WHEEL LOAD STRESS DISTRIBUTION THROUGH FLEXIBLE TYPE PAVEMENTS

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SYNOPSIS

The object of the experiments described herein is to provide basic knowledge concerning the magnitude and distribution of the vertical pressures on a subgrade beneath a flexible or non-rigid type of pavement when concentrated loads, such as truck wheels are applied to the pavement surface

The work has been conducted in the laboratory under conditions which were necessarily not the same as those encountered in actual highway construction, and the results therefore, are not to be generalized too extensively. A synthetic subgrade of dry clay loam soil was constructed within a concrete bin 8 ft sq in plan and about 2½ ft deep Flexible-type pavements were constructed on this subgrade of two kinds of materials, one a stabilized gravel mixture and the other a sand-clay mixture The thickness of these pavements ranged from 3 in to 10 in Loads were applied to the surface of the pavement at the center of the 8 ft sq area through a 7 by 21, 6-ply tire in amounts ranging from 1000 lb to 5000 lb by 1000 lb increments and with the tire inflated to various internal pressures from 30 p s i to 70 p s i by 10 lb or 20 lb increments

The vertical pressures on the subgrade were measured by means of small carbon disk piles arranged at frequent intervals along elements parallel to the major and minor axes of the tire contact area About 36 carbon piles were used, 9 of which were clustered in and around a 2 in circular area directly under the applied load They were placed in the horizontal plane between the pavement and the subgrade and were calibrated by means of air pressure after being placed and before the flexible pavements were built They were confined between two thin layers of sheet rubber to protect them from moisture, dust, and other deleterious substances

In addition to the subgrade pressure measurements, an extensive study was made of the relation between the contact area between the tire and the pavement surface and the load on the tire and the tire inflation pressure.

The data taken indicate that, in these experiments, the subgrade pressure is distributed in accordance with the typical helmet-shaped surface of the classical Boussinesq solution, that the maximum pressure occurs on a small area of the subgrade directly beneath the load, that the magnitude of this pressure maximum is independent of the tire inflation pressure is nearly directly dependent upon the applied load, is inversely proportional to the thickness of the pavement, and that the load-inflation pressure quotient is not a valid criterion for determining the area of contact between a truck tire and a flexible pavement

The design of any structure involves, as a principle requirement, the determination of the stresses to which the various elements of the structure will be subjected when acted upon by the loads which it is designed to carry. The subgrade upon which the base course is constructed is one of the critical elements of flexible or non-rigid pavements. There is great need for a rational and authoritative means for determining the magnitude and distribution of the pressures due to vehicle wheel loads acting at the pavement surface, in order that adequate pavement thickness may be provided to prevent overstressed subgrade conditions

and as a first step toward the formulation of scientific procedures for subgrade design.

The Iowa Engineering Experiment Station is conducting a research project to provide information on this subject. This paper is a progress report on the project, in which the results of some laboratory measurements of subgrade pressures due to wheel loads are presented, together with the results of some auxiliary studies of the relationship between contact area, load, and inflation pressure for two tires which were used to apply the wheel loads in the pressure measuring experiments. The tentative character of the data included in this report needs to be emphasized, since the experiments were performed in the laboratory on a synthetic subgrade and under conditions of moisture, temperature, boundary restraint and traffic which were necessarily not the same as those which prevail in a highway, and it is impossible to evaluate the effect of these differences at this time. However, the qualitative character of the distribution of vertical pressures at the subgrade surface beneath a flexible pavement is revealed and some light is thrown upon the effects of variable loads and tire inflation pressures upon stresses at the subgrade surface.

PRESENT STATUS OF THE PROBLEM

A number of hypothetical rules and formulae have been advanced from time to time for relating the pressure on the subgrade to the wheel load and the pavement thickness. The earliest of these, known as the Massachusetts rule (1),[1] was evolved as early as 1901 This rule, in effect, considers a wheel load as a point load which is distributed through a volume of a flexible pavement having the shape of a pyramid with sides sloping 45 deg with the horizontal. The subgrade pressure is considered to be uniformly distributed over the base of the pyramid and may be expressed by the formula

$$\sigma_s = \frac{P}{(2t)^2} \quad \ldots\ldots 1$$

in which

σ_s = the subgrade pressure.
P = the wheel load.
t = the thickness of the pavement.

This rule came into being at a time when highway loads were for the most part applied through steel tired wagon wheels and the area of contact between tire and road was relatively small, which probably accounts for the fact that the load was considered to act at a point. With the passage of time and with changing conditions of highway traffic, other rules have been suggested by various authors, based primarily on the fundamental concepts of the Massachusetts rule, with certain modifications to take into account the area of contact between rubber tires and highway surfaces. Thus, in order, we have the Harger and Bonney formula (7) which considers the load to be distributed on a transverse line of a length equal to the width of the tire. Later, B E. Gray (5) proposed a formula which considers the load to be applied over a circular area, and retains the concept of a 45 degree angle of distribution, making the volume of base course through which the distribution takes place a truncated cone instead of the pyramid of the Massachusetts rule.

Hawthorn (8) has introduced the conception that the angle of distribution is a function of the shear strength of the base course and he has derived a formula similar to that of Gray, embodying this concept. Several other writers have suggested procedures for determining the thickness of flexible pavements, notably Lelievre (10) and Housel (9). These suggestions have been fully pre-

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

sented in the literature and need not be discussed here. It is sufficient to say that all of these suggested formulae are based on speculative concepts of flexible pavement performance and that none of them has an adequate experimental background. Very little experimental work has been done in this field. A few pertinent data were published by Goldbeck (2) in 1923 and by Older (12) in 1924. More recently, papers by Spangler (13) in 1938, and (16) in 1940, and by Goldbeck (3) in 1939 and (4) in 1940, reflect a renewal of interest in the experimental phases of the subject, but there is need for further extensive experimentation to supplement the theories already in existence or to point the way to a new theory of pressure distribution through flexible pavements, if that seems desirable in the light of the experimental observations.

APPLICABILITY OF THE BOUSSINESQ SOLUTION

The Boussinesq solution of the problem of stress distribution in a semi-infinite solid, as is well known, has been of very great value in the field of soil engineering, as a guide to the determination of actual patterns of stress distribution in soil masses Although derived for an idealized elastic, isotropic, homogeneous material, the results obtained by this solution and modifications thereof have been shown to be remarkably close to the actual stresses measured in non-elastic and semi-elastic, heterogeneous soils in a number of instances. Its use has become more or less standard procedure in foundation engineering. Extensive experiments (14) have shown that loads transmitted to underground conduits, such as culverts, sewers, water mains, etc., agree closely with those calculated by this classical solution. Likewise, lateral pressures on retaining walls (15) caused by loads applied on the backfill surface are closely related to the Boussinesq pressures, taking into account the relative rigidity of the wall and the backfill material. Other examples of the usefulness of this solution could be cited.

It is logical, therefore, to speculate concerning the distribution of pressure on a flexible pavement subgrade in the light of the Boussinesq problem. There are a number of factors which need to be considered in making such a study.

Area and Distribution of Applied Load.

The solution was originally developed for the case of a point load, but by application of the principle of superposition, the pressure at any point in the earth mass due to a load applied over an area may be integrated by considering the area load to be made up of a series of closely spaced point loads of known distribution and intensity. Some investigators have questioned the validity of the application of the principle of superposition on theoretical grounds, but numerous experiments have indicated that it may be successfully employed in many cases and that it gives results which are well within practical limits of precision for soils work.

In considering stresses at some distance from the applied load, a subdivision of the total load distributed over one half of one square foot of area may be often considered the same as a point load for the purpose of making an arithmetic summation, but in the case of flexible pavement subgrades, the thickness of the base course will usually be of the same order of magnitude as the dimensions of the loaded area, and the distances from the loaded area to points at which pressures are being determined will be relatively small. Under these conditions it is necessary that the load be considered in its true state of distribution, or nearly so Assuming the load to be concentrated at a point will yield stresses on the subgrade near the vertical axis through the load which are much higher than the

actual stresses produced by a pneumatic tire load

In this connection, the question arises as to the true distribution of load and the size and shape of the area of contact between a vehicle tire and a flexible pavement. It is not uncommon practice to consider that the area of contact of a pneumatic tire is equal to the load divided by the tire inflation pressure and that the pressure between tire and pavement is uniformly distributed over this area, in accordance with Pascal's law of fluid pressures. This would conceivably be true if the tire were of a membranous character and possessed no inherent stiffness, but tires, especially those used on highway vehicles do have considerable stiffness and there is ample evidence that this carcass stiffness appreciably affects the area of contact Sometimes the area of contact exceeds the load-inflation pressure quotient and sometimes the reverse is true. Some measurements of the actual contact area between a tire and the experimental pavements have been made in connection with this study and the results are given in Table 2 and Figure 25

Teller and Buchanan (17) have shown that the distribution of pressure over the area of contact between a tire and a rigid surface, such as a concrete pavement, is approximately uniformly distributed. There have been no similar measurements made for the case of a tire acting on a flexible type surface, so far as the authors are aware In order to eliminate any questions regarding the validity of the subgrade pressure measurements caused by uncertainties concerning the area of contact and the distribution of contact pressure over the area, the loads in these studies have been applied to the pavement surface through a tire inflated to various internal pressures. There is need at this time for authoritative information in regard to the distribution of pressure over the contact area on flexible surfaces. Some indirect evidence indicates that the pressure is much more concentrated near the center of the contact area than it is when a tire acts on a rigid surface.

