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Bases for Flexible Pavements

1. Moody, K. G., "Flexible pavements for roads," J--Instn of Eng. Australia 35: n 10-11, pp 279-291, Oct-Nov 1963.

In this paper the criteria for design of flexible pavements, and the methods of evaluating the subgrade, the effects of traffic, pavement materials, and the composition of the pavement are discussed in relation to conditions and experience in Victoria. Some aspects into which research seems desirable are noted.

It is considered that the following are the major points established:
The criterion for pavement design must be varied to suit the conditions. An elastic pavement structure is desirable for fixed level construction of major metropolitan highways, but in rural roads the aim of the designer should be for an appropriate standard for serviceability at a given age, this standard varying with conditions. Studies of the changes of serviceability of pavements in time in relation to the controlling factors may well reduce the uncertaintities which are inherent in pavement design and permit substantial savings.

The condition of subgrades under pavements is extremely variable and subject to many influences, and generalization in respect to this condition is not feasible. The major requirements is an adequate investigation of any site, and judgement and experience in interpretation of the facts so obtained, but there is little possibility of real precision in estimating the condition of a subgrade for design purposes. Studies of the properties of subgrades under pavements would be of value in indicating the order of precision feasible in estimating future subgrade strength, and the appropriate strength for design purposes.

Pavements for rural roads in Victoria have been built with a wide variety of materials, the quality required being a function of the traffic, enviromental and climatic conditions, and the standard of serviceability required. Successful use of many materials involves the proper application of the appropriate principles. The study of the properties of materials in relation to conditions of service would be of considerable value.

In fixed level construction only good quality materials should be used, and careful attention should be paid to compaction. The establishment of suitable allowance for treated materials will require considerable study and research, relative to materials used in British and American full-scale trials, before published information can be adopted.

2. Aldous, W. M., R. C. Herner and M. H. Price, "Load transmission test for flexible paving and base courses," U. S. Civil Aeronautics Administration --Tech Development Report n 144, June, 1951 34 p.

Project was initiated for purpose of supplying factual data on dissipation and distribution of concentrated loads through flexible paving materials; summary of test; results on about 250 specimens of gravel, crushed stone, crushed slag and sand.

3. Herner, Raymond C., "Load transmission tests on flexible paving and base courses, " Nat'l Research Council--Highway Research Board Abstracts 27: n 11, December 1957, p 45.

The load transmission apparatus provides a means of conducting load tests on full-scale pavement sections under laboratory conditions. A segmented loading platform supported by coil springs is substituted for the natural subgrade to insure constant test conditions over long periods, and to permit quick and accurate measurement of vertical stresses transmitted through the pavement. For a given applied load, the maximum stress on the subgrade provides a convenient means of comparing the efficiencies of various pavement sections or evaluating the effects of various design variables.

The relationship of subgrade stress to applied load should vary with pavement thickness, contact area, and respective strengths (or stiffness) of the pavement and subgrade. An analysis of 814 loading tests on 123 pavement sections varifies the essential correctness of theoretical studies and provides numberical values for use in design or for further study. These values are given in chart form, and represent a generalization of all pertinent test data. They may be used directly in a method of pavement thickness design based on limiting subgrade stress or deflection, or to extend empirical designs into areas not adequately covered by service experience.

The triaxial test was used to compare strengths of the various materials (gravel, clay-gravel, sand, limestone, slag, and asphaltic concrete) used in the pavement sections. Although further correlation studies are in considered adequate for design purposes. The validity of the test test data for use in highway pavement design will be checked by correlation with results of traffic tests on the AASHO Test Road.

4. Whiffin, A. C., "Load-spreading properties of dense tarmacadam and rolled asphalt base-courses," Roads & Road Construction 40: n 476, Aug1962, pp 222-5.

Tests and measurements by Road Research Laboratory to investigate to what extent various modifications in coated macadam give increased dynamic elastic modulus; modified tarmacadam basecourse mixtures intended for use as base-course under rolled asphalt and dense-tar waring courses; details of experimental road sections constructed to compare load spreading properties of asphalt and tarmacadam base-courses.

5. Spielmann, P. E., "Mechanical testing of bituminous road materials," Roads & Road Construction 11: n 132, Dec. 1, 1933 pp 383-4. Quarry & Roadmaking 39: n 447, Jan 1934, pp 6-14.

Abstracts of several papers read before Public Works, Roads and Transport Congress, held in London in 1933: Laboratory tests and their Correlation with Full Scale Road Experiments, R. G. C. Batson; Some Factors involved in Mechanical Testing of Bituminous Mixtures, A. G. Adam and D. G. Murdock; Mechanical Testing of Bituminous Road Mixtures, P. Hubbard; Critical Examination of Bituminous Road Materials, E. Neumann; Mechanical

Testing of Asphalt, D. M. Wilson; Mechanical Tests and Modern Highway, D. C. Broome and A. R. Thomas.

6. E. Prandi, Investigation on Cracking of Gravel-Sand Mixtures Treated With Granulated Slag, Bulletin de Liaison des Laboratories Routieres (58 Lefebvre, Paris XV^{e}), No. 15, pp. 5-5 - 5-8, Sept-Oct 1965. (In French).

   Cracks caused by thermal contraction appear during cold periods on roadways built with gravel-sand mixtures treated with granulated slags. The occurrence of this damage depends on the ratio between the tensile strength and the value of Young's modulus. The paper describes the approach to the ratio: critical examination of the method used at the beginning which was based on the measurement of both properties, followed by calculation of the ratio. A new measuring method, more closely related to actual conditions, is described.

