Flexure of a Road Surfacing, Its Relation to Fatigue Cracking, and Factors Determining Its Severity

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This paper describes some aspects of theoretical and experimental work carried out in South Africa, over the past four years, in a study of "chicken net" cracking of a road surfacing, and of the flexure induced in it by wheel loads.

The accuracies of common measures of the severity of flexure are discussed. Of these, radius of curvature has been adopted for general testing. Results of field observations which reveal a distinct relation between curvature and degree of cracking of a surfacing are presented, a radius of about 125 ft being critical in the case of one road studied.

A field study is described which revealed that Elastic Theory is applicable to a limited extent in regard to the deflection and curvature of a road under its normal traffic.

A number of factors which affect the severity of the flexure developed beneath a wheel load are discussed. Curvatures are practically independent of the nature of the materials below a depth of about 15 in., and depend mainly on the materials of the base and subbase. Curvatures are affected considerably by the tire pressures of the vehicle inducing them, but little by the wheel load.

Existing design methods do not appear to take adequate account of flexure cracking, and the likely form of possible additional design considerations is discussed.

AMONG THE possible causes of failure of a flexible road is "chicken net" cracking of the bituminous surfacing. Although in many cases it is not at first accompanied by loss of shape of the surface, such cracking can lead to failure, either by raveling and potholing of the surfacing, or by permitting rainwater to enter the foundations, with the possible consequence of loss of shape due to shear deformation. Cracking in this pattern may sometimes be attributed to internal changes in the bituminous surfacing. Work published by Hveem in 1955 (1), substantiating previous hypotheses, led to the now generally-accepted view that "chicken net" cracking may also represent fatigue failure under the repeated stresses in the surfacing which accompany the compression of the foundations and flexure of the surfacing under traffic wheel loads. It has not yet been established which of the stresses in the surfacing is the actual cause of the cracking, but it is likely that the tensile stresses at the points of greatest flexure play an important role (2, 3).

It appears that this type of failure is not adequately considered by normal methods of design, which are concerned mainly with the prevention of shear and consolidation failure in the foundations.

In about 1957, a problem arose in South Africa on the major road between Pietermaritzburg and Durban which, although designed generally in accordance with accepted CBR methods, and exhibiting no loss of shape of the surface, developed chicken net cracking in the thin premix surfacing over the major portion of its length. The heavy maintenance work undertaken proved to be of only temporary benefit, cracks often reappearing within a year. The National Institute for Road Research was invited to look into the reason for the cracking, and the investigation carried out gave the major impetus to the study of the flexure of road surfacings described in this paper.

A considerable amount of research is being carried out on flexure cracking in various parts of the world today. The work is concentrated mainly on studies of the flexibility of bituminous surfacings (2, 5), and on measurements of flexure in the field (5, 11). The emphasis in this Institute has been on the flexure developed beneath a wheel load in the field, and the various factors which affect its severity. The only similar study known to the author is that of Franck (12), which unfortunately only came to his attention during the preparation of this paper.

The first portion of the paper is devoted to a discussion of the various properties which may be used as a measure of the severity of flexure, and to field observations of the relations between two of these properties and the occurrence of cracking. Next, a study of the validity of applying Elastic Theory to a road structure is described, and the effects on the severity of flexure of various factors relating to the traffic and foundations are discussed. Finally, some aspects of a possible method of design to guard against flexure cracking are discussed briefly.

MEASUREMENT OF FLEXURE OF A ROAD SURFACING, AND SOME OBSERVATIONS OF CRACKING

If chicken net cracking represents fatigue failure of the surfacing under excessive stresses, then any study of the cracking should ideally include measurement of these stresses. The stress in a road surfacing would, however, be extremely difficult to measure. An indirect indication of its magnitude may be obtained by measuring the strains, provided the elastic moduli of the surfacing are known. In this regard, laboratory tests on bituminous mixtures by Saal and Pell (2), have suggested that strain may be more conveniently related to fatigue failure than stress, but more evidence is required before a conclusion such as this can be accepted, and stress must, for the present at least, continue to be regarded as the criterion for failure. Even strains, however, are difficult to measure in a road surfacing, and, except in special research investigations where such measurements have been carried out with success, some more simple measure is often desirable.

If an approximate measure is acceptable, then radius of curvature of the surfacing (or its reciprocal, curvature) may be used as an indication of the stresses. Curvature on its own cannot be an accurate measure, as other variables on which the stresses depend, such as the thickness of the surfacing, its Young's modulus (dependent on both its type and temperature), the Young's moduli of the foundations, and details of the traffic loading, all remain unspecified. The position can be improved slightly if reference is always made to the type, thickness, and temperature of the surfacing on which any curvature measurement is made.

The degree of approximation is further increased if only the maximum deflection beneath the wheels is measured. In addition to the other variables mentioned, that of horizontal dimension, or sharpness of the deflection pattern, now remains unspecified.

Although deflection would thus appear to be the least accurate of the four measures, and in fact to give no more than an approximate indication of the stresses, it is also the simplest to determine, and has come into widespread use. The theoretical indications that curvature would be a better measure appear to be recognized by many workers, but very few actually measure curvatures in practice.

