FACTORS INFLUENCING THE STRESS IN CONCRETE PAVEMENT FROM APPLIED LOADS

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SYNOPSIS

An investigation was made of the sizes and shapes of the contact areas between truck tires and pavement surface, and the relative effect of the size and shape of the contact area, the tire inflation pressure, the total load, the quality of the subgrade and the pavement thickness upon the stress in concrete pavements due to applied loads

Prints of the contact areas of partially worn 10-in and 11-in truck tires, under total loads of from 2,000 lb to 8,000 lb and at inflation pressures of 50, 70, and 90 p s i , were made The area and shape of the contact area was determined from these prints The stress in the pavement was determined from formulae developed by Dr H M Westergaard

It is shown that, while the shape of the contact area is approximately a rectangle under the heavier loads, only a negligible error is introduced by considering the area a circle or an ellipse of equivalent size The increase in inflation pressure as the tire distorts under increasing loads was found to be negligible The relative effects of subgrade quality and pavement thickness were determined and found to be of more importance than the variables introduced in the manner of applying the loads

The design of pavements in the earlier years of highway construction was largely based on experience. A pavement section, which had given satisfactory service under a particular set of conditions of subgrade support and traffic, would be adopted as a standard for use under other conditions with often too little consideration for the effect of these variations Methods of theoretical anlysis of the stresses in rigid pavements are now available by which the effect of many of the major factors influencing these stresses may be evaluated. In the main the methods of analysis are the result of Dean Westergaard's work and may be found in the Proceedings of the Highway Research Board, publications of the Public Roads Administration, and the Transactions of the American Society of Civil Engineers The comparative stresses given in this paper are computed by the method developed in Westergaard's paper entitled "Stress Concentrations in Plates Loaded Over Small Areas," published in the 1943 Transactions of the A S C E

Since the relative effects of the various factors of subgrade support and type and manner of loading involved are of primary interest in this study, only static loads placed at points relatively distant from the slab edges have been considered The effects of impact, temperature change, or moisture change have not been superimposed upon the load stresses The comparisons given do, however, give a picture of the relative importance of size and shape of tire contact area, tire inflation pressure, unit load and total load, subgrade support and pavement thickness

The cost of motor truck transportation is materially reduced as the pay load is increased The obvious way to increase the pay load is to increase the axle load. Motor truck operators, usually without a realization of the resulting damage to the highways, are continually pressing for an increase in the permissible axle load. Some time ago an article appeared in a trade journal sponsored by a national trucking association which went so far as to advocate the abandonment of all weight restrictions and to propose that axle load be regulated by a limitation of the tire inflation pressure This proposal was based on the supposition that the unit pressure applied by the tire to the pavement will be equal to the tire inflation pressure and that this unit pressure is the only factor of importance in load regulation

As a matter of fact, unit pressure is rather a minor factor among the many factors affecting stress in pavements Other factors that must be considered include total load, size and shape of the contact area between the tire and the pavement, thickness of the pavement, quality of the subgrade supporting the pavement, and physical properties of the pavement itself

A series of tests was undertaken to provide definite information on the size and shape of the contact areas of large truck tires under varying total loads and inflation pressures The normal operating inflation pressures for large tires is 70 p s i Inflation pressures of 90 p.s i., 70 p s i, and 50 p s i. were used in the test so as to cover the complete range of pressures which would be expected on actual vehicles.

The larger cargo trucks and the great majority of logging trucks use either 10-in. or 11-in. tires. With this in mind, a typical tire of each of these sizes was selected for the tests. The treads of the tires selected were worn down to about half their service life and thus represented average tires in use.

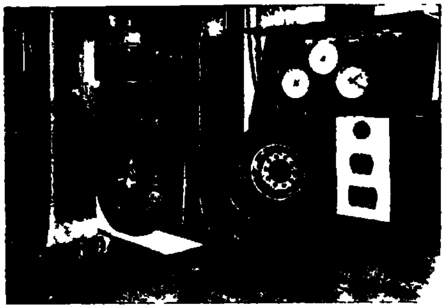


Figure 1

Test Procedure

The tests were made in the 600,000-lb. Southwark-Emery Testing machine at the Oregon State College and were supervised by S H. Graf, Professor of Mechanical Engineering, assisted by Professor C E Thomas.

A photograph of the test setup is shown as Figure 1 Rigid brackets were attached to the head of the testing machine which supported an axle fitted to a standard hub of a Budd truck wheel. When the wheel was bolted to this hub, the load was applied through the axle as would normally be the case in truck operation A smooth sheet of plyboard was placed on the base of the machine A 17 by 22-in. sheet of white paper was placed on the plyboard to receive the impression for each increment of load The portion of the tire coming in contact with the paper was coated with black printer's ink. A pressure gauge was attached to the valve stem and the inflation pressure noted at each load increment

Tire Contact Imprints

Figures 2 and 3 show the shapes and sizes of the contact areas of the two tires under different loadings and initial inflation pressures. The areas were measured with a planimeter. In measuring the areas the tread pattern was disregarded and the total area bounded by the outline of the imprint was considered as the contact area.

The exterior outline of the cross section through the tire is not circular The edges of the tread are built up so that the surface over the tread is only slightly convex and the side of the tread is almost perpendicular to the tread surface. After sufficient load is applied to straighten out the tread surface and bring the edges into bearing, no further increase in the width of the contact area occurs. Additional area is provided by an extension in length.

A study of the tire imprints shows that, as the loads increase up to approximately 4,000 lb, the shape of the contact area changes from a circle, through an ellipse, to a rectangle with rounded ends. For loads above 4,000 lb, an equivalent rectangle more nearly approximates the actual contact area than either an ellipse or a circle.

