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16. Abstract

Asphaltic concrete overlays are often used in an attempt to restore the riding quality of a roadway and extend its useful life. However, these overlays are susceptible to premature deterioration as a result of transverse reflection cracking, whereby a cracking pattern existing in the original pavement is extended into and through the new overlay.

Reflection cracking occurs in new overlays due to their inability to withstand shear and tensile stresses created by movements of the underlying pavement. These damaging movements may be caused by traffic loading, thermally induced contractions of the paving materials, or a combination of these. Various "engineering" fabrics have been used in recent years to provide reinforcement and undersealing for overlays in attempting to prevent and/or delay the occurrence of reflection cracking, and the subsequent penetration of water into the sublayers. Fabrics reduce the amount of water that enters the sublayers of a pavement both by reinforcing and by undersealing the overlay. Reinforcing delays the appearance of the reflection cracking and reduces the width of cracks that develop. Undersealing may not prevent water from entering the pavement structure below the overlay but usually reduces the amount of water that penetrates into the sublayers.

Six commercially available engineering fabrics were tested in an effort to develop a reinforced overlay design that could withstand the reflective cracking forces. Laboratory testing consisted of subjecting fabric reinforced laboratory prepared overlay specimens to cyclic tensile loads. This testing was performed on the TTI Overlay Tester, a hydraulically powered apparatus designed to simulate approximately (over)

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the thermally induced contraction and expansion of a cracked roadway pavement beneath an overlay. The testing scheme included placing reinforcement fabric in one of two locations within the overlay and using three distinct tack coat application rates (low, optimum, and high) of a liquid asphalt cement when constructing the various test specimens. Six unique overlay specimens were fabricated and tested for each fabric under investigation for a total of 36 specimens in all.

Laboratory and theoretical studies indicate that the addition of an engineering fabric, in combination with a tack coat of asphalt cement, can greatly increase the resistance of an asphaltic concrete overlay to reflective cracking. This reinforcement system appears to be most effective when the fabric is installed near the lower one-third of the overlay, in combination with a tack coat rate of liquid asphalt that is sufficient to saturate the fabric and the voids in the adjoining asphalt surfaces. The use of certain engineering fabrics in overlay design could result in a substantial reduction in reflection cracking and its accompanying problems, thereby reducing future maintenance costs.

In order to apply the laboratory test results to a specific overlay in the field, it is necessary to use the two "fracture" properties of the composite material of which the overlay is constructed to calculate the expected reflection cracking life of the overlay. As shown in this report, the "fracture" properties can be measured with the TTI Overlay Tester, and they are shown to depend upon the depth of the overlay, the location of the fabric within the overlay, the tack coat application rate, the fabric weight, and the tensile modulus of the asphaltic concrete mix. A computer program has been written to make these calculations of reflection cracking life which takes into account the effects of traffic loads as well as the effects of thermal contraction that are simulated by the TTI Overlay Tester. The computer program is not included in this report since it has been transmitted to the Texas State Department of Highways and Public Transportation in a Technical Memorandum dated October 11, 1982.

Appendices to the report give a procedure for determining the optimum tack coat application rate, descriptions of the engineering fabrics used in the testing program, original test data, computer programs for test data reduction, and data reduction results.

# LABORATORY EVALUATION OF SELECTED FABRICS FOR REINFORCEMENT OF ASPHALTIC CONCRETE OVERLAYS

by

David L. Pickett
Robert L. Lytton

Research Report 261-1
Evaluation of Fabric Underseal
Research Study 2-9-79-261

Conducted for

State Department of Highways
and Public Transportation

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ABSTRACT

Asphaltic concrete overlays are often used in an attempt to restore the riding quality of a roadway and extend its useful life. However, these overlays are susceptible to premature deterioration as a result of transverse reflection cracking, whereby a cracking pattern existing in the original pavement is extended into and through the new overlay.

Reflection cracking occurs in new overlays due to their inability to withstand shear and tensile stresses created by movements of the underlying pavement. These damaging movements may be caused by traffic loading, thermally induced contractions of the paving materials, or a combination of these. Various "engineering" fabrics have been used in recent years to provide reinforcement and undersealing for overlays in attempting to prevent and/or delay the occurrence of reflection cracking, and the subsequent penetration of water into the sublayers. Fabrics reduce the amount of water that enters the sublayers of a pavement both by reinforcing and by undersealing the overlay. Reinforcing delays the appearance of the reflection cracking and reduces the width of cracks that develop. Undersealing may not prevent water from entering the pavement structure below the overlay but usually reduces the amount of water that penetrates into the sublayers.

Six commercially available engineering fabrics were tested in an effort to develop a reinforced overlay design that could withstand the reflective cracking forces. Laboratory testing consisted of

subjecting fabric reinforced laboratory prepared overlay specimens to cyclic tensile loads. This testing was performed on the TTI Overlay Tester, a hydraulically powered apparatus designed to simulate approximately the thermally induced contraction and expansion of a cracked roadway pavement beneath an overlay. The testing scheme included placing reinforcement fabric in one of two locations within the overlay and using three distinct tack coat application rates (low, optimum, and high) of a liquid asphalt cement when constructing the various test specimens. Six unique overlay specimens were fabricated and tested for each fabric under investigation for a total of 36 specimens in all.

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Appendices to the report give a procedure for determining the optimum tack coat application rate, descriptions of the engineering fabrics used in the testing program, original test data, computer programs for test data reduction, and data reduction results.

## IMPLEMENTATION STATEMENT

This report is part of a total effort to assist the Texas Department of Highways and Public Transportation in developing specifications for selecting and properly constructing fabric-reinforced overlays. The laboratory test results reported here show which properties of fabrics, tack coat, and fabric placement within the overlay contribute to a longer reflection cracking life of an overlay. These findings, when supplemented by the results of the field observations to be reported in a subsequent report, will form the basis for a set of specifications for selecting and placing fabrics.

## DISCLAIMER

# SUMMARY

Asphaltic concrete overlays are often used in an attempt to restore the riding quality of a roadway and extend its useful life. However, these overlays are susceptible to premature deterioration as a result of transverse reflection cracking, whereby a cracking pattern existing in the original pavement is extended into and through the new overlay.

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The two fracture properties of the overlay material, A and n, are related to each other by the equation

$$n = a + b \log A$$

where log A is always negative. The constants a and b depend upon the tack coat application rate.

The larger A and n become, the faster the crack will travel through the overlay. Thus, better fabrics will reduce A as far as possible. The tests indicate that A can be reduced by placing the fabric near the bottom of the overlay, rather than near the top, using heavier fabrics, and using higher tack coat rates.

Appendices to the report give a procedure for determining the optimum tack coat application rate, descriptions of the engineering fabrics used in the testing program, original test data, computer programs for test data reduction, and data reduction results.

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# CHAPTER I

# INTRODUCTION

## Background

The primary objective of any pavement design is to provide a safe roadway with desirable ride performance characteristics. In addition, the design should extend these characteristics over a maximum useful life with a minimum of required maintenance (1). However, all pavements, whether rigid (portland cement concrete) or flexible (asphaltic concrete), require maintenance to keep them in the same, efficient operating condition. The type of maintenance required by a particular pavement depends upon the type and extent of distress the pavement is undergoing. Asphaltic concrete (bituminous) overlays are often the most economical method available to overcome a wide variety of defects in both rigid and flexible pavements (2).

An asphaltic concrete overlay is one or more courses or layers of asphalt construction placed and compacted on an existing pavement (3). The overlay often includes a "leveling course" of asphaltic concrete to correct the minor deformations of the old pavement (4). One or more uniformly thick layers of asphaltic concrete are then placed and compacted above the leveling course until the required overlay thickness is reached. A tack coat of asphalt cement is often applied to the old pavement surface prior to overlay construction. This tack coat is used to seal existing cracks and to ensure that a good bond will develop between the old pavement and the new overlay (4).

When a pavement no longer adequately performs the functions for which it was designed, the application of an asphaltic concrete overlay is often used to extend its useful life. These overlays are used to: 1) restore smoothness to distorted pavements, 2) strengthen pavements which are too weak to adequately support traffic loads, 3) improve skid resistance of slippery pavements, and 4) prevent water intrusion into base or subgrade materials by sealing cracks and joints (1). When properly designed and constructed, a bituminous overlay can add many years of safe, efficient performance to the life of a pavement.

However, many pavements which are considered to be structurally sound after the construction of an overlay, prematurely exhibit a cracking pattern similar to that which existed in the old pavement. The cracking in the new overlay surface is due to the inability of the overlay to withstand shear and tensile stresses created by movements of the underlying pavement. This movement may be due to traffic loading causing differential deflections in the underlying pavement layers, expansion or contraction of subgrade soils, or expansion or contraction of the pavement itself due to changes in temperature. Pavement movement, induced by any of the above causes, creates shear or tensile stresses in the new overlay. When these stresses become greater than the shear or tensile strength of the asphaltic concrete, a crack develops in the new overlay. This propagation of an existing cracking pattern from the old pavement into and through a new overlay is known as "reflection cracking" (5).

The occurrence of reflection cracking may take place several years after overlay construction or after only a few months. This form of cracking, together with its accompanying effects, is the primary cause of overlay deterioration. When reflection cracking occurs, the continuity of the overlay surface is destroyed, the structural strength of the pavement is decreased, and water is allowed to enter the pavement system, leading to further deterioration (6). Thus, the occurrence of reflection cracking prematurely shortens the useful life of asphalt overlays by extending the same problems which weakened the original pavement into the new overlay.

Fabrics reduce the amount of water that enters the sublayers of a pavement both by reinforcing and by undersealing the overlay. Reinforcing delays the appearance of the reflection cracking and reduces the width of cracks that develop. Undersealing may not prevent water from entering the pavement structure below the overlay but usually reduces the amount of water that penetrates into the sublayers.

Various engineering fabrics have been used in recent years to provide reinforcement and undersealing for overlays in attempting to prevent or delay the occurrence of reflection cracking and the subsequent penetration of water into the sublayers.

## Causes of Reflection Cracking

Both traffic loads and temperature changes cause cracks in an old pavement to reflect through the overlay. Everytime a load passes over a crack in the old pavement, three pulses of high stress concentrations occur at the tip of a crack as it grows up through the overlay, as illustrated in Figure 1. With each pulse of high stress concentration, the crack grows a little bit more. The first stress pulse that the crack feels is a maximum shear stress pulse shown as Point A in Figure 1. The second stress pulse is a maximum bending stress pulse shown at Point B in Figure 1. The third stress pulse is again a maximum shear stress pulse, except that it is in the opposite direction to the previous shear stress pulse. Also, because there is a void beneath the old surface course at this point, the maximum shearing stress at Point C is larger than at Point A. These stress pulses occur in a very short period of time, on the order of 0.05 seconds. The stiffness of the asphaltic concrete in the overlay and in the old pavement at these high loading rates is fairly high.

The change of temperature in an overlaid pavement can also cause a reflection crack to grow. The thermal stresses in the overlay are due to temperature changes at the surface as shown at Point A in Figure 2, and to the contraction and curling of the underlying old pavement surface as shown at Point B in the same figure. It is observed that thermal stresses can cause cracks to propagate both from the top and the bottom of the overlay. The contraction and curling of the old pavement surface layer applies a shear stress along the bottom of the overlay and produces a concentration of tensile stress at Point B. The change of temperature in a pavement occurs very slowly, over a period of several hours or even the major part of a day. The stiffness of the asphaltic concrete in the overlay and in the old

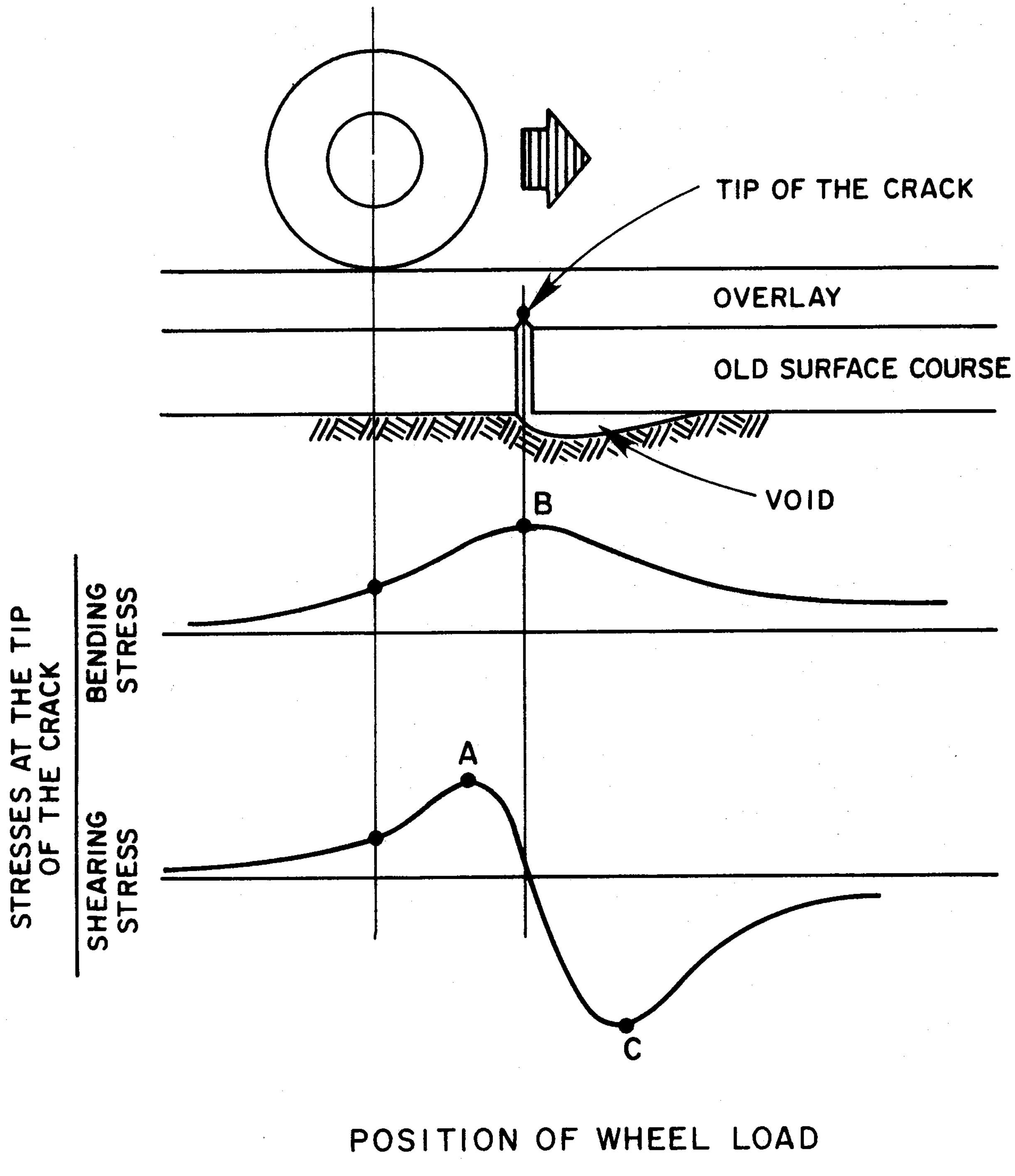


FIGURE 1. Stresses and Crack Growth in Overlays Due to Traffic

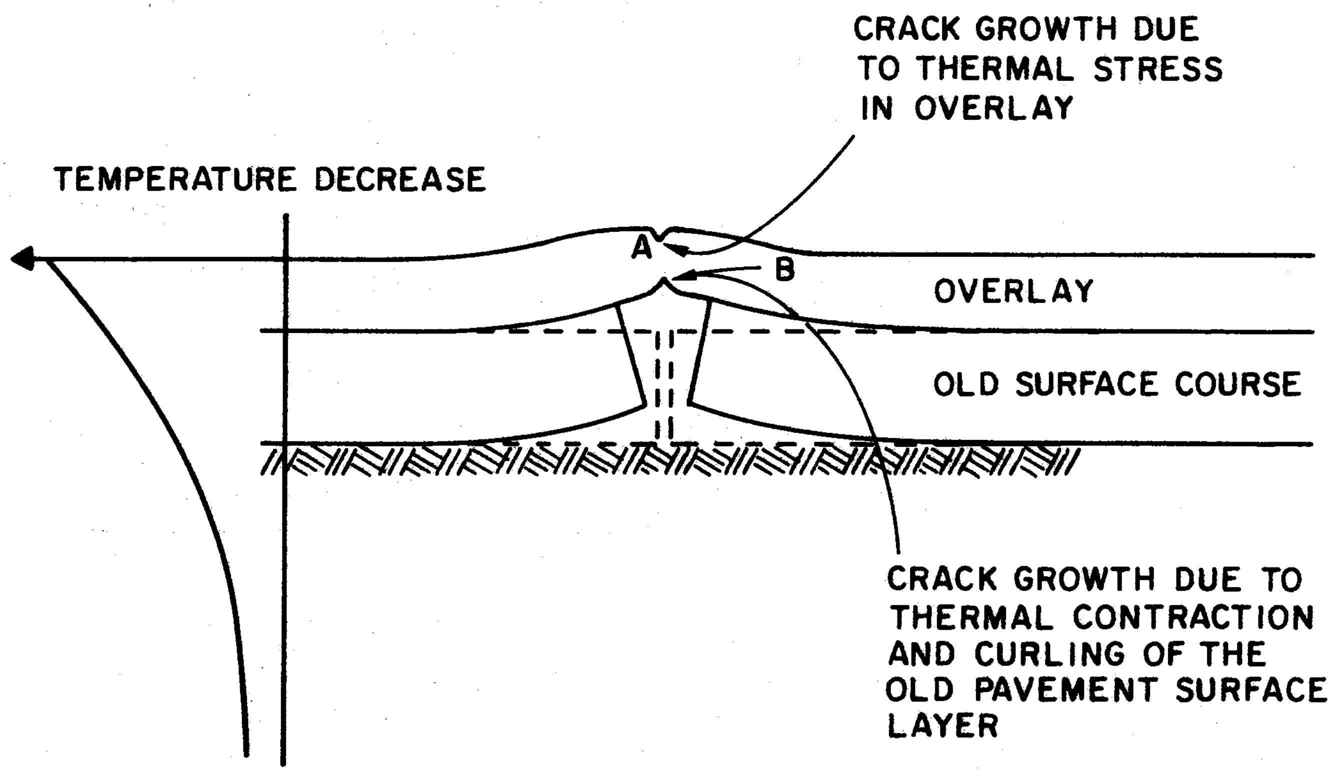


FIGURE 2. Temperature Changes and Consequent Crack Growth in Overlays

pavement is very low, as much as 1000 to 10,000 times lower than the modulus that these same materials exhibit under traffic loads.

Every time a load passes and every time the temperature decreases in an overlaid pavement the reflection crack grows a little more. The major hope that engineers have of retarding the growth of such reflection cracks is in the selection of the material properties of the overlay and of the fabrics that are used to reinforce it so as to reduce, as much as is possible, the growth of these cracks.

## Testing Reflection Cracking Properties of Overlays

Because reflection cracking has a variety of contributing causes including traffic, temperature changes, and moisture changes in the base course and subgrade, and because the application of shear and tensile stresses to the overlay occurs at different rates and temperatures, it is difficult to devise a single laboratory test that will exactly duplicate the behavior of an overlay under field conditions. The Federal Highway Administration now has under contract a research project which is attempting to build, test, and verify the applicability of such a laboratory testing device. The test must be set up to simulate a single chosen field condition in which the traffic, crack spacing, temperature change in the underlying cracked pavement, subgrade stiffness, presence or absence of voids beneath the pavement surface, degree of aggregate interlock across the crack in the old pavement, overlay thickness, fabric position, weight, and tack coat application rate are specified. Because each of these affect the rate at which the reflection crack propagates through the overlay, the extension of the test results to other field conditions requires a new test setup and a separate evaluation. The evaluation of the relative effectiveness of various fabrics at different positions within the overlay must be done on a project-by-project basis provided that all of the variables that are noted above can be specified and simulated in the testing apparatus.

There is an alternative to this approach which makes use of relatively simple tests, each of which determines the "fracture properties" of an overlay due to one of the three major means by which cracks propagate through the overlay: bending, shear, and contraction of the underlying pavement. The "fracture properties" are material properties of the overlay and depend upon the properties of the asphaltic concrete mixture, the fabric, its position within the overlay, and its tack coat application rate. The "fracture properties" for fracture due to bending, shear, and contraction are then put into a simple computer program along with data on traffic, daily temperature change, crack spacing and overlay thickness to calculate the number of load applications and temperature cycles that a given overlay can withstand. The advantage of this approach is that more of the simple tests can be made for each mode of fracture separately to permit a more careful investigation of the best fabric properties and positions within an overlay and the best tack coat application rate to reduce as much as possible the rate of crack growth through an overlay. These tests can show more clearly the contribution of the fabric to the retardation of reflection cracks in each fracture mode separately and can lead more directly to rules, guidelines and specification limits on the use and application of fabrics in overlays. This is the alternative that has been adopted by the Texas Transportation Institute with the assumption that the fracture properties due to bending and shear are the same.

A computer program has been written and transmitted to the Texas State Department of Highways and Public Transportation in a technical memorandum dated October 11, 1982 which can take "fracture properties" as measured in the beam fatigue and overlay tester laboratory testing devices and can predict how long a specific overlay will last under specified traffic and daily temperature changes. This report documents the measurement of the "fracture properties" of overlays that have been reinforced with a variety of fabrics, in different positions, and with different tack coat application rates.

The results of only one type of test are presented in this report, and that is the overlay tester. The device was built to simulate the contraction in an old pavement due to temperature changes. Tests are normally run at room temperature (77°F or 25°C) and at a load cycle rate of one every 10 seconds. The modulus of the overlay material that is produced at this temperature and loading rate is similar to what is produced by thermal contraction over a six-hour period at temperatures around 20°to 25°F (-7°to -4°C).

