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TENSILE TESTING OF ROAD MATERIALS
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TENSILE TESTING OF ROAD MATERIALS

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Texas Transportation Institute

1. "New Method for Determining the Strength of Concrete" T. Gyengo, Acta Technica Academiae Sientiarum Hungaricae (Budapest 62, Hungary), V. 26, n 1-2 Highways and Bridges Engineering Works, V. 29, n 1362, p 10, September 7, 1960.

   The tensile strength of concrete can be determined generally by two methods. In the first, test specimens are subjected to pure tension, and in the second, un-reinforced concrete beams are subjected to bending and the tensile strength is deduced from their flexural strength.

   Neither of these methods is satisfactory, and it is also a fault that the specimens used for the determination of tensile and compressive strength are differently shaped and prepared under different conditions. Consequently, the two kinds of strength cannot be considered as related values, characteristic of the concrete.

   The testing method proposed by Akazawa eliminates the shortcomings of the present practice. It determines the tensile strength on a horizontal concrete cylinder which is subjected to compression along two opposite genratrices. In this cylinder equally distributed tension acts in a sense normal to the plane of loading almost along the entire cross-section and rupture always occurs in the plane of loading when the tensile strength is exhausted.

   An upright cylinder of the same dimensions can be used for the determination of the compressive strength. An unambiguous relationship exists between the tensile strength and the compressive strength of concrete determined in this way.

   Experiments made abroad and those carried out at the Hungarian Institute for Building Research proved this new testing method to be correct. It would be advantageous to standardize the test cylinders internationally for the uniform determination of the tensile strength and the compressive strength of concrete.

2. "The Resistance in Tensile Strength and The Cracking of Neat Cement Pastes" M. A. Ilantzis. Annales de l'Institut Technique du Batiment et des Travaux Publics, n 131, pp. 1231-1254, November 1958.

   This article describes a test for determining the tensile strength of neat cement pastes. The test is performed by applying uniform pressure to the inside of a cement ring in order to break it. Numerous test results are given for two different cements and for two curing methods of the specimens in water and in an atmosphere with a relative humidity of 50 percent.

Analysis of these test results has shown that important stresses are caused by the gradient of shrinkage.

A physical analysis of the cracking test was then made in the light of the findings of the tensile strength test. This analysis shows the complexity of the phenomenon and the practical impossibility of establishing a correlation between cracking time and the other characteristics of the material. It is nevertheless shown that cracking time, although a conventional characteristic, may be used as a general indication of the quality of a cement.

3. "A New Indirect Tensile Test for Concrete. Theoretical Analysis and Preliminary Experiments" S. Rosenhaupt, A.C. Van Riel and L. Wijler, Bull. Res. Coun. Israel, C. Technol v 6C, n 1, p 13-27, 1957. Road Abstracts v 25, n 7, July 1958.

The tensile strength of concrete cubes may be determined from dimensions of the failure section when a compressive load is applied along the middle of two opposite faces. The problem has been investigated (a) theoretically, by solving the plane-strain problem of a square acted upon by two equal and opposite forces; (b) by photoelastic testing or two identically load slabs, one square and one circular, and comparing the isochromatic and isoclinic lines obtained; and (c) by testing concrete cubes and cylinders in indirect tension and unreinforced beams in bending, and comparing the results. It is stated that all cubes tested failed along a diametrical plane containing the load, thus confirming the theoretical calculations assigning the maximum tensile stress to this plane; the tensile strength determined theoretically was in close agreement with that obtained by the other two methods; and the tensile strength of prisms was about 80 percent higher than that of cubes and cylinders, which appears to be caused largely by non-linear stress distribution.

4. "Some Factors Influencing The Behaviour of Bitumen Road Surfacings" Dormon, G. M. and A. W. Jarman, J Appl Chem 8: n 12, 1958, pp 832-48

The mechanical behaviour of bitumen under stress can be adequately described in terms of its "stiffness" which is defined as the ratio of tensile stress to tensile strain. This ratio may be determined by the microviscometer (for relatively long periods of loading) or by the microelastometer (for short periods of loading). A brief description is given of these devices. A nomograph can be constructed in which the stiffness at a selected temperature can be determined from the penetration index, the time of loading, and the difference between the softening point and the selected temperature. Results obtained have been found to differ little from experimentally determined values, and the difference is equivalent to a variation in road temperature of only a few degrees. The mechanical properties of bitumen/aggregate mixtures are analyzed in relation

to types of failure which occur in road surfaces (cracking, deformation, fretting) and which are affected by changes in the properties of the mix. The behavior of any particular mix is related directly to the mechanical properties of the binder, but a major factor is the binder content and in certain circumstances the compaction may be critical. The stiffness concept is said to provide a means of evaluating bitumens for road construction purposes.

5. "Deformation characteristics of sand-asphalt mixtures under constant tensile stresses" Huang, E. H., Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, December 1964.

The deformation characteristics of sand-asphalt mixtures under constant compressive stresses were discussed by the author in a previous paper. The present paper describes a simple tension test to determine the deformation characteristics of sand-asphalt mixtures under constant tensile stresses. In the paper, particular emphasis is placed on a comparison of tensile and compression test results.

Two parameters, vix., stiffness and viscosity, were used in the work to describe the deformations characteristics, and the effects of stress and asphalt content on these two parameters were explored.

It was found the hypothesis of work-hardening and work-softening deformations as postulated in the previous study for the compression test was also valid for the tension test. However, due to the differences in the proportion of these two opposing types of deformation, some discrepancies between these two tests were noted.

An investigation was made of an equation relating stress, strain, and time. By plotting strain vs. time and strain vs. stress on a logarithmic scale, it was found that Nutting's law of deformation for semi-solid materials was valid only within a limited range of time when applied to sand-asphalt mixtures.

6. "Dense tar surfacings (I) "Hubrecht, L, Centre de Recherches Routieres, Rapport de Recherche, Brussels 1955 (In French).

Studies of the behaviour of dense tar surfacings are being carried out by the Belgian Road Research Centre. This publication gives a report on the first part of the research, which was concerned with filler-binder systems. Mixtures of a viscous tar and various proportions of fillers commonly used in Belgium were subjected to tensile tests under constant loading, and the rate of elongation was taken as a measure of the viscosity of the mix. Measurements of stability were made by means of wheel-tracking tests. It was found that: (1) For a mixture containing a given filler, the binder content giving the lowest rate of deformation was independent of the load used for the elongation test,

(2) The mixture with the lowest rate of elongation had the maximum density. (3) The binder content of the mix with the lowest rate of elongation was identical with that deduced from the measurement of voids in the filler after compaction. The second part of the publication gives a brief description of experimental dense tar surfacings laid by the Belgian Road Research Centre. The report includes a review of research on dense tar surfacings carried out in Great Britain, including work done by the Road Research Laboratory, Harmondsworth.

7. "The flow properties of bituminous materials" A. R. Lee, J. B. Warren and D. B. Waters, J Inst Petroleum 26: 101-28, 1940.

