HIGHWAY RESEARCH BOARD

Special Report 14

Structural Effects of Heavy-Duty Trailer on Concrete Pavement

A Supplemental Investigation to Road Test One-MD

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Special Report 14

Structural Effects of Heavy-Duty Trailer on Concrete Pavement

A Supplemental Investigation to Road Test One-MD

PRESENTED AT THE

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[1] Deceased May 13, 1951
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Contents

Structural Effects of Heavy-Duty Trailer on Concrete Pavement

A SUPPLEMENTAL INVESTIGATION TO ROAD TEST ONE-MD

EARL C. SUTHERLAND and HARRY D. CASHELL,
Engineers in Charge of Instrumentation and Tests, Road Test One-MD

After completion of the controlled traffic tests and the scheduled strain and deflection studies for trucks scheduled on Road Test One-MD a study of similar nature was made with a heavy-duty military tractor and semi-trailer combination that was designed for the special purpose of transporting heavy army tanks over highways. There was a total of 5 axles in the tractor-trailer combination, the combined weight being 83,000 and 198,800 lb. when unloaded and loaded, respectively. The axle weights varied from 13,250 to 23,000 lb. for the unloaded condition and from 19,290 to 46,720 for the loaded condition.

For control purposes the loaded 18,000-lb. single and 44,800-lb. tandem axle trucks were tested simultaneously with the trailer. Tests were made at two joints, the first a nonpumping joint on the granular soil subgrade and the second a pumping joint on the fine-grained soil subgrade.

Several series of tests were made in which the placement of the vehicle, with respect to the edges of the pavement, was varied.

The data obtained in these tests indicated that, (1) the most critical stresses and deflections occurred when the vehicles were traveling near the outside edges of the pavement in the vicnity of the corners, (2) the critical stresses and deflections caused by the trailer in an unloaded condition were approximately the same as those for the 18,000-lb. single axle truck and appreciably less than those caused by the 44,800-lb. tandem axle, (3) the critical stresses and deflections caused by the loaded trailer were appreciably greater than those caused by both the 18,000-lb. single and the 44,800-lb. tandem axle trucks and (4) the critical stresses and deflections along the outside edges of pavement are reduced appreciably when the outside wheels of the vehicle are placed approximately 3 or 4 ft. from the outside edge of the pavement.

The outside wheel of the 23,000-lb. front axle of the trailer combination tracked at a greater distance from the edge of the pavement than those of the other trailer axles and control trucks. Thus, for the corner loading, the stresses and deflections for this axle were proportionately less, with respect to load, than those of the other trailer axles and control trucks.

● ON completion of the scheduled investigation with conventional motor trucks on Road Test One-MD, a supplementary study was made to obtain information on stresses and deflections caused by a vehicle with heavier axle loads. The study was made with a heavy-duty military tractor-and-semitrailer combination designed for transporting heavy army tanks over highways and furnished by the Department of Defense. For control purposes, comparative data were obtained with two conventional motor trucks, one with an 18,000-lb. single-axle load and one with a 44,800-lb. tandem-axle load. These trucks followed in line with the army vehicle during most of its test runs.

Figure 1 shows two views of the military tractor-trailer combination loaded with a number of concrete blocks. The spacing and arrangement of the wheels and axles are shown in detail in Figure 2. Axle 1 on the front of the tractor has two single-tired wheels, and the spacing between these wheels is less than that between the outside wheels of the other axles. Tandem Axles 2 and 3 on the rear of the tractor have two dual-tired wheels on each axle and tandem Axles 4 and 5 on the rear of the trailer have four single-tired wheels on each axle.

The over-all length of the tractor-semi-trailer combination was 59 ft. while the over-all width was approximately 11 ft.

tation are given in the report of Road Test One-MD[1] and will be described only briefly in this report.

The pavement was 24 ft. wide, divided into two 12-ft. lanes by a longitudinal joint and was reinforced with a 59-lb. welded wire fabric. The cross-section of each lane was 9-7-9-in. and of the double parabolic type. The pavement was divided

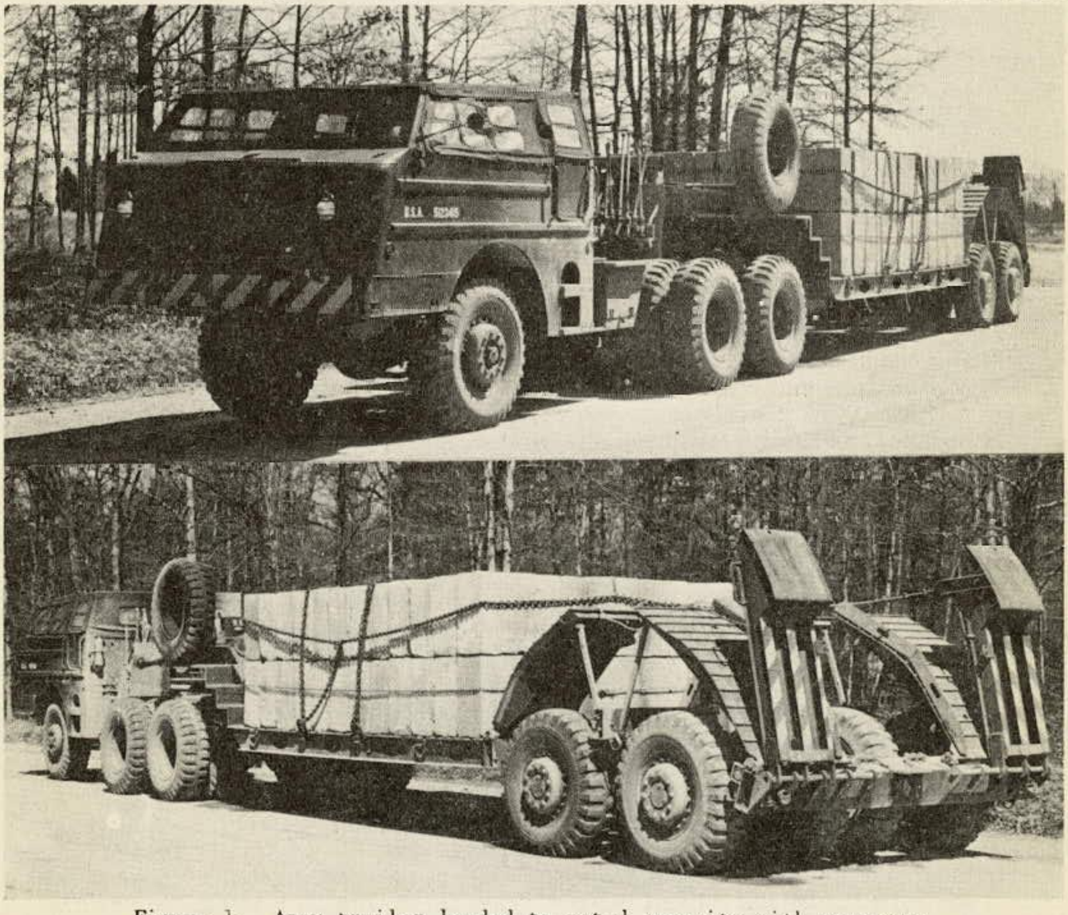

Figure 1. Army trailer loaded to rated capacity with concrete blocks.

Table 1

Tire, wheel and axle-load data pertaining to the military tractor, semitrailer combination.

Axle number	Number of wheels per axle	Type of tire	Size of tire	Trailer unloaded Axle weight	Trailer unloaded Wheel weight	Trailer Loaded Axle weight	Trailer Loaded Wheel weight
			in.	lb.	lb.	lb.	lb.
1	2	Single	14x24	23,000	11,500	19,290	9,645
2	2	Dual	14x24	16,750	8,375	42,740	21,370
3	2	Dual	14x24	16,750	8,375	44,300	22,150
4	4	Single	14x24	13,250	3,312	45,750	11,438
5	4	Single	14x24	13,250	3,312	46,720	11,680
	Gross weight			83,000		198,800	

Note: 80-psi. inflation pressure in all tires.

The unloaded and loaded axle and wheel weights of the tractor-trailer combination, together with certain data pertaining to the tires, are listed in Table 1. The gross weight of the combination was 83,000 lb. unloaded and 198,800 lb. when loaded.

The structural design of the pavement, the strength and other properties of the concrete, the soil types and properties of the subgrade and details of the instrumen-into 40-ft. slab lengths with expansion joints at intervals of 120 ft. and two intermediate contraction joints. All of the transverse joints had load transfer in the

[1]Final Report on Road Test One-MD, Highway Research Board Special Report 4 (1952).

form of $^{3}/_{4}$-in. round dowles spaced 15 in. center to center. The longitudinal joint was of the butt type with $^{5}/_{8}$-in. -diameter tie bars, 4 ft. long, spaced 4 ft. center to center.

The pavement might be considered to have a strength at its corners and longitudinal edges equal to that of a uniform thickness slab of approximately 8 or $8^{1}/_{2}$ in. The average slab thickness at the points where the transverse joint-edge tests were made was approximately 7. 3 in.

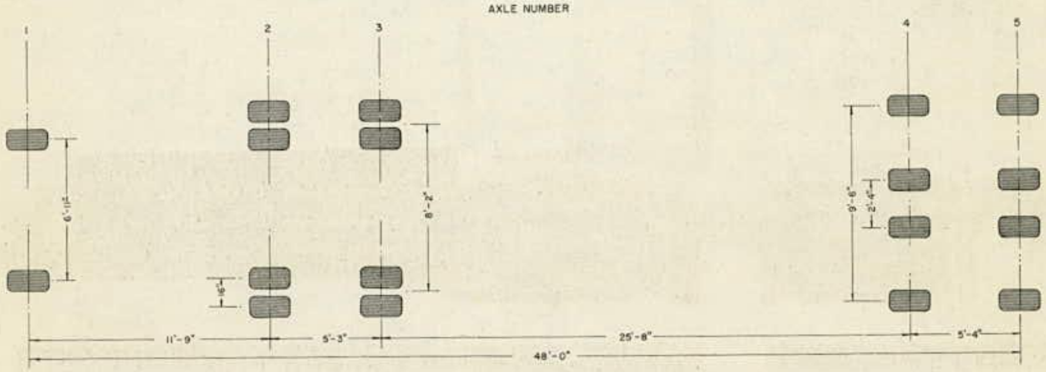

Figure 2. Plan showing the placement of the wheels and axles of the heavy-duty, military tractor-semitrailer combination tested. Truck-tractor M26A1, semitrailer M15A1.

Core and beam specimens were removed from the pavement both prior to and after traffic testing. Strength tests on these specimens showed that the concrete in this pavement was of average quality as compared to concrete in pavements of similar age. Also, the variations in strength between the different parts of the pavement were no greater than those normally found in other concrete pavements.

All strains in the pavement were measured with SR-4, Type A-9 (6-in. -length) electrical-resistance strain gages. The strain gages were cemented to the surface of the pavement (Fig. 3) and sealed against moisture. All gages were checked for bond and for resistance to ground just prior to use. The strain values were recorded with a direct-inking oscillograph, shown in Figure 4. The frequency response of the oscillograph was sufficiently high to record accurately strains at vehicle speeds up to 40 mph.

Slab deflections were obtained simultaneously with the strain measurements. The device used to measure the deflections is shown in Figure 5. The basic measuring element is an aluminum-alloy strip with resistance-type strain gages cemented to the upper and lower surfaces. The gages measure the strain as the element deflects with the pavement and, by calibration, provide a measure of pavement deflection. The fixed end of the measuring element was attached to a concrete pedestal cast in the shoulder near the pavement edge.

PROGRAM OF TESTING

The tests with the military tractor-trailer combination were made at two

Figure 3. A 6-in. SR-4 strain gage is cemented to surface of pavement.

expansion joints. The first was between Slabs 44 and 46 in a section of the pavement supported by a deep granular subgrade, and no pumping had been observed at this joint during the entire period of traffic testing. The AASHO Designation: M 145-49 of the soil at this location was A-1a. The second joint, between Slabs 102 and 104, was located on subgrade material having an AASHO Designation: M 145-49 of A-6. At the time the tests with the military trailer were started pumping had developed at this joint, but the slabs on either side of it had not cracked. A structural failure occurred during testing, but fortunately it did not seriously affect the results of the study. This development will be discussed further when the data from the tests at this joint are presented.

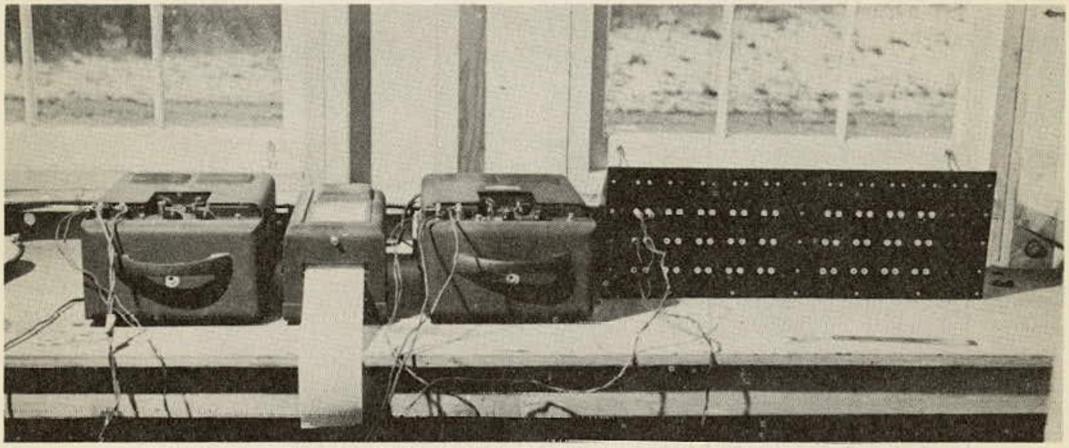

Figure 4. Direct-inking oscillograph equipment and switching panel used in measurement of strain.

The magnitude of the stresses and deflections that are caused by a vehicle moving along a pavement may vary greatly depending upon the transverse placement of the vehicle. For example, a heavy vehicle traveling with its wheels near the edges of the pavement, especially the outside edges, is potentially more destructive to the pavement than one of equal weight traveling with its wheels at some distance from the edges. Since heavy-duty vehicles, such as the trailer used in this study, travel on highway pavements only occasionally, it is possible that on those occasions the vehicles might be placed in the transverse position least likely to cause structural damage to the pavement. In this trailer study, tests were made with the vehicles in three different transverse positions on the pavement to provide information on this point. These were:

Placement I, the trailer positioned near the outside or free edge of the pavement. With this placement the outside edges of the contact areas of the outside wheels of the tandem axles tracked at a distance of 6 in. from the longitudinal free edge of the pavement.

Placement II, the trailer positioned symmetrically straddling the longitudinal joint.

Placement III, the trailer positioned at some distance from the outside or free edge of the pavement. In this case the outside edges of the contact areas of the outside wheels of the tandem axles were kept at a distance of 30 in. from the longitudinal free edge of the pavement.

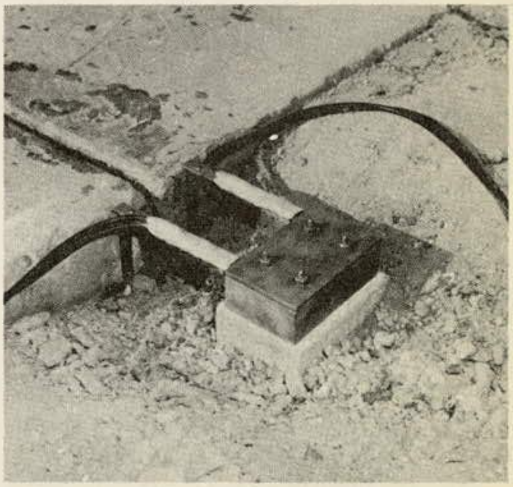

Figure 5. Electrical deflection-measuring device at corner of pavement slab.

