rather definite information on the use of steel reinforcement in concrete pavements

The curing of concrete pavements is not strictly in the province of structural design but since the strength of the structure is dependent on the curing processes, it is a matter of primary importance to the designing engineer There are methods of curing which are generally admitted to be adequate In the effort to reduce the cost of this operation alternative methods have been proposed Engineers have endeavored to determine the efficiency of these methods by tests When these tests were made in different localities under perhaps widely different conditions of temperature and humidity, sometimes different answers to the same question have been obtained This indicates that the importance of these factors on the adequacy of curing processes has not been fully recognized More data are necessary before the engineer can be certain of obtaining concrete of specified strength and durability under various climatic conditions when these curing methods are employed

In the papers which follow, the attempt is made to review briefly the research in the field of structural design, to summarize the knowledge gained, and to point out some of the important matters which need investigation

FATIGUE OF CONCRETE

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The importance of investigating the effect of repeated loads upon concrete is apparent not only from the standpoint of the economical design of road slabs and other structures, but also in the interpretation of failure occurring in concrete structures after years of service It is a well-known fact that metals exhibit the phenomenon of fatigue, and it might naturally be expected that a material like concrete, which possesses only a small degree of elasticity and a large degree of plasticity, would exhibit a similar phenomenon.

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 semi-elastic and semi-plastic 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

"In testing concrete for fatigue we shall expect to find different ratios of fatigue strength to progressive loading strength, depending upon the age and condition of the concrete and its moisture contents. Since the fatigue tests naturally extend over considerable period of time, it is well to conduct the tests on concrete approximately nine months to a year old, so that the increase of strength with age during the tests will not confuse the results.

"Concrete will indicate 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"[10]

Account of Experiments (See Bibliography, Appendix A) The seven investigations which have been recorded are:

(1) By De Joly,[1] France (1898)
(2) By J. L Van Ornum,[2,3] Washington University, St. Louis, Mo. (1903)
(3) By H. C. Berry,[4] University of Pennsylvania, Philadelphia, Pa. (1910).
(4) Division of Highways,[6,8] State of Illinois (1922).
(5) By A. N Johnson, University of Maryland
(6) Purdue University,[5,7,9,10,12,13] (1922)
(7) Tests at the Karlsruhe Technical High School,[11,14] (1925-1926)

1 Tests by De Joly[1] Tests by De Joly of cement mixtures in tension briquettes, under rapidly repeated loads (26 to 92 per minute) determined a fatigue limit of approximately 50 per cent of its strength under progressive loading The majority of his specimens were tested at early ages, ranging from 2 to 20 days His tests show that an increase in the rate of applications of load decreased the total number of applications of load necessary to cause failure Indications of recovery due to rest periods were also noticed.

2 Tests by J. L Van Ornum[2,3] Early tests by J L Van Ornum (1903) of neat cement cubes in compression under repeated loads (4 per minute) indicated a fatigue limit of approximately 55 per cent of its strength under progressive loading All specimens were tested when four weeks old

Later tests[3] (1907) of concrete prisms (5" x 5" x 12") in compression and reinforced concrete beams (4" x 6" x 72") in flexure determined a fatigue limit to be 50 per cent of their strength under progressive loading The specimens were of a 1-3-5 mix and tested at ages of one month, six months and one year The flexure beams were reinforced with 2½ per cent of steel The rate of application of load was 4 to 8 per minute in the case of the concrete prisms and 2 to 4 per mile for the flexure beams

A few tests[3] were conducted in which the rate of application of load was decreased to a minimum of one in five hours, however, the results of these tests did not differ materially from the other tests

All of Van Ornum's[2, 3] tests as well as those by De Joly[1] show that as the fatigue load is increased materially above 50 or 55 per cent of the progressive loading strength, the number of repetitions of load to cause failure is rapidly reduced.