Some results are given of the investigations now in progress on the fundamental flow properties of bitumen and bitumen-aggregate mixtures. A coni-cylindrical viscometer has been used for measuring the effect of stress and temperature on the viscosity and elastic recovery of various types of bitumens. The relation between rate of shear (D) and shearing stress (S) for all but the most plastic bitumens may be represented by an equation of the form $D = \left(\frac{1}{\sigma}\right) S^p$, where σ and p are constants. The use of the index p as a plastic -flow index provides a method of expressing the degree of plasticity of a bitumen, where this is considered as the divergence from ideal viscous flow. Different bitumens having the same penetration (65) may have very different viscosities. The bitumens so far investigated have been found to differ chiefly in their plastic and elastic properties.

The effect of stress and temperature on the flow properties of roller-compacted specimens of bitumen-aggregate mixtures has been investigated by beam and tensile tests. The relation between stress (S) and minimum rate of strain (R) may be expressed by the equation $R = KS^P$, where K and P are constants. The flow properties at the minimum rate of deformation under conditions of constant tensile stress may be expressed completely by a number of constants -- namely P, K_o (the minimum rate of strain at unit stress at 0° C), N (the rate of change of log K with change of temperature), and the extensibility at failure, the value of these constants being determined by the nature and grading of the aggregate and by the nature of the binder. Mixtures of a particular aggregate grading containing the more plastic bitumens have greater values for P than those containing non-plastic bitumens; the value of P is affected more by the grading and proportion of the aggregate than by the nature of the bitumen.

8. "The mechanical properties of bituminous surfacing materials under constant stress", Lee, A. R. and Markwick, A. H. D., Soc Chem Ind J 56: May 1937, pp 146T-156T.

The mechanical tests used hitherto measure the resistance of bituminous surfacing material to flow under certain arbitrary conditions of loading. This paper describes an attempt to devise tests giving results which are properties of the material and independent of the size and shape of the specimen. For this purpose beam, tensile and shear tests have been developed. In all these tests the material is subjected to constant stress and the deformation/time relation is obtained. In the tensile and shear tests, uniform stress is applied to the specimen and the results obtained in the shear test have been found to be independent of the size and shape of the specimen. All these tests give results which are considerably more sensitive to changes in the composition of the materials than such tests as compression, indentation, and wheel sector tests now commonly used. Roller-consolidated specimens prepared in the laboratory are used in this work and the conditions necessary to obtain reproducible results are described. The tests have been applied to study the ageing of mines made with various binders and the effect of variations in the composition of the materials tested. These include percentage and type of binder, and aggregate shape and grading. The influence of the magnitude of the applied stress has also been investigated, and it has been found that the rate of deformation increases rapidly with the magnitude of the applied stress. A brief description is given of a mechanical model which illustrates the plastic and elastic behavior of bituminous materials under stress. It is suggested that the elastic recovery exhibited by bituminous materials is due partly to air in the voids.

9. "Mesure de la resistance a l'arrachemant des goundrons", Leroux, Annales des Ponts et Chaussees 109: n 12, Dec 1939, pp 511-618.

Report on elaborate study of chemical and physical properties of bituminous materials, particularly tars, used in road construction; tests of tensile strength and resistance to rupture by pulling; effect of aging and viscosity; mechanism of setting; selection of proper bituminous materials for road bituminous materials for road construction.

10. "The mechanical testing of plastic road materials, B. G. Manton, and W. G. Wren, Soc Chem Ind J 53: n 20, pp 141-8T, 1934.

The complex influences to which road materials are subjected are discussed. At moderate atmospheric temperatures, plastic road materials are in a state intermediate between the liquid and the solid, and in testing, a definite distinction should be drawn between the two physical states by testing as a solid at temperatures of, say 0° or -10° C, and at some state approaching that of a viscous liquid at higher temperatures, say, 60° C. With regard to impact resistance, it is

suggested that tests should be made at low temperatures, when resistance to fracture is at a minimum. Experiments have been carried out with a machine of the Page falling-hammer type, using cylindrical specimens built up in alternate layers of black and red asphalt. One series was tested at 0° C. and another at 40° C. Examination of the specimens after test showed that the resulting failures at both temperatures were due to the splitting action of the wedge of material consolidated under the hammer. The second series required far more drastic treatment to produce a fracture than did the first. Tests relating to fatigue and to failure under impact in conjunction with fatigue are also discussed. Resistance to failure by shear, whether in the material itself or by separation from the foundation, is briefly considered, and it is suggested that the first is best studied by tests at high temperatures and the latter by tests at the lowest temperature encountered in service. A tentative method for the latter determination is described. In order to study the comparative suitability of tests for internal cohesion, specimens made up in layers of black and red asphalt were tested by the methods of Hubbard, Emmons and Anderton, and Wilson and then cut into two. The results are discussed, and it is shown that all three methods may be equally effective provided that the time required to produce given deformation at a special rate of loading is determined, or, alternatively, the load is developed at a given rate of strain, and the values of that strain are definitely kept below the point of incipient failure. The intensity of the compressive stress produced by external loads upon the road surface is also considered. A prolonged indentation test is regarded as a satisfactory means of obtaining the required information, and a modification of the A. S. T. M. penetration test is suggested. A test suggested by Taylor, which combines measurement of the resistance to indentation and of the internal friction, has been investigated. With regard to attrition and abrasion, it is said that tests carried out in the standard "rattler" of the British Standards Institution have demonstrated that bituminous materials and rubber compositions possess certain resistant qualities which concrete lacks. In studying resistance to bending stresses, determinations of the compressive and tensile strengths at 0° or -10° C. should serve to provide useful information. Resistance to cracking due to shrinkage. It is suggested that a standard slab of material with a reduced cross-section at one point and firmly held at the ends should be subjected to low temperatures, when shrinkage and subsequent cracking, if the cohesion were low, would be observed. Non-skid nature and low tractive resistance. The doubts and difficulties surrounding these subjects are outlined. Absorption of vibration. Tests carried out on san-asphalt and on similar material containing 2.5 percent of rubber showed considerably greater resiliency in the latter case.

11. "The Behavior of Bituminous Materials From the Viewpoint of the Absolute Rate Theory", Moreland Herrin and Gary E. Jones, Proc Asso Asphalt Paving Tech., v 32 Feb. 1963, p 82.

Since the behavior of a bituminous material in shear is influenced to a considerable extent by the temperature of the material and the rate of movement, it is desirable to have some theoretical method not only to relate these factors but also to explain the behavior of the material. The absolute rate theory, based upon statistical and quantum mechanics, appears to be applicable to many materials. The reliability and limitations of this theory of movement, when applied to bituminous materials, was investigated, and the theory of movement of units from a space into an unoccupied hole was used to explain certain aspects of the behavior of bituminous materials.

Experimental data were obtained by studying the reaction of a paving grade asphalt to variations in temperature and shear stress using a constant-load, parallel-plate microviscometer. It appears that for this bituminous material, the theory is applicable at normal and higher temperatures but might deviate from the experimental data at lower temperatures (less than approximately 12 C.).