For each vehicle placement the load-strain and load-deflection studies were divided into several cases of loading, as follows:

PLACEMENT I

Free-Edge Loading

With a wheel load acting at the longitudinal free edge of the slab at a considerable distance from any corner, critical strain was measured either directly under or immediately adjacent to the load in a direction parallel to the free edge of the slab. The position of the strain gages and wheels of an axle for this loading are shown in Figure 6.

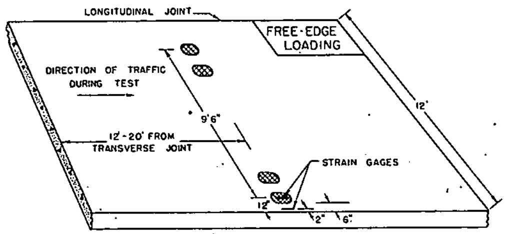

Figure 6. Position of wheels and location of strain gages for measurement of critical strains for free-edge loading.

Deflections were measured at the midpoint of the free edge of the slab, that is, 20 ft. from a transverse joint.

Corner Loading

With a wheel load acting in the immediate vicinity of an outside joint corner, critical strain was measured along the longitudinal free edge of the slab in the vicinity of the corner. The position of the strain gages and wheels of an axle for this loading are shown in Figure 7.

Deflections were measured at the slab corners on both sides of the transverse joint.

PLACEMENT II

Longitudinal Joint-Edge Loading

With the vehicles symmetrically straddling the longitudinal joint, critical strain was measured at a point on the longitudinal joint edge some distance from any corner and in a direction parallel to the edge. The position of the strain gage and the wheels of an axle for this loading are shown in Figure 8.

Longitudinal Joint-Corner Loading

With the vehicles symmetrically straddling the longitudinal joint, critical strain was measured along the longitudinal joint edge of the slab in the vicinity of the corner. The position of the strain gages and the wheels of an axle for this loading are shown in Figure 9.

PLACEMENT III

Stress and Deflection at Free Edge

The strains and deflections that developed at the free edge were measured at the same points as for the free-edge loading of Placement I.

Stress and Deflection at Corner

The strains and deflections that developed at the outside joint corner were measured at the same points as for the corner loading of Placement I.

Because of time limitations, only a limited number of tests were made with the trailer in Placement III, i. e., with the outside wheels 30 in. from the longitudinal free edge of the pavement. However, in the main testing program for trucks, previously reported, comprehensive tests were made at several joints on both the granular nonpumping and the fine-grained pumping subgrades in which the placement of the outside wheels of the vehicle was varied from 6 to 30 in. from the longitudinal free edge. That report contains graphs showing

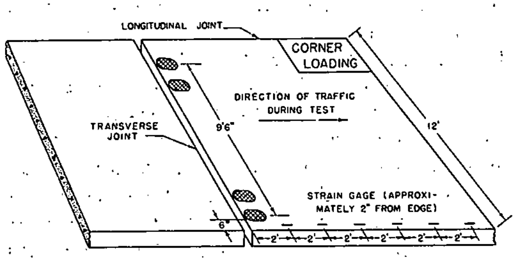

Figure 7. Position of wheels and location of strain gages for measurement of critical strains for corner loading.

the percentage reduction in the strains and deflections at the outside edges and corners of the pavement as the placement of the vehicle wheel with respect to the free edge of the pavement was increased.

The data obtained in the limited tests made with the trailer in the 30 in. placement were in agreement with comparable data obtained in the main testing program with the motor trucks. For this reason, the stress and deflection relations for the 30-in. placement of the military trailer, shown later, were obtained by making use of the stress and deflection relations developed in the earlier truck tests of the main program and the limited data obtained with the military trailer in Placement III.

In addition to the load-strain and load-deflection studies described under the three transverse vehicle placements, a study was made of the critical strain that develops with a wheel load acting at the transverse joint edge of the pavement and at some distance from any corner. For this case of loading, the critical strain was measured directly under the wheel load and in a direction parallel to the transverse

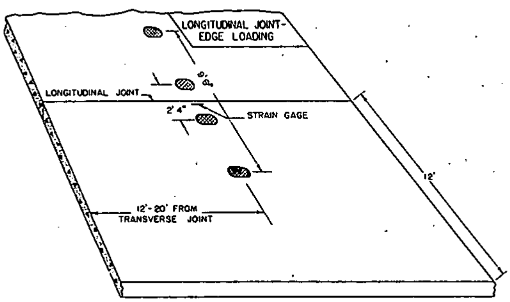

Figure 8. Position of wheels and location of strain gages for measurement of strains for longitudinal joint-edge loading.

joint edge. Measurements were made with the vehicles at several different transverse positions, as indicated by the location of the gages shown in Figure 10. The position of the wheels of an axle for one transverse placement is shown also in the figure.

Transverse joint-edge stresses are small under vehicle wheels acting in the immediate vicinity of a longitudinal edge of the pavement but increase progressively with increase in the distance of the wheel load from the longitudinal edge. For distances greater than approximately 36 in. a maximum stress value is reached, and this value remains more or less constant for loads acting at other positions along the transverse joint edge.

The transverse joint-edge stresses shown later in this report apply for all wheel loads positioned approximately 36 in. or more from any longitudinal edge of the pavement, irrespective of the transverse placement of the vehicle.

The trailer tests were made with the vehicles operating at creep speed and 30 mph., creep speed representing a vehicle speed of approximately 2 mph. Two complete sets of data were obtained for each

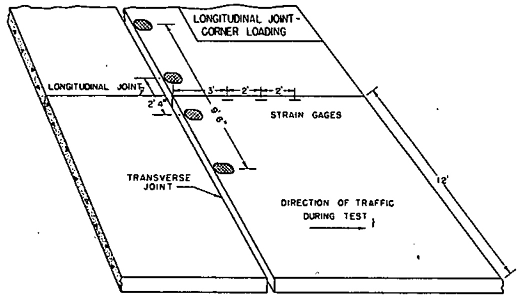

Figure 9. Position of wheels and location of strain gages for measurement of critical strains for longitudinal joint-corner loading.

test. The tests were made during the period between 9:30 p.m. and 6 a.m., because the condition of temperature warping in a pavement slab is usually more constant during this period than during the daytime and because load stresses and deflections in the vicinity of the edges of a pavement slab are more critical at night and early morning when the slab edges are, as a rule, warped upward.

The trailer data were obtained on two successive nights at each of the two joints tested.

DISCUSSION OF FACTORS AFFECTING INTERPRETATION OF TEST DATA

In the main Road Test One-MD investigation, the range and increment of the axle loads of the trucks were such as to be more suitable for establishing certain basic relations than was possible with the axle

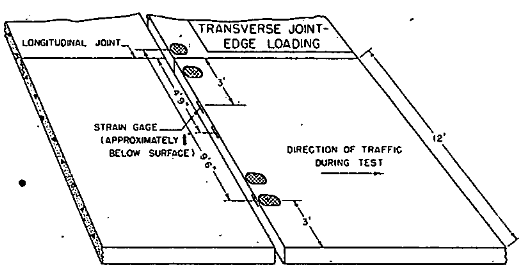

Figure 10. Position of wheels and location of strain gages for measurement of critical strains for transverse joint-edge loading.

loads of the trailer. Since some of the characteristics of these basic relations, shown in the first published report, are of importance in the interpretation of the data obtained in the tests with the military trailer, reference will be made to them in the following discussion.

night when the edges of the pavement were warped upward. Under conditions of upward warping, as the magnitude of the load is increased, the resulting deflection causes the pavement to come more and more into contact with the subgrade, and this increasing degree of subgrade support, in

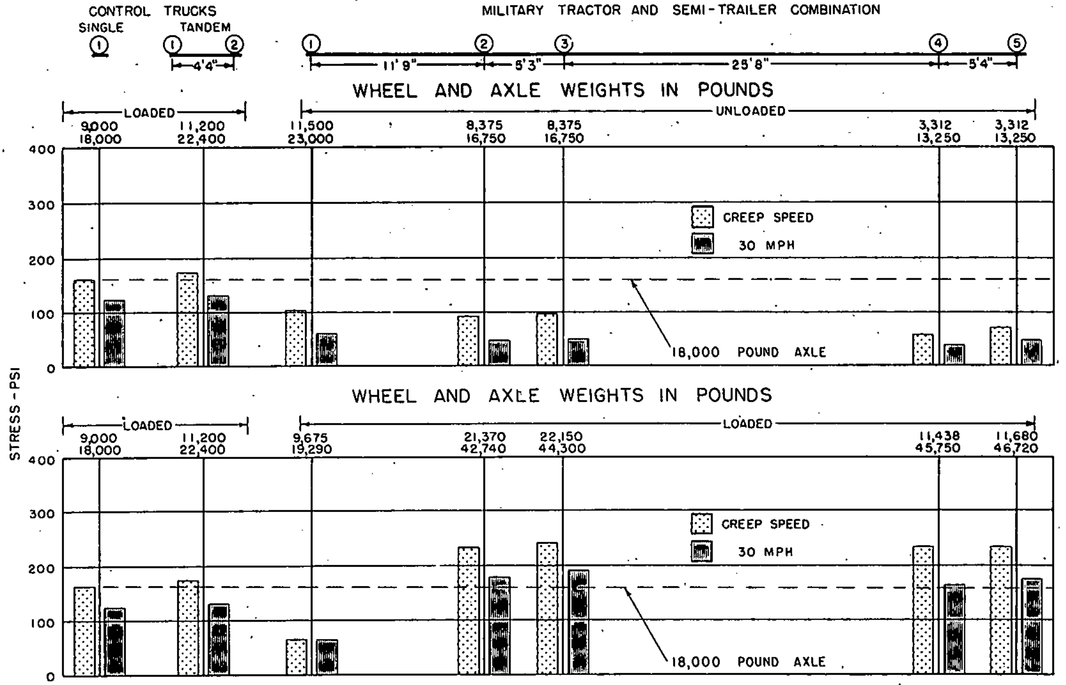

Figure 11. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for free-edge loading, granular soil.

Departure from Linearity

The load-stress and load-deflection relations were found to depart slightly from linearity for the free-edge case of loading and quite radically from linearity for the corner case of loading. The load-stress relations for the transverse joint-edge case of loading were found to be linear in some cases and to depart somewhat from linearity in others, depending upon the degree of warping in the pavement and the support afforded by the subgrade at the time the tests were made. The above statements apply for both single-and tandem-axle loadings of the main test program.

The departure of the load-stress and load-deflection relations from linearity, for certain cases of loading, is associated with the fact that the tests were made at

turn, causes progressively less deflection for each additional increment of load. Thus, it may be concluded that the observed departures from linearity are the result of a changing condition of slab support as the magnitude of the load increases. Since warping in a concrete pavement slab is more pronounced in the vicinity of the joint corners, the load-stress and load-deflection relations for this case of loading show greater departures from linearity than do those for the other cases.

In the main testing program, load-stress and load-deflection relations were not established for the longitudinal joint-edge nor for the longitudinal joint-corner loadings. It is only reasonable to expect, however, that the relations for these loadings would show the same tendencies to depart from linearity as were found for the corresponding loadings at the free edge of the pavement, although perhaps to a somewhat lesser degree.

It is believed that the above discussion furnishes an explanation for the observed fact that, in the tests with the military trailer, the measured strains and deflections usually did not increase in direct proportion to increases in axle weight, as will be noted in the graphs presented.

Relative Influence of Single and Tandem Axles

Another fact, established in the main investigation, that applies to the data of this supplementary study is the relative influence of single and tandem axles on the magnitude of stress and deflection for the various cases of loading. The load-stress relations of the main report showed that a tandem axle, with a weight double that of a single axle, caused a moderately greater stress for the corner and transverse joint-edge cases of loading than was caused by the single-axle weight. For the interior and free-edge cases of loading, however, the tandem-axle weight caused a smaller stress than was caused by the single-axle. The load-deflection relations showed that the tandem-axle weight caused a moderately greater deflection for the corner case of loading than was caused by the single axle, as was the case with stress. For the free-edge case of loading, however, the tandem-axle weight caused the greater deflection, which is contrary to the relation found for stress.

Deflection Cycles of Tandem Axles

A study of oscillograph recordings showing the manner in which pavement slabs deflected at the corner and free edge under a moving tandem-axle loading indicated little, if any, tendency for such weights to create more deflection cycles than single-axle weights. For the corner case of loading there was a slight recovery of the deflected slab between the front and rear axles of the tandem set, but for the free-edge case of loading there was none. Thus, for free-edge loading, tandem-axle weights cause but a single deflection, and for practical purposes, the same is true for corner loading.

LOAD-STRESS AND LOAD-DEFLECTION DATA FOR THE TRAILER IN PLACEMENT I, SLABS ON THE NONPUMPING GRANULAR SOIL

In the conversion of measured strains to stress values a modulus of elasticity of 5 million psi. was used, this being a fair average as determined by tests on cores and beams removed from the pavement. All stresses are extreme fiber values at the surface of the pavement, a small correction having been applied to the observed strains in cases where the gages were placed slightly below the surface.

The modulus of rupture of the concrete specimens removed from the pavement exceeded 700 psi. with few exceptions. Thus, for this pavement a working stress of 350 psi. is considered to be within safe limits.

There were no cracks or other forms of structural failure in the slabs adjacent to the joint on the granular nonpumping subgrade at which the tests were made. Also, no indication of pumping was observed in this area during the entire period of traffic testing.

Free-Edge Loading

The stress data for the free-edge loading for the slabs on the granular nonpumping subgrade are shown in Figure 11. The comparative stresses caused by the two control trucks having 18,000-lb. single- and 44,800-lb. tandem-axle weights, respectively, are on the left while those caused by the five axles of the military tractor-trailer are on the right. In this figure, and in those to follow, the stress values shown for the 44,800-lb. tandem-axle control truck are the maximum induced by either axle of the tandem set. The stresses in the upper graph are for the trailer unloaded, and those in the lower graph are for the trailer loaded.

The control trucks were loaded for both sets of tests, that is, those with the trailer unloaded and with it loaded. During the two nights of testing, only small differences were observed in the stresses and deflections caused by the axles of the control trucks, indicating little variation in the condition of warping in the pavement slabs between the two nights. For this reason, the stress values shown for these trucks for all cases of loading related to the granular soil are averages of the two nights.

The horizontal, light-weight, dashed lines indicate the stress caused by the 18,000-lb. single-axle control truck operating at creep speed and are for convenience in com-

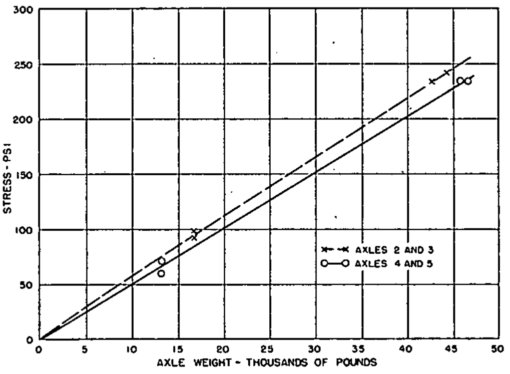

Figure 12. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles for free-edge loading on granular soil at creep speed.

paring the stresses caused by this axle weight with those caused by the several tractor-trailer axles.

It was pointed out in the discussion of Figure 2 that the wheels of Axle 1 track at a distance of approximately 15 in. farther from the edge of the pavement than the outside wheels of the other axles. This is the reason that the stresses caused by this axle were less than might be expected when compared with those for the other axles, especially the 18,000-lb. single-axle control truck. This off-tracking of the wheels of Axle 1 influences the stresses for other cases of loading, as well as the one under discussion.