Returning briefly to the neglect of the effects of stiffness and thickness of the surfacing when curvatures or deflections are measured, theory reveals a complex interrelation between these properties and the stresses, from which simple, generally applicable trends cannot be drawn. It is apparent, however, that for a given curvature or deflection, the flexural stresses are by no means constant but increase markedly with an increase in either the Young's modulus or the thickness of the surfacing. The trends between permissible deflection and thickness of surfacing given by Hveem (1), serve as an illustration of these effects. This dependence of stresses on the thickness and stiffness of the surfacing is discussed in more detail later in this paper.

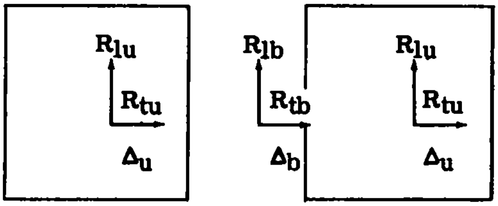
When deflections or curvatures are used as an indication of flexure, it is the general

TABLE 1

COMPARISON OF DEFLECTIONS AND CURVATURES UNDER AND BETWEEN DUAL WHEELS

SITE	$\frac{\Delta_u}{\Delta_b}$	$\frac{R_{lu}}{R_{lb}}$	$\frac{R_{tu}}{R_{lb}}$	$\frac{R_{tb}}{R_{lb}}$
A	1.19	0.85	0.73	-0.47
B	1.18	0.83	0.60	-0.47
C	1.07	0.81	0.72	-0.56
1	1.22	0.83	0.50	-0.38
2	1.13	0.83	0.49	-0.50
3	1.10	0.76	0.50	-0.52
4	1.08	0.93	0.75	-0.71

Symbols for deflections (Δ) and radii of curvature (R) induced by dual wheels



Test sites on Route 3/1 9,000- lb dual wheel load 75- psi inflation pressure 11 in. between centers of wheels.

practice to measure them between the dual wheels of a vehicle. The values so obtained are seldom, however, the highest occurring. This is apparent from the results of some tests carried out on a road in Natal (Fig. 1 and Table 1). The structure of this road was generally made up of a 1-to 2-in. premix surfacing, an 8-in. crushed rock base course, and a 6-in. silty-sand subbase, overlying a variety of natural materials. It is evident from the results that, for the conditions on this road, the deflections directly under the wheels, Δ_u, are higher than those between them, Δ_b, and also that the transverse radii of curvature, both between the wheels, R_{tb}, and under them, R_{tu}, are somewhat less (that is, more severe) than the longitudinal radius, R_{lb}, between the wheels normally measured. (These results seem to suggest that the transverse curvatures between the wheels are the ones most likely to cause cracking, because, in addition to the fact that these curvatures are the sharpest, the tensile stress occurs on the upper surface where weathering is likely to cause a deterioration in the bituminous material. The longitudinal elongation observed in many chicken net crack patterns is, as has been pointed out by others (3, 12), another indication that the factors giving rise to cracking are most severe in the transverse direction.) In addition, theory indicates that the relation between Δ_b and Δ_u, or between R_{lb} and either R_{tb} or R_{tu} is not a constant, but varies with the dimensions and spacing of the tire imprints and the relative elastic moduli and thicknesses of the layers of the structure. For example, in the case of a road where the Young's moduli of the surfacing and base are high, relative to those of the lower layers, a vehicle with closely-spaced tires may induce a completely different pattern of deflection, with Δ_b greater than Δ_u, and with R_{tb}, reversed in sign, less severe than R_{lb}. It becomes plain, therefore, that the deflection or curvature normally measured is neither equal to, nor constantly related to, the most severe occurring, and that yet another approximation is contained in the common procedure of using deflection or curvature as a measure of the stresses in the surfacing.

In the general testing work conducted in this Institute, a compromise between accuracy of representation of the stresses and simplicity of measurement has been adopted, and the longitudinal radius of curvature between dual wheels employed as the basic measure of flexure. A standard Benkelman beam is used for the measurement, deflections being recorded when a truck with dual rear wheels straddling the instrument stops

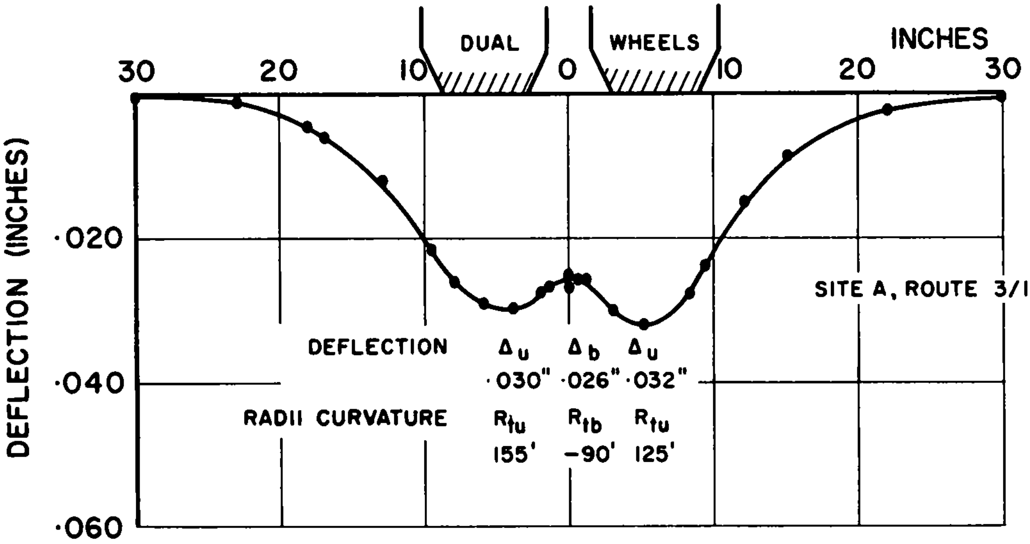


Figure 1. Typical example of transverse deflection pattern beneath dual wheels.

