Analytical Appraisal of the Effect of Bituminous Surfacing on the Stresses in Portland Cement Concrete Pavement

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Since 1941, about 3500 miles of the older concrete pavements in Illinois have been rehabilitated by bituminous resurfacing, which in most cases was preceded by widening and desirable corrections of alignment. The results obtained in the form of lowered maintenance costs and increased service life have been beyond expectation. Though the bituminous surfacing, in itself, is not capable of withstanding bending stresses of important magnitudes, it nevertheless has imparted increased structural strength to the old pavements. The benefits derived are believed to be substantially the consequence of protective properties inherent in the bituminous surfacing.

Because of the excellent results obtained in the case of the older pavements, the expediency of protecting concrete pavements with bituminous surfacing immediately after their construction is currently being studied. Included in the studies is the question as to the feasibility of using concrete relatively lean in cement to reduce the cost.

On the basis of postulated numerical quantities, most of which are supported by some investigational data, the author will attempt to show by analytical deductions the nature of some of the contributions of bituminous surfacing to structural strength of concrete pavement and, at the same time, try to clarify the problem as to the practicability of using mixtures relatively lean in cement for construction of concrete base.

It should be stressed that the values derived are not necessarily correct as to their numerical magnitudes, and that they should be considered only as indications of relative qualities.

● THE year of 1941 essentially marks the beginning of the program of bituminous resurfacing of the older concrete pavements in Illinois, for which the maintenance costs had become so high that some form of rehabilitation was imperative. The rate of resurfacing increased more or less gradually from about 40 miles during that year to a peak of nearly 800 miles in 1952, a total of about 3500 miles having been completed at the present time. In most cases, the resurfacing was preceded by widening of the slab, usually to 22 or 24 feet, and desirable corrections of alignment. The results obtained in the form of lowered maintenance costs and increased service life have been beyond expectation.

Though the bituminous surfacing, in itself, is not capable of withstanding bending stresses of important magnitudes, especially in warm weather, the excellent results obtained nevertheless indicate that it has imparted increased structural strength to the old pavements. The beneficial effect is thought to be substantially the consequence of protective properties inherent in the bituminous surfacing.

The evident existence of such properties has led to the consideration of the expediency of protecting concrete pavement with a bituminous surfacing immediately after construction, rather than waiting until it has become damaged by traffic and climate. Involved also is the question as to whether the protective qualities of the bituminous surfacing are of magnitudes that will permit the reduction of costs by construction of thinner slabs or by the use of lower strength concrete than now is the practice in concrete pavement construction.

To get information on this question, some pavement widening preliminary to bituminous resurfacing, and full width base at relocations, was constructed in 1951, 1954, and 1955 with amounts of cement varying from 3.0 to 5.8 bags per cubic yard of concrete. However, since it was expected that proper evaluation of the variable could be made only after some years of service, this investigation has attempted to picture by analytical means, on the basis of postulated quantities that appeared reasonable, the nature of the properties of the bituminous surfacing responsible for the increased structural strength of the pavement. Recently, from tests of the concrete of the various cement contents and from other sources, additional information has become available, and it was considered desirable to retrace the original analysis, which was made in 1951, on the basis of improved postulated quantities.

Some of the possible effects of the bituminous surfacing are too intangible to lend themselves readily to analytical treatment. In that category are such indefinite benefits as may be derived from the "cushioning" of dynamic loads and the possible reduction of deflections and stresses by reason of the increased inertia of the combined pavement and surfacing. That the bituminous surfacing prevents water from entering the subgrade in large amounts through joints and cracks in the concrete pavement is evidenced by the fact that subgrade pumping has been substantially eliminated in most of the rehabilitated pavements formerly showing that defect. By reason of exclusion of surface water, the bituminous surface may be expected to improve the uniformity of subgrade support from point to point and between seasons. However, the effect upon stresses in the concrete, though they cannot be satisfactorily evaluated on the basis of available information, is believed to be relatively unimportant and will not be considered here.

The bituminous surfacing, without question, serves to distribute wheel loads to the concrete slab over larger areas than those contacted by the tires. Obviously, also, some protection is afforded to the concrete below against sudden and excessive variations in temperature. The effects of both of these properties of the bituminous surfacing can be pictured analytically on the basis of certain necessary fundamental information, which will be further described. Unfortunately, the available information in some respects is of fragmentary nature and cannot be fully justified experimentally as to numerical acccuracy. The numerical values to be derived, therefore, are not necessarily correct as to their magnitudes, and should be considered only as indications of relative qualities.