7. S. R. Mehra, R. K. Ghosh, and L. R. Chadda. Consideration of Bamboo-Reinforced Soil-Cement as Material for Construction with Special Reference to its use in Pavements, Civil Engineering and Public Works Review (8 Buckingham St., London, W. C. 2, England), Vol. 60, No. 711, pp. 1457-1461, Oct. 1965; No. 712, pp. 1643-1645, Nov. 1965; No. 713, pp 1766-1768, Dec. 1965.

   A theory was suggested for design of bamboo-reinforced soil-cement beams based on ultimated load theory and bond failure. This was in good accord with the test results. With suitable modifications, this theory could be extended to beams of different support conditions and slab. It was further shown that elastic theory was not suitable for the design. Tests results showed that the safe design load might be increased by about four times for a bamboo-reinforced soil-cement structure over that obtained by elastic analysis.

   Bamboo-reinforced soil-cement base under thin concrete pavement surfacing was likely to effect a saving of about 30 percent over normal plain cement concrete pavement.

   Laboratory tests on a full size slab designed for 9,000-lb wheel load indicated that ultimate load-carrying capacities in this type of construction for both corner and edge loadings were considerably higher (65 percent higher in corner failure and 335 percent higher in edge failure) than the design load. This reserve strength would adequately cater for any temperature and subgrade restraint stresses occurring in the pavement.

8. Kaare Flaate and Nils Rygg, Light Concrete Scrap as a Road Base, State Road Laboratories (Oslo, Norway), Bull. 16, pp 6-13, 1964. (In Norweigan)

   The ground conditions encountered in Norway are frequently such that even relatively small road embankments create both stability and settlement problems. In this respect, soft clayey grounds and peat bogs represent the most difficult sites for road construction. One method of

increasing the stability of road embankments is to decrease the actual load of the embankment on the underlying ground. Such a procedure also helps to minimize settlement effects. For the above reasons, different types of light fill materials have been investigated, i.e., materials having a unit weight less than 1.1 t/m^3 after being placed and compacted. In particular, materials such as peat, sawdust, bark, slag, cellular concrete in the form of scrap aggregate, and expanded clay both in the loose state and in precast units of LECA concrete have been tried.

The different types of light fill materials are described by listing their advantages and disadvantages. A number of cases where cellular concrete and expanded clay have been used are described in detail. The object of using light fill materials in these cases has been to increase the stability of the embankments. To decrease further the load on the ground, LECA concrete has been employed in some cases as a lightweight road base with an asphalt pavement on top. A light road base, however, is not to be recommended if it can be avoided, because important factors in connection with the actual design of such bases are still unknown. The applicability of light fill materials in road construction depends to a great extent on sufficient supply at a low cost. This combination is sometimes difficult to obtain.

9. J. E. Gray and J. E. Bell, Stone Sand, National Crushed Stone Association (1415 Elliot Pl. N. W., Washington, D. C. 20007), Eng. Bull. No. 13, 1964, 70 pp.

Since the publication of the original edition of this bulletin in 1936 the use of stone sand has increased to become commonly accepted in areas where it can compete on an economic basis with natural sand. Much of the data, information, and conclusions have been summarized and retained. However, much new data have been developed in the intervening period. Air entrainment has become a standard practice. Stone sand has found acceptance for use in masonary mortar, and the production of concrete block using stone sand has grown into an industry of tremendous proportions. Problems of slipperiness, involving certain sands used in pavements subjected to highspeed high-density traffic, have developed and have been solved largely through research conducted in the Association's Laboratory. Pumping of concrete mixtures into otherwise almost inaccessible places has become commonplace, and recently completed research in this field at the National Crushed Stone Association has led to the development of apparatus for evaluating the pumpability of concrete mixes in the laboratory. New data have been presented on the thermal and chemical properties of different types of aggregates and new specifications are now in force. The Association has developed a method of test for particle shape of sand and the acceptance and use of this test method has insured better workability for concrete mixes. Data concerning these and other development are presented in summary form to provide the basis for a more enlightened use of stone sand.

10. W. Gad, Possibilities of Utilization of Flue Dust in Bituminous Road Construction, Bitumen, Teere (Strassenbau Chemie u. Technik, Verlag-agesellschaft GmbH, Box 1508, Heidelberg 17a, Germany), 1964, 15, 363-372. Journal of Applied Chemistry, Vol. 15, No. 2, p. i-114, Feb.1965.

Coal flue dust from a power plant, from a foundry, and from brown coal, flue dust (K) from a power plant, cement flue dust and $Ca(OH)_2$ were examined. Physical and chemical properties were determined, and the effect of the fillers in bituminous or tar mineral mixtures was investigated. To give the same working-up properties, a greater binder proportion is necessary when K or $Ca(OH)_2$ rather than the other fillers are used. Intergranular space content is reduced by the fillers. Use of the fillers increases stability. All the results are fully tabulated.

11. C.S.I.R. Research Review, Sulphite Lye for Gravel Roads, South African Council for Scientific and Industrial Research, (P. O. Box 395, Pretoria, South Africa), Vol. 12, No. 2, pp 38-40, June 1962.