briefly every 6 in. of its travel over a distance of 4 ft on either side of the point of measurement. The longitudinal deflection pattern (actually an "influence" curve) is plotted from the results and the radius of curvature obtained by determining the radius of the circle of best fit to the plot at the point of maximum deflection (13). More recently this plot has been obtained directly on an X-Y recorder, using a Linear Variable Differential Transformer (LVDT) mounted on the Benkelman beam and a "Helipot" resistance attached to the wheel of the truck. It has been found that the repeatability of curvature measurements is not as high as that of the corresponding maximum deflection measurements, possibly because of the difficulty in stopping the truck at exactly 6-in. intervals. The accuracy has been improved with the introduction of the instrumented procedure, but as will be seen in curvature values quoted elsewhere in this paper, some scatter remains.

Deflections and radii of curvature have been measured on a number of roads in South Africa in varying conditions (11). An example of the results obtained on one of these is shown in Figure 2.

A distinct relation is evident between both the deflection and the radius of curvature developed under the test vehicle, and the condition of the surfacing. The fact that such relationships exist is taken as an indication (although not as a proof) that the chicken net cracking under consideration is in fact due to excessive flexures and, therefore, probably to excessive stresses in the surfacing — a confirmation of Hveem's findings. There is, however, a considerable amount of scatter in the plotted points. Probable reasons for this include the neglect, in these plots, of the effects of Young's modulus, thickness, fatigue strength, and age or traffic history of the surfacing, and the measurement of deflections and curvatures which were not the most severe occurring. It has not as yet been possible to isolate in the field the effects of any of these factors.

Further, it is seen from Figure 2 that for the 1- to 2- in. dense premix surfacings encountered on this road, and for the particular wheel loads and tire pressures used in the measurements, a deflection of about 0.055 in. and a radius of curvature of about 125 ft are critical, more severe values being associated with cracking. By comparison, critical deflections quoted by other workers for apparently similar surfacings vary between 0.025 and 0.050 in. (1, 6, 9, 12).

The existence of the relationships between deflection or curvature and the condition of the surfacing cannot be taken as evidence that both deflection and curvature are accurate measures of the stresses in the surfacing. In fact, these relationships merely indicate that in practice high stresses in the surfacing are, on the average, accompanied by high values of both deflection and curvature. Similarly, the fact that the deflection-condition relationship is almost as good as that for curvature cannot be taken as an indication that, contrary to the previous theoretical predictions, deflection is as good a measure of the stresses as curvature. Other effects could also give rise to a similarity between these two relationships. For example, although in individual cases deflection and curvature are by no means constantly related to one another, when results obtained on a variety of types of foundations under mixed traffic are considered

