REPORT OF COMMITTEE ON FLEXIBLE TYPE PAVEMENTS

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WHEEL LOAD STRESS DISTRIBUTION THROUGH FLEXIBLE TYPE PAVEMENTS

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SYNOPSIS

This paper is the third of a series of progress reports on a research project being conducted by the Iowa Engineering Experiment Station for the purpose of supplying fundamental knowledge concerning the distribution of wheel-load pressures through the flexible types of pavements to their supporting subgrades The acquisition of knowledge in this area of highway science is necessary as a preliminary step toward the development of a rational method for the determination of the supporting strength of subgrades and the required thickness of flexible type pavements to adequately carry the wheel loads for which they are to be designed

In the experiments which were reported in 1940 it appeared that both the magnitude and the pattern of distribution of pressures on the experimental dry subgrade were independent of the inflation pressure of the tire through which the loads were applied to the flexible pavements For a given thickness of pavement and a given load, the pattern of pressure distribution on the subgrade and the maximum pressure directly under the load were unchanged when the inflation pressure of the tire was varied from 30 lb per sq in to 70 lb per sq in Also, in the case of the thinner pavements, higher loads, and lower inflation pressures, it was not uncommon to measure unit pressures on the subgrade which were considerably in excess of the inflation pressure of the tire When the internal pressure of the tire was increased to 70 lb per sq in for subsequent load applications the contact area was reduced to 55 3 sq in, but the maximum pressure on the subgrade and the pattern of distribution were unchanged

The report discusses additional experiments which further substantiate the above described phenomenon

The second phase of the problem discussed in this report, reveals that the maximum pressure on a dry subgrade prior to failure of the 4½ in sand-clay base course may be as much as nine times greater than the maximum pressure on a wet subgrade

Neither this report nor either of the two previous progress reports (1, 2)[1] pretends to give final answers to the many questions relative to stress distribution in the type of structure being studied and the author makes no apology for this lack of finality, being a firm believer in the value of progress reports as a means of stimulating discussion and consideration of a problem. Any conclusions indicated by these progress reports, must of necessity be considered as tentative and they are subject to revision and modification until such time as they have been adequately proved under field service conditions.

This report deals primarily with two phases of the subject: first, with the effect of the size of the contact area and the character of the forces between a tire and the pavement upon the maximum pres-

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

sure exerted on the subgrade and second, with the effect of varying amounts of moisture in the subgrade soil material

One of the most persistent indications of the experiments which were reported in 1940 was the apparent fact that both the magnitude and the pattern of distribution of pressures on the experimental dry subgrade were independent of the inflation pressure of the tire through which the loads were applied to the flexible pavements. That is to say, for a given thickness of pavement and a given load, the pattern of pressure distribution on the subgrade and the maximum pressure directly under the load were unchanged when the inflation pressure of the tire was varied from 30 to 70 lb per sq in, as shown in Figures 11, 12, and 13 of the 1940 report. Also, in the case of the thinner pavements, higher loads, and lower inflation pressures, it was not uncommon to measure unit pressures on the subgrade which were considerably in excess of the inflation pressure of the tire. For example, as shown in Figure 13 of the 1940 report, the maximum subgrade pressure under a 3-in. flexible pavement loaded with 3,000 lb. acting through a tire inflated to 30 lb. per sq. in., was 66 lb per sq. in. or 2 2 times the inflation pressure of the tire. The gross area of contact between the tire and the pavement was 69 8 sq in giving an average contact pressure of 43 lb per sq. in. which is likewise considerably less than the maximum observed subgrade pressure.

When the internal pressure of the tire was increased to 70 lb. per sq in. for subsequent load applications the contact area was reduced to 55 3 sq. in, but the maximum pressure on the subgrade and the pattern of distribution were unchanged. This lack of dependence between inflation pressure and subgrade pressure, and particularly the occurrence of pressures on the subgrade substantially greater than the tire inflation pressure, was surprising to the author and was seriously questioned by some readers of the report It seems worth while, therefore, to pursue this matter further in order to throw as much light on the subject as possible

Additional experiments conducted at Ames since presentation of the 1940 report have further substantiated this phenomenon. These experiments were conducted in the same manner and with the same apparatus as those previously reported, except that a new sand-clay base course, 4½ in thick, was constructed on the dry synthetic subgrade.