The tests give no information as to the distribution of pressure over the contact area. It is probable that under light loads the pressure is equal to, or but slightly above, the inflation pressure at the center of the contact area and decreases to zero at the edges. As the load increases and the edge of the tread comes in contact with the pavement, the side wall stiffness becomes effective. At the higher loads the distribution is probably fairly uniform over the interior of the contact area, with a narrow strip of higher pressure along the edges. It is certain that under the larger loads pressures higher than the inflation pressure are applied over parts of the contact areas. This is shown by the average unit loads given in Table 1 to 6

Tables 1 to 6 give the contact areas and the dimensions of the rectangles, ellipses and circles of equal area. The diameters of the ellipses are in porportion to the length and width of the tire imprint. The shape of the assumed figure is that which most nearly approximates the actual contact imprint.

The contact areas of the tires, with all three inflation pressures, increase as the load increases. This increase in area is not, however, directly proportional to the load increase. This lack of direct proportionality is reflected

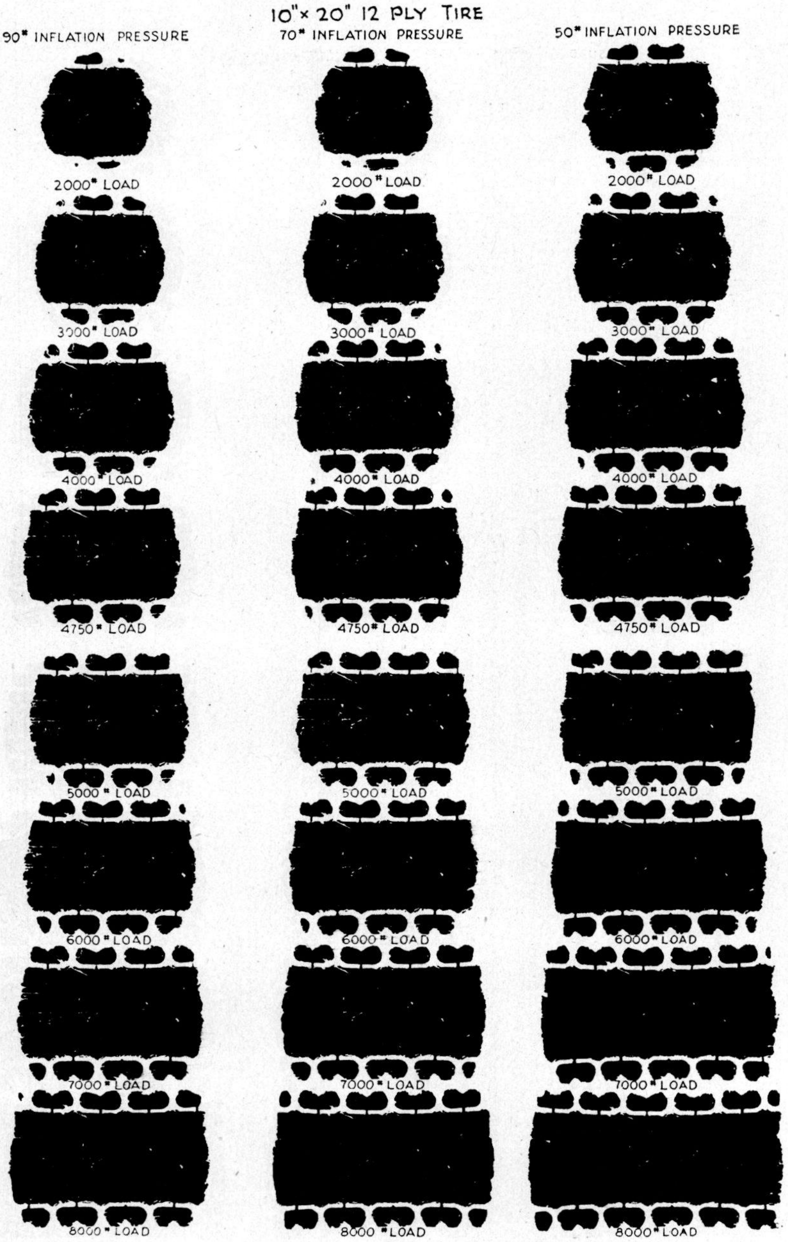


Figure 2

in the average unit loads. Under the lower total loads, the average unit load is less than the inflation pressure As the total load increases, the average unit load increases Under the higher total loads, the average unit load exceeds the inflation pressure. The range of variation in average unit loads is mainly influenced by the inflation pressure and is slightly different in the two tires tested. The average unit load from the 11-in tire with 90