With the trailer unloaded (Fig. 11) the creep-speed stresses for the several tractor-trailer axles are much less than generally accepted design limits (50 percent of the modulus of rupture of the concrete) and appreciably less than those caused by the 18,000-lb. control axle which, except possibly for Axle 1, is as would be expected.

With the trailer loaded, the creep-speed stresses for all of the tractor-trailer axles are below generally accepted design limits. For Axle 1 the stress is much less and for Axles 2, 3, 4, and 5 appreciably greater than that caused by the 18,000-lb. control axle.

It will be noted that the creep-speed stresses are somewhat greater than those

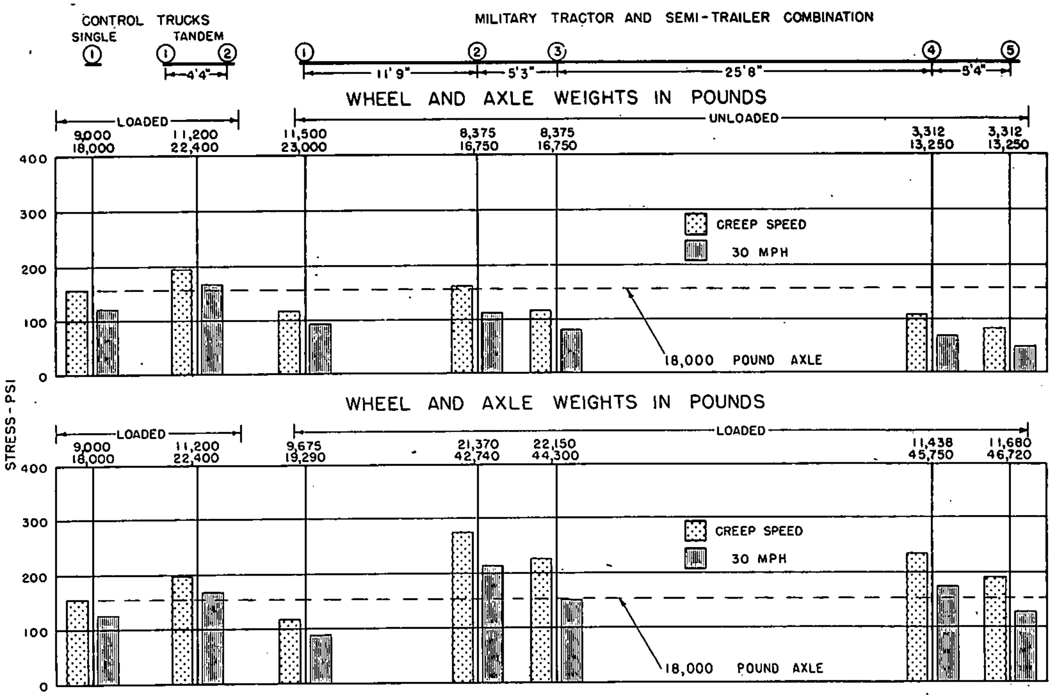

Figure 13. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for corner loading, granular soil.

for 30 mph. As shown in Special Report 4, this is generally true for all of the cases of loading, for both stresses and deflections. However, a few exceptions were found, in both the main and this supplementary study, in the stresses for the corner cases of loading at joints on the pumped fine-grained soil. In this discussion, emphasis will be placed upon the creep-speed values; the influence of speed on stresses and deflections caused by loads will be discussed after the presentation of the basic data.

As mentioned earlier in the discussion of Figure 2, the two sets of tandem axles of the tractor-trailer have different wheel and tire arrangements. That is, the front tandem, Axles 2 and 3, has two dual-tired wheels on each axle, while the rear tandem, Axles 4 and 5, has four single-tired wheels on each axle. To study the effect of these different arrangements on stress, the creep-speed data presented in Figure 11 are replotted in Figure 12 with respect to axle weight. When plotted in this manner, the load-stress relations show, only a small difference in the stress between the two types of wheel arrangements for any given axle weight. In other words, It is indicated that the distribution of an axle load to the pavement by four single-tired wheels does not appreciably reduce the critical free-edge stress below that caused by the more-common two-wheeled axles with dual tires.

Corner Loading

The stress data for the corner case of loading for slabs on the granular nonpumping subgrade are given in Figure 13. The wheels of Axle 1, being at a greater distance from the edge of the pavement than are the outside wheels of the other axles, cause stresses for this axle which are less than might be expected when compared with those for the other axles on the basis of axle weight.

With the trailer unloaded, the stresses for the several tractor-trailer axles are much less than the usually accepted design limits and, except for Axle 2, appreciably less than those caused by the 18,000-lb. control axle, the stresses for Axle 2 being approximately equal to those caused by the control axle.

With the trailer loaded, the stresses are still appreciably less than normally accepted design limits and, for several of the axles, considerably greater than those caused by the 18,000-lb. control axle.

It will be noted that the critical stresses for the front axles of each of the two sets of tandems, (Axle 2 and Axle 4) are higher than those for companion rear axles (Axle 3 and Axle 5). This condition is usual for tandem-axle loadings where the critical strain for corner loading is measured in the slab on the forward side of the joint with respect to the direction of test traffic, as was done in this study. The reason for this is that when the front axle of a tandem set is acting on the forward slab in a position to cause maximum tensile stress (see Fig. 7) the rear axle is on the slab on the opposite side of the joint, where it exerts

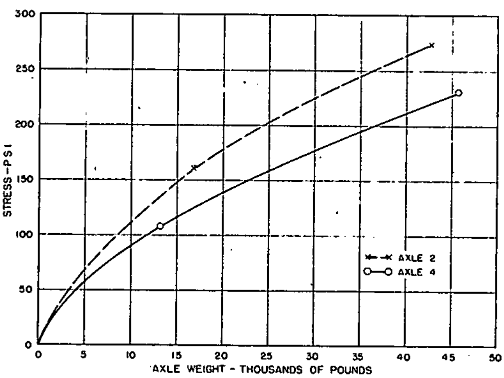

Figure 14. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles for corner loading, granular soil, creep speed.

little influence at the maximum stress point for the front axle. In contrast, when the rear axle of the tandem pair is acting on the forward slab in a position to cause maximum tensile stress, the front axle has moved forward to the immediate vicinity of the maximum stress point for the rear axle. In this position the front axle causes a compressive stress which compensates, in part, for the tensile stress caused by the rear axle. This does not mean that the front axle of a tandem set always causes the maximum stress for corner loading. If critical strains in the approach slab were to be considered, the maximum tensile stress would develop with the wheels of the rear axle nearest the joint.

The stresses determined for the front axles of the tandem sets (Axle 2 and Axle

4) are plotted in Figure 14 to show more clearly the load-stress relations with respect to axle weight.

distance from the edge of the pavement than did the outside wheels of the other axles.

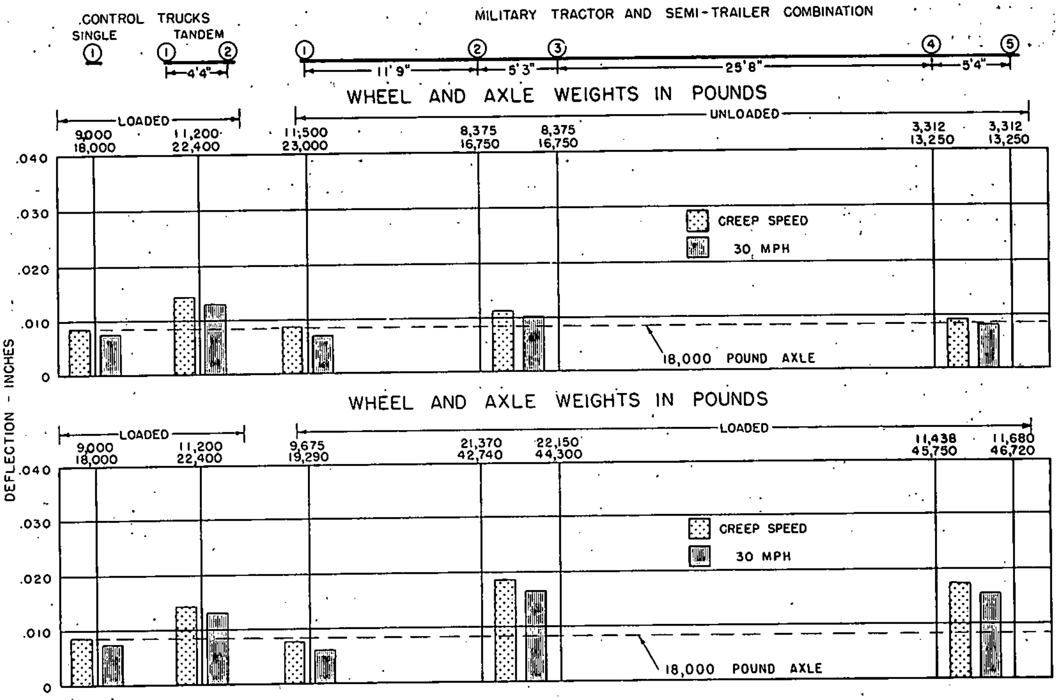

Figure 15. Comparison between the critical deflections caused by the loadings shown for the military trailer and for the control trucks for free-edge loading, granular soil.

When plotted in this manner, it is evident that, for the corner case of loading, the axle with the four single-tired wheels is more effective in stress control than one with the two dual-tired wheels. For example, for a 45,000-lb. axle load, the stress caused by Axle 4 with four single-tired wheels is approximately 20 percent less than that for Axle 2 with two dual-tired wheels.

Deflection, Free-Edge Loading

Deflection measurements were made simultaneously with the stress measurements for the free-edge and the corner cases of loading.

The measured deflections for the free-edge case of loading for slabs on the nonpumping granular subgrade are shown in Figure 15. As was found for stresses for this case of loading, the deflections for Axle 1 are influenced by the fact that the wheels of this axle tracked at a greater

It will be noted that a single deflection value is given for each tandem set, because as stated earlier, tandem axles at a normal spacing cause only a single deflection for this case of loading.

The deflections for the several tractor-

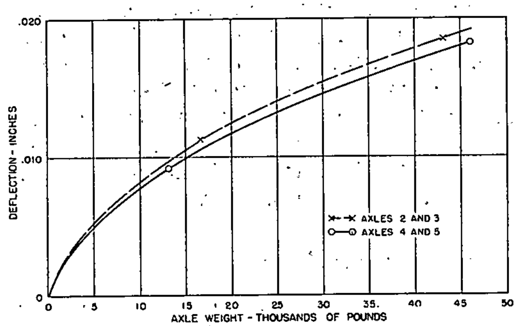

Figure 16. Load-deflection relations plotted with respect to axle weight to study the effect of the two types of tandem axles for free-edge loading, granular soil, creep speed.

trailer axles are considered to be small with the trailer both unloaded and loaded. With the trailer loaded, the deflections for the tandem axles do, however, exceed greatly those caused by the single 18,000-lb. control axle.

the deflection for the rear axle of each tandem set is slightly larger than those for the front axle. As mentioned earlier, only a slight recovery of the deflected slab takes place between the front and rear axles of the tandem set. Thus, although a separate

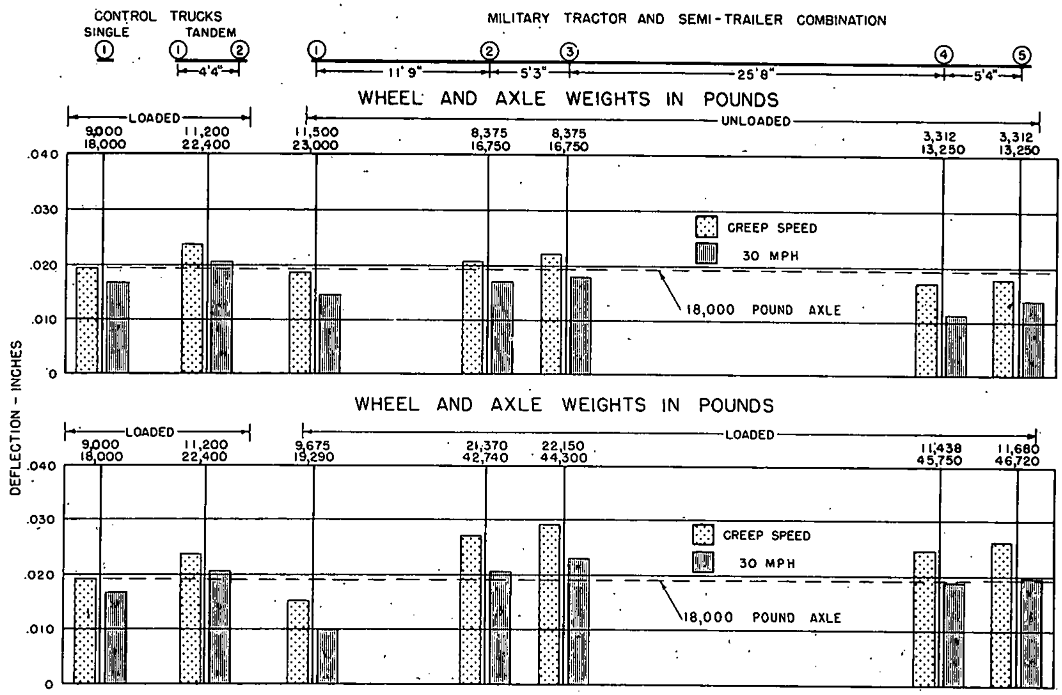

Figure 17. Comparison between the critical deflections caused by the loadings shown for the military trailer and for the control trucks for corner loading, granular soil.

The deflections for the two tandem sets of axles are plotted in Figure 16 with respect to axle weight. The magnitude of the deflection appears to be more a function of the axle weight than of the wheel weight, since the deflection caused by Axles 4 and 5 with four single-tired wheels are only slightly smaller than those caused by Axles 2 and 3 with two dual-tired wheels. Thus, for the free-edge case of loading, a distribution of the load to the pavement through four single-tired wheels is not an effective means for reducing edge deflections.

Deflection, Corner Loading

The deflection data for the corner loading are shown in Figure 17. Here again the deflections for Axle 1 are influenced by the position of the wheels of this axle as compared to that of the wheels of the other axles. It will be noted that in each case deflection value is shown for each axle, for practical purposes a single value with mag-

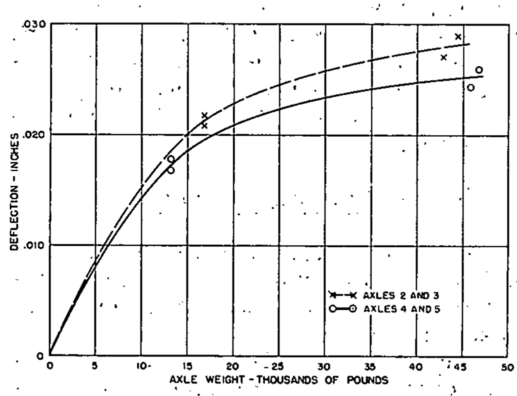

Figure 18. Load-deflection relations plotted with respect to axle weight to study the effect of the two types of tandem axles for corner loading, granular soil, creep speed.

nitude equal to that of the rear axle would be justified.

The deflections for the several tractor-trailer axles are small with the trailer unloaded and approach or slightly exceed those caused by the 18,000-lb. control axle. Even with the trailer loaded the deflections are considered to be only moderate, although appreciably greater than those caused by the 18,000-lb. control axle.

The deflections for the two tandem sets are plotted with respect to axle weight in Figure 18. This figure shows that the deflections for the axles with four single-tired wheels are somewhat less than those for the axles with two dual-tired wheels, the decrease at a 45,000-lb. axle weight being approximately 10 percent.