PROPERTIES OF CONCRETE

Since data from earlier investigational work did not provide satisfactory information with respect to variation of the strength and modulus of elasticity with the cement content of the concrete, especially over the desired range, it was found necessary to use the limited amount of data obtained in connection with the jobs constructed in 1951 and 1954 and from some laboratory tests conducted in 1955. Data representing the approximate ultimate flexural strength of the concrete are shown in the upper chart of Figure 1. Unfortunately, entirely satisfactory agreement between the various sources does not exist.

The 1951 data represent flexural strengths at the age of one year for cement contents varying over only a small range and the relationship established appears to be linear. In the 1954 data, the only flexural strengths available were for early ages and for specimens made in fairly cold weather. The data, however, included a number of tests of 6-inch modified cubes, 6- by 12-inch cylinders, and 4½-inch cores drilled from the pavement, all made at the approximate age of nine months and between which excellent agreement existed. These compressive strengths were used for estimating the flexural strengths indicated by the curve representing the 1954 data. It will be seen that this curve parallels, at a lower level, the curve representing the laboratory tests, which were made at the age of five months. The only known difference in characteristics which conceivably could cause the difference in shape of the curves is that the 1951 data represent crushed stone concrete and the 1954 and laboratory data represent gravel concrete. However, it will be noted that, for the short range of from four to six bags of cement per cubic yard of concrete, all of the curves could be approximated by straight lines. The curvilinear shape is therefore believed to be correct.

Considering that the laboratory data probably show higher strengths than ordinarily ob-

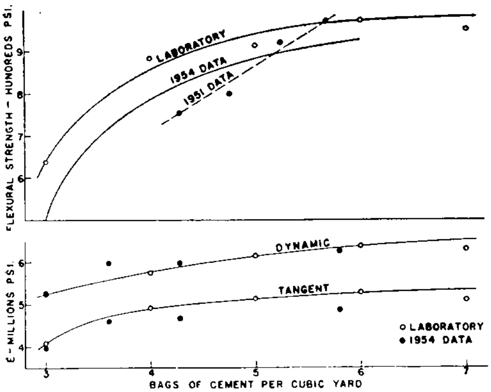


Figure 1. Relation of cement content to flexural strength and modulus of elasticity of concrete.

tained in the field and that the 1954 data cover the desired range in cement content, it was decided to use the latter, though estimated from compressive strengths, as a reasonable indication of the ultimate flexural strength that is obtained with concrete of different cement contents and of a consistency suitable for pavement construction. Attention is called to the fact that the strengths are based on the method of testing used by the Illinois Division of Highways, and that corresponding strengths by the third-point method (ASTM Designation: C 78) would be approximately 20 percent less.

The lower chart in Figure 1 shows both the tangent and the dynamic moduli of elasticity of 6- by 12-inch cylinders corresponding to the 1954 and the laboratory strength data discussed above. The tangent modulus of each cylinder was determined by loading it to about 60 percent of its ultimate strength and reading the strain at appropriate load intervals during the process. The time interval required was about two minutes. The data from the first run were discarded, but subsequent runs produced essentially linear stress-strain curves, and the modulus was determined from the average data for the second and third runs. The dynamic modulus of each cylinder was determined as an aid in studying the variability of the modulus of elasticity with cement content.

TABLE 1
POSTULATED APPROXIMATE ULTIMATE FLEXURAL STRENGTH IN PSI AND MODULUS OF ELASTICITY IN MILLIONS OF PSI

Item	Bags of Cement per Cubic Yard			
	3	4	5	6
Flexural strength: Illinois Method—psi	500	785	880	925
Flexural strength: third-point method—psi	400	630	705	740
Modulus of elasticity: millions—psi	4.08	4.91	5.14	5.29

It will be noted that the moduli of elasticity determined for the laboratory concrete show very uniform variation with cement content, while those for the field concrete show slight fluctuations, though differences in numerical magnitudes are small. Since the true variability is of greater importance than exact numerical magnitudes, it was decided to base the calculations involving modulus of elasticity upon the values obtained for the laboratory concrete. Since strains in concrete pavements are the results of external forces, it was decided to use the tangent modulus rather than the dynamic modulus. The latter, determined under a condition approaching no stress in the concrete, is believed to be numerically much too high for the use intended. Its relationship to cement content is very similar to that shown by the tangent modulus.

In conformity with the discussion presented, the quantities shown in Table 1 will be assumed to represent with reasonable accuracy the approximate ultimate flexural strengths and moduli of elasticity of concrete of various cement contents.

