Mechanical Properties of Asphalt Materials and Structural Design of Asphalt Roads

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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 described. Results of tests under short duration loadings are 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.

● IN the design of any construction three main factors of very different nature have to be considered. In the first place, the form of the construction is generally determined by the use to be made of it, which in the case of a road leads to the very simple description as thin, relatively narrow and very long; in fact, a ribbon. This simple description does not imply that the formgiving of a road is without problems. Everybody acquainted with this field of engineering knows about the complications of curvature, crossings, and the influence of form on capacity. For structural design, however, these factors are of no importance and the simple description as a ribbon will suffice.

The second point of interest for design is the load system to which the construction will be submitted. This is where complications arise for road construction. It must be recognised when we restrict ourselves to pneumatic tires the load is transmitted by a fairly uniform vertical pressure which, for a stationary wheel, is roughly equal to the inflation pressure, but may be double this value for moving loads. The form of the area over which this pressure is exerted is roughly an ellipse, the long axis in the direction of the traffic being about 1½ times the length of the other axis.

Complications arise from the fact that, in addition to these vertical pressures, horizontal forces are exerted on the road construction due to the friction between tire and road, forces serving to overcome the friction of traffic against the air, forces due to the slope of the road, and forces due to acceleration and deceleration of the traffic. In general it can be said that deceleration will give the highest horizontal forces, which may amount to 60 percent of the vertical force for straightforward slipping of the wheels but are normally a good deal lower.

A further complication is that traffic travels at speeds which may vary widely from nil (stationary traffic) upwards to 100 mph. The rate of loading that this variation in speed implies affects structures of any material, as is well-known from bridge design.

Here we arrive at the third factor affecting structural design, viz., the mechanical properties of the materials used. For the asphalt road this point has been the great hurdle during all the years these roads have been built. In actual fact, the mechanical properties of asphalt mixtures follow laws more complicated than the simple law of proportionality between stress and strain and the law of elasticity, which can be applied when using other construction materials, so that normal design formulas are only of limited applicability.

Asphalt roads have been built all these years on the strength of experience, and the whole development of road building is based on empirics. The advent of heavier loads and faster traffic, together with developments in air transport, however, have made a more-thorough and more-exact knowledge essential for sound design, not in the least in view of the enormous amounts of money involved and the economic consequences of a faulty design. Progress is being made in this field. The first step is based on the development of modern soil mechanics, the importance of which can hardly be overemphasized, as soil is one of the major components of any road construction.

The improved insight into the mechanical properties of asphalt road material may be considered as the second important step forward; both factors may lead to a more-scientific design in building asphalt roads.

In view of the great influence of the properties of the construction materials on design, these properties should be discussed first. We assume that soil mechanics is known widely enough and need not be discussed here. The knowledge of the mechanical properties of asphalt material, however, is not so widespread.

GENERAL DISCUSSION OF THE MECHANICAL PROPERTIES OF ASPHALT ROAD MATERIALS

For a good understanding of the mechanical properties of asphalt road materials it should be realized that this material is built up of asphalt cement (the binder) and mineral aggregate. The properties of both components govern the properties of the mix, so that it is necessary to gain an insight into the properties of the components and to discuss them in some detail.

Mechanical Properties of the Asphalt Cement (Binder)

The rheological properties of the asphalt cement have been studied extensively and are well known. One of the completest studies has been carried out by Saal[1] and co-workers, though it must be borne in mind that this group of investigators restricted themselves to long-duration loading processes, measuring flow properties of the material. They found that the asphalt cements used in road building show a proportionality between stress and rate of shear. In addition, asphalt cement shows limited elastic properties.

In recent years attention has been drawn to the behavior of this material under conditions of short-duration loading.

In this connection mention must be made of the work of Mack.[2]

A more-thorough investigation has been carried out by C. van der Poel[3], who tested bars of the material suspended in their nodal points, vibrations being set up at one end, the amplitude of the deflection being measured at the other end. With increasing frequency of vibration, the system passes through a state of resonance from which the modulus of elasticity and the damping of the material can be calculated.

Van der Poel has worked out a picture in which both elastic and flow properties can be represented. On the basis of dimensional considerations he writes:

$$[E] = \left[\frac{\sigma}{\epsilon}\right] = [G] = \left[\frac{\tau}{\gamma}\right]$$

and compares these magnitudes with

$$\left[\frac{\eta}{t}\right] = \left[\frac{\tau}{\frac{d\gamma}{dt}t}\right]$$

both plotted against time on a double-logarithmic scale.

Here σ = normal stress
ϵ = strain

[1] J. P Pfeiffer, The properties of asphaltic bitumen with reference to its technical applications. Elsevier, Amsterdam, 1950.

[2] C. Mack, Rheology of bituminous mixtures relative to the properties of asphalt. Proc. A.A.P.T. *13* (1942) p. 194–255.

[3] C. van der Poel, Proc. Sec. Int. Congr. Rheol., Oxford 1953, p. 331-7.

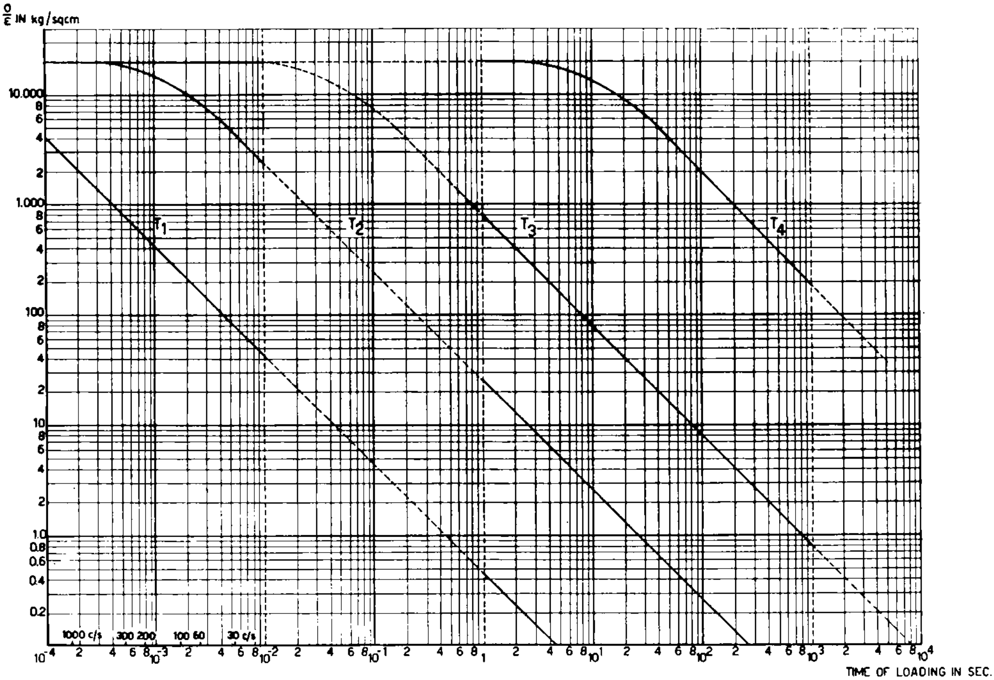

Figure 1. Stiffness modulus $\frac{\sigma}{\epsilon}$ of asphalt cements at various loading times and temperatures.