Both the heat of activation and the entropy of this asphalt do not vary appreciably with temperature. However, the amount of activation energy required to produce a movement of a flow unit into a vacancy becomes less as the temperature of the material is increased. The size of the flow unit is large with regard to the size of one molecule. It appears, then, that molecules do not move individually, but that flow is produced by movements of large groups of molecules acting as a unit. The size of these flow units tends to increase with decreasing temperature, indicating the need for greater activation energy at lower temperatures.

12. "Tensile Properties of Dense Graded Bituminous Concrete" Egons Tons and Edward M. Krokosky, Proc-Assoc. of Asphalt Paving Tech. v 32, Feb. 1963, p 497.

The resistance of asphaltic concrete to cracking is dependent upon its tensile strength and extensibility characteristics. The tensile properties are affected appreciably by temperature, loading time and other factors.

In this study, attempts were made to investigate stress-strain characteristics of certain dense graded bituminous mixes at -20° F., 20°F., 77°F., and 120°F. and rates of loading of 0.004, 0.04, 0.4, and 4 in/in/min. The coarse and fine aggregates were identical in all mixes; three microaggregates (fillers) and three asphalt contents were used.

The findings so far indicate relatively low and similar tensile failure strains for the practical (stable) mixes and the varied effects of temperature and loading time on the ultimate strength of the different compositions. Fibrous microaggregate (asbestos) increased the tensile strength of bituminous concrete at low temperatures.

13. "Theory of The Deformation Mechanism and Bearing Strength of Bituminous Pavements" Charles Mack, Proc-Assoc of Asphalt Paving Tech, v 23, Feb. 1954, p. 338.

The mechanical behavior of bituminous pavements and their sub-structures is of importance in relation to the stresses acting on them. This paper deals with a detailed study of the deformation mechanism of such structures and with the measurement of the bearing strength. The bearing strength is defined as the maximum load per unit area which a bituminous pavement can carry without causing initial failure.

The deformation of bituminous pavements consists of an instantaneous and retarded elastic deformation followed by a plastic deformation. The mechanical behavior is primarily determined by the plastic deformation which is accompanied by hardening. As a result of the hardening process, the coefficient of plastic traction, which is stress over strain rate and is related to the viscosity, increases with increasing compressive stress and time to a maximum within a certain region of stress. At this point the shearing stress and shear are zero, and the maximum coefficient of plastic traction is an isotropic or volume viscosity, i.e., the material behaves like a solid. The principal stress corresponding to this maximum coefficient is the bearing strength. At greater stresses the coefficient of plastic traction decreases rapidly and the material is in the region of failure.

A bituminous pavement at rest is conceived as containing simultaneously particles in the disordered state and in the ordered state. The latter state refers to positions of minimum potential energy. Under stress the particles in the ordered state rarely escape their positions while the remaining particles move from positions of disorder to those of order. At the maximum value of the coefficient of plastic traction the number of particles in the disordered state approaches zero. The change in free energy of activation in going from a disordered to an ordered state and the mass of a particle are also mixima at this point. The process of hardening is comparable to fusion of the disordered particles into a particle of larger mass.

The theory of the mechanical behavior of bituminous pavements applies also to the base course and subsoil as shown by data from bearing plate measurements.

14. "The Deformation Characteristics of Sand-Bitumen Mixtures Under Constant Compressive Stresses" Y. H. Huang, Paper-Annual Meeting of the Asso. of Asphalt Paving Tech Feb 15-17, 1965. 43 p.

This paper describes some factors which affect the rheological behavior of san-bitumen mixtures. These include level of stress, time of loading, density, bitumen content and type of bitumen. Three parameters, viz., viscosity, modulus of recovery, and stiffness, are used to describe the rheological behavior of both the bitumens and the sand-bitumen mixtures. From this investigation, an hypothesis is postulated that two different types of deformation exist in a sand-bitumen mixture; one strengthens the mixture and predominates at low levels of stress or short loading times; the other weakens the mixture and predominates at high levels of stress and long loading time. This hypothesis can be used not only to explain many rheological phenomena but also to introduce a new concept in predicting the creep behavior of sand-bitumen mixtures.

15. "Temperature Induced Stresses and Deformations in Asphalt Concrete" C. L. Monismith, Paper-Annual Meeting of the Asso of Asphalt Paving Tech February 15-17, 1965

In the northern section and in some desert areas of the western United States, transverse cracks have appeared in asphalt pavements, which have been attributed, at least in part, to thermal stresses which exceed the breaking strength of the asphalt concrete surface. The research study reported herein was an attempt to investigate the development of thermal stresses and deformations in asphalt concrete under controlled conditions in the laboratory and to ascertain under what circumstances, if any, the development of thermal stresses might indicate possible cracking of idealized representations of actual pavements. Utilizing the creep compliance measured for a range of temperatures from -40°F to +110°F for a particular asphalt concrete, stresses and deformations under conditions of restrained deformation and creep for varying temperatures were predicted using viscoelastic theory. Measured stresses and deformations appeared to agree reasonably well with the predicted values. Thus, the theory was extended to predict thermal stresses due to temperature changes at the surface in a slab of the same material. For temperature changes below 0°F, computed stresses at the surface of an idealized representation of an asphalt concrete pavement considerably exceeded the breaking strength for the material. Thus, it might be concluded that temperature changes, particularly in the range below 0°F, might contribute to the cracking of asphalt concrete pavements.

16. "The Splitting Test For Determination of Bituminous Concrete Strength" M. Livneh and E. Shklarsky, Proc-Assoc Asphalt Paving Techn v 31, Jan. 1962, p 457.

An ideal test of the strength of any material is one permitting detection of the factors which affect it and which can be expressed in the form of physical parameters figuring in theoretical calculation of the bearing capacity of the material in its various kinematic and static states.

The triaxial test, used in studying the engineering properties of soils and asphalts, can be considered as the most successful one from the above point of view; on the other hand, it obviously fails to satisfy the important conditon of everyday practicability either in respect of the amount of work involved in the design test at the laboratory, or as to the possibility of routine control, before and after working of the material on the job site; in these circumstances other tests have found common use in the field of asphalt mixtures; these, however, provide only indicative data, such as, for instance, the Marshall stability, the Hveem stability, etc. Their weakness lies in the fact that measured values involve strength factors governed by unknown interrelationships.

As will be explained later, asphalts have anisotropic cohesion. This property is not reflected in the routine design and control procedures for asphalt mixtures, but in view of its importance, the need arose for a new strength test permitting both laboratory and field determination. For this purpose, the authors recommend the splitting test, also known as the "Brazilian test" and commonly used in determining the tensile strength of concrete. With the aid of appropriate theoretical analysis, the method permits design and control of asphalt mixtures as well as measurement of the anisotropic cohesion factor.

In conclusion the splitting test may be considered a promising method for the design and control of asphalt mixtures.