DISTRIBUTION OF WHEEL LOADS BY THE ASPHALTIC CONCRETE SURFACING

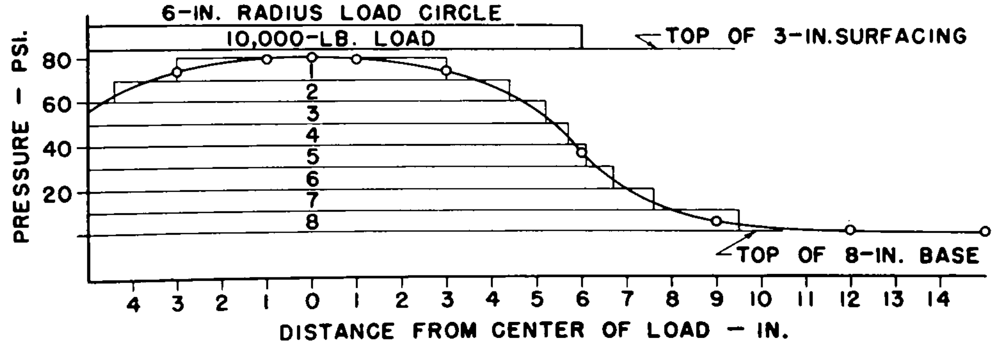
For the purpose of calculating stresses, it is necessary to consider wheel loads as uniformly distributed over appropriate circular areas, which assumption has been found to yield satisfactory results. In the case of a surfaced pavement, a wheel load is distributed to the concrete slab in the form of pressure, the intensity of which would be expected to be greatest directly under the center of the loaded area, but decreasing gradually in all directions, and extending beyond the limits of the loaded area. Much effort was expended in trying to obtain a reasonably true portrayal of the distribution of the pressure and in determining a uniformly loaded circular area that would produce the same maximum stress in the concrete as the distributed pressure. To simplify the problem, only wheel loads applied at a considerable distance from slab edges and joints were considered.

It is believed that the influence chart for vertical stresses in elastic foundations, devised by Newmark (*1*), though not strictly applicable to the problem, may be used in picturing the distribution of wheel loads through the bituminous surfacing to the concrete slab, assuming that the horizontal shearing stresses acting at the interface between the surfacing and the slab have no important effect on the stresses in the concrete. Numerically, the results obtained may not be of high accuracy, because it is understood that the introduction of a concrete slab at a certain depth tends to concentrate the load pressure slightly more than indicated by the vertical stresses determined for that depth. It is also understood that an empirical correction can be made for that tendency by determining the vertical stresses at a depth slightly less than that of the concrete slab, possibly at two-thirds or three-fourths of the depth of the bituminous surfacing. It is felt, therefore, that the true distribution of the load through a 3-inch bituminous surface probably will approximate closely the distribution of vertical stresses in the surfacing obtained at a depth somewhere between 2 and 3 inches.

The bell-shaped pressure distributions for the two depths were determined for a 10,000-pound load applied uniformly over circular areas of various sizes. Each bell was then approximated by a series of cylindrical segments having the same combined volume, or representing the same total load of 10,000 pounds. The contribution of each cylindrical segment to the maximum stress in the concrete was determined in accordance with Westergaard's equation for the case of interior loading (*2*), assuming the slab thickness as 8 inches, the modulus of subgrade reaction as 100 pounds per cubic inch, the modulus of elasticity of the concrete at 4,000,000 psi, and Poisson's ratio as 0.15. The summation of the stress contributions of the cylindrical pressure segments was taken as the maximum stress produced by the distributed pressure, and the radius of the uniformly loaded circular area producing the same maximum stress was determined. In this connection as well as in subsequent determinations of load stresses, and in the reverse operation of determining the radii of uniformly loaded circular areas corresponding to computed maximum stresses, the table provided by Teller and Sutherland (*3*) was used extensively, interpolations being made from curves plotted from the values presented.

The entire process is illustrated in Figure 2, which shows a section through the center of the pressure bell obtained for the 3-inch depth with the load applied over a circular area having a radius of 6 inches. In this particular case, it was possible to approximate the volume of the bell by eight cylindrical segments each representing a pressure of 10 psi, but of radii varying from 3.0 to 9.5 inches. The tabulation shows the area of each segment, the total pressure represented by each, and the maximum stress contributed by each. It will be noted that the combined pressure contributed by the segments is within 10 pounds of the applied 10,000-pound load, which indicates reasonable accuracy of the graphical work. The summarized maximum stress is 199.6 psi, and it was determined that the 10,000-pound load uniformly distributed over a circular area having a radius of 7 inches would produce the same maximum stress. With the load applied on an exposed slab, the stress obtained for a radius of 6 inches is 213 psi. In this particular case, therefore, the bituminous surfacing is indicated to have the effect of increasing the radius of the load circle by 1 inch, but the resulting decrease in maximum stress is only 6.3 percent.