τ = shear stress
γ = angle of shear
t = time.

In this representation a constant E value independent of time is given by a line parallel to the time axis (as holds, e.g., for steel), whilst a Newtonian liquid (η = independent of τ and t) is represented by a straight line under an angle of 45 deg. dipping down.

The general picture developed by Van der Poel on the strength of measurements over a wide range of loading times is represented in Figure 1 and shows that for very short loading times asphalt cement has a constant stiffness modulus, for very long loading times a purely viscous behavior, the two being linked up by a transition region where both phenomena are observed.

Temperature influences the place of the lines, a higher temperature (higher penetration) shifting them to shorter loading times, a lower temperature (lower penetration value) in the other direction.

It may be added that the maximum value of the stiffness modulus is as high as about 30,000 kg./per sq. cm (420,000 lb./per sq. in.).

In the second part of his investigation Van der Poel determined the strength of asphalt cement and by working at constant stress found that the span of time during which the material is able to withstand this constant stress depends on the magnitude of the stress. As a general representation Figure 2 is given, which shows that for short loading periods the material is able to withstand stresses as high as 40 kg./per sq. cm (560 lb./per sq. in.).

Mechanical Properties of Mineral Aggregate

The aggregate added to the asphalt cement, which constitutes the major part of the mix, consists of mineral particles of various sizes. It has elastic properties, which it imparts to the mixtures.

Modern soil mechanics has shown that such a mixture has no ideal elastic properties. These facts are so widely known that they need not be discussed.

It is necessary, however, to point out that, in addition to its elastic properties, a granular

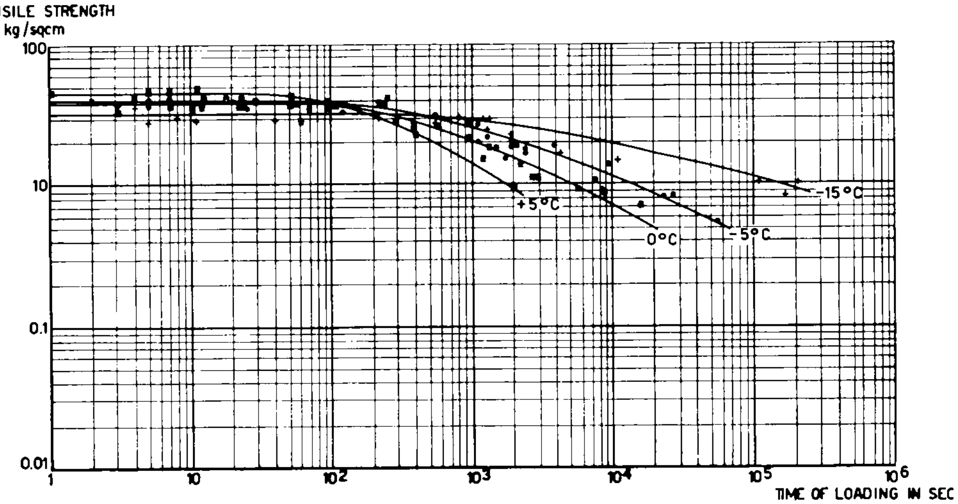

Figure 2. Tensile strength of an asphalt cement of penetration at 25 C. = 10/20 at various temperatures.

mass has plastic properties, particularly resistance to shear, dependent on the state of stress. This resistance is expressed by internal friction and cohesion or apparent cohesion, the cohesion being the latent resistance of the material in the absence of frictional resistance.

Mechanical Properties of Asphaltic Road Mixtures

As the properties of the asphalt cement depend not only on temperature—asphalt cement being thermoplastic—but also on time of loading, it can be anticipated that the properties of a road mix vary with temperature and time of loading. This was confirmed by an investigation.

It must be borne in mind that asphaltic road mixtures form a three-phase system consisting of mineral aggregate, asphaltic cement, and air. Its mechanical properties can only be represented by values expressing the contribution of the various phases to the overall performance.

Furthermore, the mechanical behavior of the asphaltic cement complicates the mechanical properties of the mixture, so that the usual simple concepts of elasticity and viscosity apply only within limited ranges.

Up to now two extreme fields have attracted most attention, viz., long-duration loading and short-duration loading. The results of these investigations will be discussed in detail below.

In general it can be stated that in the short-duration-loading interval the asphalt road material behaves like an elastic material, showing proportionality of stress and strain and complete elastic recovery when the load is removed.

Fracture will occur when stresses exceed the breaking strength of the material.

In the long-duration-loading range the material will show plastic flow. This property too will be discussed in detail.

The elasticity deformation accompanying the flow is essentially of secondary importance.

In the intermediate range of loading time, of which our knowledge is still very limited, the stress-strain ratio need not be constant and recovery might be only partial. Breaking strength may be exceeded, leading to fracture. Furthermore, it should be taken into account that deformation or accumulated deformation on repeated loading may be the criterion to be used for design.

In this complicated field, both deformation and loss of equilibrium criteria should be used, and each special case should be studied with both criteria in mind.

At this stage of our knowledge a general discussion of the properties of the material in this range is premature and will be omitted. Some special cases will be referred to in due course.

Properties on Long-Duration Loading. In long-time loading the mixture shows plastic properties, as has appeared from investigations where the triaxial-test method was applied. The use of this test method is so widespread nowadays that a description seems hardly necessary.

When using this test to the fullest extent the resistance to shear of the material under conditions prevailing in road work can be described by the three following physical magnitudes: (1) A frictional resistance, due to the friction between the aggregate particles, which exert a pressure on each other (grain pressure) and proportional to this pressure. The angle of internal friction is used as its characteristic in accordance with soil mechanics. (2) An initial resistance, a resistance the material is able to develop in the absence of frictional resistance. (3) A viscous resistance (in poises), developing only when the material is sheared off at a certain rate. This resistance is due to the presence in the material of the viscous asphalt cement. Attention should be drawn to the viscous resistance that even at low rates of deformation can acquire high values.

In the tests the rate of deformation is obtained by tapping off lateral supporting liquid at a controlled rate. Nijboer[4] used this method of test to evaluate the influence of the properties of the components and the composition of the mix on its mechanical properties.

The results can be briefly described as follows:

1. Angle of Internal Friction. Its value depends on the shape of the aggregate particles, angular particles giving higher friction. Thus it was found that the composition of the mix affects the value of the angle of internal friction and the coefficient of friction as follows:

Sandsheet	$\varphi = 28°$	$f = 0.53$
Topeka	$\varphi = 30°$	$f = 0.58$
Asphaltic concrete	$\varphi = 31°$	$f = 0.60$.

