LITERATURE REVIEW

AN ANALYSIS OF LABORATORY FATIGUE TESTS

by

J. R. Freeman, Jr.
Engineer Trainee

and

G. W. Maupin, Jr.
Research Engineer

Task A of Contract No. DOT-FH-11-8324, "Simple Procedure for Fatigue Characterization of Bituminous Concrete"

(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

November 1975
VHTRC 76-R24

1490

LIST OF FIGURES

LITERATURE REVIEW

AN ANALYSIS OF LABORATORY FATIGUE TESTS

by

J. R. Freeman, Jr.
Engineer Trainee

and

G. W. Maupin, Jr.
Research Engineer

INTRODUCTION

Repeated loadings on bituminous pavements have long been recognized to be detrimental to pavement performance. Although several authors, including F. J. Grumm[1] and O. J. Porter,[2] have written of this subject, F. N. Hveem[3] was one of the first to investigate the effects of repeated loadings.

Hveem established three major factors in the failure of bituminous pavements: (1) flexural strength, (2) the weight of the mix on the subgrade, and (3) the flexibility to withstand repeated bending. To evaluate the third factor, the flexibility of the pavement, Hveem developed a fatigue testing device capable of testing small beams cut from asphaltic pavements. This device places a controlled deflection on the beam and records the number of loadings required to crack it.

Other tests developed in the early stages of fatigue testing were by Hennes and Chen,[4] Nijboer,[5] Van der Poel,[6] and Monismith.[7] Hennes and Chen tested beam specimens in flexure on a device that supported them on a spring steel leaf. Nijboer and

Van der Poel developed a laboratory testing device for cylindrical bars of asphaltic mixtures. These bars were loaded as cantilever beams and then rotated to achieve a repeated loading. Later, this test method was further developed by Pell[8] and is discussed in detail in the following text. Monismith developed a spring base repeated flexure testing apparatus which was intended to simulate the base-subgrade combination in the pavement structure.

As fatigue testing has advanced, engineers have become more aware of the complexities entailed and many different approaches for analyzing the fatigue life of pavements have been adopted. Monismith and others[9,10,11,12,13] have developed and refined test methods using beam specimens. Jiminez has studied the effects of flexure loadings on circular plate specimens.[14] Several tests have been performed using various odd shaped specimens such as trapezoidal ones.[15,16] Methods of analysis have advanced, with Majidzadeh et al. having introduced analysis by fracture mechanics.[17]

PURPOSE AND SCOPE

The purpose of this literature review is to describe fatigue test methods and equipment, the data acquired in these tests, and the analytical methods used to evaluate the test results. The literature search was conducted under Contract Task A of the FHWA Contract No. DOT-FH-11-8324 entitled "Simple Procedure for Fatigue Characterization of Bituminous Concrete."

The discussion presented here is primarily directed toward experimental, laboratory fatigue testing; however, in some instances discussion includes the use of the test results in pavement design.

METHODS OF TESTING

Prior to the discussion of the various types of fatigue tests and equipment used, a general discussion of the testing modes used, the load variables, and definitions of the types of failure found in fatigue testing is presented.

Testing Modes

Laboratory fatigue testing methods have predominately used two modes of loading for bituminous specimens.[10] These modes, controlled stress and controlled strain, are designed to hold either the stress or strain at a desired value while an unconstrained variable is monitored.

Controlled Stress

The controlled stress mode of testing requires that a load of constant value be applied to the specimen throughout the testing process as illustrated in Figure 1. When this testing mode is used, the deflection of the specimen is monitored to determine the strain corresponding to the applied load. The controlled stress test mode is used to test bituminous materials which provide the primary structural support of the roadway, i.e. materials placed in thicknesses greater than 4 in. (10.2 cm).

Controlled Strain

The controlled strain mode of testing is performed by maintaining the strain at a desired level and monitoring the corresponding stress. In this mode, a predetermined value of deflection or strain is placed on the specimen, and the load required to produce this deflection is recorded throughout the test. Graphic illustrations of strain vs. cycles to failure and stress vs. cycles to failure are given in Figure 2.

The controlled strain test is used to test bituminous materials used as thin surface layers, the reason being that the surface layer of a bituminous roadway offers little if any structural support and deflects an amount controlled by the subgrade, base material, and bituminous base.

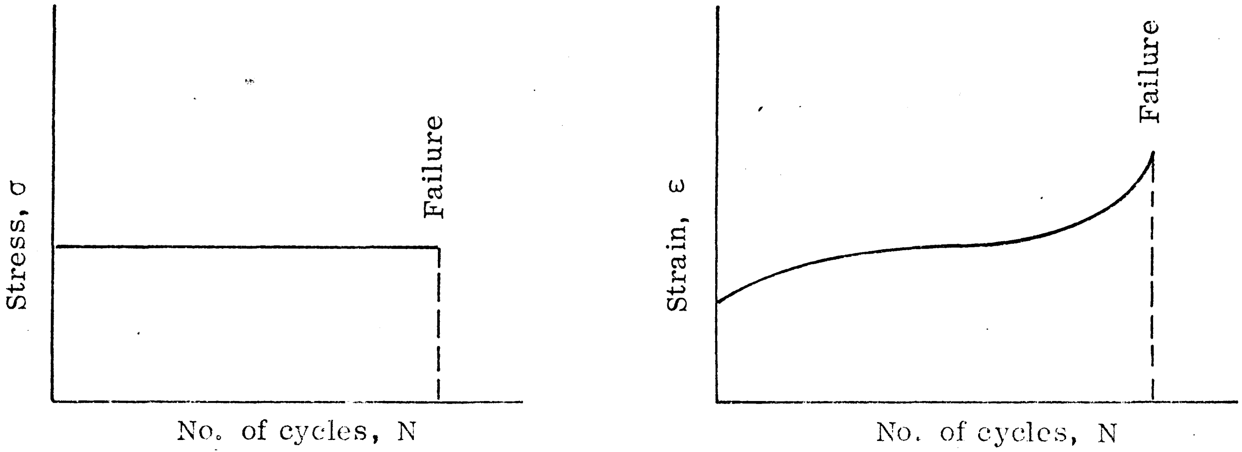


Figure 1. Controlled stress fatigue test.[10]

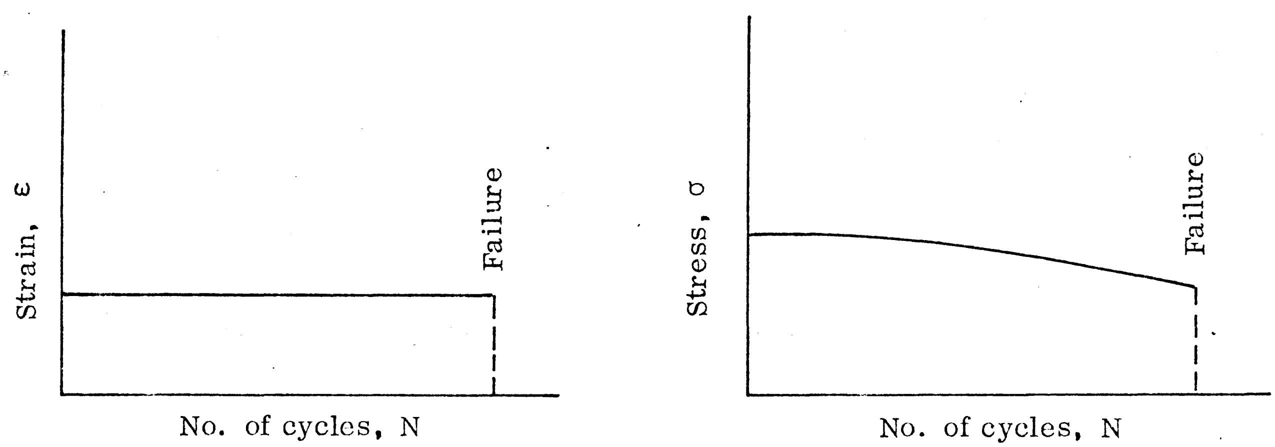


Figure 2. Controlled strain fatigue test.[10]

Load Variables

Many types of loadings can be used in a laboratory fatigue test. The primary variables are the load history, the rate of load application, and the pattern of applying the load.

Load History

A specimen may be subjected to two types of load history, simple and compound.[9] In simple loading, whether controlled stress or controlled strain, the load condition remains unchanged throughout the fatigue test. In compound loading there are changes in the load condition during the test with a change being defined as a change in the amount of stress or strain applied to the specimen or in the environment, such as an increase or decrease in temperature.

