of variables Tests made to date indicate a decided increase in impact when truck speed increases from 5 to about 15 miles per hour. A slight decrease occurs from this speed to about 20 miles per hour when a second increase is indicated which develops to a maximum at some speed beyond which the tests thus far have been made.

As regards the effect of road roughness on impact it may be of interest to both the maintenance and construction engineer, that even the slightest surface variations can, under certain conditions, greatly increase the forces delivered to the road The concrete road used in these tests is possibly more than ordinarily smooth and on the major portion of it impacts from even the solid tire were not appreciable The maximum of twice the static load occurred at but one point, which, although not in bad condition, could probably be improved and thus effect an increased safety factor against slab failure The next highest impact was about 1½ times the static This also shows the value of a recording apparatus of some type which will locate the troublesome surface variations

These indications are given at this time as general information and are not to be considered as final conclusions There does not seem to be much doubt as to accuracy of the data presented, but since it represents only several combinations of truck and tire it can not be considered applicable for all conditions In granting permission for the release of this information, it was the sense of the Committee that stress should be laid upon the fact that the relations shown are representative but should not be taken as final conclusions.

FATIGUE OF CONCRETE

W K HATT

Purdue University, Lafayette, Indiana

Loads are applied to materials in several ways (1) A fixed load continuously throughout extended periods, as books on the shelf of an unused library Here there is, in addition to elastic deformation, a plastic yielding that is especially marked in wood, stone, and concrete (2) Loads starting at zero and increasing to a maximum through periods of a few minutes, as in an ordinary laboratory test. (3) Suddenly applied loads ranging from the passage of a locomotive over a bridge producing stresses within the elastic range of the materials to an impact test of a specimen where the blow of a falling weight is intended to rupture the material (4) A large number of loads applied in close sequence without rest, either repetitive (all of the same sign, tension, or compression) or reversed (of opposite sign) as in the case of a rotating car axle (5) Alternating loads applied less rapidly than in (4) with periods of rest, as when trucks pass over a concrete road at intervals of 15 seconds with a rest over night

The term "fatigue limit" refers to the stress which can be applied many times before rupture occurs The somewhat misleading word fatigue refers to the fact that the fatigue limit under repeated loads is a lower stress than the once applied stress that the material will withstand. The analogy with muscular fatigue is not good, for it appears that failure of steel under fatigue occurs when planes of weakness in the crystals are gradually enlarged to a plane of fracture of the specimen, the metal on either side of this plane remaining unchanged in character, whether in laboratory tests or in service of the material.

LABORATORY TESTS VERSUS SERVICE CONDITIONS

Laboratory tests of fatigue phenomena generally differ from service conditions in that in the laboratory, loads are applied very quickly with no period of rest between. It has been shown by specially devised tests that steel and concrete withstand greater repeated and reversed loads if a period of rest is allowed, and if the rapidity of application is less. Service loads are seldom applied as rapidly as laboratory tests.

Therefore, in view of these conditions, we must scrutinize the findings of laboratory tests to determine their application to design.

THE FUNDAMENTAL INDEX OF FATIGUE LIMITS

It appears from tests of steel that the fatigue limit is closely related to the elastic limit. When the repeated loads exceed the elastic limit, and enter the semielastic and semiplastic range, heat develops in the piece, due, no doubt, to internal friction. It might appear, therefore, that the fatigue limit of concrete would be related to the elastic limit of concrete.

Concrete, however, is a material which is credited by some with a true elastic limit from 25 to 60 per cent of the ultimate load under a slowly applied static stress. By others the concrete seems never to be elastic. It shows a curved stress-deformation diagram from the start.

No doubt these discrepancies are due to imperfect instruments, to the condition of concrete with respect to age and moisture, qualities of cement, etc. Consideration of concrete in comparison with wood, with which it has many analogies, would seem to lead to the conclusion that concrete well mixed, without voids, of an age, say of nine months, and kept dry, should show a definite elastic limit. On the contrary, concrete that is new, poorly mixed and saturated from the time of test will show the plastic qualities of a new colloid. Therefore the curved stress-strain diagram.

Therefore, in testing concrete for fatigue we shall expect to find different ratios of fatigue strength to static strength, depending upon the age and condition of the concrete and its moisture content.

Since the fatigue tests naturally extend over a considerable period of time, it is well to conduct the tests on concrete approximately nine months to a year old, so that the variations arising at the time of tests shall not confuse the results.

Concrete, like steel, will receive a fatigue index depending upon these two factors of rapidity of application of load and period of rest between a series of loadings.