Relative Stiffness of Pavement and Subgrade.

The Boussinesq solution, as previously stated, was derived to apply to a highly idealized material, isotropic and homogeneous throughout. In the problem under discussion, aside from the normal heterogeneity and non-isotropy of soils, the base course will always be very much more rigid and unyielding than the subgrade on which it is constructed and there will be a marked difference in the deformation modulus of the two strata of soil, which may have an effect on the distribution of the subgrade pressure, the importance or degree of which is not yet known. In general it seems probable that the less stiff the subgrade in relation to the base course, the wider will be the subgrade stress distribution and the lower the maximum stress at the subgrade surface directly beneath the load. This is not to imply that a yielding subgrade is desirable in order to reduce stress, because ordinarily as the deformation modulus of a soil decreases, its ability to resist stress will be reduced more rapidly than the magnitude of stress, and the net effect will usually be detrimental

The relative stiffness of a pavement and its subgrade, or the various strata in the subgrade profile, must be borne in mind when making comparison between various experimental studies of stress distribution. Also, this consideration indicates one of the reasons why final studies of subgrade stresses should be made on pavement structures in the field rather than by depending wholly upon laboratory studies where it is impossible to duplicate actual subgrade and base course conditions. In the Iowa En-

gineering Experiment Station project, it is planned to work in the laboratory until apparatus and technique have been perfected and general principles established, and then to go into the field for final observations.

Boundary Conditions.

In the theory of elasticity, there are three general conditions or criteria which must be satisfied for the particular stressed body under consideration. First, the stresses must be in equilibrium. Second, the strains must be compatible; that is, there must be continuity throughout the stressed medium with no overlapping or separation of adjacent elements Third, the actual boundary conditions of the stressed medium must be observed; that is, the actual size of the body and the actual stress situation at the bounding surfaces must be recognized and introduced into the solution.

The Boussinesq solution dealt with a semi-infinite medium, which means that the stressed body extended laterally in all directions and downward an infinite distance. It is readily seen that a flexible pavement structure, and particularly a laboratory set-up simulating an actual pavement, is far removed from this infinite boundary conception of Boussinesq, although our knowledge of the problem is not sufficient to permit evaluation of the effect of these boundary differences.

All of the foregoing discussion of differences between the conditions predicated in the Boussinesq solution and the problem of subgrade pressure distribution indicates clearly the necessity for extensive experimental guidance in any attempt to set up a rational or empirical theory of stress distribution through flexible pavements, since the effects of these differences are not known, nor can they be authoritatively estimated or predicted at the present time.

IOWA STATE COLLEGE EXPERIMENTS

Preliminary work has consisted of a series of laboratory experiments in which subgrade pressure distribution was measured by means of a system of differentiating friction ribbons (13) (18). These differential ribbons yielded satisfactory and reasonable results and clearly indicated the witch or helmet shaped pressure surface which is typical of the Boussinesq type of stress distribution. The ribbons were limited in their application by the fact that they had to be pushed back into their initial position in the plane between the pavement and the subgrade in order to obtain repeat readings of pressure. That operation was possible in the first or 1938 series of experiments because the pavement and its subgrade were made only 5 ft. square in plan. There was evidence, however, that for the thicker pavements, the side retaining planks affected the distribution of pressure on the subgrade to some extent. It was deemed necessary, therefore, to make the next laboratory pavement and subgrade 8 ft. square in order to reduce this boundary effect.

In this larger set-up, it was impossible to push the friction ribbons back into their initial position for taking repeat readings because of the greater dead load pressure on them, and it was necessary to design a continuous type of ribbon to overcome this difficulty. This required certain shearing operations on a long strip of stainless steel sheet, 3 in. wide and 0 008 in. thick, which produced a burr on the edge of the measuring ribbon and seriously affected the friction properties of the ribbon. No practical means of removing this burr was found and this type of pressure measuring apparatus had to be abandoned. A group of carbon pile resistors, which will be described later, was substituted for the ribbon measuring devices.

For the current laboratory studies, a concrete bin, 8 ft. square and 3 ft. deep

inside dimensions, was constructed, having a small reservoir on each of two sides connected to the main bin by several 2-in. pipes at the bottom of the bin. A 6-in. layer of coarse gravel ranging in size from $\frac{3}{4}$ to $1\frac{1}{2}$ in. was placed in the bottom of the bin. Then a synthetic subgrade was constructed up to the level of the top of the bin, making it $2\frac{1}{2}$ ft. deep above the gravel stratum. A plan of the bin is shown in Figure 1 and a photograph of the laboratory layout is shown in Figure 2.

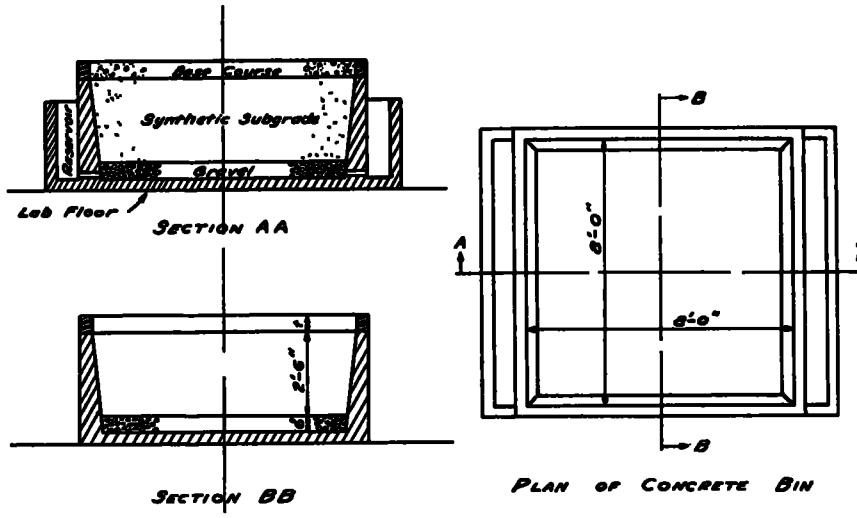

Figure 1

The subgrade was constructed of a yellow clay loam soil principally from the B horizon of a glacial deposit of the Wisconsin Drift, having a specific gravity of 2.67 and the following textural characteristics:

Gravel (larger than 2 0 mm)	1 3%
Coarse sand (2 0 to 0 42 mm)	31 7%
Fine sand (0 42 to 0 05 mm)	20 5%
Silt (0.05 to 0 005 mm)	22 7%
Clay (smaller than 0 005 mm)	23 8%
	100 0%

The Atterburg limits of the fraction of this material passing the No. 40 (0.42 mm.) sieve were:

Liquid limit	28 0%
Plastic limit	14 3%
Plasticity index	13 7%

The moisture-density relationship determined by the Proctor method indicated the optimum moisture content to be 13 8 per cent, and the maximum dry density was 116 1 lb. per cu. ft.

This clay material was air dried in the laboratory and then broken up by means of a hand tamper, after which it was

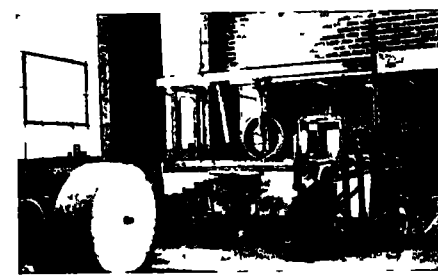

Figure 2. General View of Laboratory Experiments

screened over a $\frac{1}{4}$ in. mesh screen and then tamped in the concrete bin in about 3-in layers, applying ten blows of a 15-lb. hand tamper on each 8-in square area of the layer. The moisture content of the air-dried material as placed was 1.7 and the dry density was 114 lb. per cu. ft.

The bin was designed and the subgrade constructed with the object in mind of

first observing the pressure distribution on a dry, fairly stiff subgrade and then introducing water into the reservoirs and allowing it to rise through the dry subgrade material in a manner similar to the action of ground water. Then it is planned to measure the pressure distribution on the subgrade when moistened in this manner without the necessity of disturbing either the base course or the pressure measuring devices. This latter phase of the experiments has not been performed as yet. Only the measurements of pressure on the dry subgrade are available at this time.