LOAD-STRESS RELATIONS FOR THE TRAILER IN PLACEMENT II, SLABS ON THE NONPUMPING GRANULAR SOIL

The positions of the wheels of the critical axles and strain gages for the cases of loading studied in this part of the investigation were discussed earlier in connection with Figures 8 and 9.

Longitudinal Joint-Edge Loading

A strain gage important in the study of this case of loading failed during the progress of testing, making it impossible to complete the tests. However, a complete set of data were obtained on the pumping fine-grained soil and will be presented later.

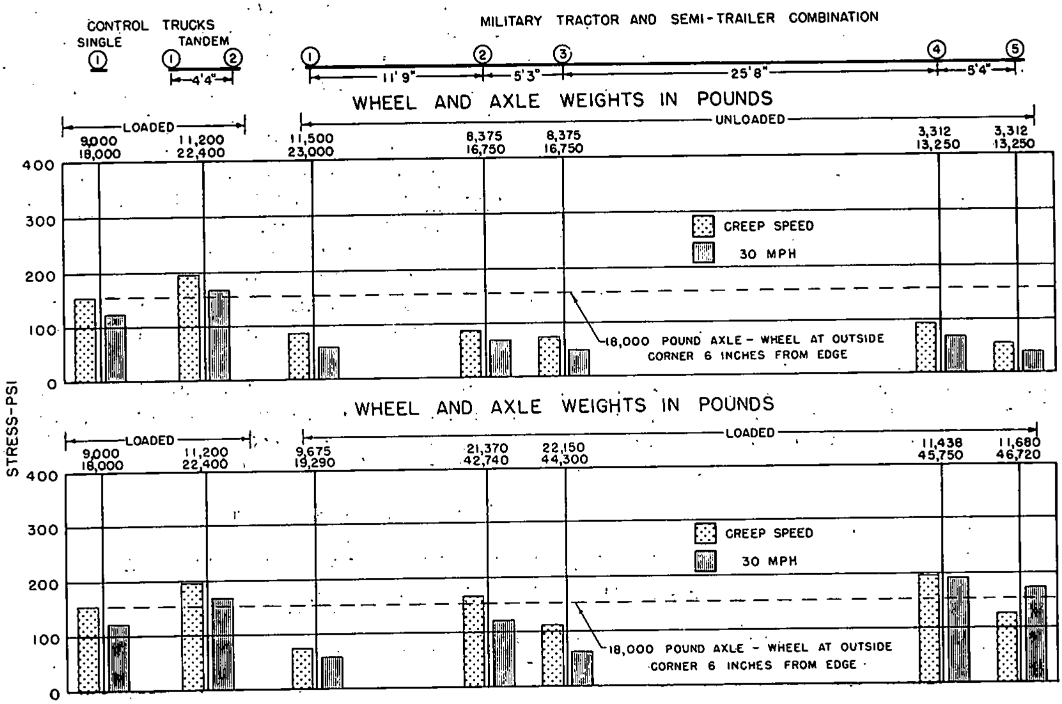

Figure 19. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for longitudinal joint corner loading, granular soil. The stresses for the trailer are with the vehicle straddling the longitudinal joint while those for the control trucks are for an outside-corner loading.

Longitudinal Joint-Corner Loading

The stress data for the longitudinal joint-corner loading for slabs on the nonpumping granular soil are contained in Figure 19. It will be noted that the stresses for the control trucks as shown in this figure are for the outside corner case of loading. Thus, the stresses for the several tractor-trailer axles with the vehicle straddling the longitudinal joint are compared with those developed by the control trucks acting near the longitudinal free edge of the pavement.

The stresses with the vehicle straddling the longitudinal joint are influenced by two important factors not encountered with the vehicle in a normal position on one lane of the pavement. In the first place, the vehicle is supported by the two slabs on opposite sides of the longitudinal joint; in the second place, the wheels of the vehicle act on the pavement at a greater distance from the longitudinal joint edge than they do from the free edge with the vehicle in a normal position on one lane. The distances from the center of the wheels of the various axles to the longitudinal joint are: for Axle 1, 41½ in.; for Axles 2 and 3, 49 in.; and for the inside wheels of Axles 4 and 5, 14 in.

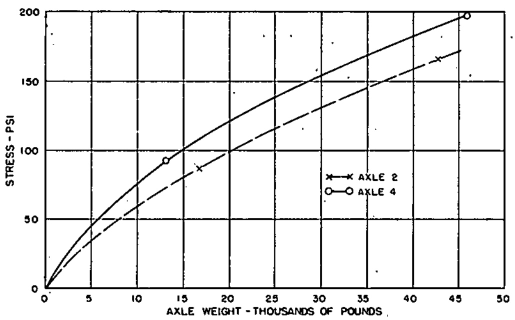

Figure 20. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles at longitudinal joint for corner loading, granular soil, creep speed.

With the trailer unloaded, the stresses for the several tractor-trailer axles are much less than normally accepted design limits and also much less than those caused by the 18,000-lb. control axle acting at the outside corner (see Fig. 19).

With the trailer loaded, the stresses for the tractor-trailer axles are much less than normally accepted design limits and, for Axles 2 and 4, somewhat greater than those caused by the 18,000-lb. control axle acting at the outside corner.

For the reason previously discussed for the outside-corner loading of Placement I, the stresses for the front axle of each tandem set are greater than those for the rear axle.

In Figure 20 the maximum creep-speed stresses for the tandem axles are plotted to show the load-stress relations and to compare the critical stresses for the two

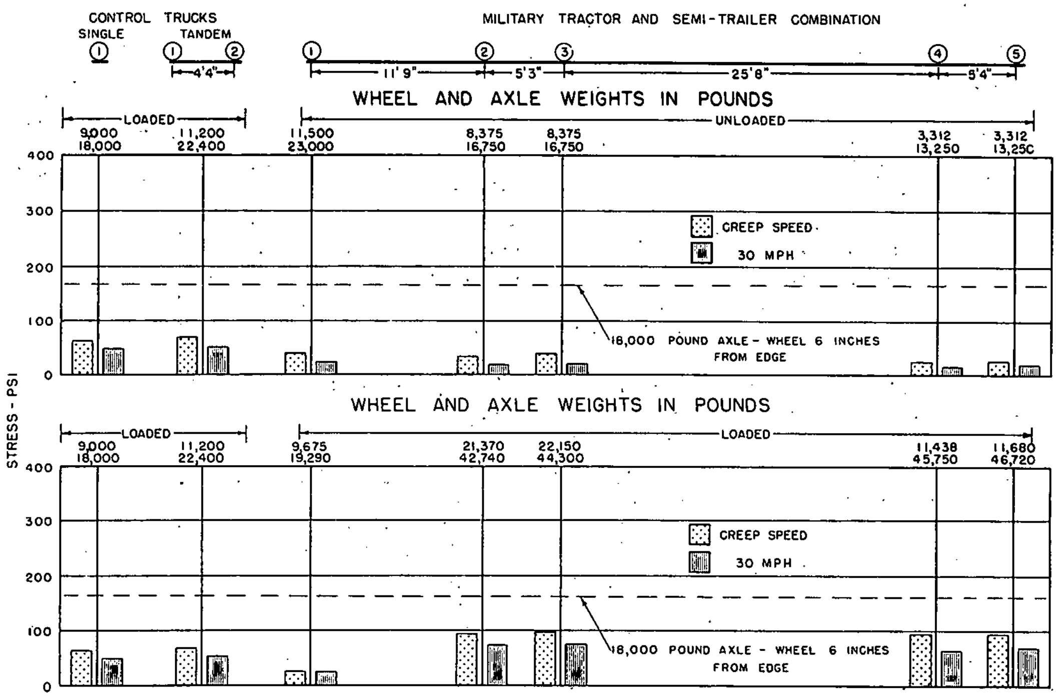

Figure 21. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, free-edge loading, granular soil.

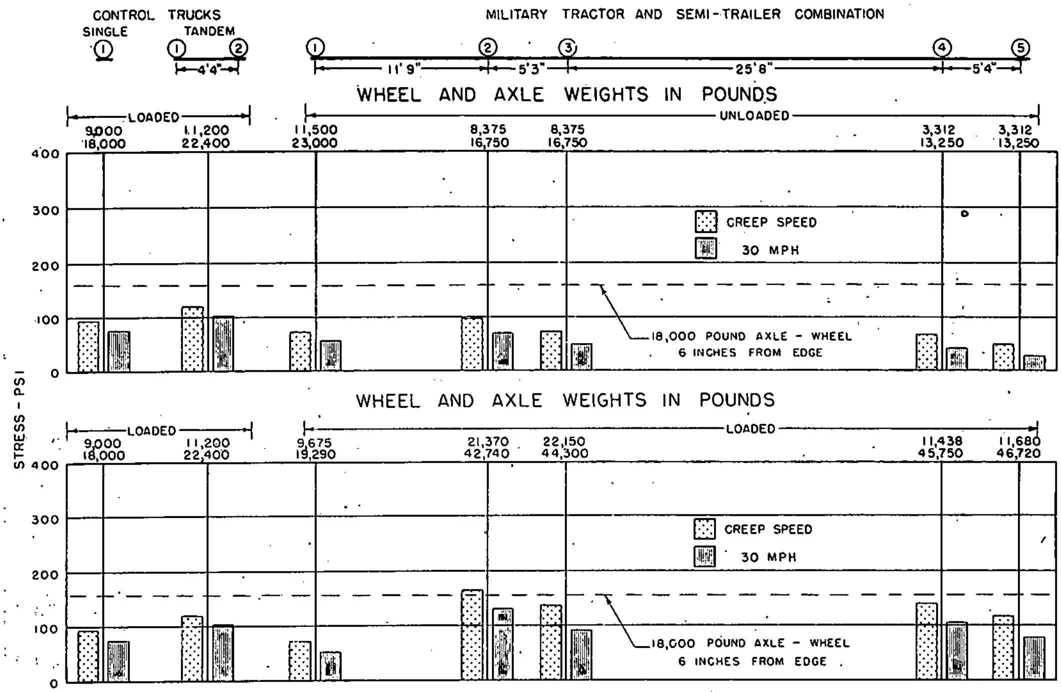

Figure 22. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, corner loading, granular soil.

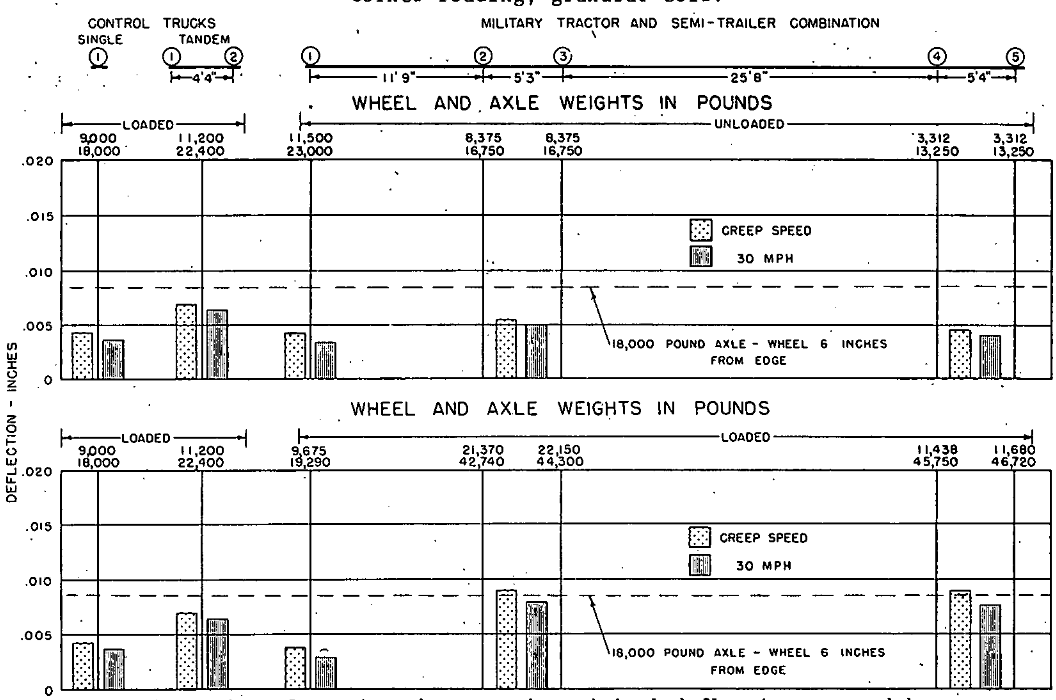

Figure 23. Comparison between the critical deflections caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, free-edge loading, granular soil.

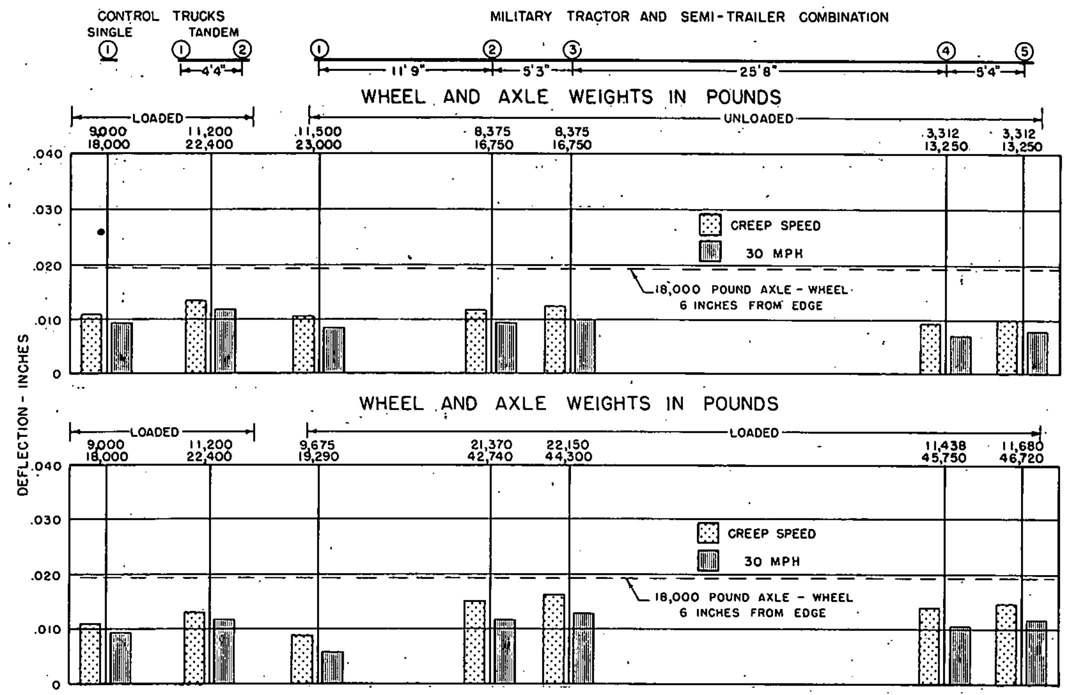

Figure 24. Comparison between the critical deflections caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, corner loading, granular soil.