The data obtained for the various sizes of load circle considered are shown in Figure 3 in the form of curves depicting the relationship of the radius of load circle, as estimated from the tire contact area, to the radius of the same load circle, as adjusted to take into account the load distribution property of a 3-inch bituminous surfacing. Curve *A* represents the data based on the vertical stresses determined at the 3-inch depth of the bituminous surface, and Curve *B* represents the similar data corrected empirically by determining the stresses at the 2-inch depth. As previously indicated, the curves are thought to be of the nature of limits between which a curve showing the true relationship probably would fall. For both, the indicated adjustment is greatest for the smaller load circles, and may be substantial, depending upon the true location of the curve. For the larger load circles, corresponding to tire contact areas for loads that produce the most critical stresses, the adjustment is relatively



SEGMENT NO.	RADIUS IN.	AREA SQ. IN.	PRESSURE LB.	STRESS PSI.
1	3.0	28.3	283	7.2
2	4.4	60.8	608	14.3
3	5.2	84.9	849	19.0
4	5.7	102.1	1021	22.2
5	6.1	116.9	1169	24.7
6	6.7	141.0	1410	28.6
7	7.6	181.5	1815	34.8
8	9.5	283.5	2835	48.8
SUMMATION			9990	199.6

ADJUSTED RADIUS = 7.0 IN.

Figure 2. Section through center of bell-shaped pressure distribution indicating method of approximating the pressure by cylindrical segments, the stress in the concrete, and the adjusted radius of load circle.

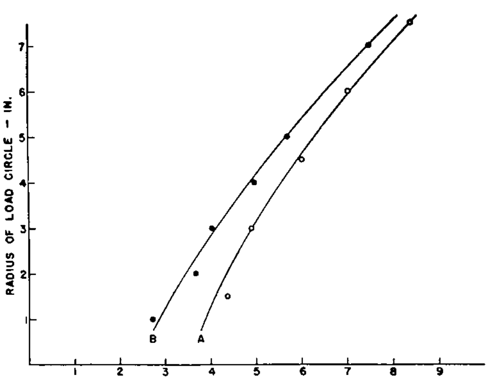


Figure 3. Relation between radius of load circle and adjusted radius of load circle. Curve A was derived from pressure distributions at the 3-inch depth and Curve B from pressure distributions at the 2-inch depth of the bituminous surfacing.

slight and it is indicated that the degree of the distribution of load by reason of the 3-inch bituminous surfacing is not a substantial factor in imparting structural strength to concrete pavements.

The fact that the larger wheel loads generally are carried on dual tires, and are in reality two loads spaced a short distance apart, may change the picture a little. The contact area of each of the tires, individually, corresponds to a load circle of relatively small size, and it is probable that the load distribution would be greater than would be the case for a single larger load circle that has been assumed to be the equivalent of the two smaller ones. Therefore, since a single load circle will be assumed for dual tire loads, the load distribution obtained will be based on the data represented by Curve *A*.

A 9000-pound wheel load, the maximum legally permissible in Illinois, is considered in the further studies herein. A load circle of 7-inch radius is assumed as corresponding to that load. This is in agreement with Bradbury's formula (*4*) for load distribution through dual tires for loads applied in the interior of slabs. This may represent a minimum tire requirement for this load under modern practice, but is satisfactory for the purpose intended. When the load is considered as applied on a surfaced pavement, the radius of the load circle will be considered as 8 inches, as determined from Curve *A* to the nearest inch.

MAXIMUM TEMPERATURE DIFFERENCE BETWEEN TOP AND BOTTOM OF CONCRETE PAVEMENT SLABS

For appraisal of the value of the bituminous surfacing in protecting concrete pavement slabs against excessive temperature variations, it is desirable to have available credible values for the approximate maximum temperature differences that will occur between the top and bottom surfaces of the slabs with and without the bituminous surfacing. At the Arlington experimental road (*5*), the maximum differences observed in the interior of 6- and 9-inch exposed slabs were, respectively, 24.3° F and 31.0° F and, since the difference in latitude is small, the same values may reasonably be assumed for Illinois. Plausible values for other slab thicknesses were estimated from a plot of the temperature difference against slab thickness on the basis of a smooth curve drawn from the origin through the points representing the two stated values. Corresponding values for surfaced slabs cannot at present be estimated in similar manner, but a small amount of investigational data is available, from tests made by the Illinois Division of Highways, showing that substantial protection against temperature variation is obtained.