This test is used alone because it is against this type of movement that fabrics are most effective. The test is simple, reliable and repeatable. As will be seen in the remainder of this report, much can be learned from a careful study of the test data of the reasons why fabrics are effective in reinforcing overlays.

## Purpose

The general purpose of this study is to develop the information necessary to evaluate the relative effectiveness of commercially available engineering fabrics in correcting the types of pavement distress caused by thermally induced reflection cracking of bituminous overlays. Evaluation of the test data will also aid in the development of realistic specification limits for the use of engineering fabrics in bituminous overlay construction.

## Specific Objectives

The specific major objectives of this study are as follows:

1. To obtain representative samples of engineering fabrics currently being used in overlay construction.
2. To determine the amount of asphalt required to saturate each of the fabric types.
3. To prepare and test laboratory samples of fabric reinforced asphaltic concrete for resistance to reflection cracking stresses.
4. To analyze the test data and determine the relative effectiveness of each of the engineering fabrics in delaying reflection cracking.
5. To evaluate the effect of fabric location and tack coat rate in delaying reflection cracking.
6. To determine those fabric material properties that have the greatest effect on overlay performance.

## Scope of the Investigation

This study examines the use of six commercially available engineering fabrics purported to reduce and/or delay the occurrence of reflection cracking in bituminous overlays. Three tack coat rates and two fabric locations within the overlay were used for each fabric type examined. (Appendix D describes the procedure used to determine the various tack coat rates.) A dense graded asphaltic concrete composed of a river gravel and 3.8 percent AC-10 asphalt (by weight of aggregate) was used to construct the overlay test samples. (Appendix C describes the sample construction procedure.) All the samples were tested on a special fatigue testing apparatus known as the "TTI Overlay Tester" which was designed to model displacements caused by the thermal stresses resulting from cyclic variation of the ambient temperature. In this testing device, the alternate expansion and contraction of the existing pavement structure is simulated by a horizontal, oscillatory motion of two platens on which the sample is mounted. The maximum opening width between the platens is limited only by the stroke of the loading ram, which may be several inches, depending upon the choice of ram. In the test series reported here, a constant crack opening width of 0.070 in. was used primarily to provide a testing period of one to four hours. However, it is a practical opening width as well since it corresponds to a thermally-induced displacement which occurs in a portland cement concrete pavement, with 15 foot joint spacings, as it undergoes a 60°F change in temperature. Information recorded during each test as been used to determine the relative effectiveness of the various overlay designs as reflection crack retarders.

# CHAPTER II

# REVIEW OF THE LITERATURE

## General

Before entering into a description of the overlay tester and its test results, it is considered opportune to describe some of the results of field trials that have been tried by other agencies than the Texas State Department of Highways and Public Transportation of methods that are intended to retard reflection cracking. As a consequence, an extensive review of the literature was conducted and the results are presented in this chapter.

A wide variety of methods and materials designed to reduce and/or delay the occurrence of reflection cracking have been employed in the past with varying degrees of success. These attempts to reduce reflection cracking may be grouped into four general classifications: (a) increased thickness of the asphaltic concrete overlay, (b) special treatment of the existing pavement, (c) treatment of existing cracks and joints, and (d) special consideration of the asphaltic concrete overlay design (7, 8, 9, 10). Most of these methods are not well suited to laboratory test procedures, and consequently the majority of reflection crack investigations to date have concentrated on field experimentations.

## Results of Field Trials

Various experimental efforts in each of the four categories listed above have proven successful to some degree in eliminating, reducing, or delaying reflection cracking. Each of these are discussed in detail below.

## Thick Overlays

Though asphaltic concrete overlays are sometimes designed to add structural strength to a pavement system, they are most often used to correct surface deformations, provide skid resistance, or prevent water intrusion into existing cracks or joints. Consequently, overlays are generally relatively thin layers of asphaltic concrete - less than three inches thick. Attempts to delay reflection cracking by increasing the overlay thickness have proved to be only partially successful. In general, increases in overlay thickness have been found to significantly delay the occurence of reflection cracking only when the overlay thickness is sufficient to significantly increase the structural strength of the pavement (generally four inches or more in thickness) (10).

The delay or reduction in reflection cracking of "thick" overlays is due to: (a) the additional material the crack must propagate through, (b) the increased structural strength of the pavement provided by the overlay, and (c) the protection against asphalt aging in lower levels of the cross section provided by the increased thickness. The maximum strain in a new overlay, due to movement of the old pavement, occurs at the pavement - overlay interface. The strain then decreases through the height of the overlay to a point where it may become zero. The decrease in strain depends on the plasticity of the overlay - the more plastic the asphaltic concrete, the more rapid is the reduction in strain. If there is enough material above the zero point, the effects of crack movement in the old pavement will not be evident in the new overlay. However, if there is insufficient thickness of material, the tensile stresses will become apparent at the surface of the overlay and if these stresses exceed the tensile strength of the material, the overlay will rupture.

The addition of a "thick" overlay to structurally weak pavements may provide sufficient additional strength to support traffic loads, thereby reducing or eliminating load-induced displacements of the old pavement. This reduction in pavement movement leads to a corresponding decrease in load-induced reflection cracking. In addition, the lower levels of the cross section are less exposed to embrittling agents than the upper surface. Exposure to the elements causes aging and embrittlement of the asphalt, resulting in a loss of resilience. With advancing age of the bituminous overlay, there is increasing embrittlement and less tolerance of movements in the existing pavement (8, 10). A state is eventually reached where the overlay is no longer flexible enough to resist pavement movements, and cracks begin to reflect upward from the lower levels to the top of the overlay. In "thick" overlays, this process is delayed and therefore the rate of reflection cracking is reduced (10).

## Treatment of Existing Pavement

Modification of existing pavements as a method of preventing reflection cracking has included breaking of the existing pavement to destroy the cracking pattern and the addition of thick layers of crushed stone (8, 9, 10, 11). Breaking of portland cement concrete pavements is generally accomplished by means of heavy roller and/or a truck mounted impact hammer. The broken pavement is then left in place, seated with a roller, and a relatively thick bituminous overlay is then applied. The fractured original pavement then acts as a base course with large voids, thus eliminating the original cracks and construction joints. Reductions in reflection cracking may be due to improved seating of the original pavement and the elimination of existing cracking patterns. With other conditions remaining the same, reflection cracking above the broken pavement is reduced with increased thicknesses of the bituminous overlay (10, 12). This method has proved to be partially successful, particularly where the original rigid pavement is poorly seated, but is very costly and time consuming.

The addition of an interlayer consisting of large size aggregate (up to four inches) prior to the placement of a bituminous overlay has become known as the Arkansas method (10). The crushed stone is applied directly to the existing pavement in a layer 4 to 6 inches thick and is then seated with a roller. A dense-graded asphaltic leveling course is then applied and this is followed by an asphaltic surface course. Total pavement thicknesses of as much as 10 inches are not uncommon with this method. Reductions in reflection cracking in the Arkansas overlays may be attributed primarily to the increased thickness of the pavement and the fact that they are installed over pavements that have been in operation for some time (10). The

Asphalt Institute describes a similar construction procedure which it claims is an effective means of combating reflection cracking (13). This method, though generally effective, is much more expensive than a normal overlay due to the large quantities of crushed stone and asphalt required and the extensive construction involved.

Heater scarification of badly cracked bituminous pavement surfaces has also been used to eliminate the existing cracking pattern in various attempts to reduce reflection cracking (1, 10). This method is most often used when the asphalt in the pavement has aged to a very brittle state, making it practically non-effective for flexible service over a wide range of temperatures. The existing pavement is usually scarified to a depth of about 3/4 inch, and this material is then treated with an asphalt emulsion or other rejuvenating agent designed to combine with the original asphalt and restore the material's flexibility. After application of the rejuvenating agent, the scarified material is then recompacted and the overlay is applied and compacted. Heater scarification is used prior to overlay construction as a means of eliminating existing cracking patterns, restoring flexibility to aged and brittle pavements, and creating a positive and effective bond between the old pavement and the new overlay. This method has been used successfully on both airfield and highway pavements. The Arizona Department of Transportation concluded that this method was the most effective means of retarding the appearance of reflection cracks of twenty different pavement treatments tested (1).

A method somewhat similar to heater scarification utilizes pulverization of the existing bituminous pavement and addition of a rejuvenating agent to remove the existing cracking pattern and restore flexibility to the pavement surface. A field trial conducted by the Vermont Department of Highways utilized this method to rehabilitate a section of aged, badly cracked bituminous pavement. Preliminary results indicated that pulverization is a viable alternative for the rehabilitation of distressed pavements and that it should help delay the occurrence of reflection cracking in bituminous overlays placed over these pavements (14). Similar results were found in field tests conducted in Ontario, Canada (15).

### Treatment of Existing Cracks and Joints

Treatment of the existing cracks and joints in pavements prior to overlay construction has had limited success in reducing reflection cracking in various field trials (8, 10, 11, 16). The larger cracks are generally cleaned of all foriegn matter and are then sealed with a compressible material. Various types of bond breaking agents have been applied in narrow strips along either side of the cracks in an attempt to reduce the strains developed in an overlay by movement of the underlying pavement. Bond breaking agents have included materials such as: sheet metal, saturated building paper, aluminum foil, wax paper, stone dust, and agricultural lime (10, 11, 17).

The application of these bond breaking agents creates a narrow area on either side of a crack where the overlay does not bond to the old pavement. This is thought to reduce the stresses in the overlay caused by movements of the old pavement. The strain produced in the overlay is spread over a wider area due to the absence of bond between the two pavement layers. This has resulted in the occurence of numerous small cracks rather than a single large reflective crack in some field trials (10). Although the use of bond breaking agents has effectively reduced reflection cracking in some field trials, their use is not widespread at the present time. Construction difficulties, concern over possible lateral dislodgement of the overlay due to horizontal shearing forces created during braking, and the introduction on other stress relieving interlayers has reduced the use of the above mentioned bond breaking agents.

### Modified Overlay Design

One rapidly developing area of reflection crack retardation study involves the modification of the overlay material properties. Since the environmental and load induced forces causing movement in the old pavements (and therefore reflection cracking in the new overlay) cannot be controlled, research efforts have been directed toward developing overlays that are more tolerant of pavement strains. Traditional methods of design modification have utilized "softer" asphalts or increased asphalt content. However, undesirable effects such as reduced stability and a tendency toward "bleeding" have prevented these methods from becoming general cures for the reflection cracking problem (10). This has led to pavement design and construction techniques which incorporate various types of additives and reinforcement or stress relieving interlayers in the bituminous overlays.

Rubber asphalt is a type of asphaltic concrete which includes "crumbs" (approximately No. 30 sieve size) of ground tire rubber. These crumbs are added to the hot asphalt and mixed with it prior to placement and compaction. The particles of ground rubber add ductility and resilience to the pavement mixture. This overlay design has proved effective in reducing both fatigue and reflection cracking (1, 8, 10). "Rubberized" asphalt has also been used to add ductility to chip seal coats. Reflection cracks through these asphalt mixes are generally fewer in number and smaller in size than reflective cracks through similar nonrubberized asphalt layers. This reduction in reflection cracking is generally attributed to the increased ductility, resilience and toughness of the mixture produced by the addition of ground rubber. This change in material properties permits greater movement of the original pavement without exceeding the rupture strength of the new overlay (10).

The addition of various types of reinforcing materials to bituminous overlays has been used for years in attempts to increase the tensile strength of overlays and make them less susceptible to reflection cracking. Early field trials employed steel reinforcing in the form of welded wire fabric or expanded metal mesh. Reinforcement of this type is typically delivered in rolls of suitable width, placed over the pavement to be overlaid, tensioned, and then anchored in place. The asphaltic concrete is then placed and compacted by conventional means. In many cases the overlay consists of two or more courses of material and the reinforcement is placed about midway within the overlay. Field trials utilizing steel reinforcement have shown conflicting results (1, 10, 15, 18, 19). Due to the marginal benefit derived from this type of reinforcement, numerous construction problems and increasing material and installation costs, the use of steel reinforcement in bituminous overlays has declined sharply in recent years.

Synthetic fibers, manufactured from polypropylene or polyester, are a relatively new form of reinforcement for asphaltic concrete. (In the past, asbestos fibers have been used as reinforcement, but due primarily to health hazards, they are no longer in use for this purpose). The fibers are added in small percentages during the mixing process. Conventional equipment is then used to place and compact the overlay. Since the fibers absorb some asphalt during the mixing operation, asphalt quantities must be greater than normal. Increases in ductility and tensile strength of pavements containing fiber reinforcement are probably due to the increased asphalt content of the composite material and the ability of the individual fibers to withstand small tensile loads. Though experimentation with fiber reinforcement is relatively new and incomplete, some promising results have been obtained thus far (10, 20).

A tremendous effort is currently underway to utilize various types of synthetic fabrics as reflection crack arrestors. These petrochemically derived "engineering" fabrics consist of various combinations of polyester, polypropylene, and nylon and may be either woven or non-woven. In general, these fabrics are nonbiodegradable and biologically and chemically resistant, as well as being resistant to rot, mold, and mildew (21). Historically, engineering fabrics have been used very successfully for other engineering applications such as subgrade restraint, embankment stabilization, erosion control and water proofing (10, 21).

Since their introduction into the construction field in the mid 1960's, the use of engineering fabrics has increased tremendously - from less than one million square yards of fabric being used in 1969 to an anticipated total of more than forty million square yards in 1980 (21). Their application as a reinforcing material to increase the tensile strength of bituminous overlays and to reduce reflection cracking is a relatively recent utilization of these materials (10, 21, 22). When installed in a bituminous overlay (in combination with a tack coat of asphalt cement), these fabrics act as reinforcement to retard cracking and as a waterproofing agent to prevent water intrusion through those cracks that do form. These fabrics have also been installed directly over old pavements prior to overlay construction to act as waterproofing underseals and stress relieving interlayers.

The present status of nationwide usage of engineering fabrics as a reinforcing material for bituminous overlays varies from a few agencies who utilize these fabrics in standard maintenance procedures to those who have not yet constructed their first experimental facility. The Federal Highway Administration has been very active in sponsoring field evaluation tests of the various engineering fabrics in cooperation with interested state agencies. Experimental field trials have been initiated in over twenty states from Maine to Texas and from South Carolina to California (10, 23, 24).

Reproducibility of the field test results is difficult to achieve due to insufficient monitoring of the many variables.

In spite of this lack of definitive, reproducible results, it does appear that the use of engineering fabrics is useful in extending the service life of bituminous overlays in many cases (7, 8, 10, 25, 26). In addition to retarding or reducing reflection cracking, the asphalt impregnated fabrics may also be helpful in reducing the amount of water intrusion (through those cracks which do reflect through the overlay) into the underlying pavement layers (7, 25). This exclusion of surface water, together with good drainage capable of preventing prolonged internal flooding is well recognized as one of the most effective means of ensuring long, trouble-free service of highway systems (27).

These field trials are generally conducted by highway agency personnel who are primarily concerned with solving problems associated with fabric installation. Therefore, many reports of field trials utilizing engineering fabrics deal primarily with installation problems and procedures and only secondarily with preexisting conditions and variables that may affect the performance of the installation (28, 29, 30, 31). Efforts are being made by some agencies to develop standardized installation procedures as well as fabric specifications that will help correct some of the installation problems that have occurred to date (32). Although these specifications do not include criteria directed at reducing reflection cracking, some unproven manufacturer's standards purport to address this problem (10, 33).

Results of Laboratory Testing

The bulk of experimentation dealing with reflection cracking in bituminous overlays has been conducted on test sections in the field rather than on laboratory prepared specimens. This is due primarily to the complexity of the reflection cracking phenomenon and the extreme variability of those factors influencing cracking. Also, most of the standard laboratory tests which are designed to evaluate the physical properties of construction materials are not sufficient to determine the effectiveness of various composite materials as reflection crack arrestors.

Due to the complex nature of experimentation involving the propagation of reflection cracks through a bituminous overlay, attempts have been made to perform laboratory tests which will aid in the determination of those material properties which will have the greatest effect on the occurrence of reflection cracking. Various laboratory experiments have been designed to evaluate the role of mixture design variables such as: aggregate type and gradation, asphalt type and content, test temperature, air void content, and the addition of stress relieving interlayers. These tests have been performed on a variety of sample types and results of tests performed to date are not entirely conclusive. These results may be due in part to variables that were not considered in the various tests (test temperature, asphalt type and amount, aggregate gradation, etc.) and variations in test procedures (controlled stress tests versus controlled strain tests, etc.)(34, 35, 36).

One of the first efforts to develop a mechanistic model using fracture mechanics to explain crack growth and predict the fatigue life of an asphalt-aggregate material was carried out at Ohio State University (37, 38, 39, 40). Fatigue tests were performed on a series of bituminous samples in order to evaluate the effects of various mix parameters on the material constants "A" and "n" in the crack propagation formula developed by Paris and Erdogan, $dC/dN = A K^n$ (41). This equation relates the rate of crack growth per loading cycle (dC/dN) to the stress-intensity factor (K).

Laboratory test results from Ohio State showed that the parameter "A" was increased by a decrease in asphalt viscosity (40). An increase in "A" leads to a decrease in the fatigue life of samples tested under controlled stress conditions. Also, open-graded mixes were found to have a shorter fatigue life than dense-graded mixes under similar test conditions (39).

Experimental fatigue tests were also performed at Ohio State on asphaltic concrete specimens reinforced with an engineering fabric (Petromat)(42). These tests were performed on bituminous beams resting on an elastic support to simulate the road structure. Bituminous beams, both fabric reinforced and non-reinforced, were tested using dynamic loads of 140, 170, and 200 pounds. Fabric reinforcement in these Ohio State test specimens was placed in one of three locations -- the upper third, mid depth, or lower third of the sample. Test results indicate that fabric reinforcement showed the greatest increase in fatigue life when placed in the lower third position in the beam for the 140 pound loading. (Fabric location made little difference in tests using the 170 and 200 pound loadings.)

All tests indicated that fabric reinforcement significantly extended the fatigue life of the samples as compared to non-reinforced samples. Additional tests conducted at various temperatures indicated that the fabric's effectiveness increases significantly as the test temperature decreases (42).

Though fatigue testing of bituminous samples provides useful information for the comparison of various overlay designs, it does not duplicate the thermally induced stresses which are the primary cause of most reflection cracking in overlays placed over pavements with crack or joint spacing greater than about 15 feet. Germann, et al. (43), in tests that were made at the Texas Transportation Institute, used an "overlay tester" designed to simulate thermally induced displacements and stresses to test the reflection cracking resistance of various overlay material samples. He then used experimental data and finite element stress analysis and fracture mechanics concepts to predict the reflection cracking life of composite bituminous overlays. This experimental program is the only one reported to date which tests composite bituminous materials for resistance to "thermally induced" stresses leading to reflection cracking.

Results from these tests indicate that the reinforcing fabrics used significantly increase the resistance of the samples to "thermally induced" cracking. Those samples with "high" asphalt contents had greater thermal fatigue lives than those with "low" asphalt contents. Also, increases in sample thickness resulted in increased resistance to cracking (43).

## Summary

Field trials of various methods of preventing reflection cracking have shown that several techniques can be applied successfully under a variety of traffic and climatic conditions. Among the important variables that affect the performance of an overlay in retarding reflection cracking include the existing condition of the pavement, material properties, and construction details. Among those techniques that have proven successful is the use of synthetic fabrics.

Field observations have been conducted of numerous test sections with fabric reinforced overlay that have been placed in Texas. The observations have been made systematically over a period of years and the results of the study are presented in the second report of this series, TTI Research Report 261-2.

Theoretical and laboratory studies are being conducted under both Federal Government and industrial sponsorship. These studies are to understand the mechanics of reflection cracking and establish criteria for design of crack resistant overlay systems. Even though they are still in their early stages, they are beginning to identify the important engineering material properties that contibute most to retarding reflection cracking. The results of laboratory tests with the "overlay tester" that are reported here represent a substantial advance in our understanding of the part that fabrics play in reducing reflection cracking.

# CHAPTER III

# MATERIALS AND APPARATUS

## Materials

This study utilized laboratory constructed asphaltic concrete beams measuring 3 in. X 3 in. X 15 in. to investigate the effects of fabric reinforcement on the rate of reflection crack propagation through a bituminous mixture. Six "engineering" fabrics purported to be beneficial in arresting reflection cracking were used as reinforcement in these bituminous "overlay" samples. Descriptions of the reinforcing fabrics used in this experiment are given in Appendix E. The mixture design and construction procedure used in fabricating each of the test samples are detailed in Appendix C.

Each beam sample was constructed of a washed, rounded, siliceous gravel and a viscosity graded AC-10 petroleum asphalt. Fabric reinforcement consisted of 3 in. X 15 in. precut strips of selected engineering fabric applied with a tack coat of AC-10 asphalt cement. Samples were designed to evaluate the effects of (a) type of fabric reinforcement, (b) location of reinforcement, and (c) amount of tack coat. Therefore, the aggregate type and gradation, asphalt type and content, and sample construction procedure were kept constant throughout the experiment.

## Apparatus

### Sample Construction Equipment

The asphaltic concrete beam samples tested during this investigation were fabricated in the laboratory in a manner similar to that used for construction of beams to be tested for their resistance to fatigue loading. (Appendix C describes the sample construction procedure in detail.) Mixing of the aggregate and asphalt was accomplished in a large bowl (at 300°F) by means of a mechanical mixer. Heat was applied to the materials during the mixing process by means of a Bunsen burner placed beneath the mixing bowl. When all of the aggregate was thoroughly coated with asphalt, the mixing was terminated and the mixture was divided into three parts.