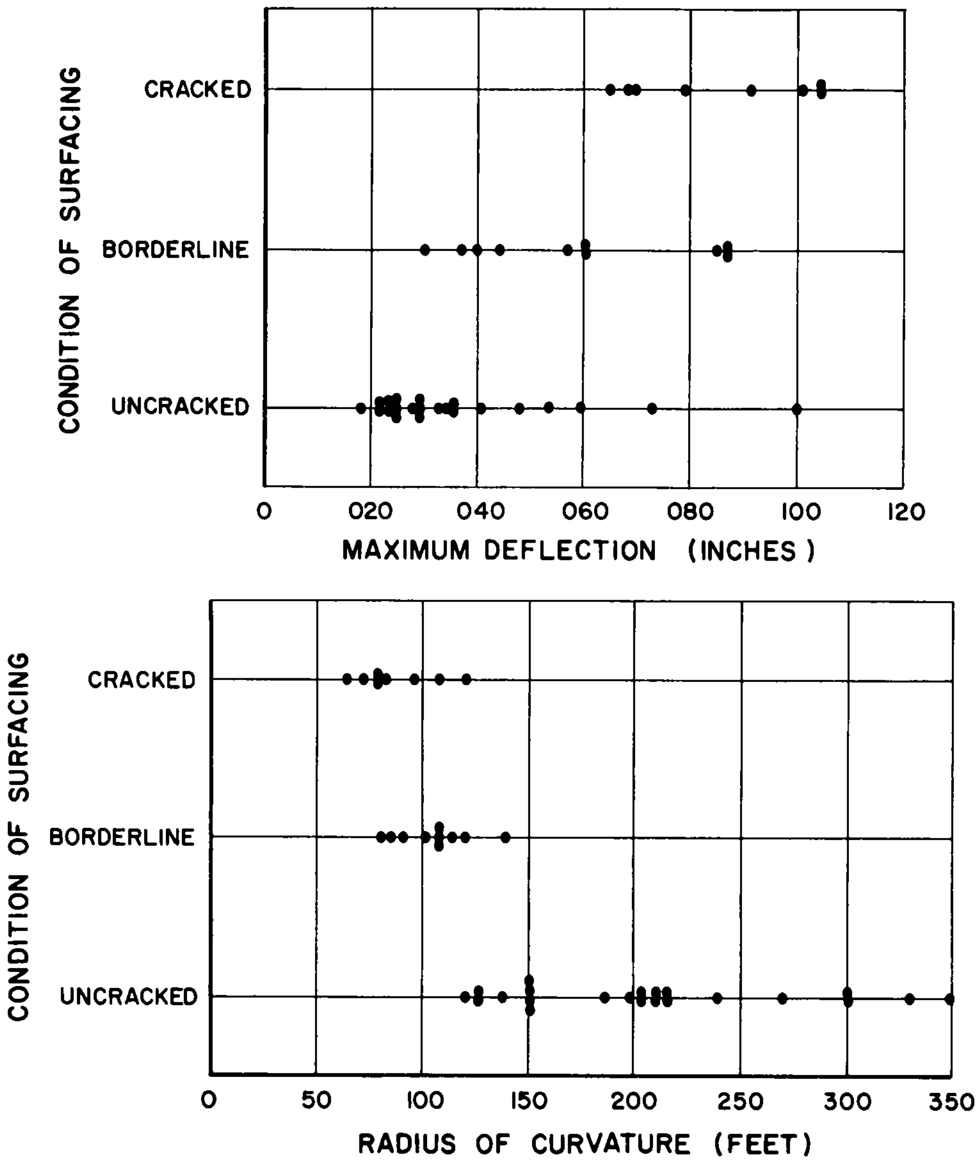


Figure 2. Relations between the degree of cracking of a surfacing, and the deflection and curvature induced by a dual wheel load (Route 3/1, 10,000-lb load at 90 psi, 1-to 2- in. premix surfacing).

together, on the average high deflections would be expected to accompany high curvatures and, therefore, apart from scatter, to be related to condition in a similar manner to curvature. Theoretical considerations thus remain the only indications at present as to the relative accuracies of deflection and curvature as measures of the stresses, and these favor curvature, as discussed previously.

Although deflection and curvature might be acceptable measures for general or routine testing, they are at best only approximately related to the stresses causing the cracking. For this reason, research using a more accurate measure, such as the strain in the surfacing, would be very desirable.

STUDY OF VALIDITY OF APPLYING ELASTIC THEORY

In much of the work conducted in studying the severity of flexure developed under a wheel load, Elastic Theory was employed at one stage or another. Use of this theory, however, was preceded by an investigation into the validity of applying it to a road structure, carried out on the major road referred to previously (14). This investigation is described in the following sections.

First, plate bearing tests of a specialized nature were conducted at twelve sites, to determine the Young's moduli of the layers of construction. Tests were carried out on the top of each layer, successive layers being removed by hand labor over an area of 12 ft by 12 ft. Inasmuch as the only concern was with those properties of the materials brought into play by normal wheel loads, and not with any consolidation or plastic shear, an attempt was made to limit the stresses applied to the same order as those to which the road had been subjected by traffic during its life. To this end, the mean pressures to be applied by the plates at various depths were selected in accordance with approximate calculations, based on Elastic Theory, of the stresses under a 9, 000-lb wheel load at 75- psi tire pressure. Because the assumption of homogeneity within the layers would probably not be fully met, an attempt was made to simulate the traffic further by increasing the plate size with depth, from 12 in. on the surface to 24 in. on the subgrade. The loads were applied as rapidly as possible, and three or four repetitions employed to reduce errors due to initial bedding of the plate. When the resulting curves were plotted, it was observed that the load-deflection relationship in the last cycle was practically linear, indicating that the assumption of linearity on which Elastic Theory is based is fairly well justified in a road subjected to stresses of the same order as those applied by its normal traffic. This was not the case, however, when higher stresses were applied. A pronounced hysteresis in the unloading cycle indicated that Elastic Theory would be less valid for decreasing loads. Very little permanent deformation occurred after the third cycle, indicating that the assumption of elasticity was also justified. Young's moduli of the subgrades were computed from the slope of the loading curve on the last cycle using Boussinesq theory, assuming a Poisson's ratio of 0. 5, and those of the subbases computed using Burmister's two-layer theory (15). (This theory unfortunately applies to a flexible loaded area, and in using it for the case of a rigid plate, as other workers had done, an error of unknown, but possibly considerable magnitude was introduced.) Because the surfacings were thin, the base and surfacing were taken together, and a combined modulus obtained using Odemark's approximate solution for a multi-layered system (16).

Second, before the excavations at these sites were begun, deflections and curvatures of the surface were measured between dual wheels in the normal way. At five of the sites, deflections and curvatures were also measured at various depths beneath the surface using a specially developed instrument fitting into a 1 1/8- in. diameter borehole. Deflections picked up at the desired depth were measured by means of an LVDT, which was referenced to a point 6 ft below the surface (10 ft in later tests). In order to have more simple loading conditions, single wheels were fitted to the truck, which then passed directly over the point of measurement.