To test the performance of roads treated with sulphite lye several full-scale field experiments have been undertaken by the National Inst. for Road Research. These experiments include trials on four miles of road near Natal, a two-mile length north of Pretoria and about 0.4 mi at Zebediela in the Northern Transvaal. Two different techniques have been employed, viz, a surface spray only and a mixed-in-place stabilization of the upper 3-4 in. layer of soil, followed by compaction. Further experiments are planned in Natal and the Kruger National Park.

The experiments conducted so far have yielded much valuable information. The binding, waterproofing and cementing effects of sulphite lye have been clearly demonstrated. On the other hand, it has been found, for instance, that particle size distribution of the gravel must be within limits that make the gravel stable in itself. Failing this, considerably larger amounts of sulphite lye have to be added. This problem is closely tied up with the leaching out of lye , as it is readily soluble in water. During heavy rains some lye is inevitably washed out. Gravels of correct particle size distribution and plasticity will, however, offer greater resistance of leaching out than gravels not complying with these requirements.

Laboratory tests and the field experiments were conducted concurrently. It has been shown that the dry strength of the soil is increased by the addition of sulphite lye. Furthermore, addition of sulphite lye reduces the optimum moisture content required for compaction and brings about an increase in the maximum dry density obtained, both effects being beneficial in road construction.

Sulphite lye, having a pH in the range 2-3 has been found to be corrosive to steel under certain conditions, and simple methods for the protection of tankers used for distribution of sulphite lye are therefore, being investigated.

In general, it may be said that the correct use of sulphite lye for treatment of gravel roads offers potential benefits through greater economy in the maintenance of these roads by road authority, and safer and more comfortable travel by the general public.

12. P. J. Beaven. Coral and Other Soft Limestones in Road Building, Gt. Brit. Road Research Laboratory (British Information Services, 45 Rockerfeller Plaza, New York 20, N.Y.), Overseas Bull. No. 15, 1962. 28 pp.

A Review has been made of references to the use and physical properties of the calcareous materials found in tropical areas. They have been classified under four headings: coral and material derived from it; concretionary calcareous material such as jigilin and caliche; granular material: calcareous sands which may be cemented to form rocks; and shell deposits.

Experience has shown that these calcareous materials make good bases for roads and high CBR values can be obtained both in laboratory and field tests. Calcareous gravels compact readily and it is usual to use sheepsfoot or grid rollers for initial compactions.

Gravels have been used as aggregates in both cement and asphaltic concrete but because of the variability of the materials, it is well worth the effort of finding the best aggregate.

The specific gravity test is useful in distinguishing between good and bad aggregates; the best material has a specific gravity approaching 2.7, but an aggregate with a lower specific gravity, not less than 2.2, may be used for some purposes. Examples of mix design for coral concrete and the strengths obtained are given in the Bulletin; coral concrete often has to be made using sea-water and this has been found to be satisfactory even for reinforced concrete.

The majority of the limestones discussed are too soft to be used to surface dressing except under light traffic, but they have been widely and successfully used in the manufacture of bituminous pre-mixes for use both as bases and as surfacings.

The use of calcareous materials, which are of a low grade compared with the usual rocks used in road construction, can considerably affect the economics in areas where the cost of quarrying is high or where alternative aggregates or stabilizers would have to be imported.

13. Frank E. Diebold, John Lemish and Carl L. Hiltrop. Determination of Clacite, Dolomite, Quartz and Clay Content of Carbonate Rocks. Journal of Sedimentary Petrology (P. O. Box 979, Tulsa, Okla.), Vol. 33, No. 1 pp. 124-139, March 1963.

The need for quantitative analysis of the major mineral constituents in carbonate rocks resulted from studies of carbonate aggregates used in highway concrete.

Three quantitative X-ray methods for calcite and dolomite are investigated. The first, a comparatively simple X-ray method, determines the relative percent of the carbonate fraction that is calcite and dolomite by measuring the intensity ratios of the largest diffraction maxima of the respective minerals. The sample preparation and X-ray procedures were changed and the altered method experimentally shown to be reliable. The second, a combination of chemical and X-ray procedures, involves the X-ray determination of the structrual formulas of calcite and dolomite and an EDTA titration procedure for determining the proportion of calcium and magnesium ions in the sample. Two sources of error were found: (1) non-carbonate minerals in the sample liberating "extra" calcium and magnesium ions during the EDTA titration procedure, and (2) incorrect structural formulas of dolomite due to inaccurate X-ray calibration curve. The third method, an internal standard technique was established and calibration curves with confidence belts constructed.

Two methods for determining the clay mineral fraction are discussed. One involves clay size separation and X-ray procedures, the other is simply a subtraction of the previously determined carbonate and quartz fractions from the total rock sample.

Two techniques employed in determining the structural formulas of the carbonate minerals were investigated. Both are X-ray procedures and involve measuring the variation of the lattice spacings in the crystal structure as related to compositional changes.

Four procedures are recommended at the present time: the internal standard; the subtraction; the clay separation-S-ray; and the corrected Harker and Tuttle methods. These are considered the most applicable to the four respective probelm areas-the quantitative determination of calcite, dolomite, and quartz; the quantitative and the qualitative evaluation of the clay mineral fraction; and the composition of the carbonate minerals calcite and dolomite.

14. A. Dvorak and P. Peter, Field Tests on Soils and Rocks, Proc. 5th Int. Conf. on Soil Mech. & Found. Eng., Paris, Vol. 1, pp. 453-460,1961, (Available from Stechert-Hafner, 31 E. 10th St., New York, N. Y.).