Compound loadings can be preprogrammed to simulate the loadings a pavement receives from traffic; however, the process is quite involved, so simple loadings are more widely used.

Load Rate

The rate of loading is the number of load applications made over an established period of time. It has been proven that the fatigue life varies with the rate of loading. Tests by Monismith and Deacon indicated that over loading rates ranging from 30 to 100 repetitions per minute, there was a significant decrease in fatigue life as the loading rate increased.[9] In tests performed by Taylor, it was found that loading rates of less than 200 repetitions per minute caused a greater variation in specimen service life than did higher loading rates.[18]

Patterns of Applying Loads

The load patterns commonly used are block, sinusoidal, and haversine.[9,19] The block pattern for a simple loading is shown in Figure 3. As was previously discussed, for a simple load rate the level of stress or strain is kept constant throughout the test. When applying a compound loading, as shown in Figure 4, the levels of stress or strain are varied. Compound loading tests are done predominately with the block pattern; however, haversine and sinusoidal patterns may also be used.

There are two ways in which a compound loading can be applied; sequentially or randomly. Sequential loading is performed by applying a fixed number of loadings under one load condition, then another fixed number under a different condition. This pattern, which is illustrated in Figure 4, is continued until the specimen fails. In random loading each load applied is selected randomly so that the probability of any load being selected is equal to that of any other load regardless of the preceding order of applied load conditions.

The haversine pattern is used mostly for simple loading rather than compound loading. It constitutes the compressive half of the sine curve, in which the simply supported beam is loaded and then enough tension is applied to force it back to the neutral axis. This pattern is preferred over the sinusoidal pattern because it more closely resembles the loadings of roadway pavements. The surface layer of a roadway undergoes both tensile and compressive forces during a wheel loading; however, the compressive forces far out weigh the tensile forces.

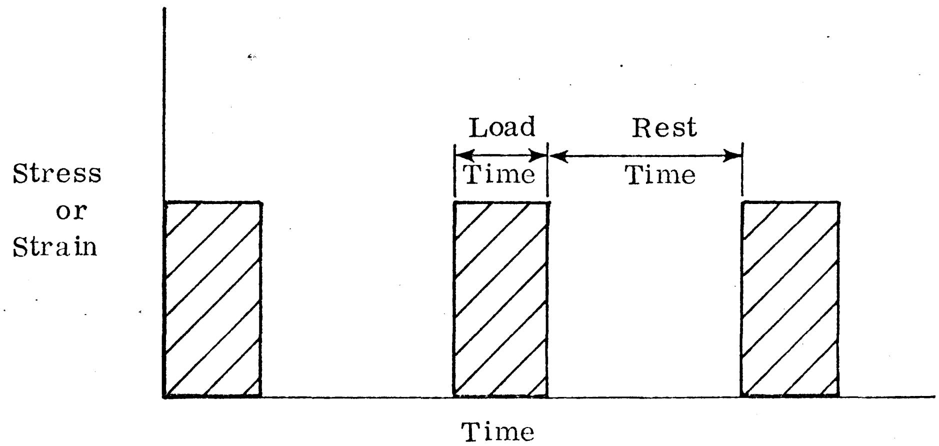


Figure 3. Block pattern for simple loading. (9)

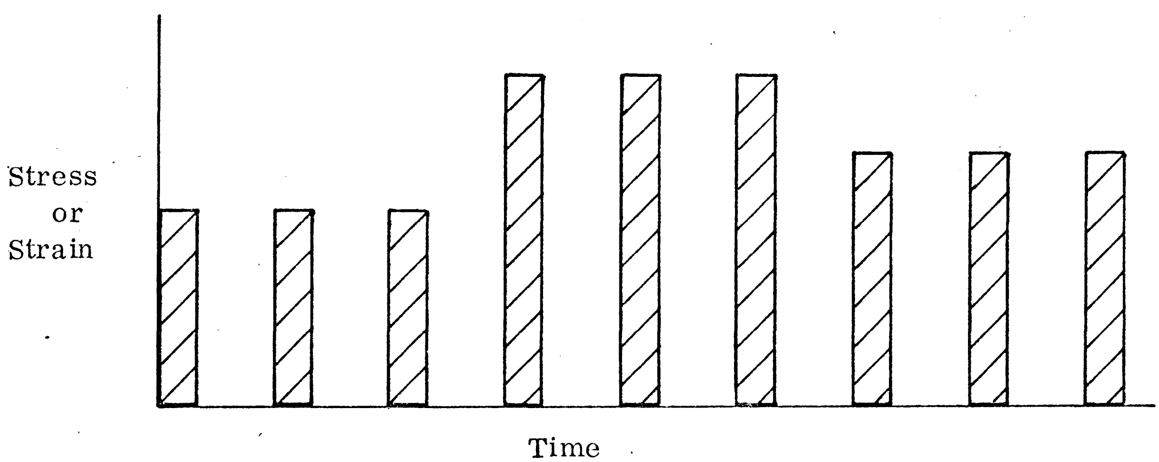


Figure 4. Block pattern for compound loading. (9)

Definition of Failure

Failure of a specimen is generally defined as the point at which the specimen no longer has the ability to satisfactorily withstand a desired load.[9] For fatigue tests, the failure condition varies depending on the mode of testing used.

In the controlled stress mode of testing, fatigue life is defined as the number of loadings required for the specimen to completely fracture. In the controlled strain mode of testing the dynamic load applied to the specimen is recorded after the first 200 to 300 load applications, and the fatigue life is reached when the dynamic load reduces to a predetermined percentage of the initial dynamic load. This percentage usually varies between 50% and 75%. It has been reported by Epps and Monismith that a 25% and 50% reduction in stiffness correspond to small and extensive crack propagation, respectively.[19]

Another method used to determine failure involves gluing foil strips to the tensile sides of the specimen, 1/2" (1.27 cm) from each bottom edge.[20] The strips are wired in parallel so that both must be broken for failure to be reached. This method of determining failure is used primarily in constant stress testing.

FATIGUE TESTS

The following discussion focuses on the various types of fatigue tests. The test methods are grouped by the type of specimen (beam, plate, Marshall, etc.) used and the discussion under each type of specimen covers (1) the type of fatigue testing equipment needed and the capabilities of this equipment; (2) the data acquired from the test; and (3) the analytical methods used in evaluating the data.

Beam Specimen

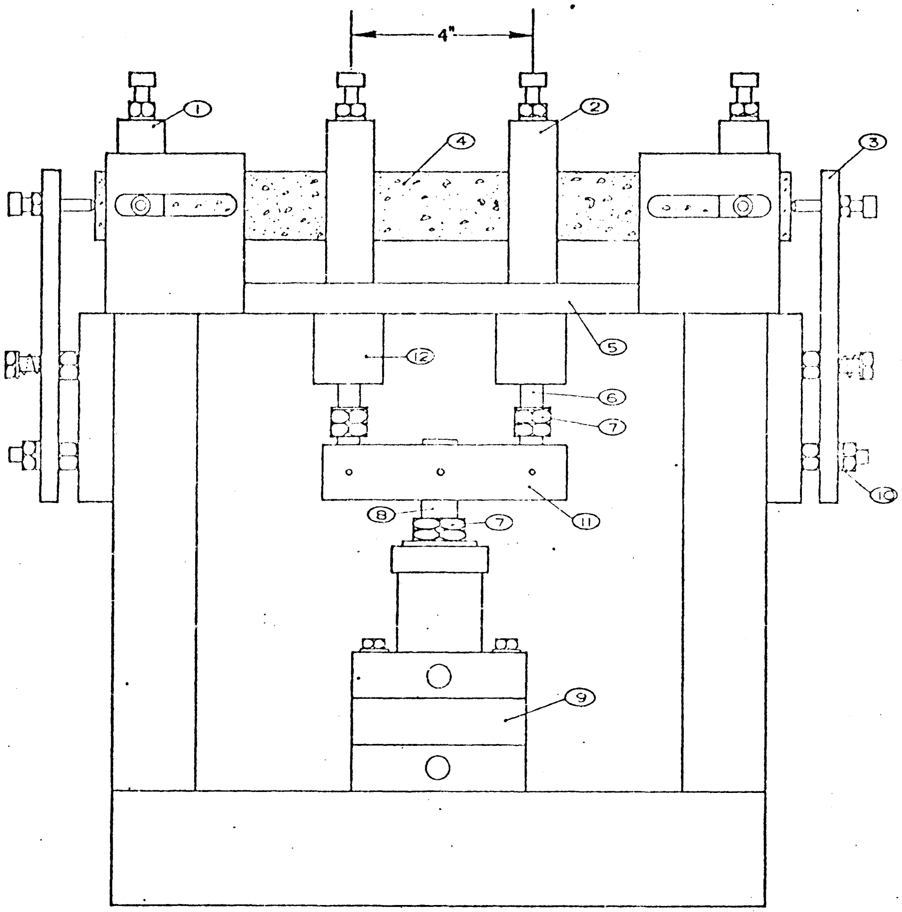
Equipment

The fatigue testing equipment that has been developed for beam specimens has two major components — the repeated-flexure apparatus and the control and loading systems. The repeated-flexure apparatus[9,12] is basically the same for any control and loading system[9,10,11,12,13] used. The only variations in the apparatus would be changes made to accommodate various sizes of specimens. The control and loading systems are of two types — air or pneumatic pressure systems and electrohydraulic systems.