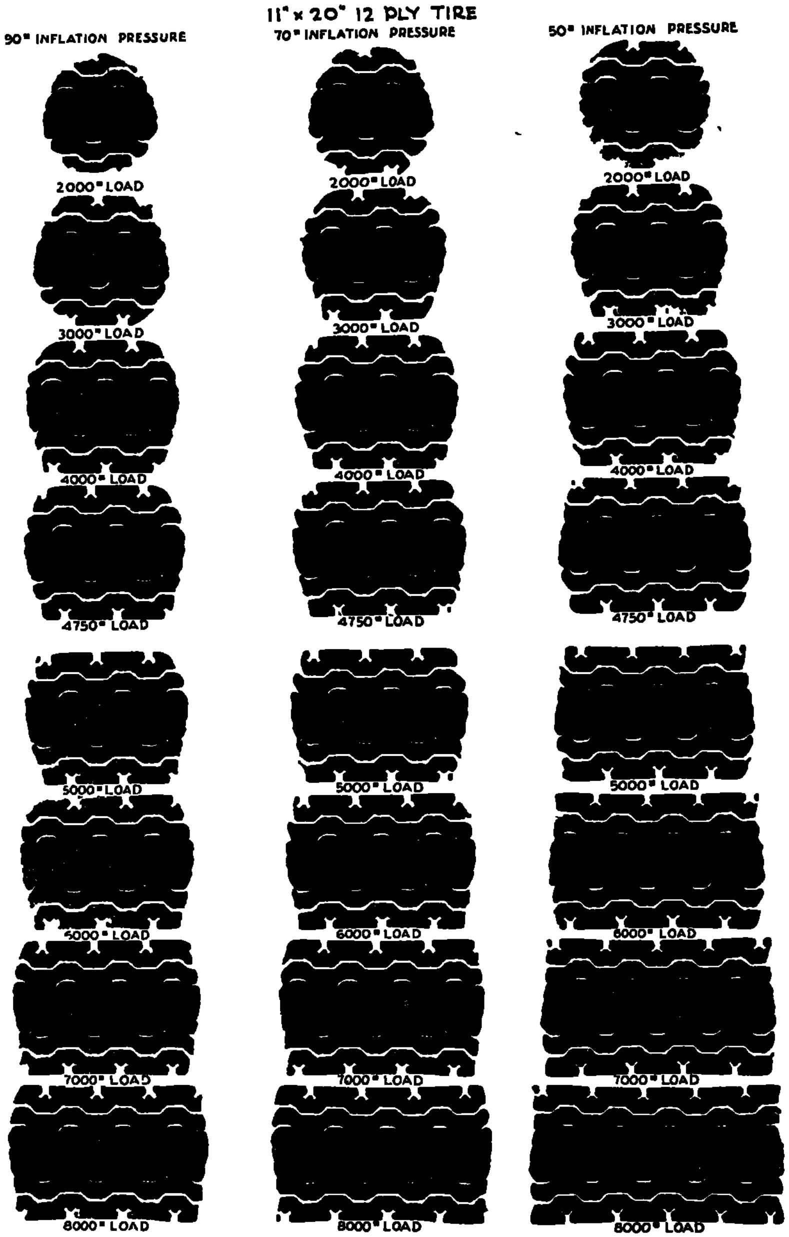


Figure 3

p.s i. inflation pressure did not equal the inflation pressure until the total load reached 8,000 lb , while with the 10-in tire inflated to 50 p s i. the inflation pressure was exceeded when the total load reached 3,000 lb. The stiffness of the side walls of the tire undoubtedly account for variation from inflation pressure.

TABLE 1

TIRE CONTACT IMPRINTS

10-in by 20-in -12-Ply Tire—90 p s i Initial Inflation Pressure

Load (lb)	Tire Pressure Under Load (p s i)	Contact Area (sq in)	Average Unit Load (p s i)	Rectangle		Ellipse		Circle Radius (in)
				Width (in)	Length (in)	Width (in)	Length (in)	
2,000	90 0	31 54	63 4					3 168
3,000	90 1	43 92	68 3					3 739
4,000	90 2	53 50	74 8			7 905	8 616	
4,750	90 2	59 44	80 1			8 098	9 345	
5,000	90 3	61 80	80 9	7 8	7 92			
6,000	90 4	68 76	87 3	7 8	8 82			
7,000	90 6	75 74	92 4	7 8	9 71			
8,000	91 0	82 22	97 3	7 8	10 54			

TABLE 2

TIRE CONTACT IMPRINTS

10-in by 20-in -12-Ply Tire—70 p s i Initial Inflation Pressure

Load (lb)	Tire Pressure Under Load (p s i)	Contact Area (sq in)	Average Unit Load (p s i)	Rectangle		Ellipse		Circle Radius (in)
				Width (in)	Length (in)	Width (in)	Length (in)	
2,000	70 1	37 72	53 0					3 465
3,000	70 3	49 64	60 4					3 975
4,000	70 3	60 90	65 7			8 196	9 458	
4,750	70 4	67 26	70 6	7 8	8 62			
5,000	70 4	68 00	73 5	7 8	8 72			
6,000	70 5	75 96	79 0	7 8	9 74			
7,000	70 6	84 34	83 0	7 8	10 81			
8,000	71 1	93 82	85 3	7 8	12 03			

TABLE 3

TIRE CONTACT IMPRINTS

10-in by 20-in -12-Ply Tire—50 p s i Initial Inflation Pressure

Load (lb)	Tire Pressure Under Load (p s i)	Contact Area (sq in)	Average Unit Load (p s i)	Rectangle		Ellipse		Circle Radius (in)
				Width (in)	Length (in)	Width (in)	Length (in)	
2,000	50 0	45 54	44 0					3 803
3,000	50 1	58 44	51 3			8.039	9 277	
4,000	50 2	70 08	57 1	7 8	8 98			
4,750	50 4	77 26	61 5	7 8	9 91			
5,000	50 4	79 68	62 8	7 8	10 22			
6,000	51 0	90 20	66 5	7 8	11 57	8 465	13 569	5 359
7,000	51 2	100 40	69 7	7 8	12 87			
8,000	51 8	110 36	72 5	7 8	14 15			

As the total load increased, the cross section of the tire deformed, the volume of air decreased, and the inflation pressure increased. This increase in inflation pressure is given in tables 1 to 6 It is so slight as to be of little practical importance

TABLE 4

TIRE CONTACT IMPRINTS

11-in by 20-in -12-Ply Tire—90 p s i Initial Inflation Pressure

Load (lb)	Tire Pressure Under Load (p s i)	Contact Area (sq in)	Average Unit Load (p s i)	Rectangle		Ellipse		Circle Radius (in)
				Width (in)	Length (in)	Width (in)	Length (in)	
2,000	90 0	35 40	56 5					3 358
3,000	90 0	48 90	61 3			7 732	8 046	
4,000	90 0	60 20	66 4			8 196	9 352	
4,750	90 5	64 70	73 4	7 8	8 29			
5,000	90 4	67 00	74 6	7 8	8 58			
6,000	90 5	73 48	81 7	7 8	9 42			
7,000	91 0	80 70	86 7	7 8	10 35			
8,000	91 1	86 94	92 0	7 8	11 15			

TABLE 5

TIRE CONTACT IMPRINTS

11-in by 20-in -12-Ply Tire—70 p s i Initial Inflation Pressure

Load (lb)	Tire Pressure Under Load (p s i)	Contact Area (sq in)	Average Unit Load (p s i)	Rectangle		Ellipse		Circle Radius (in)
				Width (in)	Length (in)	Width (in)	Length (in)	
2,000	70 0	43 12	46 4					3 704
3,000	70 0	55 04	54 5			8 067	8 687	
4,000	70 3	65 22	61 3	7 8	8 36			
4,750	70 5	70 80	67 1	7 8	9 08			
5,000	70 5	74 06	67 5	7 8	9 49			
6,000	70 6	80 24	74 8	7 8	10 29			
7,000	70 6	88 90	78 7	7 8	11 40			
8,000	70 8	96 12	83 2	7 8	12 32			