The authors put forward a theory of non-linear and semi-infinite solids based on the results of field loading tests. They give values of plastic and elastic properties applicable to certain typical rocks and soils. Their theory has been confirmed by the direct measurement of surface displacement near the loaded area.

They discuss the influence of shear tests undertaken with blocks of reinforced concrete on rocks, and they analyze the results of shear tests in coarse grained soils using a steel frame. They consider the effect of grain size, correlation with laboratory tests and decrease of shear strength as a result of repeated shear tests.

They also refer to the use of radioactive isotopes for measuring the subterranean flow of water through soils, giving equations for the loss of activity from various causes. They explain differences in absorption of soils, referring to some problems of field measurement techniques.

15. L. H. Robinson, Jr. The Effect of Pore and Confining Pressure on the Failure Process in Sedimentary Rock. In Third Symposium on Rock Mechanic: Colorado School of Mines, Quarterly (Golden, Colo.), Vol. 54, No. 3, pp 177-199. July 1959, GeoScience Abstracts, Vol. 1, No. 12, pp. 52, Dec. 1959.

Results of the investigation of the effects of pore and confining pressure on the failure characteristics of sedimentary rocks are summarized in the following conclusions:

1. Common sedimentary rocks will undergo either malleable or brittle failure, depending upon the difference which exists between confining pressure and internal pore pressure.
2. Although shales, limestone, and sandstone have inherently different strengths, it was observed (a) that brittle failure always occurs when the confining and pore pressure were equal, and (b) that the mode of failure changes gradually from brittle to malleable as the differential between the confining and pore pressures increases the transition pressure depending on the nature of the rock and the pressure level.
3. The yield strengths of rocks increase only slightly as the confining pressure increases if the confining and pore pressures are maintained equal.

16. D. R. Gilley, The Use of Emulsified Asphalt in Base Stabilization and Surface Course Mixes, Roads and Engineering Construction (341 Church St., Toronto, Canada), Vol. 96, No. 5, pp. 116-118-120 1958. Road Abstracts, Vol. 26, No. 4, p 80, April 1959.

A general review is presented of the application of bitumen emulsion in surface course mixes and base stabilization. Mixture specifications and methods for stabilization of pit-run gravel, sands and soils according to design requirements are discussed. Reference is made to the modified Florida bearing value test and to stabilized and unstabilized soils test for determining the amount of bitumen emulsion required. The effect of water on colloidal soil particles is discussed and a remedy is suggested. The economic and functional advantages of bitumen emulsion in preparing cold mix from low-cost, local materials are considered.

17. Adkins, J. E., "Dynamic properties of resilient materials: constitutive equations," Roy Soc of London -- Philosophical Trans Series A 250: n 985, 31 July 1958, pp 519-541.

Constitutive equations are formulated for a class of resilient materials for which the stress distribution at any instant is assumed to depend both upon the deformation and upon the time rates of variation of the tensors defining it. Particular attention is given to aeolotropic bodies, the stress deformation relations for orthotropic and

transversely isotropic materials being put in forms whihh exhibit the symmetry properties of the material. In the discussion of symmetry properties, attention is confined to the case where the stress tensor is a polynominal function of two only of the kinematic tensors.

Convected co-ordinate systems are employed in the development of the theory, but the method of transormation of the equations to a fixed frame of reference is also given. The modifications which are required for materials exhibiting curvilinear aeolotropy are briefly indicated, and some discussion is included of the manner in which certain types of geometrical constraint can be accounted for in the stress-deformation relations.

18. Burmister, D. M., "The theory of stresses and displacements in layered systems and applications to the design of airport runways," HRB Proc. 23: 126-149, 1943.

In foundation and practicularly in airport design and construction, the engineer is dealing basically with layered soil deposits. The theory of stresses and displacements in a two-layer system was developed in accordance with the methods of the mathematical theory of elasticity and is presented in order to reveal some of the fundamental relations existing between the physical factors, which control the load-settlement relations, and in order to provide a practical method of analysis for the design of airport runways. The theory reveals the controlling influence of two important ratios on the loadsettlement characteristics of the "two-layer system," namely: (1) the ratio r/h_1 of the radius bearing area to the thickness of the reinforcing or pavement layers; and (2) the ratio E_2/E_1 of the modulus of the subgrade to that of the pavement. For practical design purposes, the theoretical results have been evaluated numericaly and expressed in Basic Influence Curves, giving values of the settlement coefficient F_w in terms of these basic ratios. The settlement coefficient if applied as a simple multiplying or correction factor to the familiar Boussinesq Equation for surface settlement at the center of a circular flexible bearing area. The practical design problem for airport runways involves the selection of suitable and economical types of pavement construction and the determination by means of the influence curves for the "two-layer system" of the thickness required to give adequate support to airplane wheel loads and reasonable length of service.

19. Dehlen, G. L., "Flexure and cracking of a road surfacing under wheel loads," Nat'l Research Council--Highway Research Board Abstracts, 31: n 11, Dec 1961, p 17 (also presented at HRB annual meeting, 1962).

Surface "crocodile" cracking, one of the various possible causes of failure of a road, is a result of excessive stresses due to flexing of the surfacing under wheel loads. This paper is concerned mainly with

the severity of flexure occurring in a road and those factors relating to both traffic and foundations which affect it. The work described was carried out mainly during the investigation of extensive failures of this type on a major road in South Africa.