This factor of period of rest between successive applications of the load will be more important in the case of a material like concrete than in the case of steel For instance, if the testing process, such as that used at the Illinois Department of Highways by Clifford Older, applies the loads rapidly and without rest, a condition is set up which is very different from the condition of loading in the road slab where there is a period of rest over night, and where the interval between the passage of the trucks in the day time is perhaps 15 seconds

The rapid applications of loading in Dean Johnson's tests must also affect the results of the test.

ACCOUNT OF EXPERIMENTS

The three investigations which have been recorded are—

1. Department of Highways, State of Illinois
2. University of Maryland.
3. Purdue University

FATIGUE TEST OF CEMENT MORTAR AT PURDUE UNIVERSITY

November, 1924

An investigation of the fatigue of cement mortar has been carried on for the past three years in the Testing Materials Laboratory of Purdue University as a cooperative project of the Engineering Experiment Station and the U S Bureau of Public Roads The early findings have been reported by R B Crepps in the Proceedings of the American Society for Testing Materials, 1923, and all of the results to date are reported in that paper. There are still several phases of the investigation to be studied before the project is completed

ACKNOWLEDGMENT

The investigation has been conducted under a plan and apparatus devised by Professor W K Hatt, Director of the Testing Materials Laboratory, under the direct charge of Professor R B Crepps and Mr R E Mills, representatives of the Purdue Engineering Experiment Station

APPARATUS

Deflections of a concrete slab occur in the form of a wave action as a wheel passes over the surface The direction and nature of the resulting stress is constantly changing, from tension or compression in the upper fibers, to compression or tension in the lower fibers With these facts in mind the idea of investigating the effect of reversed stresses upon concrete was conceived by W K. Hatt and later incorporated in the design of an apparatus with which to carry on the investigation The original device provided for the inspection of only one specimen at a time, the improved machine allows four beams to be inspected simultaneously.

The machine illustrated in Figure I consists mainly of a steel frame supporting test specimens, a motor, and the essential working units. The principle of the application of the loads to the test specimens lies in the operation of an eccentric cam, which raises and lowers a load upon the ends of a horizontal straining member, supported in the center by a vertical test specimen. Four rocker arms, pivoted directly above the same number of test specimens, operate through a small angle by means of the cams rotated from a central line shaft. The U-shaped ends of the rocker arms fit around the cams as shown in the illustration.

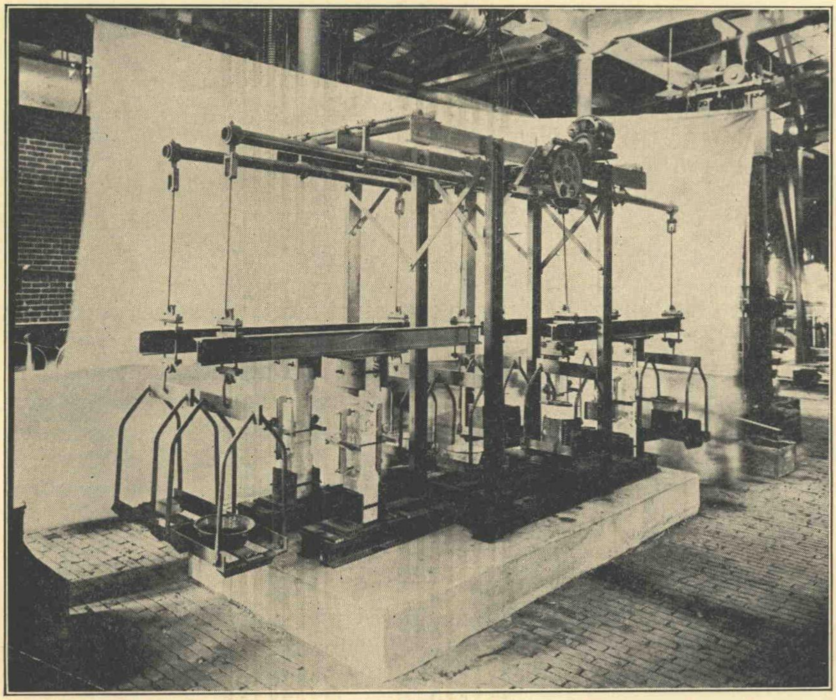

FIGURE 1.
Fatigue Testing Machine.

One end of a beam under test is clamped rigidly to the base of the steel frame and the upper end is clamped to the straining member. The operation of the machine subjects the outer fibers of the beam to alternate tension and compression at the rate of 10 cycles per minute. A revolution counter attached to the machine indicates the actual number of reversals of stress for the separate beams.

Ten-inch Berry strain gauges provided with Ames dials reading to 0.0001 inch are attached to both sides of the specimen, and observations of the total deformation from tension to compression are taken at designated intervals throughout the period of tests.