3 Tests by H C Berry[4] Tests by H C. Berry of 1-2½-5 concrete cylinders (8" x 16") in compression under rapidly repeated loads show a progressive deformation and permanent set as a result of the fatigue action, however, no definite fatigue limit was determined

4. By the Illinois Division of Highways[6, 8] "In these tests, as reported by H F Clemmer[6] and by Clifford Older,[8] a fatigue limit of concrete was found The loading device was a rear axle of an automobile turning about a vertical axis which coincided with the center of the horizontally and radially projecting beams The free ends of the beam were loaded by the rubber-tired wheels actuated by the axle. The speed of the loading was 40 applications per minute."[10]

Several series of beams (6" x 6" x 36") of 1-2-3½, and 1-3-5 concrete and 1-3 mortar were used The testing ages of the beams were 30 days, 174 days, and 11 months to one year It will be noted that the stresses were not reversed, but only repeated

"It appears from the tests that plain concrete beams will sustain without failure from bending an indefinite number of repetitions of a load if the tensile fiber stress induced is less than 50 per cent of the modulus of rupture Typical beams have withstood without failure about 5,000,000 repetitions of a load sufficient to produce a fiber stress of approximately 50 per cent of the modulus of rupture It is interesting to note in this study that the repeated application of a load less than 50 per cent of the modulus of rupture increases the strength of the concrete at the stressed section.

"For loads causing fiber stress in excess of 50 per cent of the modulus of rupture, the tendency to failure increases rapidly with the increase of this excess of stress For instance, loads causing fiber stresses of about 60 per cent of the modulus of rupture repeated a few thousand times (rarely more than 30,000) will cause failure; for stresses in excess of 70 per cent of the modulus of rupture, only a few hundred repetitions (rarely more than 5000) are required."[8] "The critical percentage or fatigue limit of the concrete specimens was between 51 and 54 per cent of the modulus of rupture as determined from one application of load."[9] The phenomenon of accelerated failure was also noted in the Bates Test Road when the stress exceeded 50 per cent of the modulus of rupture.

5. *By Dean A. N. Johnson, of the University of Maryland.* "Dean A. N. Johnson shackled two mortar beams together at the ends. At the center of lengths was an eccentric shaft, by the rotation of which the beams were spread apart 002 of an inch. Dean Johnson, therefore, worked with deformations rather than stresses He has not as yet published the results of his investigation, except it is understood that the 2,000,000 of applications of load on these beams does not appear to have changed the nature of mortar as shown by subsequent static tests"[10]

6. *Tests at Purdue University.* "An investigation of the fatigue of cement mortar and concrete has been carried on for the past five years in the Testing Materials Laboratory of Purdue University as a cooperative project of the Engineering Experiment Station and the United States Bureau of Public Roads

"The apparatus that has been used bends a vertically disposed beam back and forth through the medium of a horizontal straining beam.

"The machine consists mainly of a steel frame supporting test specimens, a motor and the essential working units The loads are applied to the test specimens by an eccentric cam, which raises and lowers a load successively upon each end (or, one end only) of a horizontal straining member supported in the center by the vertical test specimen. One end of the 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 reversals of tension and compression, or repeated application of tension and compression (depending upon the manner in which the machine is being operated) at the rate of ten reversals, or repetitions, per minute A revolution counter attached to the machine indicates the actual number of applications of stress for the separate beams

"Ten-inch Berry strain gages provided with Ames dials reading to 0 0001 inch are attached to each side of the specimen, and observations are taken at designated intervals throughout the period of tests" [10]

TEST SPECIMENS

The specimens were small beams 30 inches long, 4 x 4 inches cross-section in the middle, with enlarged ends. Various mixes have been used in the fabrication of test specimens, consisting of 1-2 sand mortar, 1-1½-3, 1-2-3 and 1-2-4 gravel concrete Half of the concrete specimens were reinforced with 0.33 per cent of mesh reinforcing placed ⅜ inch from the tension face In another series of tests which are under way at the present time, a limestone and a diabase stone are being used as the coarse aggregate Half of these beams are reinforced in the same manner as the other concrete beams

All of the mortar beams were cured 14 days under wet burlap and then stored in the laboratory until time of test In the case of the concrete beams, most of them were cured 14 days under wet burlap and then exposed to the weather, while a few were cured only two or three days, and then either exposed to the weather or stored in a shed until time of test.

STRENGTH OF SPECIMENS

The tests to determine the static properties were made in the same machine in which the fatigue tests were carried out Duplicate beams were broken by the application of progressive loads in 10-pound increments to one end of the straining beam, the strength factor as determined by this test is considered as representative of the particular series of beams under question The fatigue loads are then determined as a percentage of this strength

DISCUSSION OF TESTS

"A typical mortar beam (m-17) under reversed stresses which caused failure shows a progressive deformation in the extreme fibers until failure of the test specimen takes place A fairly uniform increase of deformation 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 curve increases An additional 35,000 reversals of stress were necessary to produce complete failure.