Because cracking is a stress phenomenon, measurements of flexure should ideally be made by measuring the stresses in the surfacing. But stresses and even strains, are difficult to measure. An approximate indication of the stresses is given by the radius of curvature of the surfacing, and a less accurate indication by the deflection of the surfacing under the wheel load. If curvature or deflections are measured between the dual wheels of a truck, as is done with the Benkelman Beam, a further inaccuracy is introduced in that the curvatures and deflections in this position are less severe than those occurring directly beneath the tires as is evidenced by some field results presented. In measuring the radius of curvature of the surface between, and more recently, under the wheels, obtained by finding the circle of best fit to the deflection-distance plot at the point of maximum deflection. Some results presented indicate a definite relation between radius of curvature and the degree of cracking of the surfacing. The relation between deflection and condition is not as marked. Such relations would be expected to be affected by such factors as the stiffness, thickness, age, and tensile resistance of the surfacing, but it has not been possible to isolate their effects as yet.

Before discussing the influence of various factors on the severity of curvatures developed, the results of a study of the validity of applying elastic theory under these circumstances are presented. The most important finding was that actual deflections were more concentrated around the load, giving sharper curvatures than were indicated by theory. This, which means that elastic theory in its pure form is not reliable for anything more than approximate qualitative indications, is beleived to be due to the lack of tension-resisting properties in the crushed rock base and sand subbase.

It has been found, both from theory and field experiment, that although the maximum deflection under a wheel load is dependent to a large extent on the Young's moduli of the materials of the subgrade and lower layers, radius of curvature, and thus also the stress in the surfacing, is dependent mainly on the Young's moduli of the materials in the upper layers of construction, the base and subbase. Thus it appears that in the design of roads, when considering the aspect of prevention of flexure cracking, the major attention should be given to the quality of the materials of the base and subbase, rather than to the depth of cover to the subgrade, a slight shift in emphasis from conventional design. Further, it has been found that for the thin chip-and-spray and premix surfacings used in South Africa (less than 2 in) the bituminous surfacing has little effect on the curvatures developed. Thick (4 in) dense bituminous surfacings do, however, appear to have a considerable effect in reducing curvatures.

Both theory and experiment have indicated that while deflections are influenced considerably by wheel load and only slightly by tire pressure and only slightly on wheel load. Moreover, at given tire pressure severity of curvature decreases as wheel load increases (with increasing dimensions of the tire imprint). The fallacy of considering heavy wheel loads, as such, as being detrimental in causing flexure cracking is thus revealed, and attention should be changed to tire pressure or dimension of imprint.

An important requirement in the study of the severity of curvatures developed is a knowledge of the Young's moduli of typical subbase and base materials, as these are not directly related to their strengths. Little knowledge, however, exists on these moduli. Preliminary work in selecting a method of testing for Young's moduli in the laboratory is mentioned.

20. Ekse, Martin and Leon M. LaCross, "Model analysis of flexible pavement and subgrade stresses," AAPT Proc 26: 1957, pp 312-320.

Findings of the recently conducted WASHO Road Test at Malad, Idaho have pointed toward a need for further study and evaluation of such factors as the superiority of 4-inch paving mats over 2-inch mats; the benefits of paved shoulders; and various conditions of soil and climate upon the performance of flexible pavements. The Civil Engineering Department of the University of Washington is presently conducting a research porgram which will investigate these and other factors affecting flexible pavement design and construction, with the use of a scale model laboratory highway test track, using a linear scale ratio of about 1 to 3.

21. Goldbeck, A. T., J. E. Gray, and L. L. Ludlow, Jr., "A Laboratory Service Test for Pavement Materials," ASTM PROC 34: Pt. 2: 608-26; Discussion 627-34, 1934.

The need for a service test for pavement materials, which may be made conveniently and under controlled conditions of temperature, moisture, subgrade and traffic has become apparent. In the present paper, such a test is described. It consists of a 14-ft diameter circular track in which pavement section are laid and subject either to the action of roller or to pneumatic tire wheel which may be equipped with tire chains.

Several tests are described to indicate the usefullness of the testing device. One of the tests was made to give an indication of the relative inherent stability of aggregates of various gradations. Still another investigation involved a determination of the value of stone screenings when used as a "blanket layer" under macadam to prevent upward intrusion of a clay subgrade into the stone. A third test had to do with a study of the effect of percentage of bitumen on stability of road mix surfaces. The stabilizing effect of a top dressing of chips when used with open type bituminous mixtures is discussed. Still another and quite different problem had to do with a study of the resistance of aggregates to crushing under the roller and under traffic. Finally,

some preliminary tests of cold lay bituminous mixtures are discussed. These problems, which are quite diverse in nature, serve to illustrate the versatility of the testing device.

22. Hank and Scrivner, "Some numerical solutions of stresses in two and three layered systems," HRB Proc 28: 457-468, 1948.

From Burmister's theory of stress in elastic, layered systems, equations for stress are developed for a point at the first interface on the axis of a circular loaded area. Numerical results are given for various degrees of relative stiffness of the layers comprising two- and three-layered systems.

The case of the frictionless interface in two-layered systems and the case of perfect continuity at the interface in some typical two- and three-layered systems, are treated.

Laboratory measured strengths of three soil-cement mixes and two flexible base materials are compared with stress computed from the two-layer theory for a typical condition of loading, and the corresponding required depths of base are arrived at by a graphical method based on the use of the Mohr's rupture envelope.

The three-layer theory is employed to study the effect of thin subbases under concrete slabs.