Compaction of the asphaltic concrete was accomplished in three layers at 250°F in a steel mold measuring 3 in. X 4 in. X 15 in. A Soiltest, Inc. Model CN-425A pneumatic static compactor was used to compact the three lifts (layers) of each sample. (Refer to Figure 1 on the following page.) This compactor utilizes pneumatic pressure to apply a predetermined load to the material within the mold by means of a 3 in. X 4 in. compaction "foot" attached to a movable loading ram. Though this compactor allows the applied load and compaction dwell time to be adjusted to meet a variety of needs, a ram pressure of 500 psi and a dwell time of 1.5 seconds were used during the compaction of all samples. Uniform compaction throughout the entire length of each layer was accomplished by moving the location of the beam mold incrementally with relation to the loading ram. This was done by manually moving the beam support (and attached mold) by

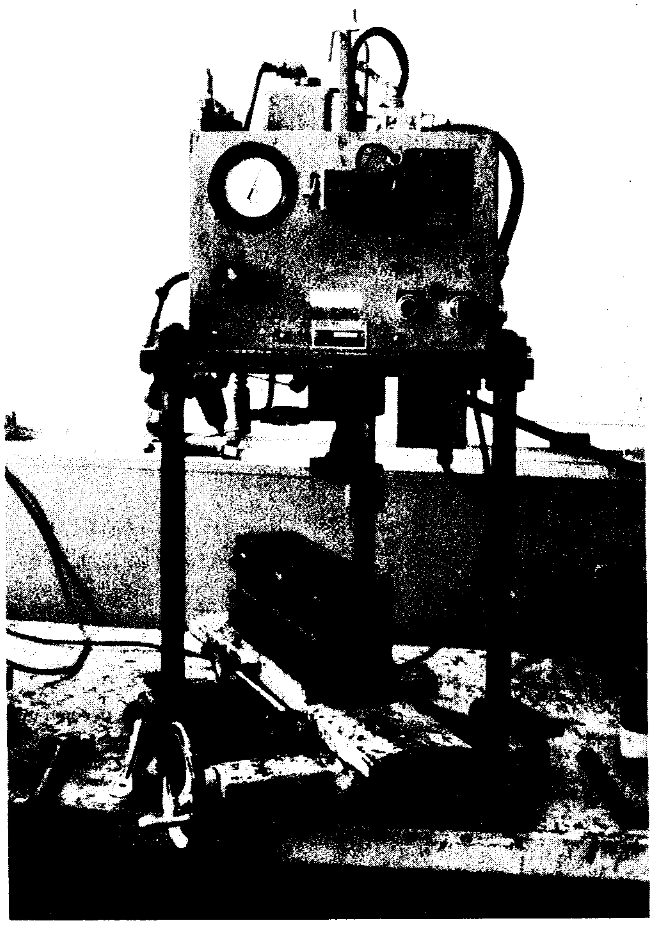

Figure 3. Soiltest, Inc. Model CN-425A pneumatic compactor with beam mold in position.

means of a crank-controlled gear assembly.

Upon completion of the compaction process, a leveling load of 12,000 pounds (approximately 270 psi) was applied for five seconds to provide final compaction and remove surface irregularities. This leveling load was applied by means of a hydraulic universal testing machine manufactured by the Baldwin Southwark Corporation. A heated steel beam (3 in. X 4 in. X 15 in.) was used to distribute the leveling load uniformly over the surface of the sample. Figure 2 illustrates a sample prepared for application of a leveling load.

After the leveling load was applied, each beam was manually extruded from the mold, placed on a 1/2 in. X 4 in. X 16 in. aluminum plate and allowed to "cure" at laboratory room temperature for approximately 24 hours. After this period, all samples were stored in an environmentally controlled room (77$^{O}$F, 25% relative humidity) until tested.

Testing Equipment

Tests of the asphaltic concrete beam samples were conducted on a machine called the "TTI Overlay Tester". The Overlay Tester is a fatigue testing machine designed and constructed by personnel at the Texas Transportation Institute (43). This apparatus utilizes a hydraulic servo-control mechanism to model displacements which occur in pavements as a result of thermally induced stresses. These displacements are the result of expansion and contraction of the pavement surface or base materials with changes in temperature.

To simulate the horizontal displacements that occur in pavements due to temperature associated expansion and contraction of the

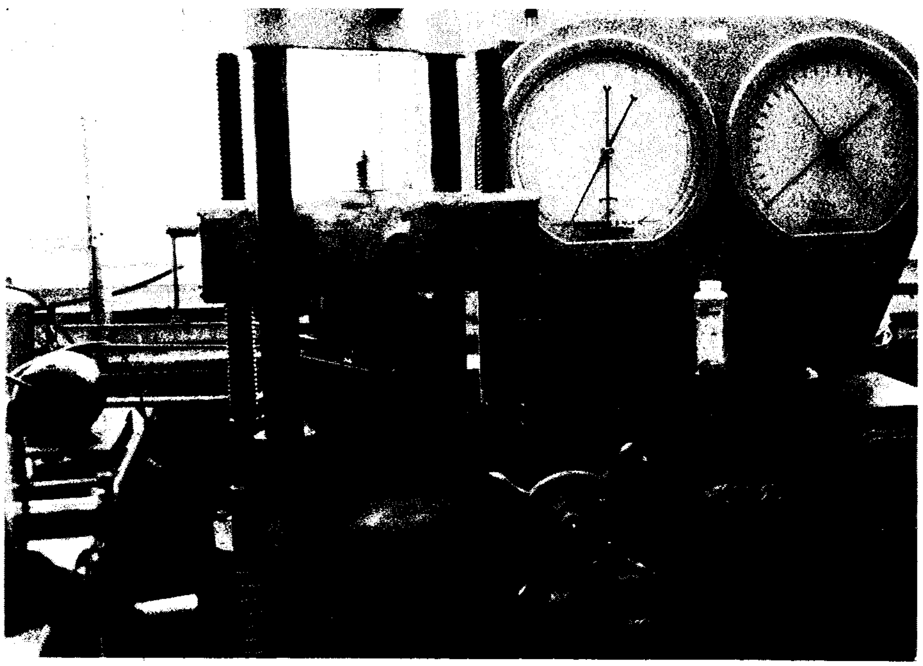

Figure 4. Baldwin Southwark Corporation hydraulic universal testing machine with beam sample (in mold) prepared for final leveling load.

pavement, the Overlay Tester utilizes a hydraulically powered ram. This ram is equipped with a load cell and is mounted in a horizontal position to a support frame. Two aluminum plates 3/8 in. X 9 in. X 12 1/2 in. are also mounted horizontally to the support frame. One of these plates is rigidly fixed to the support frame. The other plate is attached to the loading ram and is allowed to move freely within two "tracks" in the support frame as the ram is moved. Beams tested on the Overlay Tester were first glued to two aluminum plates as described in Chapter IV. These plates (with attached sample) were then bolted to the two plates of the Overlay Tester. Figure 3 shows an overlay sample bolted into position and prepared for testing on the Overlay Tester.

The Overlay Tester is electronically controlled by means of a command console manufactured by Gilmore Industries, Inc. Although this system allows the test rate (cycle frequency) and displacement magnitude to be varied, all samples were tested under similar conditions. The test frequency used was 6 cycles per minute and the maximum horizontal displacement was 0.070 inches. (One "cycle" is defined as movement of the ram from the "closed" position to the "open" position and back to the original "closed" position.) Refer to Chapter IV for details of the test procedure.

A graph of load versus displacement was made of selected cycles during testing of each sample by means of a Hewlett-Packard Model 7046A X-Y Recorder. This load-displacement information was also stored on magnetic cassette tape by means of a cassette recorder and a microcomputer developed by personnel of the Texas Transportation

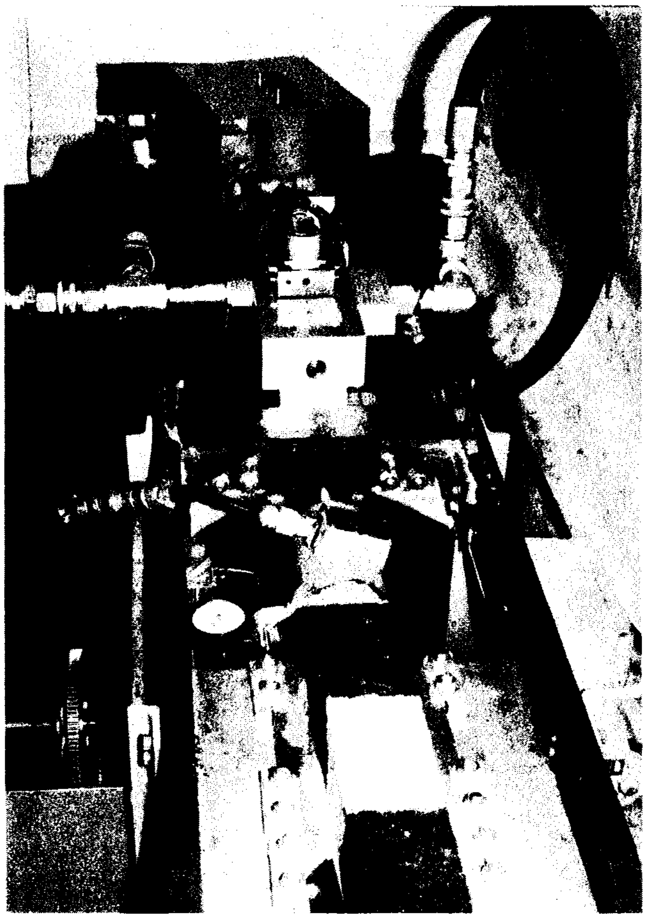

Figure 5. TTI Overlay Tester with 3 in. X 3 in. X 15 in. beam sample prepared for testing.

Institute. A Texas Instruments "Silent 700" Electronic Data Terminal was used to enter sample and cycle number identification information and crack length data to be recorded on the magnetic tape. Figure 4, page 31, illustrates the X-Y Recorder, Data Terminal, and Microcomputer used to record the test data. Figure 5 shows the Gilmore Electronic Command Console, as well as the above mentioned data recording equipment.

The load and displacement experienced by a test specimen during each cycle were transformed into electronic voltages by a load cell and a linear variable differential transformer (LVDT) respectively. The X-Y Recorder then used these voltages to produce a graph of load versus displacement for selected cycles. The TTI Microcomputer was used to convert these voltages into a computer-usable form and store these data on magnetic cassette recording tape. Data recorded and stored in this manner were later analyzed by means of a second computer system.

Data Analysis Equipment

Test data stored on magnetic cassette tape was analyzed by means of a second microcomputer system. The data analysis program was stored on a disk which was used in a Smoke Signal Broadcaster Model BFD-68 Disk System. This system was interconnected to a cassette tape player and a Smoke Signal Broadcaster Model 6800 Mnemonic Assembler Microcomputer. These systems were also connected to a Micro-Term, Inc. Model ACT-5A Video Terminal and a Teletype Model 43 Electronic Data Terminal. The data analysis procedure is described in detail in Chapter V.

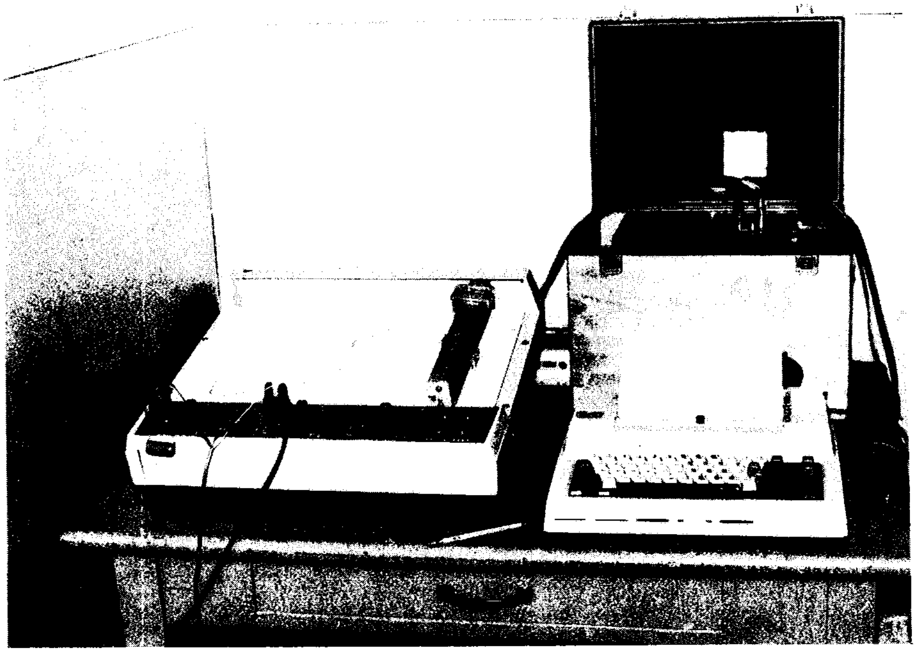

Figure 6. Hewlett-Packard Model 7046A X-Y recorder,Texas Instruments "Silent 700" electronic data terminal, and TTI microcomputer.

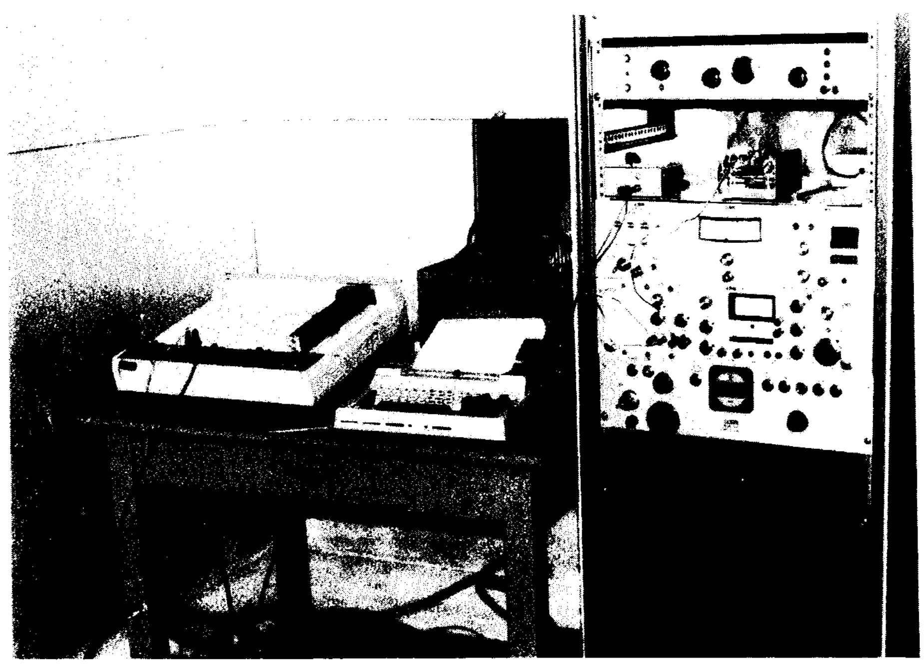

Figure 7. X-Y recorder, data terminal, microcomputer, and Gilmore electronic command console.

CHAPTER IV

# PROCEDURE

## General

As mentioned previously, this experiment investigated the influence of fabric reinforcement on the rate of reflection crack propagation through a bituminous mixture. Asphaltic concrete beams reinforced with a selected "engineering" fabric (applied with a tack coat of asphalt cement) were tested for their resistance to reflection cracking. The sample construction procedure is described in detail in Appendix C. The procedure used to determine the optimum fabric tack coat rate is described in Appendix D. The following discussion describes the sample preparation and actual testing procedures in detail.

## Sample Preparation

Each beam sample was compacted and "cured" at laboratory room temperature for approximately 24 hours. After this initial curing period, the samples were stored in an environmentally controlled room (77°F, 25% relative humidity) for a minimum period of seven days before they were tested. Prior to testing, each beam was glued to a pair of aluminum base plates (1/2 in. X 6 in. X 9 in.) by means of an epoxy resin cement. Prior to gluing, the two base plates were aligned, a hacksaw blade was placed between adjoining ends of the plates, and a narrow (approximately 1/4 in. wide) strip of tape was placed over the hacksaw blade. This arrangement simulates the construction of a bituminous overlay over a cracked or jointed pavement. The hacksaw blade was used to provide a uniform spacing or "crack" between the two base plates. This blade was removed prior to testing. The tape was used to prevent excess glue from entering the space between the base plates and thereby gluing the plates together. A second asphaltic concrete beam, similar to the test specimen was used as a weight during the gluing process. Figure 6 shows a sample being glued to the base plates.

A minimum of 24 hours was allowed for the glue to reach final "set" prior to testing. After this allotted time, the weight and hacksaw blade were removed. The sample was then marked with white chalk in the area where cracking was most likely to occur. This was done to aid visual detection of the reflective crack as it propagated through the sample during testing. The base plates, with sample attached, were then bolted to the plates of the Overlay Tester - one to the fixed plate and the other to the moveable plate. Figure 7 shows a sample bolted into position on the Overlay Tester. (Note the reflection crack extending through the specimen at the conclusion of testing. This photograph was taken with the Overlay Tester in the "open" position.) Figure 8 illustrates the test arrangement in schematic form.

## Sample Testing

Prior to testing, the Overlay Tester was calibrated to ensure a maximum ram displacement (and therefore differential gap opening) of 0.070 inches. (A movement of 0.070 in. is approximately equivalent to the displacement experienced by a portland cement concrete pavement with 15 foot joint or crack spacings as it undergoes a 60$^{o}$F change in pavement temperature.) The X-Y Recorder was also calibrated and the

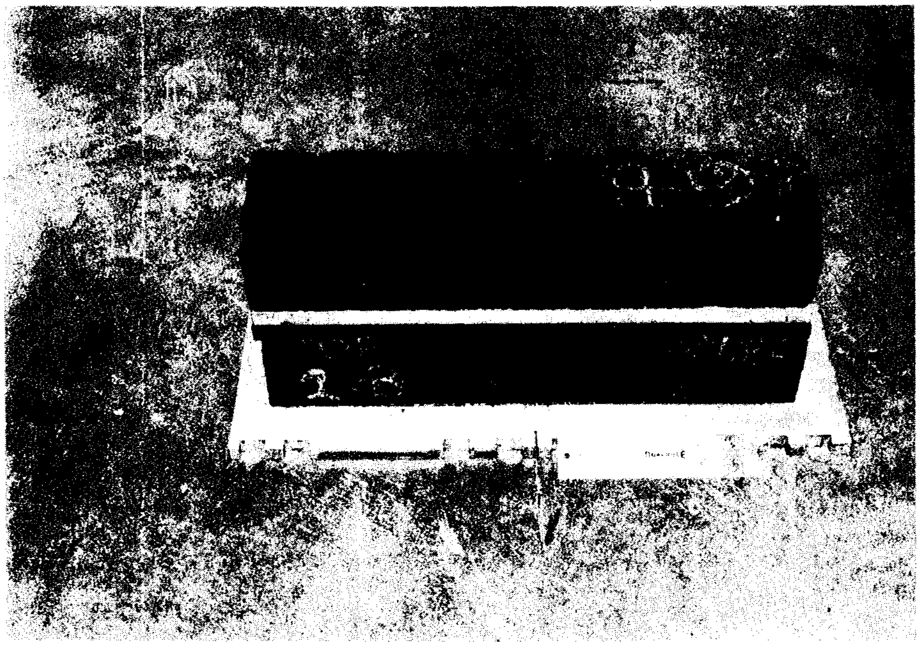

Figure 8. Beam sample being glued to aluminum plates with a second beam being used as a weight.

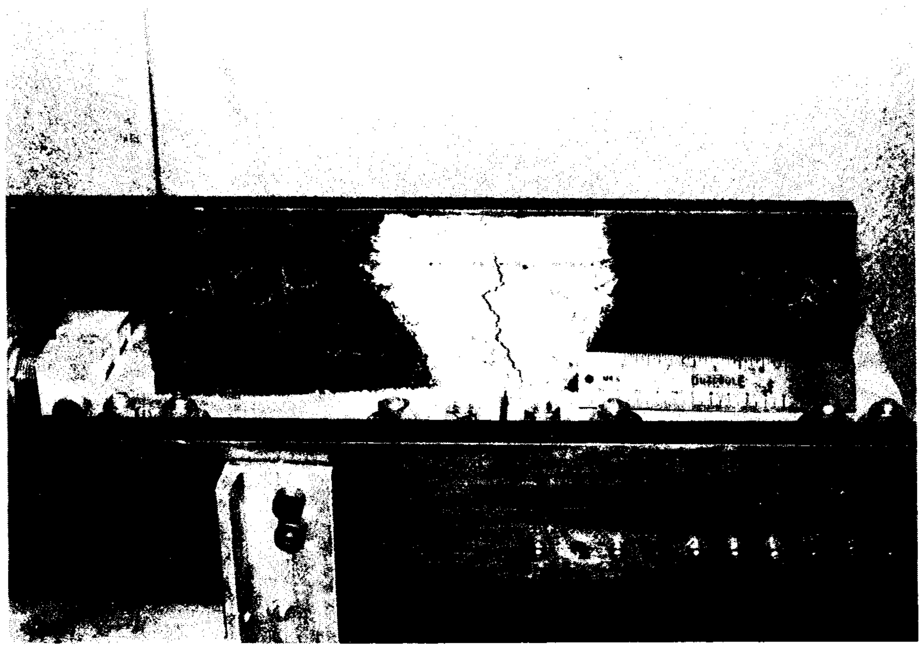

Figure 9. Beam sample at failure with crack extending through specimen.