With these two independent sets of observations it was possible to obtain a check on the validity of applying Elastic Theory. Deflections and curvatures of the surface and deflections at depth were computed from the Young's moduli measured, using Odemark's theory, and compared with those observed under the truck. (The fact that the Young's moduli used in these computations were themselves based on Elastic Theory was unfortunate, as it was later found that the isolation of reasons for discrepancies between observed and computed values was made more difficult.) Because of the doubtful validity of Odemark's theory away from the axis of load, no attempt was made to compute deflections or curvatures between dual wheels and, in the case of such tests, computations were made simply for a single circular load of the same area as the dual wheel imprint. The results are shown in Figures 3 and 4.

First, it is seen that there is a fair relation between the observed and computed deflections in Figure 3a. The scatter is probably due, in part, to experimental errors. In the tests with dual wheels, it is also probably due to the fact that the deflections beneath a single loaded area and those at a point between dual loads are not constantly related to one another, as discussed previously. A comparison between the absolute values can be made in the case of the tests with single wheels, and a major discrepancy is evident here in that computed deflections are some 30 percent less than those observed. No experimental error likely to cause a difference of this magnitude is apparent, and the discrepancy must therefore represent some limitation in the applicability of the theory.

The second test, the comparison of measured and computed curvatures, is more exacting, in that curvature is a more complex property than deflection, and it would be expected that any difference between theory and practice would be magnified. The relationship in Figure 3b is seen to be more scattered than that for deflections. Further, there is again a large difference between the absolute values, the radii of curvature computed beneath a single wheel being some 60 percent higher than those observed, for which no reason other than a limitation in the applicability of the theory is apparent. Viewed in another way, the deflections observed were more concentrated about the load than is indicated by theory. This was also the case at depth, the deflection pattern at subgrade level being more concentrated than even the Boussinesq theory for homogeneous

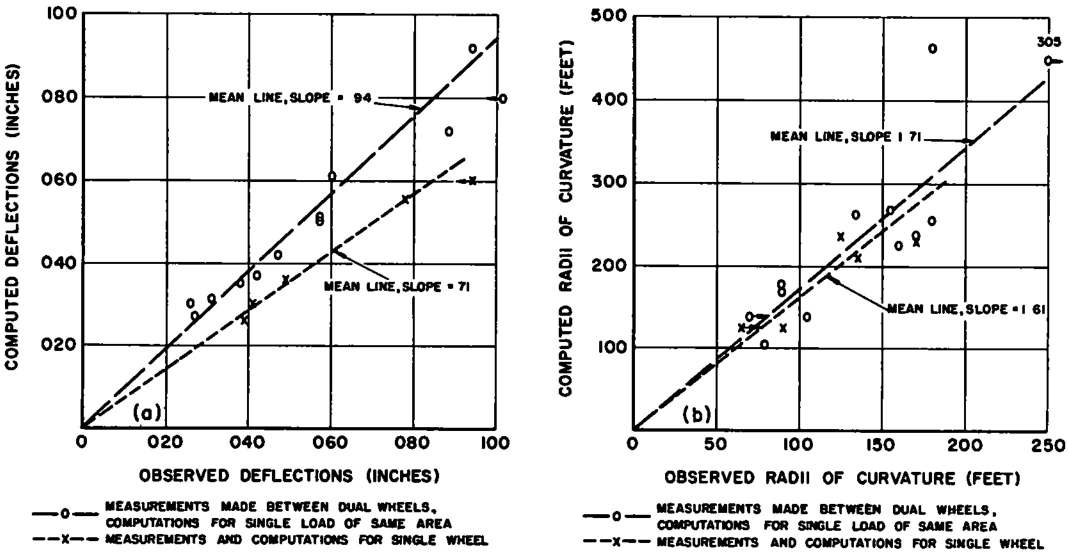


Figure 3. (a) Comparison of observed and computed deflections (Route 3/1); (b) Comparison of observed and computed radii of curvature (Route 3/1).

materials indicates. A similar effect was noted in the Waterways Experiment Station test on homogeneous soils (17). It is possible in the case of a layered structure that this is due to the lack of tensile strength in a crushed rock base course. Tensile resistance is implicit in Elastic Theory, and if the high tensile stresses in the upper layers cannot be carried, there will be less "slab effect" and more concentration of the deflections than indicated by theory. An error such as this would also have affected the moduli determined from the plate tests. The fact that the two errors would tend to cancel one another suggests that the true error is even greater than the difference indicates. It is possible that the observed discrepancies might be reduced by the introduction of some form of concentration factor into the theory, as has been suggested previously for stresses.

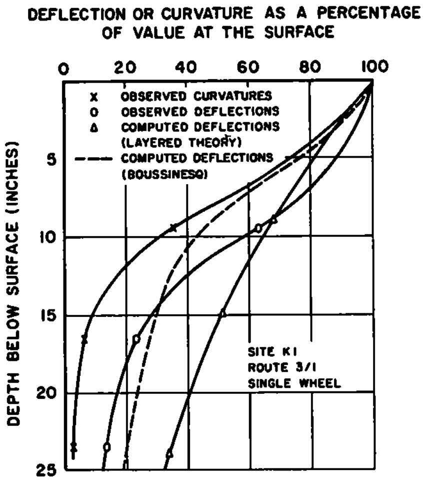


Figure 4. Comparison of observed and computed variation of deflection with depth.