These figures apply only to mixtures with more than 2 percent of voids (volume), because at lower void content part of the external pressure is brought to bear not on the aggregate but on the liquid phase (hydrostatic pressure), so that no friction develops. For mixtures with insufficient void content, the value for the angle of internal friction is apparently lower, and this loss in frictional resistance is probably the most-widespread cause of insufficient stability of road carpets.

[4] L. W. Nijboer. Plasticity as a factor in the design of dense bituminous road carpets. Elsevier, Amsterdam, 1948.

TABLE 1
VALUES OF THE TRUE INTERLOCK

Cv (volume concentration of angular particles in the mix)	τ_{hh}
	Kg. per sq. cm.
0	0
0.10	0.05
0.20	0.10
0.20	0.18
0.50	0.40

2. Initial Resistance. The initial resistance has a complicated character. Part of it is due to the true interlock (τ_{hh}) of the angular components of the aggregate, and the magnitude of this resistance increases with the amount of angular particles in the mix, independent of their size.

This property is independent of the presence of asphaltic cement.

For mixtures without a true interlock (sand asphalt) it was found that the value of the initial resistance depends on the hardness of the binder and consequently on temperature. For this reason this resistance was called the bituminous initial resistance (τ_b), and the hypothesis was put forward that it is due to the resistance to shear of very thin layers of bitumen on the aggregate near the contact points of the aggregate. In agreement with this hypothesis it was found that the number of contact points between the aggregate particles, which is greatly influenced by the (volume) ratio of filler to binder (*F/B* ratio), has a very marked effect on the value of τ_b.

As the value of τ_b is lowest at the highest penetration of the binder, the values of τ_b at the highest road temperatures (+50 C.) are given in Figure 3 for a 80/100-penetration asphaltic cement (at 25 C.).

It can be added that a 10-C. change in temperature, as well as a variation in penetration by a factor of 2, influences the value of τ_b by a factor 1.7, an increase in temperature as well as an increase in penetration leading to lower values.

It was further found that the presence of angular aggregate in combination with bituminous material leads to another type of initial resistance, proportional to the value of τ_b and further dependent on the concentration

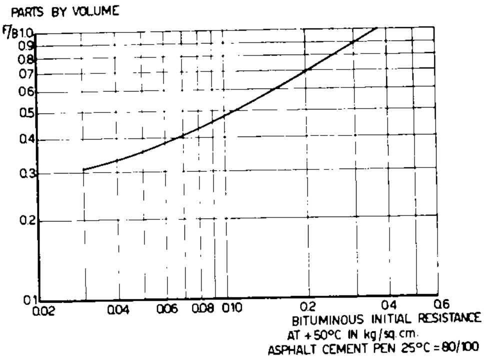

Figure 3. Relation between the bituminous initial resistance at +50 C. and the F/B ratio (asphalt-cement penetration 25 C. = 80/100).

TABLE 2
INCREASE IN INITIAL RESISTANCE PROPORTIONAL TO τ_b DUE TO ANGULAR AGGREGATE IN A BITUMINOUS MIX (FACTOR r_T)

Vol. concentration of angular aggregate	r_T
0	0
0.10	0.05
0.30	0.40
0.50	1.00

of angular material. This relationship is shown in Table 2.

3. Viscosity of the Mass. The value of the viscosity of the mass depends again on the hardness of the binder, i.e. on the temperature and on the *F/B* ratio. Values are found as high as 3–10 x 10^{10} poises for sandsheet, those for asphaltic concrete being twice as high. The viscosity at higher temperatures is considerably lower and governs the compaction process, because the viscosity, together with the internal friction, counteract the shear stresses under which the material flows, the void content being reduced at the same time. The practical means available in road-building practice are sufficiently potent to allow full compaction being obtained on the job, if only due care is taken in selecting equipment and working temperatures. In the design of road mixtures this viscosity will therefore be of minor importance.

Properties on Short-Duration Loading. The properties of asphalt on short-duration loading approach, in many respects, those which are measured on the normal elastic building materials. Here we have to deal with rigidity properties and strength of the materials, though the picture is complicated by the fact that the duration of the loading influences the properties of the material.

A convenient representation has been worked out by Van der Poel, who plots these properties against duration of loading, thus obtaining a picture parallel to that of the mechanical properties of the pure asphalt cement. Also, the strength of the material under repeated loading was determined.

In view of the importance of these properties in the design of asphalt road, it is necessary to go more fully into details.

1. Stiffness of Asphaltic Mixtures. On the strength of results of torsional vibration tests, Van der Poel calculated the shear modulus at short loading times. In these tests vibrations were set up in a cylindrical bar of the material, the amplitude of the torsional deformation being determined at various frequencies. From the resonance frequency, the dimensions of the bar, and the moment of inertia of a mass attached to it, the value of the shear modulus $\frac{\tau}{\gamma}$ and thus the stiffness modulus $\frac{\sigma}{\epsilon} = 3\frac{\tau}{\gamma}$, are easily found.

Furthermore, by making use of compression tests, from which the value of the stiffness modulus was determined in the classical way, a simple picture was found for the variation in $\frac{\sigma}{\epsilon}$ with duration of loading.

Figure 4 gives the results for various temperatures as obtained on a sandsheet mixture containing a penetration 50/60 (at 25 C.) asphaltic cement.

Tests at one and the same frequency (60 c. per sec.) and at various temperatures showed that the same values for $\frac{\sigma}{\epsilon}$ are found for normal road asphalt cements of the same penetration at testing temperature. For other compositions, using the same aggregate, but asphalt cement of another penetration, the $\frac{\sigma}{\epsilon}$ values can thus be read off at the temperature for identical penetration.

It should be noted that at very-short loading times and at lower temperatures a maximum value for $\frac{\sigma}{\epsilon}$ is found of 300,000

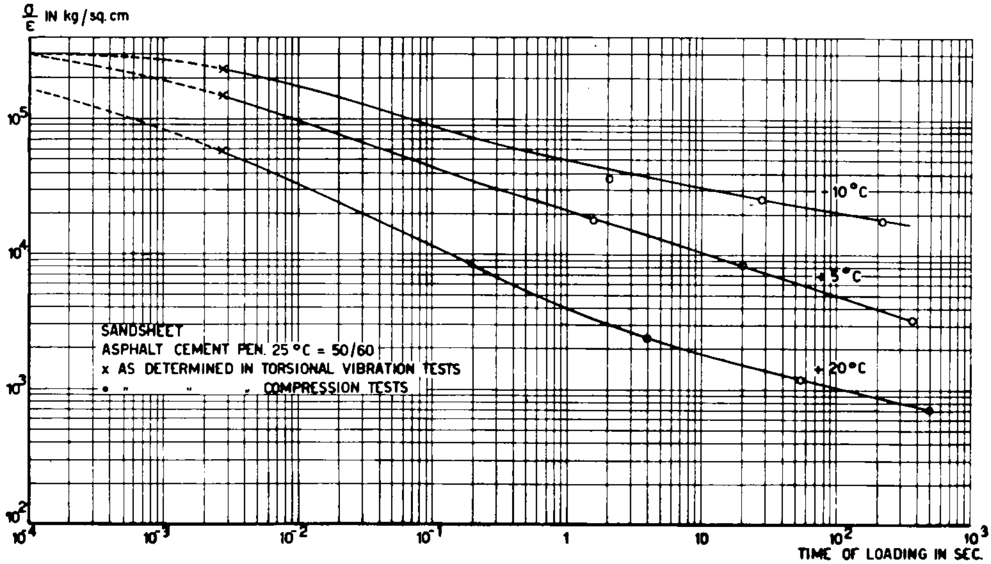

Figure 4. Stiffness modulus as a function of duration of loading at various temperatures.

kg. per sq. cm (4,200,000 lb. per sq. in.), whilst at long loading times no slope of 45 deg. is observed, as the mixture is not a Newtonian liquid, but a plastic material, due to the presence of the mineral aggregate.