"Rupture occurs first on the extreme outer fibers where the deformation is a maximum, and progresses toward the center of the beam until complete failure results.

"A test for impact effect in this type of loading showed that no increase in deformations could be measured due to the more or less sudden application of the load compared to its quiescent effect.

"The deformations are affected to come degree by shrinkage of the concrete during the tests, especially when green concrete is used, by temperature movements and by plasticity under the load. The latter were measured on 1-2 mortar under a continuous load of 50 per cent of the breaking load, applied for seven weeks No plastic set was recorded under this loading The load was then increased to 75 per cent After four weeks there was a permanent set in the beam of (00008), equal to about ¼ the total deformation accompanying failure under reversed fatigue loading" [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 ultimate strength under progressive loading

(a) For 28-day tests. No definite fatigue limit between 40 and 60 per cent can be assigned to mortar of this age.
(b) For 4-month tests The fatigue limit is approximately 50 to 55 per cent.
(c) For tests over 6 months The fatigue limit is 54 to 55 per cent.

"The number of reversals of stress necessary to cause failure decreases in proportion to the increase of the percentage of stress above the fatigue 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" [10]

Dry mortar beams tested in fatigue at ages of 6 months or over yield values of unit extension at the first crack visible to the naked eye of approximately 00015 to 00016. Similar beams tested under progressive loading yield slightly higher values of about 00016 to 00017. The number of applications of load required to cause failure in fatigue will vary from about 50,000 to 150,000 when the fatigue load is 54 to 55 per cent of the progressive loading strength

RECOVERY PHENOMENA DURING REST PERIOD

"The recovery in deformation and stiffness of the cement mortar during rest periods has been marked in these fatigue tests An appreciable recovery in the unit deformation for periods of rest of fifteen hours over night was noticed, while aged beams would recover almost completely when allowed to rest for 96-hour periods after being operated in fatigue for a like period Cycle deformations and progressive loading deformations taken before and after rest periods indicated a similar condition of recovery

"During one series of tests it became necessary to stop the machine for five weeks, and as a result the effects of a prolonged rest period was clearly evident from the trend of the deformation curves The beneficial or strengthening effect of the rest period was the most pronounced in the case of a specimen, in which it is believed the stress approached the critical limit and that failure was imminent The degree of deformation following the rest period indicated 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

"When mortar is being stressed near its fatigue limit, the duration of the rest may be the controlling feature between failure and the resistance to the fatiguing forces" [10, 7]

FATIGUE ACTION BELOW ENDURANCE LIMIT AS A STRENGTHENING FACTOR

"A characteristic of the fatigue action for percentages of load below the fatigue limit is that the deformation curve flattens out or drops under continued fatiguing, thereby indicating that the specimen will not rupture By the process of building up gradually the fatiguing load, but keeping below the usual fatigue limit, the final fatigue limit is elevated. The experiments of the Illinois Division of Highways also indicates this phenomenon A typical beam was operated for a time at a 50 per cent load which later was increased to values from 53 to 68 per cent load during 1,121,000 applications of stress From the deformation curve it appeared as though the 61 per cent load, perhaps, would have caused failure if allowed to continue. However, the 58 per cent load would not have caused rupture." [10,7]

FATIGUE LIMIT OF WET MORTAR

"The mortar in the tests reported above was dry Two additional series of tests were made on mortar that was (a) aged 19 months, and saturated by immersion in water for 200 hours previous to test, and (b) aged 4 months and kept continuously saturated.

"A record of these tests, although limited, indicates an interesting and important feature of the fatigue action on cement mortar The wet mortar in (a) under progressive loading showed a strength of 89 per cent of the dry mortar; in (b) 83 per cent

"The fatigue limit of (a) was 33 per cent of the strength of the dry mortar, or 37 per cent of the wet mortar In (b) the values were not so well defined, approaching 37 per cent and 45 per cent, respectively.

