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Bates Experimental Road

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SPRINGFIELD, ILLINOIS

INTRODUCTION.

With the large amount of money made available to the State of Illinois by the passage of the Sixty Million Dollar Road Bond Issue Act and the allotments made to the State by the Federal Government, for road construction, it was decided, early in 1920, that the State would be justified in undertaking the construction of an experimental road of unprecedented magnitude. At that time the State had in contemplation the expenditure of possibly one hundred million dollars for a road improvement program. To undertake a program of this size without definite scientific knowledge of the behavior of certain pavements under truck traffic and rural conditions—without knowing definitely how to design pavements to sustain truck traffic—was deemed unwise. The result was the construction of the Bates Experimental Road.

The Bates Road was started in June, 1920, and finished in July, 1921. It is about two miles in length and includes 63 sections, each approximately 200 feet long and representing all types of modern pavements, several thicknesses of each type being used so that when trucks are operated over the road with increasing loads, the capacity of each section, measured in terms of weight and numbers of trucks, will be plainly obvious.

This Bulletin gives a summary of the results of the scientific research which has been carried out, both as to the construction and subsequent behavior of this road.

Since the last of October, 1920, an average of ten investigators have been occupied in research work. An enormous volume of data has been collected, and preliminary analyses made. It would obviously be impossible to give in detail all of the data collected. Typical illustrations in the way of photographs and diagrams are used to show conclusions which may reasonably be deducted from the data obtained.

Prepared by
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Jan. 1922

SUBGRADE MOISTURE.

For more than a year subgrade samples for the determination of moisture content have been collected periodically from several hundred stations located along the Bates Road and along about 60 miles of paved highways adjacent to Springfield.

In Figure 1 is platted the moisture content curve of the subgrade of the Bates Road. The moisture content is expressed as a percentage of the dry weight of the soil. The soil in this case is the brown silt loam of the Mississippi Valley Corn Belt. It is a finely divided material that ordinarily would be called a clay soil. The sampling stations in the Bates Road were established in positions such that the results would show any variations which might occur in the moisture content, due to the proximity of the station to the edge of the pavement, to cracks and to joints, as well as in areas as far removed from such features as possible. It soon developed, however, that the moisture content of the subgrade soil in proximity to edges and cracks was at no time materially different from that observed elsewhere. This conclusion has been checked from time to time up to the present date. This condition might not prevail in localities where prolonged rainless seasons occur. A further observation of interest in this connection is that at the point in the Bates Road where a tile drain with a cinder backfill was laid 30 inches below each edge of the pavement for a distance of 200 feet, the moisture samples show no variation from those obtained elsewhere.

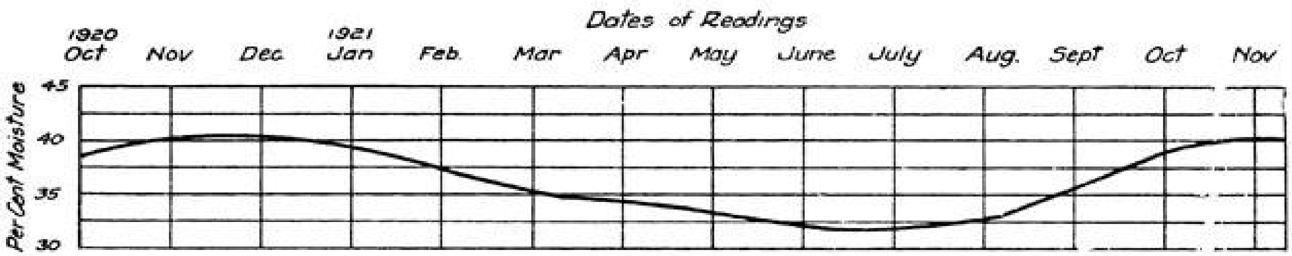


Figure 1
Subgrade Moisture Indications

About eight miles from the Bates Road a section of pavement, 1,000 feet long, was selected for a drainage experiment. Tile drains were laid immediately under each edge of the pavement a depth of 36 inches below the bottom of the slab. The trenches were back filled with cinders and sampling stations were established throughout the 1,000 feet. The moisture content of the soil under this section has been uniformly lower than that under the Bates Road. However, it is believed that this result is due to the difference in the character of the subgrade soil (which is a yellow clay) rather than to the effect of the tile drainage. This conclusion was deducted from the fact that moisture samples taken from the subgrade of undrained sections, where the soil is of the same nature, also shows a lower moisture content than that under the Bates Road and approximately the same as that of the tiled sections. A sufficient number of samples from undrained subgrades having soil of this character has not as yet been tested to make this conclusion positive.

Prof. Eno, in a paper read before the American Road Builders Convention at Chicago, which was held February 8th to 12th, 1921, brought out the fact that certain clay soils of Ohio when moulded in a moist condition resisted to a marked extent the further absorption of moisture, while the same soils after having been dried, disintegrated rapidly when placed in water and absorbed a much larger volume of water in a short period of time. It seems probable that this is true of many if not all clay soils; and no doubt accounts for the rapid saturation of the Bates Road subgrade in the fall of 1920, as a large portion of the pavement was laid on an air dry subgrade. Within three days after the fall rains started the subgrade was found to contain the high percentage of moisture indicated in this diagram. It is to be noted that more than five months during the summer of 1921 the moisture content varied less than 5% although frequent rains occurred. At the present time the moisture has again reached a high figure but the increase has been gradual.

In order to determine the possible rate of saturation of the subgrade from the edges to the center, in July a trench was cut along the edge of the pavement and kept filled with water for some days. At first this trench was cut immediately against the edge of the slab, but as the warping of the pavement due to changes in temperature, (described later) immediately permitted sheets of water to flow under the pavement it was impossible to obtain the desired results. Later, a trench—about one foot from the edge of the pavement—was cut at a different point, leaving the shoulder undisturbed between the edge of the trench and slab. This trench was kept filled with water for a period of three weeks. Although the nearest sampling stations were only 30 inches from the edge of the trench, the moisture content of the subgrade at these stations showed no increase and no variation from that at other points under the pavement.

In order to ascertain whether or not the freezing of soil would render it more susceptible to saturation, a number of blocks of the subgrade were cut out very carefully so as not to disturb the natural compaction; then frozen, and after having been thawed out were immersed in water. After freezing most of the blocks fell to pieces upon immersion. Samples that had not been frozen remained practically intact and absorbed moisture slowly. The samples which had been frozen and then immersed in water absorbed moisture at a much more rapid rate. Typical of these experiments, four blocks, when taken from the subgrade showed an average moisture content of 28 per cent; after immersion for 20 hours, the moisture content was increased to 33 per cent or an increase of 5 per cent. Another set of four blocks, having the same initial moisture content, after having been frozen for 6 hours and then immersed in water for 24 hours, showed an average moisture content of 42 per cent or an increase of 14 per cent. From the results of these tests, it seems altogether probable that although a clay subgrade may resist, markedly, saturation from an occasional rainfall, yet the same soil may quickly become saturated after a freeze. An examination of the curve Figure 1 shows further that although the moisture content has not increased rapidly, yet a high degree of saturation has again been reached, although we have had no freezing weather.

SUBGRADE BEARING POWER.

Much time has been spent in an effort to ascertain the factors having influence on the supporting capacity of subgrade soils. Believing that soils might behave differently under repeated loads as compared with loads applied but once, an apparatus was devised and perfected, by means of which loads up to 50 pounds per square inch could be repeated indefinitely on subgrade soils in place. This apparatus was briefly described in an article which appeared in Public Roads, Volume 4, No. 5. The results of its use, up to the present time, have not been entirely satisfactory owing to the apparent difficulty in securing a perfect contact of the shoe with the subgrade soil before a load is applied. No means yet tried have eliminated an initial deformation under a light load comparatively much greater than that obtained under the same load on subsequent applications. However, the use of this apparatus points strongly towards the conclusion that a soil, having a given moisture content, may under repeated loads have a fairly definite elastic limit—For example: On a clay soil subgrade a load of five pounds per square inch was applied approximately 1,000 times. After the initial deformation, caused by the first few applications of the load, subsequent applications produced a definite deformation under each repetition with complete recovery as the load was released. The load was then increased to 25 pounds per square inch with the result that progressive deformation continued until a total penetration of 0.25″ occurred when the test was discontinued. The general behavior of subgrade soils as determined on small areas by this machine was closely confirmed by loading concrete slabs having areas of several square feet, which were cast on the same subgrade. These slabs were loaded repeatedly by means of an hydraulic jack. Even in the case of these slabs which were presumably in perfect contact with an undisturbed subgrade the first few light loads caused permanent depressions. In this connection it should be understood, however, that different points on the same subgrade soil, although having the same moisture content, did not exhibit uniform results. This perhaps is partially due to lack of perfect contact between the loaded shoe and the subgrade; but most likely to inequalities in the compaction of the subgrade soil. It remains to be determined whether or not a subgrade soil at all seasons of the year, or at seasons when the greatest degree of saturation prevails, may be counted upon to exhibit elastic resistance to deformation when subjected to pressures as great as the lowest that may practically be obtained with economic pavement designs. It is certain that this resistance for the Illinois Corn Belt soil containing at times 40% moisture is very low, probably less than 1 pound per square inch. For the good of the cause we hope this condition is peculiar to Illinois, but we doubt it.