Repeated- Flexure Apparatus

The repeated-flexure apparatus,[9] often termed the testing frame, is used to hold the specimen so that the loadings can be applied. This apparatus, shown in Figure 5, is designed so that a symmetrical, two-point load is applied to a simply supported beam and results in undirectional bending stresses.

The specimen is held in position by four clamps, two of which apply the load (load clamps) while the other two (reaction clamps) support the specimen. These clamps, as shown in detail in Figures 6 a and 6 b, have lubricated rockers that eliminate torsional stresses resulting from the specimen not being perfectly square. The reaction clamps are designed so that there is no relative movement between the clamps and the specimen. These clamps are also equipped with ball bearings that allow longitudinal movement and rotation under load. The load clamps have a transverse pin that allows rotation during loading and thus eliminates any bending movement which may be introduced. To allow longitudinal movement of the specimen, a lubricant must be used to minimize friction between the specimen and the load clamp. Teflon tape and Molykate powder can be used for this purpose.



Key:

1. Reaction clamp
2. Load clamp
3. Restrainer
4. Specimen
5. Base plate
6. Loading rod
7. Stop nut
8. Piston rod
9. Double-acting, Bellofram cylinder
10. Rubber washer
11. Load bar
12. Thomson ball bushing

Figure 5. Repeated flexure apparatus. (9)

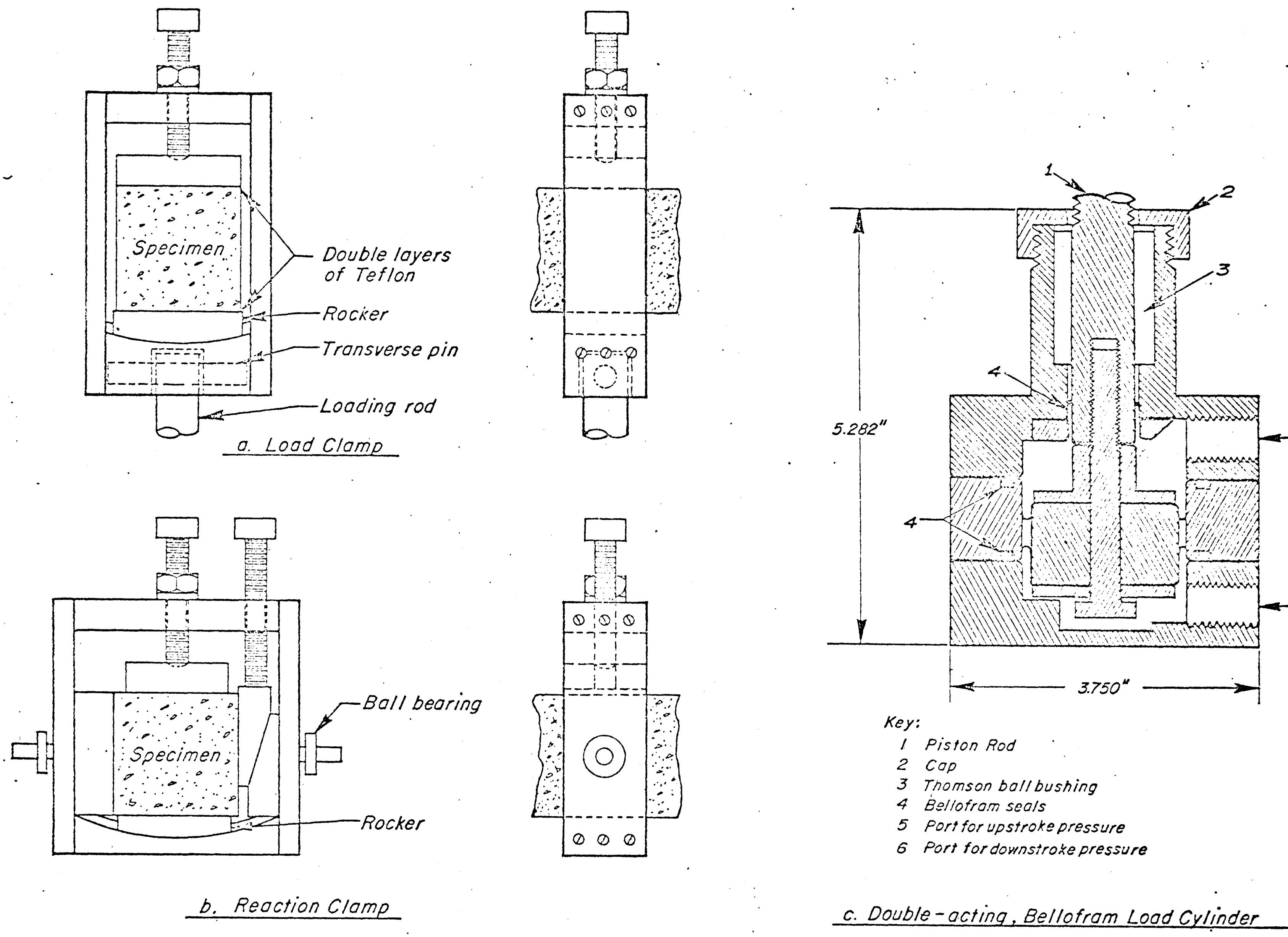


Figure 6. Details of components of repeated flexure apparatus. (9)

The apparatus is designed to fit one specific size beam. Square beam sizes used have varied from a vertical cross section of 1.5 in. x 1.5 in. (3.8 cm x 3.8 cm)[9,11] to 3.0 in. x 3.0 in. (7.6 cm x 7.6 cm).[10,12] Beams not having a square cross section have been tested by Kirk,[13] who used a beam having cross sectional dimensions of 2 in. x 2 3/4 in. (5 cm x 7 cm). The beams are usually 15 in. (38.1 cm) in length, however, Kirk varied this dimension also and used a beam 13 3/4 in. (35 cm) in length.

Control and Loading Systems

As stated earlier, two systems are used to generate and control the applied load. These systems, the air or pneumatic pressure[9,11] and the electrohydraulic,[12,13] are discussed in detail below.

Air or Pneumatic System — The air or pneumatic pressure system developed by Deacon,[9] supplies a controlled pneumatic pressure to a double acting Bellofram cylinder. The Bellofram cylinder, shown in Figure 5 and in more detail in Figure 6c, applies the load to the specimen. The pneumatic pressure is controlled by mechanical air control (MAC) valves regulating the air pressure between the air tanks and the Bellofram cylinder. These valves are three-way solenoid-operated pressure valves activated by the control system. The MAC valve is designed to allow air to enter either the upstroke chamber or the downstroke chamber, or to completely block off the flow of air into the Bellofram cylinder.

The frequency of loading is regulated through the central system by a mechanically powered cam and microswitch arrangement. The frequency of loading is approximately 120 applications per minute, with the duration of the load increasing from a minimum of 0.05 second. An illustration of the load vs. time and deflection vs. time is shown in Figure 7.