17. "Preliminary Report of an Apparatus for the Testing of Asphaltic Concrete Diaphragms" Rudolf A. Jimenez and Bob M. Gallaway, Proc-Assoc of Asphalt Paving Tech. v 31 Jan. 1962 p 477

This report is concerned primarily with the design of a machine for testing asphaltic concrete diaphragms subjected to repetitive flexures. Procedures and data of the fabrication and testing of specimens approximately 18 inches in diameter are presented. The apparatus, called a "Deflectometer," was evaluated by testing a coarse sheet asphalt mixture. Several variables which are thought to affect the endurance of a specimen to repeated flexures were investigated and the resulting effects were compared to the number of load applications to cause failure.

18. "Flexible Design and Experimentation in Missouri", R. M. Rucker Paper from Missouri State Highway Commission, Issued 1964 43 p.

Missouri over the past twenty years has had a rather extensive experimental program in the area of flexible design and construction. Since the completion of the AASHO Road Test our efforts have been greatly increased. We now have in progress a Satellite Type experimental program. a Benkelman Beam deflection study and special studies in the area of lime and phosphoric acid stabilization.

This paper is made up of three parts dealing with our flexible design through the years, correlation of our design procedure with the AASHO Road Test results and our current flexible experimental program.

Part one of the paper traces Missouri's flexible design procedure through the years from the inception of a definite design policy in 1947 to our current design procedure. Design charts and typical sections are shown and described. Modifications and reasons for them are discussed. Fundamentally our flexible design procedure is based on an empirical relationship between traffic intensity, group index of the typical soils in Missouri and the resultant thickness required. Economics of available materials is considered in determining type of construction. Despite considerable modification, our design procedure has retained this relationship as well as its inherent simplicity of use.

Part two of the paper relates to the adequacy of our current design procedure. Missouri design is compared with AASHO Road Test recommended design for both inner and outer wheel paths, for group index 10 soil (GI of Road Test soil) at various traffic intensities. Comparative tables are included. Our resultant designs were found to compare quite favorably with AASHO recommended design for the inner wheel path when a modest safety factor is added to Road Test recommendations. This safety factor (of approximately 4" of stone) is added to account for longer exposure and normal construction control. Since Missouri designs are full width in all courses, inner rather than outer wheel path design is also included which supports Missouri's use of full width construction.

The third and concluding part of the paper deals with Missouri's current flexible pavement experimentation. Missouri is vigorously pursuing a "Satellite Type" experimental program. We have three programs under contract at this time, one of which is flexible construction. In the flexible Satellite the thickness and width of bituminous bound base and the thickness of rolled stone subbase are purposely varied.

Statistically this would be considered a complete factorial experiment with replication. Laboratory CBR as well as Group Index will be determined on all test sections. The analysis of this program will provide a basis for modification of our flexible design chart and procedure. In addition to design adequacy, we also hope to determine the equivalencies between Missouri materials, the effect of environment or region, the effect of traffic intensity, and the effects of base compaction and stability of bituminous mixes. To compliment this study, control sections meeting Satellite ground rule requirements are being selected on many of our recent flexible projects throughout the state.

In addition to our Satellite program our continuing Benkelman Beam study and our recent subgrade stabilization experiment are discussed. To date only trends are indicated on these studies, however, due to the limited time elapsed since they were initiated.

19. "An Appraisal of Failure in Bituminous Pavements" Charles Mack, Presentation - Asso of Asphalt Paving Techn. Feb. 1965 23 p.

Failure in bituminous pavements consists in general in the formation of cracks which result from external forces being larger than the cohesive forces of asphalts. Based partly on experimental evidence, it has become customary to relate loss in cohesive forces of weather asphalts with an increase in consistency as determined by viscosity, penetration and ductility tests. Weathered asphalts have at constant temperature flow properties which vary with the magnitude of the shearing stress. At low stresses up to a certain limit, the viscosity is constant and the shear stress is proportional to the shear rate raised to the power of b. It required therefore three constants to characterize the flow properties of non-Newtonian asphalts in the described stress range. It has been suggested to compare the viscosities at a given shear rate of an asphalt before and after weathering as a measure of durability without taking the flow properties into consideration. It is shown that this disregard can lead to wrong interpretations of the tests and can lead under certain circumstances to lower viscosities and higher penetrations of the weathered asphalts than those of the originals. Flow properties at low stresses are difficult to measure, but based on the behavior of asphalts in pavements, a large amount of weathering is accompanied by a large decrease in the value of the parameter b which can be easily obtained from viscosity as well as penetration measurements. The significance of ductility is discussed in the light of present knowledge and it is shown that a decrease in ductility of an asphalt after weathering is also accompanied by a decrease in the value of the parameter b.

A great change in the flow properties of a weathered asphalt is not the cause but the effect of failure in a pavement. Failure is due to the presence of large residual stresses in the asphalt film which are mainly caused by the considerable difference in the coefficients of expansion of mineral aggregate and asphalt. This phase is discussed on the basis of the total energy present. It is demonstrated that residual stresses can be reduced and the durability of the pavement improved by proper selection of the mineral aggregate.

20. "Design Parameters for Layered Pavement Systems" John P. Nielson and Robert J. Lowe Paper-Asso of Asphalt Paving Techn Feb. 1965, 23 pp.

The layered Pavement Method for the design of flexible pavements has been adopted by the Bureau of Yards and Docks for airfield pavement design. The U. S. Naval Civil Engineering Laboratory has a device (mechanical subgrade) which simulates the action of a natural subgrade and provided a facility in which typical pavement sections can be built and subjected to plate bearing tests. Two- and three-layered pavements have been constructed and tested in the mechanical subgrade. The objective of these studies is to provide values for the design parameters; modulus of elasticity, and Poisson's ratio of various types of materials used in designing airfield pavements by the Layered Pavement Method. Theoretical analyses have also been undertaken to produce the settlement influence curves which correspond to the boundary conditions of the mechanical subgrade.

Select base, crushed rock and sand have been used to construct two- and three-layered systems. Analysis of these tests indicates that the modulus of elasticity is dependent upon the depth of the base and that thin bases (8-inches) in two-layered systems do not perform as expected. These thin bases undergo excessive settlements and cracking and rutting of overlying wearing surfaces will be imminent. Closely associated with both the increase in the modulus of elasticity with depth and the excessive settlement of thin bases is the observation that compaction of the base is not the sole criteria for stability and that development of a mechanical bond in the form of particle interlock is essential.

21. Fuels and Mining Practice Division Report, "A Loading System For the Investigation of The Inelastic Properties of Geologic Materials", H. R. Hardy, Jr., Paper No. 103, 55 pp.

This paper describes the theory and development of a loading system for the laboratory investigation of the inelastic properties of small rock and mineral specimens under a variety of loading modes, including constant load, incremental loading and constant rate of loading.

The application of basic feedback control theory to the design of the control system is outlined along with details of the construction and testing of the completed system. The problem of obtaining uniform loading of cylindrical test specimens under compressive load is discussed and details of a special specimen loading jig developed for this purpose are described.

22. "A Study of Variability in an Asphalt Concrete Mix" Edward R. Oglio, and Joseph A. Zenewitz, Paper-Asso Asphalt Paving Techn February, 1965, 16 pp.