TEST SPECIMENS

The specimens were 1 2 mortar beams 30 inches long and 4 by 4 inches cross-section in the middle with enlarged ends (See Figure 2) Some of the earlier tests were conducted upon specimens only one month old, but all of the later tests were made upon test pieces over six months in age, thereby reducing the effect of age All specimens were tested in an air dry condition

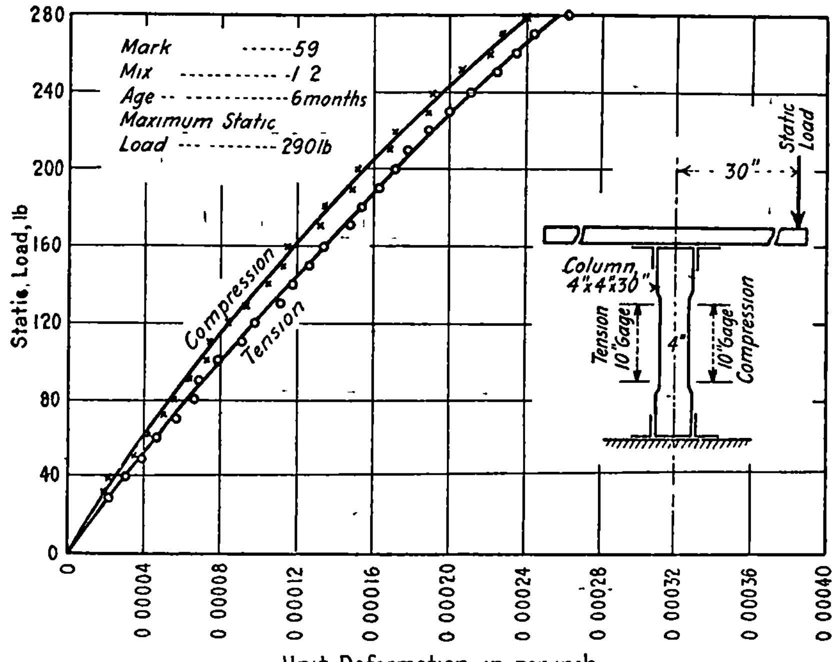

FIGURE 2

Static Loading Curve

STRENGTH OF SPECIMENS

Figure 2 illustrates the procedure used in determining the strength of the specimens Duplicate test beams supported as in the fatigue machine are broken by the application of static loads in 10-pound increments on one end of the straining beam The strength factor as determined by the static-load breaks is considered as representative of the particular series of beams under question In spite of all possible precaution observed in the construction of the test specimens, the maximum variation in strength from an average of six beams was about 15 per cent It is appreciated that this variation creates a source of considerable error in the attempt to arrive at definite conclusions concerning fatigue of mortar.

DISCUSSION OF TESTS

The curve shown in Figure 3 illustrates the typical effect of reversed stresses which caused failure of the mortar specimen It is to be noted that there is a progressive deformation in the extreme fibers until failure of the test specimen takes place A straight line of constant slope relation is indicated up to 110,000 reversals of stress At this point, four cracks appeared on the outermost fibers of the specimen, and the slope of the line changed. An additional 35,000 reversals of stress were necessary to produce complete failure The critical point in the progressive deformation cycle is designated as the premature failure limit

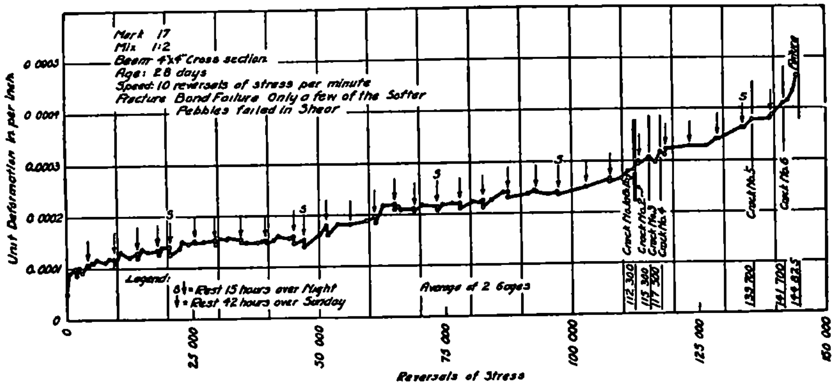

FIGURE 3
Typical Fatigue Curve

The curve is representative of the tests completed to date, although in many cases the premature failure limit is not so pronounced and the additional number of reversals necessary for complete failure is less A parallel cycle of action is indicated, nevertheless, by the general trend of the deformation curves.

It is apparent that rupture or failure of the bond occurs first on the extreme outer fibers where the deformation is a maximum. This action is progressive toward the center of the beam until complete failure results. Progressive deformation occurred in some cases for a certain number of reversals of stress, when it became evident from the flatness of the deformation curves that the material was suffering no ill effects from the load, as shown in Figure 5, curve G, and in Figure 10.