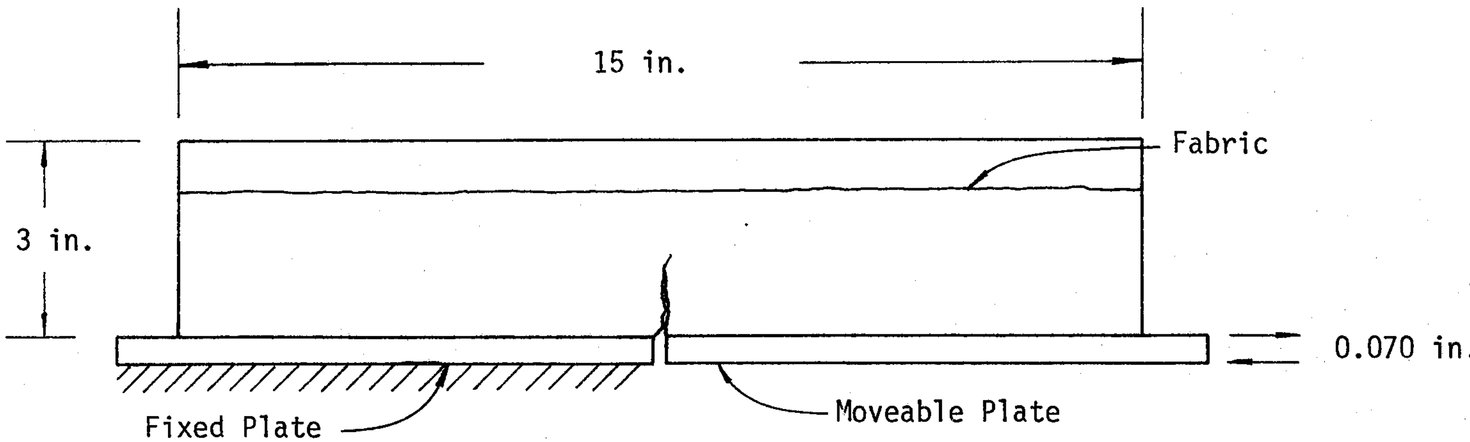


Figure 10. Schematic diagram of test specimen and TTI Overlay Tester.

calibration values for load and displacement were recorded. The TTI Microcomputer was then programmed to receive the overlay test data. For programming convenience, the "Overlay Test Initialization" program was recorded on magnetic cassette tape. A copy of this program is included in Appendix A. After the TTI Microcomputer was programmed to receive the test data, the initialization tape was replaced by a "blank" tape to be used for data collection and storage. Sample identification information and calibration values for load and displacement were entered into the TTI Microcomputer by means of the Texas Instruments Electronic Data Terminal. This information was then stored on the data collection tape.

Actual testing of the overlay samples consisted of moving the loading ram) with the sample bolted into position on the Overlay Tester) from the "closed" position to the "open" position (a displacement of 0.070 in.) and back to the original "closed" position. (This movement from "closed" to "open" and back to the "closed" position is defined as one "cycle.") This oscillating horizontal movement simulates the opening and closing of pavement cracks and joints produced by thermal contraction and expansion of the pavement materials. Continued oscillating movement of this type ("thermal" cycling) causes a crack to propagate from the bottom of the sample (near the butt joint of the two base plates) upward through the sample. "Failure" is defined as the condition in which a continuous reflection crack is visible up both sides of the sample and across the entire width of the top of the sample, as observed when the Overlay Tester is in the "open" position. Under this condition, the load required to open the gap between the sample base plates is due to the frictional forces that must be overcome to separate the two sample parts and the energy required to stretch the unbroken fabric reinforcement fibers. A view of a typical test specimen at failure is shown in Figure 7.

A loading rate of one cycle per ten seconds was used throughout the entire test program. Loading and unloading were carried on in a continuous cycling motion except for short delays prior to cycles for which data were to be recorded. (The sample was left in the "closed" position during these delays.) The load and displacement values were monitored and recorded only during selected loading cycles of each test. The X-Y Recorder was used to plot the applied load versus displacement relationship during the selected cycles. (Copies of these graphs are included in Appendix B.) Figure 9 illustrates the general shapes of typical load versus displacement graphs at various stages during an overlay test. This load and displacement information was also collected (in the form of varying electronic voltages) by the TTI Microcomputer. These voltages were converted into a computer usable form and stored in the TTI Microcomputer memory until the sampling for an individual cycle was completed. The converted information was then stored on the magnetic cassette data tape.

An engineer's scale was used to visually measure the crack height on both sides of the test specimen during those cycles in which the load and displacement data were recorded. Crack height measurements were made when the sample reached its maximum displacement or completely "open" position. (The full length of the crack is most

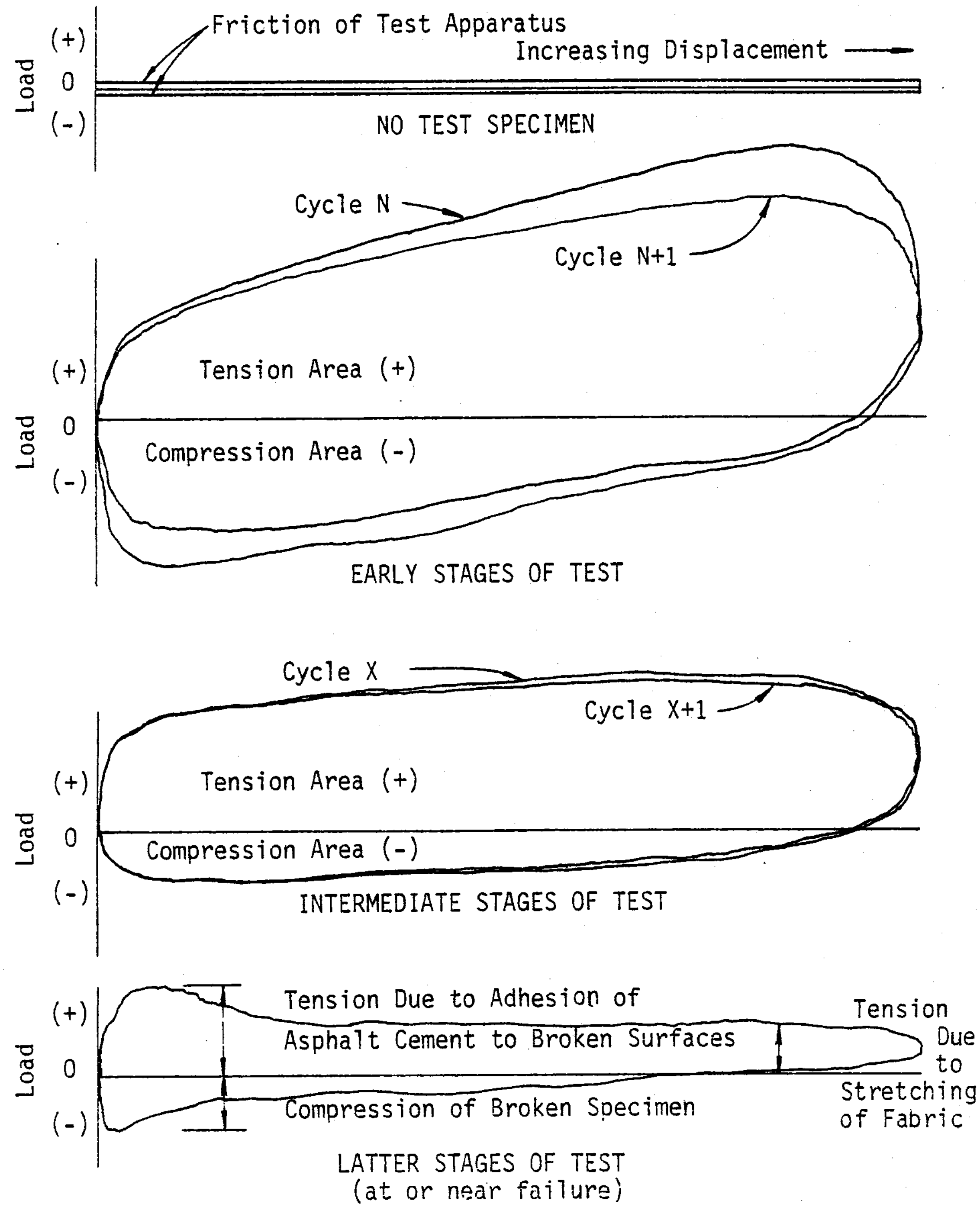


Figure 11. Typical recordings of load versus displacement at various stages during an overlay test.

readily visible when the sample is in this position.) This crack height information was entered into the TTI Microcomputer through the Electronic Data Terminal and was then stored on the magnetic cassette data tape. The arithmetic average of the two crack heights was used in the data analysis calculations.

## Summary

Each test specimen was subjected to repetitive tensile loading, by a cyclic opening and closing of a predetermined gap, until failure occurred. The load, displacement and crack height information were recorded at selected cycles throughout the testing of each sample. These data were stored on magnetic tape for future analysis. The data analysis procedure is described in Chapter V. Original data are included in Appendix B.

# CHAPTER V

# DATA REDUCTION AND ANALYSIS

## General

The computer-based collection/reduction system used in this experiment was developed by the personnel of the Texas Transportation Institute in an effort to expedite the collection and reduction of data obtained from various laboratory tests. This system utilizes a microcomputer to collect and store test data on magnetic cassette tape. A second microcomputer is used to reduce these data into forms that may be readily analyzed by performing various mathematical calculations.

The TTI data collection/reduction system may be adapted for use with a number of different testing devices. When used with the TTI Overlay Tester, six separate computer programs are used to collect, store and reduce the test data. Copies of these programs are included in Appendix A.

Voltages representing load and displacement were monitored during selected loading cycles of each overlay test. The crack length, load and displacement data were recorded on magnetic tape. The load and displacement data were also recorded in graphical form by the X-Y plotter. Copies of these graphs are included in Appendix B.

In this chapter, data reduction and analysis methods used in determining strain energy release rate and fracture properties for each sample are described in detail.

Determination of Strain Energy Release Rate, G

The first step used in the data reduction procedure was to determine the total energy required to produce the 0.070 in. displacement (gap opening) during each of the selected loading cycles. This crack opening energy, E, is represented by the area under the tension portion of the load versus displacment graph for each loading cycle. Energy values were calculated for the selected loading cycles by mathematical integration of the load versus displacement data. These calculations were performed by the Smoke Signal Broadcaster 6800 Mnemonic Assembler which utilized the computer program shown on page 108 of Appendix A. A number of these calculations were also performed manually to check the accuracy of the computer data collection/ reduction system. The manual data reduction procedure utilized a planimeter to determine the area under the tension portion of the load versus displacement curves. Energy values were then calculated from this area using the appropriate load and displacement scaling factors.

The second step in the data reduction procedure was to determine the relationship between crack length, C, and loading cycle number, N. The computer program shown on page 111 was used to calculate the logarithm of each crack length and loading cycle number for the selected cycles in which data were recorded. The relationship of log C versus log N was then represented mathematically by the equation:

$$C = aN^b \quad (5\text{-}1)$$

where

- C = the crack length (average of two sides) measured (in inches) from the base of the sample,
- a = a regression constant representing the average crack length at the first cycle opening (i.e. the Y - intercept of the log C versus log N curve)
- N = the loading cycle number, and
- b = the slope of the log C versus log N curve.

The values of a and b were determined by the computer by representing all the log C versus log N data with a single straight line by using simple linear regression techniques. A similar procedure was performed graphically for a number of test samples to check the accuracy of the computer program. A typical graph of log C versus log N is shown in Figure 12.

The third step in the data reduction procedure was to determine the relationship between the crack opening energy, E, and the loading cycle number, N. The computer program shown on page 111 was used to calculate the logarithm of each energy value and loading cycle number. The relationship of log E versus log N was then represented mathematically by the equation:

$$E = cN^d \tag{5-2}$$

where

- E = the crack opening energy (or tensile work for one cycle) measured in inch-pounds,
- c = a regression constant representing the energy required to produce the predetermined gap opening in the first

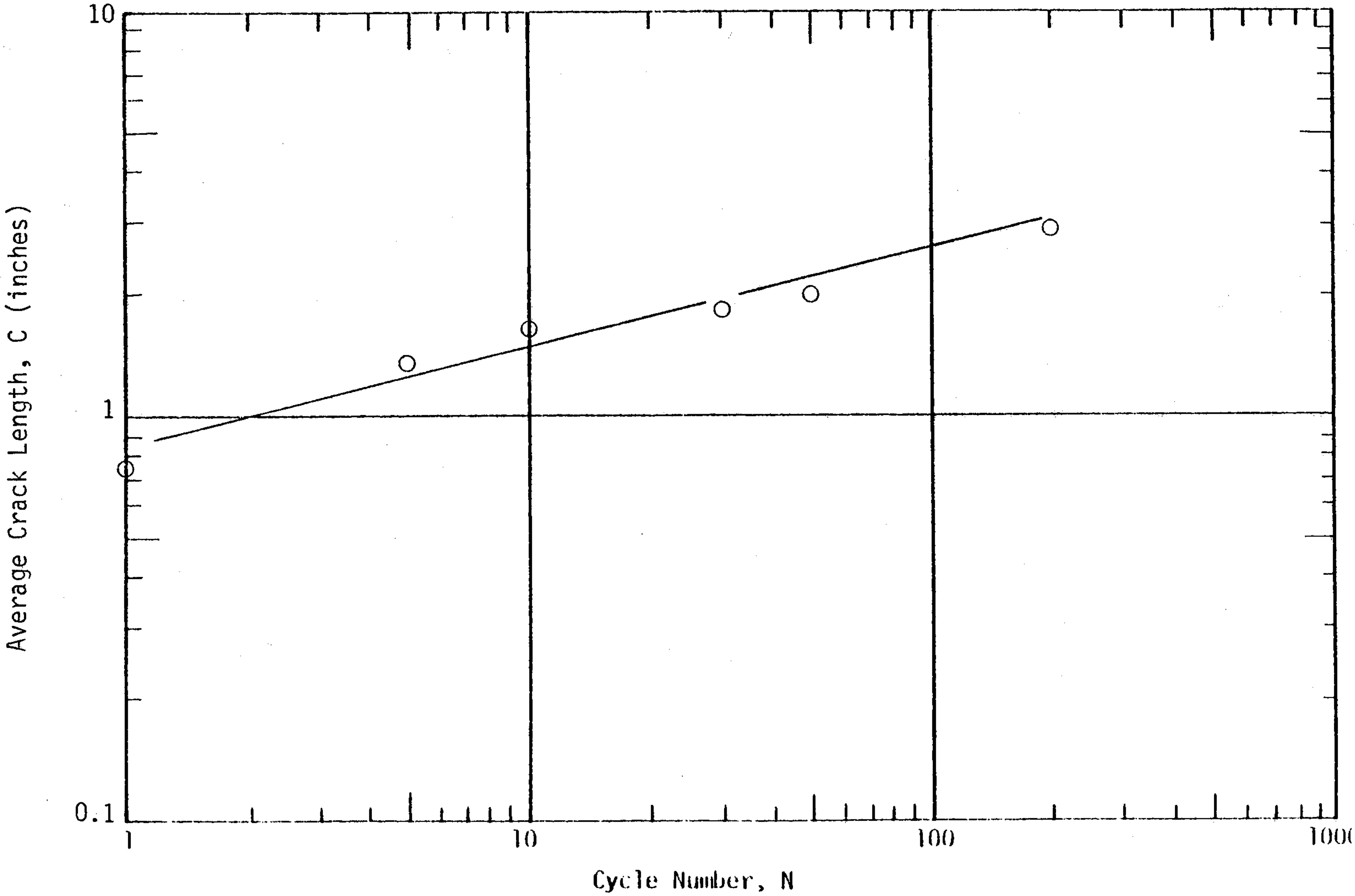


Figure 12. Log C versus Log N for Sample 110.

loading cycle,

N = the loading cycle number, and

d = the slope of the log E versus log N curve. (Since the crack opening energy, E, decreases with additional loading cycles, the slope of the log E versus log N curve is always negative. Therefore d is also negative.)

Linear regression techniques were also used here to represent the log E versus log N data with a single straight line. Data for selected samples were also graphed manually to check the accuracy of the computer program. A typical graph of log E versus log N is shown in Figure 13.

The fourth step in the data reduction process involved the calculation of the strain energy release rate, G, for each of the test specimens. The strain energy release rate used here is defined as the initial change of work per unit of increased crack surface area and therefore calculated at the first loading cycle. Computation of the strain energy release rate, G, was performed by the computer using Equation (5-7). A brief derivation of this equation is given below.

Equation (5-1) related crack length to cycle number as follows:

$$C = aN^b \tag{5-1}$$

Taking the derivative of C with respect to N gives the rate of crack growth per cycle as a function of the number of cycle repetitions. This is represented by the following equation:

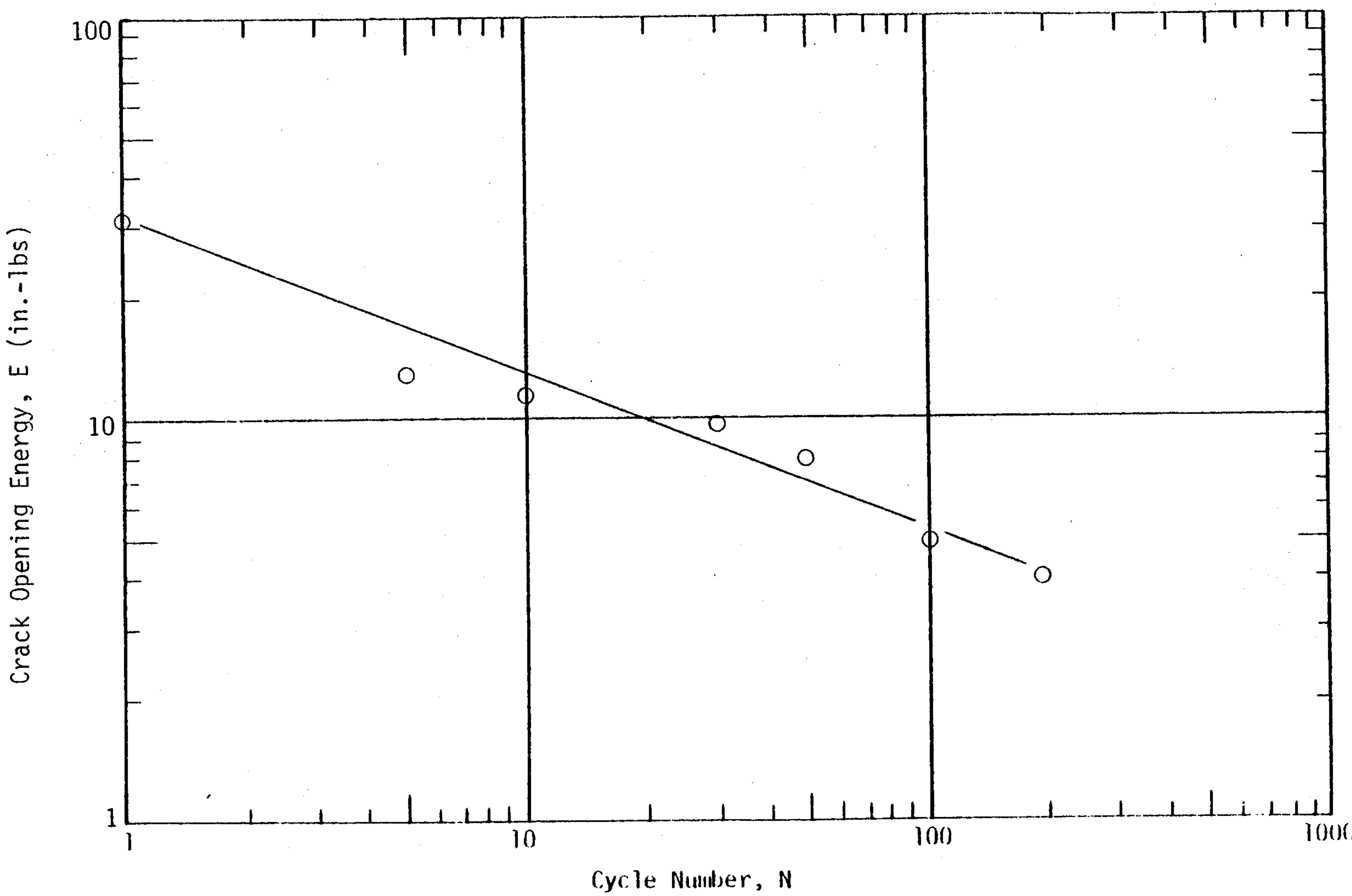


Figure 13. Log E versus Log N for Sample 110.

$$\frac{dc}{dN} = (ab)\ N^{b-1} \tag{5-3}$$

The rate of change of work with each cycle is found by taking the derivative of Equation (5-2) with respect to the number of loading cycles as follows:

$$\frac{dE}{dN} = (cd)\ N^{d-1} \tag{5-4}$$

The rate of change of energy (work) with crack length is then found by dividing Equation (5-4) by Equation (5-3), as follows:

$$\frac{dE/dN}{dc/dN} = \frac{dE}{dc} = \frac{(cd)N^{d-1}}{(ab)N^{b-1}} = \frac{(cd)}{(ab)} \cdot N^{d-b} \tag{5-5}$$

The rate of change of energy per unit area, A, of the crack is obtained by dividing Equation (5-5) by twice the width of the overlay specimens (i.e. 6 inches).

$$\frac{dE}{dA} = \frac{1}{b} \cdot \frac{dE}{dc} = \frac{1}{b} \cdot \frac{(cd)}{(ab)} \cdot N^{d-b} \tag{5-6}$$

Since the rate of strain energy release is calculated at the <u>first</u> loading cycle, it is given by the following equation:

$$G = \frac{1}{b} \cdot \frac{(cd)}{(ab)} \tag{5-7}$$

The strain energy release rate, G, as calculated here, has units of in/lbs per sq. in. Note that since d is always a negative number and the remaining constants are positive, the strain energy release rate, G, is always negative.