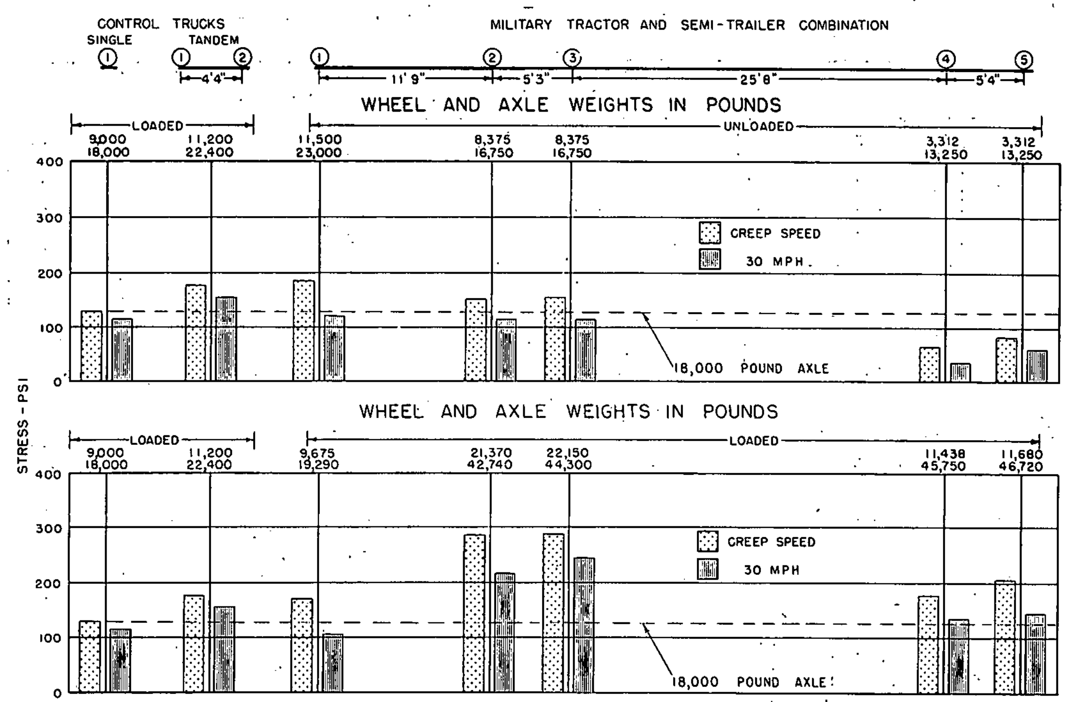

Figure 25. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for transverse joint-edge loading, granular soil.

types of tandem axles. Unlike those of the outside corner (Fig. 14) these relations show that the stresses for Axle 4, with the four single-tired wheels, are higher than those for Axle 2, with the two dual-tired wheels. This reversal is associated with the fact that the inside single-tired wheels of Axle 4 are closer to the longitudinal joint than the dual-tired wheels of Axle 2.

It is of interest to compare the maximum stresses that developed under the longitudinal joint-corner loading with those that developed under the outside-corner loading. For example, at a 45,000-lb. axle weight, the maximum stresses for the axles with the dual-tired wheels, Axles 2 and 3, are approximately 40 percent less at the longitudinal joint corner than at the outside joint corner. Correspondingly, the stresses for the four-wheeled axles with single tires, Axles 4 and 5, are 15 percent less at the longitudinal joint corner than at the outside-joint corner.

As just mentioned, however, Axle 2 caused the maximum stress at the outside corner, whereas Axle 4 caused the maximum stress at the longitudinal joint corner. Thus, based on a 45,000-lb. axle weight and the maximum stress for any axle, the stresses that develop under the longitudinal joint-corner loading are apporximately 30 percent less than those that develop under the outside-corner loading.

LOAD-STRESS AND LOAD-DEFLECTION DATA FOR THE TRAILER IN PLACEMENT III, SLABS ON THE NONPUMPING GRANULAR SOIL

With the vehicle in the 30-in. placement (Placement III) stresses and deflections were measured only at the free edge and outside corner of the pavement. However, because of the width of the trailer, stresses for such a vehicle placement may be higher at other points of the slab, for instance, the longitudinal joint edge. This possibiiity will be discussed later after the presentation of all data.

Stresses at Free Edge

The stresses that developed at the longitudinal free edge of the pavement with the vehicle in the 30-in. placement are given in Figure 21 for slabs on the nonpumping granular subgrade. The light-weight, horizontal, dashed lines indicate the magnitude of the creep-speed stresses at the free edge of the pavement for the 18,000-lb. control axle positioned in Placement I, i. e., 6 in. from the free edge.

It will be noted that, with the vehicles in the 30-in. placement, the stresses that developed at the free edge of the pavement were quite small for all of the tractor-trailer axles, as well as for those of the control trucks.

Stresses at Corner

The stresses that developed at the outside corner with the vehicles in the 30-in. placement are shown in Figure 22. For both the trailer and the control trucks, these stresses are approximately 40 percent less than the corresponding stresses that developed when the vehicles were positioned for the corner case of loading of Placement I and also appreciably below generally accepted design limits, with the trailer both unloaded and loaded.

Deflections at Free Edge

The deflections measured at the free edge of the pavement with the vehicles in the 30-in. placement are shown in Figure 23 for slabs on the nonpumping granular subgrade. These deflections are approximately 50 percent less than those that developed with the vehicles in Placement I, or 6 in. from the free edge. The deflections for both the trailer and the control trucks are definitely low, but with the trailer loaded the deflections for the tandem axles slightly exceed those caused by the 18,000-lb. control axle acting 6 in. from the free edge.

Deflections at Corner

The deflections measured at the outside corner with the vehicles in the 30-in. placement are presented in Figure 24. These deflections are definitely low and do not exceed in any case those caused by the 18,000-lb. control axle acting 6 in. from the free edge and, also, are approximately 45 percent less than the corresponding deflections that developed under the corner case of loading of Placement 1.

LOAD-STRESS DATA FOR THE TRAILER WHEELS ACTING AT THE TRANSVERSE JOINT EDGE, SLABS ON THE NONPUMPING GRANULAR SOIL

The stresses for the transverse joint-edge case of loading for slabs on the granular, nonpumping subgrade soil are shown in Figure 25. These data represent an average of all values obtained for this case of loading and, as explained earlier, are valid for wheels positioned approximately 36 in. or more from any longitudinal edge, irrespective of the transverse placement of the vehicle. In the tests for this loading the trailer was so positioned that the outside wheels of Axles 2, 3, 4, and 5 passed directly over the strain gages, while the wheels of Axle 1 passed a short distance to one side of the gages. Thus, the strains recorded for Axles 2, 3, 4, and 5 were maximum, while those for Axle 1 were probably somewhat less than those which actually occurred under the wheels of this axle.

It will be noted that, with the trailer unloaded, the stresses that developed at the transverse joint edge for the several tractor-trailer axles are much less than normally accepted design limits; for Axle 1, with two single-tired wheels, and Axles 2 and 3, with two dual-tired wheels, they are somewhat larger than those caused by the 18,000-lb. control axle; for Axles 4 and 5 with the four single-tired wheels they are much smaller than those caused by the 18,000-lb. control axle.

With the trailer loaded the stresses caused by the axles of the tractor-trailer are less than normally accepted design limits and also somewhat larger for Axles 1, 4, and 5 and much larger for Axles 2 and 3 than those caused by the 18,000-lb. control axle.

It is evident from the data of Figure 25 that the stresses for the transverse joint-edge case of loading are more a function of the wheel than of the axle weight. This effect is shown more clearly in Figure 26, where the stresses for the two sets of tandem axles, 2-3 and 4-5, are plotted with respect to axle weight. When plotted in this manner, it is apparent that the stress caused by the axle having the load distributed to the pavement through four single-tired wheels is considerably less than that for the axle with two dual-tired wheels. For example, at a 45,000-lb. axle weight, the stresses for Axles 4 and 5 with four single-tired wheels are approximately 35 percent less than those for Axles 2 and 3, with the two dual-tired wheels.

The critical stresses that develop at the transverse joint-edge of the pavement are those directly under the wheel load and in a direction parellel to the transverse joint. For this reason they are influenced by the width of the area of tire contact for a given wheel load. The comparison between the stresses induced by the two types of axles (Fig. 26) is affected by this factor, since the width of the effective tire contact area for the dual-tired wheel is appreciably greater and the radius of slab curvature is less than that for the same wheel load applied through a single tire. To illustrate: With the axle weight constant, the stresses caused by the wheels of Axles 4 and 5 would have been approximately 50 percent less than those caused by the wheels of Axles 2 and 3 had the width of effective tire contact area been the same for the wheels of the two wheel arrangements. Actually, because of the greater width of contact area with the dual-tired wheels, the difference was only about 35 percent, as noted above.

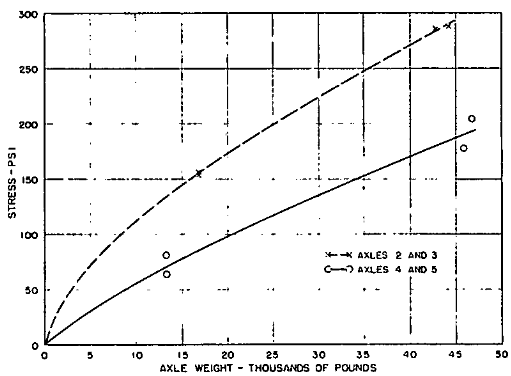

Figure 26. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles for transverse joint-edge loading, granular soil, creep speed.

LOAD-STRESS AND LOAD-DEFLECTION RELATIONS FOR THE TRAILER IN PLACEMENT I, SLABS ON THE PUMPED FINE-GRAINED SOIL

The joint selected on the fine-grained soil had been pumping moderately for some time prior to testing with the tractor-trailer, but the adjoining pavement slabs had survived, without structural failure, 238,000 applications of the 18,000-lb. single-axle-weight test truck.

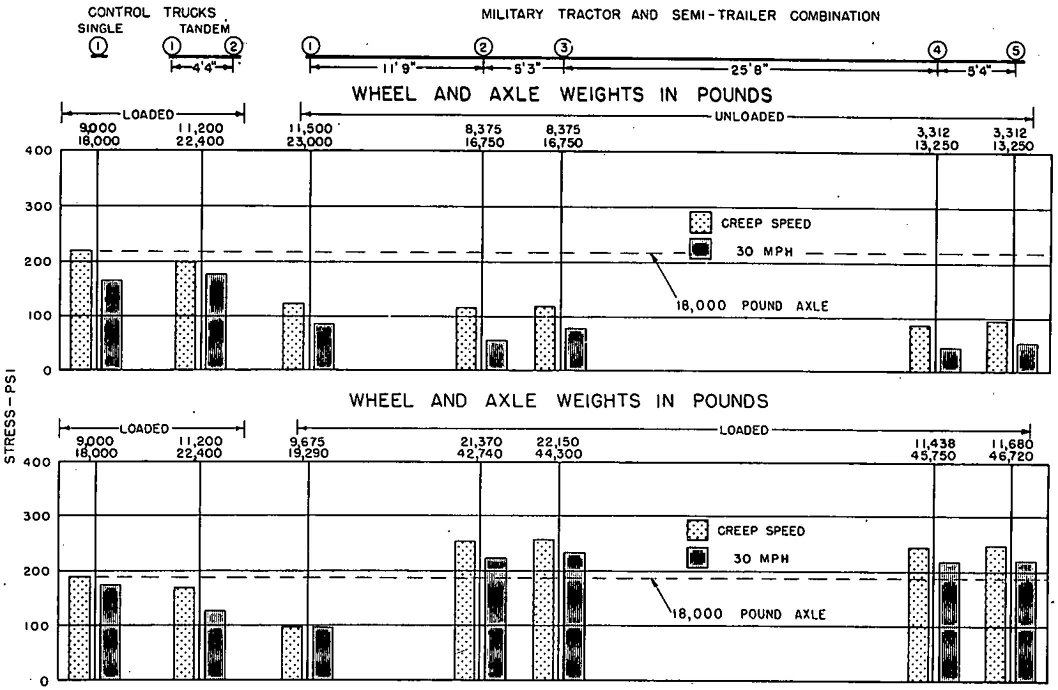

Figure 27. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for free-edge loading, pumping joint on fine-grained soil.

Because of circumstances beyond control, this joint was tested with the trailer loaded before being tested with the trailer unloaded. This sequence proved to be unfortunate, because after completion of the tests for the corner loading with the trailer loaded, a fracture occurred in the forward slab in the direction of test traffic. The fracture was indicated by a considerable drop in the magnitude of corner deflection recorded for the last test run of the loaded trailer under Placement I, and on the first test run of Placement III, the gage at the longitudinal joint edge 3 ft. from the transverse joint registered a strain that indicated a stress far in excess of the modulus of rupture of the concrete.

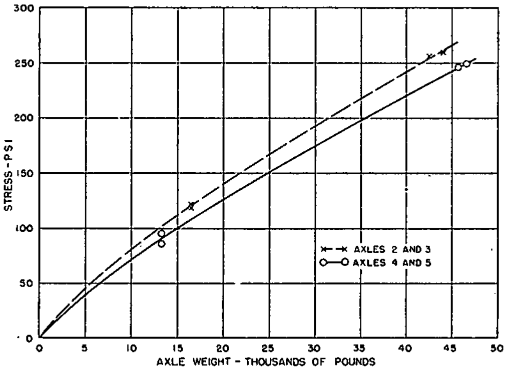

Figure 28. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles for free-edge loading, pumping joint on fine-grained soil, creep speed.

After completion of the tests with the trailer loaded, a close examination made of the pavement in the vicinity of the transverse joint revealed a slightly diagonal crack, barely visible to the naked eye. It started at the outside edge of the pavement at a distance of 6 ft. from the transverse joint and ended at the longitudinal joint at a distance of 3 ft. from the transverse joint. At this point it passed throught the strain gage that had indicated the excessive strain.

It would seem reasonable that a crack located as described and held tightly closed by wire-fabric reinforcement would not have a great effect on the critical stresses caused by the transverse joint-edge case of loading and should have no effect on stresses that develop under the free-edge and the longitudinal joint-edge cases of loading. The decision was made, therefore, to obtain the data, as planned, with the trailer unloaded an to utilize as much of the data as possible rather than to start anew on another slab. This decision was influenced also by a time factor and by a doubt as to whether or not a test with the values are not influenced by the fracture that occurred during testing.

For a given case of loading at the joint on the pumped fine-grained soil, moderate differences were observed in the stresses and deflections caused by corresponding control trucks on the two nights of testing. These differences were probably associated with the progressive development of pumping during the period of testing or with variations in the condition of warping in the pavement slabs between the two nights.

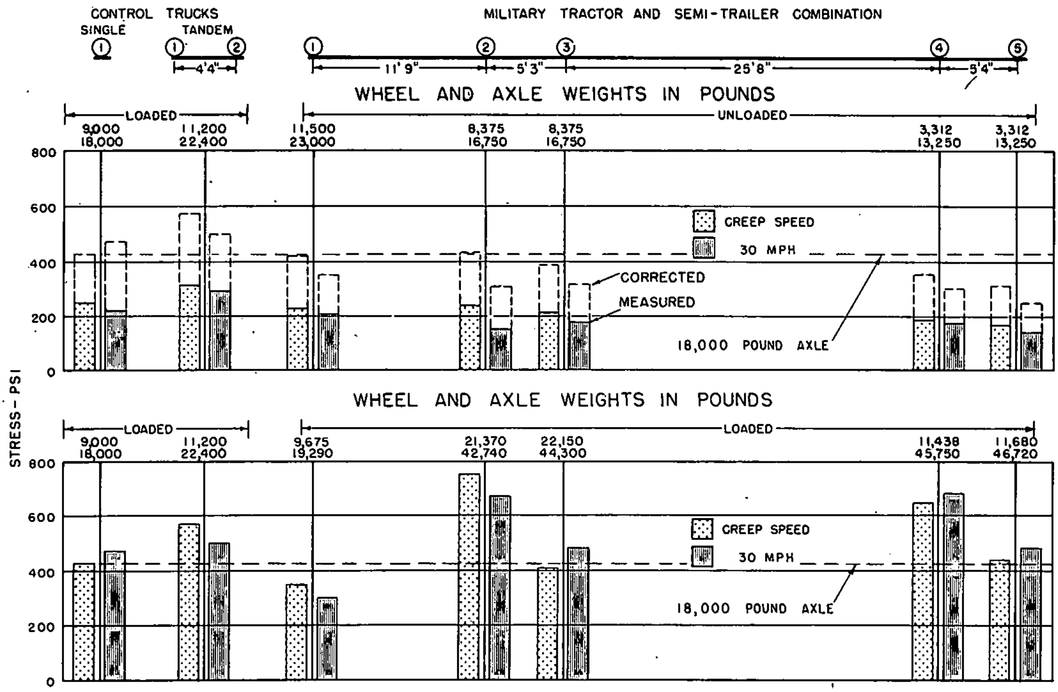

Figure 29. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks, corner loading, pumping joint on fine-grained soil.

heavily weighted axles of the tractor-trailer could be carried to completion at another pumping joint without a similar mishap.