This study was undertaken as part of the first phase in a broad program being undertaken by the Bureau of Public Roads to develop control and acceptance procedures, based on statistical quality control techniques, to all aspects of highway materials and construction. As the program is now constituted, the first phase calls for determination of two basic statistical parameters - the average and the standard deviation - for the materials and structural elements now being obtained in good highway construction.

In the work reported here, averages and variations in temperature, asphalt content and aggregate gradation were determined in an asphalt concrete wearing course mix produced for a construction job. A statistical analysis was made to show the effect of test method, sampling procedure and material (batch-to-batch) variation on the over-all variations obtained.

23. "Fatigue Characteristics of Bitumen and Bituminous Mixes" P. S. Pell, Conf Proc - Struc Design of Asphalt Pavements, University of Michigan, 1962, p 310-323.

Details are given of a laboratory investigation into the fundamental fatigue properties of bitumen and bituminous mixes. Tests were carried out in two different types of machine, rotating bending under constant stress amplitude, and oscillating torsion under constant strain amplitude, to investigate the effect of such factors as temperature, speed of loading, bitumen content of the mix, void content, surface finish, rest periods, and rate of crack propagation.

Fatigue tests on sandsheet specimens carried out under constant amplitude bending stress at various temperatures between -13.5°C and +25°C show that the material exhibits fatigue properties over wide ranges of stress and that for a particular temperature and speed of loading the relationship between the logarithm of the stress and the logarithm of the number of cycles of loading to cause failure is linear between 10^8 cycles. The life under constant stress amplitude tests is highly dependent on the temperature, a low temperature giving a longer life at a particular stress; it is also dependent to some extent on the speed of loading.

However, taking into account the stiffness of the material which depends on temperature, speed of loading, rheological characteristics, and composition of the mix, it has been found that when the logarithm of the strain, calculated as the stress amplitude divided by the stiffness, is plotted against the logarithm of the number of cycles to failure, all experimental results at different speeds and temperatures for one mix lie with a certain amount of scatter about one straight line. It appears, that the fatigue life is primarily controlled by the magnitude of the applied strain and not by the stress, and that the effects of temperature and speed of loading can be accounted for by their effect on the stiffness of the specimen.

The results of fatigue tests on sandsheet specimens under constant amplitude torsional strain at different temperatures between -20°C and +48°C confirmed the bending results, but at the higher temperature under this type of loading the fatigue life includes a considerable crack propagation time, the rate of propagation depending on the stress at the tip of the crack. Examination of the fatigue cracks and failure surfaces showed that in nearly all cases failure originated on the principal tensile plane.

Similar results have been obtained for mixes containing different amounts of aggregate but as the quantity of aggregate in the mix is reduced so the life for a given strain increases, suggesting that the criterion of fatigue crack initiation in bituminous mixes may be one of tensile strain in the bitumen present in the mix.

Tests on bitumen alone at various temperatures both in bending and shear also give comparable results on the basis of tensile strain, but under certain conditions, particularly at low stresses, the measured fatigue life includes a considerable length of time necessary to propagate the crack or cracks sufficiently to terminate the test. Unlike sandsheet specimens, bitumen alone showed beneficial effects of rest periods particularly at higher temperatures.

24. "Model Study of Stresses in Asphalt Pavements" BH. Subbaraju, Conf Proc-Struc Design of Asphalt Pvmts, University of Michigan, 1962, p 324-331.

In order to obtain a better understanding of stress conditions existing in asphaltic concrete surface layers of highway and runway pavements a model of a thin asphaltic concrete slab, 23 inches long, 21½ inches wide and 2½ inches thick was prepared. The slab was supported on a soil base of ML material (Unified Soil Classification System) contained in a 25½ inches by 23½ inches by 23 inches wooden box.

The load was applied to the model pavement slab either through a 3-3/4 inches diameter by 1/2 inch thick circular steel bearing plate or through a hard rubber wheel of 4 inches diameter attached to the head of a Universal testing machine.

Strains were measured at different parts of the slab using strain gages of the equiangular rosette type. The strain data obtained from about 700 strain measurements were reduced to principal stresses and shear stresses.

The results obtained in this study indicate the presence of rather large tensile stresses in the slab and must therefore, be given careful consideration in the design of asphalt pavements. Under the conditions of the experiments, the maximum stress in the asphaltic concrete pavement could be computed very closely by the equation,

$$S_i = \frac{0.195\ W}{d^2}\left[4 \log_{10}\left(\frac{L}{b}\right) + 1.069\right]$$

where the symbols used have the same meaning as given in this paper.

25. "Behavior of Asphaltic Concrete Diaphragms to Repetitive Loadings" Rudolf A. Jimenez and Bob M. Gallaway, Conf Proc - Struc Design of Asphalt Pvmts, University of Michigan, 1962, p. 339-344.

This paper presents data on the behavior of asphaltic slabs subjected to repetitive loadings in the laboratory. The specimens, 17-1/2 inches in diameter, were produced in the laboratory by a special molding procedure and also were obtained by coring from existing roads in the State of Texas.

An apparatus was built which loads the test specimen with forces that very sinusoidally with time clamps the specimen about its periphery, and gives the specimen support of uniform magnitude on the bottom surface.

Several loading and mixture variables were investigated to determine their effects on the flexibility and endurance to repeated loads of coarse sheet-asphalt mixtures. The results of the investigation show expected findings that (a) resistance to repetitive loads is a function of specimen thickness, (b) different types of asphaltic concrete have different degrees of endurance to repetitive loads and (c) thicker specimens are not capable of bending as much as the thinner ones.

26. "Analyses of Road Test Data Using Procedures Developed In The U. S. Army Corps of Engineers Accelerated Traffic Tests" Charles R. Foster, Conf Proc - Struc Design of Asphalt Pvmts, University of Michigan, 1962, p 358-364.

When a flexible pavement system is loaded, each layer deforms elastically and non-elastically. Non-elastic deformations are the concern in most methods of flexible pavement design.

Non-elastic deformation can be of two types: (1) a change in shape with no change in volume; or (2) a change in shape accompanied by a change in volume. The first is shear deformation and the second is compaction.

In the analysis of the several accelerated traffic tests conducted by the U. S. Army Corps of Engineers on flexible pavements it was necessary to separate the effects due to shear deformation and compaction and to make separate analyses. Also, separate procedures were developed to provide designs against shear deformation and compaction.

Shear deformation occurs when a layer is overstressed and for any given loading condition the primary variables are the strength of the layer being considered and the thickness above it. All existing flexible pavement designs are concerned primarily with thickness. In the analysis of thickness requirements as indicated by the Corps of Engineers accelerated traffic tests and by actual airfield performance it was found necessary to consider the in-place strength of the layer being studied. Also, since the available data for any one condition of loading were limited it was found desirable to develop methods of expressing the loading conditions in dimensionless values so that all the available data on thickness versus strength could be compared simultaneously.