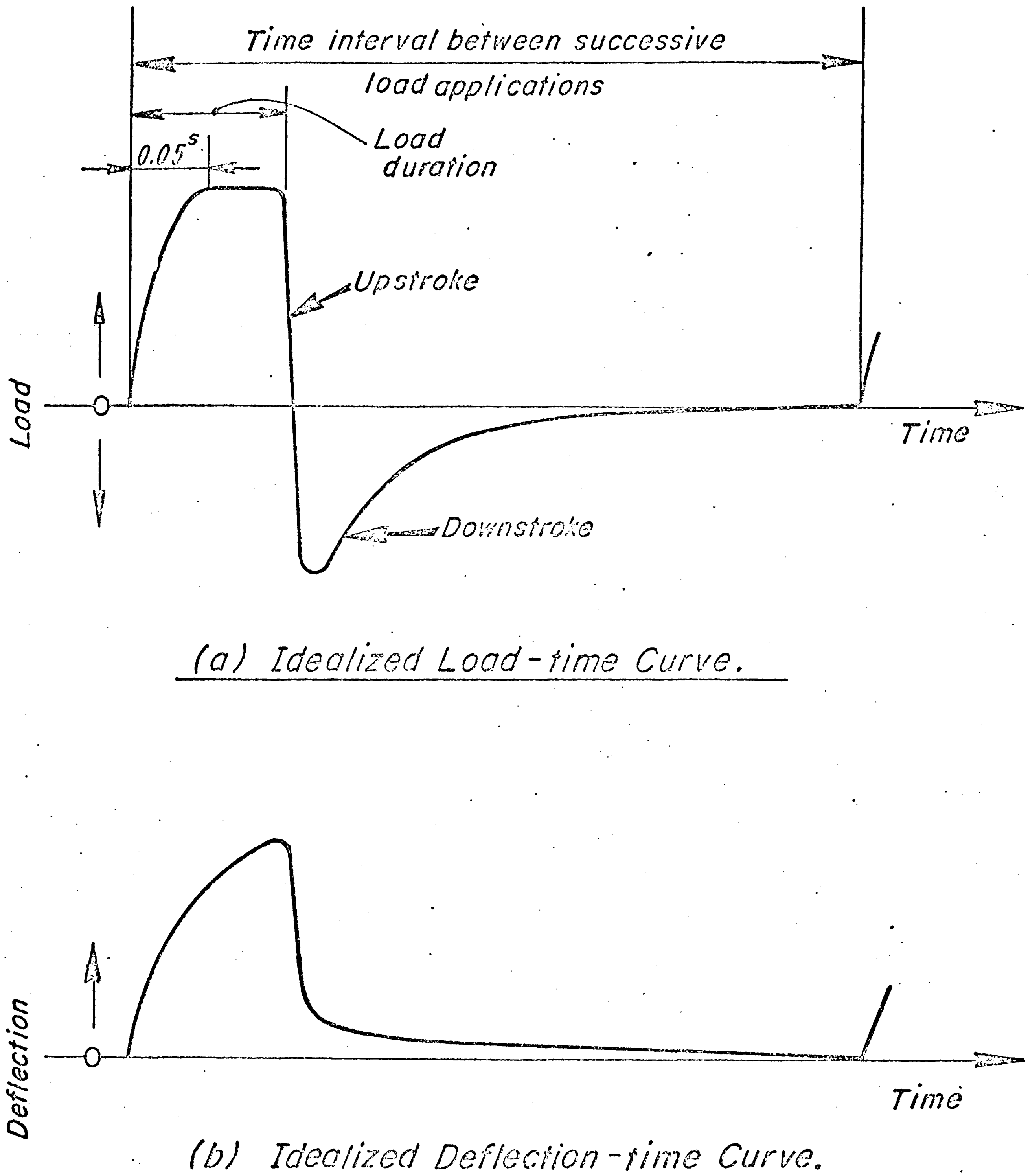


Figure 7. Load vs. time and deflection vs. time relationships for constant-stress test equipment. (9)

The magnitude of the load is controlled by the pneumatic pressure system through a pressure cylinder under an air pressure regulated to provide the desired loading. A compound block load can be applied by use of a series of pressure cylinders with MAC valves connected to the Bellofram cylinder. By programming the control system to switch the various MAC valves on and off, changes of load magnitudes can be accomplished. The design of this system allows the block loading pattern to be used with either simple or compound loading and the controlled stress or controlled strain testing mode.

The air or pneumatic pressure system is used predominately for tests in the controlled stress mode, because of the difficulty in varying the load to maintain a constant strain in the controlled strain test. To perform a controlled strain test with this equipment, the test must be constantly monitored so that the adjustments in the load necessary to maintain a constant strain level can be made manually.

Electrohydraulic System — The electrohydraulic system(12,13) is very different from the air pressure system, both in the control mechanism and in the generation of the load. This system uses a totally electronic control subsystem to activate the hydraulic subsystem that generates the load.

The testing system(21) operates in a closed loop, as shown in Figure 8, initiated by an electrical signal (load, deflection or strain) from the manual command control in the input module (performed by operator). This input is applied to the specimen and the system then compares the polarity and the magnitude of the command signal to those given by the feedback transducer. If the difference between the command signal and that of the feedback transducer is not zero, the controller makes the necessary adjustment by signaling the loading system.

The hydraulic supply is the link between the control system and the loading system. The control system, through a servo valve, regulates the flow of hydraulic fluid moving

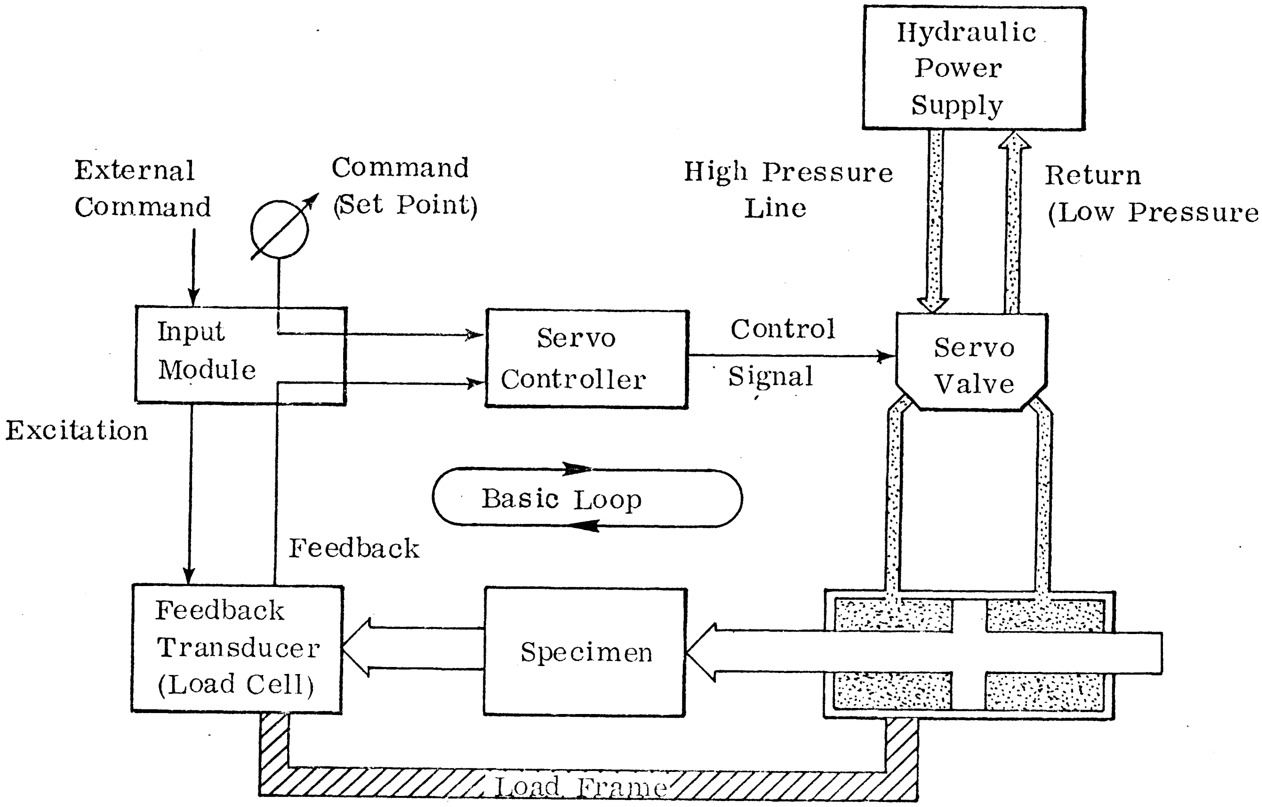


Figure 8. The basic loop of the electrohydraulic testing system. (24)

the piston. The movement of the piston provides the loading that the repeated-flexure apparatus applies to the specimen.