Comparatively little work has been done on soils other than the brown silt loam of the Mississippi Valley Corn Belt. A number of observations, however, on a very finely divided sandy soil shows the same general characteristics with no marked variation either as regards bearing power or saturation tendencies; but this soil contains a considerable portion of clay and might be expected to exhibit materially different characteristics from coarse and clean sand or gravel.

Efforts have been made to determine the bearing capacity of subgrade soils in place when highly saturated; but inasmuch as the bearing power determinator was not perfected until the moisture content of all subgrades available had dropped below 35 per cent and as attempts at artificial saturation of the soils in place failed, no material results have been obtained up to the present time. As the Bates Road moisture curve indicates that Illinois is again about saturated we now hope to obtain the desired information.

SUBGRADE UNIFORMITY.

There were installed in the Bates Road many subgrade cylinders each having a brass disk in contact with the subgrade, and a reference plug screwed in the cylinder in such a manner that measurements taken from the plug to the brass disk would show the relative position of the subgrade and the pavement slab at any time. (For detailed description, see Public Roads, Vol. 4, No. 5.) Throughout the year readings have been taken once each week. The results of these observations are of considerable interest. They show distinctly a periodic separation of the pavement slab and the subgrade due to warping of the slab under temperature changes which will be described later. They show, also, to a very marked extent erratic variations due in all probability to uneven settlements of the subgrade. Some of these brass disks show a separation of the slab and the subgrade as much as one-half inch over areas of considerable magnitude. Just how far these areas extend it is impossible to determine, as the spacing of the cylinders is not close enough. At practically all of the observation cylinders, a separation of the subgrade and the slab has occurred at one time or another. This separation by no means can be entirely accounted for by the warping of the slab. The erratic movement of the brass disks relative to the slab would lead us to believe that not only is the slab itself constantly warping, but that the subgrade also, is not stable even although there be no traffic on the road. As the moisture content of the subgrade was fairly uniform for several months it seems hardly likely that this is due entirely to a changing moisture condition. It may be due to changes of temperature; but it would seem more probable that the operations of grading, plowing, harrowing and rerolling the subgrade did not produce a uniform compaction. No doubt voids remained after harrowing and rolling; and the slacking or breaking down of the soil in a non-uniform manner under different portions of the pavements probably accounts for a large portion of the erratic subgrade movement. In this connection, methods used in preparing the subgrade may be of interest. No heavy grades occur throughout the two miles section; the deepest fill is about two feet, and deepest cut about 18 inches. After the rough grading was done, the entire subgrade was plowed, harrowed, rolled and wetted the day before the pavement was laid. It is not believed that any economically practical method of compacting a subgrade may be applied with reasonable economy to secure absolutely uniform results.

FROST ACTION.

Observations of frost heaving on the Bates Road were made during the winter of 1920-1921. After these observations were started only one period of low temperature occurred at which time the ground became frozen in the open fields and the shoulders of the road to a depth of about eight inches.

Precise levels taken from bench marks, carefully protected from frost action, showed a heaving or lifting of the edges of the slab throughout the entire length of the road, at a much more rapid rate than at the center. On sections where a longitudinal joint was provided, the edges of the pavement slabs lifted on an average of about three-fourths of an inch, while during the same period the center lifted but an average of about one-fourth of an inch. Many sections not provided with longitudinal joints showed approximately the same behavior. All such sections when examined in the spring were found to be cracked longitudinally. A few sections lifted at the edges about three-fourths of an inch and at the center about one-half of an inch; these sections showing no discernible longitudinal cracks when examined in the spring. As no loads were permitted on the road during this period, it is evident that the longitudinal cracks were caused by the breaking of the slab under dead load while supported at or near the edges only. If the heaving of the soil due to freezing is universally more rapid under the edges of the pavement than elsewhere, it would appear impossible to avoid the longitudinal breaking of wide slabs, where freezing temperatures occur, especially under heavy traffic. Mathematical analyses indicate that it is likely to be economically impracticable to design wide slabs of sufficient strength to avoid breaking longitudinally when the edges only are supported; hence the present Illinois design provides for a longitudinal joint in order that erratic longitudinal cracks may be avoided as far as possible.

TEMPERATURE EFFECTS.

The lateral and longitudinal expansion of a pavement slab, due to temperature and moisture changes, is well appreciated. It is doubtful if lateral contraction or expansion is responsible for longitudinal cracks. It is more probable that such cracks are due to freezing subgrades or perhaps to conditions of support caused by the warping of the slab. It seems altogether likely that contraction due to temperature or moisture changes accounts for at least the first transverse cracks that appear in all concrete slabs.

In the fall of 1920 while attempting to take strain gauge and deflection measurements on concrete slabs under load, the results obtained at first were so erratic as to be useless unless the cause for the erratic behavior could be determined. We undertook one series of tests to determine whether or not the subgrade under a corner of a slab would be compressed under repeated loads to such an extent as to afford no definite support to the pavement. With the apparatus at hand it was impossible to repeat the loads rapidly and in order to avoid possible subgrade recovery during periods of rest, the loads were repeated continuously for periods of forty-eight hours. It was then discovered by an examination of the results that at night the slab corner under load might be at a higher elevation than the unloaded corner during the day. We have no knowledge of any previously conducted research work indicative of this important feature.

Figure 2 shows the air temperature, and the vertical movement of the corner of a 9-inch plain concrete slab loaded and unloaded. This diagram is typical of several hundred all of which show the same characteristics. Hourly elevation readings to thousandths of an inch were taken by means of Ames Dials. The 6,000 pound load was applied to the corner for three minutes each hour. Under this load the computed fibre stress in the slab was 220 lbs. per square inch. Note that for about 2/3 of the 54 hour period the 3-ton load did not depress the corner to its unloaded afternoon position. It is obvious that the subgrade offered but little if any support for two thirds of the time.