The third check of the theory relates to the variation of the deflection with depth. A typical result is shown in Figure 4. The most striking fact, which recurs to a greater or lesser extent in all the tests, is that the reduction in observed deflection with depth was more rapid than that computed. This was most pronounced in the lower layers where in many cases, such as the one pictured here, deflections were less even than those computed from Boussinesq theory. Independent checks revealed that this was not an experimental error due to excessive movement at the depth of founding of the reference rod (6 or 10 ft); in fact, movements at this depth were also smaller than those predicted by theory. No other likely experimental error is apparent. The Waterways Experiment Station tests gave similar results.

The results of the study indicate that differences exist between Elastic Theory and practice, mainly in that deflections are more concentrated about the load than indicated by theory, and that they decrease more rapidly with depth. Although it would be of considerable value if the actual reasons for these differences could be established, this is not essential for the problem under consideration. It may be concluded from the results that Elastic Theory, for a given type of construction and under the normal traffic, may be used with fair confidence as far as relative values of deflections at the surface are concerned and also, although with a lesser degree of confidence, for relative values of curvature at the surface. Elastic Theory could therefore be used, for example, to indicate qualitatively a deficiency in any of the layers of construction, or to indicate general trends in the effects of certain variables on deflection or curvature.

FACTORS DETERMINING SEVERITY OF FLEXURE

In the course of the investigations into the road failures referred to previously, a considerable amount of attention was paid to possible reasons for the severe flexures which developed under traffic loads. Some of the findings of this study are as follows.

Factors Relating to Road Structure

As became evident in the previous section, deflection of a road structure under a wheel load is an elastic phenomenon, and the magnitudes of the deflection and curvature developed are dependent on the elastic moduli of the layers of construction, together with their thicknesses. Elastic Theory, however, reveals an important difference between deflection and curvature in this regard. This is given in Table 2, where the effect of a change in the Young's modulus of any one of the layers of construction on the deflection and curvature at the surface has been computed for a range of flexible road structures using Odemark's theory. It is seen that, while the value of the maximum

TABLE 2

DEPENDENCE OF DEFLECTIONS AND CURVATURES ON STIFFNESSES OF MATERIALS IN UPPER AND LOWER LAYERS OF FOUNDATIONS

Layer	Thickness[a]	Percentage Change in Deflection or Radius of Curvature at Surface Resulting from a 50 percent Change in the Young's Modulus of the Layer Indicated					
		Case 1[b]		Case 2[b]		Case 3[b]	
		Δ	R	Δ	R	Δ	R
Surf and base	8 in.	16	38	14	32	21	32
Subbase	8 in.	11	9	9	13	11	14
Subgrade	Semi-infinite	25	3	28	5	19	4

[a]Assumed a 12-in. diameter circular load-equivalent to 9, 000 lb at 75 psi.
[b]Computed for the following relative Young's moduli of the layers (base, subbase and subgrade): Case 1—10:2:1; Case 2—10:5:1; Case 3—4:2:1.

deflection is dependent to a large degree on the Young's moduli of the materials at depth (subgrade and below) in addition to those of the upper layers, the radius of curvature is dependent mainly on the moduli of the upper layers of construction, and very little on those of the materials at depth. The shortcomings found in Elastic Theory in the previous section would mean, if anything, that the effects of the materials at depth were even less. (If desired, the dependence of curvature mainly on the materials in the upper layers of construction may be visualized simply by considering the small area of the base which is stressed by the wheel, contributing a sharp depression and curvature, and the larger area of subgrade stressed by the spreading load, which contributes a more gentle deflection pattern.) Comparisons between deflection and curvature were also obtained experimentally in the subsurface tests referred to previously. A typical example of the results is shown in Figure 4. It is evident that the curvature developed in regions closer to the surface than did the deflections, substantiating the foregoing theoretical indications, qualitatively at least.

As might be expected from Table 2, Elastic Theory indicates that, although a very poor subgrade could give rise to curvatures at the surface of a severity normally associated with cracking, this would be an extreme case. If curvature is an adequate measure of the stresses giving rise to cracking, and a better measure than deflection, then for all practical purposes the nature of the materials below a depth of 15 or 18 in. would not appear to be of any importance as regards flexure cracking—a conclusion of considerable importance in regard to design, and one contrary to the present general belief that the "resilience" of the subgrade is the important factor.

The factor requiring the main consideration in design against flexure cracking, therefore, is that of the Young's moduli of the materials in the upper layers and particularly in the base. Common design specifications usually preclude the use of anything but a high-quality material in the base, and to a lesser extent in the subbase. It is, however, not as yet known whether these materials, although being of "high quality" in the general sense of the term, will always also possess a correspondingly high Young's modulus. There are, in fact, indications to the contrary, among which is the experience in Natal with certain subbase materials which were generally satisfactory as regards CBR, but unsatisfactory as regards Young's modulus (14).

Turning now to a second structural aspect, it appears that the laying of a thin (up to 1 1/2-in.) chip and spray or premix surfacing has very little effect on the deflections or curvatures developed under a wheel load. This is not the case with a thick (4-in.)

dense asphaltic concrete which, with its high Young's modulus and "slab" action, may have a considerable effect in reducing the flexures developed. For example, at a site near Pinetown in Natal, a 4-in. overlay of rolled asphalt to B.S. 594 reduced deflections from 0.057 to 0.028 in., and increased radii of curvature from 90 to 350 ft (14). Similar effects of asphaltic premixes in decreasing the pressures transmitted to the subgrade have been described by Whiffin (18).