This type of equipment can perform in both the controlled stress and controlled strain modes. The tests are generally performed with a simple haversine load pattern, but other patterns may be used.

Data Collection

Because of the general acceptance of the repeated-flexure apparatus for loading the specimen, the data collection methods and equipment are generally the same regardless of the control and loading system used. The only major difference lies in the method of recording and the load applied to the specimen. The electrohydraulic system has a load cell in the repeated-flexure apparatus which determines the load applied to the specimen. (12) The air pressure system can measure the load directly from the pressure maintained in the air pressure tank, provided it has been calibrated with a load cell. (9)

The centerline beam deflection is measured by a linear, variable, differential transformer (LVDT). The value measured by the LVDT is recorded on a strip chart recorder.

Analytical Methods

Linear Fatigue Life Relationships — The methods used to analyze the data are the same regardless of the size of specimen used. The basic equations(12) for extreme fiber stress, stiffness modulus, and extreme fiber strain are listed below. The equation applies to a beam of uniform cross section which is simply supported at the ends and loaded by two symmetrical, concentrated loads applied near the center.

$$\sigma = \frac{3aP}{bt^2} \qquad (1)$$

$$E_s = \frac{Pa(3l^2 - 4a^2)}{48Id} \qquad (2)$$

$$\varepsilon = \frac{12td}{(3l^2 - 4a^2)} \qquad (3)$$

where

σ = extreme fiber stress, psi

a = 1/2 (reaction span length - distance between load clamps), in.

P = dynamic load applied to deflect beam, in.,

b = specimen width, in.

t = specimen depth, in.

E_s = flexural sitffness modulus based on deflection, psi.

l = reaction span length, in.

I = specimen movement of inertia, in.^{4}

d = dynamic deflection of beam center, in.

ε = extreme fiber strain of mix in region of equal moment calculated from deflection of beam center, in./in.

The stress, σ , and fracture life, N_f, can be correlated using a least squares regression analysis that results in a linear log-log plot of σ versus N_f.[12] This relationship is shown in the form:

$$N_f = K_2 \ (1/\sigma)^{n_2} \tag{4}$$

where N_f = number of load applications to failure

K_2 = constant depending on the mix

σ = extreme fiber bending stress, psi

n_2 = constant (slope of regression line)

With the above the above equation, the fatigue life for a given bending stress can be estimated.

A similar relationship can be established for strain, ε , versus fatigue life, N_f. This relationship is also obtained from a least square regression analysis,[12] and is shown as

$$N_f = K_1 \ (1/\varepsilon)^{n_1} \tag{5}$$

where N_f = number of load applications to failure

K_1 = constant depending on the mix

ε = initial bending strain based on center point deflection of specimen

n_1 = constant (slope of regression line)

Fracture Mechanics — The fatigue behavior of bituminous pavements has been analyzed from the fracture mechanics viewpoint by Majidzadeh et al.[17] This analysis has been developed using beam specimens tested in a controlled stress mode with loading of 0.1 sec. duration and a 1.0 sec. rest period. During loading it is necessary to measure the crack length or determine it by indirect methods. The direct methods are X-ray, ink-staining, and visual observation. The indirect method uses the inverse slope of the load/deflection diagram for each loading cycle to represent the compliance of the beam, with an increase in compliance being directly related to an increase in crack depth.

The fracture mechanics analysis uses the equation

$$N_f = \int_{C_o}^{C_f} \frac{1}{AK^n} \quad dc \qquad (6)$$

where N_f = number of cycles of load to failure

A = crack growth parameter relative to materials

K_n = the stress intensity factor with n being a material constant

dc = the rate of crack propagation

C_f = the critical crack depth

C_o = the original crack depth

n = crack growth parameter relative to foundation stiffness

The stress intensity factor, K^n, can be determined by using the equation

$$K^n = P\sqrt{\frac{E}{2\,(1-U^2)} \quad \frac{L}{C}} \qquad (7)$$

where L = compliance, which is the inverse slope of the load/deflection diagram under each loading cycle

C = crack depth

P = load

E = Young's modulus

U = Poisson's ratio

The values of parameters A, n, C_o and C_f also must be determined before the fatigue life can be computed. These parameters are used to describe the fatigue process and help predict fatigue life.

The parameter A is affected by mixture variables such as percent asphalt, asphalt hardness, and mixture density. The value of A is variable and is computed by using the equation

$$A = \frac{1}{K^n} \quad \frac{dc}{dN} \qquad (8)$$

The values of the non-dimensional parameters C_o and C_f are determined during the fatigue tests, which C_f being based on the crack depth at failure and C_o on the initial cracks and their sizes. Typical values for C_o range from 0.025 to 0.1 for sand-asphalt and asphaltic concrete mixes, respectively.

The value of n is the slope of the line representing the crack growth rate, $^{dc}/dN$, plotted against the stress intensity factor. The slope of this line increases as the elastic modulus of the foundation increases. An illustration of the relationship is shown in Figure 9.

By determining the parameters C_o, C_f, and n, through a fatigue test, the fatigue life of a bituminous mix may be predicted for any load through the use of equations 6 and 7.

Plate Specimens

A fatigue testing machine capable of testing a plate specimen under a sinusoidal load was developed by Jiminez.(14) This machine, called the deflectometer flexure fatigue tester, is capable of testing both laboratory specimens and road samples. A special vibratory kneading compactor is used to make laboratory specimens 18 in. (45.7 cm) in diameter and between 1 in. (2.5 cm) and 5 in. (12.7 cm) thick.

Equipment

The test specimen is supported by the reaction unit shown in Figure 10. This unit consists of a metal chamber that contains oil and air and is covered by an airtight rubber membrane. The membrane provides support for the specimen by entering a controlled amount of air pressure into the chamber. The specimen is held in place along its circumference by a steel ring having an inside diameter of 14 in. (35.6 cm) and an outside diameter of 20 in. (50.8 cm). This ring is secured to the chamber by 16 bolt-spring units.