In the discussion that follows a statement is made under each case of loading regarding the possible effect that the fracture in the slab could have on the magnitude of the strain and deflection values reported.

Free-Edge Loading

The stress data for the free-edge case of loading for slabs on the pumped fine-grained soil are given in Figure 27, These differences were of sufficient magnitude to make it desirable to show separately, for all cases of loading related to the fine-grained soil, comparable stresses and deflections measured for the control trucks on each of the two nights, rather than average values as was done for the joint on the granular soil.

The data show that with the trailer unloaded, the stresses for the several tractor-trailer axles are much less than generally accepted design limits and much less than those caused by the 18,000-lb. control axle. With the trailer loaded, the stresses for the tractor-trailer axles are less than generally accepted design limits and, for

Axles 2, 3, 4, and 5, somewhat greater than those caused by the 18,000-lb. control axle (see Fig. 27).

The stresses for the two sets of tandem axles of the tractor-trailer are plotted with respect to axle weight in Figure 28. As observed, at a 45,000-lb. axle load, the stresses for Axles 4 and 5, equipped with four single-tired wheels, are approximately 10 percent less than those for Axles 2 and 3, equipped with two dual-tired wheels.

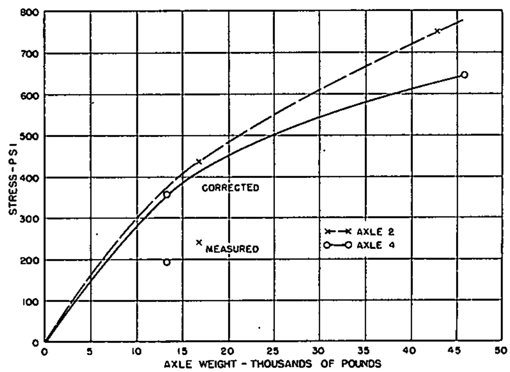

Figure 30. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles for corner loading, pumping joint on fine-grained soil, creep speed.

Corner Loading

Figure 29 shows the stress data for the corner case of loading for slabs on the pumped fine-grained soil. The stress values for the trailer loaded were obtained just before the slab fractured and, therefore, are not inflrenced by the failure, whereas those for the unloaded trailer were obtained after the fracture occurred. It will be noted (Fig. 29) that two sets of stress values are shown for the unloaded condition. The lesser value in each case is computed directly from measured strain after the fracture of the slab had occurred. The greater value was obtained in each case by multiplying the lesser value by a ratio. This ratio, based on the data for the control trucks, is a measure of the change in critical stress for the corner loading as observed before and after the slab fracture occurred. It is the best estimate that could be made of the stress that would have obtained had the slab fracture not occurred.

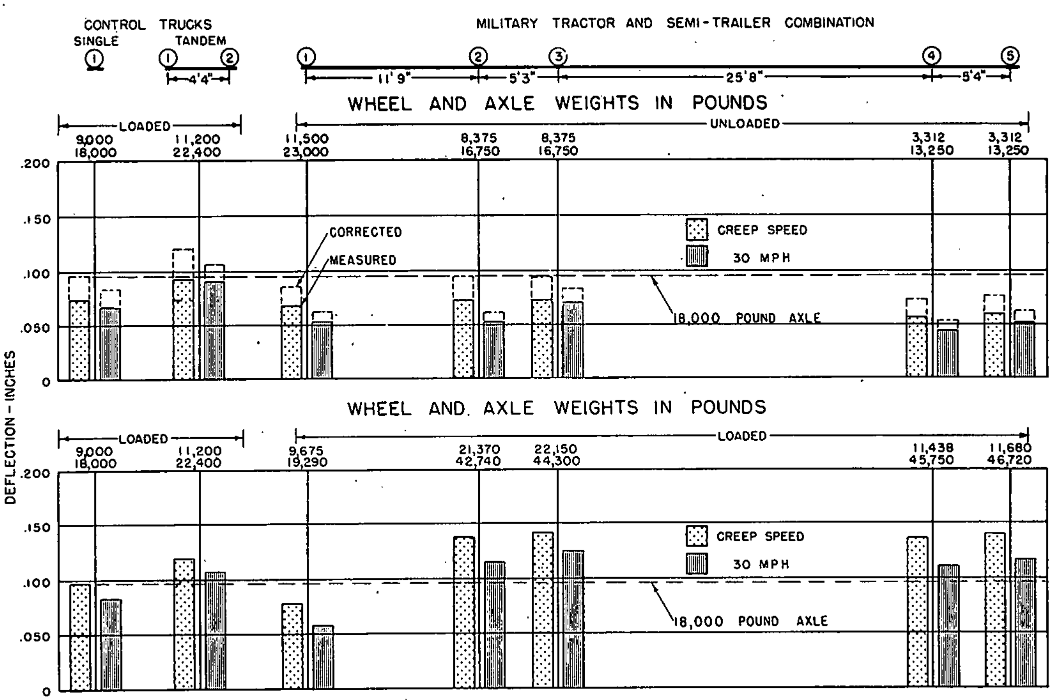

Figure 31. Comparison between the critical deflections caused by the loadings shown for the military trailer and for the control trucks for corner loading, pumping joint on fine-grained soil.

It is evident by the data of Figure 29 that the crack caused a marked reduction in stress for the corner loading. For this reason, in the discussion of the data for this loading, the corrected or estimated stress values will be those referred to in the case of the unloaded trailer.

The stress values shown in Figure 29 are considerably higher than those shown earlier in Figure 13 for the same case of loading for slabs on the granular nonpumping soil. With the trailer unloaded, the stresses for four of the five tractor-trailer axles exceed usually accepted design limits but do not exceed stresses caused by the 18,000-lb. control axle. With the trailer loaded, the stresses exceed usually accepted design limits for all axles and, for Axles 2 and 4, greatly exceed those caused by the 18,000-lb. control axle. The stresses for Axles 2 and 4 are of sufficient magnitude to indicate impending structural failure. Failure did occur several test runs later.

It will be noted (Fig. 29) that the creep-speed stress values are less in some instances and greater in others than the 30-mph. values. As mentioned earlier, this behavior is not unusual for the corner loading at joints on pumped fine-grained soil.

The stresses for Axles 2 and 4, with the trailer both loaded and unloaded, are plotted with respect to axle weight in Figure 30. It is indicated that at a 45,000-lb. axle weight the stress for Axle 4, with the four single-tired wheels, is approximately 18 percent less than that for Axle 2, with the two dual-tired wheels.

Deflection-Corner Loading

The deflection data of the corner loading for slabs on the fine-grained soil are shown in Figure 31. It will be noted that the deflections for the front and rear axles of each tandem set are approximately the same.

With the trailer unloaded, the deflections for all of the trailer axles are considered to be greater than desirable, but they do not exceed those for the 18,000-lb. control axle. With the trailer loaded, the deflections are greater than desirable for Axle 1 and excessively large for Axles 2, 3, 4, and 5. For Axles 2, 3, 4, and 5, the deflections are much greater than those for the 18,000-lb. control axle.

The deflection data for the two sets of tandem axles are plotted with respect to axle weight in Figure 32. Only a small difference is noted in the deflections caused by the two types of axles, those for the axles with four single-tired wheels being the smaller.

LOAD-STRESS RELATIONS FOR THE TRAILER IN PLACEMENT II, SLABS ON THE PUMPED FINE-GRAINED SOIL

Although the tests for Placement II were made in an area where pumping had developed along the free edge of the pavement, there had been no visible pumping along the longitudinal joint or in the transverse joint in the immediate vicinity of the longitudinal joint.

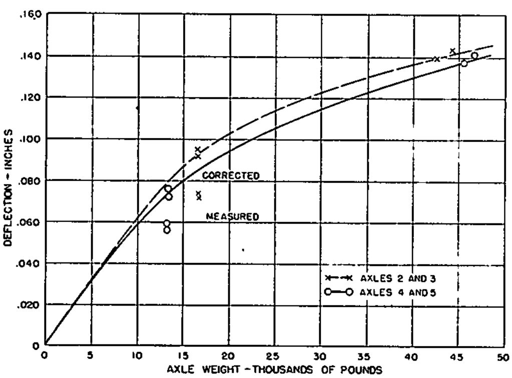

Figure 32. Load-deflection relations plotted with respect to axle weight to study the effect of the two types of tandem axles for corner loading, pumping joint on fine-grained soil, creep speed.

Longitudinal Joint-Edge Loading

The stress data for the longitudinal joint-edge loading for slabs on the pumped fine-grained soil are given in Figure 33. It will be noted that the stresses for the 18,000-lb. control axle, shown for comparative purposes, are those that developed for the free-edge loading of Placement I. The stress data for the longitudinal joint-edge loading were not influenced by the fracture that occurred during testing.

With the trailer unloaded, the stresses for all of the tractor-trailer axles are very small, while with it loaded, they are small for Axles 1, 2, and 3 and moderate for Axles 4 and 5. The stresses caused by the axles of the tractor-trailer are much less than those caused by the 18,000-lb. control axle acting at the longitudinal free edge of the pavement, except for loaded Axles 4 and 5, the stresses for these axles being approximately equal to those caused by the control axle.

The great reduction in the tractor-trailer stresses at the longitudinal joint edge, as compared to those caused by the control axle acting at the free edge, is largely explained by the differences in the distances that the wheels of the two vehicles track from the respective edges of the pavement. Also, the greater magnitude of the stresses caused by the four-wheeled axles (4 and 5) as compared to those caused

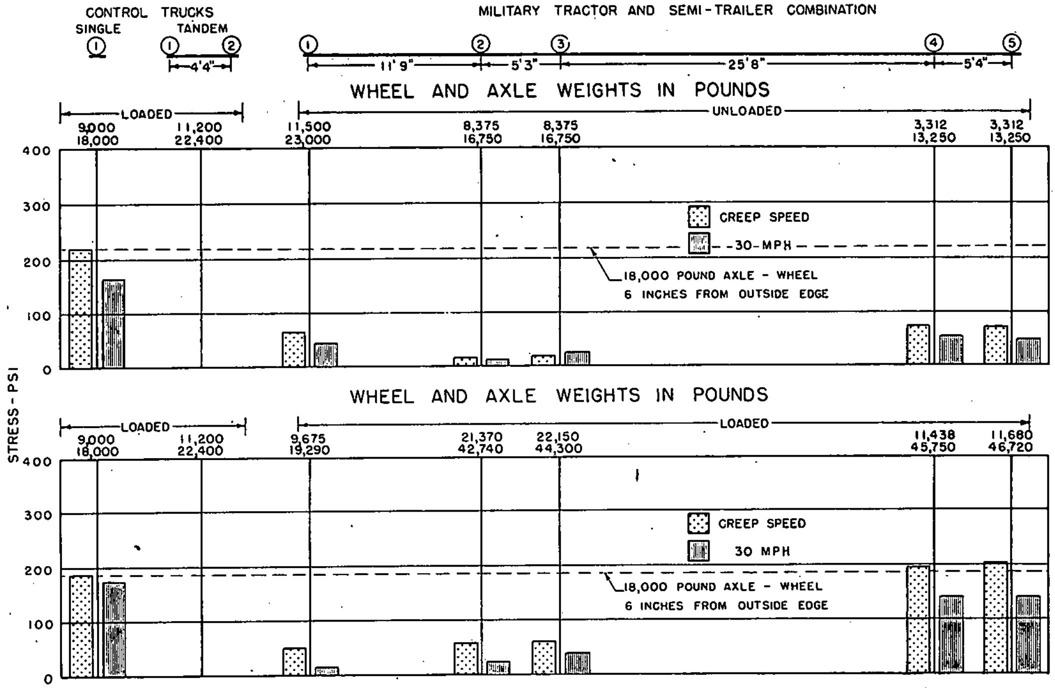

Figure 33. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for longitudinal joint-edge loading, pumping joint on fine-grained soil. The stresses for the trailer are with the vehicle straddling the longitudinal joint, while those for the control truck are for a free-edge loading.

by the two-wheeled axles (2 and 3) is attributed to the fact that the inside wheels of the four-wheeled axles track much closer to the longitudinal joint than do the wheels of the other axles.

Longitudinal Joint-Corner Loading

Stress data for the longitudinal joint-corner loading for slabs on the pumped fine-grained soil are given in Figure 34. The magnitude of the tractor-trailer stresses shown in this figure undoubtedly were reduced by the slab fracture that occurred during testing.

Referring to Figure 9, it will be noted that the strain gages for this case of loading were located at distances of 3, 5, and 7 ft. from the transverse joint. Before the tests were started for this loading, the gage located 3 ft. from the joint was eliminated by the crack passing through it. The strains measured by the remaining two gages indicated that the subsequent maximum stress occurred at the gage located 5 ft. from the joint, or only 2 ft. from the crack. The stress values determined by this gage are those given in Figure 34.

The data of Figure 34 show that, in spite of the influence of the fracture, the recorded stress values for the loaded trailer are higher than desirable.

LOAD-STRESS AND LOAD-DEFLECTION DATA FOR THE TRAILER IN PLACEMENT III, SLABS ON THE PUMPED FINE-GRAINED SOIL

As mentioned earlier, the stresses and deflections reported for this part of the study are those at the free edge and corner of the pavement when the outside edges of the contact areas of the outside wheels of the tandem axles of the trailer track at a distance of 30 in. from the longitudinal free edge of the pavement.

Stresses at Free Edge

The stresses at the outside edge of the pavement with the trailer in Placement III are shown in Figure 35. In all of the graphs pertaining to this placement, the lightweight, horizontal dashed lines indicate the stresses or deflections caused by the 18,000-lb. control axle positioned 6 in. from the longitudinal free edge of the pavement.

With the trailer in the 30-in. placement, the stresses that developed at the free edge of the pavement are small for all axles, both with the trailer loaded and unloaded.

Stresses at Corner

The stresses that developed in the vicinity of the corner under the 30-in. placement are shown in Figure 36.

The stresses for the various tractor-trailer axles, trailer unloaded, are less than usually accepted design limits and are appreciably less than those caused by the 18,000-lb. control axle positioned 6 in. from the edge of the pavement.