FATIGUE ENDURANCE LIMIT OF CEMENT MORTAR BEAMS

The beams are subjected to alternate stresses of tension and compression The loads may be expressed as percentages of the static breaking loads in a static test Examining Figure 4 it is seen that to cause failure in the beams, over 6 months old, the fatigue limit under alternating loads is at least 54 per cent of the static breaking load.

The curve in Figure 4 also shows that the number of reversals of stress necessary to cause failure decreases in proportion to the increase of the percentage of stress above the endurance limit, as for example, a beam operating at 65 per cent load will require a lesser number of reversals to cause failure than one operating at 56 per cent load.

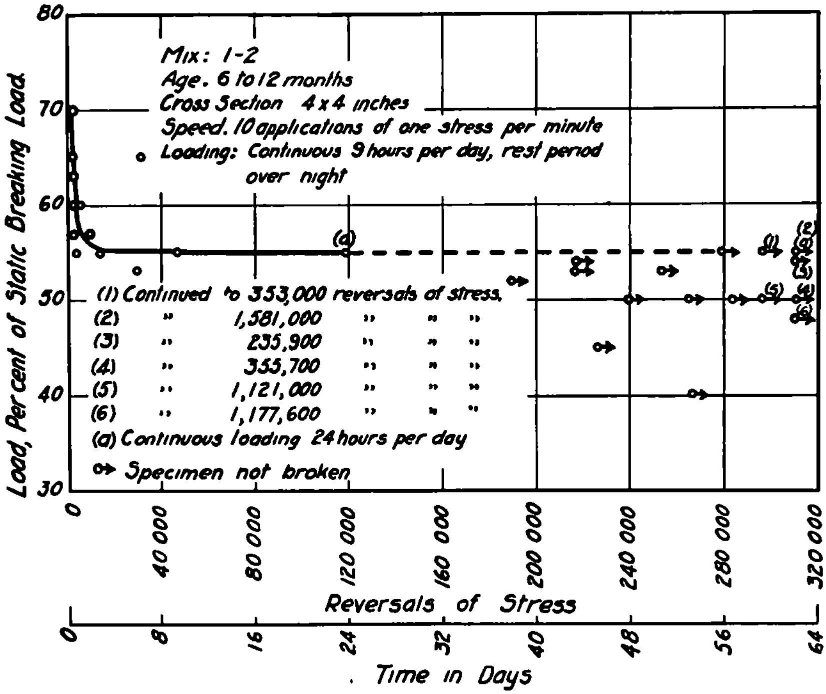

FIGURE 4.
Fatigue Endurance Limit of Cement Mortar Beams

Experience in these tests shows that no definite endurance limit can be assigned to mortar beams of early age, for the ageing of the material during the test may produce a greater effect than the fatigue action. For beams 28 days old, the endurance limit may be as low as 40 per cent of the static breaking load.

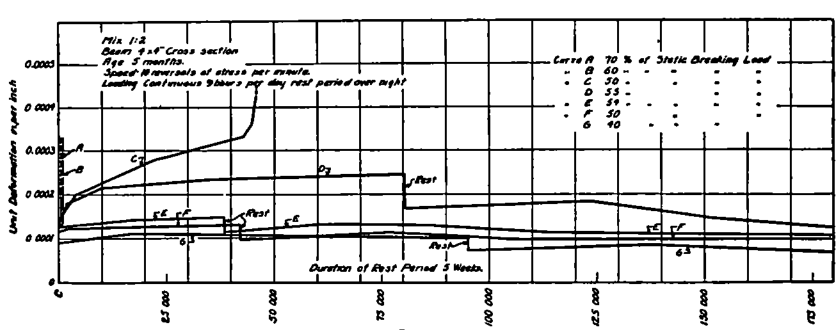

FIGURE 5
Showing Effect of Prolonged Rest Period

From the results of a limited number of tests, the endurance limit for aged beams subjected to a continuous fatiguing action does not appear to differ from that found for beams operating with short rest periods.