Some experiments conducted at the University of Illinois by M L. Enger (3), in connection with the extensive studies of stresses in railroad track carried out at that institution, are confirmatory Enger applied loads to layers of dry compacted sand supported on a rigid concrete floor. The loads were applied through the medium of rigid circular disks having diameters of 9, 13½, and 21 in, respectively. The pressures on the receiving plane were measured by means of the water pressure under a 6-in. diaphragm placed flush with the surface of the concrete floor As a result of these experiments with layers of sand 6, 12, and 18 in. thick, Enger stated ". . that if a load is applied to a 9-in plate such that the intensity of pressure on a small area at a certain distance directly below the center of the plate is 10 lb per sq in, then if the same total load is applied to a 21-in plate the intensity of pressure on the same small area would be 8 9 lb per sq in. That is, with the area carrying the load increased 5 44 times, the intensity of the pressure in the sand directly below the plate at a given depth has been decreased but little, a conclusion very different from usual assumptions."

Thus it is seen that in Enger's experiments an increase in area of contact of the applied load of 544 percent only decreased the maximum pressure on the receiving plane 11 percent In the Ames experiments being reported, the increase in area

of contact when the inflation pressure of the tire decreased from 70 lb. per sq. in. to 30 lb. per sq. in. was from 55 3 sq. in. to 69 8 sq. in , an increase of only 26 percent. This, according to Enger's results, is too small an increase to produce a measurable decrease in subgrade pressure, and the conclusion that the maximum subgrade pressure was independent of the inflation pressure appears to be tenable.

Furthermore, Enger found that the average unit pressure on the 6-in. measuring diaphragm readily exceeded the average unit pressure on the loaded plates, particularly in the case of the shallow layers of sand and the larger plates. In the case of the 13½-in. plate on a 6-in. layer of sand, the average pressure on the receiving diaphragm was 160 percent of the average unit pressure on the loaded plate, while in the case of the 21-in plate on a 12-in. layer, this ratio was 200 percent.

While it may be argued that these findings by Enger are not entirely applicable to the case under discussion since the conditions of his experiments were considerably different in many details than those which have been conducted at Ames, they do serve to demonstrate the possibility that the maximum pressure on a receiving plane beneath a relatively thin layer of soil can be in excess of the average applied pressure at the surface of the soil layer.

Another factor which may influence the pattern of distribution of stress on the subgrade and partially account for the high concentration of stress directly beneath the tire contact is the probable existence of tangential shearing forces between the tire and the pavement surface due to the "gripping" action of a pneumatic tire on the pavement. There are evidences to indicate that the deformation of a tire carcass under load tends to reduce the width of the tire tread in a transverse direction and in so doing to induce shearing forces at the pavement surface which are directed inward toward the longitudinal axis of the tire contact area. If these shearing forces exist they would combine with the vertical pressures between the tire and pavement and cause resultant pressures directed downward and inward, which may partially account for the seemingly high concentration of subgrade pressures under the center of the loaded area.

One indication that such shearing forces exist is the fact that when a tire with a ribbed tread is loaded and an imprint of the tire contact made, the print of the ribs, which are parallel on the tire, will show them to be slightly closer together at the center of the contact area than they are at the ends of the area This convergence of two parallel ribs on a new 6-ply 7 by 21 Goodyear tire may be observed in Figures 20 and 24 of the 1940 report. The actual distance between the inside edges of the tread ribs was 2 15 in., while the distance between the imprints of the ribs at the transverse axis of the contact area averaged about 2.00 in.

Another indication of the existence of inward shearing forces, or rather a demonstration that they may exist, may be observed by pushing a short transverse section of a tire, such as tire companies use for sales purposes, downward on a table top or other surface. The inward movement of the tire tread elements as the tire deflects can easily be seen during this operation.

It seems reasonable to suppose that this tendency for the tread to deform inwardly during loading will set up tangential shearing forces between the tire and the pavement directed toward the longitudinal axis of the contact area. That these ideas are not pure conjecture but have a basis in fact is indicated by some measurements of both normal and shearing stresses on a tire-pavement contact area which have recently been published in England by A. H. D. Markwick and H J. H. Starks (4) of the Road Research Laboratory. The report of these measurements was

abstracted in Highway Research Abstracts for September, 1941. Concerning the shearing stresses, which were measured by means of a carbon resistor element, Markwick and Starks state, in part: "Measurements of shear stress on stationary pneumatic tires have been made with the apparatus described in the Appendix Figure 6 (reproduced as Fig 1 of this paper) shows the shear stress measured under a stationary 3-in. by 20-in. motorcycle tire along the minor axis of the ellipse of contact on a plunger ⅛ in. in diameter projecting 0 01 in. The stresses are directed inwards, and it is evident that