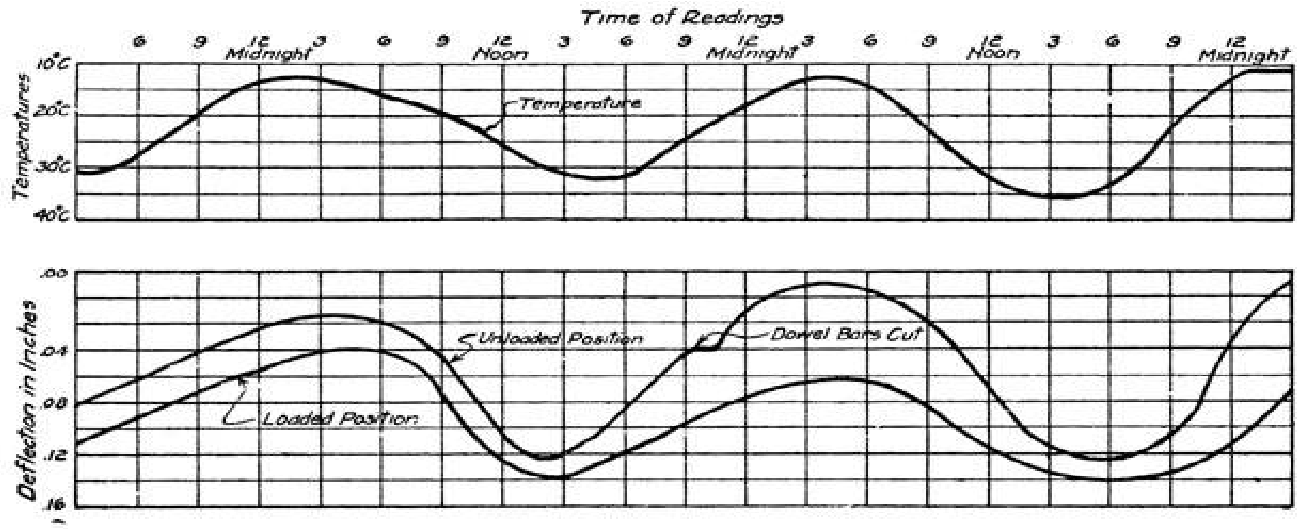
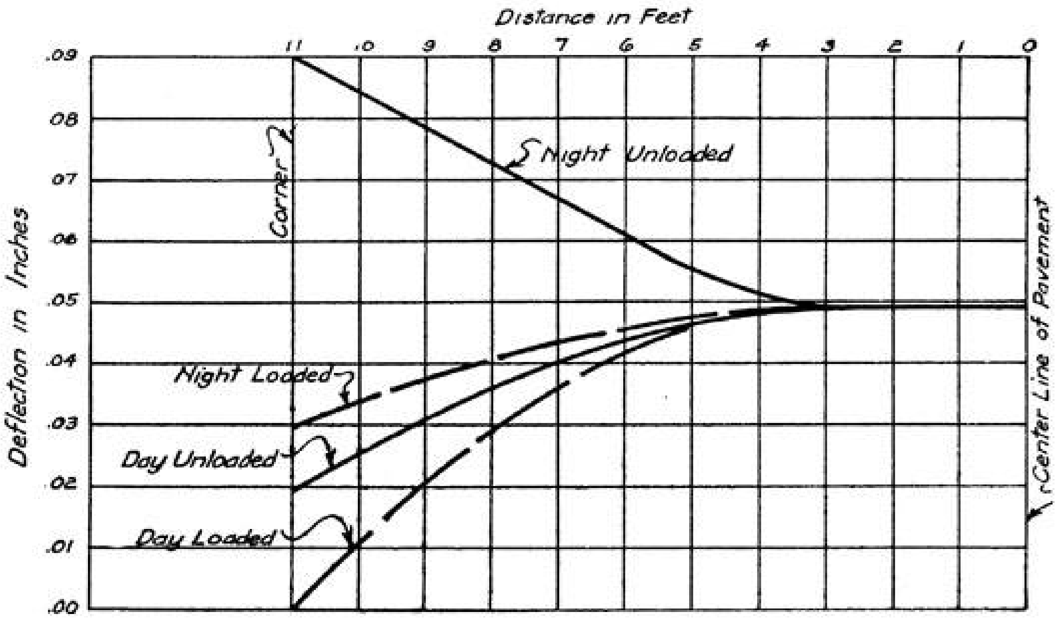


Figure 2
Application of 6000 Pound Load
Corner of Slab
Number 40-9 in. P. C. C.

Figure 3 shows the curvature of a 7-inch slab on a line bisecting the corner angle. The upper solid line diagram A shows the upward warped position of the surface of the slab along a 45° line from the corner to the center of the pavement. The upper dashed line shows the position of the slab while a load of 6,000 pounds was applied on an area of two square inches at the corner. The lower solid line shows the position of the unloaded slab at the point of maximum downward deflection. The lower dashed line shows the position of the slab under the 6,000 pound load when applied during the day. It is obvious that the slab corner acted purely as a cantilever in supporting the night load. It is also obvious that, as the increased deflection was not as great when the load was applied during the day as when applied at night, subgrade support had some influence on the amount of deflection. The computed fibre stress of the concrete, considering the corner as a cantilever under the night load, amounts to 368 pounds per square inch which is certainly not too low for the working stress of plain concrete. It is obvious that a much greater load with a correspondingly high fibre stress would be required to deflect the corner to contact with the subgrade at night.

Diagram B, Figure 3, shows the effect under similar conditions of a longitudinal crack or joint. In such case it is evident that the warping effect does not ordinarily pivot about the center of the full width of the slab, but probably approximately about the center of the half slab as defined by the longitudinal joint. It is of interest to note, however, that even in this case the upward warping of the slab due to temperature effects was greater than the downward deflection of the slab under the 6,000 pound load producing a fibre stress of 368 pounds per square inch.



Number 44-7 in. Plain, No Longitudinal Dividing Plane
Closed Transverse Crack, 6000 Pound Load

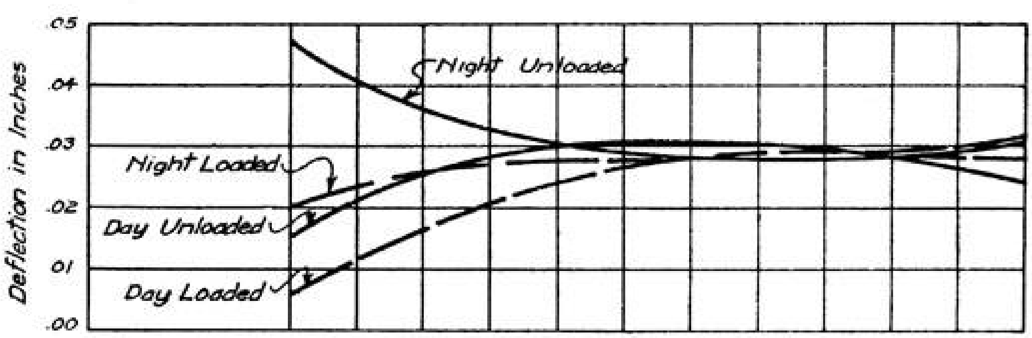


FIGURE 3

Number 63B Standard, Longitudinal Dividing Plane
Closed Transverse Crack, 6000 Pound Load

That curling of the edges of an 18-foot concrete slab may be sufficient to render the most perfect of subgrades ineffective under the edges of the slab may readily be determined without the aid of accurate measuring devices. To visualize this condition the photographs—Figure 4—were made.