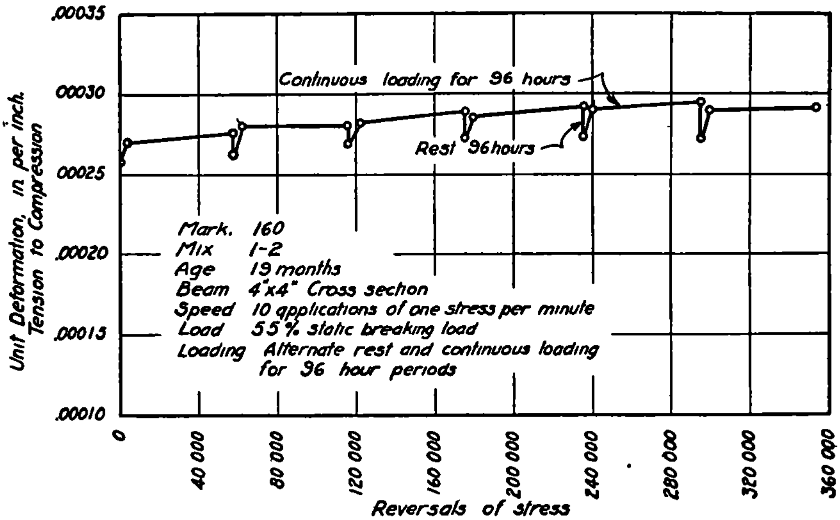

FIGURE 6

Effect of Rest Periods Upon Plain Cement Mortar Beam

RECOVERY PHENOMENA DURING REST PERIODS

The recovery in deformation and stiffness of the cement mortar during rest periods has been marked in these fatigue tests Both a short period of rest over night and a long one of five weeks duration are reflected in

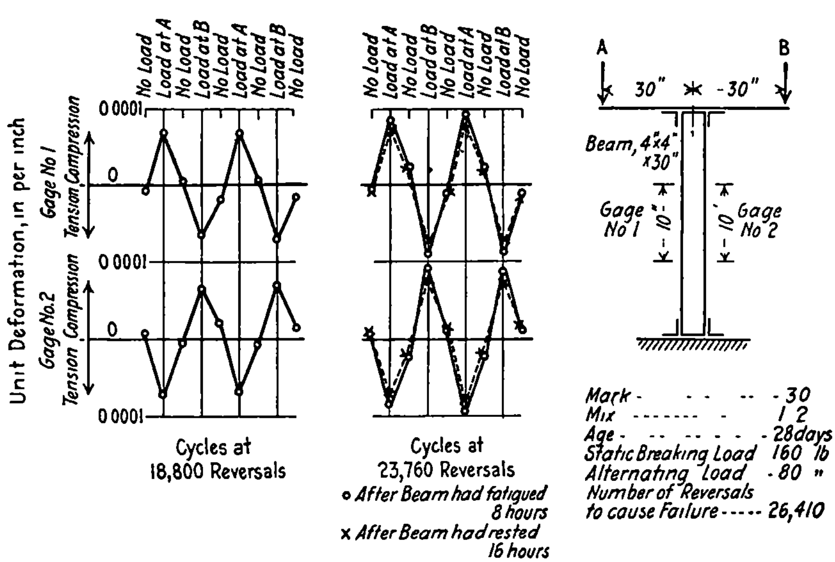

FIGURE 7

Typical Cycle Curve of Cement Mortar Beam Age 28 Days.

the deformation curves. Observing the typical fatigue curve, Figure 5, there is seen an appreciable recovery in the unit deformation for periods of rest of sixteen hours over night and also of forty-two hours over Sunday. Figure 6 also shows how an aged beam recovers when allowed to rest for ninety-six hour periods after being operated in fatigue for a like period.

The typical cycle curve at 23,760 reversals, appearing in Figure 7, for a beam only 28 days old, shows, too, that there is a smaller unit deformation in both tension and compression after a 16 hour rest period than there was just previous to the rest. Again in Figure 8 which repre-

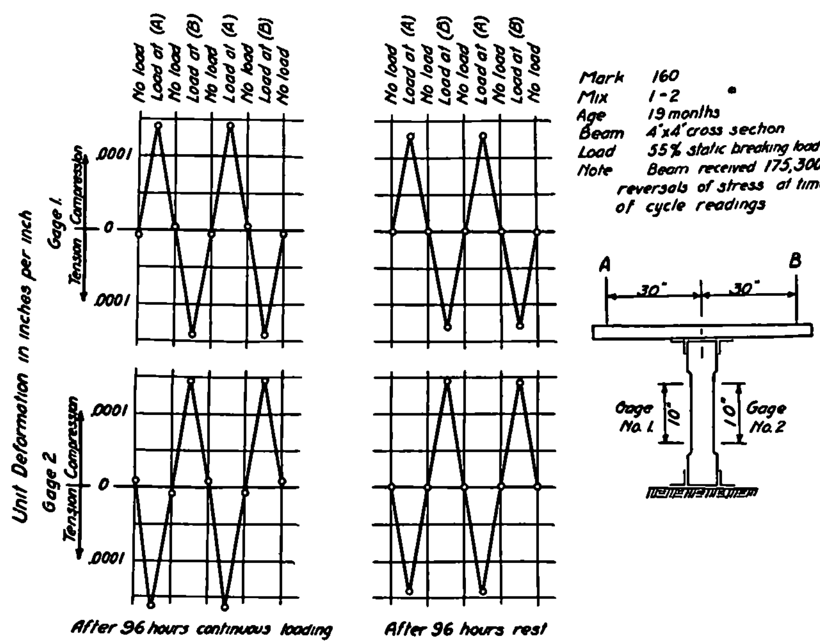

FIGURE 8

Typical Cycle Curves of Cement Mortar Beams Age 19 Months

sents a typical cycle curve of a beam 19 months old, it is seen that the unit deformation in both tension and compression is less after the 96 hour rest than it was before the rest period.