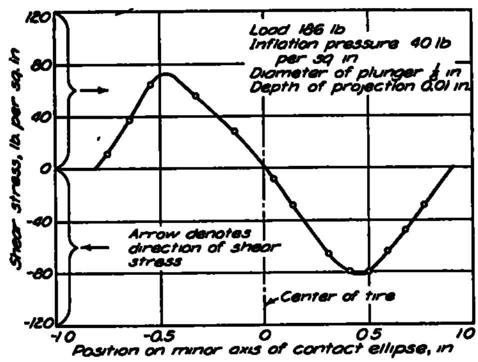

Figure 1. Distribution of Shear Stress Along Minor Axis of Contact Ellipse Under a Stationary 3-in.x20-in. smooth tire. (After Markwick and Starks.)

the shear stress is zero at the center and at the periphery of the ellipse of contact and that the areas under the positive and negative parts of the curve are approximately equal, that is, there is no resultant force along the minor axis. This also is in agreement with the results of Martin (5)."

It is interesting to note that their findings indicate that the shearing stresses between a solid tire and a road surface act in the opposite direction from those of a pneumatic tire, that is, they are directed outward instead of inward

In regard to the second phase of the problem to be discussed in this report, experiments have been completed at Ames by Kneeland (6) in which the subgrade pressures induced by the application of a load through a pneumatic tire acting upon a 4½-in sand-clay pavement have been measured, first with the subgrade in a very dry condition, and second with the subgrade in a very wet, almost saturated condition. Using the apparatus described in Progress Report No. 2 (2) the pavement was constructed on an air dry synthetic subgrade (moisture content 1 7 percent) and the pressures between the pavement and the subgrade measured by means of the carbon disk resistors previously described. Then water was introduced into the reservoirs at the sides of the concrete bin in which the subgrade material was contained and permitted to rise vertically by gravity and by capillarity through the full height of the 2½-ft. thick subgrade. After the subgrade was thoroughly wetted in this manner, loads were reapplied to the pavement surface and the pressures again measured, without the pavement or the measuring devices having been disturbed

The moisture content of the subgrade at the time it was loaded in the wet state was as follows:

	Moisture content %	Degree of saturation %
Top zone (0 to 6 in)	14 6	65
Intermediate zone (6 in to 18 in)	17 1	78
Lower zone (18 in to 24 in)	19 2	100

Loads ranging from 1,000 lb. to 3,000 lb. by 500 lb. increments were applied to the pavement on both the dry and the wet subgrade. It was expected, as stated in the 1940 report, that the maximum pressure on the wet subgrade would be less than the maximum pressure on the dry subgrade, but the actual reduction of pressure revealed by these measurements far exceeded the author's expectation. Typical results of these experiments are given

in Figure 2 where the pressures along the longitudinal and transverse axes of the tire contact area on both the dry and wet subgrades for an applied load of 2,000 lb are shown As indicated in this figure, the maximum wet subgrade pressures prior to failure of the base course were only about one ninth the maximum dry subgrade pressures

The loads on the wet subgrade were applied in ascending order, beginning with 1,000 lb and increasing by increments of 500 lb The subgrade pressures increased with a uniform relationship to the applied loads up to and including the 2,500 lb load. Upon application of the 3,000 lb load, the pressures increased sharply and unconformably, and a distinct failure of the pavement was observed after application of this last increment. The pavement failed by cracking along an approximately circular path concentric with the loaded area and having a diameter of approximately 40 in. A sketch of the locus of the