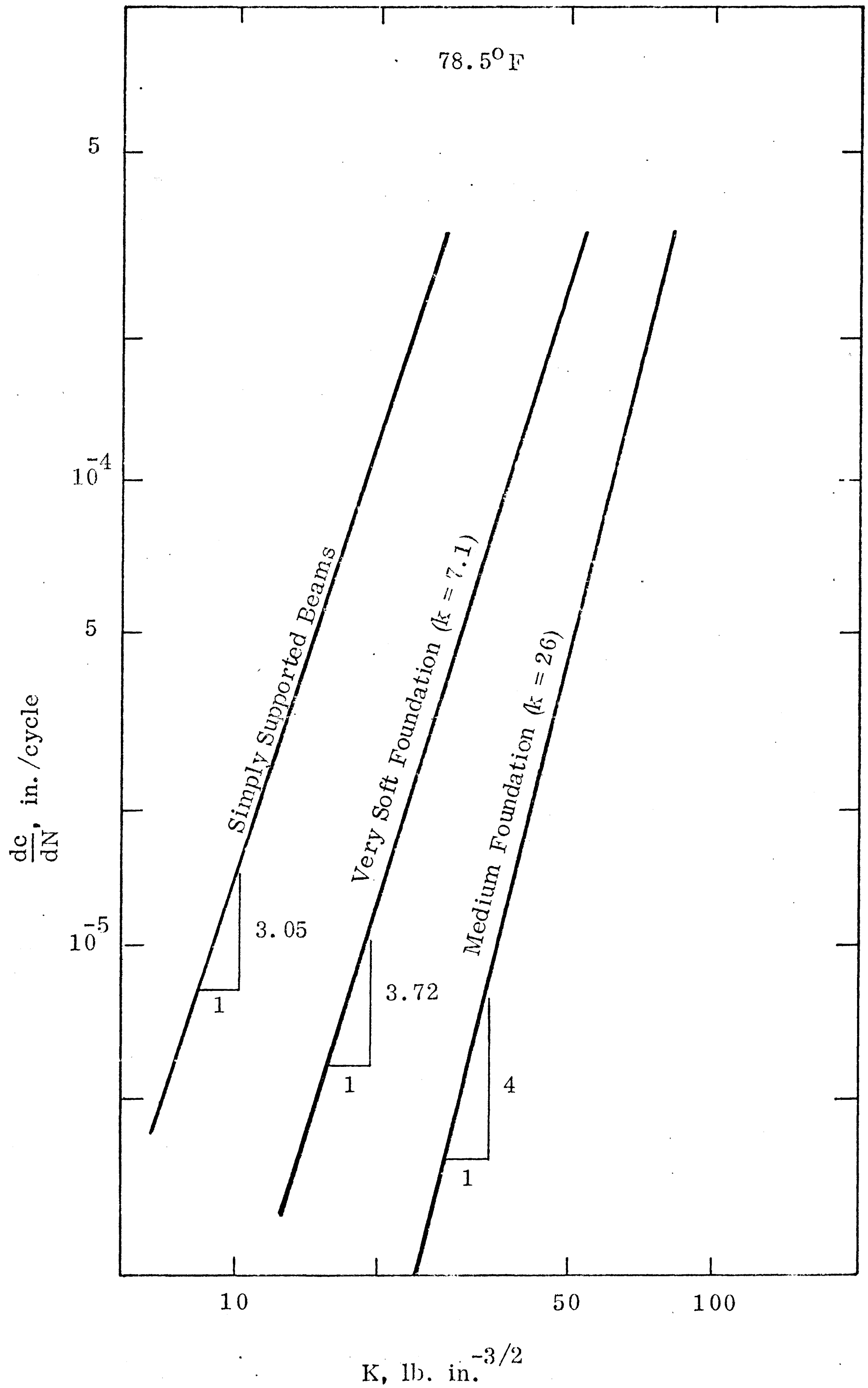
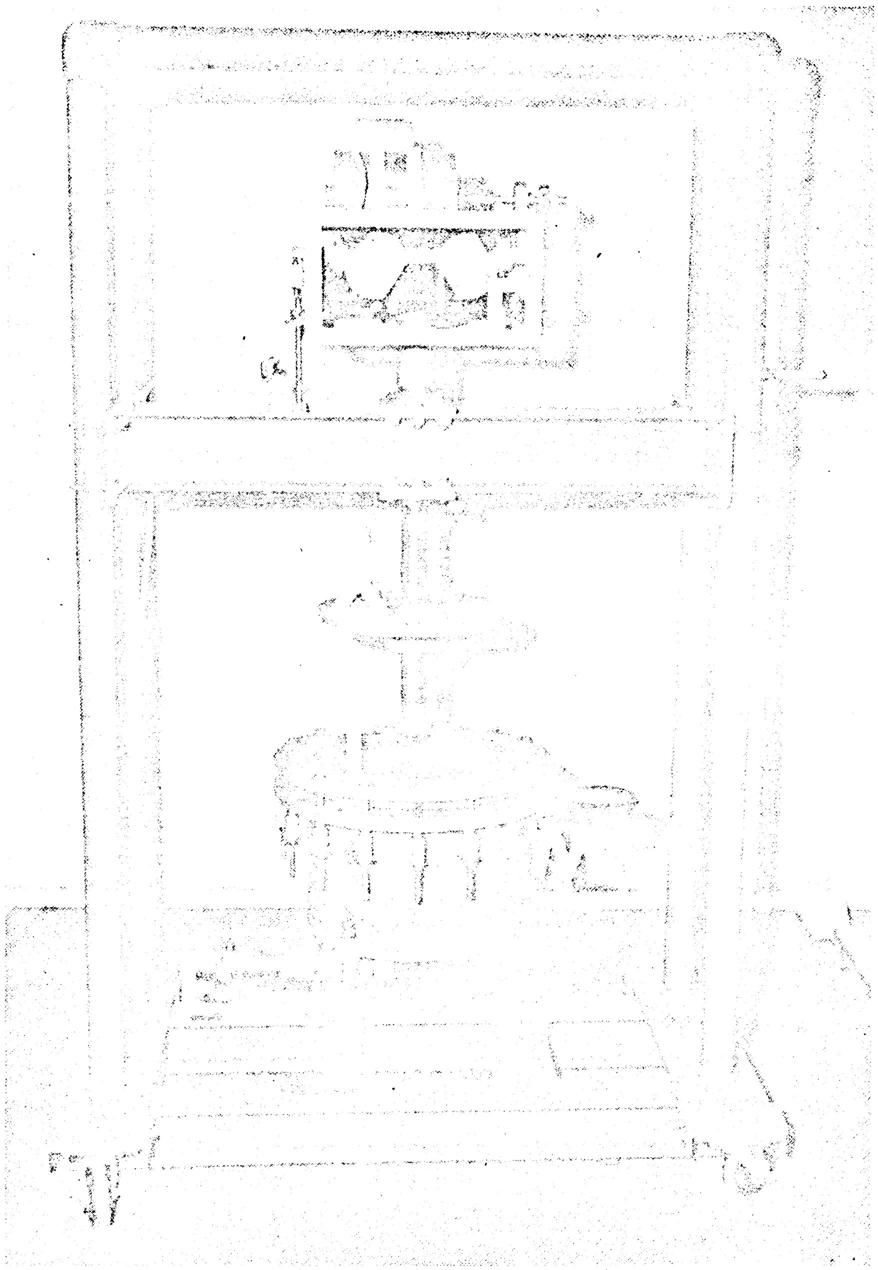


Figure 9. Comparison of rates of crack propagation in simply supported beams and beams on elastic foundation.(17)



A — Reaction unit supporting 18" diameter specimen
D — Loading system of counter rotating eccentric masses
E — Displacement pump
H — Electric motor for loading system
M — Pressure gage for reaction unit
T — Specimen
X — Ballast for dead load

Figure 10. Deflectometer flexure fatigue tester. (14)

The specimen is loaded in the center using a load disk with a contact area of 5 in.^{2} (32.3 sq. cm). The loading system is designed to allow it to move with the deflection of the specimen. The total load applied to the specimen is fixed and comprises a 150-lb. (68.0 kg) dead load and a 130-lb. (59.0 kg) live load. The dead load is the weight of the motor and loading system acting on the specimen. The live load is applied in a sinusoidal form using counter-rotating eccentric masses. The live loading is applied at a frequency of 12 repetitions per second.

Data Collection

The deflectometer flexure fatigue tester uses only the controlled stress mode of testing. The data collected are limited to the number of loadings, support pressure, and deflection. The deflection is measured by dial extensometer gages which are read by the operator. The number of loadings is recorded by a counter driven by the shaft rotating the eccentric masses.

The initial deflection reading is taken after the first 1,000 loadings. The specimen reaches failure when a running plot of the deflections vs. number of loadings deviates from a straight line, the point of tangency is the failure point.

Analytical Methods

The deflectometer type of fatigue testing equipment is extremely limited because it is capable of using only a controlled stress mode of testing with a sinusoidal load pattern. Since only one loading can be placed on the specimen, a strain vs. fracture life relationship cannot be developed. This test can give the data necessary for computing the dynamic modulus of elasticity using the total load, twice the repeated live load, the repeated mid-point deflection and a support pressure of 1.5 psi (10.4 KPa).

Cylindircal Specimens

The use of cylindrical specimens in fatigue testing has been limited. Moore and Kennedy[22] used a specimen 4 in. (10.2 cm) in diameter and 2 in. (5.1 cm) in height.

The testing equipment is the closed-loop electrohydraulic loading system with an indirect tensile loading head shown in Figure 11. The recording equipment is a light-beam oscillograph that records both the load and its corresponding deformation. The load is controlled by a strain gage type load cell and has a frequency of one cycle per second.

The use of this equipment has been directed toward testing and evaluating the effect of various material properties on fatigue life. The test data have been used in a multiple regression analysis to develop equations for estimating fatigue life. Variables such as asphalt content, asphalt cement type, mixing temperature, compaction temperature, and stress levels have been used in the regression analysis.

Trapezoidal Specimen

The trapezoidal specimens originally were used by Bazin and Saunier[15] and then later by Coffman et al.[16] The specimens can be either laboratory fabricated or taken from the pavement. They are then sawed into a trapezoidal shape.

The testing equipment consists of a closed-loop, electrohydraulic system. The specimen is firmly connected to steel plates as shown in Figure 12, then bolted to the loading frame as shown in Figure 13. It is loaded through a pretensioned wire attached through the top plate. The C-shaped steel frame is attached to the closed-loop, electrohydraulic system.

The specimen is loaded under a controlled stress mode and a sinusoidal load pattern. Failure is monitored by using lines of conductive paint placed on the sloping faces of the trapezoid and connected to a galvanometer which detects the cracks and their magnitudes. The deflections are measured with a LVDT and recorded on an oscillograph.