"The fatigue limit of wet concrete applies to concrete road slabs that are likely to be wet from a saturated subgrade. The present data indicate that this fatigue limit for saturated mortar may be taken as 35 per cent of the strength found under a standard laboratory test.

"The unit extension at the first visible crack under fatigue was: For dry mortar about 0 00016, for saturated mortar 0 00018. The average number of applications of load to cause failure of dry mortar was 100,000, for saturated mortar 75,000"[10]

EFFECT OF REINFORCEMENT ON FATIGUE UNDER REPEATED LOADS

"If small amounts of reinforcement will increase extensibility of concrete at first crack visible to the naked eye, the fatigue strength should also increase, since it appears that concrete will fail under fatigue when the limit of extensibility is reached"[10]

During 1925 some preliminary tests were conducted upon two sets of beams to determine the effect of mesh reinforcement on 1-2-3 gravel concrete Both sets of beams were cured three days under wet burlap, one set was then exposed in a draft of hot air in a shed and the other exposed outside to summer weather. The age of the concrete at the time of testing ranged from 7 to 135 days In each set of beams half of the specimens were plain sections and half were reinforced with 0.33 per cent of mesh reinforcing placed 3/8 inch from the tension face. The loading was by repeated rather than reversed stress. The extension of the reinforced beams was 36 per cent in excess of that of the plain beams, the strength was 30 per cent greater. The number of applications of load before failure occurred in the reinforced beams was approximately three times the number of applications of load to cause failure of the plain concrete beams

These comparisons of extensibility are based on the appearance of the first eye-visible crack.

7. *Tests at the Karlsruhe Technical High School.* (Taken from "The Fatigue of Metals" by Moore and Kommer.)[13] Interesting tests were conducted by Probst[11] and Mehmel[14] at the Karlsruhe Technical High School These tests were on 1-6 gravel concrete compression speciments 7 by 7 cm in cross-section and 28 cm. long The average age of the specimens was one year and the loading was repeated at the rate of 60 per minute

Deformations were measured with a Marten's mirror apparatus on a gage length of 20 cm. Unit deformations could be read directly to 0 00001 cm per centimeter

In one case, where the fatigue loading was 38 per cent of the ultimate static strength, with an increase in the number of cycles the elastic deformations increased at first faster than the permanent sets, but later this was reversed The elastic deformations finally reached a constant value followed somewhat later by the permanent sets After 453,000 cycles the test was discontinued because both the elastic and permanent deformations had reached a stable condition The modulus of elasticity had decreased during the progress of the test, from an initial value of 3,590,000 lb per sq inch to 2,800,000 lb. per sq inch at the end of 453,000 cycles The increase in permanent deformation had been accompanied by a decrease of modulus of elasticity.

In another case, where the fatigue loading was 29 5 per cent of the ultimate static strength, deformation readings were taken at various intervals The elastic deformation was 0 000158 at 10 cycles, increased to 0 000179 at 150,000 cycles, and then remain constant up to 610,000 cycles The permanent set was 0 00001 at 10 cycles, increased to 0 000086 at 400,000 cycles, and then remained constant up to 610,000 cycles and the test was discontinued The specimen was then subjected to a progressive load test At 38 2 per cent of the ultimate static strength, a permanent set was developed, and at the same time the modulus of elasticity decreased The stress-deformation curve was steeper than it was for similar specimens which had not been subjected to repeated stress The specimen had evidently been strengthened by the repeated stressing

A study of the relation between unit stress and unit deformation under repeated stressing, showed that the modulus of elasticity is not merely a function of unit stress, but is dependent on the method of applying the stress, the number of times the stress is applied, the previous history of stressing, and other factors When a specimen has been repeatedly stressed many times, it is possible for it to become elastic within the limits of stress to which it has been subjected, and within these limits Hooke's law is valid This condition may be reached for all stresses from zero up to the fatigue limit.