For sandsheet mixtures of varying composition, and as such characterized by variations in the F/B ratio, a bundle of lines is found converging to a point roughly at the maximum value of $\frac{\sigma}{\epsilon}$. Thus, it is possible to take this variation into account for different sandsheets at various temperatures, after which the $\frac{\sigma}{\epsilon}$ values at various times of loading can be read off.

A further variation to be accounted for is the amount of coarse aggregate. Here the picture has not yet been developed in detail, though for specific conditions the data necessary for design work have already been established, as will be discussed.

At this stage something should be said about a peculiar property of the mix showing up in compression and tensile tests. As could be expected on the strength of the viscous properties of the mixtures, the compression and the tensile strength increased with increasing rate of deformation. The maximum stress was, however, obtained at a constant deformation of the material, amounting to 2.5 to 3.5 per cent in compression and 1.5 to 2 per cent in tension, both at higher temperatures, these values decreasing by a third at lower temperatures.

It was further found that the elastic recovery of the material is fairly complete up to 1 percent deformation and independent of temperature and hardness of the binder. The available data were determined after loading times up to several minutes and it may be that at longer loading times recovery will be incomplete. For shorter loading times the above data hold.

Breaking Strength of Asphaltic Mixtures. In analogy to what was found for the asphaltic binder, the breaking strength of the asphaltic mixture is dependent on the time of loading. Some results are represented in Figure 5, but up to the present only a variation in temperature and in F/B ratio has been studied and the influence of the coarse aggregate in the mix has not yet been investigated. Similarly, it was found that on repeated loading at higher stress the material fractures after a smaller number of repetitions of the load than at lower stresses. The material thus shows the phenomenon of fatigue, well-known from other materials (steel, timber).

Figure 5 gives some data on the tensile

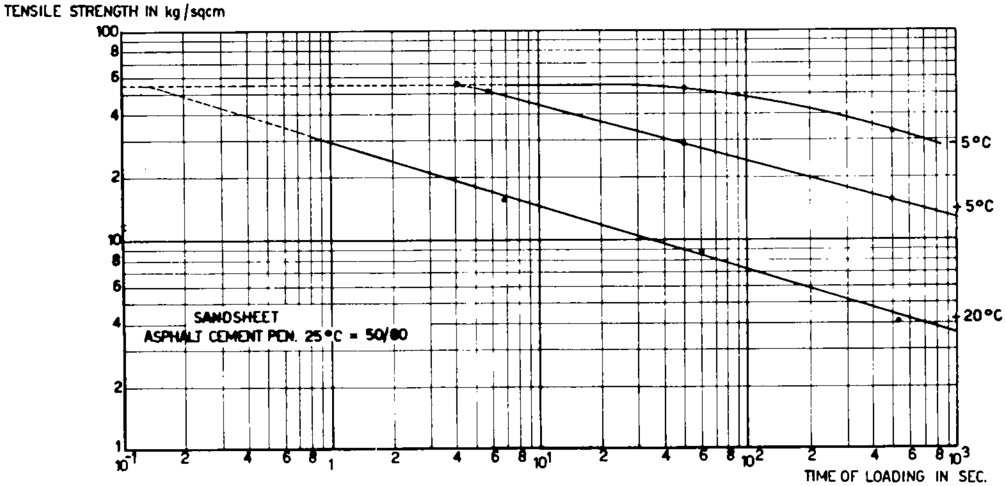

Figure 5. Tensile strength at various times of loading and various temperatures.

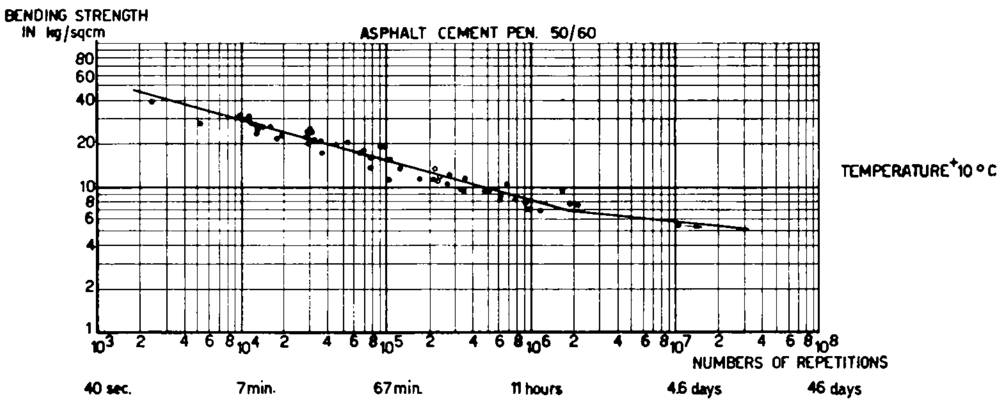

Figure 6. Fatigue test on sandsheet mixture.

strength of a sandsheet at various temperatures and times of loading. Figure 6 shows the bending strength of the same material against the number of repetitions of the load at +10 C. and a frequency of 25 cps.

Here again data on Topeka and asphaltic concrete mixtures are still lacking, but the general picture permits some qualitative conclusions.

On the strength of the properties discussed above, the criterion which follows can serve as a measure of the ability of a road carpet to withstand flection or repeated flection. Though it is recognized that the rigidity may influence the strains in the carpet, we assume that the flection of the carpet is mainly governed by the rigidity of base, subbase, and subsoil, the stresses in the carpet will be proportional to the stiffness modulus of the asphaltic mix. Therefore, for any number of repetitions of the load the quotient $\frac{\sigma}{\epsilon}/F$ will be an indication of the risk of crack formation.

Variations in the F/B ratio of sandsheet mixtures lead to the results illustrated in Figure 7. For a sandsheet increasing values of the F/B ratio lead to increasing values of $\frac{\sigma}{\epsilon}/F$ and thus to increasing risk of crack formation. The reason why 10 C. was chosen as critical temperature will be discussed below.