Simultaneous temperature measurements were made in two 7-inch pavement slabs, one exposed and the other having a 3-inch bituminous concrete surface, by means of thermocouples set at the top surface of the concrete and at 1 inch above the bottom surface. The maximum temperature differences between the two thermocouples observed on October 4 and 11, 1951, were 22° F on both days for the exposed slab and 15° F and 13° F, respectively, for the surfaced slab, the latter differences averaging about 64 percent of the former. Another run made on July 9, 1952, showed corresponding values of 27° F and 15° F, or a temperature difference for the surfaced slab of only 56 percent of that observed for the exposed slab. The 27° F corresponds to the maximum estimated for a 7-inch slab (see Table 2). However, since the lower thermocouple was set 1 inch above the subgrade, the measurements described might more nearly represent the condition that would have been present in a 6-inch slab, for which the measured 27° F is higher than the estimated value.

TABLE 2
POSTULATED MAXIMUM TEMPERATURE DIFFERENCES BETWEEN TOP AND BOTTOM SURFACES OF EXPOSED AND SURFACED SLABS—DEGREES F.

Condition	Slab Depth—Inches				
	6	7	8	9	10
Exposed	24.3	26.8	29.0	31.0	32.8
Surfaced	14.6	16.1	17.4	18.6	19.7

Similar installations of thermocouples of more permanent character have been made in exposed and surfaced 8-inch pavement slabs, which may be expected to yield more definite information eventually. Duplicate installations were made for concrete containing 4.28 and 5.8 bags of cement per cubic yard. At present, the amount of cement in the mixture does not appear to constitute a noteworthy variable. From measurements made on July 28, 1955, the average maximum temperature difference for the two exposed slabs was observed to be 25° F and that for the two surfaced slabs 17° F, or 68 percent of the difference for the exposed slabs. On October 27, 1955, corresponding values observed were 16° F and 10.5° F, the latter being 66 percent of the former. Figure 4 illustrates the data obtained on July 28, 1955.

The temperature measurements described were made on sunny days and over a sufficient part of 24-hour periods to insure that approximately the maximum temperature differences

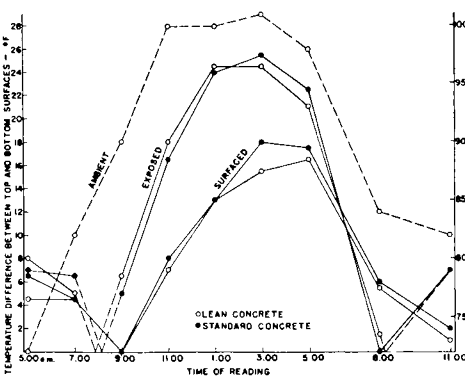


Figure 4. Temperature differentials on July 28, 1955, between top and bottom surfaces of 8-inch concrete slabs, exposed and with 3-inch bituminous surfacing.

were observed in each case. It is not expected that approximately maximum conditions were encountered in the few observations made, except perhaps on July 9, 1952, for which the temperature difference for the surfaced slab was only 56 percent of that found for the exposed slab, which was the minimum percentage observed. There is, therefore, a slight indication that the bituminous surfacing yields the highest degree of protection when the temperature warping stresses in exposed slabs approach critical magnitudes. Also, though severe conditions of sudden occurrence could not be studied, such as the effect of a cold rain on a relatively warm slab, the surfacing would be expected to offer very material protection in such cases.

The selection of a degree of protection approaching the maximum found in the described temperature measurements as a basis for the calculations made herein therefore seems tenable and, since the investigational data described indicate that the maximum temperature difference in surfaced slabs are of the order of 55 to 70 percent of those existing in exposed slabs, the value of 60 percent will be used. The question as to whether the percentage varies with slab thickness is pertinent, but no information with respect to this seems to be available. Since a 3-inch bituminous surfacing was used in the tests and is assumed throughout, and since the slab thicknesses to be considered range only a little above and below those represented by the data, the same degree of protection will be assumed for all slab thicknesses. Table 2 shows the postulated maximum temperature differences between top and bottom surfaces of exposed and surfaced concrete slabs, determined in accordance with the presented discussion.

CRITICAL STRESSES

Modern pavements generally are designed to withstand stresses produced by maximum permissible loads. However, stresses due to forces in nature may greatly exceed the stresses produced by the loads. The two types of stress combined may approach or exceed the strength of the concrete, and result in failures in the form of transverse cracks. Existing pavements indicate that the number of transverse cracks increases with the years of service and depends greatly upon the volume of heavy traffic. They are, therefore, a function of the opportunity afforded during the time the pavement has rendered service for critical tensile stresses of the two types to coincide. Fatigue of the concrete under the high combined stresses possibly is a factor in the formation of transverse cracks. That stresses of such high magnitudes occur has been amply illustrated both at the Arlington experimental road (*6*) and the Maryland test road (*7*).