Crack propagation was significantly retarded at or near the fabric reinforcement layer in some test specimens. Therefore, the log C versus log N and log E versus log N test data for these specimens could not be accurately represented in a single straight line. The computer program shown on page 113 used linear regression techniques to describe the test data in two separate segments. The first segment includes all test data up to the time (or cycle number) when the reflective crack reaches the fabric layer. The second segment includes all test data from the time the reflective crack penetrates the fabric layer until sample failure. Figure 14 illustrates a typical graph of log C versus log N for test data where there was a significant delay in reflective crack propagation. Figure 15 shows the log E versus log N relationship for the same test specimen. The strain energy release rate in these samples were calculated using the regression coefficients obtained for the first segment which represents the data before the crack reached the fabric.

## Determination of Fracture Properties, A and n

The analysis of sample failure due to crack propagation was done using fracture mechanics concepts. The basic equation in fracture mechanics, known as Paris' Law, relates the rate of crack growth per load cycle, $\frac{dc}{dN}$, to the stress intensity factor change during loading, K, in the following manner.

$$\frac{dc}{dN} = A(\Delta K)^n \tag{5-8}$$

where

A, n = fracture properties of the material

Finite element analysis methods were used to obtain relationships between the dimensionless quantities K/P and 2K/Eu and the relative crack length c/d. These relationships are shown in graphical form in

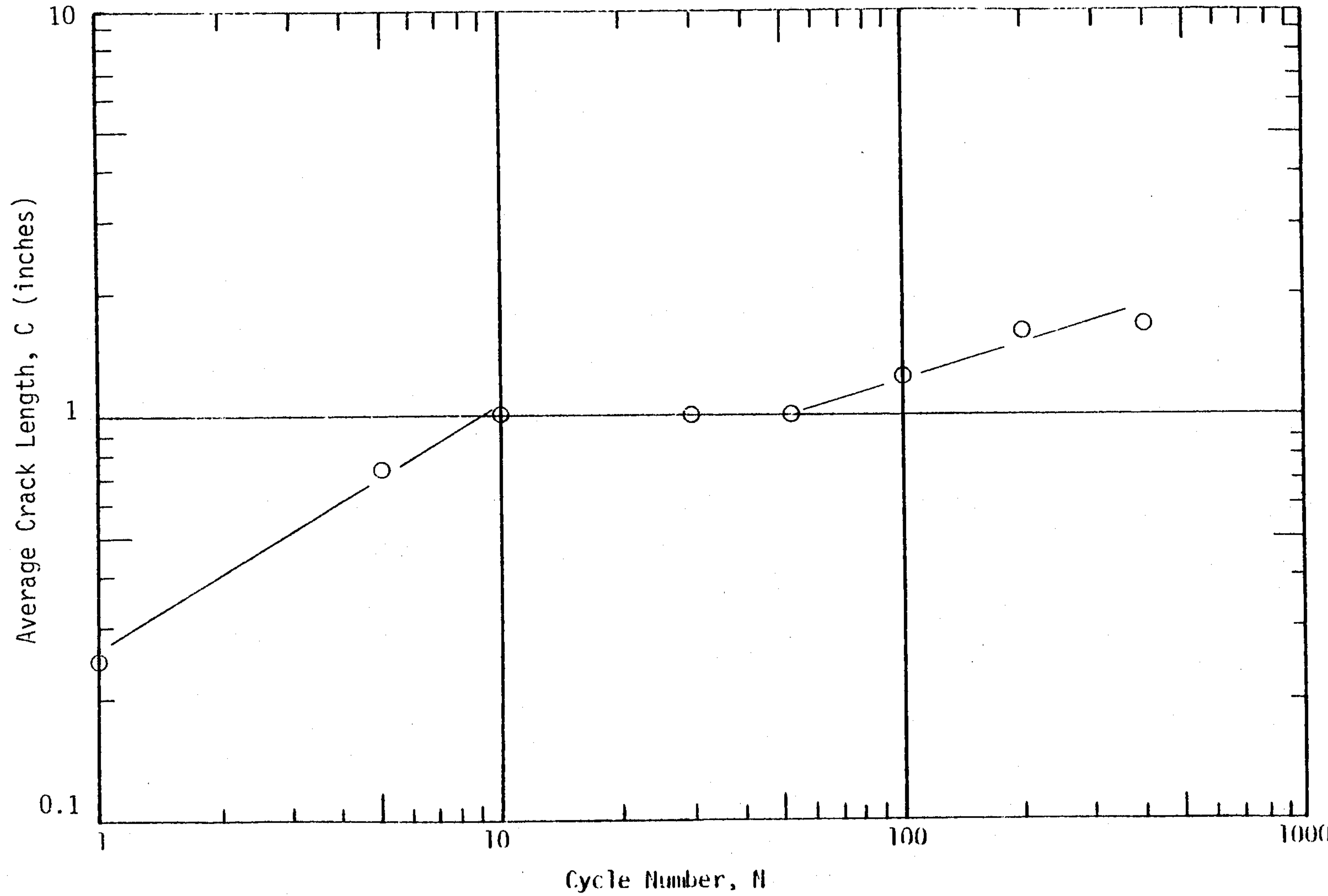


Figure 14. Log C versus Log N for Sample 101.

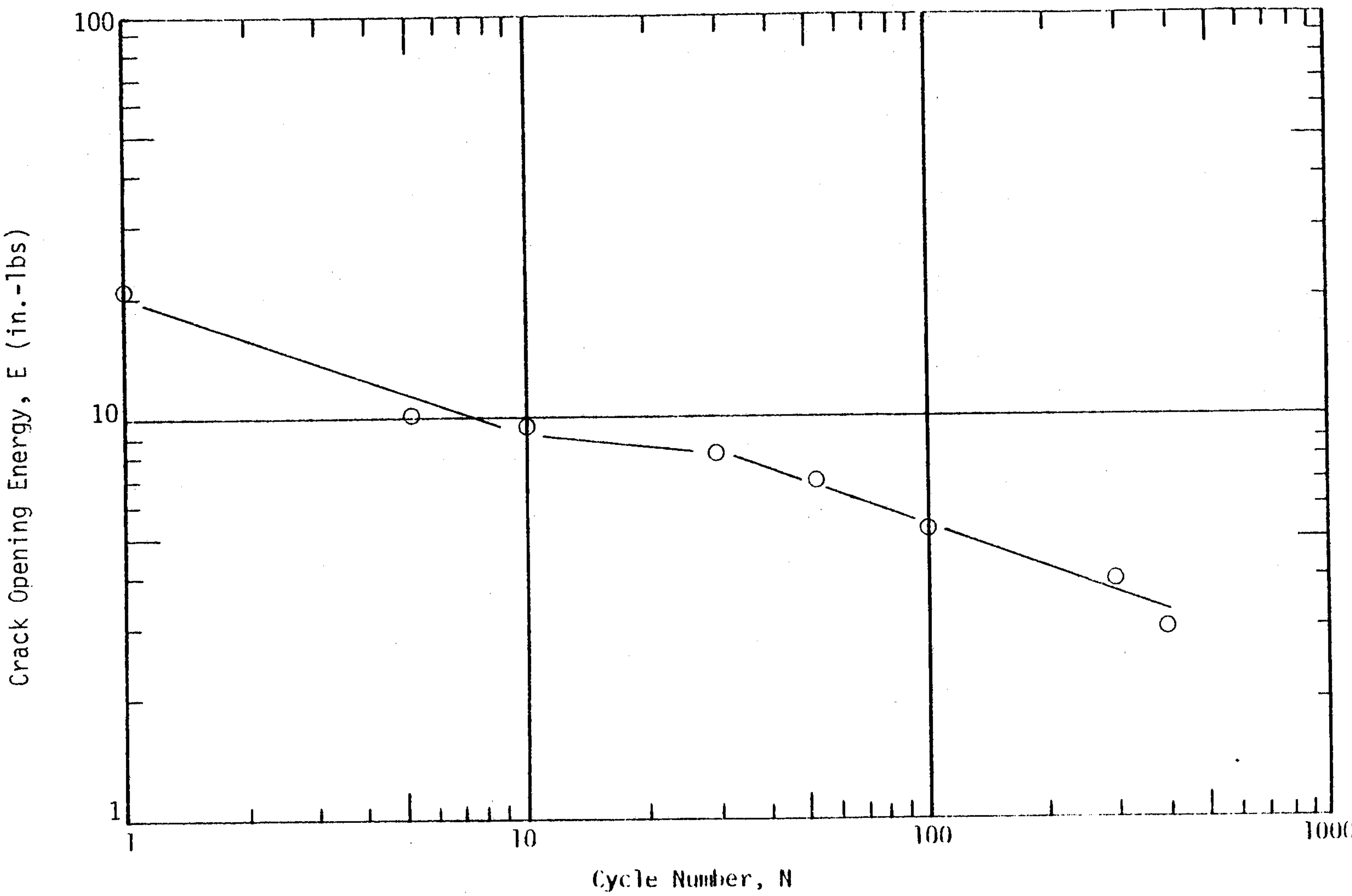


Figure 15. Log E versus Log N for Sample 101.

Figures 16 and 17. The following definitions apply to the symbols used.

K = Stress Intensity Factor

P = Peak Load

E = Relaxation Modulus

u = Crack opening at the bottom of the sample

c = Crack Length

d = Depth of the sample

The procedure used in the determination of the fracture properties A and n for each specimen is described below.

The first step in this analysis is to calculate the average of the crack lengths measured on either side of the sample. The ratio of this average crack length, c, to the depth of the overlay sample, d, is used on the graph shown in Figure 16 to obtain the corresponding K/P value. This quantity when multiplied by the measured load, P, gives the required stress intensity factor, K. The value of 2K/Eu is then determined using the c/d ratio calculated above on Figure 17. Since the stress intensity factor, K, is already known, the relaxation modulus, E, corresponding to the current level of crack length can be determined. Using Equation (5-3), the rate of crack growth, $\frac{dc}{dN}$, can then be computed for each cycle number for which the stress intensity factor has been determined. Finally, linear regression analysis techniques are used to determine the constants, A and n, which relate the logarithm of crack growth rate, $\frac{dc}{dN}$, to the logarithm of stress intensity factor, K. The relevant equation is

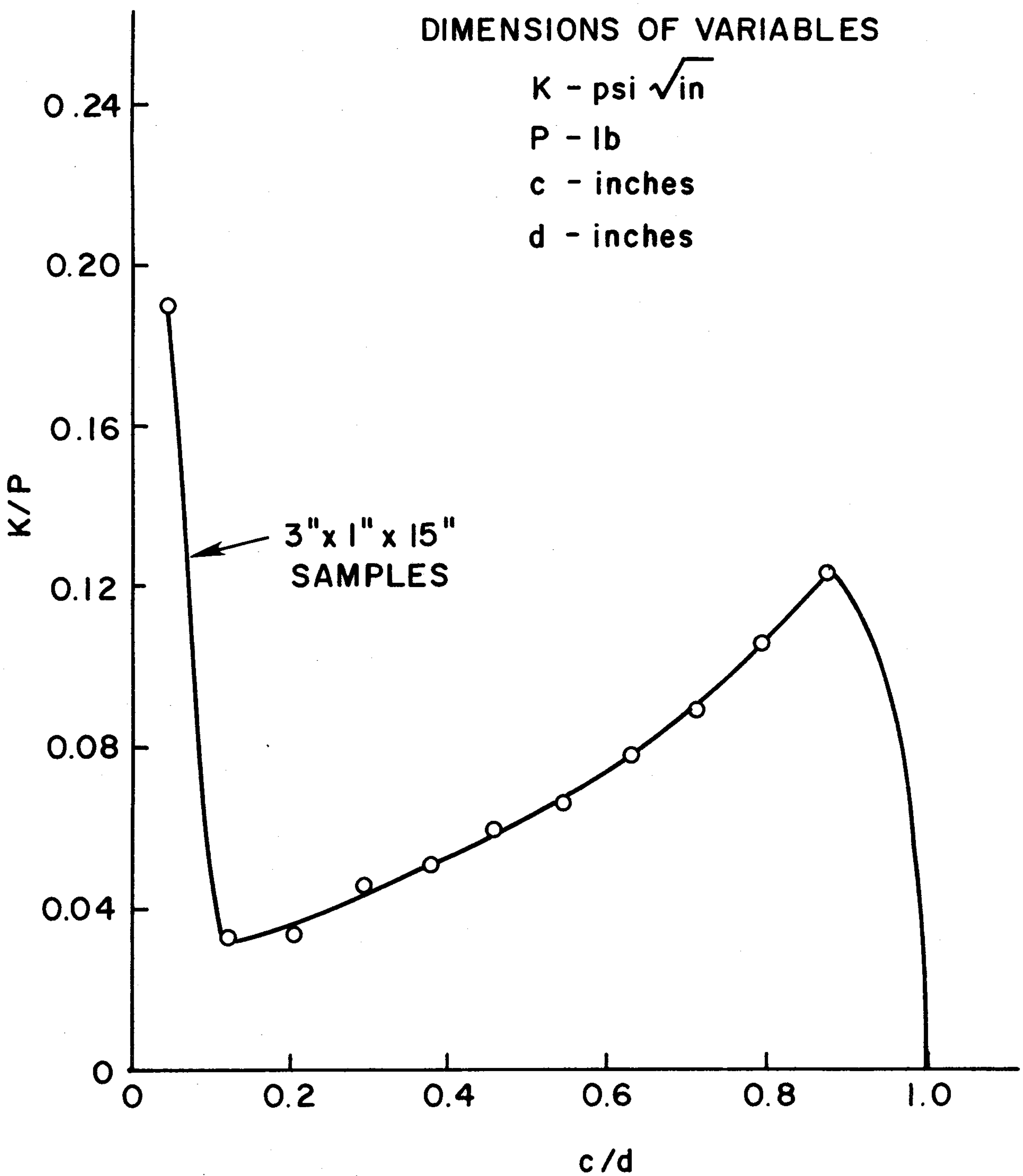


FIGURE 16. K/P versus c/d

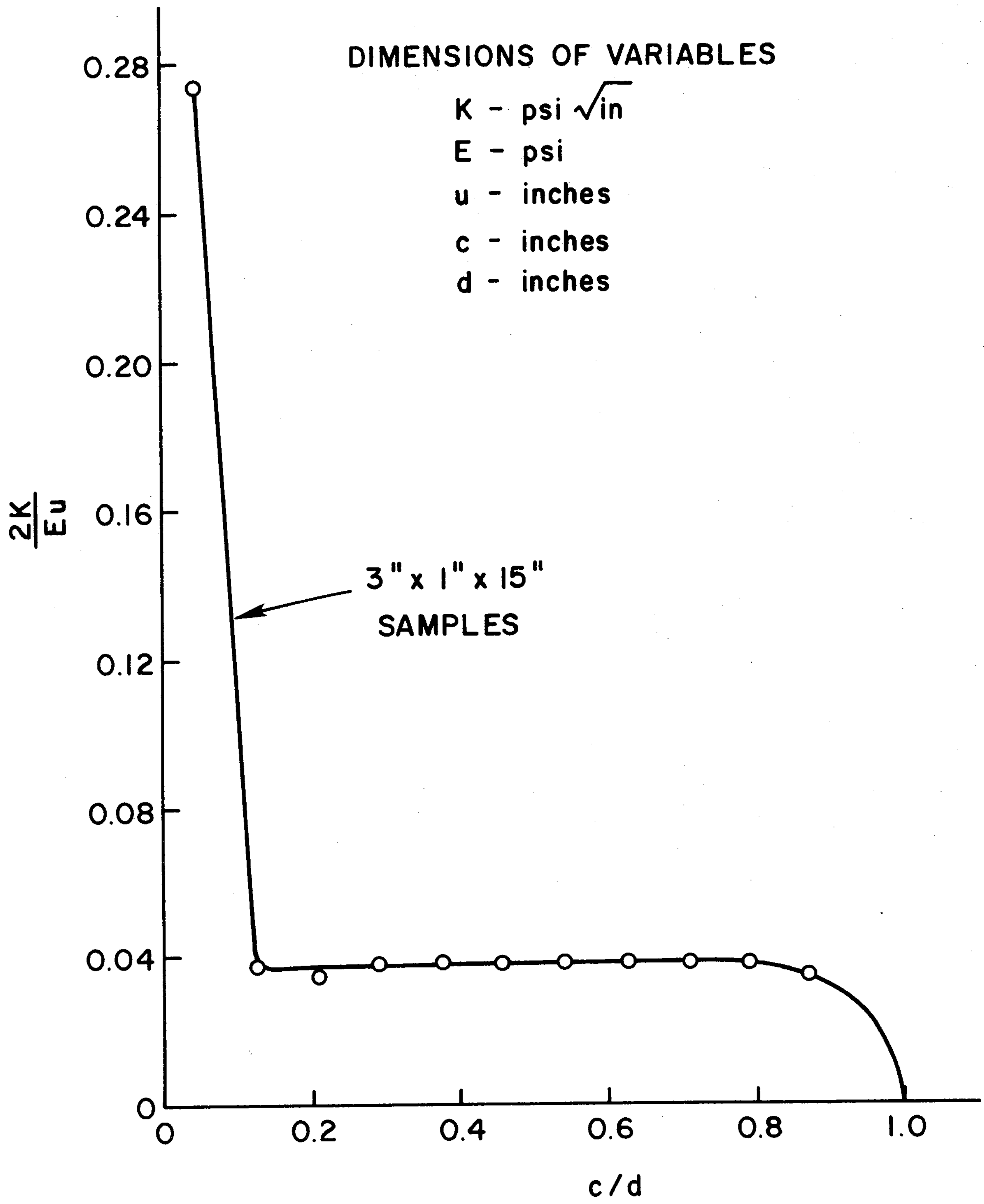


FIGURE 17. 2K/Eu versus c/d

$$\log\left(\frac{dc}{dN}\right) = \log A + n \log(K) \qquad (5\text{-}9)$$

## Summary

Data obtained during testing included: (a) the number of loading cycles required to produce failure, (b) the crack length at selected load cycles, (c) a graphical plot of load versus displacement for selected loading cycles, and (d) measurements of load and displacement throughout selected loading cycles. Using various computer programs these data were analyzed to obtain the strain energy release rate, G, and the fracture properties, A and n, for each of the test specimens. A detailed account of the data reduction and analysis procedures adopted were given in this chapter. The results of these analyses are presented and discussed in Chapter VI.

CHAPTER VI

# PRESENTATION AND DISCUSSION OF RESULTS

## General

The data reduction and analysis procedures described in Chapter V were used to determine the strain energy release rate, G, and the fracture properties A and n for each of the test specimens. These results and other information recorded during testing can be used to determine the relative effectiveness of the different overlay designs in delaying reflection cracking. The details of this analysis are presented in this chapter.

## Analysis of Loading Cycles to Failure, N

One of the most obvious methods of evaluating the relative resistance of each of the test specimens to reflective cracking is to compare the number of loading cycles required to produce failure in each sample. Table 1 lists the number of loading cycles each test specimen was subjected to during testing. "Failure" is defined as the condition in which a continuous reflection crack is visible up both sides of the sample and across the entire width of the top of the sample, as observed when the TTI Overlay Tester is in the "open" position. This implies that an overlay sample that has reached failure would consist of two separate portions of the original sample. (However, this does not imply that the fabric reinforcement is broken

Table 1. Summary of Test Results.

| Sample Number | Fabric Type | Tack Coat Ratio | Cycles to Failure | Energy Release Rate $G(lb\text{-}in/in^2)$ | a | b | c | d |
|---|---|---|---|---|---|---|---|---|
| 100* | Old Petromat | Low | 675(1) | -8.24 | 0.59 | 0.24 | 12.32 | -0.59 |
| 101** | Old Petromat | Low | 1150+ ⊛ | -22.20 | 0.35 | 0.26 | 27.83 | -0.44 |
| 102* | Old Petromat | Optimum | 290 | -17.74 | 0.12 | 0.64 | 23.73 | -0.35 |
| 103** | Old Petromat | Optimum | 500 | -9.58 | 0.50 | 0.25 | 20.32 | -0.35 |
| 104* | Old Petromat | High | 600 | -6.34 | 1.01 | 0.16 | 20.87 | -0.29 |
| 105** | Old Petromat | High | 1575(2) | -8.96 | 0.20 | 0.32 | 19.36 | -0.18 |
| 106* | New Petromat | Low | 110 | -12.00 | 1.07 | 0.23 | 29.20 | -0.61 |
| 107** | New Petromat | Low | 300+ ⊛ | -39.51 | 0.23 | 0.31 | 32.34 | -0.53 |
| 108* | New Petromat | Optimum | 225 | -11.07 | 0.36 | 0.43 | 29.20 | -0.35 |
| 109** | New Petromat | Optimum | 125 | -11.08 | 0.32 | 0.47 | 27.65 | -0.37 |
| 110* | New Petromat | High | 350 | -7.21 | 0.85 | 0.22 | 25.96 | -0.31 |
| 111** | New Petromat | High | 2325(2) | -21.99 | 0.24 | 0.46 | 34.12 | -0.44 |
| 112* | Mirafi 140 | Low | 450 | -11.41 | 0.76 | 0.24 | 30.29 | -0.42 |
| 113** | Mirafi 140 | Low | 300+ ⊛ | -47.46 | 0.92 | 0.02 | 21.14 | -0.30 |
| 114* | Mirafi 140 | Optimum | 500 | -8.82 | 0.36 | 0.37 | 21.71 | -0.33 |
| 115** | Mirafi 140 | Optimum | 725+ ⊛ | -21.82 | 0.50 | 0.14 | 25.19 | -0.38 |
| 116* | Mirafi 140 | High | 1000(2) | -8.41 | 0.31 | 0.42 | 21.81 | -0.30 |
| 117** | Mirafi 140 | High | 1450 ⊛ (2) | -16.63 | 0.36 | 0.26 | 32.45 | -0.29 |

Table 1. (Continued)

| Sample Number | Fabric Type | Tack Coat Ratio | Cycles to Failure | Energy Release Rate $G(lb\text{-}in/in^2)$ | a | b | c | d |
|---|---|---|---|---|---|---|---|---|
| 118* | Bidim C34 | Low | 250 | -14.56 | 0.36 | 0.40 | 25.79 | -0.51 |
| 119** | Bidim C34 | Low | 550 ⊛ | -6.01 | 0.62 | 0.18 | 15.80 | -0.26 |
| 120* | Bidim C34 | Optimum | 375 | -11.66 | 0.49 | 0.32 | 31.16 | -0.36 |
| 121** | Bidim C34 | Optimum | 1300 ⊛ | -9.32 | 0.52 | 0.20 | 18.73 | -0.31 |
| 122* | Bidim C34 | High | 1100(2) | -9.59 | 0.95 | 0.18 | 32.21 | -0.32 |
| 123** | Bidim C34 | High | 2050 ⊛ | -10.08 | 0.27 | 0.33 | 19.86 | -0.28 |
| 124* | Woven Tape | Low | 175 | -6.59 | 0.74 | 0.27 | 22.21 | -0.37 |
| 125** | Woven Tape | Low | 1000+ ⊛ | -33.50 | 0.77 | 0.10 | 34.25 | -0.50 |
| 126* | Woven Tape | Optimum | 475 | -11.03 | 0.36 | 0.34 | 28.18 | -0.29 |
| 127** | Woven Tape | Optimum | 875(1) | -6.63 | 0.63 | 0.17 | 27.09 | -0.16 |
| 128* | Woven Tape | High | 625(2) | -6.80 | 0.58 | 0.25 | 21.20 | -0.28 |
| 129** | Woven Tape | High | 300 | -6.78 | 0.19 | 0.43 | 19.86 | -0.17 |
| 131** | Burlington 2532 | Low | 340+ ⊛ | -36.75 | 0.63 | 0.11 | 24.36 | -0.67 |
| 132* | Burlington 2532 | Low | 500(2) | -8.26 | 0.54 | 0.29 | 22.63 | -0.35 |
| 133** | Burlington 2532 | Optimum | 450 | -7.15 | 0.48 | 0.26 | 17.86 | -0.30 |
| 134* | Burlington 2532 | Optimum | 485 | -6.66 | 0.73 | 0.23 | 19.85 | -0.34 |
| 135** | Burlington 2532 | High | 475 | -15.50 | 0.23 | 0.39 | 23.97 | -0.36 |
| 136* | Burlington 2532 | High | 675 | -8.96 | 0.53 | 0.27 | 23.88 | -0.33 |

Notes:
* Reinforcement fabric is located 3/4 inches from top of sample.
** Reinforcement fabric is located one inch from bottom of sample.
(1) Cracking pattern resulted in "hinge effect".
(2) Multiple cracking occurred.
\+ Failure was not reached due to excessive slippage at the fabric.
⊛ Slippage occurred at the fabric layer.

at "failure". Due to stretching and slippage of the reinforcement fabrics, each fabric remained essentially intact throughout the full extent of the overlay test for each sample.) This "ideal" mode of failure was not observed in some specimens for reasons discussed below.