In order to study the behavior of concrete under repeated stress which would cause failure, a specimen was stressed in fatigue, under a load equal to 80 per cent of the static ultimate strength. The first few loadings gave a stress-deformation curve convex upward, but even after 20 cycles this had become concave upward, and as the number of cycles increased, this concavity upward increased, the curve being steeper at the higher values of stress. Similar stress-deformation curves were obtained for stresses as low as 47 per cent. It was concluded that the character of the curve between stress and elastic deformation is the criterion for fatigue, and not the permanent set

A fatigue limit was found which lies between 47 and 60 per cent of the ultimate static compressive strength

SUMMARY ON FATIGUE OF CONCRETE

(Taken from "The Fatigue of Metals" by Moore & Kommers) [15]

"Some of the conclusions which follow must be looked upon as tentative until verified by further experiments, yet the indications are such that the following summary of the important phenomena may be regarded as fairly well established

"(1) Concrete will fail under repeated loads at unit stresses which are much less than the ultimate static strength

"(2) When the unit stress to which concrete is subjected in fatigue is decreased, the number of cycles for rupture is increased

"(3) For concrete, as for metals, as the maximum limiting stress in a cycle is increased, the minimum stress must be increased algebraically if failure is not to occur. No formulas for the effect of range of stress have been developed for concrete

"(4) While tests of many millions of cycles of stress have not been carried out on concrete, yet the indications are that its endurance limit for cycles of stress ranging from zero to maximum, is about 50 to 55 per cent of the static ultimate strength, both for compression cylinders and for beams

"(5) Even when the cycle of stress (from zero to a maximum) is less than the endurance limit, a permanent set occurs during the first few loadings If, however, the cycle of stress is such that the permanent set reaches and maintains a constant value, then the indications are that failure will not occur

"(6) For stresses below the endurance limit concrete seems to be able to adjust itself to the imposed cycles of stress, the stress-deformation curve becomes a straight line, and the stress can be withstood indefinitely

"(7) In the above process of adjustment to a cycle of stress the modulus of elasticity also reaches and maintains a constant value.

"(8) Stresses above the endurance limit cause progressive deformation and final failure

"(9) Periods of rest seem to have only a temporary effect on the recovery from deformation, and do not seem to change the endurance limit.

"(10) Stressing concrete below the endurance limit increases its strength just as is the case with metals

"(11) In order that the effect of increase of strength with age shall not seriously affect the factors being investigated in fatigue tests of concrete, it is necessary that tests be made on concrete which has an age of 6 months or greater"

FUTURE RESEARCH

Considerable research has already been conducted on neat cements, mortars and concrete, and a fatigue or endurance limit of approximately 50 to 55 per cent of the ultimate strength under progressive loading seem to be fairly well established, these values holding true for aged specimens when tested in either compression or flexure. However, many of the characteristics involved in the manufacture, placing and service of concrete have only been touched upon

Some suggested researches along this line are as follows:

(1) Fatigue of concrete under *reversed* stresses Only a small amount of work has been done with this type of loading and since concrete road slabs as well as other concrete structures may be subjected to reversed as well as repeated loads, additional research along this line should prove of considerable value.

(2) Fatigue of concrete with varying moisture conditions.
  (a) Dry concrete.
  (b) Saturated concrete.
  (c) Concrete with unequual distribution of moisture.
(3) Fatigue of concrete under impact loads
(4) Long-time tests involving many millions of cycles of stress.
(5) Effect of the various physical properties of the concrete such as:
  (a) Type of aggregate.
  (b) Gradation of aggregate.
  (c) Mix.
  (d) Consistency
  (e) Kind of cement, etc
(6) Effect of curings and exposures.
(7) The significance of various phenomena which have already been noticed such as:
  (a) Plastic set.
  (b) Recovery during rest periods
  (c) Fatigue action below endurance limit as a strengthening factor.

APPENDIX A—BIBLIOGRAPHY

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EFFECTS OF LOADS ON PAVEMENTS AS INDICATED BY STRESS MEASUREMENTS

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In discussing the effect of loads on concrete pavements it has generally been the custom to divide the discussion into two parts and consider static and impact loads as being separate and distinct from each other Extensive researches are being conducted on the subject of motor truck impact and it may be that by these invesigations some law will be established which will show that the only difference between the effect of static and impact loads on pavements is that due to the time of application of the load It seems extremely probable that such a law exists, but at present our knowledge of it is very limited

The most direct method for determining the effect of loads upon a concrete pavement is by means of strain measurements The development of a suitable strain gage and a method of making strain measurements in concrete pavements under actual traffic loads has placed in the hands of the research engineer a most useful tool which has already added greatly to our knowledge of the behavior of the pave-