TABLE 6

TIRE CONTACT.IMPRINTS

11-in by 20-in -12-Ply Tire—50 p s i Initial Inflation Pressure

Load (lb)	Tire Pressure Under Load (p s i)	Contact Area (sq in)	Average Unit Load (p s i)	Rectangle		Ellipse		Circle Radius (in)
				Width (in)	Length (in)	Width (in)	Length (in)	
2,000	50 0	47 22	42 4					3 877
3,000	50 2	61 20	49 0			8 216	9 481	
4,000	50 3	71 98	55 6	7 8	9 23			
4,750	50 3	80 04	59 3	7 8	10 26			
5,000	50 4	84 10	59 4	7 8	10 78			
6,000	50 6	92 28	65 0	7 8	12 73			
7,000	51 0	101 66	68 9	7 8	13 03			
8,000	51 5	111 48	71 8	7 8	14 29			

The data concerning contact area, average unit load, and inflation pressure are shown in Figures 4 and 5

Effect of Shape of Contact Area

Figures 2 and 3 show that the shape of the contact area changes as the load increases. At

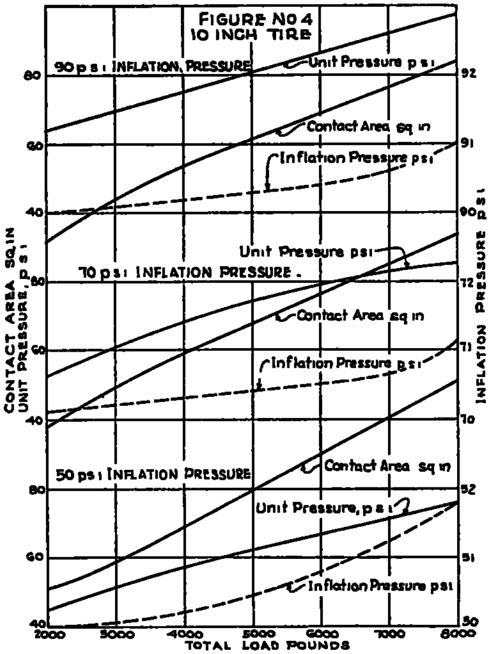


Figure 4

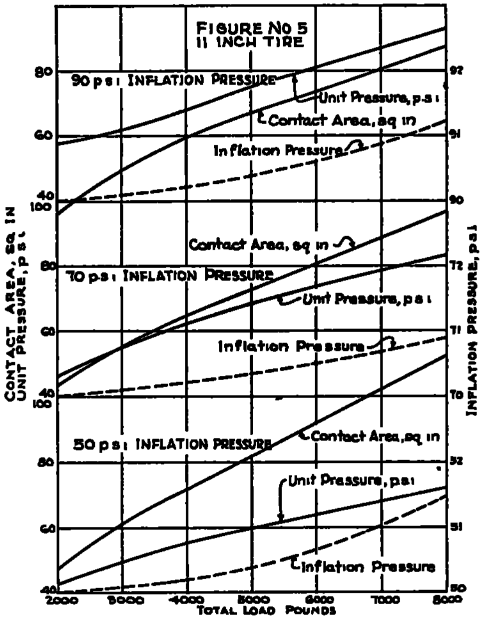


Figure 5

the lowest load the contact area is circular As the load increases, the contact area becomes elliptical with the major diameter parallel with the direction of travel. When the loads are 4,000 lb. or more, the shape of the contact area is a rectangle with rounded ends. At the higher loads this rounding is negligible, and the shape is, for all practical purposes, a true rectangle. Since most truck axles carry dual tires and are limited by law to maximum loads of from 16,000 to 24,000 lb. per axle, the greatest practical interest is in wheel loads of from 4,000 lb. to 6,000 lb.

Figure 6 compares the actual contact area of the 10 by 20-in tire, inflated to 50 p.s.i. and carrying a 6,000-lb. load, with a rectangle, an ellipse, and a circle, all of which have areas equal to the actual contact area. It will be noticed that the correspondence of the rectangle with the contact area is much closer than is the case with the other figures. The slight differences in outline occur at the ends of the figure where the effect upon the maximum stresses at the center of the loaded area are the least

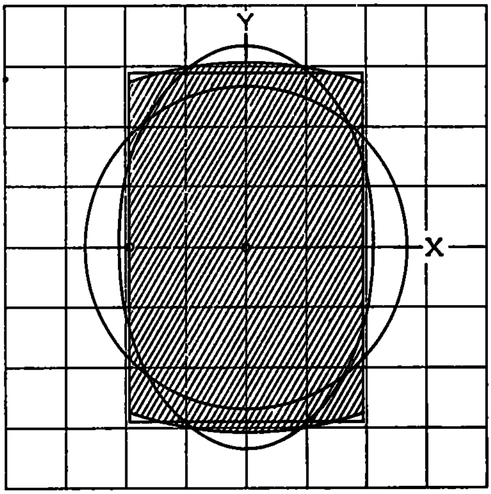


Figure 6. Correspondence of Rectangle, Ellipse, and Circle To Contact Area of Tire, 10-in. x 20-in. Tire, 000 lb. load, 50 p.s.i. inflation pressure.

A comparison of the theoretical stresses in a 7-in pavement from a 6,000-lb load, applied though the 10 by 20-in tire inflated to 50 p s i , is given in Table 7 for the rectangle, the ellipse, and the circle shown in Figure 6 (Stresses are given for the center of the loaded area and for a point on the transverse axis at the edge of the tire imprint) The physical qualities of the pavement were assumed as follows· Modulus of Elasticity—4,000,000; Poisson's Ratio—0.2; Subgrade Modulus—200.