Some of the test specimens developed a cracking pattern in which two primary cracks formed, one on either side of, and extending into, the beam sample. Failure of these cracks to join each other as they propagated upward and across the top of the sample resulted in development of a "hinge" effect. When this condition occurred, the load distributed to the uncracked material was reduced and the number of loading cycles required to produce failure was therefore increased. Failure was not reached in other test specimens, due to the breaking of the bond between the fabric reinforcement and the adjoining layer of asphaltic concrete. When this situation developed, slippage along the bottom of the reinforcement layer reduced the amount of load which could be distributed to the uncracked material. In extreme cases excessive slippage resulted in termination of the reflective crack at or near the fabric layer.

Table 2 summarizes the loading cycle data. Examination of these data lead to the following observations:

1. Cracking patterns resulting in the development of a "hinge" effect occurred in only two cases. In each of these cases, continued loading produced failure.
2. Multiple cracking, i.e. formation of more than one primary crack, occurred in five cases. (Four of these cases were in

Table 2. Number of loading cycles to failure.

| Fabric Type | Low Tack Coat Rate | | Optimum Tack Coat Rate | | High Tack Coat Rate | |
|---|---|---|---|---|---|---|
| | Fabric Position | | Fabric Position | | Fabric Position | |
| | Top | Bottom | Top | Bottom | Top | Bottom |
| Old Petromat | 675(1) | 1150+ ⊛ | 290 | 500 | 600 | 1575(2) |
| New Petromat | 110 | 300+ ⊛ | 225 | 125 | 350 | 2325 |
| Mirafi 140 | 450 | 300+ ⊛ | 500 | 725+ ⊛ | 1000 | 1450(2) ⊛ |
| Bidim C34 | 250 | 550 ⊛ | 375 | 1300 ⊛ | 1100(2) | 2050 ⊛ |
| Woven Tape | 175 | 1000 ⊛ | 475 | 875(1) | 625(2) | 300 |
| Burlington 2532 | 500(2) | 340+ ⊛ | 485 | 450 | 675 | 475 |

Notes:

(1) Cracking pattern resulted in "hinge effect".

(2) Multiple cracking occurred.

\+ Failure was not reached due to excessive slippage at the fabric layer.

⊛ Slippage occurred at the fabric layer.

samples with high tack coat rates.)

3. Slippage along the fabric reinforcement layer was observed in ten cases.

   a. All slippage cases occurred in samples with the fabric located near the lower one-third of the sample.

   b. Every sample constructed with a low tack coat rate with the fabric positioned in the lower one-third of the sample experienced some slippage.

4. Considering only those cases where the "ideal" mode of failure occurred (i.e. one primary crack propagating from the bottom to the top of the sample without slippage) overlay sample life appears to be increased by increasing the tack coat rate.

## Analysis of Strain Energy Release Rate, G

The values for the rate of energy release listed in Table 1 have units of in-lbs per sq. in. It can be seen that larger (absolute) values of energy release rate, G, occur most often when excessive slippage along the fabric layer was observed very early in the testing period. Smaller values of energy release rate generally occur where no excessive slippage was observed. Other cracking patterns do not appear to have much effect on the magnitude of the energy release rate.

## Analysis of Crack Growth Coefficients, a and b

Equation (5-1) related crack length to cycle number as follows:

$$C = aN^b \tag{6-1}$$

where

| | | |
|---|---|---|
| C | = | the crack length, |
| N | = | the loading cycle number, |
| a | = | a regression constant representing the average crack length at the first cycle opening, |
| b | = | the slope of the log C versus log N curve. |

Values of a and b were determined for each sample by the use of regression techniques applied to the crack length versus loading cycle number data. These values, listed in Table 1, may be interpreted in the following manner.

The constant, a, is the distance, in inches, that the crack travels into the overlay specimen the first time the sample is "opened" (i.e. the first loading cycle). Examination of the values listed in Table 1 reveals that "a" ranged from 0.12 to 1.07 with an overall mean of 0.52 inches. The mean values for samples having low, optimum, and high tack coat rates at 0.63, 0.45, and 0.48 inches, respectively. These data indicate that an excessively low tack coat rate may result in accelerated initial crack growth. The type of fabric reinforcement used was not found to have a significant effect on the magnitude of "a". Samples with fabric located near the top of the sample have a mean "a" value of 0.44 inches. This indicates that fabric placement near the bottom of the overlay has a greater effect on the reduction of initial crack growth than does fabric placement near the top of the overlay. With the values of b, c and d remaining constant, smaller values of "a" result in larger (absolute) values of the energy release rate.

The power, b, represents the slope of the log C versus log N curve and is a measure of crack retardation. Smaller values of b indicate slower rates of crack growth and therefore, extended overlay life. The values of b listed in Table 1 range from 0.02 to 0.64 with an overall mean of 0.28. (The value of 0.02 recorded for Sample 113 is unusually low due to the crack propagation reaching the fabric layer on the first loading cycle and not advancing beyond that level due to slippage at the fabric layer.) The mean b values for samples having low, optimum, and high tack coat rates are 0.22, 0.32, and 0.30, respectively. The low mean value of b observed for samples with a low tack coat rate may be attributed to insufficient bond development and resultant slippage along the fabric layer. As previously noted, slippage occurred only when the fabric was located in the lower one-third of the sample. Comparison of the mean value of b for samples with fabric located near the bottom of the sample (b = 0.26) with the mean value of b for samples with fabric near the top of the sample (b = 0.30) indicates that fabric location has little effect on the magnitude of the b value. The slightly lower mean value of b for samples with fabric near the bottom of the sample may be attributed to the amount of slippage observed in this group of samples. The type of fabric reinforcement used was not found to have a significant effect on the magnitude of b. With the values of a, c, and d remaining constant, smaller values of b result in larger (absolute) values of energy release rate.

Analysis of Tensile Work Coefficients, c and d

Equation (5-2) related the crack opening energy to the loading cycle numer as follows:

$$E = cN^d \qquad (6\text{-}2)$$

where

E = the crack opening energy (or tensile work for one cycle) measured in inch-pounds,

c = a regression constant representing the energy required to produce the predetermined gap opening on the first cycle,

N = the loading cycle number, and

d = the slope of the log E versus log N curve.

Table 1 lists the values of c and d obtained (by the use of regression techniques) for each of the test specimens. These values may be interpreted in the following manner.

The constant, c, is the initial work, measured in inch-pounds, that must be done to open the crack. Examination of the values of c listed in Table 1 reveals that c ranged from 12.32 to 34.25 with an overall mean of 24.56 inch-pounds. The mean values for samples having low, optimum and high tack coat rates were 24.85, 24.22, and 24.63, respectively. These values indicate that the tack coat rate used has very little effect on the magnitude of c. "Old" Petromat reinforced samples had the lowest mean value of c (i.e. 20.74) while "New" Petromat reinforced samples had the highest value of c (i.e. 29.75). The mean values of c for samples reinforced with the other fabrics were more nearly equal to the mean value of c for all the samples.

The location of the fabric reinforcement within the sample had no effect on the magnitude of c. With the values of a, b, and d remaining constant, larger values of c result in larger (absolute) values of strain energy release rate.

The power, d, represents the slope of the log E versus log N curve. Smaller absolute values of d indicate a greater resistance to further crack extension. This means that greater amounts of energy are required to extend a reflection crack through an overlay with a small (absolute) d value than through the same thickness of overlay having a larger absolute d value.

The values of d listed in Table 1 range from -0.16 to -0.67 with an overall mean of -0.36. The mean d values for samples having low, optimum and high tack coat rates were -0.46, -0.32, and -0.30, respectively. The higher mean (absolute) value of d observed for samples with a low tack coat rate indicates that insufficient rack coat quantities may significantly reduce an overlay's overall resistance to reflective cracking. The location of the fabric reinforcement within the sample was not found to have a significant effect on the magnitude of d. "New" Petromat reinforced samples had the highest mean (absolute) value of d (i.e. -0.44) while the Woven Tape reinforced samples had the lowest mean (absolute) value of d (i.e. -0.30). No direct correlation between the magnitude of d and the type of fabric used is apparent from the test data. With the values of a, b, and c remaining constant, larger (absolute) values of d result in larger (absolute) values of strain energy release rate indicating less overall resistance to crack propagation.

## Analysis of Peak Load Versus Cycle Number Data

The peak load, P, required to open a test specimen 0.070 inches was determined for selected loading cycles from the load versus displacement graph for each sample. A summary of the peak load recorded on the first loading cycle for each sample is shown in Table 3. Plots of the log P versus log N data are included in Appendix B.

The log P versus log N curves characteristically have three sections or stages of development. In the first stage, a relatively high peak load for the first loading cycle is generally followed by a rather rapid decrease in peak loads for the next few cycles. Thus, the first stage of crack advancement appears as a rather steeply sloping curve in the initial portion of the log P versus log N graph. In a few instances, this rate of decrease in peak load per cycle continues until failure, indicating a nearly uniform crack growth rate occurs with each cycle. However, in the majority of cases, the rate of decrease in peak load per cycle lessens with increasing load cycles, indicating a second stage of crack development is taking place.

This second stage appears as a "flatter" portion of the graph due to a reduction in the crack growth rate per cycle. Samples exhibiting an essentially flat curve in this second stage indicate that much of the observed load was supported by the reinforcing fabric. As a result of this, crack growth often stopped or proceeded at an undetectable rate. Occasionally, fine cracks appeared on the top of the sample before the primary crack penetrated above the fabric layer.

Penetration of the reflection crack beyond the fabric layer and

Table 3. Peak load, P, values (measured in pounds) for the first loading cycle.

| Fabric Type | Low Tack Coat Rate | | Optimum Tack Coat Rate | | High Tack Coat Rate | |
|---|---|---|---|---|---|---|
| | Fabric Position | | Fabric Position | | Fabric Position | |
| | Top | Bottom | Top | Bottom | Top | Bottom |
| Old Petromat | 465 | 498 | 465 | 525 | 585 | 442 |
| New Petromat | 660 | 645 | 738 | 670 | 633 | 697 |
| Mirafi 140 | 600 | 465 | 547 | 502 | 525 | 622 |
| Bidim C34 | 637 | 525 | 600 | 555 | 825 | 525 |
| Woven Tape | 582 | 507 | 622 | 661 | 541 | 532 |
| Burlington 2532 | 447 | 383 | 531 | 309 | 615 | 555 |

through the remainder of the sample comprised the third stage of crack advancement. This stage of crack development generally appears as a steeply sloping curve in the final portion of the log P versus log N graph. The overall mean peak load observed for samples at "failure" was 80 pounds, (about fifteen per cent of the overall mean initial peak load) rather than zero, as one might expect. The residual load required to separate the two parts of the sample after it has reached failure is due to one or more of the following causes: stretching of the fabric; breaking of the asphalt bond that is established when the sample is in the "closed" position; and overcoming friction forces created by movement of the broken sample parts past irregularly cracked surfaces of the asphaltic concrete.

Maximum observed peak loads for the first loading cycle range from 309 to 825 pounds with an overall mean of 562 pounds. The mean values for samples having low, optimum, and high tack coat rates are 534, 560, and 591 pounds, respectively. These data indicate that the force required to propagate a new crack into fabric reinforced overlays tend to increase as the tack coat rate is increased. Samples with fabric located near the top of the sample have a mean initial peak load value of 590, while those with reinforcement located near the bottom of the sample have a mean initial peak load value of 534 pounds. The lower mean values for both the samples with low tack coat rates and the samples with fabric located near the bottom of the sample are due primarily to the extent of fabric slippage which occurred in these samples.

The mean initial peak loads for the six different types of fabric are as follows:

| | |
|---|---|
| Old Petromat | 497 |
| New Petromat | 674 |
| Mirafi 140 | 544 |
| Bidim C34 | 611 |
| Woven Tape | 574 |
| Burlington 2532 | 473 |

Although it can be expected that the initial peak load would be related in some manner to the type of reinforcement, it is difficult to establish any direct correlation between these two variables. This is because the variations in other parameters such as tack coat rate are also dependent upon the type of fabric. However, it is significant to note that, with the exception of one case, samples reinforced with New Petromat exhibited higher initial peak load values than did samples reinforced with any of the other fabrics.

The initial peak load values listed in Table 3 provide an indication of the amount of thermally induced tensile stress a newly constructed overlay can be expected to withstand. If the load induced in a new overlay by thermal contraction of an old pavement is significantly less than the initial peak load observed for a similarly constructed overlay sample, the overlay will either resist the tensile forces and remain intact, or a reflection crack (smaller than the laboratory induced 0.070 inches opening) will develop. Overlay tests performed on both fabric reinforced and nonreinforced samples indicate that fabric reinforcement increases the initial peak load value. This increase may be due, at least in part, to the increased asphalt content associated with fabric reinforcement and a resultant decrease in air void content in the immediate vicinity of the fabric.

Analysis of the fracture properties, A and n

The analytical procedure described in Chapter V was used to determine the fracture properties A and n for each overlay specimen. The samples in which failure was brought about by excessive slippage at the fabric was excluded from this analysis. The results obtained are given in Table 4.

As indicated by Paris' Law (Equation 5-8)

$$\frac{dc}{dN} = A(\Delta K)^n \qquad (6\text{-}3)$$

Smaller values of the coefficient, A and the power, n would mean slower rates of crack propagation and therefore greater resistance to fracture. Also, it was observed that there is a linear relationship between $\log_{10}A$ and n which could be represented by an equation of the form:

$$n = a + b \log_{10}A \qquad (6\text{-}4)$$

where $\log_{10}A$ and the coefficient, b will always be negative.

This equation relating the two material properties shows that when A gets smaller (more negative), n will get larger. These observations suggest that the sum of $\log_{10}A$ and n can be regarded as a measure of resistance to fracture. The following rule may be

TABLE 4. Fracture Properties of Fabric Reinforced Asphaltic Concrete Overlay Samples

| Sample Number | Fabric Type | Fabric Weight (oz/sq.yd) | Fabric Position | Optimum Tack Coat Rate (gal/sq.yd) | Actual Tack Coat Rate | | Relaxation Modulus at Fabric ($lb/in^2$) | A | n |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | L/O/H | (gal/sq.yd) | | | |
| 100 | | | A | | Low | 0.13 | 1401 | $2.51x10^{-4}$ | 4.29 |
| 101 | | | B | | Low | 0.13 | * | * | * |
| 102 | Old | 3.50 | A | 0.26 | Optimum | 0.26 | 4133 | $1.21x10^{-2}$ | 0.54 |
| 103 | | | B | | Optimum | 0.26 | 2705 | $3.63x10^{-6}$ | 6.16 |
| 104 | Petromat | | A | | High | 0.52 | 3326 | $9.33x10^{-5}$ | 2.97 |
| 105 | | | B | | High | 0.52 | 1350 | $2.61x10^{-4}$ | 2.25 |
| 106 | | | A | | Low | 0.11 | 3151 | $4.10x10^{-4}$ | 2.70 |
| 107 | | | B | | Low | 0.11 | * | * | * |
| 108 | New | 4.10 | A | 0.22 | Optimum | 0.22 | 5254 | $1.25x10^{-3}$ | 1.66 |
| 109 | | | B | | Optimum | 0.22 | 4185 | $4.38x10^{-3}$ | 1.14 |
| 110 | Petromat | | A | | High | 0.44 | 2699 | $2.01x10^{-5}$ | 4.19 |
| 111 | | | B | | High | 0.44 | 2362 | $3.77x10^{-4}$ | 1.80 |
| 112 | | | A | | Low | 0.10 | 2626 | $3.27x10^{-4}$ | 3.16 |
| 113 | | | B | | Low | 0.10 | * | * | * |
| 114 | Mirafi | 4.00 | A | 0.20 | Optimum | 0.20 | 2277 | $3.40x10^{-3}$ | 1.16 |
| 115 | | | B | | Optimum | 0.20 | * | * | * |
| 116 | 140 | | A | | High | 0.50 | 2102 | $6.06x10^{-4}$ | 2.23 |
| 117 | | | B | | High | 0.50 | 2993 | $1.59x10^{-4}$ | 2.30 |
| 118 | | | A | | Low | 0.20 | 5254 | $3.25x10^{-2}$ | 0.05 |
| 119 | | | B | | Low | 0.20 | 2232 | $2.95x10^{-4}$ | 2.83 |
| 120 | Bidim | 8.00 | A | 0.40 | Optimum | 0.40 | 5323 | $1.07x10^{-4}$ | 2.91 |
| 121 | | | B | | Optimum | 0.40 | 1944 | $2.07x10^{-6}$ | 6.21 |
| 122 | C34 | | A | | High | 0.80 | 3852 | $3.77x10^{-7}$ | 5.52 |
| 123 | | | B | | High | 0.80 | 2232 | $7.10x10^{-6}$ | 4.68 |
| 124 | | | A | | Low | 0.07 | 2801 | $1.20x10^{-3}$ | 2.32 |
| 125 | | | B | | Low | 0.07 | * | * | * |
| 126 | Woven | 4.50 | A | 0.14 | Optimum | 0.14 | 2689 | $2.84x10^{-3}$ | 2.67 |
| 127 | Tape | | B | | Optimum | 0.14 | 3551 | $4.35x10^{-7}$ | 5.74 |
| 128 | | | A | | High | 0.28 | 2521 | $4.42x10^{-5}$ | 4.28 |
| 129 | | | B | | High | 0.28 | 2413 | $3.84x10^{-3}$ | 0.95 |

TABLE 4. Fracture Properties of Fabric Reinforced Asphaltic Concrete Overlay Samples (cont'd)

| Sample Number | Fabric Type | Fabric Weight (oz/sq.yd) | Fabric Position | Optimum Tack Coat Rate (gal/sq.yd) | Actual Tack Coat Rate | | Relaxation Modulus at Fabric ($lb/in^2$) | A | n |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | L/O/H | (gal/sq.yd) | | | |
| 131 | Burlington 2532 | 6.91 | B | 0.16 | Low | 0.08 | * | * | * |
| 132 | | | A | | Low | 0.08 | 2977 | $1.94 \times 10^{-2}$ | 0.06 |
| 133 | | | B | | Optimum | 0.16 | 2367 | $2.89 \times 10^{-5}$ | 5.73 |
| 134 | | | A | | Optimum | 0.16 | 3151 | $9.50 \times 10^{-5}$ | 3.38 |
| 135 | | | B | | High | 0.32 | 1603 | $2.67 \times 10^{-3}$ | 1.23 |
| 136 | | | A | | High | 0.32 | 2941 | $2.10 \times 10^{-4}$ | 2.79 |

A = Reinforcement Fabric Located 3/4 in. from top of the sample.
B = Reinforcement Fabric Located 1 in. from bottom of the sample.

*Failure due to excessive slippage at fabric used to rank different fabric reinforced overlay samples.