The pressure measurements which have been made on the synthetic subgrade up to the time of this report, may be conveniently divided into three series. Series I was begun in December, 1939, with a 4-in. stabilized gravel base course and with the carbon pile resistors spaced 1 to 3 in. apart over an area about 24 in. in diameter on the surface of the subgrade. This was a preliminary or trial series in which the carbon piles were tried out under an actual base course. Loads from 1000 to 5000 lb. were applied to the base course through a tire with various inflation pressures and through three circular cast iron disks, having diameters of 7 in., 9 in., and 11.5 in. As a result of this preliminary work, several desirable changes in procedure were indicated. Therefore, the first base course was removed and Series II planned in the light of the experience gained.

In the second series, the carbon pile resistors were placed closer together than before, and concentrated along the major and minor horizontal axes of the tire contact area, as shown in Figure 6. The base course was constructed of stabilized gravel, the same as in the first series and was made 3 in. thick. After a complete set of loads had been applied to the 3-in. pavement, the surface was scarified and an additional increment of thickness added. In this manner pavement thicknesses of 3, 4, 5, 6, 8, and 10 inches were studied. The tire loads applied ranged from 1000 to 5000 lb. by 1000 lb. increments and inflation pressures ranged from 30 to 70 lb. per sq. in. by 20 lb. increments. The disk loads were not used in this series or in Series III.

In Series III the carbon pile mountings were improved somewhat, but were arranged essentially the same as those in Series II, except that the cluster of piles around the vertical axis through the load was made circular instead of square. A photograph of the carbon pile assembly used in this series is shown in place on the subgrade in Figure 7. A sand-clay base course, 5 in. thick, was constructed for this series of measurements.

The data concerning the type and thickness of base course material and the kind and magnitude of loads applied in the various series of measurements are shown in Table 1.

The base courses were constructed within a 4-in. thick plank retaining box of the same dimensions in plan as the concrete bin. For Series I and II the material consisted of an arbitrary mixture of pit run gravel passing a 1½ in. sieve, plus Nevada clay. The gradation curve of the combined material is shown in Figure 3. The material passing the No. 40 sieve had a plasticity index of 7.7 and a shrinkage limit of 11.1 per cent. The optimum moisture content for maximum density by the Proctor method was 9.1 per cent which gave a maximum dry density of 130 9 lb per cu. ft

The moisture content of the base course as constructed was approximately 5 to 6 per cent. The material was hand mixed and hand tamped in layers about 2 in. thick and then rolled with a roller weighing about 215 lb. per lin. in. and showed an average dry density in place of about 126 to 127 lb. per cu ft. This base course material was similar to that which has been used successfully in pavements on several miles of low and medium traffic streets in Ames, Iowa.

The unconfined axial compressive strength of this base course material was determined by molding twelve 8.6 cm. by 17.8 cm. cylinders by the Proctor method from a single batch of the material mixed with 8.9 per cent of water. These cylinders were exposed to the air in the laboratory and were broken under axial compression at various intervals of time from 1 hour up to 120 hours. A moisture determination was made on a sample of soil taken from near the center of each cylinder after compressive failure. The results of these strength tests are shown in Fig. 5. They show a definite relationship between moisture loss and gain in strength. When the experimental base courses were constructed, they were allowed to cure and dry out for a period of at least 40 hours before any loads were applied. At the conclusion of the pressure measuring operations, the material showed a moisture content of about 2 per cent

TABLE 1

Series No	Type of base course	Thickness of base course in.	Method of loading		Applied loads lb
			Tire inflation pressure lb.	Disk in	
I	Stabilized gravel	4	30		1000, 2000, 3000
			40		"
			50		"
			60		"
			70		"
				7	"
				9	1000, 2000, 3000, 4000, 5000
				11 5	"
II	Stabilized gravel	3	30		1000, 2000, 3000
			50		"
			70		"
		4	30		1000, 2000, 3000
			50		"
			70		"
		5	30		1000, 2000, 3000
			50		1000, 2000, 3000, 4000
			70		"
		6	30		1000, 2000, 3000
			50		1000, 2000, 3000, 4000, 5000
			70		"
		8	30		1000, 2000, 3000
			50		1000, 2000, 3000, 4000, 5000
			70		"
		10	30		1000, 2000, 3000
			50		1000, 2000, 3000, 4000, 5000
			70		"
III	Sand-Clay	5	30		1000, 2000, 3000
			50		1000, 2000, 3000, 4000
			70		1000, 2000, 3000, 4000, 5000

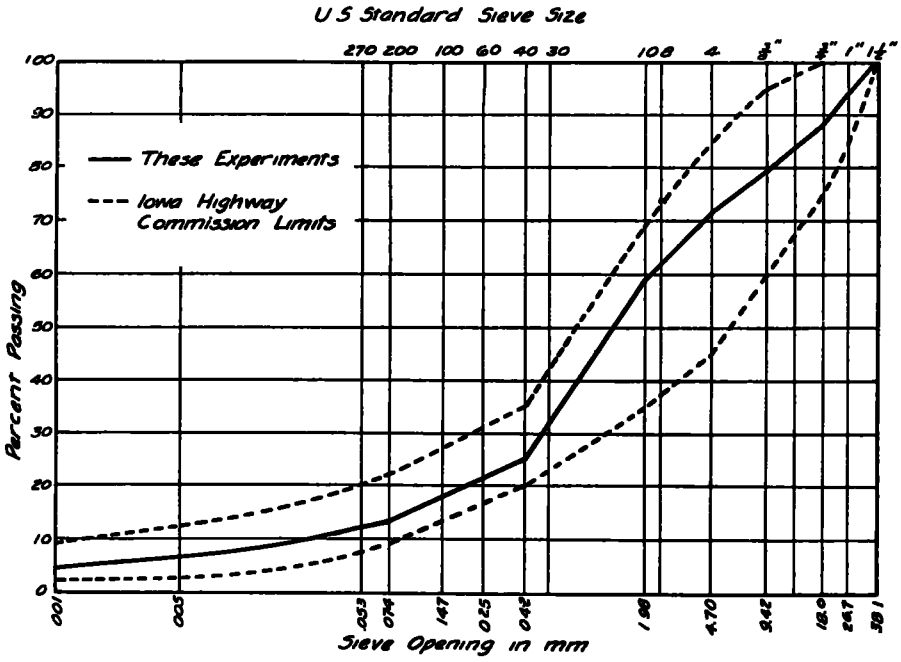

Figure 3. Gradation Curve—Base Course for Series I and II

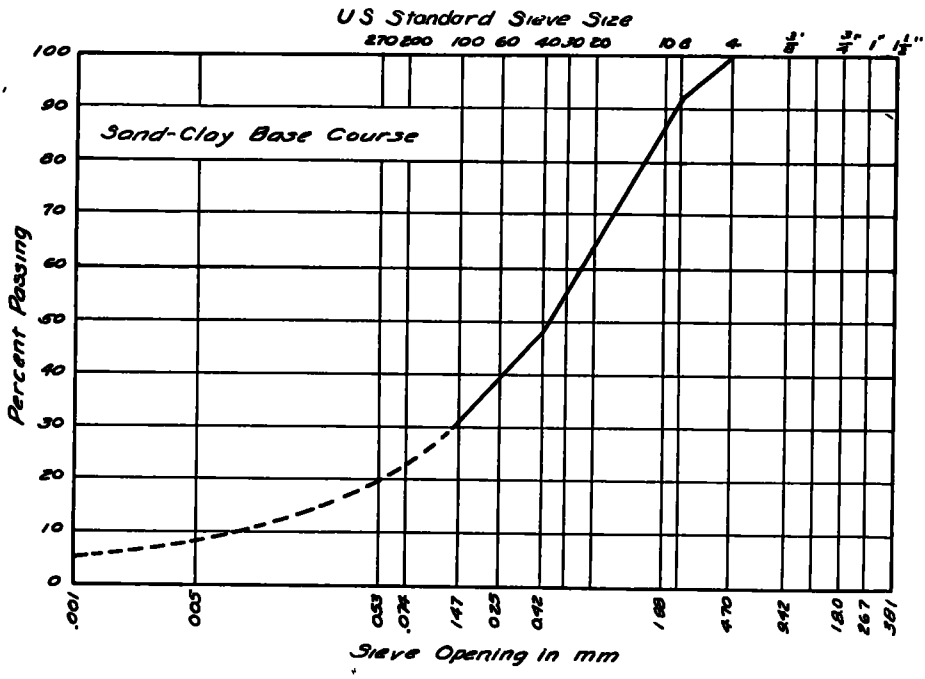

Figure 4. Gradation Curve—Base Course for Series III

The gradation curve for the sand-clay mixture used for the base course in Series III is shown in Figure 4 The fraction of material passing the No. 40 sieve had a plasticity index of 7.0 and a shrinkage limit of 13.1 per cent. The optimum moisture content for maximum density by the Proctor method was 9.1 per cent which gave a maximum dry density of 132.0 pounds per cubic foot. The base course was constructed with the material containing 8.9 per cent moisture and it was mixed and compacted in the same manner as the stabilized gravel pavements of Series I and II The dry density of the sand-clay base course in place was 138 lb. per cu. ft.