It is concluded that further computations from the theory should be made in conjunction with experimental work directed toward the measurement of stresses in layered systems, and the development of more accurate methods of testing our materials in tension.

23. Hargett, Emil R. and Emory E. Johnson, "Strength Properties of Bituminous Concrete Tested in Tension and Compression," Nat'l Research Council Highway Research Board Proc 40: 1961, pp 430-440.

The rapid increase in auto and truck transportation is forcing highway agencies to develop design and construction procedures that reflect high-quality porfessional engineering ability. For many years flexible pavements (bituminous pavements) provided the highway industry with a high-type surface at a low cost. This type of construction consists of a subbase, base course, and a bituminous surface. Such a surface will normally carry moderate traffic without adhering to rigid design and construction specifications. However, present traffic volumes and heavy wheel loads are focing highway engineers to develop sound design and construction procedures for each layer in order to prevent early deterioration of the entire pavement.

For this study, the layer of primary concern is the top layer or the bituminous surface. This surface is designed for the following functions:

1. Withstand contact wheel loads.
2. Protect the base, subbase, and subgrade from weathering elements.
3. Distribute the wheel load over an area larger than the contact area, thereby decreasing the intensity of stress in the base and subbase courses.
4. Provide a smooth riding surface with non-skid characteristics
5. Provide a surface for good visibility during night and daylight hours.

24. Long, R. W., "The role of the triaxial compression test in flexible pavement design," Thesis, M.D. in Civ Eng. Univ. of Washington, 1958.

A number of rational methods have been proposed for flexible pavement design but none have been widely accepted as design tools, although they have contributed to knowledge and serve to guide our thinking in respect to the problem. A major difficulty is that when the theory of elasticity is applied to a material such as soil, even though the approach may be rational, there is no assurance that the elastic coefficients are determinable, much less constant. Standard triaxial testing procedures, used to furnish the numerical values for the elastic coefficients, are purely empirical unless the triaxial test duplicates field conditions. Presented here is a comparison between standard triaxial tests of a uniformly graded clean quartz sand and triaxial tests on the same material in which the lateral pressure is varied, as we might expect it to vary in a subgrade that is being subjected to a surface load.

Two triaxle test series were programmed according to this concept; one, in which the lateral pressure was constant throughout the test (standard procedure), and the other in which the lateral pressure was increased uniformly from a relatively low value to the maximum value just before the point of ultimate failure. The shear strength and stress-strain characteristics are presented for both types of test and the differences are illustrated. A comparison of the states of stress on the plane of ultimate failure for both test types is made for conditions throughout tests.

Since the testing program considers the lateral pressure to vary as a function of strain, Boussinesq's stress equations are used to compute the lateral pressures that might develop if they are a function of the applied vertical load. In order that the stresses may be approximated, the soil is assumed to approach the state of a semi-infinite isotropic elastic solid that has a Poisson's ratio of 3/8. Stress conditions are predicted on this basis and the results are compared with those of the triaxial testing program.

Although quantitative results were not obtained in this investigation the indications are that stresses on the plane of ultimate failure are closer to the Coulomb failure envelop than is indicated by a standard triaxial test, particularly during the early stages of loading. This may explain road surface failures that occur at loads much lower than the design limit.

The results of this testing program also indicate that the standard triaxial tests, in which the lateral pressure is constant during the application of the load, do not, for granular materials, yield significant stress-strain relationships that can be rationally applied to flexible pavement design. When the triaxial test is programmed realistically, it will furnish accurate data for this use.

25. McLeod, Norman W., "Relationships between applied loads, surface deflections, traffic volumes and thicknesses of flexible pavements," Proc 5th Int Conf on Soil Mech & Found Eng. Paris Vol II, pp 277-281, 1961.

On the basis of the Canadian Department of Transport's load test data, a method for calculating the surface deflection of an existing flexible pavement under a loaded rigid bearing plate is described. When all other factors are equal, the surface deflection depends upon (a) the thickness of flexible pavement, and (b) the subgrade strength. For any specified traffic volume (less than unlimited) or a given design wheel load and tire inflation pressure, the permissible surface deflection when measured by means of a rigid bearing plate carrying the same total load and unit pressure, must be varied with the strength of the underlying subgrade. This implies that for flexible pavements not strong enough to carry unlimited traffic, a given Benkelman beam deflection under a specified wheel load does not indicate the same ability to carry traffic, if the strengths of the under lying subgrades are different.

26. McLeod, Norman W., "Some basic problems in flexible-pavement design," Nat'l Research Council--Highway Research Board Proc 32: 1953, pp 90-118.

With respect to the stresses applied by wheel loads to airport and highway surfaces, there are three basic problems of flexible pavement design: (1) sufficient thickness of base and surface must be placed over the subgrade to prevent failure within the subfrade; (2) the shearing strengths of the layers of flexible pavements close to the loaded area, i.e., of the base course and bituminous surface, must be high enough that failure along shear surfaces entirely within the base and surface will not occur; and (3) the possibility of failure of any one layer by squeezing out laterally under the applied lead must be studied, e.g., a poorly designed bituminous surface may be squeezed out between the tires of traffic and the base course.

During the past 10 or 12 yr. the first of these three problems has been intensively investigated, and various organizations believe they have developed satisfactory solutions, although there is still no universally adopted method. With the advent of tire pressures up to 300 psi. on jet aircraft, and the possibility that these inflation pressures may go higher, answers to the second and third problems have become important. A rational solution to the third problem, insofar as the stability of the bituminous pavement is concerned, has been described in previous papers. It is the principal objective of the present paper to

outline a rational approach to the solution of the second major problem--to the problem of avoiding failure along shear surfaces entirely within the base course and bituminous surfacing.