In comparison with the stresses given by the rectangular contact area, the error resulting from the use of either the equivalent ellipse or circle is not important, especially for the center of the contact area where maximum stresses occur. For stresses at the edge of the contact area and for stresses outside the contact area, both the ellipse and the circle give results which are too high. The ellipse, however, approaches the true stress more closely than does the circle. Calculations using the rectangular area are difficult for points outside the contact area. The determination of stresses outside the contact area is, however, necessary in building up the stress pattern from dual wheels and tandem axles. For this purpose the use of an elliptical rather than a circular area is preferable.

TABLE 7
COMPARISON OF STRESSES FROM CONTACT AREAS

	Rectangle	Ellipse	Circle
Transverse Stress at Center	161 5	162 2	158 6
Percentage of Error	0	+0 4	−1 8
Longitudinal Stress at Center	151 0	151 0	158 6
Percentage of Error	0	0	5 0
Transverse Stress at Edge	123 5	129 8	133 9
Percentage of Error	0	5 1	8 4
Longitudinal Stress at Edge	131 3	137 2	146 2
Percentage of Error	0	4 5	11 4

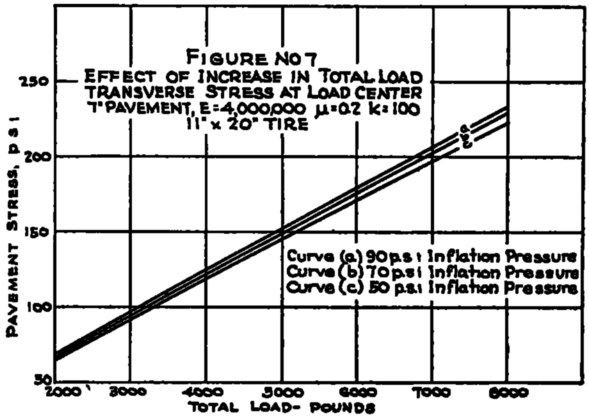


Figure 7

Effect of Increase in Total Load

The tire contact area increases as the total load is increased. Because of this increase in area, the stress in the pavement does not quite increase in the same ratio that the total load increases. As an example, the stresses under the load center of an 11 by 20-in. tire at inflation pressures of 90, 70, and 50 p.s.i. are shown in Table 8. These stresses are computed for a 7-in. concrete pavement with a modulus of elasticity of 4,000,000 and Poisson's ratio of 0 20. The pavement is assumed to be resting on a subgrade having a modulus of k = 100. Data for the transverse stresses are also shown in Figure 7.

In Figure 7 it will be noted that the stresses are almost in linear relationship to the total load. The stress at the 8,000-lb load, however, is only 3.43 times the stress at the 2,000-lb. load, instead of four times as would have been the case if the contact area had not increased.

Effect of Inflation Pressure

The data previously given in Tables 1 to 6 show the variation in contact area with three different inflation pressures. As would be expected, the contact area increases as the inflation pressure decreases even though the total load is kept constant. This increase in contact area results in slightly less stress with the lower inflation pressures. The decrease in stress in the range of 50 to 90 p.s i. inflation pressure is not of great importance. Table 8 shows that it amounts to about 3 5 per cent. Under a 4,000-lb. total load, the decrease in stress as the inflation pressure is lowered from 90 p.s.i to 50 p s.i. amounts to 3.3 p.s.i.

Varying the inflation pressure affects the stress only through changing the contact area

TABLE 8

EFFECT OF INCREASE IN TOTAL LOAD

7-in Concrete Pavement, Subgrade Modulus $k = 100$
Stress Under Center of Load

Load (lbs)	90 p s i Inf Pressure		70 p s i Inf Pressure		50 p s i Inf Pressure	
	Trans-verse	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse	Longi-tudinal
	Stress p s i	Stress p s i	Stress p s i	Stress p s i	Stress p s i	Stress p s i
2,000	67 9	67 9	65 6	65 6	64 5	64 5
3,000	96 2	96 1	94 5	93 6	92 3	92 0
4,000	123 3	123 1	122 8	119 7	120 0	117 1
4,750	144 4	143 1	142 7	139 5	140 1	134 3
5,000	151 5	149 5	149 3	145 0	146 4	139 3
6,000	179 4	174 5	176 7	169 1	173 0	162 2
7,000	206 4	197 6	203 2	191 6	198 2	182 7
8,000	233 0	220 5	228.9	213 0	222 3	201 7

TABLE 9

EFFECT OF SUBGRADE MODULUS

7-in Pavement, 11-in. by 20-in Tire

	Subgrade Modulus						
	50	100	200	400	600	800	1,000
4,000-lb load, 70 p s i inflation pressure							
Transverse Stress	130 9	122 8	114 7	106 6	101 8	98 4	95 8
Longitudinal Stress	127 8	119 7	111 6	103 5	98 8	95 4	92.8
8,000-lb. load, 50 p.s i inflation pressure							
Transverse Stress	238 6	222 3	206 2	189 9	180 5	173 7	168 5
Longitudinal Stress	217 9	201.7	184 8	169 3	159 8	153 1	147.9

Effect of Subgrade Modulus

The quality of the subgrade under the pavement is a more important factor than the shape and size of the contact area or the inflation pressure. Pavement stresses increase rapidly as the subgrade becomes softer. Two examples of the effect of subgrade variation are given in Table 9 and shown in Figure 8. It will be noted in Figure 8 that the shapes of the curves for two different loads and inflation pressures are similar The numerical differences in stress between any two subgrade moduli is greater under the 8,000-lb load than under the 4,000-lb. load, but the percentage change is practically the same. For example, the stress under the 8,000-lb. load increases 7 1 per cent between $k = 1{,}000$ and $k = 600$, while under the 4,000-lb. load the stress increases 6 3 per cent.