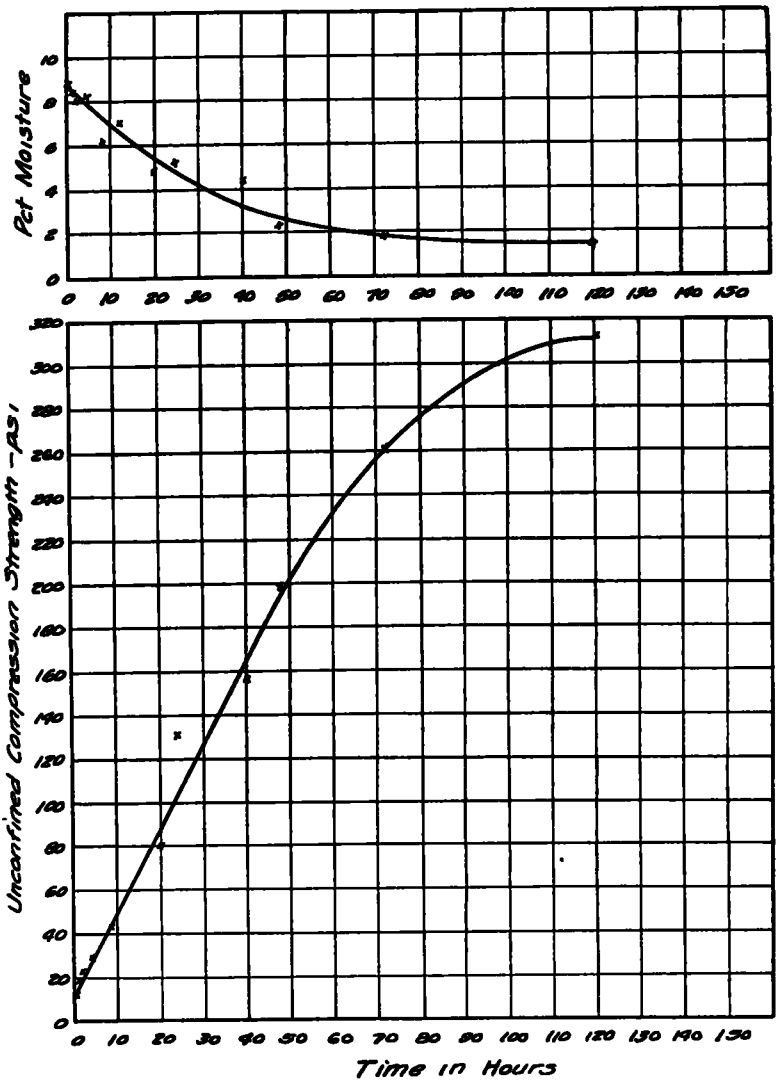

Figure 5

The carbon pile resistors, used for meas-

uring subgrade pressures, were placed in the plane between the base course and the subgrade, in accordance with the plan of arrangement shown in Figure 6. Each resistor consisted of a pile of 6 carbon disks 0.44 in. in diameter and 0.020 in thick with a copper disk of the same diameter and slightly thicker at the top of the pile. The copper disk was connected to an insulated conductor wire which extended laterally to terminal posts mounted on a board at the north and at the south sides of the concrete bin. The piles of carbon disks, including the copper disk at the top, were held in a bakelite ring in which the disks fit loosely and which was slightly shorter than the combined thickness of the disks, to allow for compression of the pile. This ring and the pile rested on a small copper plate, which was connected to a conductor wire similar to that connected to the top copper disk. The resistor assemblies were mounted in holes drilled in a piece of rubber packing which acted as a spacer as well as a retaining medium for the piles. The whole assembly, including the conductor wires, was confined between two

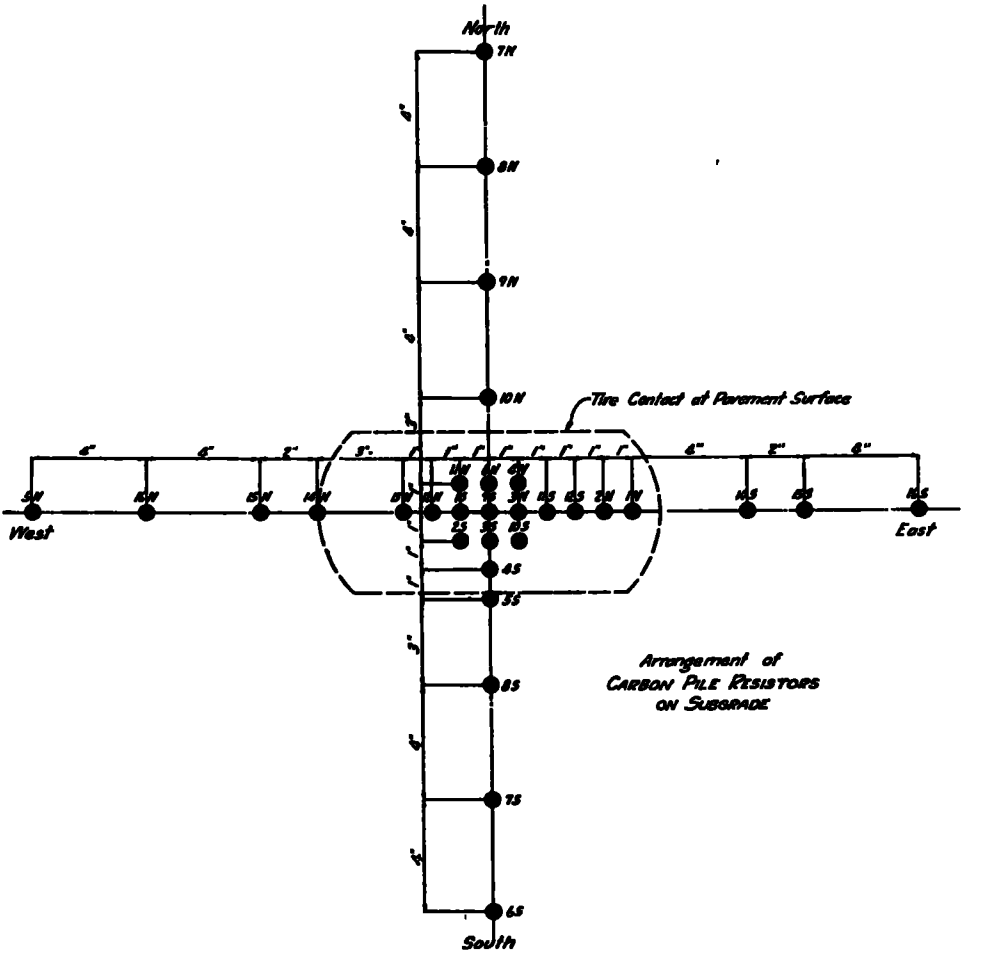

Figure 6. Arrangement of Carbon Pile Resistors on Subgrade

sheets of $\frac{1}{16}$-in. pure gum rubber lying between the subgrade and base course to protect the carbon piles from moisture and other detrimental materials.

The use of carbon pile resistors for measuring pressure is not new. The only novel feature involved in their use in this project is the method of installation of the carbon piles They depend for their operation on the well-known fact that if a pile of carbon plates is held under pressure, a change in pressure will be accompanied by a change of electrical resistance along with a change in length of the pile This action is reversible, the pile acting as an elastic body.