From the data recorded, the relationship for predicting fatigue life by the least sequares regression analysis, $N = K\ (1/E)^n$, as mentioned previously can be developed.

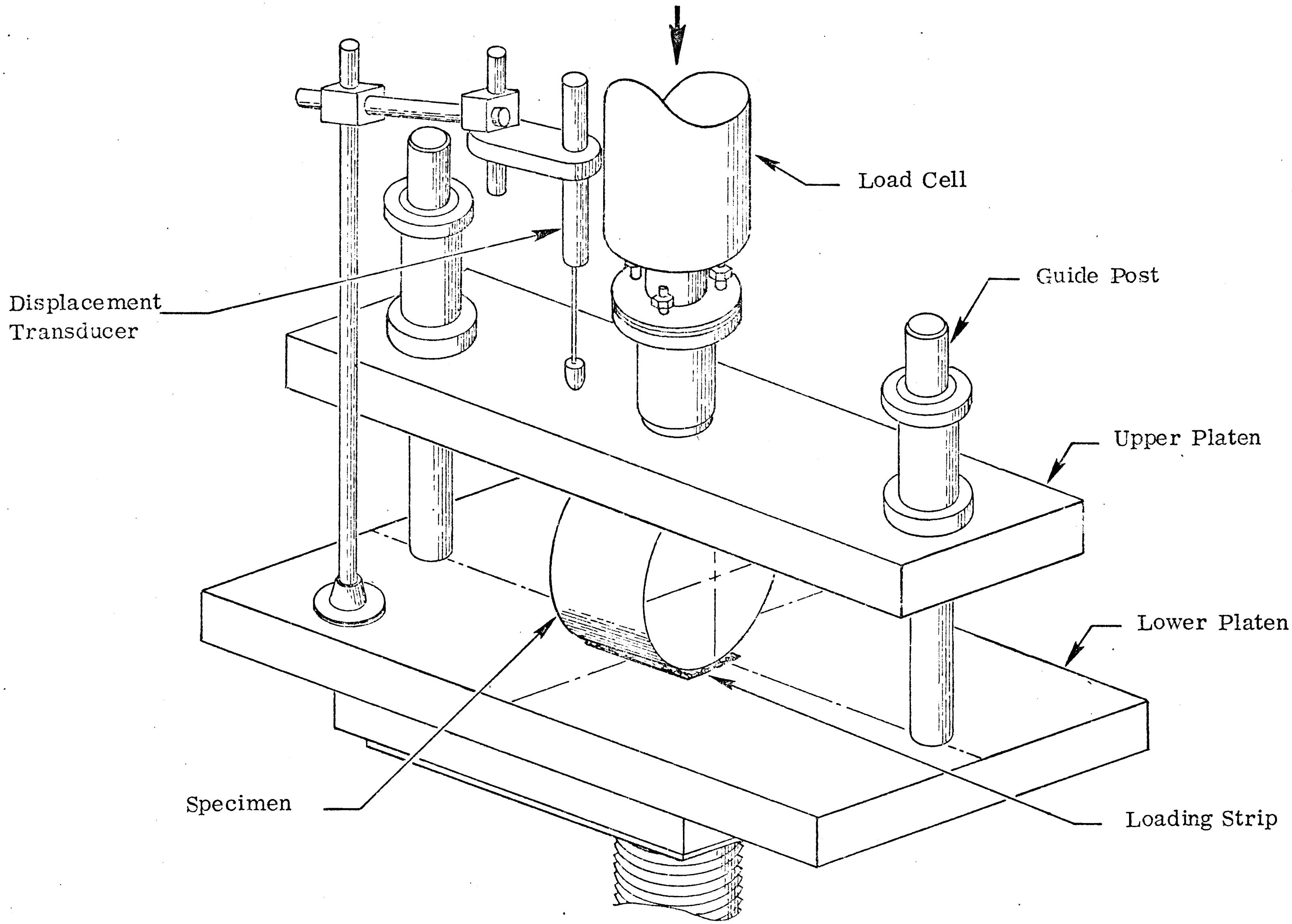


Figure 11. Loading head with rigid parallel platens. (23)

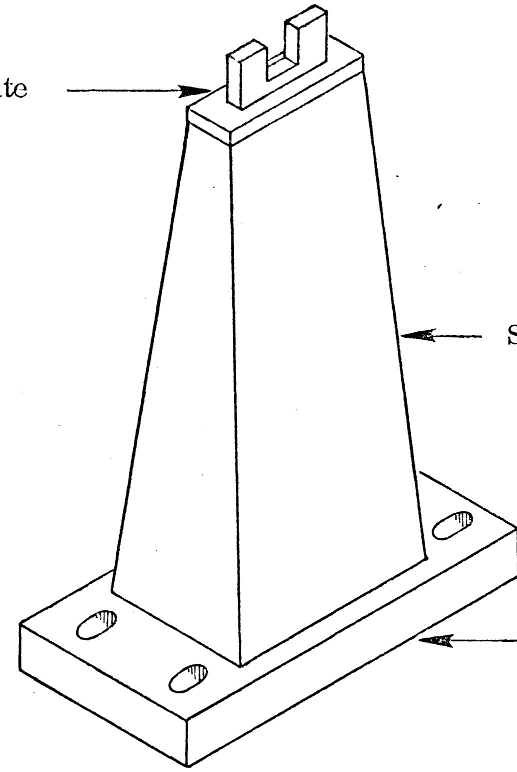


Figure 12. Trapezoidal specimen epoxyed to steel plates.[16]

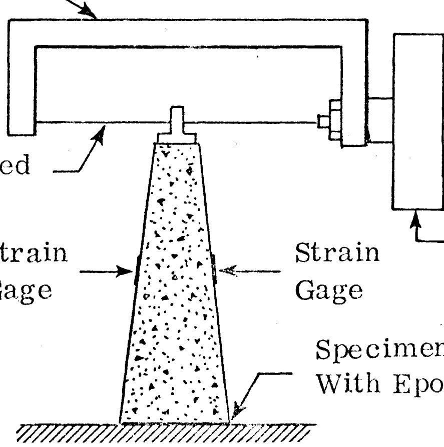


Figure 13. Trapezoidal specimen loading apparatus.[16]

Pell Specimen

A fatigue test method using a specimen of the shape shown in Figure 14 was developed by Pell.[8,24] This specimen is unique because the diameter of its "neck" varies from 3 1/2 in. (8.9 cm) to 2 1/2 in. (6.4 cm). The metal specimen end fittings, shown in Figure 14, are placed on the specimen during its fabrication. The specimen is clamped in a vertical position using the chuck of the rotating type cantilever fatigue machine.

The loading is applied to the top bearings by a loading stirrup connected to weights, which places a constant bending stress on the specimen. The specimen is then rotated by the main shaft connected to the base of the testing machine. The rotation subjects the specimen to a sinusoidal loading. The maximum bending stress is developed in the neck of the specimen, and when fracture occurs the specimen will break completely in half. The motor driving the rotating shaft is a variable speed D.C. electric motor of 1.5 HP capable of varying the loading frequency from 80 to 3,000 cycles per minute. The loading frequency used by Pell was 1,000 cycles per minute.

Pell used a controlled temperature bath of alcohol and water that enabled tests to be performed with temperatures controlled to an accuracy of $\pm 0.2^{o}C$ over a range of $-5^{o}C$ to $+30^{o}C$.

The data recorded during the test are the load applied to the specimen and the deflection of the specimen at the loading head. The deflection can be determined by measuring the movement of the loading wire from its initial unloaded position.

Again, the least squares regression analysis is used to relate strain to fatigue life by the equation $N = K\ (1/E)^{n}$.