It is thought that the beneficial effect of bituminous surfacing in imparting structural strength to concrete pavements lies chiefly in its ability to reduce the magnitudes of the critical combined stresses and, consequently, in preventing or retarding the continued formation of transverse cracks during the service life of the pavement.

Changing climatic conditions bring about various effects that create stresses in concrete slabs. It is expedient to assume a subgrade not subject to frost heaval, pumping, or other conditions that produce excessive local stresses. Also, it is felt that horizontal slab movements and warping effects caused by variations of the moisture content of the concrete are so small that they may be disregarded. Temperature variations produce horizontal expansion and contraction movements of the slab that are retarded to some degree by the resistance of the subgrade and consequently result in stresses. However, investigational data from the Arlington experimental road (*5*) and especially from the Stilesville road (*8*) indicate that the resistance offered by the subgrade against the horizontal movements is very small for slab lengths at least up to 75 feet, and that the stresses produced may reasonably be disregarded for slab lengths ordinarily encountered.

Temperature variations also produce a temperature gradient through the concrete tending to produce warping movements that are effectively resisted by the weight of the slab itself and, therefore, cause appreciable stresses at points some distance removed from transverse joints and cracks. It is believed that the temperature warping stresses overshadow all other effects due to forces in nature to the degree that their sole consideration in connection with load stresses will portray with good approximation the maximum stresses likely to occur in concrete slabs. It is expedient to consider in detail only combined stresses that occur in the interior of slabs.

LOAD STRESSES

Stresses determined for a 9000-pound load applied in the interior of slabs over circular areas of the radii stipulated for exposed and surfaced slabs are shown in Table 3 for various slab depths and cement contents, assuming the modulus of subgrade reaction as 100 pounds per cubic inch and Poisson's ratio as 0.15. The very slight increase in stress with increase of cement content is due to the variation in the value of the modulus of elasticity shown in Table 1. Reduction in stresses in the surfaced slabs from those determined for the exposed slabs are of the order of from 5 to 7 percent. Depending upon the accuracy of the postulations with respect to the radii of load circles, therefore, it is demonstrated that the bituminous surfacing is not a substantial factor in reducing the stresses produced by the 9000-pound load.

TEMPERATURE WARPING STRESSES

The investigational work at the Arlington experimental road (*5*) indicates satisfactory agreement between temperature warping stresses as measured along the longitudinal axis of slabs and as calculated from the Westergaard formula applicable to the interior of large slabs (*9*). Stresses calculated by that formula are shown in Table 4 for various slab depths and cement contents, using the moduli of elasticity shown in Table 1 and the temperature differentials stipulated for exposed and surfaced slabs in Table 2. The temperature coefficient of expansion for concrete was taken as 0.0000055 per degree F and Poisson's ratio was taken as 0.15.

The variations observed in the calculated stresses are direct reflections of the variability of the postulated quantities and, insofar as these are correct, it is demonstrated that the warping stresses increase with cement content and slab depth, and that the protection afforded by the bituminous surfacing yields a very substantial reduction of these stresses. However, reduction in warping stress brought about by decrease of slab depth and cement content must be balanced against corresponding increase in load stress and reduction of the strength of the concrete.

COMBINED STRESSES

Since the greatest temperature differentials between the top and bottom surfaces of concrete slabs occur in the daytime and tend to produce downward deflection of all slab edges, the most critical warping stresses in pavements occur in the longitudinal direction as tension in the bottom surface, which diminishes toward the slab ends and becomes zero at transverse joints and cracks. Critical load stresses also occur as tension in the bottom surface, except in the immediate vicinity of corners, and therefore add to the warping stresses. Table 5 shows the combined load and warping stresses from Tables 3 and 4. Under the stipulations forming the basis for their derivation,

TABLE 3

STRESS IN SLABS IN PSI DUE TO 9000-POUND LOAD APPLIED IN THE INTERIOR, AND CORRESPONDING TO THE RADII OF LOAD CIRCLES POSTULATED FOR EXPOSED AND SURFACED SLABS

Slab Depth—Inches	Bags of Cement per Cubic Yard			
	3	4	5	6
Exposed Slabs				
6	289	295	296	298
7	225	230	231	232
8	181	184	185	186
9	148	150	151	152
10	123	125	126	127
Surfaced Slabs				
6	269	275	276	277
7	212	216	217	218
8	169	173	174	175
9	140	142	143	144
10	117	119	120	121

TABLE 4

TEMPERATURE WARPING STRESSES IN THE INTERIOR OF SLABS IN PSI, DETERMINED ON THE BASIS OF THE POSTULATED MAXIMUM TEMPERATURE DIFFERENTIALS BETWEEN TOP AND BOTTOM SURFACES OF EXPOSED AND SURFACED SLABS