McCollum and Peters (11) of the U. S. Bureau of Standards have made an exhaustive study of this type of pressure measuring device. They state, in part,

" . A serious difficulty was encountered in the fact that carbon-contact resistances as heretofore constructed have shown a more or less erratic performance, their resistances varying from time to time, and the sensitivity or change of resistance for a given change of pressure varying greatly A careful study of the cause of this instability has been made, and it is found that if two or more pieces of carbon be placed in contact and subjected to a certain pressure there will be a definite relationship between the resistance and the pressure as long as the points at which contact between the separate pieces occur remain absolutely the same If, however, there is the slightest change in the number or location of the areas of contact, there will be sudden and erratic changes in resistance as well as in sensitivity to further variations of pressure These changes in the number and location of the contact areas may occur if the contact areas are stressed beyond the elastic limit, resulting in crushing, or they will occur in case the slightest move is made in a tangential direction between two adjacent surfaces in contact Such a tangential displacement, even though very small, will cause large changes in resistance "

From the above discussion, it will be realized that a certain amount of scattering of measured pressures will be inevitable in which work, since the vibrations and disturbances caused by tamping and consolidation of the base course material in the experimental flexible pavements will cause a certain amount of rearrangement of the contact surfaces between the carbon disks after the pressure-resistance relationship has been determined by calibration The authors believe, however, that the results so far obtained show that the carbon pile resistors have definite possibilities for this type of pressure measurement, and that improvements in mountings and methods of calibration are possible which will result in greater precision. The greatest advantages of these devices are their small size, the speed with which pressure measurements can be made, and the fact that they give promise of being adapted to the measurement of pressures due to moving wheel loads Their size, about $\frac{1}{2}$ in. in diameter by $\frac{1}{4}$ in high, makes it possible to observe rapid pressure changes over a relatively small area by placing the piles as close as 1 in. center to center. In this study nine piles were placed in and around a 2-in. square area directly under the load, as shown in Figure 6 A reading can be taken in as short a time as it takes to make a spring clip connection, adjust a rheostat to a given ammeter reading, and read a voltmeter; a matter of only a half minute or less. In case it is desired to adapt these devices to the measurement of moving load pressures, it is possible to attach them to an automatic recorded device as has been done in the McCollum-Peters Strain Telemeter. With this arrangement, simultaneous measurements of pressure can be made at a number of different points, and for any position of the moving load

The electrical circuit employed in connection with these carbon piles is shown in Figure 8 In accordance with Ohm's law,

$$E = IR$$

in which

E = the potential.
I = the current.
R = the resistance.

When pressure is applied to the carbon pile, the resistance of the circuit changes and if the current is held constant, the potential will be proportional to the pressure. For any given current, it is possible to determine the pressure-voltage relationship of the pile by applying known pressures and observing the corresponding voltage.

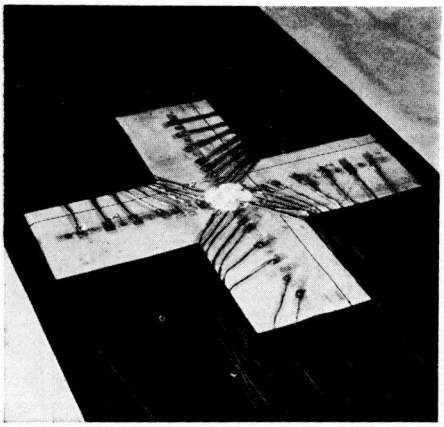

Figure 7. Carbon Pile Assembly on Subgrade Prior to Construction of Base Course

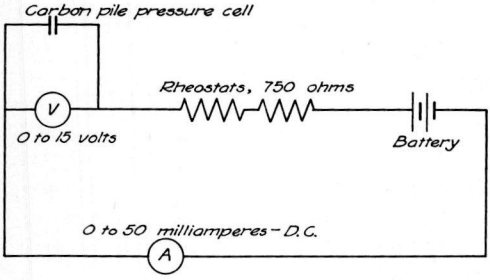

Figure 8. Carbon Pile Resistor Circuit

In this investigation, the carbon piles were calibrated by applying air pressure to the piles after they were installed in place on the subgrade prior to construction of the base course. Air pressure was applied by means of a bottomless box, made of aluminum, in which a section of automobile inner tube was placed and fitted with a valve stem and a pressure gage. This box was placed over a group of the carbon piles with the open side down and then strutted from above to prevent upward movement when the inner tube was inflated. A photograph of the set-up during calibration operations is shown in Figure 9. The carbon piles were calibrated for normal pressures ranging from 5 to 75 lb. per sq. in. by 5-lb. increments, and for several different amounts of current. After the base course was built and loaded, it was re-

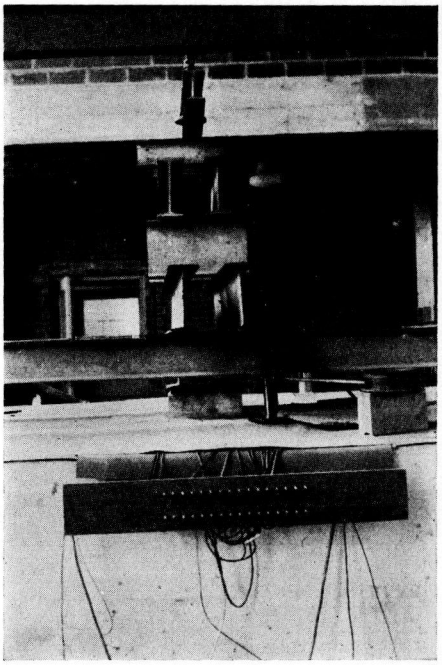

Figure 9. Calibration of Carbon Piles

moved and the piles recalibrated. In general the second calibrations checked fairly well with the initial calibrations, though there were a number of exceptions to this. One of the better sets of calibration curves, for pile No. 11-S of Series II is shown in Figure 10.

After the initial calibrations were completed, the base courses were constructed and allowed to cure for about 40 hours. Then loads were applied through a 7- by 21-in., 6-ply Goodyear tire in all three

series, and through the three rigid cast iron disks in Series No. I. This tire has a rated load capacity of 1200 lb. and the recommended inflation pressure is 40 lb. per sq in.

The cast iron disks were 7 in., 9 in., and 11.5 in. in diameter, having areas of 38.5, 63.6, and 103 9 sq. in., respectively. The average maximum pressure on the subgrade beneath the pavement supporting these disk loads was, in some cases, about the same as that produced by the tire loads of the same magnitude. In other cases, however, there was a marked

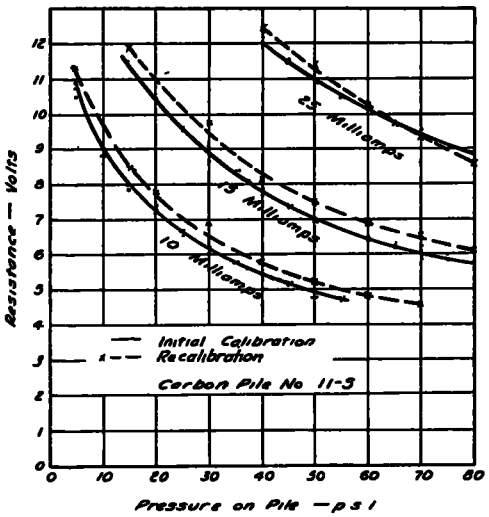

Figure 10

difference between the two pressures and this fact, coupled with the fact that there is little resemblance between the actual tire contact area and the load-inflation pressure quotient, as will be shown later, led to the abandonment of the disk loads. All loads in Series II and III were applied through the tire described.

The measured pressures on the subgrade beneath the experimental stabilized gravel pavement of Series II, having a thickness of 3 in. and applied loads of 1000, 2000, and 3000 lb., are shown in Figures 11, 12, and 13 for three different tire inflation pressures of 30, 50, and 70 lb. per sq in., and consequently three different contact areas. These measurements clearly indicate that, within the range of inflation pressures studied and for the particular tire used for applying the load, both the magnitude and distribution of pressure on the subgrade are independent of tire inflation pressure. This indication has persisted throughout the studies so far conducted and may be accepted as a definite conclusion.

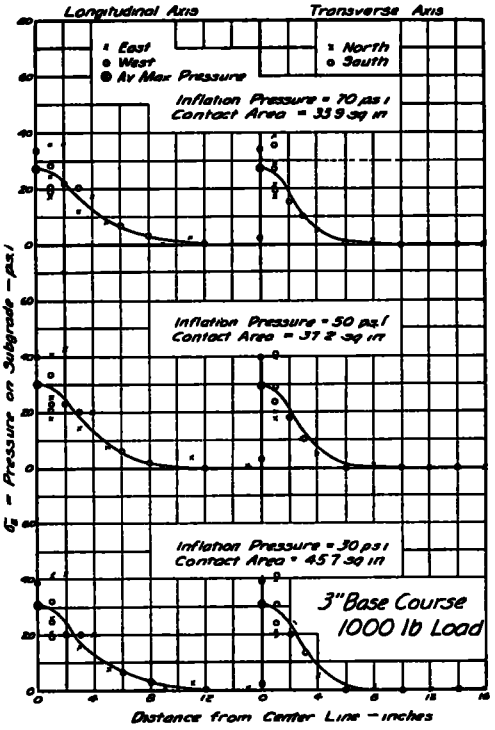

Figure 11

Measured pressures on the subgrade beneath the experimental pavements of Series II, having thicknesses of 4, 5, 6, 8, and 10 inches for an applied load of 3000 lb. and tire inflation pressure of 50 lb. per sq. in , are shown in Figures 14 and 15.

The data shown in these figures are typical of all the measurements made in Series II. Typical data for all the measurements of subgrade pressure under the

5-inch thick sand-clay pavement of Series III are shown in Figure 16 which gives the results for a 2000-lb. load with the tire inflated to 30, 50, and 70 lb. per sq. in.