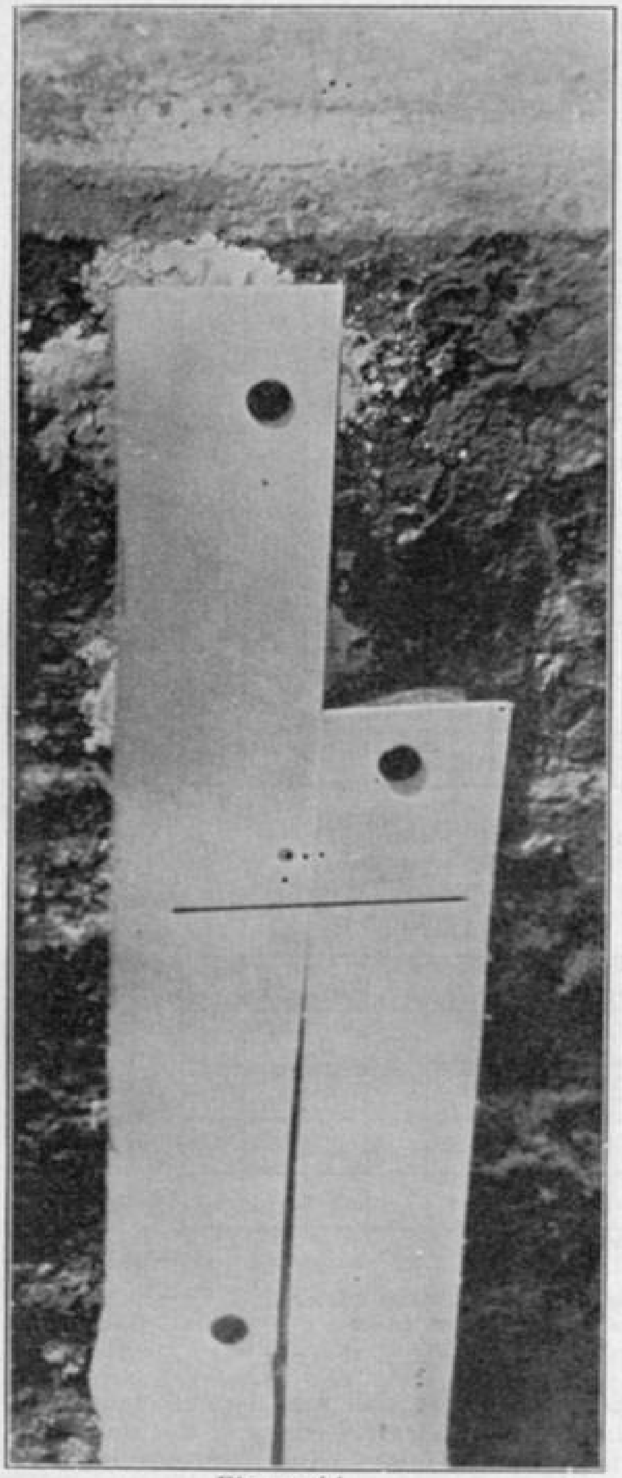


Figure 4A

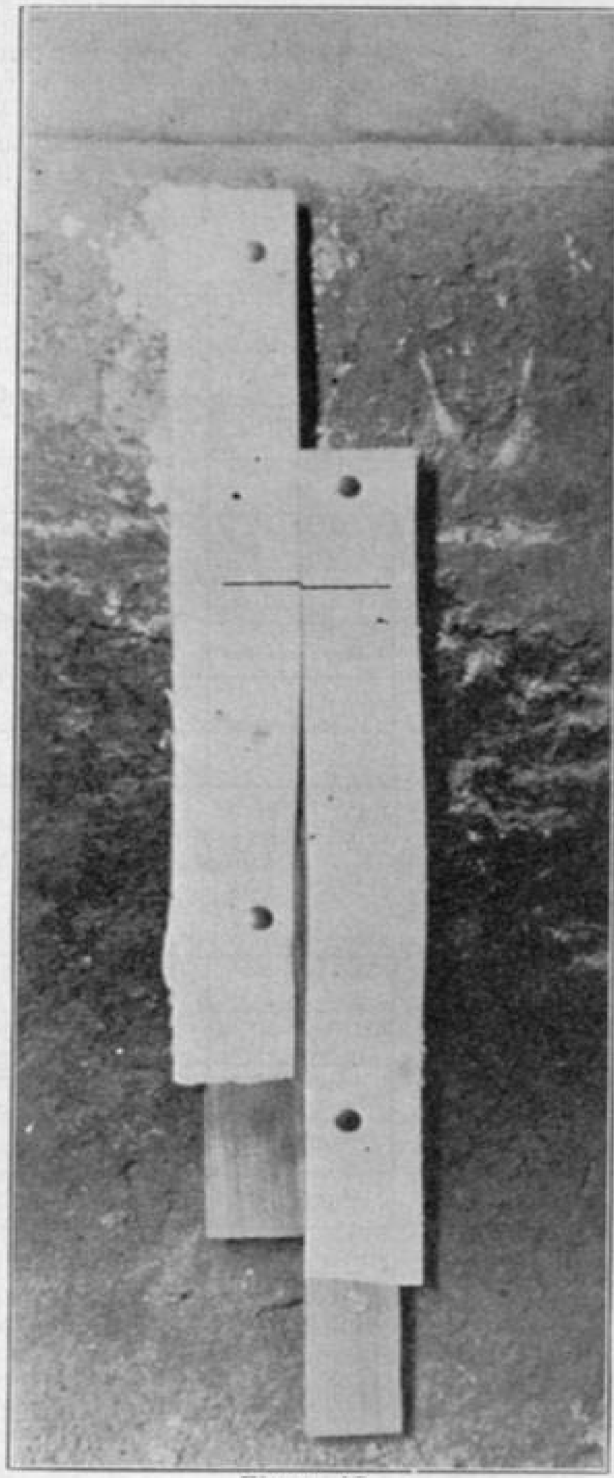


Figure 4B

FIG. 2.—RUNWAY AND AUXILIARY TRUCK FOR APPLYING EQUIVALENT STATIC LOAD AT POINT OF IMPACT.

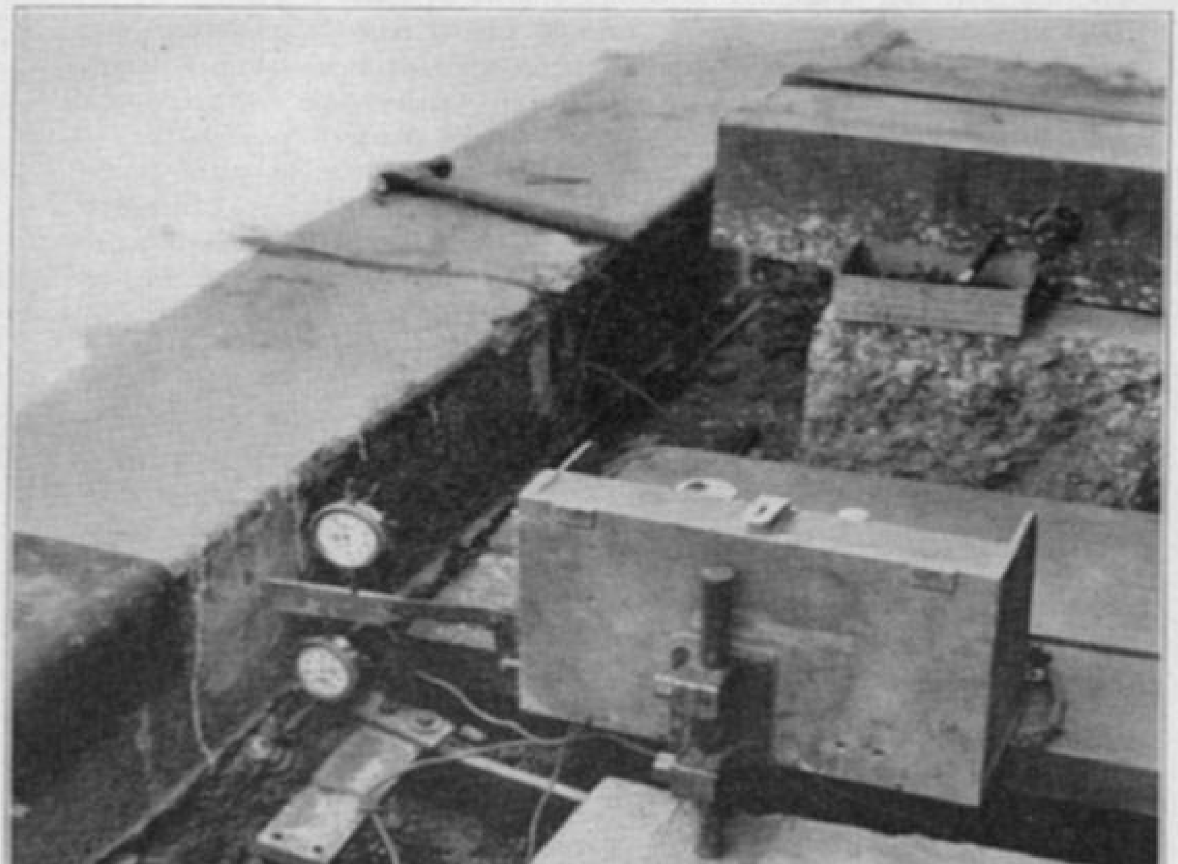


FIG. 3.—APPARATUS USED FOR RECORDING STATIC AND IMPACT DEFLECTIONS.

clouds may be noticed in the reading of Ames Dials set for those observations. Wetting the surface of the pavement has a similar effect. Monolithic brick pavements exhibit practically the same degree of warping as concrete slabs. The effect is much reduced when a bituminous concrete surface is applied, as might be expected. It is similarly reduced when a brick wearing surface having a bituminous jointfiller is used on a concrete base. Figure 5 shows the edge movement of various slabs. All readings were taken practically simultaneously for 24 hours.

Special attention is called to the slight warping of slabs having plastic surfacing materials of considerable thickness. Such surfacings no doubt tend greatly to reduce the ordinary range of temperature between the upper and lower surfaces of the rigid base, thus materially diminishing the warping of the slab. Under load, pavements of this character would no doubt receive material support from rigid subgrade or subgrades having a high elastic resistance, even under night traffic. The fact that clay subgrades are more than likely to become saturated at times, and when in such condition have very low supporting power, should not be overlooked.

Attention is also called to the comparatively small warping of the concrete slab having a longitudinal joint. Pavements so constructed may also be expected to receive some edge support from good subgrades under night as well as day traffic.

It is evident that the warping of rigid slabs away from the subgrade provides open channels for the free passage of surface water to all parts of the subgrade. Not only was this in evidence when the ditch, mentioned before, was cut along the edge of the pavement but was observed many times during the last twelve months. Throughout the year with distressing regularity, free water was found in the subgrade cylinders after heavy rains. Further, our latest observations indicate even greater warping effects during the coldest weather that has prevailed this fall than appeared in July and August.

It seems entirely possible that water from rains or melting snow, that finds its way under the edges of a slab as it curls up in the early part of the night, later freezes, thus forming a higher support for the edges and causes an excessive lifting of the entire slab the next day unless it breaks longitudinally under its own weight.