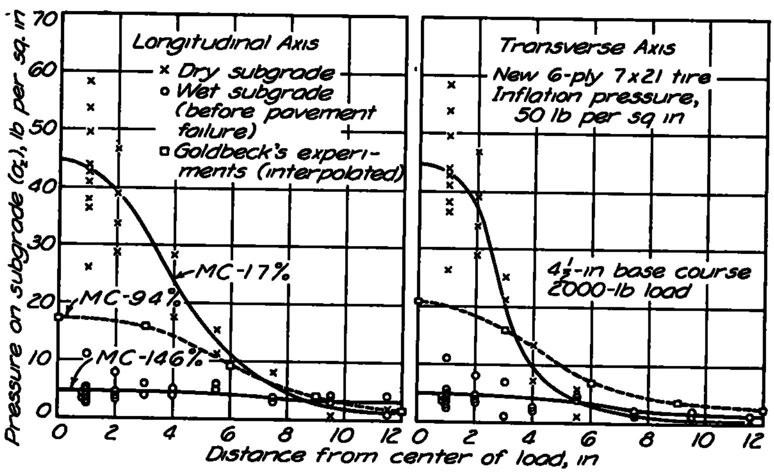

Figure 2. Load Tests

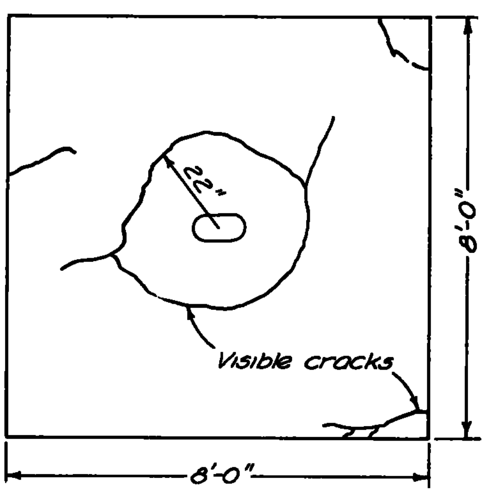

Figure 3. Failure of 4½-In Sand-Clay Base Course on Wet Subgrade

observed failure crack is shown in Figure 3

Further applications of load were made subsequent to the foregoing noted failure beginning with 3,000 lb. and decreasing to 1,500 lb The maximum pressures on the wet subgrade after failure of the pavement averaged nearly 60 percent greater than for the same loads prior to the failure, as is indicated in Figure 4.

These measurements of pressures on the wet and dry subgrades throw considerable new light on the rôle of subgrade moisture in its affect upon the magnitude and distribution of wheel load stresses on subgrades and indicates a very wide range in maximum pressures between the very wet and very dry subgrade conditions

With this new information available, it has been possible to correlate the subgrade pressure measurements made at Ames with those conducted by Mr A. T. Goldbeck (7) at the laboratories of the National Crushed Stone Association of Washington, D. C., the results of which were presented to the Highway Research Board at the annual meeting in 1939 Goldbeck measured pressures on synthetic laboratory subgrades induced by loads applied to the surface of flexible pavements made of stone screenings The loads were applied through rigid elliptical-shaped bearing blocks by means of a hydraulic jack. A ½-in. rubber pad was placed between the bearing blocks and the pavements Pressures at the surface of the subgrade were measured by means of soil pressure cells, popularly known as the Goldbeck cell.

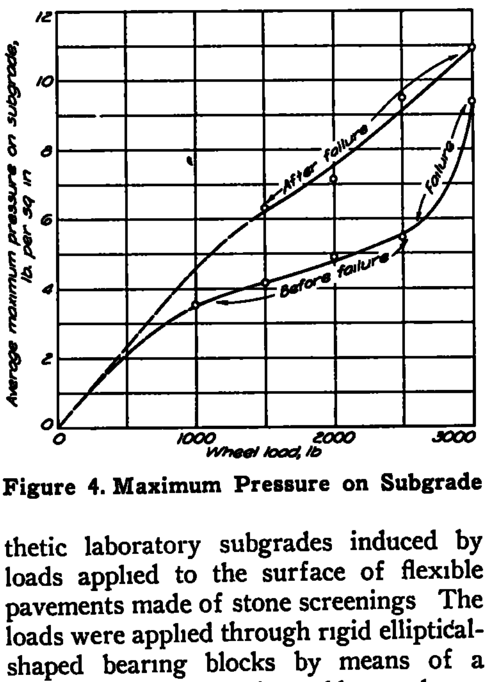

Figure 4. Maximum Pressure on Subgrade

The results of these measurements appeared to be in serious conflict with the similar experiments made at Ames. For example, as shown in Figures 6 and 7 of Goldbeck's paper, a 4,000-lb. load applied to a 4-in. pavement produced maximum pressures on the subgrade of approximately 31 lb. per sq. in., whereas in the Ames tests on a dry subgrade a load of only about 1,300 lb produced a similar maximum pressure However, Goldbeck's subgrade contained 9 4 percent of moisture, whereas the Ames subgrade contained only 1 7 percent and in the light of the newer knowledge concerning the effect of this variation in moisture content, the above apparent discrepancy disappears and the two independent studies are revealed to be in substantial agreement.

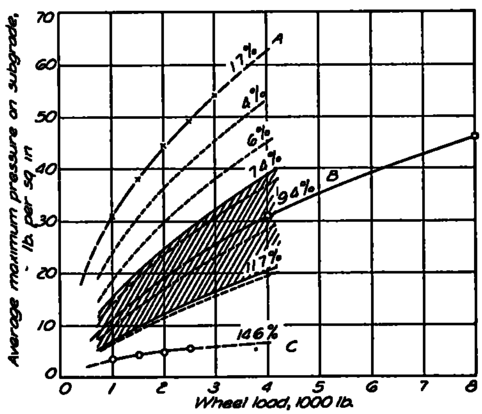

Figure 5

A—Ames experiment on 4½-in. sand-clay pavement with 2% moisture on sandy clay loam subgrade with 1.7% moisture.