The pressure measurements were made along the axes parallel to the longitudinal and transverse axes through the tire contact, as shown in Figure 6 Each of the plotted points in these diagrams represents the pressure indicated by a single carbon pile resistor and is an average of six individual readings of pressure, representing three separate applications of the load and two readings for each loading. The range of variation of these six readings was remarkably small, being not more than about 2 per cent either way from the average. The point plotted on the vertical axis through the center of the load and labeled "average maximum pressure" is the average of the pressure indicated by piles No. 1-S, 2-S, 3-S, 9-S, 10-S, 3-N, 4-N, 6-N, and 11-N. Those nine carbon piles were grouped in and around 2-in. square or a 2-in. circle on the subgrade directly under the loaded area, as shown in Figure 6.

In the region directly under the loaded area where the higher subgrade pressures are encountered, the measured points are quite widely scattered; a situation which always causes the research worker some concern and stimulates him to seek the cause of the dispersion. There are several possible reasons in this case to which the scattering of the data may reasonably be attributed. In the first place, some disperson of actual data is to be expected in all engineering measurements, the amount depending upon the type of structure and kind of material being studied. For example, if the modulus of elasticity

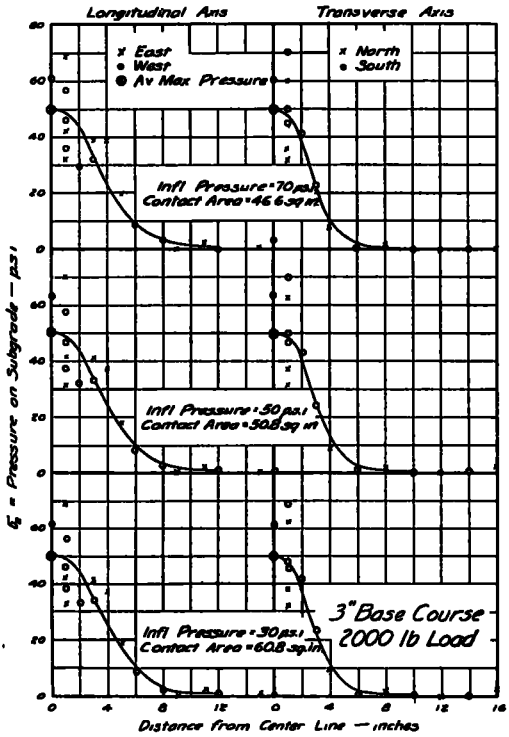

Figure 12

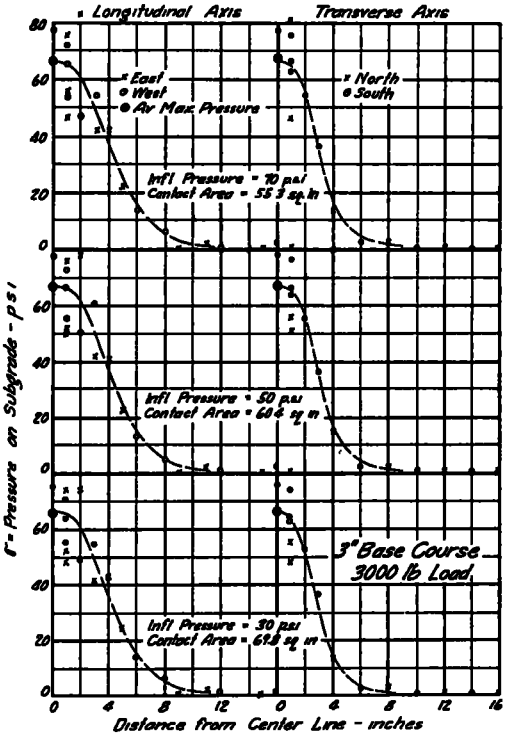

Figure 13

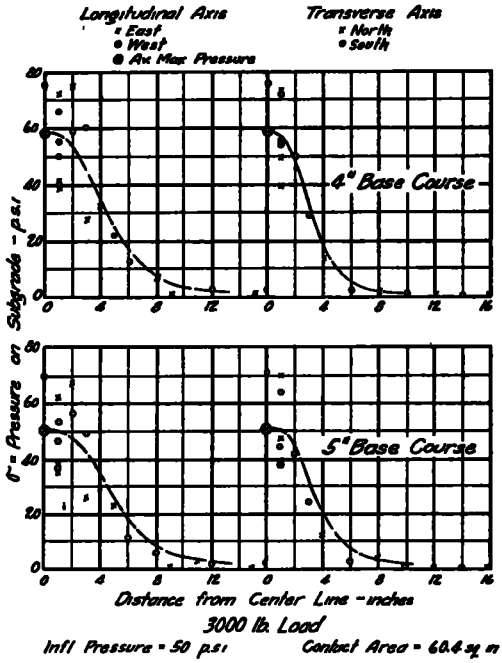

Figure 14

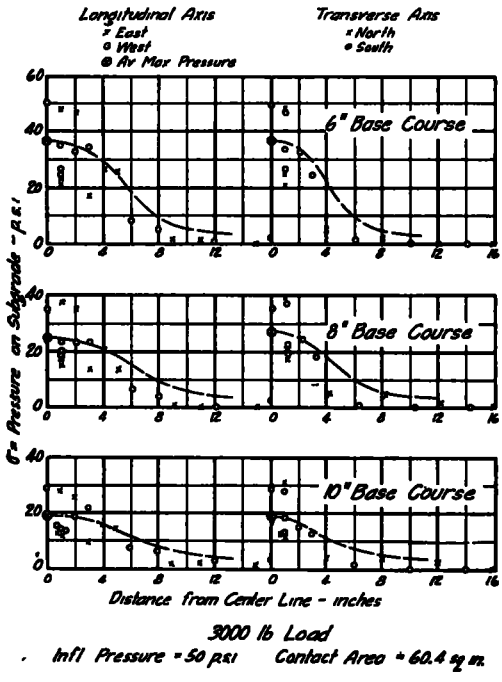

Figure 15

of a large number of concrete cylinders, all made as nearly identical as possible, were to be determined, the individual values of the modulus would vary considerably and such variation has come to be an accepted phenomenon which does not hamper the widespread and successful use of this material in engineering structures. Many similar examples of normal dispersion of engineering measurements

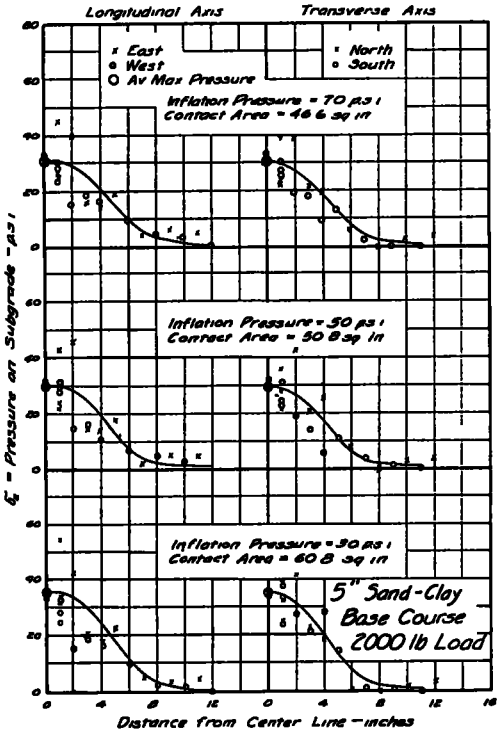

Figure 16

could be cited. It is not surprising, therefore, that measurements of stresses in soil masses should vary widely from point to point, and while making every effort to improve methods and apparatus for making such measurements, the researcher must recognize the statistical character of soil stress data and formulate his conclusions accordingly This fact dictates the necessity for large numbers of individual stress measurements in soil masses

from which general patterns of stress distribution may be more accurately deduced. A stress measurement at a single isolated point, while being perhaps better than no measurement at all, may be very misleading and lead to erroneous conclusions.

A study of the apparatus and technique employed in this project indicates several possible sources of error in the measurements, and points the way for improvement in procedures for future similar studies. First, even very slight disturbances of the initial orientation of the faces of the adjacent carbon disks in the carbon pile resistors may throw them out of calibration, and there was ample opportunity for such disturbances in the tamping operations involved in the construction of the base courses. Second, the base course material in Series II contained many large pieces of aggregate which added to the heterogeneous character of the medium through which the stresses were transmitted. It is not inconceivable that these relatively large inclusions, accidentally placed and oriented as they were, may have caused interruptions and distortions in the lines of stress radiating from the load, to an extent which would account for a considerable part of the dispersion in the measured pressures. In Series III the base course material was relatively fine in texture, and in general the individual data points do not scatter so much as in Series II, although there are some notable exceptions, as may be noted in Figure 16.