It also seems probable that the formation of ice under the edges at night and under the middle portion during the day is a more reasonable explanation of the presence of layers of ice which have been observed under pavement slabs, than the theory of capillary action.

IMPACT.

Specifications of the Illinois Division of Highways provide that the variation of the elevation of the surface of concrete pavements shall not exceed one-fourth inch. Some difficulty has been encountered in securing this degree of smoothness especially on grades of more than two or three per cent and on curves. However, the variations are not abrupt and a constant improvement is being obtained. It is believed that the above variation may be reduced materially by more careful construction methods, perhaps aided by hitherto untried equipment. By careful maintenance methods it is believed that the application of crack filler can easily be handled in such manner as to avoid any material differences in elevation from this source. We have as yet not attempted to devise an accurate means for determining the value of impact on average road surfaces. We do have some data which may be taken to indicate that possibly this matter is not of extreme importance—for example, Ames Dials have been placed so as to read deflections of the pavement slab, these dials being carried on independent supports. Trucks have been operated past these dials at speeds up to twenty miles per hour; the trucks were directed so that the rear wheels would pass as close to the dials as might be possible. During the approach and passage of the load, the hand on the dial was observed very carefully. These investigations were carried out on uncracked pavement sections of ordinary smoothness, adjacent to cracks having the usual jointfiller, adjacent to open joints, etc., yet no movement of the hand of the dial has been observed which would indicate more than a gradual and steady application and release of the load as the truck passed. It is possible that sudden movements occurred which were not observed; but this seems unlikely as a blow of a sledge could easily be detected. Further, in the machine devised to determine the effect of repeated loads on plain concrete beams each repetition of the load occupies one-tenth of a second. In this case the deflection of the beam, as shown by the hand of an Ames Dial, is easily distinguished and its magnitude can accurately be determined. These observations are of course but indications of what may occur but point to the prime importance of the development of some means for conclusively setting at rest all doubts as to impact effects caused by roughness of the average pavement slab as now constructed.

ALL CRACKS NOT SERIOUS.

It may be assumed that a pavement need not be so designed as to avoid all possible cracks or even all load breaks. The usefulness of a pavement is destroyed only when it becomes so broken or disintegrated that it no longer affords a smooth and comparatively unyielding surface. Transverse cracks or joints in rigid pavement slabs may be accepted as inevitable. Illinois for about six years has not provided for transverse joints; yet possibly with the exception of a few roads carrying very heavy trucks and in one unexplained instance, transverse cracks do not average less than about 30 feet apart. This average covers pavements more than three years old. On two stretches of concrete road in Cook County subjected to very heavy truck traffic, transverse cracks are much more frequent regardless of the character of the subgrade soil or drainage, and longitudinal cracks occur throughout. It seems quite possible that the frequency of the cracks in these sections may be due to the existence at one time or another of comparatively large areas where the subgrade was not in contact with the road slab, as was found in the case of the Bates Road, and represent load breaks. These sections, however, although they are in the main broken up into pieces of from three or four to perhaps sixty square yards in area, are still rendering practically unimpaired service to traffic. While the breaking of the pavement into slabs of large area may be detrimental only on account of appearance and slightly increased maintenance costs yet the breaking down and pulverizing of comparatively small areas at corners and the consequent reconstruction at these places causes serious traffic delays as well as expense. Complete destruction as observed in Cook County is usually confined to a few square feet or at the most two or three square yards and only occasionally do such breaks occur except along the edge of the pavement at corners. The exceptions so far noted occurred at the intersection of a transverse crack with a widely separated longitudinal crack.

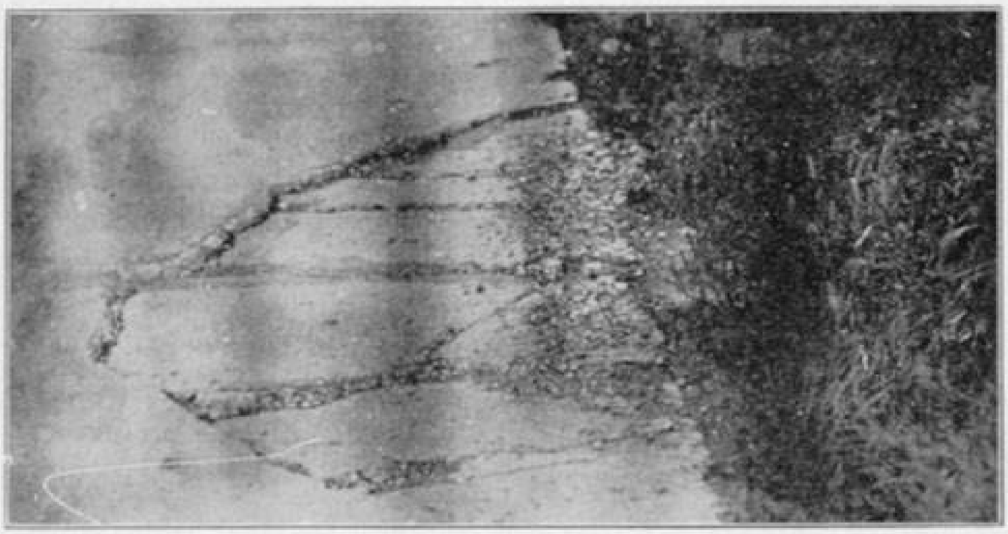


Figure AA illustrates a typical corner load break

ALLOWABLE STRESS IN PLAIN CONCRETE.

Whatever design formulae are eventually developed, it becomes of great importance to determine what may be a safe working load for plain concrete in tension. An apparatus was outlined by the writer and built in accordance with designs made by Mr. Clemmer, our testing engineer, for determining the effect of repeated loads on the transverse strength of plain concrete beams. This apparatus consists of a pair of automobile wheels carried on a horizontal axle which are revolved around a circular track by means of a vertical shaft carrying a pulley operated by a belt from a motor. Load boxes are placed on the axle so that the weight carried by the wheels may be varied as desired. Test specimens consist of 6x6 inches plain concrete beams, radiating as the spokes of a wheel and cantilevered from a central support. Between the beams, but separated therefrom by one-eighth inch openings, are blocks of concrete flush with the beams so that a smooth track is provided for the passage of the wheels. Seven beams are placed in the machine for each test. The apparatus is so arranged that when any beam breaks a switch is thrown and the motor stopped. By this means the fatigue machine may be operated day and night regardless of the presence of the observer. This apparatus provides also the advantage of having beam ends of sufficient length, after rupture in the fatigue machine for modulus of rupture determinations in a Universal Testing Machine. As the beams invariably break over the support, the length of the cantilever end is sufficient to make two modulus of rupture determinations on span lengths of 12 inches. This is of importance, as the determination of modulus of rupture of similar beams, presumably of the same character as those subjected to repeated loads, is by no means a safe guide as to the strength of the beams subjected to the repeated loads.

The first set of beams were subjected to more than 1,130,000 repetitions of a load which was presumed to be seventy-five per cent of modulus of rupture of the concrete but which later proved to be but about 37%. As none of the beams failed, the load was increased to about 53% when one beam broke at 43,174 loads; it was then found that the modulus of rupture of this beam was about 1000 pounds per square inch. Another interesting fact that developed was that five other beams of the same mix, and cast at the same time as the original seven, broke under an average of 60,000 repetitions of the same load when placed in the space left vacant by the breaking of the first beam of the original seven while the remaining original beams remained unbroken under 214,000 applications of this load. The load was then increased to about 60% when all but one broke at an average of about 40,000 loads. This would indicate the possibility that a large number of repetitions of a light load may have a beneficial effect on the transverse strength of plain concrete.

Two additional sets of beams have been broken, 12 beams in each set. In order to avoid the possibility of the effect of initial light loads, before the machine was started two beams cast at the same time were placed in the testing machine and modulus of rupture determined. The load on the wheels for the first additional set was then proportioned to approximately seventy per cent of the modulus of rupture. Under this load all of the new set of beams broke under repetitions varying from a few hundred to a few thousand applications.

An additional set of 12 beams is now being tested with a load on the wheels which will give a stress approximately equal to sixty per cent of the modulus of rupture. This set of beams is carrying a considerably higher number of repetitions than was the case where beams were loaded seventy per cent of modulus of rupture. They are, however, breaking under number of repetitions much less than might be expected during a year's time on a road slab carrying traffic of considerable intensity. From the behavior of the second and third sets of beams there is good reason to suppose that the per cent of the ultimate load that may be applied indefinitely may be affected materially by the age of the beams when first subjected to repeated loads. The tests now under way, therefore, are all being made on beams 28 days old when placed in the machine. From the results so far obtained it would seem probable that plain concrete in transverse bending may be able to withstand an indefinite number of repeated loads provided the stress is something less than 50% of the modulus of rupture. We hope soon to be able to say what a safe value for this per cent should be. Figure 5A is a photograph of the fatigue machine.