Slab Depth—Inches	Bags of Cement per Cubic Yard			
	3	4	5	6
Exposed Slabs				
6	321	386	404	416
7	354	426	446	459
8	383	461	482	496
9	409	492	515	531
10	433	521	545	561
Surfaced Slabs				
6	193	232	243	250
7	213	256	268	276
8	230	276	289	298
9	245	295	309	318
10	260	313	328	337

TABLE 5
APPROXIMATE MAXIMUM COMBINED LOAD AND TEMPERATURE WARPING STRESSES IN PSI

Slab Depth—Inches	Bags of Cement per Cubic Yard			
	3	4	5	6
Exposed Slabs				
6	610	681	700	714
7	579	656	677	691
8	564	645	667	682
9	557	642	666	683
10	556	646	671	688
Surfaced Slabs				
6	462	507	519	527
7	425	472	485	494
8	399	449	463	473
9	385	437	452	462
10	377	432	448	458

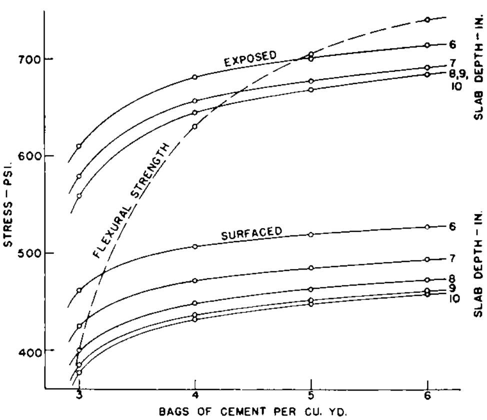


Figure 5. Relation between cement content and approximate maximum combined load and temperature warping stresses in concrete slabs. Broken line curve indicates the approximate ultimate flexural strength of the concrete by the third-point method.

they are the approximate maximum stresses likely to occur in the interior of the slabs with any degree of frequency. The data are illustrated graphically in Figure 5. Superimposed on the chart is the curve representing the flexural strength of the concrete as stipulated in Table 1 for the third-point method of testing.

From the tabulated values for the exposed slabs, it will be noted that there is a reversal in the trend of the combined stresses occasioned by the fact that, as the slab depth increases, the reduction in load stresses becomes overbalanced by the increase in warping stresses, resulting in practically the same combined stresses for the 8-, 9-, and 10-inch slab thicknesses. These slab depths, therefore, are represented by one curve indicating the average stresses. No such reversal is noted for the surfaced slabs within the thicknesses considered.

The points falling above the flexural strength curve represent slab depths and cement contents that result in factors of safety less than unity against transverse cracking. For the exposed slabs, this includes all slab thicknesses for the two lower cement contents. However, regardless of cement content, the exposed slabs do not show substantial factors of safety against the combined stresses, the greatest ratio of strength to stress being about 1.1. It is indicated, therefore, that exposed slabs regardless of thickness or cement content will show some transverse cracking, at least under repeated loads. This undoubtedly is in agreement with conditions observed in concrete pavements not provided with transverse joints at sufficiently close intervals to reduce the stresses. With respect to the surfaced slabs, it will be noted that all, except the two thinnest ones at the lowest cement content, show factors of safety greater than unity, and substantially in excess of those observed for the exposed slabs. In fact, disregarding the lowest cement content, the factors of safety range approximately from 1.25 to 1.60, depending upon slab depth and cement content.

The relative values of the factors of safety should be considered as demonstrating primarily the nature of certain properties of the bituminous surfacing that impart increased structural strength to concrete pavements. Whether the protection yielded is sufficient to warrant the use of substantially thinner slabs or lower cement contents than ordinarily used for concrete pavements is problematical. It should not be taken for granted that the numerical values are of great accuracy, or of direct use in determining slab thickness. Only the combined stresses in the interior of slabs were considered in the demonstration, and pavements must be of sufficient thickness, and the concrete of adequate strength, at all points to safely withstand the stresses that may occur. Having demonstrated that the asphaltic surfacing evidently is not a substantial factor in reducing stresses in the interior by reason of its ability to distribute load pressures, it seems reasonable to assume that the same is true also at other points. Under this assumption, the stresses at edges and corners will be briefly considered.

