MICHIGAN
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EFFECT OF VARIOUS AXLE LOADINGS ON HIGHWAY PAVEMENTS

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ON HIGHWAY PAVEMENTS

The question has come up relative to the maximum axle load that should be permitted upon the highway in respect to present design limitations. It is believed that the most logical way to answer this question, in the light of our present knowledge, is to compare the computed theoretical stresses which might occur in a pavement slab under various axle loadings.

The computation of the stresses has been based on H.M. Westergaards' formulae for determining the stresses in concrete pavements. The problem will be treated under static conditions and infinite and semi-infinite abutting slabs, without considering the relieving effect of joint load transfer devices.

Included in the report is a summary of the Michigan Load Law, a statement by R.H. Baldock, Chief Engineer of the Oregon State Highway Department, relative to axle loads and the calculation of stresses for different axle loadings based on the Michigan Load Law.

THE MICHIGAN LOAD LAW

Axle loads on highways are restricted by law in Michigan as follows:

Axle Spacing	Solid Rubber Tires	Pneumatic Tires
9' or more	16000#	18000#
3' -6" to 9'	11600#	13000#
Less than 3' -6"	8000#	9000#

The number of axles is limited only by the legal maximum length restriction which is 35' for any single unit and 50' for any combination of tractor and trailer. Thus, the law would permit the operation of a vehicle combination 50' long having 15 - 13000# axles spaced 3' -6" centers, or having 6 - 18000# axles spaced 9' centers.

The Oregon State Highway Department has been concerned with highway loadings on their pavements. A brief summary of their conclusions has been included in this report.

OREGON STATE HIGHWAY DEPARTMENT

Mr. R.H. Baldock, Chief Engineer, Oregon State Highway Department, in a paper presented at the American State Highway Officials Convention in Detroit, October 1941, entitled "Load Limitations - Defense and Non-Defense" makes the following statement. "I recommend to this association that the wheels of all vehicles shall be equipped with pneumatic tires, that no wheel shall carry a load in excess of 9000 pounds, and that the total load carried by a single axle shall not exceed 18,000 pounds. An axle load shall be the total load on all wheels whose centers are included between two parallel transverse planes 40 inches apart. The use of additional axles and the control of axle spacings permits greater gross weights - this necessarily limits axle weights" ...... "Moreover, the grouping of axles, as long as the axles are 40 inches or more apart, does not increase the pavement stresses over those induced by single-axle loads."

These statements are based on studies started in 1936 by the Oregon State Highway Department to determine the maximum weights and dimensions of motor vehicles that could safely operate over Oregon highways without placing undue stresses in pavements and bridges and without causing undue hazard to the motoring public. The data from the survey has been published in Oregon Technical Bulletin No. 6, entitled "The Effect of Heavy Motor Transport on Highway Bridge Stresses".

The following calculations have been made to determine the possible stresses which might occur in concrete pavement slabs due to Michigan Load Law and for other combination of axle loadings.

CALCULATION OF STRESSES

The following calculations are based on H.M. Westergaards' [1] formulae for computing stresses in concrete pavements.

The formulae for computing stresses in the slab at the free edge, the interior and at the corner are as follows:

1. $$S_e = 2.117(1+0.54\mu)\frac{P}{h_2}\left[\lg_{10}\left(\frac{h}{B}\right)+1/3\ \lg_{10}\left(\frac{E}{K}\right)-0.2666\right]$$

2. $$S_i = 1.1(1+\mu)\frac{P}{h^2}\left[\lg_{10}\left(\frac{h}{B}\right)+1/3\ \lg_{10}\left(\frac{E}{K}\right)-0.089-13.64\left(\frac{1}{L}\right)^2 Z\right]$$

3. $$S_c = \frac{3P}{h^2}\left[1-\left(\frac{12(1-\mu^2)K}{Eh^3}\right)^{0.2} x\ (a\sqrt{2})^{0.6}\right]$$