In spite of the dispersion of the stress measurements at individual points, the helmet shaped surface representing the pressure distribution at the subgrade, which is typical of the Boussinesq type of distribution is clearly revealed. No attempt has been made to formulate a quantitative expression for this distribution, but the data appear to lend themselves to such an interpretation. It may be that some modification of the Boussinesq expression such as that discovered first by Griffith (6) and later by Frolich, (19) involving a so-called "concentration factor," can be found which will fit the data.

Griffith's concentration factor, sometimes spoken of as a "dispersion factor," does not give a strictly rational expression for the distribution of pressure through a soil medium, if the soil is considered to be an ideally elastic medium. His solution complies with the strain compatibility criterion only when the concentration factor is equal to 5, which gives the Boussinesq solution. It was Professor Griffith's thought, however, that soil materials deviate from the ideal, in many cases to such an extent and in such a manner that a semi-empirical expression such as he suggested would fit experimental data for stress transmission much better than the wholly rational Boussinesq solution. He therefore derived his formula to comply with the stress equilibrium criterion only and without regard to the strain compatibility criterion, introducing the concentration factor as a disposable variable whose value is to be chosen in the light of experimental data for any particular problem.

The relationship between the average maximum pressure on the subgrade and the thickness of the experimental flexible pavements is shown in Figure 17. The data points on this diagram include the results of all the pressure measurements which have been made to date on this project, including two series of observations made in 1938 using the differential friction ribbon measuring devices (12) and the three series of 1940 All the data have been plotted on the basis of an applied load of 3000 lb., assuming the principle of superposition to be valid That is, the pressure measured under a 1000-lb. load has been multiplied by 3; under a 2000-lb. load by 1 5, etc The extent to which data for all loads coincide indicates that the principle of superposition is roughly applicable in these studies.

An empirical equation for the pressure-thickness relationship as revealed by these experiments has been devised, having the form

$$\sigma_s = \frac{CP}{t^n} \qquad 2$$

in which

C and n = disposable parameters.
P = the tire load in pounds.
t = the pavement thickness in inches.
σ_s = the average maximum pressure on the subgrade in pounds per square inch.

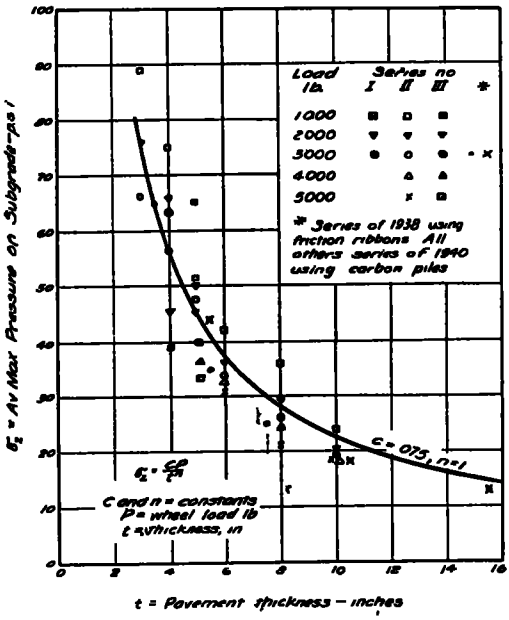

Figure 17

For the conditions which prevailed in these experiments, the values of the parameters C and n may be taken as 0.075 and 1.0, respectively. It will be noted in Figure 17, however, that in most cases the points representing subgrade pressures under 1000-lb. loads are at the top of the group of points for any one thickness of pavement, and the points graduate downward to those for the 5000-lb. load which are at the bottom of the group, as a general rule. This situation indicates that the relationship between subgrade pressure and applied load is not strictly a linear one for this particular tire, and this fact is clearly shown in Figure 18 where the average maximum subgrade pressure is plotted against the load for each pavement thickness. It will be noted in this figure that these curves, while essentially straight lines, do not pass through the origin, but tend to slope downward and to the right. This deviation from a linear relationship may be a reflection of the influence of the increased tire contact area caused by increased loading, although no similar influence of

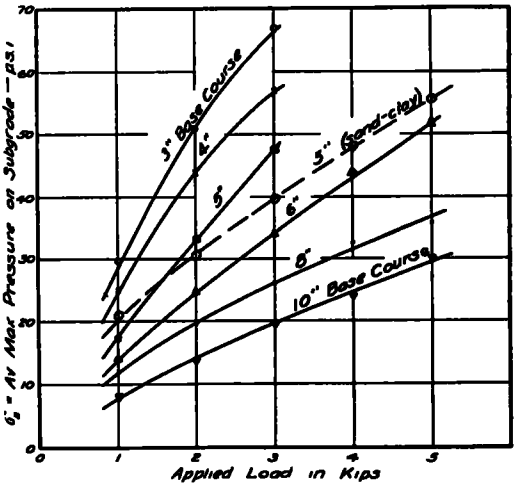

Figure 18

increased area due to reduction in inflation pressure could be detected.

It is possible that the values of the constant C in formula 2 should be varied with the load from 0.090 for a 1000-lb. load to about 0.060 for a 5000-lb. load, although the authors do not believe the data justify such refinement at the present time.

It is interesting to note that the measured values of pressure in the 1938 experiments agree closely with those obtained in the 1940 work. This lends a degree of confidence in both series of measurements

and in both types of measuring apparatus, since the conditions of the experiments were, in general, the same in both years.

a valid criterion for determining the area of contact between a pneumatic tire and a flexible pavement surface. Under cer-

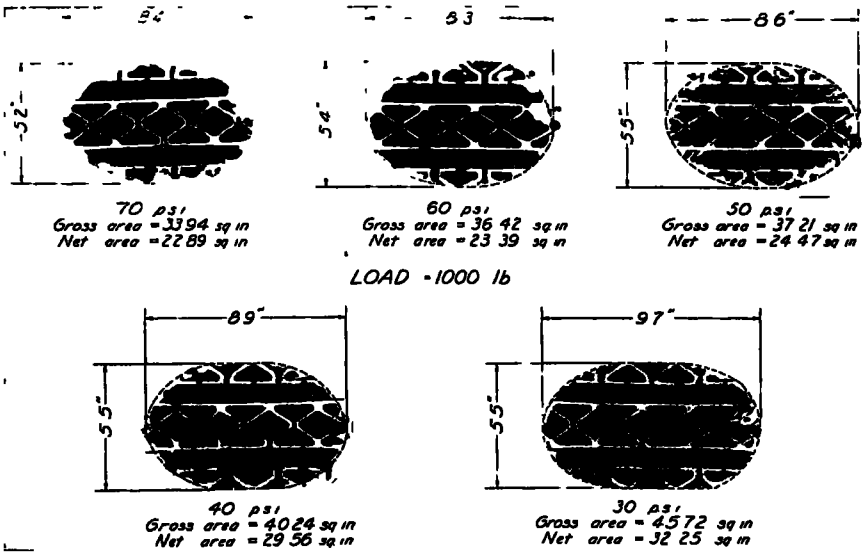

Figure 19. Tire Imprints for 1,000 lb. Loads on New 6 Ply 7 x 21 Goodyear Tire

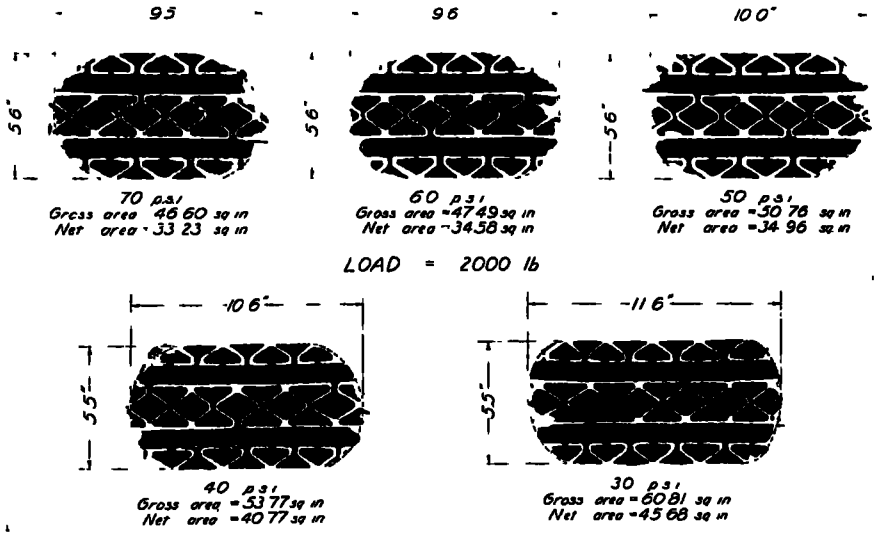

Figure 20. Tire Imprints for 2,000 lb. Loads on New 6 Ply 7 x 21 Goodyear Tire

LOAD-AREA OF CONTACT RELATIONSHIPS

During the conduct of the experiments it has become increasingly evident that the load-inflation pressure quotient is not

tain conditions, the $\frac{L}{I}$ quotient is equal to the actual contact area, but in many cases it is not and the variation may be very