Maximum combined stresses that may occur at longitudinal edges of a pavement probably do not differ greatly in magnitude from those in the interior. It is understood that the warping stresses in the longitudinal direction at the edge differ from those calculated for the interior only because Poisson's ratio does not enter into their determination, and may be taken as 85 percent of those stresses. Load stresses at the edge are somewhat higher than for the interior by amounts estimated to range approximately from 15 percent for the thinner to 30 percent for the thicker slab thicknesses considered, assuming the radius of load circle in conformity with the applicable formula given by Bradbury (*4*). Considering further that the maximum combined stresses occur when the edges of the slab are warped downward, increasing slightly the subgrade support at the edges and decreasing it in the interior, the load stresses that actually occur probably are slightly less at the edges and slightly greater in the interior than those calculated from the formulas. It is seen, therefore, that the conditions tend to equalize, and that the discussion presented may be considered as essentially applicable also to longitudinal pavement edges.

Effectively doweled joints and fabric reinforcing may provide adequate strength to a pavement at all points. However, it is the practice to construct concrete bases for bituminous surfacing without these features, and the transverse joints and cracks form unprotected corners and slab edges. Since the corners are practically unrestrained, the warping stresses are small, but may be of some importance in transverse direction some distance away from the corner along the joint or crack. The bituminous surfacing undoubtedly is effective in reducing these stresses, but since they are relatively small, this would not be expected to result in substantial reduction of combined stresses. Load stresses at corners are relatively high, and at transverse edges they may be expected to be higher than at longitudinal edges because of greater concentration of load. Assuming radii of load circles in conformity with Bradbury's formulas (*4*), it is estimated that load stresses at both corners and transverse edges may run from 30 to 40 percent higher than those calculated for the interior.

There are additional effects that cannot be ignored though they are not easily evaluated. Load stresses for corners in the upward warped condition may run nearly 50 percent greater than the calculated values (*10*), though the degree of upward warping, and consequently the increase in stress, would be expected to be reduced by the bituminous surfacing. Dynamic effects brought about by the sudden application of the wheel loads moving from one slab to another across the joints or cracks increase the stresses in both corners and transverse slab edges. Critical stresses at corners are not confined to a small area directly beneath the load, as at other points, but are distributed over a considerable area and may have a greater destructive effect than combined stresses at other points, and also tend to cause failures that are more serious than transverse cracks. Finally, since the stresses at corners are largely due to loads, it should be considered that there is a distinction between warping and load stresses in that the former generally are applied gradually and probably are in part relieved by plastic flow of the concrete. Regardless of the bituminous surfacing, therefore, it appears that slab ends, and especially the corners, may be subjected to high load stresses that for the thinner slab depths and lower cement contents may approach the flexural strengths of the concrete. Nevertheless, the experience with the older pavements, which showed considerable distress at the time of resurfacing, has been so satisfactory that it is felt that the feasibility of some reduction of slab depth and cement content, below those considered necessary for exposed pavement, should not be dismissed without further study and investigation. It is evident that reduction in slab depth is more detrimental to corner strength than reduction in cement content. The latter is, of course, limited by the necessity of obtaining concrete of satisfactory durability.

In the construction of the experimental full-width base previously mentioned, the 8-inch slab depth used does not represent an undue reduction in thickness from the 9-inch concrete pavement which would otherwise have been built. However, the amount of cement for most of it was about 4.28 bags per cubic yard of concrete, which is a considerable reduction from the approximately 5.80 bags that would have been used for an exposed pavement.

Good soundness of this concrete was obtained with air contents in the close vicinity of 5 percent. The base, consisting of several relatively short stretches on two jobs, will be observed for the occurrence of cracks that reflect through the 3-inch surfacing. This pavement is subjected to only a moderate amount of commercial traffic. Another section of pavement about four miles in length, having a 9-inch base of similar cement content and a 3-inch bituminous surface, is being planned and probably will be built. This pavement will be subjected to fairly heavy commercial traffic.

CONCLUSION

The discussion presented is an attempt to define and appraise the properties of bituminous surfacing that are primarily responsible for increased structural strength of concrete pavement.

On the basis of postulated quantities that at the moment appear reasonable, it is deduced that the 3-inch bituminous surfacing does not greatly reduce load stresses, but is very effective in reducing temperature warping stresses and consequently the combined load and warping stresses, which are generally considered responsible for the continued development of transverse cracking in concrete pavements.

Reduction in cement content serves to reduce the modulus of elasticity of the concrete and consequently the warping stresses. The benefit derived in this manner, however, appears to be outweighed by the corresponding reduction in concrete strength. The indicated substantial increase in the factor of safety against transverse cracking nevertheless suggests the possibility of some reduction in cement content or slab thickness, or both, below those ordinarily considered necessary for exposed pavements, to offset at least a part of the cost of the bituminous surfacing.

While consideration of the stresses in pavement corners indicates that material savings in cost in that manner may be impracticable, the experience with the older pavements, resurfaced after exhibiting a considerable degree of distress, has been so satisfactory that this possibility should not be dismissed without further study and investigation.

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