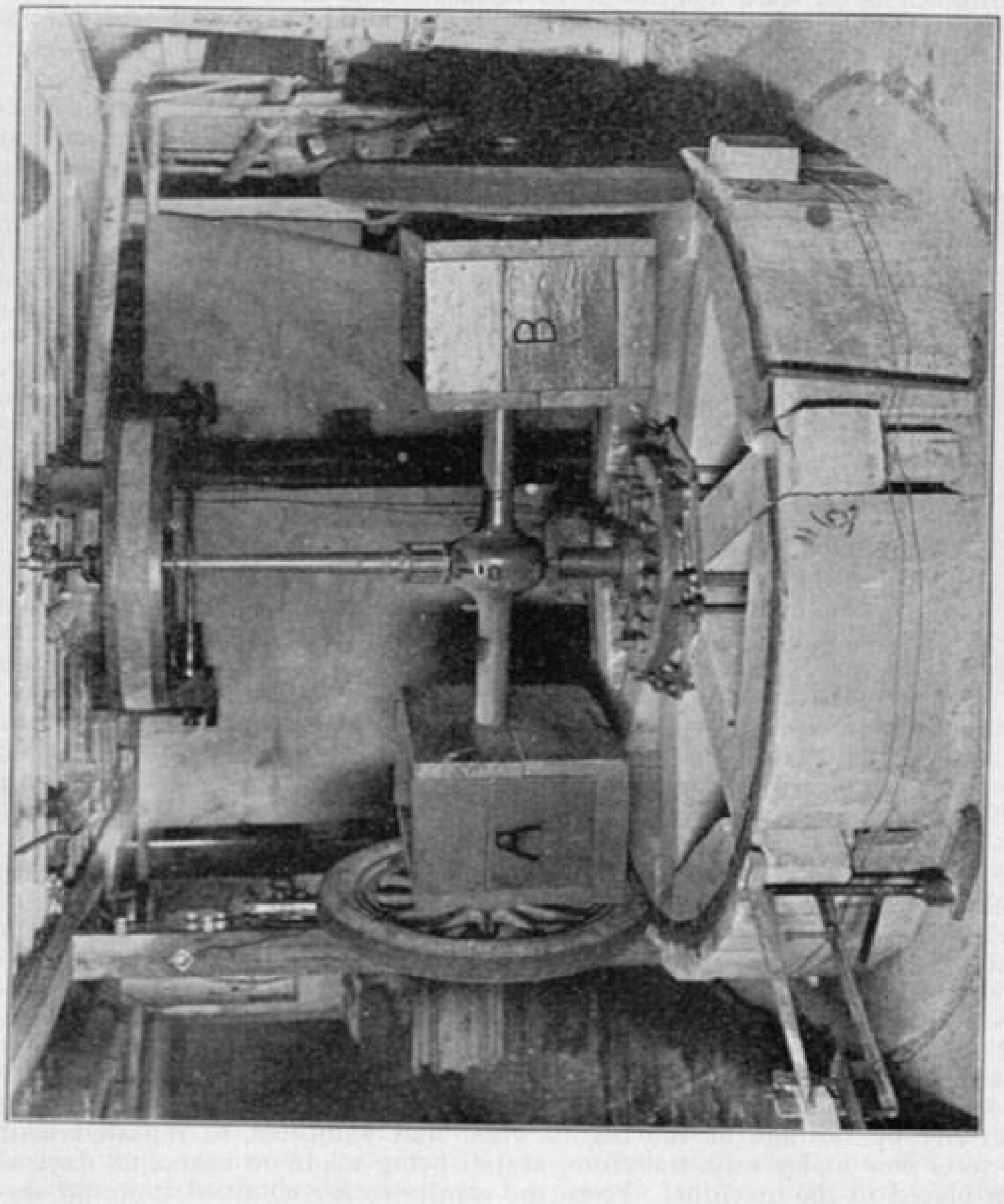
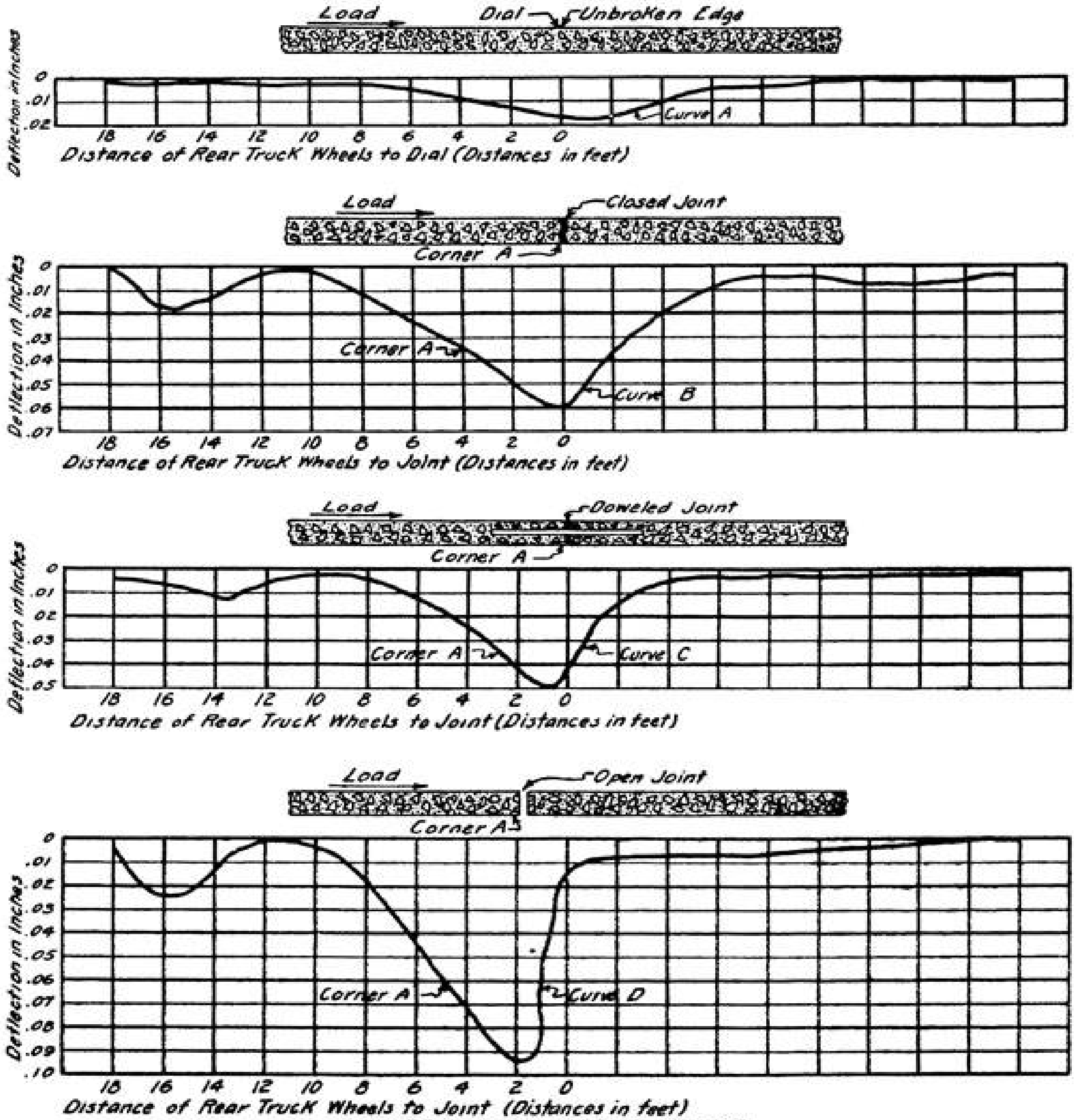


Figure 5A. Fatigue Machine

POSITION OF LOADS FOR MAXIMUM STRESSES.