This rational approach is based upon the determination of the c and ϕ values for each layer of the flexible pavement by means of the triaxle test, and upon the assumption that the surfaces of shearing failure are logarithmic spirals. By trial and error, the position of the critical logarithmic spiral is located along with the shearing resistance of the materials will support the smallest ultimate applied load. The wheel load and tire pressure for which the flexible pavement is designed must not exceed this ultimate strength after it has been reduced by a suitable safety factor.

In essence, this method involves the determination of c and ϕ values for an equivalent homogenous material having the same ultimate strength as the layered system of the flexible pavement. The ultimate strength of this equivalent homogenous material is calculated on the basis of a logarithmic spiral failure surface.

27. Nijboer, L. W., "Mechanical properties of asphalt materials and structural design of asphalt roads, "Nat'l Research Council--Highway Research Board Proc 33: 1954, pp 185-200.

Numerous proposed rational approaches to bituminous road design contributed by previous investigators are reviewed. An effort is made to explain the various types and combinations of forces to which modern road pavements are subjected. The paper discusses the mechanical properties, and the test methods for the properties of materials entering into construction of the road carpets. The characteristics of asphalts and aggregates which affect both the elastic and plastic behavior of mixtures are discribed. Results of tests under short duration loadings contrasted with those derived from long duration loadings. Properties of the component materials affect the stiffness, breaking strength, resilience and fatigue behavior of the road carpet. Temperature of specimen was an important factor in these studies.

The paper takes up the problem of analyzing the properties and functions of base courses, subbases, and subsoil layers. In discussing the performances of these elements, distinction is made between conditions for equilibrium and the deformation phenomena. Here, again, are studied the relationship of stress and deformation under both short duration and long duration loadings.

The last part of the paper presents the design methods for road constructions. Designs for the entire layered system for static loads and the designs for only the road carpet for static loads are brought out in good detail. On the other hand, the design methods for dynamic loadings are still the subject of investigations that will be reported later.

28. "PRA to make field tests of nonrigid bituminous pavements," Roads & Streets 87: 66, Nov 1944.

The Public Roads Administration performed field tests on nonrigid bituminous pavements under loads ranging in magnitude from those of automobile and truck wheels to those developed by the wheels of some of the largest airplanes in use at that time.

Loads up to 80,000 lbs were transmitted to the pavement, base, and subgrade through bearing surfaces 6, 12, 18, 24, and 30 in. in diameter or equivalent area.

Results are not given, just preparatory planning and purposes are given.

29. Sanborn, J. L., "Stress & deflection in an elastic mass under semi-ellipsoidal loads," Joint Highway Research Project, Purdue University, n 13, May 1963, 38 pages.

A common problem in the design and evaluation of highway and airfield pavements is the estimation of theoretical stresses and deflections at points within the pavement due to applied wheel loads. Elastic stress distribution in a homogenous mass is generally used for such estimates, but its application in this field has been limited to assumptic of concentrated load or of uniformly distributed circular loads. Formal integration of the expression for stress and deflection for non-uniform loads is either impossible or impracticable.

This report describes the application of numerical integration, by means of a high speed digital computer, to the solution of elastic stress and deflection equationf for a semiellipsoidal load at the surface of a uniform, semi-infinite mass having a plane boundary. Normal stresses are computed by the Boussinesq equations, and the strain due to those stresses determined by accepted elastic theory. Integration is performed by Simpson's Rule. Three sets of curves representing stress and deflection on three planes normal to the surface are included. The curves were compiled from data developed, with the program described, on an IBM 7090 computer.

The actual program, in 7090 Fortran language, and an example of the use of the curves are appended to this report.

30. "The load transmission test for flexible paving and base courses, Part VI: Summary of tests with single-tire loading," Div Aeronautics Adm. Technical Development Center, Tech. Development Rept. No. 347, May 1958, 26 pages.

The load transmission apparatus provides a means of conducting load tests on full-scale pavement sections under laboratory conditions. A segmented loading platform supported by coil springs is submitted for the natural subgrade in order to insure constant test conditions over

long periods of time, and to permit quick and accurate measurement of vertical stresses transmitted through the pavement. For a given applied load, the maximum stress on the subgrade provides a convenient means of comparing the efficients of various pavements sections or evaluating the effects of various design variables.

The relationship of subgrade stress to applied load should vary with pavement thickness, with contact area, and with the respective strengths or stiffnesses, of the pavement and subgrade. An analysis of 804 loading tests on 123 pavement sections verifies the essential correctness of theoretical studies and porvides numerical values for use in design or for further study. These values are given in chart form, and represent a generalization of all pertinent test data. They may be used directly in a method of pavement thickness design based on a limiting subgrade stress or deflection, or they may be used to extend empirical design into areas not adequately covered by service experience.

The triaxial test is used to compare strengths of the various materials, gravel, clay-gravel, sand, limestone, slag, and asphaltic concrete, used in the pavement sections. Although further correlation studies are in progress, the method outlined in this and previous reports is considered adequate for design purposes. The validity of the test data for use in highway pavement design will be checked by correlation with results of traffic tests on the American Association of State Highway Officials Test Road.