In discussing surfacings, however, curvature does not give a sufficiently true indication of the flexural stresses and, the aforementioned advantages are offset to some extent by the general increase in stresses for a given curvature as the thickness or modulus of the surfacing increases. Turning to theory, it appears that for the case of a single wheel, stresses are a maximum in a surfacing of some intermediate thickness —for greater thicknesses the reduction in curvature due to the structural effect predominating over the tendency for the stresses to increase, and inversely for thinner surfacings (16, 19, 20). For common foundations, types of surfacings, and traffic, theory gives this critical thickness as being in the range 2 to 4 in. There is, however, not sufficient evidence at this stage for it to be suggested, for example, that intermediate thicknesses be avoided in design. Similarly, theory indicates that an increase in Young's modulus of a surfacing will generally result in an increase in the flexural stresses. An increase in Young's modulus, therefore, appears to be a disadvantage as regards flexure cracking although, in practice, depending on the design of the surfacing, this is often offset by an accompanying increase in the fatigue strength (3).

Factors Relating to Traffic

In addition to being dependent on the properties of the foundations, the flexure developed under a wheel load is affected by various factors relating to the traffic.

The effects of wheel load and tire inflation pressure on the flexure developed were studied at six of the sites referred to previously, by varying each independently in a series of tests. The surface deflection pattern was measured with the subsurface instrument, one of the dual wheels passing directly over the point of measurement. Inflation pressure was selected as one of the variables in preference to the contact pressure between the tire and the road surface (from which it differs considerably), because although contact pressure was the more fundamental property and of interest to the research worker, it was inflation pressure which was of greater interest to the practicing engineer. Typical results obtained are shown in Figure 5.

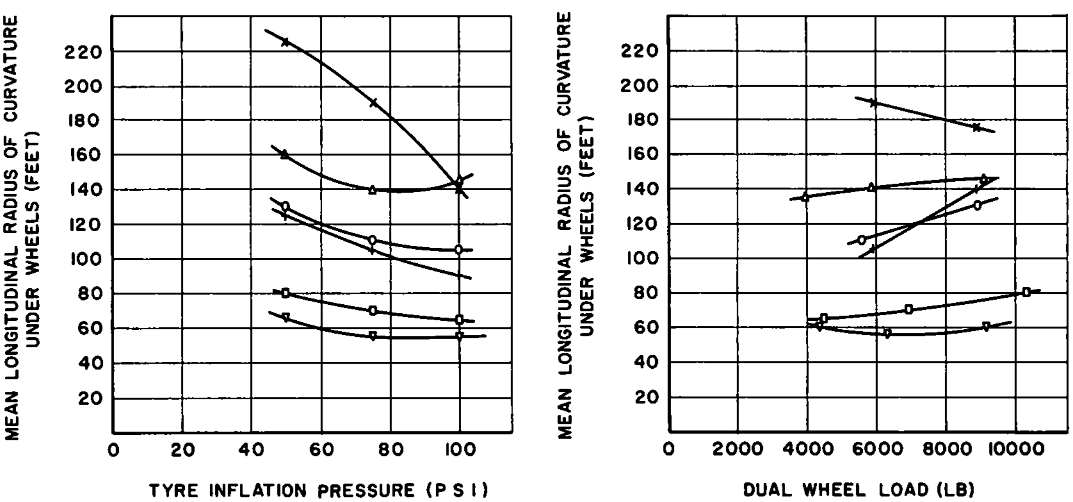


Figure 5. Variation of radius of curvature with wheel load and tire pressure at six sites (Route 3/1).

First, a marked trend is apparent in the plot of curvature against tire pressure. The scatter is probably due, in part, to experimental errors in the measurement of curvatures, as discussed previously. A simple relation between radius of curvature and inflation pressure fitting the mean results of all the tests over the range studied is $R \alpha P_i^{-0.5}$, whereas the corresponding relation in terms of the mean contact pressure is $R \alpha P_c^{-1.25}$. The pronounced decrease in radius of curvature may be visualized as being the product of two opposing effects. First, the decrease in size of the loaded area as pressure increased, giving rise to a more concentrated pattern of deflection and lower radius of curvature (the major effect); and second, the decrease in the effective depth of influence of the load with increasing pressure which, in the common case where the Young's moduli of the layers decreased with depth, would mean an increase in the effective stiffness of the construction, and hence an increase in the radius of curvature. The theoretical relation between radius of curvature and contact pressure for the case of a circular load on a homogeneous material is $R \alpha P_c^{-1.5}$. In view of the great number of variables involved, it is not possible to express a simple, generally-applicable theoretical relation for the case of a multi-layered system. A few simple deductions may, however, be made. According to theory, in the case where the moduli of the layers decrease with depth, the index n in $R \alpha P_c^{-n}$ would always be less than 1.5, and for common flexible road structures, excluding any with a thick bituminous surfacing or a cement-stabilized base, n would generally lie between about 0.75 and 1.5—a range within which the observed value of 1.25 falls. This pronounced effect of tire pressure on radius of curvature is a point of considerable importance in view of present-day tendencies to increase the tire pressures of vehicles, and one which would merit further study, both as described here, and with direct measurements of the strain in the surfacing.