Where S_e, S_i, S_c = stress at free edge interior and corner of the slab respectively,

P = load on slab

h = slab thickness

μ = Poissons ratio

a = radius of area of load distribution

$b = \sqrt{1.6a^2 + h^2} - 0.675h$ when $a < 1.724h$

$b = a$ when $a > 1.724h$

K = modulus of subgrade reaction

(1) Analytical Tools for Judging Results of Structural Tests of Concrete Pavements, by H.M. Westergaard, Public Roads, Vol. 14, No. 10, December 1933.

$$l = \left(\frac{Eh^3}{12(1-\mu^2)K}\right)^{1/4}$$

k = subgrade modulus

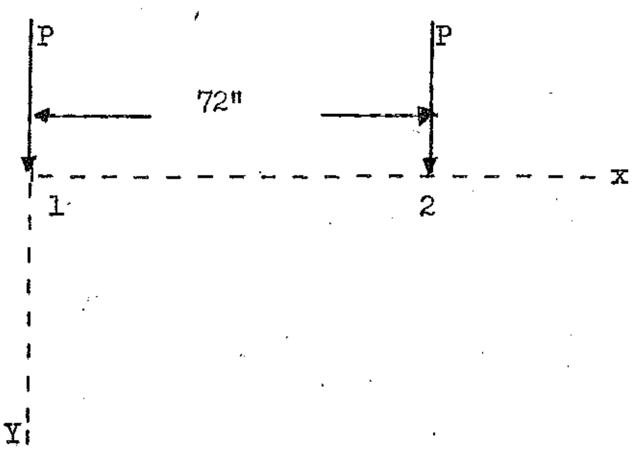
K = kl

E = modulus of elasticity of the concrete

The computations will be computed for a uniform thickness pavement slab under the following assumptions: $h = 7$ inches; $E = 5 \times 10^6$ p.s.i.; Poissons ratio $\mu = 0.15$; radius $a = 6$ inches; $L = 51$; $Z = 0.20$; Subgrade modulus $k = 50$ p.s.i.; $l = 41.3$ inches; $kl^2 = 85{,}500$; $K = 2{,}065$; $b = 5.58$ inches.

STRESSES FROM AXLE LOAD OF 18,000 POUNDS

Case I - Stress in Interior of Slab.



Stress at point (1) from load P at (1) is +239 p.s.i by equation (2)

Stress at point (1) from load P at (2) is obtained from Westergaards' coefficient curves [(2)].

$M_r = M_x = -0.02 \times 9000 = -180$

$M_t = M_y = +0.021 \times 9000 = +189$

(2) "Computation of Stresses in Concrete Roads", by H.M. Westergaard, 5th Annual Proceedings, Highway Research Board, 1926. Figure 5.

The stresses S_x and S_y are obtained by dividing the respective bending moments by the section modulus which, in this case, is 8.167, therefore,

$S_x = -180 \div 8.167 = -22$ p.s.i.

$S_y = +189 \div 8.167 = +23$ p.s.i.

Maximum combined stress is found to be equal to 239 + 23 or 262 p.s.i.

Case II - Stress at Joint Edge.

Stress at point (1) from load P at (1) is found to be +402 p.s.i. by equation (1).

Stress at point (1) from load P at (2) is obtained from Westergaards' curves(3) as follows.

$M = -0.07 \times 9000 = -630$

$S_x = 630 \div 8.167 = -77$ p.s.i.

Therefore, the maximum combined stress at joint edge is equal to (+402 - 77) or 325 p.s.i.

Case III - Stress at the Free Edge.