Figure 6 indicates conditions which may apply along the edges of a pavement slab. Diagram A represents the deflection readings of an Ames Dial placed at the edge of the pavement during the passage of a four ton wheel load along the edge of the slab as close to the dial as feasible. The dial in this case was placed at some distance from the nearest transverse crack. It is of interest to note the shape of the curve showing the deflection of the edge at the dial as the wheel passed and the total amount of this deflection. Diagram B shows the curve of deflection when two dials were placed on the corner formed by a transverse crack. In this case the crack was very fine, the observations having been made during a period of high summer temperature when the slab was expanded and apparently all cracks closed very tightly. Note that the total deflection is much greater than shown in Diagram A, although it is apparent that the closed crack prevented each corner from acting independently. Diagram C shows a similar condition in which, although the crack was open, short dowel bars passed across it. Note that the deflection is approximately the same as that which occurred at the closed crack. Diagram D shows the very marked effect occasioned by an open crack or joint with no dowel bar or other means for causing both corners to act together. Deflections of the center of a slab under load were too small to be platted to this scale. While deflections only are platted in these diagrams, yet strain gauge measurements show the same proportionate results. As stresses are in proportion to strains the position of loads to produce maximum slab stresses are easily apparent from these diagrams. All of these deflections are platted from observations on slabs of the same thickness and taken during the night when the edges of the pavement were not in contact with the subgrade.

The advantage of providing means for causing adjacent corners to act together in supporting concentrated loads is also unmistakably illustrated by Figure 2. The readings from which these curves were platted were taken on a corner formed by a construction joint entirely open to the subgrade except that short dowel bars were in place across the joint. The load was imposed upon the corner on which these deflections were taken. Note that during the first night while the dowel bars were in place the maximum deflection under load was only about 0.03 inches. The dowel bars were cut at about 9 o'clock the next night with the result that the maximum deflection under load increased to about 0.08 inches.



DEFLECTION UNDER MOVING LOAD
Figure 6

THE DESIGN OF RIGID PAVEMENTS.

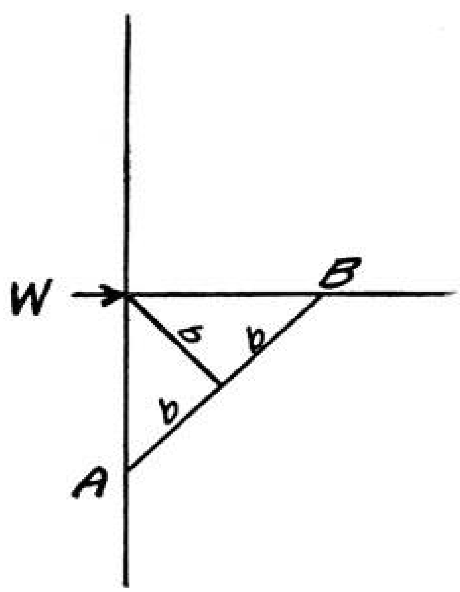
In the light of the foregoing observations, the possibility of applying rational designing methods to rigid slabs seems to be within reach.

It is of course fundamental that in order that any structure may rationally be designed the maximum loads to which it will be subjected must be known. The position and frequency of the application of the loads must also be known or assumed to be such as to produce the maximum destructive effect on the structure. It would also seem to be of prime importance that the actual impact factor of highway wheel loads on pavements constructed as smoothly as may be practical under modern methods should be determined.

Until exhaustive investigations can be made to determine the economic truck unit, we are faced with the problem of controlling maximum wheel loads by legislation based upon arbitrary judgment. The Illinois law provides for a maximum axle load of 16,000 pounds. This may be assumed to correspond with an 8,000 pound wheel load. As to the frequency of the passage of such wheel loads over pavement slabs, it is our observation that on trunk line roads in the near future great numbers of trucks, loaded to the limit prescribed by law, may be expected. Allowable stresses must also be fixed and the subgrade support duly considered.

In the light of what we believe to be conclusive evidence that an uncovered rigid slab may become warped by temperature effects so that it will, for from 8 to 12 hours out of every 24, be completely unsupported along the edges by even the best of subgrades, and considering the probability that at least on clay subgrades at certain seasons of the year the soil may have an exceedingly low supporting capacity, and further considering the fact that during the period of greatest subgrade saturation which no doubt occurs immediately upon the thawing out of the ground in the spring when low temperatures prevail, the cracks are open to the maximum amount, **it would seem that to resist local breaks it is necessary to design the corners of the pavement as unsupported cantilevers.** Unbroken edges are far less susceptible to traffic breaks than corners, as is clearly illustrated by Figure 6.

It is the writer's firm belief that if the thickness of the pavement be designed to carry the maximum load at the corners in accordance with the formula $d = \sqrt{\frac{3W}{S}}$ which formula covers conditions at unsupported right-angled corners, the remainder of the pavement will be well able to carry the same load without breaks which would damage its usefulness as a pavement surface.



The derivation of this formula is as follows:

Assume load W applied at corner
b = Moment arm to section A — B.

Then if A — B makes a 45° angle with the edge of the slab A — B = 2b.

M = W b.

S = allowable tensile stress.

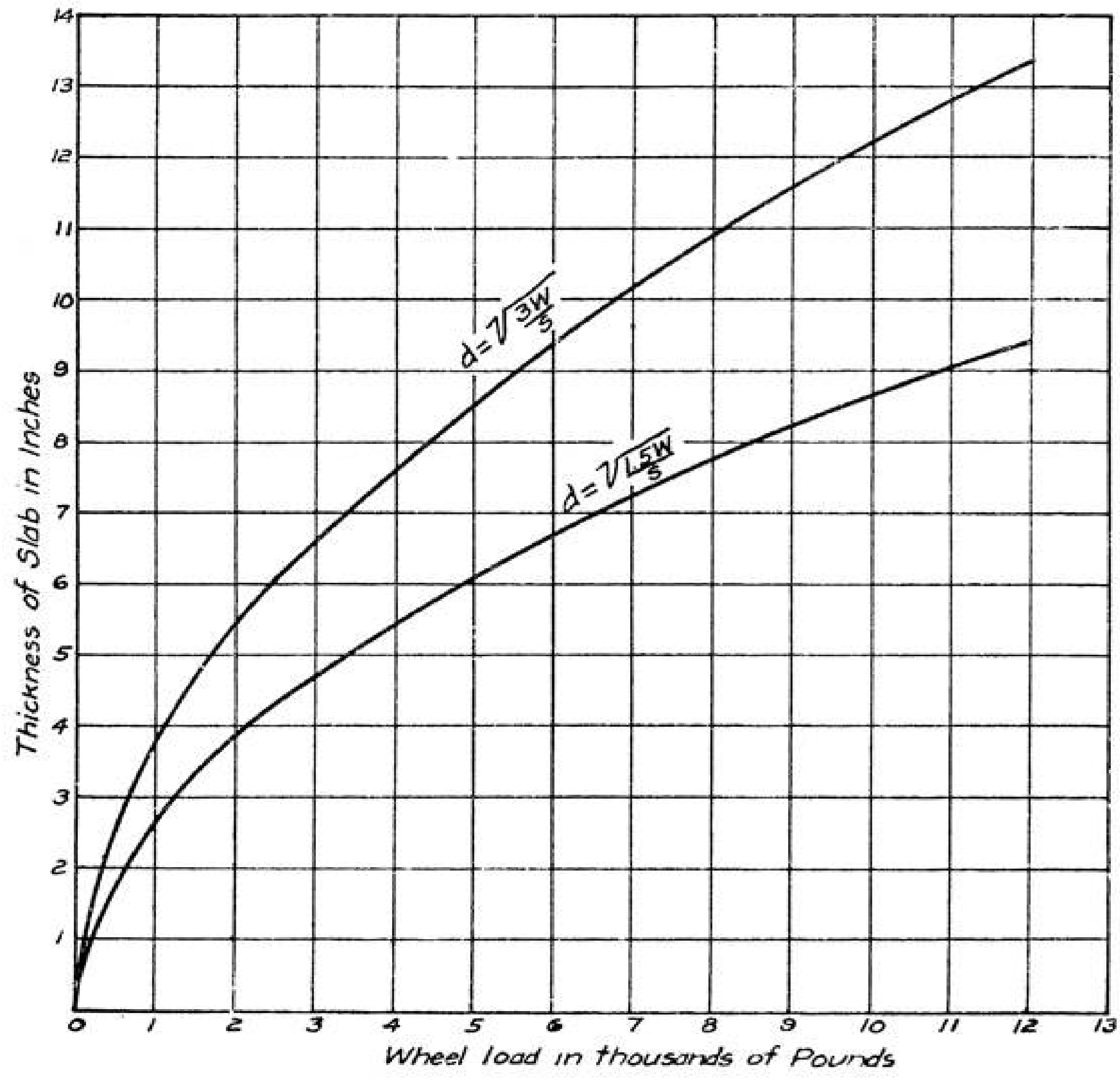
I = Moment of inertia of stressed section $= \frac{2bd^3}{12}$

$c = \frac{d}{2}$

Substituting these values in the formula $S = \frac{Mc}{I}$ it reduces to

$S = \frac{3W}{d^2}$ or $d = \sqrt{\frac{3W}{S}}$

If means could be found to make both corners act together by placing longitudinal shear bars along the edges of the pavement, or by some other means and the corner weakness thus be reduced by one-half, the design formula $d = \sqrt{\frac{1\frac{1}{2}W}{S}}$ could be used with a reasonable degree of safety. In order that all possible corners might be taken care of it is believed that the position of the longitudinal crack should be controlled by constructing a longitudinal joint and the adjacent slabs held in close contact by transverse tie bars. The interior corners, being held in close contact along the longitudinal joint by the transverse tie bars, should be fully as safe as the edge corners. The shear bars along the edges should also be continuous in order to take care of corners formed by transverse cracks regardless of their position.