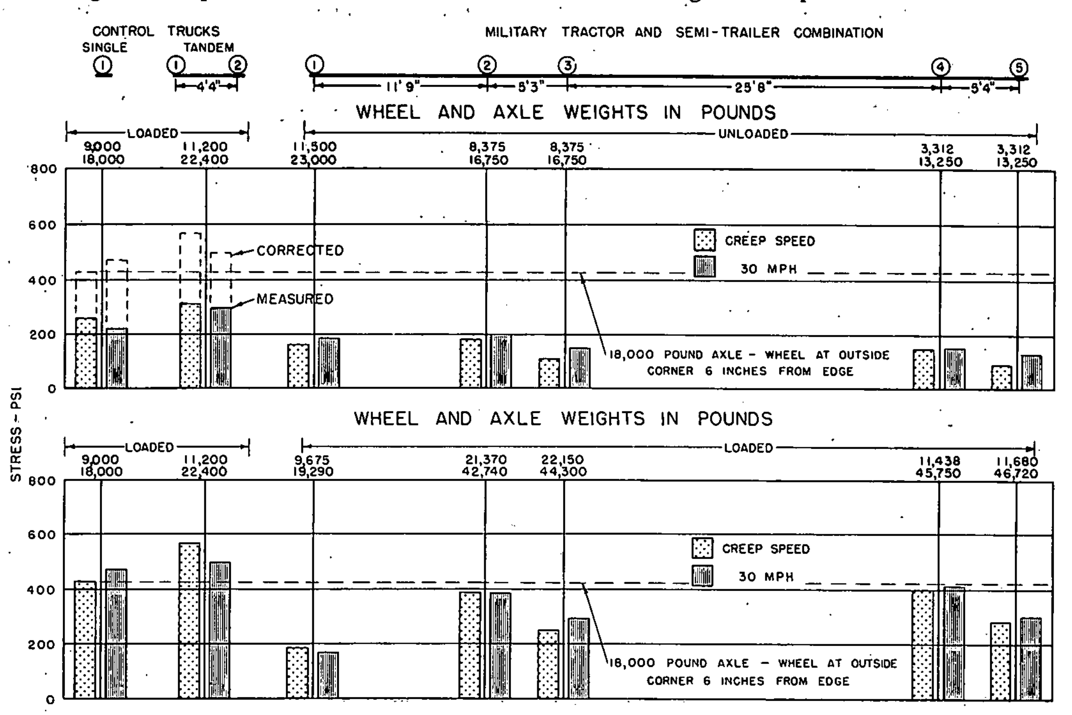

Figure 34. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for longitudinal-joint corner loading, pumping joint on fine-grained soil. The stresses for the trailer are with the vehicle straddling the longitudinal joint, while those for the control trucks are for an outside-corner loading.

With the trailer loaded, the stresses are less than usually accepted design limits for Axles 1, 3, and 5 and much greater than these limits for Axles 2 and 4. The stresses are appreciably greater for Axles 2 and 4 and less for the remaining axles than those caused by the 18,000-lb. control axle positioned 6 in. from the edge of the pavement.

Deflections at Corner

The deflections measured at the outside

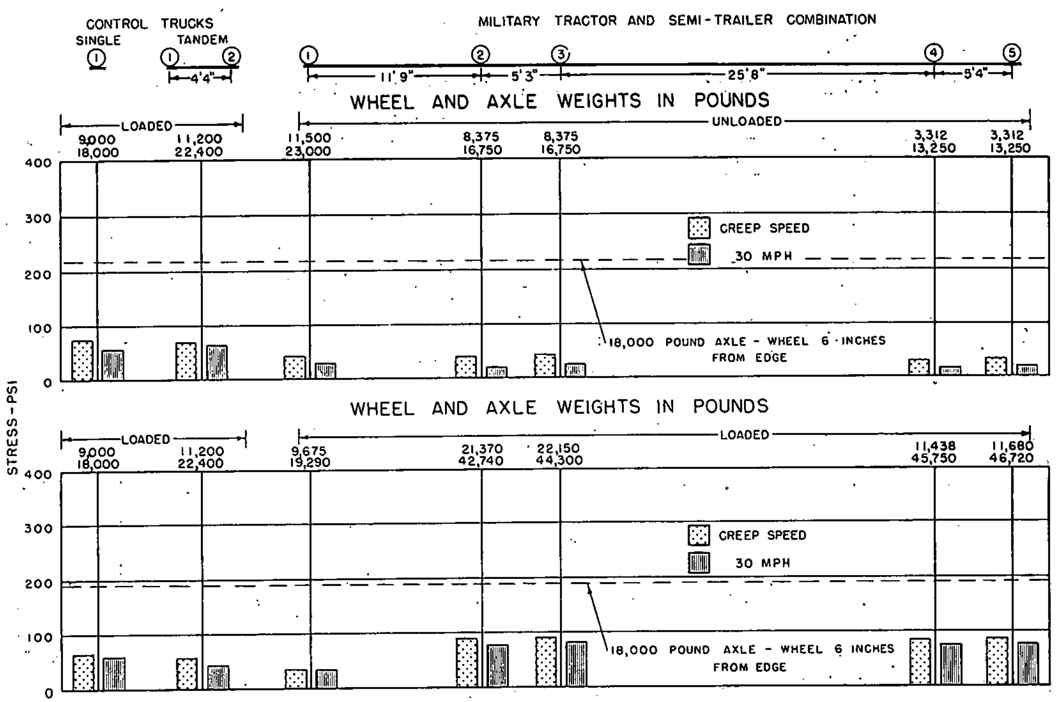

Figure 35. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, free-edge loading, pumping joint on fine-grained soil.

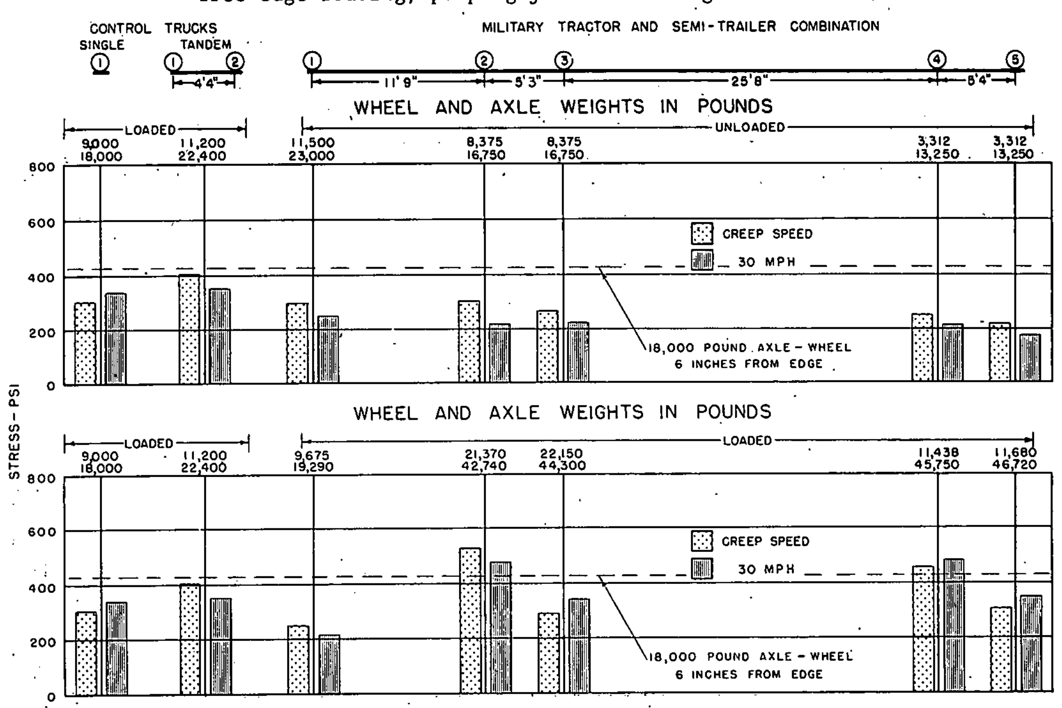

Figure 36. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, corner loading, pumping joint on fine-grained soil.

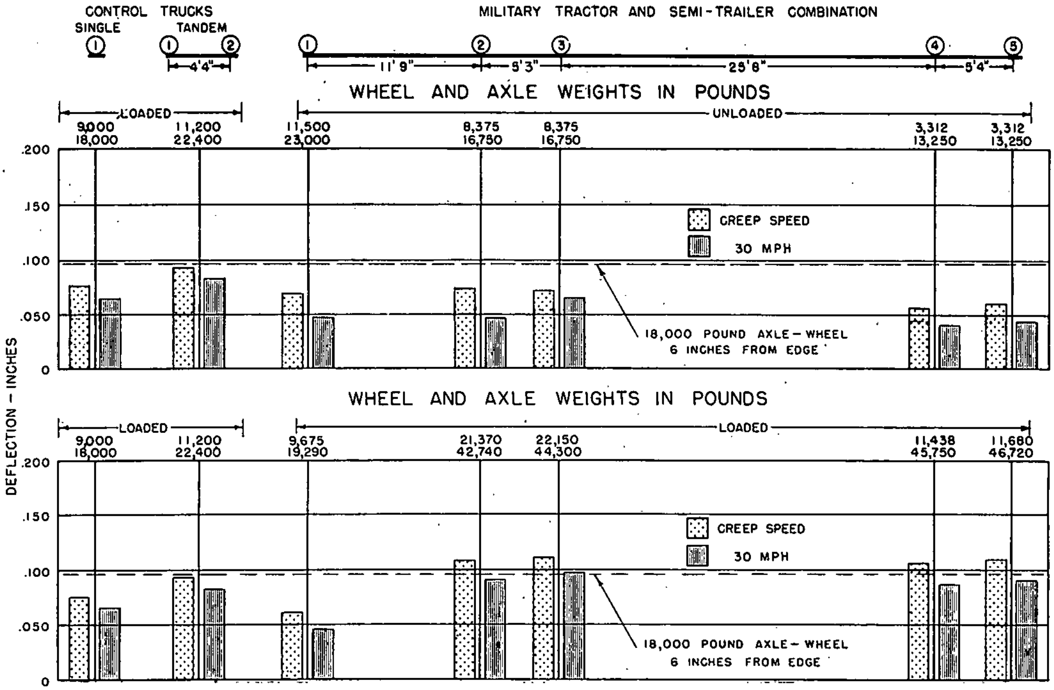

Figure 37. Comparison between the critical deflections caused by the loadings shown for the military trailer and for the control trucks with all vehicles 30 in. from the outside edge of the pavement, corner loading, pumping joint on fine-grained soil.

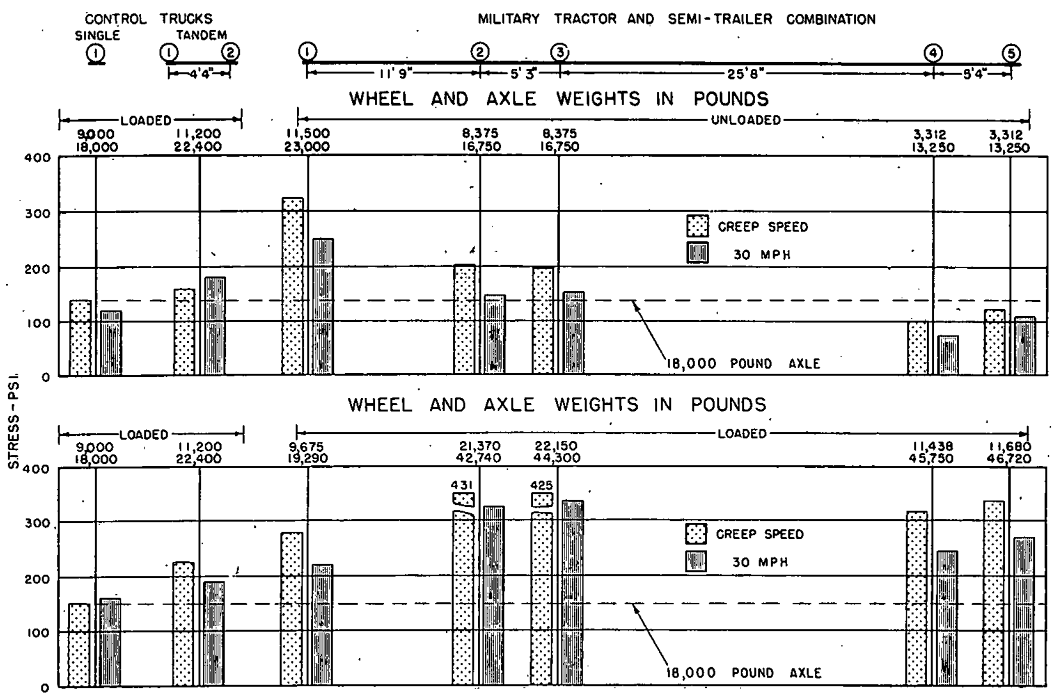

Figure 38. Comparison between the critical stresses caused by the loadings shown for the military trailer and for the control trucks for transverse joint-edge loading, pumping joint on fine-grained soil.

corner with the vehicles in the 30-in. placement are shown in Figure 37.

With the trailer unloaded, the deflections caused by the tractor-trailer axles are considered to be moderate and are appreciably less than those caused by the 18,000-lb. control axle positioned 6 in. from the edge of the pavement.

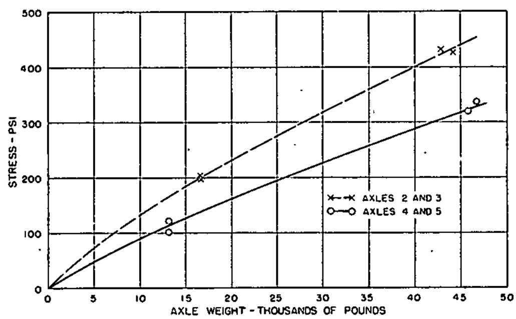

Figure 39. Load-stress relations plotted with respect to axle weight to study the effect of the two types of tandem axles for transverse joint-edge loading, pumping joint on fine-grained soil, creep speed.

With the trailer loaded, the deflections for Axles 2, 3, 4, and 5 are excessively large and even exceed those for the 18,000-lb. control axle positioned 6 in. from the edge.

LOAD-STRESS DATA FOR THE TRAILER WHEELS ACTING AT THE TRANSVERSE JOINT EDGE, SLABS ON THE PUMPED FINE-GRAINED SOIL

The stresses for the transverse joint-edge loading for slabs on the pumped fine-grained soil are shown in Figure 38. These data represent an average of all values obtained for this case of loading.

The data show that, with the trailer unloaded, the stresses for the tractor-trailer axles do not exceed usually accepted design limits but approach them for Axle 1; for Axles 1, 2, and 3, the stresses exceed appreciably those caused by the 18,000-lb. control axle.

With the trailer loaded, the stresses do not exceed usually accepted design limits for Axles 1, 4, and 5 but exceed these limits appreciably for Axles 2 and 3. For all trailer axles the stresses exceed greatly those caused by the 18,000-lb. control axle.

The stresses caused by the two sets of tandems, Axles 2-3 and Axles 4-5, are plotted with respect to axle weight in Figure 39. As will be noted, the stresses for Axles 4 and 5, with the four single-tired wheels, are appreciably smaller than those for Axles 2 and 3, with the two dual-tired wheels, the reduction at a 45,000-lb. axle weight being about 27 percent.

INFLUENCE OF VEHICLE SPEED ON STRESS AND DEFLECTION

It will be recalled that the tests with the tractor-trailer were made at two vehicle speeds, creep and 30 mph. Although the stress and deflection data for both speeds are included in the graphs, the influence of this variable has not been discussed.

The percentage decreases in the average stresses and deflections induced by tractor-trailer Axles 2, 3, 4, and 5 at a vehicle speed of 30 mph. as compared to those measured at creep speed are shown in Table 2. It is evident, for slabs on the nonpumping granular subgrade, that both the stresses and deflections for all cases of loading are appreciably less for the vehicle operated at 30 mph. than at creep speed. For the slabs on the pumped fine-grained soil the stresses for the vehicle operated at 30 mph. are appreciably less than those at creep speed for all cases of loading, except (1) that of the outside corner where the stresses for the higher speed averaged only 7 percent less than at creep speed and (2) that of the longitudinal joint corner where the stresses averaged 15 percent greater in the tests at 30 mph. than in those at creep speed. The deflections in all cases investigated were appreciably less at 30 mph. than at creep speed.

Table 2

Effect of the speed of the trailer on the critical stresses and deflections for the various cases of loading.