Very little information is available on the range of values of subgrade modulus which may be expected. It is known, however, to vary over rather wide limits. Teller and Sutherland[1] found a subgrade modulus of approximately 300 for a subgrade described as a uniform brown silt-loam (Classification A-4). Their tests were made under rigid circular plates of varying diameter. When the diameter of the plate was 24 inches or more, the subgrade modulus remained practically constant. Tests on a compacted subgrade described as a gravelly sand (Classification A-2) have been reported which show subgrade moduli as high as 900 under a 36-in. disk. In many states heavy subbases of talus rock or river run gravel are used. In Oregon these subbases vary from 6 in. to 12 in. in compacted thickness. It is probable that the subgrade modulus will exceed 1,000 under such conditions. In view of the importance of the subgrade quality and the relative economy of subgrade stabilization, the need for the measurement of the subgrade modulus of subgrades built by different methods and of a wide variety of materials is apparent

Effect of Pavement Thickness

The thickness of the pavement has more effect upon stress than any of the other variables considered. Pavement thickness enters into the computation of stress in two ways: first, in determining the radius of relative stiffness, and second, as the lever arm in converting moment into stress. The rate of change of stress with variation in pavement thickness differs with each change of any of the other variables, such as subgrade modulus, total load, and inflation pressure

[1] *Public Roads*, Vol. 23, No. 8, April-May-June 1943.

Table 10 and Figure 9 show the effect of pavement thickness on stress for 11 by 20-in. tires inflated to 70 p s i and carrying a 6,000-lb. total load. The effect with two widely varying subgrade conditions is shown. It will be noticed that the shapes of the curves for subgrades of modulus 200 and modulus 1,000 are quite similar. The rate of change in stress is slightly greater for the softer subgrade and thinner pavement An increase in pavement thickness from 7-in. to 7½-in. for the k = 200 subgrade decreases the stress 11 per cent, while an increase from 9½-in to 10-in. for the k = 1,000 subgrade decreases the stress 8 per cent.

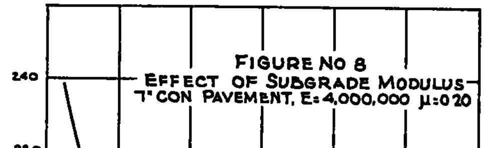


Figure 8

Subgrade Quality Vs. Pavement Thickness

The relationship of the effect of improving the subgrade quality and of increasing the pavement thickness is of practical interest The data shown in Figure 10 will serve as a typical example.

With the softer subgrades, a relatively slight increase in bearing power results in a large decrease in stress As the subgrade becomes stiffer, the proportionate decrease in stress becomes less. After a certain point, dependent upon conditions peculiar to each project, the cost of subgrade strengthening will be out of proportion to the improvement gained. The strengthening of the subgrade k = 100 to k = 500 decreases the stress by 16 per cent, while the strengthening from k = 800 to k = 1,200 decreases the stress only 5 per cent

Pavement thickness and stress are more nearly in straight line relationship. An increase in thickness from 7 inches to 7½ inches decreases the stress 11 per cent, while an increase from 9½ inches to 10 inches decreases the stress 8 per cent. In the example shown in Figure 10, an improvement in subgrade from k = 200 to k = 600 has the same effect upon stress as thickening the pavement from 7 inches to 7½ inches.

TABLE 10

EFFECT OF PAVEMENT THICKNESS

11-in by 20-in Tire, 70 p s i Inflation Pressure, 6,000-lb Load

E = 4,000,000 Poisson's Ratio 0 20

	Pavement Thickness						
	7 inches	7½ inches	8 inches	8½ inches	9 inches	9½ inches	10 inches
Subgrade Modulus, k = 200							
Transverse Stress	164 7	146 5	131 5	118 5	107 6	97 7	89 8
Longitudinal Stress	157 0	139 9	125 6	113 4	103 0	93 5	86 1
Subgrade Modulus, k = 1,000							
Transverse Stress	136 4	122 0	109 7	99 4	90 5	82 5	76.0
Longitudinal Stress	128 8	115 3	103 9	94 2	85 9	78 4	72 3

SUMMARY

The tire contact imprints shown in Figures 2 and 3 and the areas, dimensions, and pressures given in Tables 1 to 6 show conclusively that the average load per square inch of contact area is only remotely related to the tire inflation pressure. For small total loads

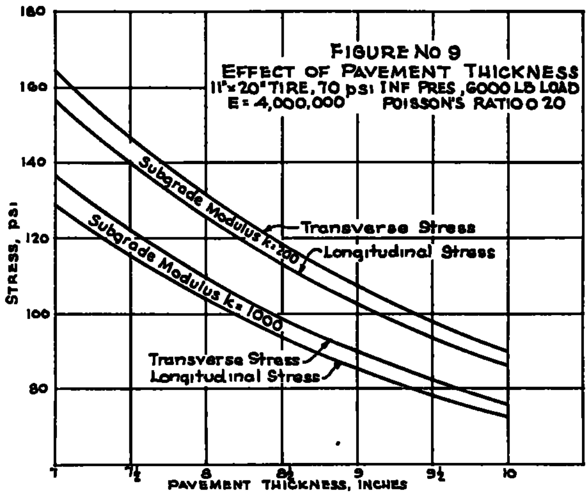


Figure 9

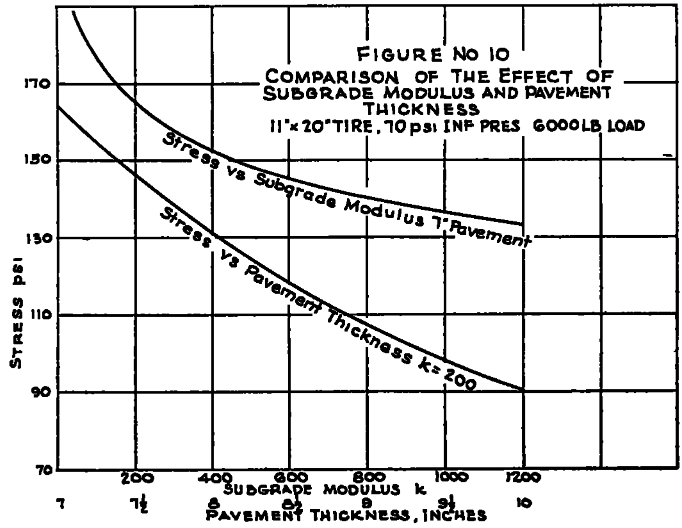


Figure 10

the average load per square inch is less than the inflation pressure, while for large total loads the reverse is true.