The smaller (more negative) the sum of $\log_{10}A$ and n, the more crack resistant is the fabric reinforced sample.

Table 5 gives the ranking of the different overlay designs in the order of decreasing fracture resistance. It is difficult to observe any general trend in this tabulation since the results reflect the influence of several design variables.

Plots of n versus $\log_{10}A$ for the three different tack coat ratios used (viz. low, optimum, and high) are given in Figure 18. Linear regression techniques were used to obtain the coefficients a and b in each case. The results of this analysis are tabulated below.

TABLE 6. Coefficients a and b in Plots of n versus $\log_{10}A$ for Different Tack Coat Ratios

| Ratio of Actual Tack Coat to Optimum Tack, (AT/OT) | | a | b | $R^2$ |
|---|---|---|---|---|
| Low | 0.5 | -2.668 | -1.694 | 0.92 |
| Optimum | 1.0 | -2.208 | -1.429 | 0.91 |
| High | 2.0 | -1.967 | -1.242 | 0.93 |

From the above discussion it becomes clear that a line of n versus $\log_{10}A$ lying further below would indicate better resistance to crack propagation. Therefore, from the results shown in Figure 16 it can be concluded that better crack resistance can be obtained by having higher tack coat ratios.

TABLE 5. Ranking of the Overlay Samples in the Order of Decreasing Fracture Resistance

| Sample Number | Fabric Type | Fabric Weight (oz/sq.yd) | Fabric Position | Optimum Tack Coat Rate (gal/sq.yd) | Actual Tack Coat Rate | | Relaxation Modulus at Fabric ($lb/in^2$) | $n+\log_{10}A$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | L/O/H | (gal/sq.yd) | | |
| 132 | VI | 6.91 | A | 0.16 | L | 0.08 | 2977 | -1.652 |
| 111 | II | 4.10 | B | 0.22 | H | 0.44 | 2699 | -1.624 |
| 117 | III | 4.00 | B | 0.20 | H | 0.50 | 2993 | -1.499 |
| 129 | V | 4.50 | B | 0.14 | H | 0.28 | 2413 | -1.466 |
| 118 | IV | 8.00 | A | 0.40 | L | 0.20 | 5254 | -1.438 |
| 102 | I | 3.50 | A | 0.26 | O | 0.26 | 4133 | -1.377 |
| 135 | VI | 6.91 | B | 0.16 | H | 0.32 | 1603 | -1.343 |
| 105 | I | 3.50 | B | 0.26 | H | 0.52 | 1350 | -1.333 |
| 114 | III | 4.00 | A | 0.20 | O | 0.20 | 2277 | -1.309 |
| 108 | II | 4.10 | A | 0.22 | O | 0.22 | 5254 | -1.243 |
| 109 | II | 4.10 | B | 0.22 | O | 0.22 | 4185 | -1.218 |
| 120 | IV | 8.00 | A | 0.40 | O | 0.40 | 5323 | -1.061 |
| 104 | I | 3.50 | A | 0.26 | H | 0.52 | 3326 | -1.060 |
| 116 | III | 4.00 | A | 0.20 | H | 0.50 | 2102 | -0.988 |
| 122 | IV | 8.00 | A | 0.40 | H | 0.80 | 3852 | -0.904 |
| 136 | VI | 6.91 | A | 0.16 | H | 0.32 | 2941 | -0.888 |
| 119 | IV | 8.00 | B | 0.40 | L | 0.20 | 2232 | -0.700 |
| 106 | II | 4.10 | A | 0.22 | L | 0.11 | 3151 | -0.687 |
| 134 | VI | 6.91 | B | 0.16 | O | 0.16 | 2367 | -0.642 |
| 127 | V | 4.50 | B | 0.14 | O | 0.14 | 3551 | -0.622 |
| 110 | II | 4.10 | A | 0.22 | H | 0.44 | 2699 | -0.600 |
| 124 | V | 4.50 | A | 0.14 | L | 0.07 | 2801 | -0.507 |
| 123 | IV | 8.00 | B | 0.40 | H | 0.80 | 2232 | -0.469 |
| 112 | III | 4.00 | A | 0.20 | L | 0.10 | 2626 | -0.325 |
| 128 | V | 4.50 | A | 0.14 | H | 0.28 | 2521 | -0.074 |
| 121 | IV | 8.00 | B | 0.40 | O | 0.40 | 1944 | 0.526 |
| 100 | I | 3.50 | A | 0.26 | L | 0.13 | 1401 | 0.690 |
| 103 | I | 3.50 | B | 0.26 | O | 0.26 | 2705 | 0.720 |
| 133 | VI | 6.91 | B | 0.16 | O | 0.16 | 2367 | 1.191 |

Fabric Type -
I = Old Petromat
II = New Petromat
III = Mirafi 140
IV = Bidim C34
V = Woven Tape
VI = Burlington

Fabric Position -
A = Reinforcement Fabric Located 3/4 in. from the top of the sample.
B = Reinforcement Fabric Located 1 in. from the bottom of the sample.

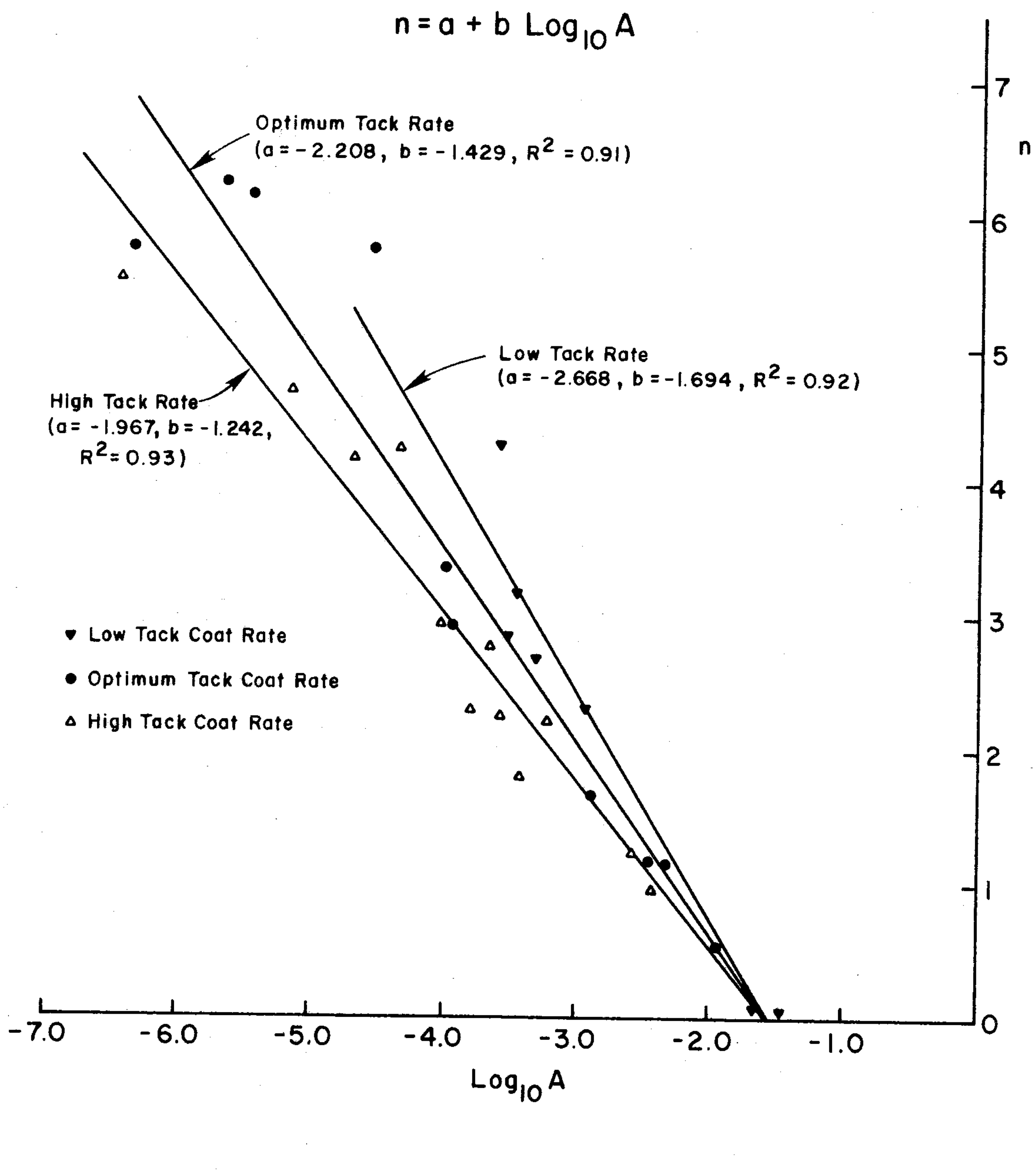


FIGURE 18. Fracture Properties of Overlay Samples Reinforced with Fabric

The results obtained also suggest a relationship between the magnitude of the coefficients a and b and the tack coat ratio. Figure 19 shows $\log_{10}$ a and $\log_{10}$ b plotted against $\log_{10}(\frac{AT}{OT})$. The linear variation observed between the above parameters yields the following equations.

$$a = -2.265(\frac{AT}{OT})^{-.217}$$
$$b = -1.445(\frac{AT}{OT})^{-.225} \qquad (6\text{-}5)$$

Thus it can be seen that a knowledge of the tack coat ratio would enable one to determine the n versus $\log_{10}A$ relationship for a fabric reinforced asphalt concrete overlay.

Relative Influence of Overlay Design Variables on Fracture Resistance

Since the crack growth rate, $\frac{dc}{dN}$, (and therefore the useful life of an overlay) depends on the fracture properties, A and n, it is desirable to be able to determine those factors which have the greatest effect on these properties. A computer program which utilized select regression techniques was employed to determine the relative influence of each of the four variables on the magnitude of the fracture property, A. (Since n can be evaluated when A is known, it was not considered necessary to include the former fracture property into the analysis.)

This data analysis procedure related $\log_{10}A$ to three of the independent variables by using an equation of the form given below:

$$\log_{10}A = C_0 + C_1(FP) + C_2(FW) + C_3(AT) \qquad (6\text{-}6)$$

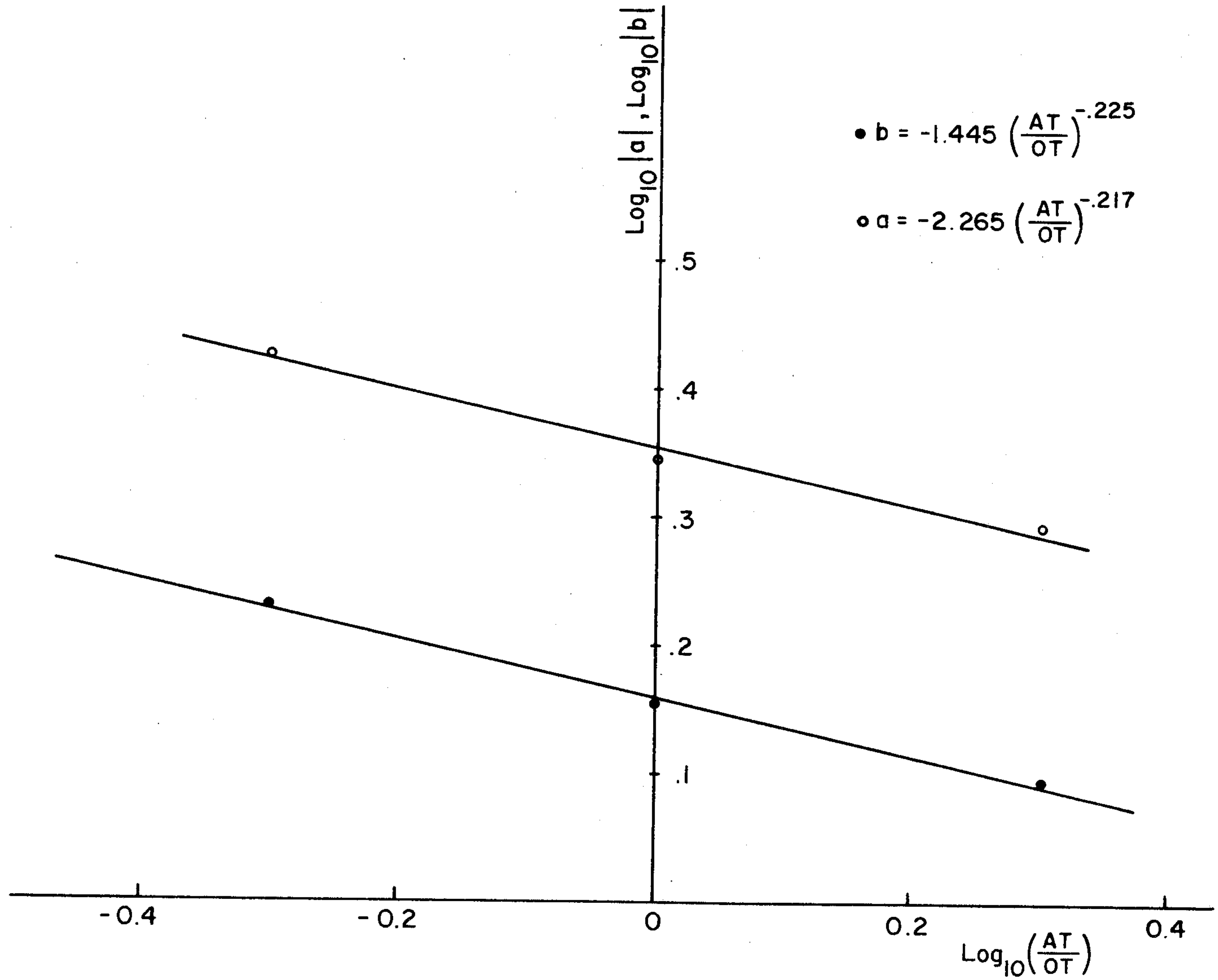


FIGURE 19. a and b versus Tack Coat Ratio Relation for Fabric Reinforced Overlays

where

$A$ = a fracture property relating the crack growth rate to the stress intensity factor in Paris' Law.

$C_0$ = a regression constant

$C_1, C_2, C_3$ = regression coefficients for the independent variables.

FP = the fabric position within the overlay specimen, measured in inches from the bottom of the sample.

FW = the fabric unit weight, oz/sq. yd.

AT = the actual tack coat rate used during the fabric installation, gal/sq. yd.

The optimum tack coat rate, OT, was excluded from this analysis because a select regression analysis performed on the full model indicated that this variable and the fabric weight, FW, are not independent of each other.

The analysis performed on the data obtained from each overlay test resulted in the following equation:

$$\log_{10}A = -3.196 + 0.356(FP) - 0.0574(FW) - 2.591(AT) \quad (6\text{-}7)$$

From the above equation it can be concluded that the value of $\log_{10}A$ (and therefore A) can be decreased by:

(i) placing the fabric reinforcement near the bottom of the overlay, rather than near the top

(ii) using heavier fabrics

(iii) using higher tack coat rates.

These results reinforce the observations and tentative conclusions previously made concerning the effects of these variables on the resistance of the overlay to crack propagation.

Examination of Equation (6-7) also reveals that, of the three independent variables considered, the actual tack coat rate has the greatest influence on the magnitude of A. The other two variables, listed in the order of decreasing influence are: the fabric position and fabric weight.

A similar analysis was carried out using the following quantities as the independent variables.

FP = the fabric position, measured in inches from the bottom of the overlay sample

FW = the fabric unit weight, oz/sq. yd.

ET = the tack coat rate used in excess of the optimum, gal/sq. yd.

RM = the relaxation modulus at fabric, lb/sq. in.

The select regression analysis performed using the above as independent variables resulted in the following equation:

$$\log_{10}A = -3.473 + 0.292(FP) - 0.143(FW) - 2.651(ET) + 0.723\times10^{-4}(RM) \qquad (6\text{-}8)$$

This equation confirms the conclusions made previously regarding the influence of fabric position, fabric weight, and tack coat rate on the magnitude of A. In addition, it also indicates that higher relaxation moduli would result in lower fracture resistance. In other words, better performance of an overlay can be obtained by designing it to be more flexible.

Equation (6-8) also indicates that the value of $\log_{10}A$ is influenced primarily by the tack coat rate used. The location of the fabric and the fabric weight also have significant influence on

$\log_{10}A$ while the relaxation modulus has a relatively small effect.

A third select regression analysis was performed in order to develop an equation relating Relaxation Modulus, RM, to other variables. The relationship obtained by this analysis can be represented by the equation given below:

$$RM = 1127 + 618(FP) + 31.8(FW) - 989(AT) + 3749(OT) \quad (6\text{-}9)$$

This equation shows that the relaxation modulus increases by:

(i) having the reinforcement fabric at a higher position

(ii) using heavier fabric

(iii) using lower tack coat rates

(iv) using fabrics with larger optimum tack coat rates.

## Summary

In the present chapter, the results of the data reduction and analysis methods described previously were examined with the objective of determining the effects of different overlay design variables in improving the performance of an overlay against reflection cracking. The discussion included: (a) examination of the number of loading cycles required to cause the "failure" of an overlay specimen; (b) analysis of the strain energy release rate values calculated for each test specimen; (c) analysis of the crack growth coefficients, a and b; (d) analysis of the tensile work coefficients, c and d; (e) comparison of the relationship of peak tensile load to loading cycle number of each specimen; (f) analysis of the fracture properties, A and n, obtained for each specimen, and (g) determination of the relative influence of different design variables on fracture properties.

Final conclusions of this study will be outlined in Chapter VII.

# CHAPTER VII

# CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

Based upon review of the current literature, observations made during laboratory preparation and testing of overlay specimens, analysis of experimental data, and other information gained from this study, the following conclusions are made:

1. Asphaltic concrete overlays are often the most economical method available to overcome a wide variety of defects in both rigid and flexible pavements.
2. Overlays often exhibit a (reflective) cracking pattern similar to that which existed in the original pavement, even when the "new" pavements are considered to be structurally sound.
3. The occurrence of transverse reflection cracking, and the consequent penetration of water into the pavement sublayers, is the primary cause of highway pavement overlay deterioration.
4. Reflection cracking in overlays may be caused by cyclic traffic loading and unloading, thermally induced tensile stresses produced when pavement materials contract, or a combination of these two.
5. Efforts are currently underway both in Texas and elsewhere to develop economical overlay systems which can be used to prevent and/or delay reflection cracking in overlays. These efforts

include numerous field trials, laboratory evaluation programs, and theoretical studies of the reflection cracking problem.

6. The complexity of the reflection cracking problem will necessitate the combined use of information gained from field trials, laboratory test programs and theoretical studies in order to develop the optimum overlay design to resist reflection cracking.
7. One of the most promising methods of providing reflection crack resistance utilizes synthetic "engineering" fabrics, installed in combination with a tack coat of asphalt cement, as a reinforcing membrane within the overlay. Fabrics reduce the amount of water that enters the sublayers of a pavement by both reinforcing and undersealing the overlay. Reinforcing delays the appearance of the reflection cracking and reduces the width of the cracks that develop. Undersealing reduces the amount of water that penetrates into the sublayers. Field observations of the degree of success obtained by the fabrics in these two functions are contained in the next report in this series, TTI Research Report 261-2.
8. Field test trials and laboratory studies indicate that fabric reinforcement of overlays can delay reflective cracking caused by both fatigue traffic loads and thermally induced cyclic tensile stresses. The amount of benefit gained by adding fabric reinforcement depends on a great many variables.
9. Controlled displacement tests using the TTI Overlay Tester that were reported in TTI Research Report 207-5 showed that fabric

reinforcement can greatly increase the reflective crack resistance of laboratory-prepared overlay specimens. The study reported herein involved testing similar to that in Research Report 207-5 and an evaluation of the test data obtained from 36 fabric reinforced samples.

10. The TTI Overlay Tester was designed to subject laboratory-prepared asphaltic concrete "beam" specimens to tensile loads sufficient to produce a predetermined displacement (crack) in the overlay specimen, and then to exert a compressive load sufficient to return the sample to its zero-displacement position. This test apparatus effectively simulates thermally induced loading (and unloading) of an overlay, but the characteristics of the apparatus, and the test in general, must be considered when overlay test data are evaluated:

    a. The modulus of the asphaltic concrete material when tested at this loading rate in a constant temperature environment (77°F) is approximately the same as the modulus of the same material when loaded for several hours at a temperature of 20° to 25°F. Thus, there is an approximate correspondence between the laboratory test conditions and the thermal loading rates in the field at lower temperatures.

    b. The laboratory test procedure applied a tensile load to each overlay specimen through a loading ram attached to a plate epoxied to the bottom of the specimen. This loading system simulates the loading produced by contraction of an old pavement below the new overlay. Under field conditions, the new overlay will also tend to contract with decreases in temperature. Thus, the overlay will be subjected to thermally induced stresses developing within itself, as well as those transferred to it from the underlying old pavement.

c. The construction control employed in the laboratory is not available in the field. Inconsistencies in overlays, resulting from construction difficulties, may reduce the ability of the overlay to withstand the reflection cracking forces.

d. The TTI Overlay Tester was used to induce only horizontal tensile loads in the test specimens. No attempt was made to model traffic loading.

e. All tests were performed on "new" overlay specimens. The aging process which occurs in the field will undoubtedly reduce the ability of an overlay to withstand reflection cracking.

11. The number of loading cycles required to produce "failure" in an overlay sample is only a <u>relative</u> measure of the resistance to reflection cracking that a similar overlay would exhibit in the field.