Required Slab Thickness
Allowable Fibre Stress 200 lbs. per Sq. In.
Figure 7

Figure 7 shows the thickness of slab required if designed in accordance with the formulas heretofore given, assuming a safe working stress for 1-2-3½ concrete in tension of 200 pounds per square inch. The upper line is platted from the formula $d = \sqrt{\frac{3W}{S}}$ and the lower line the formula $d = \sqrt{\frac{1\frac{1}{2}W}{S}}$. The result of our fatigue tests although not yet complete seems to indicate that a working stress higher than 200 pounds per square inch may be safe for concrete of the quality ordinarily used in road construction. The data so far obtained indicates that a single three-quarter inch shear bar placed along each edge of the pavement may not be 100 per cent efficient in making both corners act equally under a load applied to one corner only. This may be due to the use of a heavy coat of asphalt on the bar, which has been the practice up to date. The yielding of this more or less plastic coat may be the principal cause of this trouble. Experiments are under way to determine, if possible, more effective means of transmitting one-half of the load across the crack.

The following tests bear out the value of the above formula for use in designing concrete slabs to resist corner breaks.

Example 1. On a corner formed by an open crack an 8,000 pound load was applied repeatedly by means of a hydraulic jack. The slab was 6½ inches thick, 1-2-3½ mix, and about 1 year old. Fibre stress computed by the formula $S = \frac{3W}{d^2}$ is 569 pounds per square inch. The corner broke under the 76th application of the load. The subgrade had been removed from under the slab after the 30th application.

Example 2. On a similar corner a 6,000 pound load was applied on a 6½ inch slab of the same mix and age. Computed fibre stress 426 pounds per square inch. The 62nd load broke the slab. The subgrade was a sand loam and had not been disturbed. The corner broke in the day time when the subgrade support should have been at a maximum.

Example 3. An 8,000 pound load was applied in the same way to a corner formed by a construction joint. Short ⅝ inch dowel bars were in place across the otherwise open joint. Slab thickness 4¼ inch, mix 1-2-3½, age about 6 months. Fibre stress computed by the formula $S = \frac{1.5W}{d^2}$ is 666 pounds per square inch. The corner broke at night under the 14th application of the load.

By means of the same outfit the behavior of several hundred other corners subjected to less than breaking loads have been observed. Using strain gauge readings as a measure of stresses we have been forced to the conclusion that under average conditions, material subgrade support to corners does not exist.

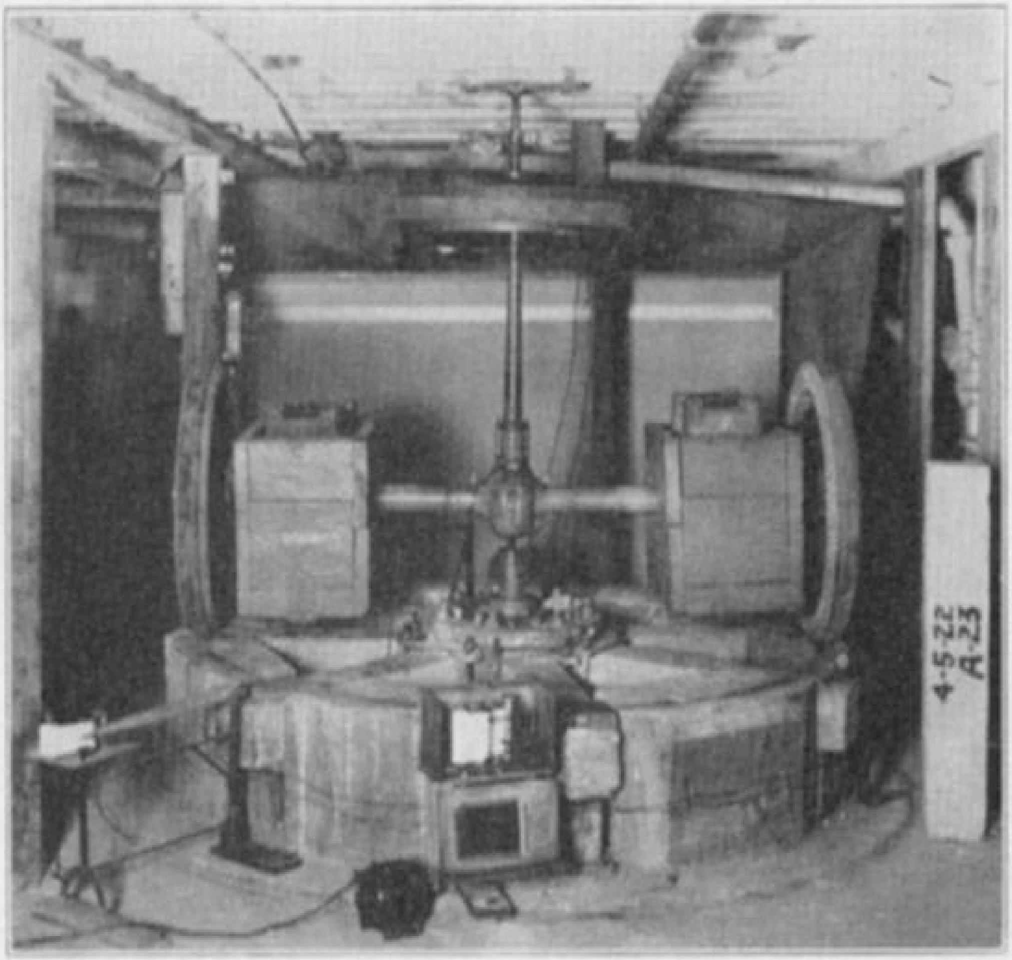


Fig. 10.—Apparatus for Determining Fatigue or Endurance Limit of Plain Concrete Beams.

Fig. 11.—Typical Failure of Asphaltic Concrete Surfacing on Macadam Base.

THE EFFECT OF INTENSITY OF TRAFFIC.

From the above discussion, it is evident that aside from traffic accommodation considerations, roadways of a width such that under normal traffic conditions frequent turning off and on the slab by heavy trucks may be avoided, are much to be desired.

The fatigue experiments above referred to indicate clearly that the life of a concrete slab may be long or short depending upon the frequency of the passage of loads great enough to stress the concrete up to fifty per cent or more of its modulus of rupture—For example, our fatigue tests show that a few thousand repetitions of loads sufficient to stress the concrete up to sixty per cent of its modulus of rupture cause failure. If on a given road about 5,000 loads sufficient to stress the concrete to this figure occur during the first month's use, the slab in all probability would fail the first month. If the same number of equal weight loads should not occur for several years it is entirely possible that the life of the pavement might be indefinite, as undoubtedly the modulus of rupture would have materially increased.

In the light of the investigations showing the marked warping of concrete and monolithic brick pavements, due to temperature changes, it is the writer's judgment that such slabs should be designed for a corner strength sufficient to reduce the fibre stress to a safe limit regardless of the character of the subgrade. It is no doubt true that the higher the supporting power of the subgrade, the lower will be the fibre stress of the slab under day time applications of load; nevertheless the warping of the edges and corners upward at night is so great that the best of subgrades would be of little value in reducing the slab stress under night applications of maximum loads. Good subgrades may therefore materially prolong the life of a pavement by reducing the frequency of the occurrence of critical stresses. In such case, however, the occurrence of load breaks would be merely a matter of the intensity of traffic at night and during periods when the pavement is least supported by the subgrade unless the slab is designed for such critical conditions.

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