It is doubtful, though this point has not yet been investigated, whether the addition of

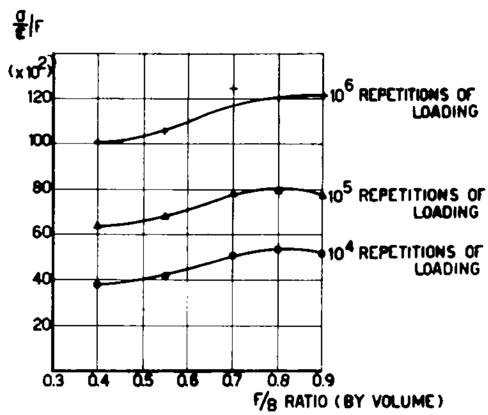

Figure 7. Relation between F/B ratio (by volume) $\frac{\sigma}{\epsilon}$/F for sandsheet mixtures at +10 C. (asphalt cement pen. 25 C (= 50/60)

coarse aggregate will increase the value of F, but it has already been found that the value of $\frac{\sigma}{\epsilon}$ increases with increasing stone content. It can be concluded, therefore, that to avoid crack formation carpet design must aim at the lowest value of the F/B ratio compatible with other criteria. Whether the composition thus obtained is quantitatively good enough for the traffic the road is going to carry can only be found out when the strains the material has to withstand are known.

MECHANICAL PROPERTIES OF MATERIALS USED AS BASE, SUBBASE AND SUBSOIL

The materials used in the asphalt road construction for base, subbase, and subsoil are all of the granular type. During the last few decades their mechanical properties have been widely studied in the branch of technology which is in general indicated by the name of soil mechanics. In relation to the problems discussed here, only some aspects of soil mechanics need be enlarged upon.

In soil mechanics two classes of phenomena must be distinguished: conditions for equilibrium (or loss of equilibrium), and deformation phenomena. The latter cover both elastic and plastic deformations, of which consolidation problems constitute an important part.

In the discussion on road-construction design, this latter part will be left out, as it is intended to restrict the subject to the relationship between load, properties of the materials used, and dimensions of the various layers of those materials.

Furthermore, it should be borne in mind that consolidation problems in road construction run mainly parallel with those in other foundation work, the long-time reaction of the subsoil to the superimposed load governing the phenomena. However, it should be remembered that acceleration due to the vibration set up in the material by traffic is possible. Data on this point are, however, very scarce.

For the relationship between stress and deformation of these materials it is, however, essential to make a distinction in connection with the duration of loading. The studies of the Degebo[5] have been a leading element in this field.

Work by Tschebotarioff[6, 7], on repetitional loading of soil, followed by a study of A. Casagrande[8] on deformation in relation to time of loading of various clay samples confirm that for soil materials the loading time has a distinct influence on the deformation. C. van der Poel[9] further developed the line indicated by the Degebo in his studies on the mechanical behaviour of asphalt road constructions under vibrational loading.

In this investigation he determined the rate of propagation of the transverse waves in the various layers of a road construction and, from this rate of propagation, calculated the shear modulus G of the various materials under this system of loading.

Comparing the results with those derived from a static loading test (long-duration loading) he found that the value of the shear modulus for short-duration loading was for a given sand up to five times higher than at long-duration loading; for a sandy clay even a factor of 8 was found.

Without any quantitative argument it is clear that such a variation in the rigidity of the subbase or the subsoil must seriously affect the deformation of the carpet and should therefore be taken into account in the design

[5] See Heft 1-6 Veröffentlichungen des Instituts der Deutschen Forschungsgesellschaft für Bodenmechanik (Degebo).

[6] G. P. Tschebotarioff, Effect of vibrations on the bearing properties of soil. Proc. Highway Res. Bd. *24* (1944) p. 404-25.

[7] G. P. Tschebotarioff and G. W. McAlpin. Vibration and slow repetitional loading of soil. Proc. Highway Res. Bd. *26* (1946) p. 551-62.

[8] A. Casagrande and S. D. Wilson: Harvard Soil Mech. Series No. 39 (1950). Investigation of effect of long-time loading on the strength of clays and shales at constant water content.

[9] C. van der Poel, Dynamic testing of road constructions. J. Appl. Chem. *1* (1951) No. 7, 281-90.

of road carpets. From field tests[10] it is known that the deformation of a road carpet under a given load is greatest during the spring breakup. The temperature of the carpet may then be about +10 C. and for this reason the value of $\frac{\sigma}{\epsilon}/F$ at this temperature has been chosen β to compare the influence of F/B ratio on $\frac{\sigma}{\epsilon}/F$.

The fact that the properties of base etc. vary with time of loading necessitates a separate discussion of the mechanical properties of the materials under short- and long-duration conditions.

Mechanical Properties of Base, Subbase and Subsoil at Long-Duration Loading

The most-widely used test in soil mechanics for determining the resistance to shear of the material is the triaxial-shear test, whilst for the stiffness determination consolidation tests are used. In this determination the drainage of water may play an important role.

For road building, however, other tests have found widespread application. In these tests a certain imitation of loading conditions in road work has been aimed at.

For the laboratory the California bearing test[11] has been developed, which is also applicable in the field. In this test a flat steel die of 3 sq. in. of surface area is pushed into the material at the rate of $\frac{1}{20}$ inch per minute and the resisting stress at 0.1-inch penetration is compared to a resistance of a standard material under the same conditions. Variations in test procedure can be found in the literature and need not be reviewed here.

The name of this test suggests that it deals with bearing capacity and is therefore related to loss of equilibrium. Kerkhoven[12], however, in critically studying test results came to the conclusion that these results must be interpreted as a measure of stiffness. Following Boussinesq's theory he pointed out that from the test results a stiffness modulus of the material can be worked out. Here the term *modulus of elasticity* would be a misnomer, as the material is not fully elastic. Kerkhoven therefore justly uses the term *Modulus of deformation* (D). The value of D follows from Boussinesq's formula

$$D = \frac{1.18\sigma r}{\delta}$$

where σ = stress
r = radius of loaded area
δ = indentation.

In terms of the CBR test this leads to

$$D = 118 \text{ CBR}$$

(D in lb. per sq. in., CBR in percent)

In field testing use is often made of the plate-bearing test, the results of which must be interpreted in the same light. Some informative tests on a sand in comparison with CBR tests led to identical values for D.

Mechanical Properties of Base, Subbase and Subsoil at Short-Duration Loading

The short-duration tests as carried out by the Degebo, and by Tschebotarioff and Casagrande have, to the best of our knowledge, not yet found application in road building.

Tests on the road as carried out by the Degebo and by Van der Poel[13] are directly related to road work. By exerting a vertical force varying as a sinusoidal function with time the complete road construction is set into vibration. To measure the vertical deflections at various points away from this generator, the deflections are taken up by a pickup and are shown on an oscilloscope and with the help of a time mark it is possible to measure the length of the transverse waves which propagate the vibration through the various layers of the construction. It was found that the rate of propagation varies with frequency. As the shear modulus of a material is related to the rate of propagation of a transverse wave by

$$v = \sqrt{\frac{G}{\rho}}$$

v = rate of propagation
G = shear modulus
ρ = density,

[10] Load Carrying Capacity of Roads as affected by Frost action. Highw. Res. Bd. Research Report 10-D (1951).