This paper reviews the dimensionless methods developed in the analysis of the Corps of Engineers accelerated traffic tests for thickness and illustrates the use of these methods with the WASHO test results.

The compaction that develops in a given layer in a flexible pavement structure under load is primarily a function of (a) the soil type, (b) the loading, and (c) the depth from the point of load application to the layer. The variability produced by differences in soil types has traditionally been treated in a semi-dimensional manner by expressing the degree of compaction in terms of the maximum unit weight obtained in a standard laboratory compaction test.

In the analysis of the compaction requirements as indicated by Corps of Engineer accelerated traffic tests, methods of expressing loading conditions in dimensionless numbers were developed so that simultaneous comparisons could be made of the compaction-thickness relationships for all available data. These are reviewed in this paper.

The paper points out that although the developments were based on airfield pavements they are applicable to road test data.

27. "Theoretical Concepts Applied To Asphalt Concrete Pavement Design" Eugene L. Skok, Jr. and Fred N. Finn, Conf Proc - Struc Design of Asphalt Pavements University of Michigan, 1962, p 412-440.

In this paper we have attempted to show how stresses and strains computed from the elastic theory can be related to the performance of an asphalt concrete pavement. To make correlations between stresses, strains and performance, it was necessary to (1) enumerate the solutions which are available; (2) estimate the properties of the materials to be used in the pavement structure for the conditions in the field; (3) combine the material properties and the loading conditions with theory to obtain the stresses and strains theoretically produced by each application of load; and (4) correlate these stresses and strains to some measure of the performance of the pavement system.

It was decided to use the equations presented by Burmister and developed by others for the two-layer and three-layer system because they represented solutions for layers which are "fully elastic".

In order to use the elastic layered system theory for analysis, the components of a pavement were assumed to be elastic (have a constant modulus of elasticity). Consideration of the magnitude and duration of the stresses imposed on a pavement system by normal Highway loads leads us to believe that stresses calculated from the elastic theory are proportional to the actual level of stress in a pavement system. With one application of a load, an adequate pavement will rebound almost completely, although in many cases permanent deformations occur after a number of applications. We feel, therefore, that a section can be permanently treated elastically with each load application. When the visco-elastic theory is made more workable, it may provide a better approximation to the actual stresses and permanent deformations occurring a pavement system.

The paper reviews the use of present methods for determining strength coefficients of the various components in a pavement section. These methods are used to establish proper "working" moduli of the materials. If the materials are tested at a stress-strain level close to that imposed on a pavement structure (which would be near the origin of stress-strain curve), the stress-strain ratio can be used as a modulus of elasticity, and the determination of theoretical stresses and deflections of various load and design conditions can be based on that value. In most cases for an adequate design, the strain level was low; therefore, a close approximation to an elastic condition can be based on the value of assumption. "Working" moduli are determined for the pavement components at the WASHO and AASHO Road Tests using plate load tests, deflection tests and some vibratory triaxial data on the pavement materials. These "working" moduli were then used to compute stresses in the various sections of the WASHO and AASHO Road Test.

For correlation of stresses with field performance, it was assumed that accumulated transverse permanent deformation would be correlatable with the vertical stresses imparted to the subgrade (ZZ_2) and shear stresses in the layers. Also, because cracking occurs primarily in the surface layer, the tensile radial stresses in that layer (RR1) were considered to correlate with cracking or disintegration in the surface layer. The servicability concept as used at the AASHO Road Test because of its definition incorporates both cracking and accumulated permanent deformation; therefore, it was correlated with the vertical stress on the subgrade which was considered to be a measure of the general stress level in the pavement system. Mathematical formulae were developed to show these various relationships.

Although the relationships in the paper cannot as yet be used to design an asphalt concrete pavement section, we have attempted to show that the elastic theory can be used as a possible performance model. To set up the proper relationships, it will be necessary to work further to establish proper "working" moduli for the pavement components. We do not propose that the use of the elastic theory will result in a completely rational design, but by using the elastic theory in this manner, it is possible to relate the load on the pavement to the strength of the components in a more rational way than is now possible by most existing design procedures.

It is hoped that the advantages of using a theoretical approach to the design of an asphalt pavement have been shown and that further planned studies will be directed toward verifying these relationships.

28. "Basic Material Properties For The Design of Bituminous Concrete Surfaces" Emil R. Hargett, Conf Proc - Struc Design of Asphalt Pavements, University of Michigan, 1962, p 606-610.

This paper emphasizes the growing need for a flexible pavement design procedure that is based on the engineering properties of highway materials or material combinations. The rational design approach is recommended as a replacement for the empirical design methods that are now in use by highway and airport engineers. The engineering properties of primary concern are shearing resistance, elastic properties, and fatigue resistance. These engineering properties are then used to explain the stability and performance characteristics of bituminous concrete surfaces.

A new method of tension and decompression testing is described and the test results explained in view of our needs for basic design data. This method of tension and compression testing enables the research and design engineers to evaluate the stability of bituminous concrete in terms of basic strength components. Shearing resistance and angle of internal friction may be obtained graphically from a Mohr diagram plotted from tension and compression test data. Averages of the test results obtained from a limited amount of testing are included. The application of these test data to a rational design approach is discussed briefly. This paper advocates the collection and evaluation of data regarding basic material properties as a means of upgrading the design methods now in popular use.

29. "The Extension to Practice of A Fundamental Procedure For the Design of Flexible Pavements" G. M. Dormon, Conf Proc - Struc Design of Asphalt Pavements, University of Michigan, 1962 p 785-793.

Solutions of fundamental elastic equations are used to determine the stresses and strains developed in the layers of a road structure. Structures strong enough to carry defined traffic loads are designed by adjusting the thickness and properties of the various layers so that the stress and strains developed at critical points in the structure are within permissible limits.

The elastic properties which unbound soils and granular base materials develop in situ are limited by their ability to maintain equilibrium under load stress conditions (e.g., tensile stresses), and the moduli of successive layers are in consequence determined primarily by the "geometry" of the system. For mathematical convenience all granular base layers are considered to act as a single layer for which the "effective" modulus, assumed uniform over the whole thickness will generally vary only between 1.5 and 4

times that of the subgrade. The stiffness modulus, and breaking properties of the bitumen-bound layers will vary with time and temperature of loading. For practical conditions, however, a limiting low value of the stiffness modulus exists in situ at high service temperatures, which is governed by the mix composition.

Deformation of the structure is controlled by limiting the vertical compressive strain in the subgrade and granular base. This will usually be greatest at high service temperatures for construction incorporating thick bitumen-bound layers, or at thaw temperature if the subgrade is frost-susceptible. Brittle and fatigue fracture of the bitumen bound layers are governed by the tensile stress at low temperatures and the tensile strain respectively in the bottom of the layer.