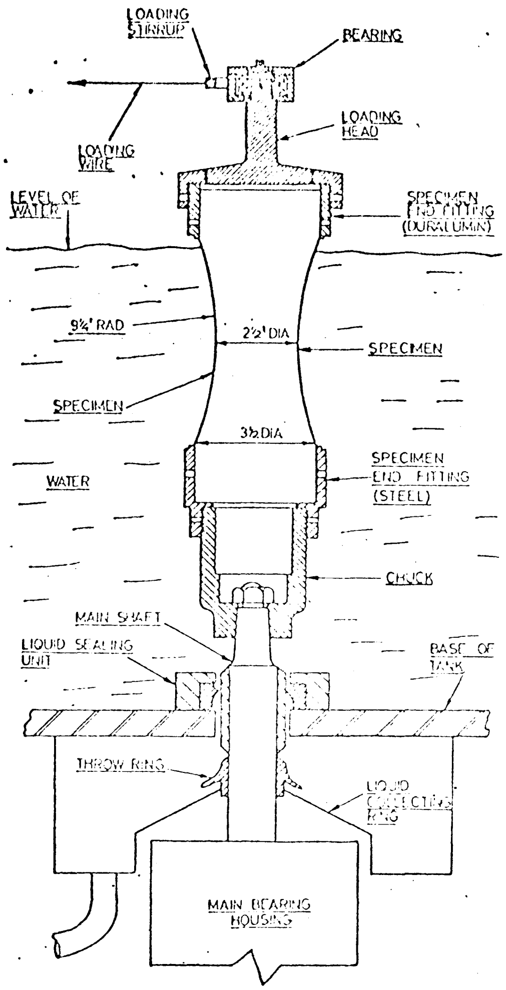


Figure 14. Details of the specimen and loading apparatus. [24]

EVALUATION OF TEST METHODS

In evaluating the test methods, each was examined against the following criteria:

1. The capability of the method to perform both controlled stress and controlled strain modes of testing.
2. The capability of applying both simple and compound loadings.
3. The capability of varying the frequency of loading.
4. The capability of using various load patterns.
5. The difficulty of fabricating the specimens.

Beam Specimens

The test methods used to test beam specimens — the air or pneumatic pressure system and the electrohydraulic systems — both use similar repeated-flexure apparatus. The control and loading mechanisms are also quite similar; each being capable of using controlled stress and controlled strain and simple and compound loading, and of varying the frequency of loading as necessary. The distinguishing characteristic is that the electrohydraulic system is capable of using any load pattern, while the pneumatic pressure system is limited to a block pattern. The fabrication of the specimen is relatively simple using the procedure outlined by ASTM Designation D3202-73 for the California Kneading Compactor.

Plate Specimens

The deflectometer test, used with a plate specimen, is capable of applying only a controlled stress mode. The testing mechanism applies a simple loading of constant magnitude and frequency. Since the magnitude and frequency are constant, the curve for predicting fatigue life cannot be developed. This test method is further limited by its inability to apply any load pattern other than sinusoidal. The fabrication of the specimens is difficult because of the size of the specimens and the type of compaction equipment necessary.

Cylindircal Specimens

The method of fatigue testing cylindrical specimens uses a 4 in. (10.2 cm) diameter specimen made under standard Marshall compaction procedures. The testing mechanism can place only compressive loads on the specimen and in a sinusoidal pattern. The test method is a controlled stress using simple loading. The frequency of loading can be varied, with high frequencies most often being used. Since there is no tensile force applied to the specimen, which would represent the elastic rebound of the pavement, the laboratory fatigue life values may not be comparable to roadway fatigue life values.

Trapizoidal Specimen

The trapizoidal specimen uses the electrohydraulic load and control system discussed under beam specimens. The testing mechanism is capable of performing controlled stress and controlled strain tests, applying simple and compound loadings, varying the frequency of loading, and using various load patterns. The major drawback of the test method is the difficulty of specimen fabrication and the placement of the specimen in the loading apparatus.

Pell Specimen

The Pell specimen is tested using the rotating cantilever machine. This machine is capable of producing a controlled stress mode under a sinusoidal loading pattern. The specimen can be tested under simple or compound loadings and at different frequencies. However, the odd shape of the specimen makes fabrication difficult.

Summary

In summary, the test method showing the greatest overall capability in fatigue testing is the electrohydraulic control system using a 3 in. x 3 in. x 15 in. (7.6 cm x 7.6 cm x 38.1 cm) beam specimen. This method is capable of performing all modes of testing desired.

1522

REFERENCES

1. Grumm, Fred J., "Designing Foundation Courses for Highway Pavements and Surfaces," California Highways and Public Works, Vol. 20, No. 3, March 1942, pp. 6-9, 20.
2. Porter, O. J., "Foundations for Flexible Pavements." Proceedings, Highway Research Board, Vol. 22, 1942, pp. 100-143.
3. Hveem, F. N., "Pavement Deflections and Fatigue Failures," Bulletin, Highway Research Board, Washington, 1955, pp. 43-87.
4. Hennes, R. G., and H. H. Chen, "Dynamic Design of Bituminous Pavements," The Trend in Engineering, University of Washington, January 1959, pp. 22-25.
5. Nijboer, L. W., "Mechanical Properties of Asphalt Materials and Structural Design of Asphalt Roads," Proceedings, Highway Research Board, Vol. 33, 1954, pp. 185-198.
6. Van der Poel, C., "Road Asphalt," Building Materials, Their Elasticity and Inelasticity, edited by M. Rainer, New York, Interscience Publishers, 1954, pp. 361-413.
7. Monismith, C. L., "Flexibility Characteristics of Asphaltic Paving Mixtures," Proceedings, Association of Asphalt Paving Technologists, Vol. 27, February 1958, pp. 74-106.
8. Pell, P. S., "Fatigue Characteristics of Bitumen and Bituminous Mixes," Proceedings, International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, Michigan, 1962, pp. 310-323.
9. Deacon, J. A., and C. L. Monismith, "Laboratory Flexural Fatigue Testing of Asphaltic Concrete with Emphasis on Compound Loading," Paper presented at the annual meeting of the Highway Research Board, Washington, D. C., January 1966.

10. Maupin, G. W., "Effects of Aggregate Shape on the Fatigue Behavior of an Asphaltic Surface Mixture," Virginia Highway & Transportation Research Council, Charlottesville, Virginia, June 1968.

11. Monismith, C. L., K. E. Secar, and E. W. Blackmer, "Asphalt Mixture Behavior in Repeated Flexure," Proceedings, Association of Asphalt Paving Technologists, Vol. 30, February 1961, pp. 188-222.

12. Kallas, B. F., and V. P. Puzinauskas, "Flexure Fatigue Tests on Asphaltic Paving Mixtures," Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP 508, American Society for Testing and Materials, 1972, pp. 47-65.

13. Kirk, J. M., "Results of Fatigue Tests on Different Types of Bituminous Mixtures," Proceedings, Second International Conference on the Structural Design of Asphaltic Pavement, Ann Arbor, Michigan, 1967, pp. 571-575.

14. Jiminez, R. A., "Fatigue Testing of Asphaltic Concrete Slabs," Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP 508, American Society for Testing and Materials, 1972, pp. 3-17.

15. Bazin, P., and J. B. Saunier, "Deformability, Fatigue and Heating Properties of Asphaltic Mixes," Proceedings, Second International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, Michigan 1967, pp. 553-569.

16. Coffman, B. S., G. J. Ilves, and W. F. Edwards, "The Fatigue of Flexible Pavements," Report EES 296B-1, Transportation Research Center, Ohio State University, Columbus, Ohio, February 1971.

17. Majidzadeh, Karman, E. M. Kauffman, and C. L. Saraf, "Analysis of Fatigue of Paving Mixtures from the Fracture Mechanics Viewpoint," Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP 508, American Society for Testing and Materials, 1972, pp. 67-83.

18. Taylor, I. F., "Asphaltic Road Materials in Fatigue," Thesis, University of Nottingham, October 1968.

19. Epps, J. A., and C. L. Monismith, "Fatigue of Asphalt Concrete Mixtures — Summary of Existing Information," Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP 508, American Society for Testing and Materials, 1972, pp. 19-45.

20. Monismith, C. L., J. A. Epps, D. A. Kasianchuk, and D. B. McLean, "Asphalt Mixture Behavior in Repeated Flexure," Report No. TE 70-5, Office of Research Services, University of California, Berkeley, California, December 1970.

21. "An Introduction to MTS Closed-Loop Testing Systems" published by Materials Testing Systems Corporation.

22. Moore, Raymond K., and Thomas W. Kennedy, "Tensile Behavior of Subbase Materials under Repetitive Loading," Research Report 98-12, Center for Highway Research,

23. Anagnos, James N., and Thomas W. Kennedy, "Practical Method of Conducting the Indirect Tensile Test," Center of Highway Research, University of Texas at Austin, August 1972.

24. Pell, P. S., "Fatigue of Asphalt Pavement Mixes," Proceedings, Second International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, Michigan, 1967, pp. 577-593.