This general stiffening effect or reduction in deformation caused by a given load due to rest is also illustrated in the load-deformation diagrams shown in Figure 9. The broken line represents the load-deformation data taken after 96 hours of alternate loading and just before a 96 hour rest period, while the full line represents corresponding data secured at the completion of this rest. It is evident from these curves that the deformation for the same static load is less after, than before, a rest period. Although the operating fatigue load, in this case, immediately before taking the load-deformation data, was 55 per cent of the static breaking load which may or may not cause final failure of the test piece, yet the same stiffening phenomena has been noted for beams operating at lower fatiguing loads which do not cause failure.

The effect of a long rest period upon the recovery phenomena is shown in Figure 5.

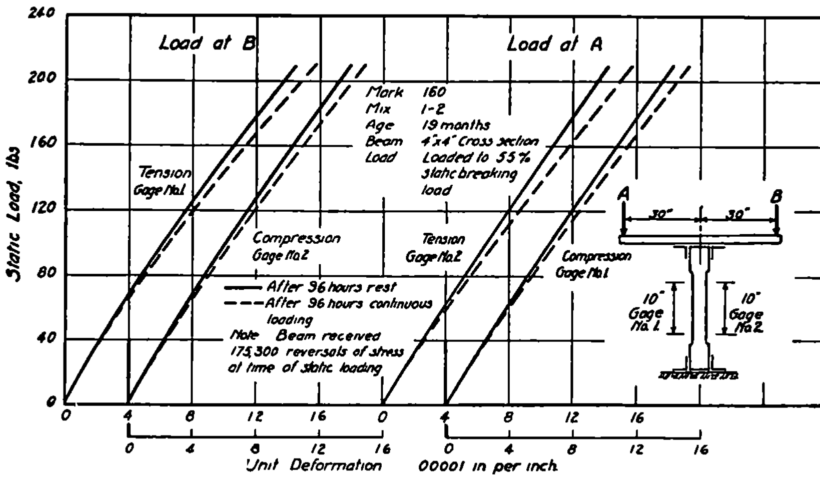

FIGURE 9

Effect of Rest on the Stiffness of a Plain Cement Mortar Beam

During this series of tests it became necessary to stop the machine for five weeks, and as a result the effects of a prolonged rest period is clearly evident from the trend of the deformation curves. The beneficial or strengthening effect of the rest period is the most pronounced in the case of the specimen represented by curve D. In this instance it is believed that the induced stress approached the critical limit and that failure was imminent. The degree of deformation following the rest period indicates that the beam had fully recovered from the initial overstressings As these beams were five months old, it is thought that the increase in strength due to age over the rest period exerted a minor influence upon the subsequent resistance of the mortar.

It is to be noted that the effect of the rest period is less pronounced in the case of specimens represented by curves E, F, and G. In these beams, however, the induced stresses were apparently below the endurance limit and no fatiguing action had taken place. The general trend of the deformation curves after 140,000 reversals seems to be in a downward direction.

A marked contrast can readily be detected in the magnitude of the plastic set occurring at 18,800 and 23,760 reversals of stress, respectively The broken line appearing in the cycle curve at 23,760 reversals shows the unit deformation after the beam had rested for a period of 16 hours. These maximum deformations are less than those of the same beam just previous to the rest period, which shows a partial recovery from the fatigue action. This action is typical of all tests, in that progressive plastic set simultaneously accompanies fatigue.

Aside from the fact that the present tests show the stiffening effect of mortar for different durations of the rest period, this phenomenon is most important when the mortar is being stressed near its endurance limit If the mortar is stressed below its endurance limit, it will not fail, but should its endurance limit be exceeded by only a small amount, then a relatively few reversals of stress may cause failure. (See Figure 4.)