The increase in inflation pressure due to the distortion of the tire with increased total load is so small as to be negligible. In the entire range of the tests the increase did not exceed 1.5 lb. The heating of the tire in operation will have more effect on inflation pressure than the distortion.

The tire contact area imprints shown in Figures 2 and 3 disclose that, for axle loads approximating the maximum allowed under almost all of the state traffic codes, the assumption of a rectangular outline is more accurate than either an ellipse or a circle. The error involved in assuming the more easily handled ellipse or circle is not serious. The maximum stress, which occurs under the center of the load, is in error by less than 2 per cent.

Varying the inflation pressure affects the pavement stress only through change in the contact area. Lower inflation pressures result in larger contact areas for equal total loads, and because of this wider distribution, the pavement stresses are lower. The reduction in stress is so small as to be of no great importance. Under 4,000-lb. wheel loads, the stress is reduced 3 5 per cent when the inflation pressure is lowered from 90 p.s.i. to 70 p.s i The proposal to regulate loads by inflation pressure of the tires is impractical and not in accordance with the facts.

The total load is, of course, the greatest factor affecting pavement stress. The increase in contact area, as the total load is increased, reduces the ratio between total load and stress from one to one to approximately six to five. In other words, doubling the total load increases the maximum pavement stress about 85 per cent

The quality of the subgrade has a relatively great effect upon pavement stress. This is particularly noticeable in the softer range of subgrades. As the subgrade quality is built up the decrease in stress becomes relatively less. A point will eventually be reached where the cost of subgrade improvement is out of proportion with the decrease in stress. There are comparatively few numerical data on the value of the subgrade modulus of typical subgrades. More experimental work along these lines would be well repaid.

Increasing the pavement thickness is the most obvious method of reducing pavement stress An increase in thickness of ½ in will reduce the stress due to load by approximately 10 per cent. The additional thickness is less effective as the pavements become thicker. One-half inch added to a 7-in. pavement decreases the stress 8 per cent. Either reinforcement of the subgrade or increase in pavement thickness will effect a decrease in pavement stress. The two factors should be compared as to their relative cost.

DISCUSSION

MR L. W. TELLER, *Public Roads Administration*: This paper brings out clearly the fallacy of trying to control stress in rigid pavements by adjusting tire inflation pressures When this proposal was first being advocated. as a method for traffic load control about three years ago some study of it was made by the Public Roads Administration on the basis of data obtained in load tests on pavement slabs conducted at Arlington, Virginia By making use of relations between load, area of contact and load stress developed in those tests it can easily be shown that the benefits of increased area of tire contact associated with an increase in load does not produce a stress reduction that will compensate for the increase in stress caused by that same increase in load With these experimental data it can be demonstrated further that, to control pavement stress at a desired safe value, the inflation pressure would have to be high in small tires and low in large tires, a trend which obviously is contrary to present practice in tire design for motor vehicles and one which would not be acceptable to the motor vehicle operator.

The inflation pressure recommended by the Tire and Rim Association for a 10 by 20, 12-ply, truck tire is 70 p.s i inflation pressure and at that inflation pressure the recommended maximum load is 4,000 lb. For a 11 by 20, 12-ply, truck tire the recommended inflation pressure is 70 p.s i, and at that pressure the recommended load is 4,500 lb. It is well to keep these figures in mind when examining the data presented in this report since it is at these inflation pressures and loads that the tire imprint data are most nearly representative.

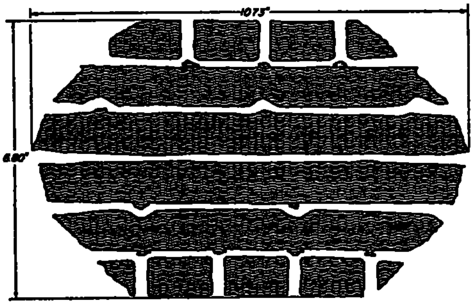
In paragraph 1 of the summary it is stated that "The average load per square inch of contact area is only remotely related to the tire inflation pressure" This would seem to be supported by the data in Tables 1 to 6, inclusive. It should be remembered, however, that many of the load conditions included in the tests reported are far removed from those for which the tire was designed and this tends to distort the impression given by the data. To illustrate this point Table A gives data obtained in load tests on eleven motor vehicle tires of the bus and truck balloon type ranging in load capacity from 1,400 to 8,200 lb. which show that at the recommended loads and inflation pressures the ratio of inflation pressure to average load pressure over the area of contact varies within the relatively narrow limits of 1 006 to 1 150. These data were obtained with a set of tires from one manufacturer and all had the same tread pattern.

In the third paragraph of the summary it is stated that "The assumption of a rectangular outline is more accurate than either an ellipse or a circle" and reference is made to Figures 2 and 3 and presumably to Figure 6 to support this statement The shape of the area of contact of a tire is influenced by a number of conditions such as load, inflation pressure, carcass stiffness, tire diameter, cross section design and state of wear. The influences of load and inflation pressure are brought out very clearly by the author's Figures 2 and 3. For these particular tires in their particular state of wear the impressions vary from a roughly circular outline for an underloaded condition to one that is roughly rectangular for an overloaded condition. The effect of underinflation is to cause the change in shape with change in load to develop more rapidly. At the load condition and inflation pressure for which the tire was designed the area of contact for these well-worn tires is intermediate between a circle and a rectangle. For comparison the attached Figures A and B show the outline of the area of contact of two tires of the same sizes as were used in the tests described in this paper. These were made at the recommended inflation pressure and capacity load and show the typically elliptical shape of the area of contact of tires that have treads that are still in good condition. Data on the area of contact and the length and width of the contact area for a wide range of motor vehicle tire sizes are shown in Table B. These areas were all of the general shape of those shown in Figure A of this discussion and the ratio of length to width varies from 1.96 for the 6 by 20 size to 1.49 for the 14 by 20 size.