Case of loading	Percentage decrease in stresses and deflections measured in tests at 30 miles per hour as compared to those at creep speed			
	Nonpumped granular soil		Pumped fine grained soil	
	Stress	Deflection	Stress	Deflection
Free-edge	29	20	28	
Outside-corner	26	23	7	16
Transverse joint-edge	19		22	
Longitudinal joint-edge			25	
Longitudinal joint-corner	28		+15	

Note: No sign indicates that the stress at 30 miles per hour was less than that at creep speed while a + sign indicates that the stress at 30 miles per hour was greater than that at creep speed.

Referring to the corner loading at the joint on the pumped fine-grained soil, the data show that, when based on an average value for all of the axles, the stresses observed in tests at 30 mph. were 7 percent less than those at creep speed, but for certain axles, the stresses for the tests at 30 mph. were actually somewhat greater than those recorded at creep speed.

The study of the influence of vehicle speed on stress and deflection was much more comprehensive in the main testing program with trucks than in the supplementary program with the trailer. The truck tests indicated that, in some cases, the stresses for the corner loading on the pumped fine-grained soil were greater at the 30-mph. speed than at creep speed.

SUMMARY OF MAJOR FINDINGS

To aid in understanding the major findings, the three transverse placements investigated for the heavy-duty tractor-trailer combination will be redescribed:

Placement I. The trailer positioned so that the outside edges of the contact areas of the outside wheels of the tandem axles tracked at a distance of 6 in. from the longitudinal free edge of the pavement.

Placement II. The trailer positioned symmetrically astride the longitudinal joint

Placement III. The trailer positioned so that the outside edges of the contact areas of the outside wheels of the tandem axles tracked at a distance of 30 in. from the longitudinal free edge of the pavement.

1. Observed Effect of Tractor-Trailer on Pavement

The study of the heavy-duty tractor-trailer combination was conducted on Section 1 (see Special Report 4), which had been subjected to 238,000 applications of an 18,000-lb., single-axle loading. Many of the slabs that had structurally survived this load application were undermined by pumping. The tractor-trailer in loaded condition made some 60 test runs over Section 1, half of which were with the vehicle positioned near the outside edge of the pavement.

The loaded trailer had no visible effect on the pavement supported by the granular nonpumping soil. On the pavement supported by the fine-grained soil, the loaded trailer caused (1) more violent pumping, other conditions being equal, than that which existed during traffic testing and (2) transverse cracking in the vicinity of several transverse joints.

2. Stresses with Trailer in Placement I, Granular Soil

With the trailer unloaded and positioned near the outside edge of the pavement, the stresses are less than the usually accepted design limits (50 percent of the modulus of rupture of the concrete) for the free-edge and corner cases of loading and are approximately equal to or less than those caused by the 18,000-lb. control axle (see Figs. 11 and 13).

With the trailer loaded and positioned near the outside edge of the pavement, the stresses for both cases of loading are less than usually accepted design limits, although for some axles they are considerably greater than those caused by the 18,000-lb. control axle (see Figs. 11 and 13).

3. Stresses with Trailer in Placement I, Pumped Fine-Grained Soil

With the trailer unloaded and positioned near the outside edge of the pavement, the stresses are less than usually accepted design limits for the free-edge loading but are somewhat higher than those limits for the corner loading. For both cases of loading, the stresses are approximately equal to or less than those caused by the 18,000-lb. control axle (see Figs. 27 and 29).

With the trailer loaded, the stresses for the free-edge loading are less than usually accepted design limits but, for all axles except the front axle of the tractor, are appreciably greater than those caused by the 18,000-lb. control axle (see Fig. 27). For the corner loading the stresses for several axles are of a magnitude that would be expected to cause failure and are much greater than those caused by the 18,000-lb. control axle (see Fig. 29).

4. Deflections with Trailer in Placement I, Granular Soil

The deflections, with the trailer both unloaded and loaded and positioned near the outside edge of the pavement, are within reasonable limits at the free edge and corner. However, for several axles of both cases of loading, the deflections are slightly greater with the trailer unloaded and much greater with the trailer loaded than those caused by the 18,000-lb. control axle (see Figs. 15 and 17).

5. Deflections with Trailer in Placement I, Pumped Fine-Grained Soil

With the trailer unloaded and positioned near the outside edge of the pavement, the deflections at the corner are greater than desirable but no greater than those caused by the 18,000-lb. control axle (see Fig. 31).

With the trailer loaded and positioned near the outside edge of the pavement, the deflections at the corner are much greater than desirable and much greater than those caused by the 18,000-lb. control axle (see Fig. 31).

6. Stresses with Trailer in Placement II, Granular Soil

With the trailer unloaded and in a position symmetrically astride the longitudinal joint, the stresses at the longitudinal joint corner are much less than usually accepted design limits and much less than those caused by the 18,000-lb. control axle in Placement I (see Fig. 19).

With the trailer loaded and positioned symmetrically astride the longitudinal joint, the stresses for the longitudinal joint-corner loading are less than usually accepted design limits, although for some axles they are higher than those caused by the 18,000-lb. control axle in Placement I (see Fig. 19).

7. Stresses with Trailer in Placement II, Pumped Fine-Grained Soil

With the trailer unloaded and positioned symmetrically astride the longitudinal joint, the stresses for the longitudinal joint-edge and corner cases of loading are less than usually accepted design limits and much less than those caused by the 18,000-lb. control axle in Placement I (see Figs. 33 and 34).

With the trailer loaded and in the same position, the stresses at the longitudinal joint edge are less than the usually accepted design limit but, for several axles, are slightly greater than those caused by the 18,000-lb. control axle in Placement I (see Fig. 33). For the longitudinal joint-corner loading the stresses for several axles are greater than would be desirable (see Fig. 34).

8. Stresses with Trailer in Placement III, Granular Soil

With the trailer unloaded and positioned 30 in. from the outside edge of the pavement, the stresses at the outside edge are small both at the free edge and in the vicinity of the outside corner (see Figs. 21 and 22).

With the trailer loaded and in the same position, the stresses at the outside edge are moderate at both the free edge and in the vicinity of the outside corner and are approximately equal to or less than those caused by the 18,000-lb. control axle in Placement I (see Figs. 21 and 22).

9. Stresses with Trailer in Placement III, Pumped Fine-Grained Soil

With the trailer unloaded and positioned 30 in. from the outside edge of the pavement, the stresses at the outside edge are small at the free edge and not excessive in the vicinity of the corner. They are also less than usually accepted design limits and less than the magnitude of stress caused by the 18,000-lb. control axle in Placement I (see Figs. 35 and 36).

With the trailer loaded, the stresses are small at the free edge. In the vicinity of the corner they are much higher for some axles than usually accepted design limits and higher than those caused by the 18,000-lb. control axle in Placement I (see Figs. 35 and 36).

10. Deflections with Trailer in Placement III, Granular Soil

With the trailer positioned 30 in. from the outside edge of the pavement, the deflections at the outside edge and corner are small with the trailer both unloaded and loaded (see Figs. 23 and 24).

11. Deflections with Trailer in Placement III, Pumped Fine-Grained Soil

With the trailer unloaded and positioned 30 in. from the outside edge of the pavement, the deflections at the corner are greater than desirable but appreciably less than those for the 18,000-lb. control axle in Placement I (see Fig. 37).

With the trailer loaded, the deflections at the corner are greater than desirable and somewhat greater than those for the

18,000-lb. control axle in Placement I (see Fig. 37).

12. Stresses at Transverse Joint Edge, Granular Soil

The transverse joint-edge loading applies for all three of the transverse placements studied for wheel loads approximately 36 in. or more from a longitudinal edge.

With the trailer unloaded and the wheel loads acting at the transverse joint edge, the stresses are less than usually accepted design limits but, for some axles, somewhat higher than those caused by the 18,000-lb. control axle (see Fig. 25).

With the trailer loaded, the stresses are less than usually accepted design limits but much greater than those caused by the 18,000-lb. control axle (see Fig. 25).

13. Stresses at Transverse Joint Edge, Pumped Fine-Grained Soil

With the trailer unloaded and the wheel loads acting at the transverse joint edge, the stresses are less than usually accepted design limits but, for several axles, much greater than those caused by the 18,000-lb. control axle (see Fig. 38).

With the trailer loaded the stresses for several axles are higher than usually accepted design limits and much higher than those caused by the 18,000-lb. control axle (see Fig. 38).

14. Influence of Wheel Arrangement on Stresses and Deflections with Vehicle in Placement I

With the trailer positioned near the outside edge of the pavement, the stresses for Axles 4 and 5, with four single-tired wheels, caused slightly less stress for the free-edge loading and moderately less stress for the corner loading than Axles 2 and 3 with two dual-tired wheels on each (see Figs. 12, 14, 28, and 30).

The deflections for Axles 4 and 5 were slightly less than for Axles 2 and 3 for both the free-edge and corner loadings (see Figs. 16, 18, and 32).

15. Influence of Wheel Arrangement on Stresses with Vehicle in Placement II

With the trailer positioned symmetrically astride the longitudinal joint, the stresses caused by Axles 4 and 5, with four single-tired wheels, are much greater for the longitudinal joint edge and moderately greater for the longitudinal joint corner than those caused by Axles 2 and 3, with two dual-tired wheels on each (see Figs. 20 and 33).

16. Influence of Wheel Arrangement on Stresses and Deflections with Vehicle in Placement III

With the trailer positioned 30 in. from the outside edge of the pavement, the stresses caused by Axles 4 and 5, with four single-tired wheels, are slightly less at the free edge and moderately less at the outside corner than those caused by Axles 2 and 3, with two dual-tired wheels on each (see Figs. 21, 22, 35, and 36).

The deflections for Axles 4 and 5 are slightly less than those for Axles 2 and 3 at both the free edge and corner (see Figs. 23, 24, and 37).

17. Influence of Wheel Arrangement on Stresses at the Transverse Joint Edge

With the wheel loads of the trailer acting at the transverse joint edge the stresses caused by Axles 2 and 3, with two dual-tired wheels are much greater than those caused by Axles 4 and 5, with four single-tired wheels (see Figs. 26 and 39).

18. Complications of Different Wheel Arrangements on Same Vehicle

The different wheel arrangements on the several axles of the tractor-semitrailer combination tested offer complications in placing such a vehicle in the most-advantageous transverse position on the pavement. It would, therefore, appear to be advantageous to use the same wheel and tire arrangement on all of the axles, excepting possibly the front axle.

DISCUSSION OF RESULTS

The data presented in this and other related studies show clearly that, where concrete pavements rest on soils that are susceptible to pumping, the most serious damage develops in the vicinity of the outside corners when the vehicles are tracking near the outside edges of the pavement. This damage increases progressively with an increase in soil consolidation or an undermining of the pavement by pumping.

By positioning vehicles some distance away from the outside or free edges of the pavement, the critical conditions existing at the outside corners are relieved and damage in their vicinity is minimized. This method of relief was investigated for the heavy-duty tractor-trailer combination under Placements II and III of this study, and the relative merits of each will be briefly discussed.

When vehicles of greater than conventional width are positioned 30 in. away from the outside edge of the pavement (Placement III), the left wheels may track very near the longitudinal joint edge. For example, the center-to-center spacing of the outside tires of the tandem axles of the tractor-trailer used in this study was 9.5 ft.; thus, one of the tires would track very near the longitudinal joint on 10-, 11-, or 12-ft. pavement lanes.

Longitudinal joints are usually designed to transfer load which might be expected to relieve the critical stresses caused by loads acting in their vicinity. However, it was found in the Arlington[2] investigation that, while the common types of longitudinal joints are quite effective in controlling the stresses for the longitudinal joint-corner loading, some are ineffective in controlling the stresses for the longitudinal joint-edge loading.

Unlike the pavement tested in this study, the majority of thickened-edge pavements do not have edge thickening at the longitudinal joint. As a result, the stresses that develop in that region when the wheels of a heavy vehicle track near the joint may be very critical.

Probably the most-advantageous position on a pavement for a vehicle of this type is symmetrically straddling the longitudinal joint (Placement II). However, there are circumstances that might make it impractical to maintain the inside wheels of four-wheeled axles at an appreciable distance from the longitudinal joint edge at all times. Thus, for the vehicle in the straddling position, two-wheeled axles will be advantageous.

The stresses for the interior and transverse joint-edge cases of loading are of interest in this discussion, because their magnitude is influenced by the different arrangements of the wheels on the two types of axles. Tests were not made with the tractor-trailer combination for the interior case of loading, but it has been established from related tests that the stresses for this loading are, to a large degree, a function of the wheel load and would, therefore, be appreciably smaller in the present arrangement for the four-wheeled axles with single tires than for the two-wheeled axles with dual tires.

As shown by the data presented earlier, stresses that developed at the transverse joint edge were appreciably smaller for the axles with the four single-tired wheels than for the axles with the two dual-tired wheels. The stress caused by the four-wheeled axles did not, in any case, exceed generally accepted design limits, but that caused by the two-wheeled axles appreciably exceeded these limits for the slab on the pumped fine-grained soil. Therefore, for stress control at the transverse joint edge and slab interior, four-wheeled axles have considerable advantage over two-wheeled axles. However, in this investigation it was found that on the fine-grained soil the outside-corner loading was more critical than the other cases of loading; for this loading the four-wheeled axles with single tires had only a small advantage over two-wheeled axles with dual tires.

In the report of Road Test One-MD (HRB Special Report 4) there were included the results of certain studies of the influence of temperature variations on stress conditions in pavement slabs. The first study pertained to the influence of temperature warping on the magnitude of the critical stresses and deflections at the free edge and corner caused by loads acting in the vicinity of the edges of pavement slabs. It is shown (Figs. 141 to 144 of that report) that the magnitudes of the critical stresses and deflections caused by such loads acting near the edges during the daytime, when the slab edges are warped downward, are considerably less than those caused by the same loads acting during the night when the slab edges are warped upward. The degree to which the stresses and deflections caused by loads are affected by this condition naturally varies with the amount of warping in the pavement. When the sun is shining, the daytime load stresses are considerably smaller than the nighttime

[2]Teller, L. W., and Sutherland, Earl C. "The Structural Design of Concrete Pavements" (in 5 parts). Public Roads, Vol. 16, Nos. 8, 9 and 10, October, November and December 1935; Vol. 17, Nos. 7 and 8, September and October 1936; and Vol. 23, No. 8, April-May-June 1943.

load stresses from April to September, but the difference in the magnitude of the two stresses is less at other times of the year. Thus, the stresses caused by the critical corner loading may be reduced appreciably by proper selection of the time at which the passage of the vehicle is to be made.

The second study pertained to the temperature - stress conditions in concrete pavements caused by restraint to warping. It is shown (Fig 151 of the report) that the warping stresses which combine with those induced by the transverse joint-edge loading are much smaller than those that combine with some of the other loadings studied. This might be reason for tolerating a greater working-load stress for the transverse joint-edge loading than for some of the others.

The subject of the relative load-supporting properties of a natural granular subgrade, such as the granular subgrade tested in this investigation, compared to a fine-grained subgrade with a base course of normal thickness was discussed in Special Report 4. It was indicated by references to related studies that the supporting power of a natural granular subgrade is much superior to that of a fine-grained subgrade with a base course of moderate thickness. Thus, for a pavement on a fine-grained subgrade, either with or without a base course of normal thickness, it is to be expected that the tractor-trailer combination would cause stresses somewhat higher than those that developed in the slab supported by the nonpumping granular soil of this investigation.

The results of this investigation, pertaining to the influence of the different axle and wheel arrangements of the tractor-semitrailer combination tested, are not applicable to bridges or pavements of the nonrigid type. Also, the magnitude and relationship of the stresses, for the different cases of loading investigated, would be different for concrete pavements of other thicknesses and types of cross sections.

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