On the basis of these considerations, the relative influence of the thickness and properties of the construction layers on the critical stress conditions is assessed and it is shown that the over-all advantage of a dense bitumen-bound layer over a granular layer of the same thickness will increase as their thicknesses increase. The risk of cracking of the bitumen-bound layer is found to be influenced only to a small extent by the thickness of the granular layers, but to depend mainly on the properties of the subgrade and the thickness of the bitumen-bound layer. Fatigue fracture is for example, more likely to occur on weak subgrades (particularly during thaw periods) and a small increase in the thickness of a dense bitumen-bound layer will considerably reduce the risk in this respect. Provisional design curves have been drawn up which show, for any particular subgrade, alternative constructions with the dense bitumen-bound and granular base layers, meeting specific design requirements for motorways. The design thicknesses are in reasonable agreement with practical experience and lend support to the applicability of the theory and its usefulness for indication performance trends in both conventional and unusual constructions.

30. "California Method For The Structural Design of Flexible Pavements" F. N. Hveem and George B. Sherman, Conf Proc - Struc Design of Asphalt Pavements, University of Michigan, 1962, p 851-865.

This paper discusses briefly the problem of structural design of flexible pavements, the factors that influence performance and the variables that can be measured with existing tests. The problem of design deformation; and (c) tensile strength of the pavement structure.

A method is shown for converting mixed truck traffic into a single number, called the Traffic Index which indicates the relative destructive effect of traffic. The statistical approach is used to evaluate traffic. A large sample of trucks are weight and average axle weights determined for trucks of various axle groupings. From these average axle figures, constants are determined which can be applied to various axle load groups to determine the Equivalent Value in terms of 5000-pound wheel loads.

From the EWL (Equivalent Wheel Load) calculations based on the number and weight of trucks expected to use the road, a Traffic Index may be determined. The Traffic Index is directly proportional to the thickness of structure needed to carry the anticipated traffic.

The factor which measures the resistance of soil or granular base to deformation is determined by the Hveem Stabilometer and is known as "Resistance Value".

The paper discusses the effect of cohesion (tensile strength) upon the performance of the pavement. Included in this phase of the paper is a discussion of equivalency of asphalt concrete in terms of inches of gravel or stone base. Data from our study of the AASHO Test Road is shown which indicated that the equivalency varies with the load of the vehicle and the strength of the asphalt mixture.

A design formula is proposed, which is as follows:

$$\text{Thickness of Structure} = \frac{0.080\ (\text{Traffic Index})(90-\text{Resistance Value})}{(\text{Cohesionmeter Value})\ 0.2}$$

The paper discusses modifications in the California Design Formula which might be made as a result of the study of the AASHO Test Road data. Charts showing correlation with the Test Road performance are included. The formula shows a possible coefficient of correlation of 0.97 and a standard error of estimate of $\pm$ 1.5 inches.

The paper also briefly discusses the variability of correlation statistics depending upon which layer or layers are corrected to accommodate the error.

The primary and important advantages of the California formula are:

1. The California procedure utilizes numerical values derived from physical tests of the layered system consisting of the basement soil, the subbase, base and pavement.

2. The method recognizes the effects of both structural strength and surcharge effect of the pavement and base layers.

3. The California method recognized the effect of load repetition, individually and in combination, as well as weight and provided a logical means for converting miscellaneous traffic wheel loads to a single number, the Traffic Index, which number bears a direct linear relationship to the thickness of pavement structure required.

4. The California method has been in use for approximately 13 years and has demonstrated that it can accommodate wide variations in the type of soil, type of base and type of pavement as well as variations in wheel loads and the number of load repetitions. It also shows excellent correlation with the Test Road data on flexible pavements.

31. "The Application of Elastic Theory to Flexible Pavements" A. C. Whiffin, N. W. Lister, Conf Proc - Struc Design of Asphalt Pavement, University of Michigan, 1962, p 499-521

Amongst other things, a road should spread wheel loads so that the repeated stresses applied to the soil subgrade become too small to compact the soil appreciably or cause it to fail in shear, while the road itself should not experience stresses leading to failure of any of its layers.

The present methods of pavement design are ad hoc in character and based upon experience of the behavior of different types of road over a wide range of traffic and soil conditions. A more reliable method of design might be developed on the basis of the dynamic stresses produced in the road by moving vehicles, the stress/deformation characteristics of the layers in the road under repetitive loading, and the variation of these properties with time. The present paper reviews the position, but it is not yet possible to present a technique for designing roads from this information.

Several theories for computing stresses and deflections in multi-layered elastic systems have been developed and are reviewed. That devised by Burmister appears to fit the conditions applying in a flexible road. Diagrams are given showing how the various stresses in a multi-layered elastic system road vary with the dynamic elastic moduli of the layers and their thicknesses, the curves being based on an analysis of the computations performed by Acum and Fox. The vertical stress at the soil/base interface under a moving wheel rises with increase of the elastic modulus of the soil. This stress falls with increase of the

elastic modulus or thickness of the road base or surfacing. A road base of high elastic modulus has good load-spreading properties, but this is accompanied by high horizontal tensile stresses in the base near to its interface with the soil. Some road bases, although having the high elastic modulus necessary for good load-spreading characteristics, do not have sufficient tensile strength to withstand the stresses generated within them and failure occurs.

A review is given of the information available concerning the dynamic elastic moduli of road-making materials and shows that much more information is needed. It has so far proved difficult to devise in situ tests for determining the moduli of bitumen or tar-bound materials at the rates of loading applying to traffic conditions.

Values of the dynamic elastic moduli have been obtained for some of the materials in roads where measurements have been made on the dynamic stresses generated in the subgrade. Reasonable agreement then occurred between the measured and computed values of the dynamic stress. The measurements of stress showed that, of the base materials tested so far, rolled asphalt appeared to have the best long term load-spreading properties. When any of the layers of the road contained tar or bitumen, the dynamic stress applied to the soil rose with increase of the temperature of the road. The stresses were found to be proportional to wheel load.

Before data on stresses and deflections can be used in pavement design, detailed information is required on the behavior of the layers under the conditions of repeated stress to which they are subjected in a road. Asphalts have been studied, but little work has been done on mixes of high void content such as bitumen macadam or tar macadam, while no information is available on the fatigue properties of road bases.

Measurements of the deflections of roads under moving vehicles will eventually lead to information concerning the elastic moduli of the layers. The Benkelman Deflection Beam is being used in several countries to assess the quality of a road, the measurements being made when subgrades are normally in their weakest condition. Results obtained so far indicate that the magnitude of deflection criteria depend on the intensity of the traffic using the road, the type of subgrade and the type and thickness of base and surfacing. The most important factors seem to be the type of the base material and the traffic intensity.

The elastic approach outlined in the paper may never give a complete design method, but it is already being used to analyze road failures and a typical example is outlined in detail.

32. "A Laboratory Study of The Degradation of Aggregates in Bituminous Mixes", Joint Highway Research Project, Purdue University, Fred Moavenzadeh, July 1962, n 17.

A laboratory study was performed on bituminous mixtures using a gyratory testing machine study in order to determine the factors affecting degradation of aggregate in bituminous mixtures.