[11] O. J. Porter, Foundations for flexible pavements. Proc. Highway Res. Bd. *22* (1942). Abundant literature is available on this test method mainly from American sources.

[12] R. E. Kerkhoven. Het ontwerpen van buigzame wegconstructies. (The design of flexible road constructions). Dep. Ingenieur *64* (1952) 26 B 89.

[13] C. van der Poel. loc. cit.

TABLE 3
VALUES OF DYNAMIC SHEAR MODULUS

Type of soil	Rate of propagation	Dynamic shear modulus	Static shear modulus
	m. per sec.	*Kg. per sq. cm.*	*kg. per sq. cm.*
Compact sand	170–240	560–1100	—
Sand fill	140	330–400	60–100
Clay-sand		750–1700	
Sandy clay	110	240	30
Peat	90–120	80–150	

the shear modulus of the material can be determined in situ. A soil profile is needed to determine the thickness of the various layers.

Some values of the shear modulus (at short-time loading) of various soils are given in Table 3 in comparison with some static values. The variations in the value of the dynamic shear modulus as well as the difference with the value of the static shear modulus are self-explanatory.

It must be pointed out that the G value of the base material may be so high that greater frequencies than available (50 c/s) are needed to measure the dynamic shear modulus of this material.

DESIGN OF BITUMINOUS ROAD CONSTRUCTIONS

It is essential in the design of bituminous roads to take the loading time into consideration and to distinguish between long-duration loading (stationary vehicles) and short-duration loading (moving traffic).

It is also clear that different design methods have to be used for the carpet and for the other parts of the construction.

This logically leads to the design of: (1) road construction for static loads; (2) carpet for static loads; (3) road construction for dynamic loads; and (4) carpet for dynamic loads.

It must be stated that the development of design methods for the various conditions are not equally far advanced. Particularly the design methods for dynamic loading are still the subject of investigation.

Design of Road Constructions for Static Loads

The most-widely used design method is the CBR method,[14] which has been brought out as an empirical approach to the problem. In this method design graphs are used indicating the thickness of layers of better quality needed above any given layer to obtain satisfactory road construction. As a criterion for the quality of any layer the CBR test result is used, and the graphs give the CBR value of any layer against the desirable thickness of superimposed material of better quality.

Kerkhoven[15] has tried to give this method a theoretical background. Interpreting the CBR test as determining the modulus of deformation, D, of the material it was found that the CBR design curve corresponds with the formula

$$D_H = D_0 \frac{r^2}{r^2 + H^2},$$

where D_H = modulus of deformation at depth H
D_0 = modulus of deformation at surface
r = radius of loaded area,

or

$$D_H = D_0(1 - \cos^2 x)$$

$$\left(\text{where } \cos^2 x = \frac{H^2}{r^2 + H^2}\right)$$

Frohlich describes the vertical stress under the middle of the load by

$$\sigma_H = \sigma_0(1 - \cos^\nu x)$$

where ν = stress concentration factor.

By applying the minimum energy theorem to the rigidity distribution as given by the CBR curves it follows that the stress distribution can be described by the Frohlich formula as ν = ca 2.3. As the differences in stress values between $\nu = 2$ and $\nu = 2.3$ are extremely small, both the rigidity and the vertical stress at various depths can be described by the same function and are therefore proportional to each other. In other words, the vertical strain is constant at any depth and total settlement decreases linearly with depth.

As the settlement of various constructions is known from full-scale trials, it is possible to develop a formula showing the relationship between stress and CBR values. In a dimensionless form this formula reads

[14] O. J. Porter, loc. cit., and further abundant literature mainly from American sources.

[15] R. E. Kerkhoven, loc. cit.

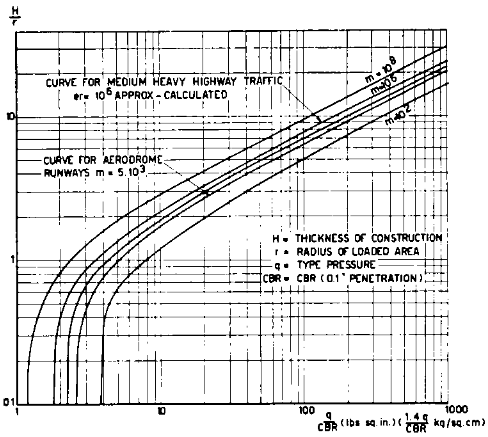

Figure 8. Relation between $\frac{\text{tire pressure}}{\text{CBR}}$ and $\frac{\text{depth}}{\text{radius of loaded area}}$

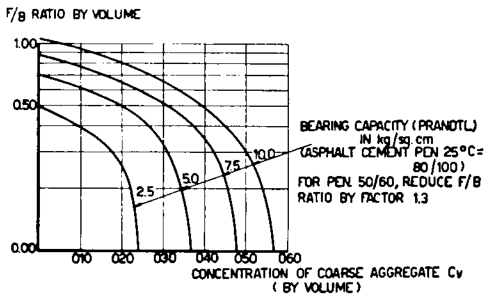

Figure 9. Bearing capacity (Prandtl) in kg. per sq. cm• at 50 C. (binder pen. 80/100 at 25 C.).

$$\frac{H}{r} = \sqrt{\frac{q}{10\ \text{CBR} \times \text{Cm}} - 1},$$

where q = applied stress
Cm = a constant.

From full-scale trials (Californian Highways, runway trials) it can be deduced that for runways with 5×10^3 repetitions of the load $Cm = 0.25$, whilst for roads (about 10^6 repetitions) $Cm = 0.17$.

Figure 8 gives these relationships and permits easy application for varying wheel loads, for which the radius of contact area r and the tire pressure q are known or can be easily worked out.

Kerkhoven further worked out a relation between Cm and the number of repetitions of the load m by tentatively applying the relation known from plate-bearing tests to road traffic.

If this relation is further confirmed by experimental data it is possible to take the intensity of traffic quantitatively into account. His full formula reads

$$\frac{H}{r} = \sqrt{\frac{q}{10\ \text{CBR}}(1.1 + 0.8 \log m) - 1}$$

and is also represented in Figure 9.

The design thus represented is in full agreement with the newer developments in CBR design as found in the literature.

Design of Bituminous Carpets for Static Loads

Static loads give long-duration loading of the carpet, so that the plastic properties of the material are determinative for its behavior. As it is the purpose of design to avoid indentation of the carpet, its resistance to flow must be derived from internal friction and initial resistance. The former is fairly independent of the properties of the binder and therefore independent of temperature. The initial resistance, however, decreases with increasing temperature, and thus, the highest road temperature has to be taken into account.