When mortar is being fatigued near its endurance limit, the duration of the rest may be the controlling feature between failure and the resistance to the fatiguing forces. As may be seen in Figures 3 and 6, there is a recovery due to the short periods of rest, but upon continued fatiguing this effect is shortly overcome and the rest may not be sufficient to prevent failure. However, the effect of a long rest period (see Figure 5, curve D) allows the mortar to become stiff enough to prevent failure by the fatiguing action

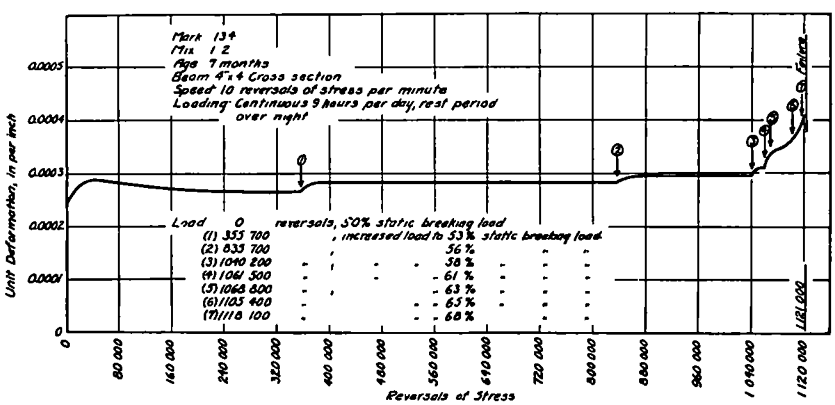

FIGURE 10

Effect of Increasing the Load During Fatigue Action

CYCLE CURVES AND PLASTIC SET

Cycle curves showing the sequence of deformation and the plastic set or failure of the mortar to return to its original position in both tension and compression are illustrated in Figures 7 and 8 In Figure 7, typical conditions for mortar 28 days old are illustrated. It can be readily detected that the magnitude of the plastic set and also the tension and compression deformations occurring at 23,760 reversals, which is near failure in this particular beam, is greater than the corresponding values at 18,800 reversals of stress. The cycle curves in Figure 8 which are typical for mortar 19 months old, show the magnitude of the plastic set to be small at the completion of 96 hours continuous fatiguing and practically zero after a 96 hour rest period.

The magnitude of plastic set during the fatiguing process is dependent upon the age of the mortar, being inversely proportional to the age

FATIGUE ACTION BELOW ENDURANCE LIMIT AS A STRENGTHENING FACTOR

A characteristic of the fatigue action for percentage of load below the endurance limit, is for the deformation curve to flatten out or drop under continued fatiguing thereby indicating that the specimen will not rupture By the process of increasing the fatiguing load and at the same time noting the behavior of the deformation curve, it has been found that a load greater than the endurance load of 55 per cent has been necessary to cause failure of mortar specimens Figure 10 shows the deformation curve of a beam which operated for a time at a 50 per cent load and later the load was increased to values from 53 to 68 per cent load before failure occurred From this diagram it seems as though the 61 per cent load perhaps would cause failure if allowed to continue However, the 58 per cent load would not cause rupture

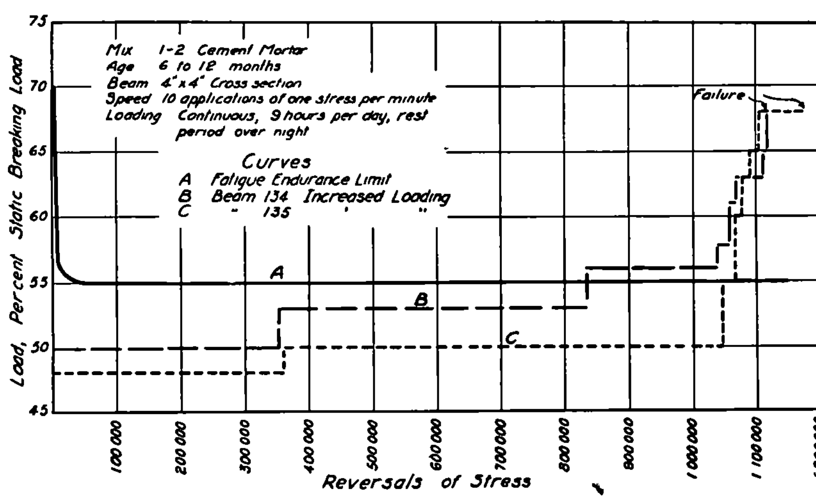

FIGURE 11
Effect of Increasing the Load During Fatigue Action

In Figure 11, curve A shows the fatigue endurance limit for beams operating under one continuous load, and curves B and C show how this endurance limit was exceeded by gradually increasing the fatiguing load, starting below 55 per cent static breaking load

INDICATIONS AND SUMMARY

This investigation of the fatigue phenomena, in cement mortar, covers a wide field, and involves a time-element of considerable magnitude. Although the tests have been carried on for a considerable length of time, yet all phases of the work are not completed. However, the data secured while not being sufficient from which to draw definite conclusions in all cases, give several indications of promise which are emphasized as follows:

1. (a) 28-day test No definite endurance limit between 40 and 60 per cent of that static load required to break the beam under a single application can be assigned to cement mortar of this age
   (b) Four-month test The endurance limit is approximately 50 to 55 per cent of the static load
   (c) Over 6 months The endurance limit is 54 to 55 per cent of the static load
2 The endurance limit does not seem to differ materially for beams under continuous fatigue loading from that for beams under fatigue loading with short rest periods.
3 The number of reversals of stress necessary to cause failure decreases in a proportion to the respective increase of the percentage of static load above the endurance limit
4. Stresses above the endurance limit cause continual progressive deformation.
5. Stresses below the endurance limit may cause progressive deformation for short periods with a tendency to become constant or to decrease with continued loading
6 The endurance limit may be raised by fatiguing below the 55 per cent static load
7 The amount of recovery in deformation seems to depend somewhat upon the length of rest period
8 Plastic set in fatigue is more pronounced in mortar of early age. A sufficient rest period may reduce the plastic set to zero

PLASTIC FLOW UNDER CONTINUOUS STATIC LOAD

Since some of the beams have been under reversed stresses for four months, it is necessary to inquire into the possibilities of plastic or time flow of the mortar

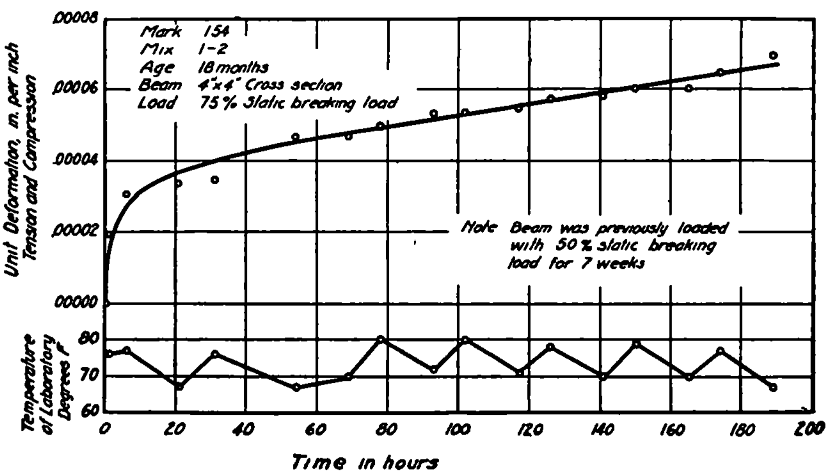

FIGURE 12
Plastic Flow of Plain Cement Mortar Beam

If the failure of concrete under fatigue is due to working the cement back and forth through a plastic range, the time flow should be known

For this inquiry one beam was subjected, as in Figure 2, to a continuously applied static load on one side of the straining beam for 11 weeks to date, that is, 50 per cent of static breaking load for 7 weeks with no appreciable effect and 75 per cent for 4 weeks

Figure 12 shows the results for a specimen of age 18 months. The deformations are the sum of the tension and compression deformations without regard to sign.

The temperature of the laboratory which would drop 10° F. in one day will throw an extension to a compression as shown on the instrument If the temperature of the concrete were known, temperature corrections could be applied. When the heat was turned on in the laboratory the beam became drier and shrunk, this again changed the readings.

By recording the sum of the deformations on each side (tension and compression), the uniform changes of length due to temperature and to shrinkage are eliminated

The total unit time flow to date, three weeks duration, is 0 000087 for 75 per cent of static strength The increase ceased at 1½ weeks The unit deformation under reversed stresses for this age of concrete at the 55 per cent of static load was 0 0003 or nearly 3½ times as great.

THEORY OF STRESSES IN ROAD SLABS

H M WESTERGAARD
University of Illinois, Urbana, Illinois

A theoretical investigation of stresses and deformations in road slabs on the basis of mathematical theory of elasticity has been carried on for the U. S. Bureau of Public Roads by H M. Westergaard of the University of Illinois The progress of this work was reported at last year's annual meeting The work has been continued, with interruptions, during the present year, and a report of the results which have been obtained so far is now under preparation for publication This report takes up the following subjects (I) general principles and methods of the analysis; (II) the corner break, (III) deflections and stresses which are caused by wheel loads at a considerable distance from the edge of the slab; (IV) corresponding results for wheel loads at the edge, (V) effects of changes of temperature, especially the blow-up of the road slab due to expansion, and (VI), in the form of an appendix, particular features of the theory and method.

The analysis leads to diagrams of such deflections and moments as are due to wheel loads which act either at an appreciable distance from the edge or at the edge By comparing the contour lines which have been obtained for the deflected surface by tests and by theory, respectively, numerical values of the elastic constants which are involved, especially a certain constant which measures the stiffness of the subgrade, may be determined in any given case. The relative stiffness of the slab and the subgrade is of consequence, in regard to the distribution of