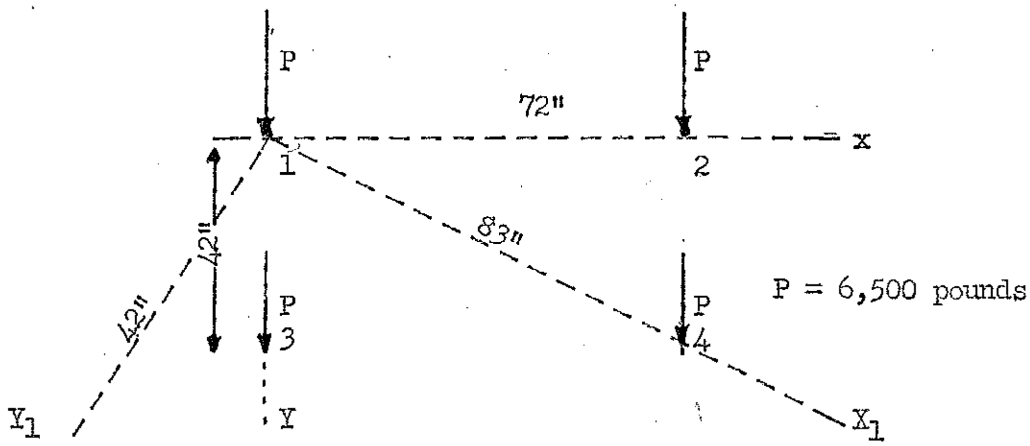
The stress at the longitudinal free edge of a slab for a load of P = 9000 pounds is calculated in the same manner as for a joint edge. In this case the stress is 402 p.s.i.

Case IV - Stress due to Corner Load.

The stress from one load of P = 9000 pounds at the corner at a distance of $2.38\sqrt{2}\sqrt{al}$, or $2.38\sqrt{2}\sqrt{6 \times 41.3} = 53$ inches along the free edge from the corner, is computed by means of formula (3). The stress is equal to $S_c = 0.375 \times P = 337$ p.s.i.

(3) "Spacing of Dowels", by H.M. Westergaard, Proceedings of 8th Annual Meeting, Highway Research Board, 1928. Figure 2.

STRESSES FROM TWO 13,000 POUND AXLE LOADS SPACED 3.5 FEET



Case I - Stresses in Interior of Slab.

Stresses at point (1) from loads at (1) and at point (2) are computed by the method explained previously and found to be

S_x = +157 p.s.i. and S_y = +190 p.s.i.

Stress at point (1) from load P at (3) is

$M_y = 0$ therefore, $S_y = 0$

$M_x = +.054 \times 6500 = +351$ or $S_x = 351 \div 8.167 = +43$ p.s.i.

Stress at point (1) from load P at point 4.

$M_{x1} = -0.022 \times 6500 = -143$ or $S_{x1} = -143 \div 8.167 = -18$ p.s.i.

$M_{y1} = +0.016 \times 6500 = +104$ or $S_{y1} = +104 \div 8.167 = +13$ p.s.i.

Stresses at point (1) from loads at point (1) and point (4) reduce to

$S_{x1} = 173 - 18 = +155$ p.s.i.

$S_{y1} = 173 + 13 = +186$ p.s.i.

$S_{x1y1} = 0$, S_{x1y1} = shear force or further reduced to the x and y axes as follows:

$$S_x = S_{x1} \cos^2 30° + S_{y1} \sin^2 30° = 163$$

$$S_y = S_{x1} \sin^2 30° + S_{y1} \cos^2 30° = 134$$

$$S_{x_y} = 1/2\ (S_{y1} - S_{x1}) \cos 30° = 13.4$$

Therefore, the stresses at point (1) from loads at points 1, 2, 3 and 4 will be

$$S_x = 163 + 43 - 16 = 190 \text{ p.s.i.}$$

$$S_y = 178 + 17 = 195 \text{ p.s.i.}$$

$$S_{x_y} = 13.4 \text{ p.s.i.}$$

Hence, the principal stresses at point (1) from loads at points (1), (2), (3) and (4) will be

$$S_1 = \frac{190+195}{2} + \sqrt{\left(\frac{195-190}{2}\right)^2 + (13.4)^2} = 206 \text{ p.s.i.}$$

$$S_2 = \frac{190+195}{2} - \sqrt{\left(\frac{195-190}{2}\right)^2 + (13.4)^2} = 179 \text{ p.s.i.}$$

Case II - Stresses at Joint Edge.