The maximum vertical stress the material is able to withstand without showing flow (the bearing capacity) has been studied theoretically by Prandtl. His formula is only valid for a material of infinite thickness and for purely vertical loading stress. The low modulus of elasticity of rubber and the great deformability of a pneumatic tire make it probable that the contact stress between type and road will be practically vertical, so that in this respect a standing wheel meets Prandtl's supposition.

However, for normal road constructions the thickness of the carpet H is in general far less than the diameter D of the contact area: tire-carpet, so that there are considerable deviations from the Prandtl assumption.

McLeod[16] has worked out formulas taking into account the friction between carpet and tire and between carpet and base. Experimental work in hand indicates that for road traffic conditions the H/D ratio has little influence on the bearing capacity of a carpet and can be left out of account.

[16] N. McLeod, A rational approach to the design of bituminous paving mixtures. Proc. A.A.P.T. *19* (1950) p. 82–224.

It must be stressed that in considering the stability of the carpet the assumption is made that the base is stable. For design use can be made of the graph published by Nijboer,[17] who drew lines of equal stability against F/B ratio (filler to bitumen by volume) and Cv (concentration of coarse aggregate by volume in compacted mix).

Figure 9 gives a picture for some bearing capacities at +50 C., based on the use of an 80/100-penetration asphaltic cement.

When using a 50/60-grade, the F/B ratios can be reduced by a factor 1.3, whilst a change in temperature of 10 C. can be accounted for by the same factor.

Design of Road Constructions for Dynamic Loads

The behavior of the road construction under dynamic load is being studied at present. Determination of this behavior is now possible. From Van der Poel's work[18] it follows that by measuring the vertical displacement at various spots it is possible to calculate the magnitude of the strains in the carpet. Further work led to direct measurements of the strains with the help of strain gauges. The same method has been successfully ap-aplied to measure the strains under moving traffic; the results indicate the same order of magnitude of the strain.

It was found that under short-duration loading, the shear moduli of base, subbase, and subsoil have values exceeding the static values by a factor 5 or more, and undoubtedly these high values have to be taken into account.

However, it still remains to be seen whether one of the design methods known for the calculation of strains due to a static load on a layered system can be applied with confidence.

It may be that Odemark's method,[19] as worked out for a multilayered system, will lead to the desired result, though the calculations seem rather complicated. Further research is needed to come to final conclusions, but it should be borne in mind that the CBR design method, though represented as valid for static loads, must in itself have an element of dynamic design, as in the experimental work moving (dynamic) loads were applied.

[17] Nijboer, loc. cit.
[18] C. van der Poel, loc. cit.
[19] N. Odemark, Investigations as to the elastic properties of soils and design of pavements according to the theory of elasticity. Statens Väginstitut Meddelande 77, Stockholm 1949.

Whether a separate fully dynamic design will lead to greater thicknesses of the various construction layers must be doubted, though it is possible that the intensity of the traffic will play a dominant part. It will ultimately depend on factors such as properties of the various materials, traffic conditions, whether dynamic or static design will lead to greater dimensions of the various layers.

Design of Bituminous Carpets for Dynamic Loads

Dynamic loading of the carpet occurs under moving traffic, but the conditions vary widely with the speed of the vehicles and with the conditions of driving. Particularly the stresses exerted on the carpet will be greatly influenced by the degree of acceleration or deceleration.

Under a wheel rolling at constant speed the stress will be mainly vertical. Under a decelerating or accelerating wheel the friction between tire and carpet will reach high values, and the shear stress may be as high as 60 percent of the vertical stress. For dynamic design of an asphalt carpet we have therefore to consider both cases, which renders our our design two-fold: (1) design for decelerating (accelerating) traffic and (2) design for traffic at constant speed.

Design for Decelerating (Accelerating) Traffic. Accelerating and decelerating traffic will exert a horizontal stress on the carpet in addition to vertical stress.

For the normal deceleration the coefficient of friction (the ratio of horizontal to vertical stress) will, according to Moyer,[20] not exceed 0.4, higher values only being applicable to emergency cases (blocked wheels). This will occur occasionally, but for normal driving blocking of the wheels will be avoided by the driver as it increases the danger of skidding. For design a coefficient of friction of 0.4 will therefore be adhered to.

The time of loading can be calculated by considering that at the low speed of 3.6 Km. per hr. of the vehicle or 1 m. per. sec. a 30-cm. tire-road contact area will be exposed to the stress for ⅓ sec.

The vertical stress can be taken equal to the tire pressure, the horizontal stress equal to 40 percent of this value.

Assuming sufficient friction between carpet

[20] R. A. Moyer, Vehicle Costs, Road Roughness and Slipperiness. Proc. Highw. Res. Bd. *22* (1942) p. 50.

and base plastic flow in the carpet will take place in the absence of initial resistance when the internal friction of the carpet is below 0.4. It is clear that this condition will always be met for mixes containing voids, but the problem as stated does not take the accompanying deformation into account.

On the strength of the fact that on compression it was found that 1 percent strain is elastic, and in view of the repetitions of the load it follows that the permissible shear stress is limited by this 1-percent strain, so that

$$\tau = \frac{\tau}{\gamma} \times 0.01$$

taking $\tau = 0.4p$ it follows that

$$0.4p = \frac{\tau}{\gamma} \times 0.01 \quad \text{or}$$

$$\frac{\tau}{\gamma} = 40p$$

(p = tire pressure, $\frac{\tau}{\gamma}$ = stiffness at ⅓ sec. loading time, and at the highest road temperature, so at +50 C for moderate climates). As the support of the carpet at the periphery of the contact area has been neglected a safety factor, which may be assumed to be of the order of 1.5 or perhaps 2, is taken into account.

The values of $\frac{\tau}{\gamma}$ can be derived from curves as given in Figure 4 for a certain sandsheet mixture, by making use of the following rules:

A temperature difference of 10 C. corresponds to a variation by a factor of about 10 in the time of loading, so that ⅓ sec. loading time at +50 C. corresponds in the $\frac{\tau}{\gamma}$ value with 330 sec. at +20 C. A time factor 6 accounts for the difference between a 50/60- and an 80/100-penetration asphaltic cement at 25 C. Therefore, at 2,000 sec. loading time at +20 C. for a 50/60-penetration asphalt the same $\frac{\tau}{\gamma}$ value is found as for ⅓ sec. loading time at +50 C. for an 80/100-penetration asphaltic cement.

This has been worked out for mixtures with various F/B ratios and with various amounts of coarse aggregate. From the data the values

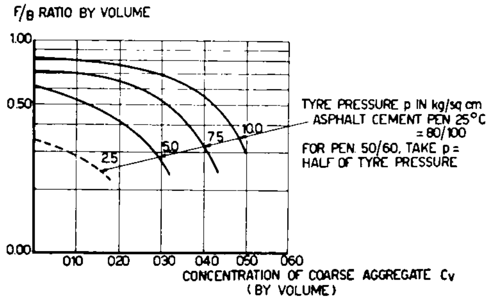

Figure 10. Resistance to decelerating traffic at various tire pressures.

of the F/B ratio for various coarse aggregate contents have been calculated as corresponding with various tire pressures. The results are represented in Figure 10.