B—Goldbeck's experiment on 4-in. stone screenings with 3.4% moisture on sandy loam subgrade with 9.4% moisture.

C—Same as A except 14.6% moisture in subgrade.

---- Interpolated pressures for various moisture contents of subgrade.

Shaded area denotes range of moisture contents in two actual subgrades of similar material.

The correlation between the tests has been shown in Figure 2, and is further indicated in Figure 5 where the maximum subgrade pressures are plotted against the applied loads for the case of a 4½-in pavement on both the wet and dry subgrades in the Ames tests and for the case of a 4-in pavement on a subgrade containing 9.4 percent moisture in the Goldbeck tests The shaded area in this diagram represents the range of moisture contents ob-

TABLE 1
PROPERTIES OF SUBGRADE SOILS

Subgrade soil	Size fractions, percent: Gravel (over 2 0 mm)	Sand (2 0 to 05 mm)	Silt (05 to 005 mm)	Clay (under 005 mm)	Textural class	Dry density, lb per cu ft	Liquid limit	P I	Shrinkage: Limit	Ratio	F M E	C M E	P R A class
Ames Experiments	1	52	23	24	Sandy clay loam	114	28 0	13 7	11 4	1 95	14 8		A-2
Goldbeck's Experiments	1	62	19	18	Sandy loam		21 2	6 2	14 4	1 93	18	18	A-2
I H C, No AAD8-3151	13	39	28	20	Gravelly clay loam	121	31	15					
I H C, No AAD8-3163	9	47	24	20	Sandy clay loam	127	31	16					

served by the Iowa Highway Commission in two subgrades under flexible pavements in Iowa These two subgrades were selected for comparison with the Ames test subgrade because they had essentially the same textural characteristics, the same plasticity index and other properties. Fortunately the Goldbeck test subgrade was very similar to these other subgrades so that a comparison of all four soils on the basis of moisture content is probably valid The properties of the four subgrade soils involved in the preparation of Figure 5 are shown in Table 1. Particle size distribution curves are shown in Figure 6

The Goldbeck tests and the Ames tests differed in some minor points so that the correlation shown in Figure 5 should probably be considered as qualitative rather than quantitative For example, Goldbeck's crushed stone pavement was 4 in thick while the Ames sand-clay pavement was 4½ in thick, a fact which normally would produce relatively higher subgrade pressures in the Goldbeck tests. On the other hand, the use of rigid bearing blocks to apply the load to the pavement would normally reduce the maximum subgrade pressures as compared to those induced by a pneumatic tire load because of the lack of inward surface tangential forces induced by the gripping action of the tire on the pavement as previously discussed in this paper. The results of these differences between the two experiments would tend to be compensatory, but to an unknown degree.

It is recognized that moisture content alone is not the significant factor controlling the distribution of the wheel load stresses on subgrades. In all probability the pattern of distribution will be dependent upon the soil density and shearing resistance Further studies will be required to identify the specific properties of subgrades which control the stress distribution pattern, but for the same or nearly identical soils, the moisture content is probably the most significant variable.

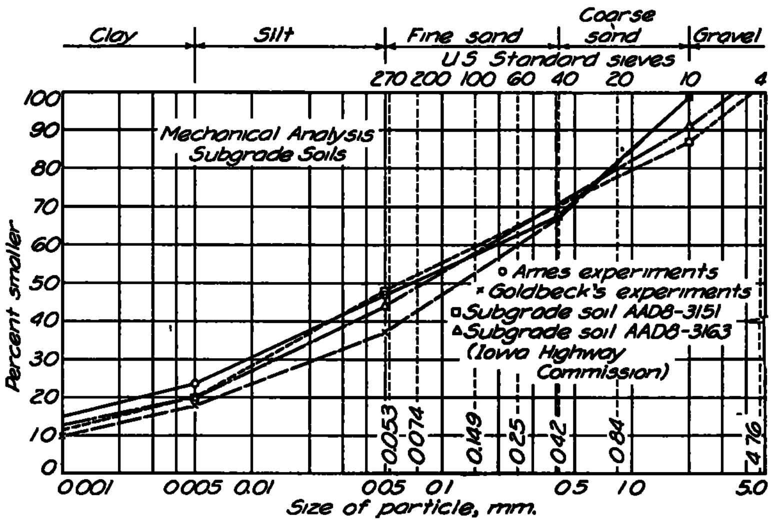

Figure 6. Particle Size Distribution

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