The stress at point (1) from loads at (1) and (2) may be determined by direct proportion as follows:

$$S = \frac{325}{9000} \times 6500 = 234 \text{ p.s.i.}$$

Where 325 p.s.i. is the stress produced by the 9000 pound load. Since it is difficult to evaluate the effect of loads at (3) and (4) on the stresses at point (1) without complicated calculations, we assume that the load at point (3) produces the same percentage of stress as in the case of the interior of the slab or $(43 \div 173)\ 100 = 25\%$ or $0.25 \times 290 = 73$ p.s.i. In the same way we can appraise the effect of load at point (4) as follows: $-(18 \div 173)290 = -30$ p.s.i. The the combined stress will be $234 + 73 - 30 = \underline{277}$ p.s.i.

Case III - Stress at Free Edge.

The stress from two loads of 8000 pounds spaced 42 inches apart at the free edge may be determined in the following manner:

$$S_c = \frac{8x402}{9} - \frac{0.025x8000}{8.167} = 358 - 25 = \underline{\underline{333}} \text{ p.s.i.}$$

Case IV - Stress Due to Corner Load.

The stress from one load, P = 8000 pounds at the corner, at a distance of $2.38\sqrt{2}\sqrt{al}$ along the free edge from the corner, is determined by formula (3). The stress is found to be $S_c = 0.0375 \times 8000 = \underline{\underline{300}}$ p.s.i.

The second load is 42 + 6 = 48 inches from the joint edge, or only 5 inches from the line of maximum corner stress. The second load, P = 8000 pounds in this position will add practically nothing to the stress found from the first load.

The various computed stresses have been summarized in the following table.

SUMMARY OF COMPUTED STRESSES

A summary of the computed stresses have been tabulated below for consideration and study. The stresses for two 16,000 pound axles and two 18,000 pound axles were computed by proportion.

	Computed Stresses in Pounds per Square Inch			
Condition of Loading	Center of Slab	Joint Edge	Free Edge	Corner
One axle of 18,000 pounds.	262	325	402	337
Two 13,000 pound axles at 3.5 feet.	206	277	270	244
Two 16,000 pound axles at 3.5 feet.	254	341	333	300
Two 18,000 pound axles at 3.5 feet.	286	384	374	338

It is noted that two 16,000 pound axles 3.5 feet apart produce joint edge stresses approximately the same as for one 18,000 pound axle. Also, the free edge and corner stresses from two 16,000 pound axles do not exceed the respective stresses from one 18,000 pound axle.

CONCLUSIONS

On the basis of the above computations, it is evident that two 16,000 pound axle loads spaced 3.5 feet apart produce very closely the same maximum tensile stresses at the joint edge as similar stresses produced by one axle carrying a load of 18,000 pounds.

In the same manner, two 18,000 pound axle loads spaced 3.5 feet apart may produce tensile stresses at joint edge of approximately 18 percent in excess of those caused by one 18,000 pound axle.

The 13,000 pound axle load requirement of Michigan for 3.5 foot spacing is apparently quite conservative, since the stresses produced under any condition are at a minimum of 15 percent below those caused by one 18,000 pound axle.

These findings do not substantiate Mr. Baldocks' statements to the effect that two 18,000 pound axles spaced 40 inches apart will not increase the pavement stresses over those induced by single axle loads of the same magnitude.

It may be concluded that if one 18,000 pound axle load is permitted, two 16,000 pound axle loads might be allowed provided the axles are not closer than 42 inches apart.

At the present time there are no convenient methods for the evaluation of edge stresses produced by loads not at the joint edge. The only practical way of solving this problem is by full size experimental concrete slabs on subgrades of definite known and constant characteristics.