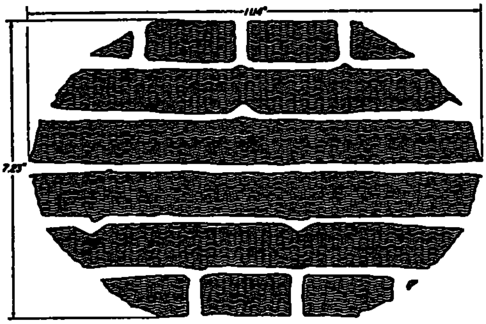
TABLE A

RELATION OF INFLATION PRESSURE TO AVERAGE UNIT LOAD OVER AREA OF TIRE CONTACT TRUCK AND BUS BALLOON TIRES.

Tire size	Plies	Infl pressure	Max rec load	Gr area contact	R Load	R Infl press / Ave cont press
in		p s i	lb	sq ins		
6 00-20	6	50	1,400	28 18	49 7	1 006
6 50-20	6	50	1,700	34 46	49 3	1 013
7 00-20	8	55	1,950	36 96	52 7	1 043
7 50-20	8	55	2,250	41 38	54 4	1 011
8 25-20	10	60	2,750	46 18	59 5	1 008
9 00-20	10	65	3,450	56 13	61 4	1 058
10 00-20	12	70	4,000	60 73	65 9	1 062
11 00-20	12	70	4,500	68 54	65 6	1 067
12 00-20	14	80	5,475	73 55	74 4	1 075
13 00-20	16	85	6,750	86 10	78 4	1 084
14 00-20	16	90	8,200	104 76	78 3	1 150



(A) 10 00-20, 12PLY, 70 PSI INFLATION PRESSURE, 4000 POUNDS LOAD, GROSS AREA 60 73 SQUARE INCHES



(B) 11 00-20 12PLY 70 PSI INFLATION PRESSURE 4500 POUNDS LOAD, GROSS AREA 68 54 SQUARE INCHES

Figures A and B. Impressions from New Truck and Bus Balloon Tires at Recommended Inflation Pressure and Capacity Loads.

TABLE B

LOAD VERSUS AREA OF CONTACT DATA TRUCK AND BUS BALLOON TIRES

Tire size	Plies	Max rated load	Rec infl pressure	Imprint		
				Gr Area	Length	Width
in		lb	p s i	sq in	in	in
6 00-20	6	1,400	50	28 2	7 97	4 06
	8	1,700	70	26 9	7 86	4 06
6 50-20	6	1,700	50	34 5	8 63	4 39
	8	1,950	65	32 4	8 38	4 41
7 00-20	8	1,950	55	37 0	8 78	4 89
	10	2,250	70	33.2	8 05	4 84
7 50-20	8	2,250	55	41 4	9 22	5 19
	10	2,700	75	39 0	8 88	5 16
8 25-20	10	2,750	60	46 2	9 71	5 56
9 00-20	10	3,450	65	56 1	10 34	6 27
	12	3,850	80	52 6	10 03	6 31
10 00-20	12	4,000	70	60 7	10 73	6 80
11 00-20	12	4,500	70	68 5	11 14	7 23
12 00-20	14	5,475	80	73 6	11 48	7 55
13 00-20	16	6,750	85	86 1	12 91	8 31
14 00-20	16	8,200	90	104 8	13 64	9 17

In Figure 6 of the paper there is a comparison of the shape of the area of contact for an overloaded underinflated tire with an ellipse and a circle of equal area Since the fact that the tire was both overloaded and under inflated is not pointed out, the casual reader might conclude that this is the normal shape for the area of contact of truck tires.

In the fourth paragraph of the summary it is stated that "Varying inflation pressure affects the pavement stress only through change in contact area." The studies of motor vehicle impact by the Public Roads Administration showed that for given conditions of load, speed and road surface roughness the magnitude of the vertical impact reaction varied almost directly with tire inflation pressure. This being the case, the statement quoted would be true only if no impact reactions were being developed, that is, only for loadings produced by static or slowly rolling wheels.

AN ELEVEN-YEAR STUDY OF THE EXPANSION AND CONTRACTION OF A SECTION OF CONCRETE PAVEMENT

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SYNOPSIS

The paper reports measurements over an 11-year period of expansion and contraction of a section of concrete pavement built in 1934 Three sets of measurements were taken. (1) opening and closing of the joints, (2) expansion and contraction of a 20-in section of the slab at four interior locations, (3) creep of the pavement at two points Air and slab temperatures were measured During the first 2 years readings were taken monthly, since then once or twice a year

Measurement of movement at the joints has shown a progressive closing of the joints during the 11-year period Measurement of growth between 20-in gage points support the theory that growth due to chemical and physical changes is an important factor in concrete pavement behavior Although a tendency to creep downhill was observed, the amount was so small that it is not thought to be a factor in the observed growth of the concrete.

Data are also given on the service behavior of concrete pavement in Iowa which further indicate the importance of various factors contributing to growth of concrete.

Concrete pavements have been built in Iowa both with and without expansion joints. On a large mileage of the early concrete paving in Iowa, no expansion joints were used and for the most part the "blowup" failures, which may be attributed to the lack of expansion joints, have not developed to such an extent as to indicate that the cost of expansion joints for this early paving and the extra maintenance expense for maintaining expansion joints would have been less than the cost of repairs of "blowups" on these pavements.

By 1934, "blowups" on some of the older paving in the neighboring counties of Marshall and Polk developed fairly regularly each summer and attracted considerable attention. A satisfactory and complete explanation of "blowup" failures was not established at that time and, as a matter of fact, even today engineers are not in agreement in regard to the cause of "blowups" and the need for expansion joints to prevent "blowups."

During the summer and fall of 1934, a large amount of concrete pavement was placed on the Iowa State College campus and this offered an excellent opportunity for selection of a section of the new pavement near the College Highway Materials Testing Labor-