The study was subdivided into three parts. In the first part tests were performed on one-sized aggregate; in the second part, a dyeing process was utilized to identify the separate fractions of each size in the grading in order to determine the influence of the presence of other sizes in the degradation of each size; and in the third part a detailed study of factors affecting degradation of aggregate was made.

Three kinds of aggregates with different Los Angeles values were used. The aggregates were blended according to three different gradations ranging from an open gradation to a Fuller maximum density gradation. Four different asphalt contents ranging from zero to 6 percent were used for most of the gradations. Use of a gyratory testing machine made it possible to produce specimens having densities and structure similar to field pavement. The mechanism of the machine also made it possible to change the compactive efforts in two different ways: change in magnitude of load, and change in repetition of load. In order to study the effect of shape of particles on degradation, artificially rounded pieces were produced by subjecting angular pieces to a few thousand revolutions in the Los Angeles machine.

The results of this study indicated that, regardless of type of aggregate, gradation, compactive effort, method of compaction, and presence of asphalt, each fraction of aggregate degraded in such a way that its sieve analysis curve was a smooth curve approaching a parabolic one, which implied that the pattern of degradation is constant. The magnitude of degradation as measured by percent increase in surface area was found to vary and to depend on the above variables. The gradation of aggregate was found to be the most important factor affecting degradation; the denser the mix the less the degradation. Soft aggregate with a high Los Angeles value degraded less than hard aggregate with a low Los Angeles value when the former was blended in a dense mixture and the latter in an open mixture.

Degradation also varied with type of aggregate. This variation correlated well with the Los Angeles value and with the nature of grain interlocking and cementation. In general, aggregates with high Los Angeles values resulted in more degradation than those with low Los Angeles values. The rocks with good interlocking or strong cementation between the grains produced less degradation than rocks with loose interlocking and weak cementation. Increase in compactive effort, either by increase in load magnitude or by increase in number of repetitions of load, increased the degradation. However, the magnitude of load was found to effect degradation more than repetition of load. The effect of asphalt was found to be dependent on other factors, and there was no definite pattern for the effect of asphalt content on degradation without considering other variables.

It must be kept in mind that this study was solely a laboratory study using a gyratory testing machine. The test results have not been correlated with field performance of the mixtures and type of aggregate involved.

33. "Laboratory Thermal Expansion Measuring Techniques Applied to Bituminous Concrete" Joint Highway Research Project, Purdue University, Jan. 1965, Collis C. Hooks, n 20.

A laboratory study was conducted to investigate several methods of measurement applicable to determining the thermal expansion and contraction of bituminous concrete. The primary objective was to select the test methods which would measure most adequately thermal expansion and contraction. Both linear as well as volumetric techniques were investigated over the temperature range of - 30 to 40°C.

Three volumetric and three linear techniques were investigated in the course of this investigation. The best of the volumetric techniques was found to be a mercury-filled dilatometer, constructed of stainless steel and accommodating a standard size Marshall specimen. The best of the linear techniques investigated as an optical one, composed of two microscopes separated by a 10-inch gage length and mounted on a chassis which provided accurate positioning along two perpendicular lines in the horizontal plane. The linear specimens were 12-inch by 2-1/2-inch by approximately 2-inch beams.

In an attempt to evaluate these methods more completely, variables were introduced into the linear and volumetric test specimens for the purpose of observing whether the measuring technique could distinguish adequately any change in the expansion resulting from the addition of these variables.

The variables introduced included: type of aggregate, grade of asphalt cement, asphalt content and method of compaction.

Although the variables were not introduced intentionally for the purpose of evaluating the effects they produced on the resulting mixture, certain general trends were observed. In most cases there existed a reasonable correlation between volumetric and linear coefficients of expansion for specimens of similar composition tested with the respective techniques.

The results from both the volumetric and linear techniques demonstrated that a linear relationship existed between temperature and expansion over the temperature range of - 30 to 15°C, inconsistencies were observed in the expansion rates of replicate specimens, indicating an inadequacy in the establishment of a consistent temperature-expansion trend for higher temperatures.

After subjecting specimens to a cyclic temperature change, the linear specimens exhibited differences between their original and final lengths which were subject to the conditions and limitations of the test technique involved.

After subjecting specimens to a cyclic temperature change, the linear specimens exhibited differences between their original and final lengths which were subject to the conditions and limitations of the test technique involved.

The coefficients of expansion for the mixes were found to increase with increasing asphalt content.

On the basis of over-all results, there was no appreciable difference in the measured coefficient of expansion between individual mixes composed of a single type aggregate mixed with the two different grades of asphalt cement used in this study. On the basis of the over-all results, there was no appreciable difference in the measured thermal coefficient of expansion for individual mixes composed of the same grade asphalt and two different types of aggregate, a limestone and a gravel.

The measured coefficients of expansion for one of the mixes tested in this study was shown to vary approximately in proportion to the thermal coefficient and volume of the respective components in the mixtures.

The average linear coefficient of thermal expansion for all the mixes tested in this report was of the order of 2.0×10^{-5} in/in/°C. The average volumetric coefficient of thermal expansion for all the mixes tested was of the order of 7.0×10^{-5} $in^3/in^3/°C$.

34. "Tensile Strength and Diagonal Tension Resistance of Structural Light-Weight Concrete" J. A. Hanson. Am Concrete Inst-J n 1 July 1961, p 1-39.

Simple means of establishing diagonal tension resistance to be associated with particular aggregate is suggested by analysis of new investigation between indirect tension measurement and shear resistance of beams at diagonal cracking; proposed ultimate load design recommendations are made for structural light-weight concrete, in accord with recommendations of ACI-ASCE Committee 326.

35. "Analysis of Deformation and Failure Characteristics of Concrete" A. L. L. Baker, Mag Concrete Research v 11 n 23 Nov. 1959, p 119-28.

Internal structure of concrete is similar to series of lattices; diagonal number of lattice are stiffer than cross numbers, which represent mortar in "voids" bonded to diagonal members; idealized system is analyzed, equations are derived, and curves plotted from which Poisson's ratio is related to stiffness ratios; model used to show internal structural system of concrete and to determine distribution of maximum tensile stresses.

36. "Correlation of Bendability of Materials with Their Tensile Properties" J. Datsko, C. T. Yang, ASME-Trans-J Eng for Industry v 82 Ser B n 4 Nov 1960, p 309-14.

Simple equation correlates minimum bend radius with percentage reduction of area of material; theoretical derivation and experimental data given, with very good agreement between them; it is therefore possible to predict minimum bend radius for specific material, provided that percentage reduction of area, as determined by standard tensile test is known; relationship applies to metals and nonmetals. Paper n 59-A-110

37. "Tensile Testing of Materials at Impact Rates of Strain" J. Harding, E. O. Wood, J. D. Campbell, J Mech Eng Science v 2 n 2 June 1960, p 88-96

Problems involved in obtaining reliable tensile stress-strain curves at high strain rates are discussed; new apparatus, designed to give accurate stress-strain curves in tension at strain rates of order of 1000/sec, is described; theretical basis of method and some experimental results are presented for materials that exhibit difinite yield point, and for those that do not. 23 refs.