31. Walker, Richard D., Eldon J. Yoder, and Walter T. Spencer, "Significance of layer deflection measurements," Nat'l Research Council--Highway Research Board Bul 321, 1962, pp 63-79.

An understanding of pavement behavior is essential to the development of an effective method of pavement design. To this end, a system for evaluating the structural performance of existing pavements is required. One system of evaluation and its effectiveness is described in this paper.

Data obtained from a test road located on US 31 near Columbus, Indiana, were used to develop the evaluation methods. Procedures such as the analysis of existing crack patterns and wheel track such as the analysis of existing crack patterns and wheel track rutting and their relationships to subgrade soil type were examined. Total surface deflections under load, measured with a Benkelman beam, were analyzed in an attempt to establish a relationship between deflection and cracking of the pavement surface.

Failure to establish total deflection as an indicator of the pavement behavior led to the development of a method using the Benkelman beam to measure deflections of the individual layers of the pavement structure. Four-inch holes were drilled to the interface of the different layers of the pavement, and the holes were cased with pipe. Steel rods were referenced at the bottom of each hole, extending upward to near the top of the pavement. Measurements were made under rear axle loads of 12,000, 18,000, 22,000 and 27,000 lb.

Relative modulus values using layer deflections were calculated to compare the relative deflection of one pavement layer with another. Theoretical stress distribution was used as a basis of the calculations.

The important conclusions reached by this study were that total deflections were ineffective in establishing the cause of the flexible pavement cracking and that knowledge of the individual layer deflections was required in order to evaluate the pavement fully.

32. Weissenberg K., "Specification of rheological phenomena by means of a rheogoniometer," Proc--International Rehological Congress, Holland, 1948, pII-114-118.

A new type of instrument, termed Rheogoniometer has been envisaged which in its ideal form would yield a complete specification of rheogoniometer a motor driven precision lathe with appropriate supplementary equipment. Various application are described, including the use of the rheogoniometer for a comprehensive testing of the mechanical properties of materials.

33. Werner, Robert R., "A study of Poisson's ratio and the elastic and plastic properties of Ottawa sand," Texas A & M Thesis, 1957.

Engineering achievements have paced the rise of civilization through the ages. Today the cries for greater strength, capacity and eoonmoy are heard with ever increasing frequency. Transportation and defense requirements have never lagged industry despite its tremendous growth and expansion. A simple example, yet of vital importance, is that of wheel loads. Two decades ago the maximum vehicle wheel load was 5000 pounds and airplane wheel load, 15,000 pounds. Today these have been increased to 20,000 and 60,000 pounds respectively. Pavement design has struggled to keep pace with these demands - to the extent where in a number of instances design is no longer both safe and economical. A rational approach to highway and airfield design that will accurately equate stresses to loads would appear to be needed.

The theory of elasticity has long been accepted and considered the basis of design where steel, concrete, and other engineering materials are employed. The application of this theory to designs involving soil masses has been sadly outdistanced by its use for structures above the earth's surface. The reticence of the profession to embrace the theory of elasticity for design may stem from two possible causes. Initially there may be doubt as to whether the material can truly be termed elastic. Further, there may be factors or elements required in intelligent employment of elastic theory upon which there is insufficient background. A search of literature makes it appear that this is so. The essential elastic constants, the modulus of elasticity and Poisson's ratio, of soil-like materials are either ignored or treated lightly by assumptions largely unsubstantiated by factual knowledge. With major emphasis on Poisson's ratio, it is the purpose of this thesis to explore this technological void.

34. Whiffin, A. C. and N. W. Lister, "The application of elastic theory to flexible pavements," Proc. Internat. Conf. Struct. Design Asphaltic Pavements, 1962, 499-521.

This paper, prepared at the Road Research Laboratory, Harmondsworth, describes a method of estimating by means of elastic theory the major stresses produced in a road by traffic, and shows that agreement has been achieved in certain circumstances between the measured and computed values of the dynamic stress in the subgrade. The method indicated that the higher the elastic modulus of the pavement the greater the reduction of this stress; the enchanced load-spreading however is accompanied by high tensile stresses in the lower layers of the pavement, are likely to crack under these stresses. Sufficient information on the elastic properties and stress-deformation and strength characteristic of road materials is now available to help in the analysis of road failures and for use in studies of pavement design.

35. Johnson, A. W., "WASHO and other current road tests," Road & Eng Construction 90: n 11, Nov 1952, pp 130-195-9.

Road tests, for study of effect of truck traffic on road bases and surfaces described; particular attention is given to tests now being carried out in Idaho under auspices of Western Assn of State Highway Officials with many co-operating agencies. Before Can Good Roads Assn.

36. Johnson, J. C., "Loading design for asphalt pavements," Pub Works 90: n 1, Jan 1959, pp 77-80, 172, 164, 176-7.

Economy requires use of locally available materials for lower course or layers and suitable design for anticipated conditions; consideration of density of vehicles and maximum single axle load; alternate designs should be made to enable consideration of various combinations of available materials; cost analysis of alternate designs; type and CBR value of subgrade soil determines required thickness of structure; use of two subbases, lower being "improved subgrade."

37. Pirie, J. E., "Pavimento de hormigon asfaltico sobre base de caliche (Asphaltic Concrete Pavement on Caliche Sub-base)," Ingenieria International 19: n 4, Apr 1931, p 172, 3 figs.

Spanish version of paper indexed in Engineering Index 1930, p 1528 from Eng. News-Rec. Nov. 6, 1930.