It should be pointed out that to account for a factor 2 in the penetration at 25 C of the binder, which influences the value of $\frac{\tau}{\gamma}$ by a factor of 2, it suffices to apply a corrected tire pressure, equal to half the actual one.

Design for Traffic at Constant Speed. At constant speed the stresses exerted on the carpet will be mainly vertical, but here we have to take very short loading times into account. These times may be as short as 1/100 sec. for traffic moving at the rate of about 100 Km. per hr., so that the values of the $\frac{\sigma}{\epsilon}$ modulus will be very high, especially at lower temperatures. As the carpet bends under the load this will lead to high bending stresses, which will have values that may approach the strength of the carpet. A repetition of loading may sometimes lead to fracture. For a quantitative interpretation the strains and stresses under moving loads must be accurately known, together with details of the breaking strength of the material.

The study of this problem is not yet advanced far enough to permit a definite opinion in this respect, but it can be stated that strains of the order of 10^{-4} and stresses of 20 kg. per sq. cm. are quite possible. As the fatigue strength of the material on repeated loading falls below this value, the cracking of asphalt carpets must be at least partly due to these phenomena.

Though no quantitative interpretation is at the moment possible, some qualitative answers can be given. It has already been found that on increasing the F/B ratio in sandsheet mixtures the quality $\frac{\sigma}{\epsilon}/F$ $\left(\text{proportional to } \frac{\text{stress}}{\text{strength}}\right)$ increases in value, as does also the risk of cracking. The same probably holds on increasing the stone content in a sandsheet mixture, and so it is clear that any increase in F/B value over the one needed to obtain sufficient stability to stationary traffic or to moving traffic is detrimental to the quality of a carpet. The use of a soft binder is favorable in this respect.

A more-definite opinion can be expressed when the influence of thickness and the quality of the various construction layers on the magnitude of the strains in the carpet has been established quantitatively. It may then be possible to decide upon measures to make sure that the carpet will be able to follow the strains imposed on it.

Composition of Asphaltic Mix

Finally some remarks should be made about the way in which a road carpet with the desired properties can be obtained. In the previous chapters these properties were discussed in mechanical terms and related to F/B ratio, percentage of coarse aggregate and hardness of the binder. From these design considerations it follows that for given traffic and subsoil, subbase, and base conditions a certain value of the F/B ratio at given concentration of coarse aggregate and a given penetration of the asphalt cement is needed to obtain sufficient resistance to stationary load and to decelerating (accelerating) traffic.

It was further stressed that with regard to cracking of the carpet it is advisable, on the strength of the above considerations, not to surpass the minimum value of the F/B ratio.

It further remains to consider by which ways and means a mixture with the desired properties can be obtained.

A graphical method has been indicated by Nijboer.[21] A drawback of this method is however that, as the properties of the filler have a considerable influence on the voids in the aggregate, this influence must be known for the fillers under consideration to enable the designer to work out his mix by the graphical method only.

In general, it might be preferable to adhere to local practice and this is quite feasible if the following considerations are taken into account: (1) The compacted mix must have sufficient voids (2 percent by volume or more). (2) At the proposed asphalt content the void content in the aggregate must have its minimum value. Both criteria are incorporated in the Marshall design method,[22] but its stability criterion is not used here, as the stability of the possible mixes is judged on the strength of the mechanical properties as expressed by F/B ratio, stone content, and hardness of the binder, taking into account time of loading and temperature.

It must be stressed that the composition of the mix to be used is restricted to one meeting the following conditions: (1) F/B ratio and (2) stone content, as follows from design, based on mechanical properties; (3) hardness of binder; (4) sufficient voids (>2 percent vol.); and (5) minimum voids in aggregate.

If a check is needed on the stability to standing load the triaxial shear method at low rate of deformation (W. Smith method)[23] or at equilibrium (Nijboer method)[24] are preferable to any relatively rapid deformation test. Unconfined-compression tests can be used to determine the stability of the carpet to decelerating traffic. For control work on the job various types of tests are suitable. Here the Marshall test has the advantage that its flow figure gives another warning of lack of voids. The stability figure can be used to compare the mechanical properties of field samples with those of samples prepared during the design work in the laboratory.

DISCUSSION

RAYMOND C. HERNER, *Chief, Airport Division, CAA Technical Development and Evaluation Center*—Nijboer has performed a useful service in outlining the theoretical background for pavement characteristics and service behavior with which many of us are familiar. More important, he has provided quantitative information on such factors as viscosity,

[21] L. W. Nijboer, loc. cit.

[22] See U.S.A. Corps of Engineers, Techn. Memorandum 3-254, Waterways Exp. Station Vicksburg.

[23] W. Smith, Manual on Hot Mix Asphaltic Paving Concrete. The Asphalt Institute.

[24] L. W. Nijboer, loc. cit.

duration of loading, angularity of particles, and percentage of filler. Unfortunately, the consideration of all these factors in a design problem is sufficiently complicated that the average design engineer will tend to continue use of the most convenient empirical approach. Also, the data are not complete in all respects. It is the responsibility of research organizations, therefore, to supply additional factual data where the present information is incomplete, and to present the whole in a simple form for design use.

Nijboer is correct in pointing out that the California bearing test is simply a miniature plate-bearing test. The writer, however, cannot agree to the implication that the two tests may be used interchangeably for determination of a "modulus of deformation." Although Nijboer mentions tests on sand where identical moduli were obtained from the two test methods, the writer has records of many plate-bearing tests where significant differences in moduli seem to be due to moderate variations in plate diameter. This appears entirely reasonable when one considers that the conditions of a field plate-bearing test may vary widely from the ideal situation visualized in Boussinesq's formula. Under the circumstances it would appear unwise to use the CBR for determination of the modulus of deformation in design problems involving large loading areas.

L. W. Nijboer, *Closure*—Herner's discussion draws attention to the complicated character of asphalt pavements and his desire for simplification is fully appreciated by the author, who would like to point out, however, that several of the graphs given in the paper are certainly not more difficult to apply than those normally used in other branches of engineering.

Completion of design data in the field of dynamic loading is undoubtedly a necessity and may be closer at hand than was anticipated at the time when the paper was written.

The discussion on CBR versus plate bearing test is much appreciated as apparently the wording of the paper leads to a slight misunderstanding. The author wanted to point out that as a matter of principle CBR and plate-bearing tests are essentially the same to which Herner agrees.

This point of view was confirmed by some tests on sand.

Now the greater part of the deformation in such tests is confined to a zone the depth of which bears a given ratio to the diameter of the loaded area.

In a CBR test this zone will probably consist of a single type of material, but in plate-bearing tests several layers of a road construction with their differences in properties may be involved and thus lead to complications.

Another point that needs investigation arises when pore pressure is developed in the material due to the loading as the time for release of this pressure is restricted and so the deformations will be influenced by the dimensions of the area affected.

An investigation along the lines indicated above may considerably help to come to a better understanding of the results obtained in tests of the types discussed above.