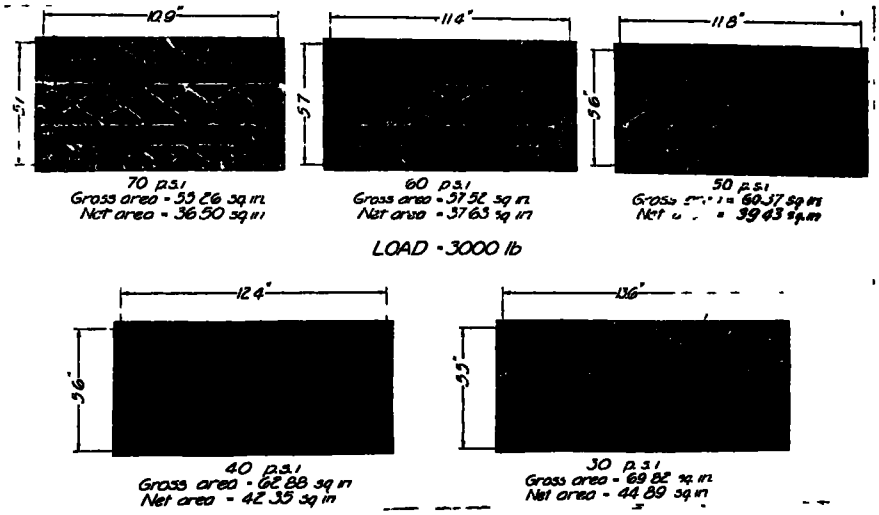

Figure 21. Tire Imprints for 3,000 lb. Loads on New 6 Ply 7 x 21 Goodyear Tire

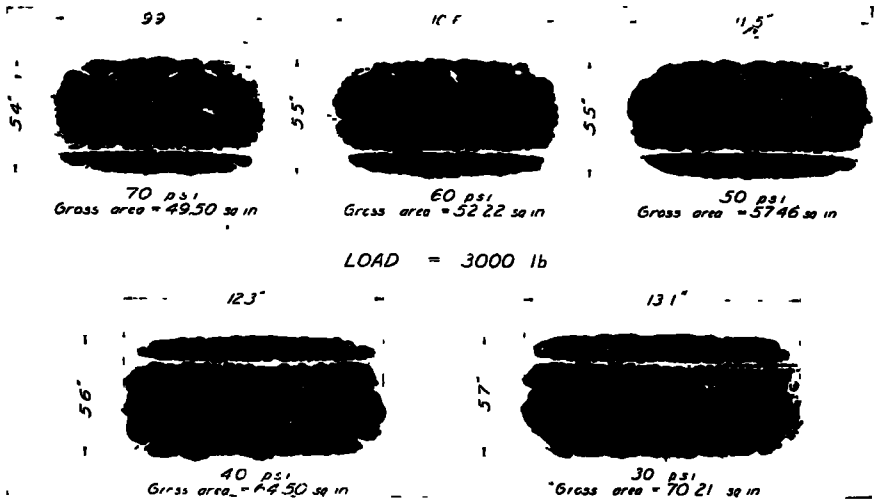

Figure 22. Tire Imprints for 3,000 lb. Loads on a Badly Worn 10 Ply, Heavy Duty, 6 x 32 Goodyear Tire

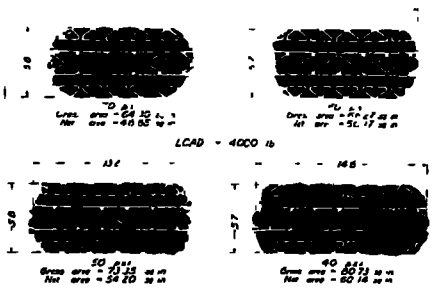

Figure 23. Tire Imprints for 4,000 lb. Loads on New 6 Ply 7 x 21 Goodyear Tire

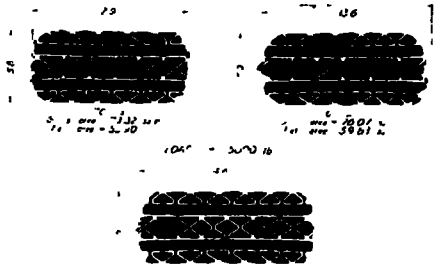

Figure 24. Tire Imprints for 5,000 lb. Loads on New 6 Ply 7 x 21 Goodyear Tire

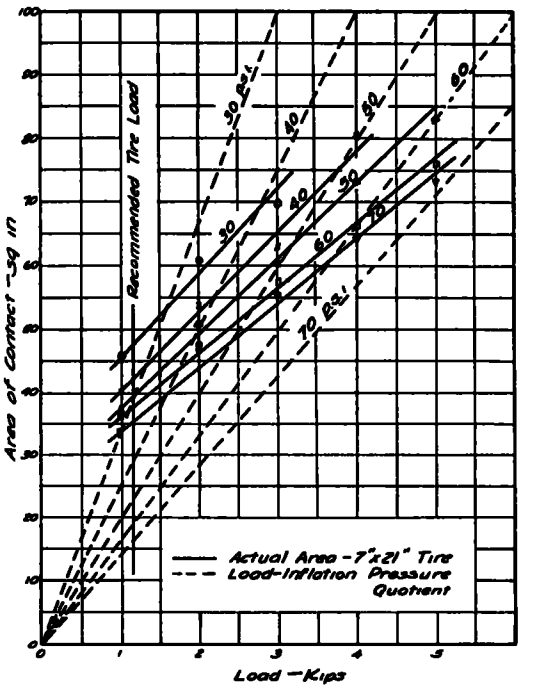

Figure 25

TABLE 2

COMPARISON BETWEEN GROSS AREA OF CONTACT AND LOAD-INFLATION PRESSURE QUOTIENT

Inflation pressure, p.s.i.	Load—lb									
	1000		2000		3000		4000		5000	
	Gross area of contact—sq in.									
	Actual	L/I	Actual	L/I	Actual	L/I	Actual	L/I	Actual	L/I
New 6-ply, heavy duty, 7 by 21 Goodyear tire										
30	45 7	33 3	60 8	66 7	69 8	100 0	—	—	—	—
40	40 2	25 0	53 8	50 0	62 9	75 0	80 7	100 0	—	—
50	37 2	20 0	50 8	40 0	60 4	60 0	73 4	80 0	83 2	100 0
60	36 4	16 7	47 5	33 3	57 5	50 0	66 3	66 7	76 1	83 3
70	33 9	14 3	46 6	28 6	55 3	42 9	64 3	57 1	73 3	71 4
Badly worn, 10-ply, heavy duty, 6 by 32 Goodyear tire										
30					70 2	100 0				
40					64 5	75 0				
50					57 5	60 0				
60					52 2	50 0				
70					49 5	42 9				

marked. It may be greater or less than the actual area.

The actual area of contact for the load and inflation pressure conditions employed in these experiments are shown in Figures 19 to 24. These tire imprints were made by coating the tread of the tire with prussian blue and printing the contact area on a paper laid on the pavement surface. Included for comparison are the tire imprints made by a very old 32 by 6 10-ply Goodyear heavy duty tire which had the tread pattern completely worn off in service. From these tire imprints a comparison between the load-inflation quotients and the actual areas of contact has been made and is shown in Figure 25 and in Table 2.

TENTATIVE CONCLUSIONS

It is too early in the conduct of this project to draw generalized conclusions, since, as has been pointed out, all work has been done in the laboratory on synthetic subgrades and under more or less artificial conditions However, there are some trends which are indicated quite definitely and these are summarized in the following tentative conclusions.

1. The pressure on a subgrade beneath a flexible type pavement is distributed in accordance with the typical helmet shaped surface indicated by the Boussinesq solution, and Griffith's concentration factor formula

$$\sigma_s = \frac{CP}{t^n}$$

2. The maximum pressure occurs on a relatively small area directly beneath the tire contact area, and the value of this maximum pressure is independent of the inflation pressure of the tire.

3. The maximum subgrade pressure is nearly directly dependent upon the magnitude of the applied load in these experiments, though there is some evidence to indicate a non-linear relationship.

4 The maximum subgrade pressure varies in inverse ratio with the thickness of the pavement and may be expressed by the empirical formula.

For these particular experiments, the average values of C and n may be taken as 0 075 and 1.0, respectively, with C varying between about 0 060 for a load of 1000 lb. and 0.090 for a load of 5000 lb.

5. The load-inflation pressure quotient is not a valid criterion for determining the area of contact between a tire and a flexible pavement. In these experiments the actual area of contact varied from about 70 per cent to 237 per cent of the load-inflation pressure quotient.

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