Turning to the plot of curvature against wheel load, a considerable amount of scatter is evident, probably due again to experimental errors, which prevents the immediate recognition of any general trends. Analysis of all the results obtained, however, reveals a slight tendency for radius of curvature to increase (that is become less severe) with increasing wheel load at constant tire pressure, a relation of $R \alpha W^{0.25}$ fitting the results roughly. Although this may appear anomalous at first sight, it can be visualized, as before, as being due to the increase in the size of the contact area with increasing wheel load, giving rise to a less concentrated pattern of deflection and hence to a higher radius of curvature. The effect is, however, slight and the important indication given by the tests is that wheel load, as such, is not a contributor to severe curvature.

The tests conducted also enabled the variation of maximum deflection with pressure and wheel load to be studied. However, in view of the opinion that curvature is likely to be the better measure of the stresses in the surfacing, the deflection results are not of such great significance in the flexure cracking problem, and have not been presented in detail here. It may be of interest to note, however, that the mean relation between deflection and wheel load observed was $\Delta \; \alpha \; W^{0.8}$, while no effect of tire pressure on deflections was apparent.

Another factor which probably has an important effect on flexural stresses is the speed of the vehicle, but this has not, as yet, received serious attention in this Institute.

PREVENTION OF THE OCCURRENCE OF CRACKING

There are two main ways of preventing the development of flexure cracking. The first entails the provision of a surfacing with flexibility sufficiently high to accommodate the flexure encountered on the road. Studies of the performance of surfacings in the field, and research on methods of improving their flexibilities, are being made in a number of centers (2-11). The second method is to limit the deflections or curvatures which actually develop in the road, and it is on this aspect that work in this Institute has been concentrated.

As mentioned previously, there are indications that a road designed in accordance with normal methods, considering shear and consolidation, may not necessarily be satisfactory as regards the flexure induced by traffic. It therefore appears desirable that some additional design consideration be adopted which will insure low flexures. As discussed previously, the major factors relating to the foundations which affect the flexures developed are the Young's moduli of the base and subbase. The design consideration for flexure would thus ideally be based on the Young's moduli of these materials, for which there is at present, unfortunately, no accepted method of test either in the laboratory or in the field. Further, it appears that practically no knowledge exists at present on the Young's moduli of road materials and how they vary with the simpler indicator properties, such as grading, plasticity, and density. For this reason an investigation has been started to find a satisfactory procedure for measuring Young's modulus in the laboratory, and it is planned that a study then be made of how the moduli vary between different materials. Whether a knowledge of materials which possess low Young's moduli and should be avoided will be sufficient to prevent flexure failures in practice, or whether a complete method of design will be required, cannot yet be foretold.

CONCLUSIONS

The major findings in a study of the cracking of a road surface and the flexure induced in it by wheel loads, which has been in progress for some years now in South Africa, are as follows:

1. Either maximum deflection or radius of curvature of the surface may be used to give a rough indication of the stresses induced in a surfacing by a wheel load. Which of these is the better measure is not yet certain, although theoretical considerations favor radius of curvature. In the case of dual-wheeled vehicles, the deflections directly beneath the wheels may often be higher than that between them. Similarly, the transverse curvature, both between and under the wheels, may often be more severe than the longitudinal curvature normally measured.

2. A correlation exists between the condition of a surfacing and both the maximum deflection and the radius of curvature induced by a standard vehicle. The existence of these relations is taken as an indication that "chicken net" cracking is, in some cases at least, due to excessive flexure. For the thin premix surfacings studied, and for the particular test procedure employed, deflections of more than 0.055 in. and radii of curvature of less than about 125 ft are associated with cracking.

3. Young's moduli of the layers of construction of a road can be determined in the field using specialized plate bearing tests. On the basis of a field study on one road, Elastic Theory is applicable to a limited extent in a road structure under its normal traffic. It gives a fair indication of relative values of deflections induced by traffic at the surface, and a rough indication of relative values of the curvatures. Probably a large part of the reason for observed discrepancies is the assumption that the materials in the upper layers are able to resist tension, which, in practice, is often not true.

4. The radius of curvature of a road surface under a given vehicle is dependent mainly on the Young's moduli of the materials in the base and subbase, and if, as seems likely, curvature is an acceptable measure of flexural stresses, these become the important consideration in designing a road against flexure cracking, the subgrade being of relatively minor importance. The bituminous surfacing only has a significant effect in reducing deflections and curvatures if it is thick (more than 2 or 3 in.) and of a type having a high Young's modulus. Theory indicates that there may be a critical thickness of surfacing, in the range 2 to 4 in., for which flexural stresses are a maximum.

5. Radii of curvature are dependent to a considerable degree on the tire pressure of the vehicle inducing them (a series of tests on one road having yielded a relation $R \alpha\ P_i^{-0.5}$), and only to a slight degree on the wheel load—conclusions of importance

as regards the relative detrimental effects of different vehicles in tending to cause flexure cracking. Deflections are dependent mainly on the wheel load ($\Delta \alpha W^{0.8}$) and little on tire pressure.

6. There is considerable scope for further research on various aspects of the flexure cracking problem. At present, work in progress in a number of centers is aimed at improving the flexibility of surfacings; locally attention is being concentrated on reducing the flexure itself. Little knowledge exists on the Young's moduli of common base and subbase materials, and work is being done to find a satisfactory method of testing for these properties, to obtain an insight into the variables which affect them, and, should it prove necessary, to develop a method of design for limiting flexure, to accompany existing shear and consolidation failure design methods.

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