12. Examination of the cracking patterns that formed during testing leads to the following observations:

    a. Multiple cracking (formation of more than one primary crack) is most likely to occur in overlays constructed with high tack coat rates. This indicates that the excess asphalt tends to distribute the tensile load over a wider area, thus increasing overlay life.

b. Slippage along the fabric layer was observed during testing of every sample constructed with a low tack coat rate when the fabric was located near the bottom of the sample. Slippage was also observed in two samples constructed with high tack coat rates.

c. Slippage was observed only in samples with fabric located one inch from the bottom of the sample. This indicates that the combined tensile strength of the asphaltic concrete material above the fabric and of the fabric itself is greater than the horizontal shear strength along the bottom of the fabric. This lack of horizontal shear strength is due either to a lack of an adequate tack coat or to an excessively thick film of tack coat beneath the fabric.

13. Fabric reinforcement, together with a tack coat of asphalt cement, significantly increases the maximum tensile load required to produce a given displacement (crack opening) in an uncracked overlay. This reinforcement also retards crack growth during additional loading cycles.

14. Considering only those cases where one primary crack propagated from the bottom of the sample to the top without slippage, overlay sample life appears to increase with increasing tack coat rate.

15. The tensile loads created during testing were not sufficient to rupture any of the fabrics used as reinforcement. This is due to the ability of the fabrics to stretch and distribute the tensile

load to the adjoining layers of the overlay. If these asphalt impregnated fabrics remain intact under field conditions, they should serve to effectively retard water intrusion into the pavement system, thereby reducing the detrimental effects of reflection cracking.

16. Analysis of test results does not lead to a clear decision of which of the six fabrics evaluated in this study provides the best resistance to reflection cracking. However, some general conclusions about the fabrics and their use are drawn:

    a. The information available concerning the engineering properties of each fabric is generally incomplete, and comparisons between two or more fabrics is difficult due to the wide variety of test types and conditions the manufacturers employ to evaluate their product.

    b. The woven fabrics required less tack coat than did the nonwoven fabrics.

    c. At least one case of slippage during testing was observed with each fabric type.

    d. The location of the fabric within the overlay system and the amount of tack coat applied with the fabric have a greater influence on an overlay's resistance to cracking than does the type of fabric.

17. Fracture mechanics principles together with the equations developed in Chapter VI can be used in the prediction of the reflection cracking life of an overlay and design future overlays.

Recommendations

Based upon the information gathered from this study and the conclusions drawn therefrom, the following recommendations are made:

1. Information gained from field trials, laboratory research and theoretical study should be used to update and improve both the overlay design process and the construction specifications for fabric reinforced overlays.
2. The use of thin overlays with fabrics should be avoided.
3. Economic analyses should be used to determine the cost effectiveness of using various types of engineering fabrics to reinforce and underseal overlays.
4. Standard laboratory test procedures should be developed and implemented to evaluate the engineering properties of fabrics before they are accepted for use in overlays. These tests should include a determination of the optimum tack coat rate of the fabric and its modulus at low strain levels of around 10 percent.
5. The optimum tack coat rate for any new fabrics should be determined according to the procedure described in Appendix D.
6. Evaluation of fabrics in overlays by means of tests performed on the TTI Overlay Tester and the analysis methods described in this report, should be conducted prior to field installation of the overlays.
7. The equations developed in this report should be used to estimate the relative resistance to reflection cracking of future fabric reinforced overlay systems.
8. As a basis for future design, fabrics used as reinforcement for

overlays should be placed near the bottom of the overlay, but generally no nearer than the distance a reflection crack will travel during the first opening cycle. The crack length after the first opening cycle, represented by the value "a" shown in Table 1, is generally about 1/4 to 3/4 inch. Optimum fabric placement can be accomplished by placing a level-up course of 3/4 to 1 inch thickness on the old pavement before installing the fabric and the remaining layer(s) of the overlay.

9. The tack coat rate used when installing the fabric should be the highest practical, consistent with economic, construction and maintenance considerations, but never less than the optimum rate. Too high of a tack coat can result in flushing (or bleeding) and slippage cracking. Thus, the actual tack coat rate should be about 100 percent above the optimum, and should be applied uniformly on the surface on which the fabric will be placed. More viscous tack coats such as AC-20 are more desirable.

10. The fabric should also be uniform in weight and in low strain modulus. Non-uniform fabrics will cause excesses of tack coat in the low density areas which will increase the consequent flushing and slippage problems.

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## APPENDIX A

## COMPUTER PROGRAMS FOR TEST INITIALIZATION, DATA COLLECTION, DATA REDUCTION AND DATA ANALYSIS

As mentioned previously, data collection and reduction were accomplished by the use of microcomputers using computer programs developed by personnel of the Texas Transportation Institute. A computer program was also used to prepare the data collection computer to receive the overlay test data. A total of six programs were used in the various stages of test initialization and data collection and reduction. The data analysis procedure utilized three computer programs. A brief description of the use of each of these programs is given below.

The "Test Initialization and Data Collection Program" was used to prepare the data collection microcomputer to receive test data in the form of electronic voltages, convert these data to a computer-usable form, and store them on magnetic tape. This program was also used to select the voltage monitoring rate and record the sample size and identification information, as well as calibration values for load and displacement. (The above mentioned information was manually entered into the TTI microcomputer by means of the Texas Instruments "Silent 700" electronic data terminal.) A copy of the "Test initialization and Data Collection Program" is shown on pages 99 through 105 .

Overlay test data were entered into the data analysis computer either automatically from the magnetic data storage tape or manually by means of the Micro-Term, Inc. video terminal. The program used to prepare the Model 6800 Mnemonic Assembler to receive commands for the method to be used for entering test data is shown on page 106.

The computer initialization and data reduction program for manually entered data is shown on page 107. The computer initialization and data reduction program for data reduction directly from the magnetic tape is shown on pages 108 through 110. Manually entered test data included manually calculated values of the crack opening energy, E, for the selected loading cycles. The computer program used to reduce test data directly from the storage tape provides the capability of calculating these energy values by numerically integrating the tension portion of the load versus displacement data. Both programs calculate the logarithm of the average crack length, C, loading cycle number, N, and crack opening energy, E, values.

The two remaining data reduction programs were used to relate the average crack length, C, to the loading cycle number, N, and the crack opening energy, E, to the loading cycle number. Simple linear regression techniques were used to represent these log C versus log N and log E versus log N data as single straight lines. A copy of the program used to perform the linear regression calculations is shown on pages 111 through 112.

Since crack growth was significantly retarded by the presence of the reinforcing fabric layer in many of the test specimens, the log C versus log N and log E versus log N data could not be accurately represented by a single straight line in many cases. Therefore, a multiple linear regression program was used to determine separate linear relationships for these test data in two segments. The first segment included all data from the first loading cycle until the reflection crack reached the fabric layer. The second segment included all data from the cycle when the reflective crack penetrated the fabric layer until failure. A copy of the program used to perform the multiple linear regression calculations is shown on pages 113 through 114. Both the single and multiple regression programs also performed fracture toughness calculations.

The data analysis procedure utilized the computer program shown on pages 116 through 118 to calculate the stress intensity factor, K, and the crack growth rate, $^{dC}/_{dN}$, in fifteen incremental steps. This program also calculated values for the material properties A and n for each sample. The relationship of n versus log A was then determined for all the samples by means of a computer program employing simple linear regression techniques. The final data analysis step involved relating the A value to five variables and using select logarithmic regression computer analysis techniques to determine which variables have the greatest effect on the magnitude of A.

COMPUTER PROGRAM

FOR

TEST INITIALIZATION AND DATA COLLECTION

```
        ORG    $0200
        NAM    ADTAPE
        OPT    NOG
OUTSTR  EQU    $E07E
OUTCH   EQU    $E1D1
INC     EQU    $E1AC
OUTSP   EQU    $E0CC
FBLOCK  EQU    $0800
REGIS   EQU    $0000      COMMON
XH1     EQU    REGIS
PTR     EQU    REGIS+2
CHCNT   EQU    REGIS+7
BLKNO   EQU    REGIS+13
LIB     EQU    $E400      FROM LIBR
TINIT   EQU    LIB+$09
WBLOCK  EQU    LIB+$0C
ADINIT  EQU    LIB+$2A
ADCONV  EQU    LIB+$2D
TIMER   EQU    LIB+$30
DTOB    EQU    LIB+$33
DECOUT  EQU    LIB+$36
INCHR   EQU    LIB+$39
TIMPIA  EQU    $8008      TIMER PIA
KB      EQU    $8004
MSG1    FCC    / ENTER NUMBER OF CHANNELS: /
        FCB    4
MSG2H   FCC    / HIGH CALIBR VALUE FOR CHANNEL /
        FCB    4
MSG2A   FCC    /   A-D SIGNAL (RET) /
        FCB    4
MSG2L   FCC    / LOW CALIBR VALUE FOR CHANNEL /
        FCB    4
MSG3    FCC    / ENTER FILE NAME: /
        FCB    4
MSG4    FCC    / ENTER UNITS OF MEASURE: /
        FCB    4
MSG5    FCC    / CRACKS: /
        FCB    4
MSG6    FCC    / :01 SECONDS/
        FCC    / BETWEEN SAMPLINGS: /
        FCB    4
MSG7    FCC    / SAMPLING /
        FCB    4
MSG8    FCC    / ENTER STARTING CYCLE; /
        FCB    4
```

TEST INITIALIZATION AND DATA COLLECTION

(Continued)

```
MSG9   FCC    / END OF TEST /
       FCB    4
MSG1Ø  FCC    / ENTER BEAM WIDTH: /
       FCB    4
BLK    FCB    Ø
MSREAD FCB    1
CHAN   FCB    Ø
DTOBL  RMB    4
*
ADTAPE EQU    *          A/D READINGS TO TAPE
       JSR    TINIT      INIT ROUTINES
       JSR    ADINIT
       LDAA   #4         .Ø1 SEC
       JSR    TIMER      .Ø1 SEC
       CLR    BLKNO      BLK Ø
       JSR    CHDATA     CHANN DATA
       LDX    #FBLOCK    BLØ WRITE
       STX    REGIS
       LDX    #3ØØ
       STX    REGIS+4
       JSR    WBLOCK     BLØ WRITE
ADT1   JSR    ELINE      LF,CR
       LDX    #MSG8      CYC ST
       JSR    OUTSTR
       LDX    #FBLOCK+1Ø  CYC
       LDAA   #3
       JSR    INCHR
       CPX    #FBLOCK+1Ø  END?
       BEQ    ADT8
       JSR    COMMA
       STX    PTR
       JSR    ELINE
       LDX    #MSG7      ST
       JSR    OUTSTR
       JSR    ELINE
       INC    BLKNO      NEXT BLK
       LDX    PTR        A/D START
ADT3   LDAB   MSREAD     SKIP CNT
ADT4   JSR    TIMD       CLK
       DECB
       BNE    ADT4       MORE SKIPPING
       LDAA   #1
       ANDA   KB         KB ENTRY (A/D END)?
       BNE    ADT6
       CLRA
ADT5   PSHA
```

```
        JSR    ADCONV    DATA
        STAA   Ø,X
        INX
        PULA
        INCA
        CPX    #FBLOCK+2ØØØ
        BEQ    ADT6      IF END
        CMPA   CHAN      MORE CHS?
        BNE    ADT5      NEXT A/D READ
        BRA    ADT3      WAIT TIM
ADT6    DEX
        STX    REGIS+2   END BLK
        LDX    #MSG5     CRK
        JSR    OUTSTR
        JSR    CRKIN     CRACK WIDTHS
        LDX    #FBLOCK
        STX    REGIS     BLK START
ADT7    JSR    SUB16     FIND BLK LEN
        JSR    WBLOCK
        BRA    ADT1
ADT8    LDX    #Ø
        STX    REGIS+4   Ø LEN(EOF BLK)
        JSR    WBLOCK
        JSR    ELINE
        JSR    ELINE
        LDX    #MSG9     END
        JSR    OUTSTR
        JMP    $EØE3     SWTBUG
*
*
CHDATA EQU     *         CHANNEL DATA TO TAPE
        LDX    #FBLOCK
        STX    PTR       SET PTR
        JSR    ELINE     CR,LF
        LDX    #MSG3
        JSR    OUTSTR
        LDX    PTR
        LDAA   #9        CNT
        JSR    INCHR     FNAME ENTER
        JSR    COMMA
        STX    PTR
CHD2    JSR    ELINE     CR,LF
        LDX    #MSG1     # CH
        JSR    OUTSTR
        LDX    PTR
        LDAA   #1
```

TEST INITIALIZATION AND DATA COLLECTION

(Continued)

```
        JSR     INCHR
        STX     PTR
        DEX
        LDAA    Ø,X       GET CHAR
        ANDA    #$ØF      BCD
        STAA    CHAN      CH CNTR
        JSR     ELINE
        JSR     ELINE
        CLRB
CHD3    INCB
        PSHB    SAV CHAN CNT
        LDX     #MSG2H
        JSR     RANGIN    HIGH RANGE INPUT
        LDX     #MSG2A    A/D READ
        JSR     ACTIN
        LDX     #MSG2L    LOW RANGE INPUT
        JSR     RANGIN
        LDX     #MSG2A    A/D READ
        JSR     ACTIN
        JSR     UNITR
        JSR     ELINE
        JSR     ELINE     NEXT CH DATA
        PULB              REST CHAN CNT
        CMPB    CHAN      END?
        BNE     CHD3
        LDX     #MSG6     TIMING
        JSR     OUTSTR
        LDAA    #3        DEC IN
        LDX     #DTOBL
        STX     REGIS
        JSR     INDIG
        JSR     DTOB
        STAA    MSREAD    CLOCK SKIPS
        LDX     PTR
        STAA    Ø,X       SAV TIM
        INX
        STX     PTR
        JSR     ELINE
        LDX     #MSG1Ø
        JSR     OUTSTR    BEAM W
        LDX     PTR
        LDAA    #4
        JSR     INCHR
        JSR     COMMA
        STX     PTR
        JSR     ELINE
        RTS
```

TEST INITIALIZATION AND DATA COLLECTION

(Continued)

```
*
RANGIN JSR    OUTSTR
       TBA
       ORAA   #$30      ASCII
       JSR    OUTCH
       JSR    OUTSP
       LDX    PTR
       LDAA   #5
       JSR    INCHR     CALIB VAL
RA2    JSR    COMMA
       STX    PTR
       JSR    ELINE
       RTS
*
ACTIN  JSR    OUTSTR    A/D INPUT
ACT1   JSR    INC       KB INP
       CMPA   #$4B      'K' HAND ENTER?
       BNE    ACT2
       LDX    #DTOBL    FETCH KB ENTER
       STX    REGIS
       LDAA   #3
       JSR    INDIG     DEC IN
       JSR    DTOB      CONVERT
       LDX    PTR
       STAA   0,X
       INX
       STX    PTR       INCR PTR
       BSR    ELINE
       RTS
ACT2   TBA
       DECA             CH SYNC
       JSR    ADCONV    A/D DATA
       LDX    PTR
       STAA   0,X
       INX
       STX    PTR
       LDX    #DTOBL    B-D TABLE
       STX    REGIS
       JSR    DECOUT    DISPLAY
       JSR    ELINE
       RTS
*
UNITR  LDX    #MSG4     TITL REQ
       JSR    OUTSTR
       LDX    PTR
       LDAA   #5
```

```
        JSR     INCHR
UN3     JSR     COMMA
        STX     PTR
        RTS
*
ELINE   LDAA    #$ØA        LF
        JSR     OUTCH
        LDAA    #$ØD        CR
        JSR     OUTCH
        RTS
*
SUB16   LDAA    REGIS+2     16B SUBTR
        LDAB    REGIS+3
        SUBB    REGIS+1
        SBCA    REGIS
        STAA    REGIS+4
        STAB    REGIS+5
        RTS
*
*
CRKIN   LDAA    #9          RESULT CRACKS INP
        LDX     #FBLOCK
        JSR     INCHR
        JSR     COMMA
CRK2    RTS
*
INDIG   EQU     *           NUMER INP
IND1    LDX     #DTOBL      CONV BUFF
IND2    JSR     INC         CHAR
        CMPA    #$21        '!'
        BEQ     IND1
        CMPA    #$ØD        CR?
        BEQ     IND3
        CPX     #DTOBL+4    END?
        BEQ     IND2
        ANDA    #$ØF        BCD
        STAA    Ø,X
        INX
        BRA     IND2
IND3    BSR     COMMA
        RTS
*
COMMA   LDAA    #$2C
        STAA    Ø,X
        INX
        RTS
```

TEST INITIALIZATION AND DATA COLLECTION

(Continued)

```
*
TIMD    LDAA    #$80      TIMER WAIT
        ANDA    $8009     ADDR
        BEQ     TIMD
        LDAA    $8008     RESET
        RTS
        END
*
*
```

# COMPUTER PROGRAM

# FOR

# RECEIVING DATA FORMAT COMMANDS

```
ØØ1Ø PRINT CHR$(12);"";CHR$(3Ø);TAB(25);"TTI OVERLAY TEST SYSTEM "
ØØ2Ø SKIP 5
ØØ3Ø PRINT TAB(3Ø);"ACTION CODES"
ØØ4Ø SKIP 2
ØØ5Ø PRINT TAB(1Ø);CHR$(14);"1";CHR$(14);TAB(15);
     "REDUCE TEST FROM TAPE":SKIP 2
ØØ6Ø PRINT TAB(1Ø);CHR$(14);"2";CHR$(14);TAB(15);
     "ENTER TEST DATA BY HAND":SKIP 2
ØØ7Ø PRINT TAB(1Ø);CHR$(14);"3";CHR$(14);TAB(15);"QUIT PROGRAM":SKIP 5
ØØ8Ø PRINT "ENTER ACTION CODE --->";:INPUT A
ØØ9Ø IF A=1 THEN CHAIN ADBAS
Ø1ØØ IF A=2 THEN CHAIN ENTER
Ø11Ø IF A=3 THEN END
Ø12Ø GOTO 1Ø

BASIC
#
```

COMPUTER PROGRAM

FOR

REDUCTION OF MANUALLY ENTERED TEST DATA

```
ØØØ1 LINE= 8Ø
ØØ1Ø PRINT "PROGRAM FOR ENTERING DATA BY HAND OF OVERLAY DATA REGRESSION"
ØØ15 PRINT "ENTER ZERO FOR CYCLE NUMBER TO END "
ØØ16 PRINT "ENTER FILE NAME";:INPUT A$
ØØ17 PRINT ""
ØØ18 PRINT "FILE NAME IS ";A$
ØØ2Ø OPEN #1,"OVLDAT":SCRATCH#1
ØØ21 PRINT "ENTER THE BEAM WIDTH ";:INPUT X
ØØ22 WRITE #1,A$,X
ØØ3Ø PRINT "CYCLE ";:INPUT A:IF A=Ø THEN CLOSE #1:GOTO 7Ø
ØØ4Ø PRINT "ENERGY ";:INPUT B
ØØ5Ø PRINT "CRACK LENGTH AVG. ";:INPUT C
ØØ51 PRINT ""
ØØ52 PRINT "CYC= ";A;TAB(15);"E= ";B;TAB(25);"C= ";C
ØØ6Ø LET D=LOG(A):E=LOG(B):F=LOG(C):WRITE #1,B,C,A,D,F,E:GOTO 3Ø
ØØ7Ø PRINT "DO YOU WANT TO PERFORM A SINGLE OR MULTIPLE REGRESSION ";
ØØ8Ø INPUT A$:IF LEFT$(A$,1)="S" THEN CHAIN REGRES
ØØ9Ø IF LEFT$(A$,1)="M" THEN CHAIN REG2
Ø1ØØ GOTO 7Ø

BASIC
#
```

COMPUTER PROGRAM

FOR

REDUCTION OF AUTOMATICALLY ENTERED TEST DATA

```
0001 PRINT ""
0010 REM PROGRAM TO CONVERT A/D DATA
0020 REM U$=UNITS;Y$=NAME;Z$=NUMBER
0030 REM C=CALIBR DATA ((MAX,MIN),CH),N=CHANS
0040 REM I=CNTRS;K=CONSTS;L=MEM LOCS
0043 DIM C(2),D(2),F(8),U$(8)
0044 LET N1=0
0045 DIGITS= 3
0046 DEF FNF(X9)=(PEEK(X9)-128)*F(1)
0047 DEF FND(X9)=(128-PEEK(X9+1))*F(2)
0048 DEF FNL(X9)=LOG(X9)/2.3025851
0050 REM
0055 OPEN #1,"OVLDAT"
0056 SCRATCH #1
0060 REM READ BLOCK 0 CHANNEL DATA
0070 REM
0080 LET L1=61440
0090 LET L2=14080
0100 LET L7=L1
0110 GOSUB 800
0120 LET Y=USER(L7)
0130 IF PEEK(8)<>0 THEN 510
0140 REM
0150 REM FILE NAM
0160 REM
0170 LET L=L2-1
0180 GOSUB 900
0190 LET Y$=Z$
0200 PRINT "FILE NAME IS ";Y$
0205 PRINT
0210 REM
0220 REM # CHANNELS
0230 REM
0240 LET L=L+1
0250 LET N=VAL(CHR$(PEEK(L)))
0260 REM
0270 REM MAX,MIN CALIBR,A/D PER CHANNEL
0280 REM
0290 FOR I=1 TO N
0300 GOSUB 900
0310 LET C(1)=VAL(Z$)
0320 LET L=L+1
0330 LET D(1)=PEEK(L)
0340 GOSUB 900
```

REDUCTION OF AUTOMATICALLY ENTERED TEST DATA

(Continued)

```
Ø35Ø LET C(2)=VAL(Z$)
Ø36Ø LET L=L+1
Ø37Ø LET D(2)=PEEK(L)
Ø38Ø GOSUB 9ØØ
Ø39Ø LET U$(I)=Z$
Ø42Ø LET F(I)=(C(1)-C(2))/(D(1)-D(2))
Ø43Ø NEXT I
Ø431 LET F(2)=-F(2):L=L+1:J=PEEK(L):GOSUB 9ØØ
Ø437 LET W=VAL(Z$):WRITE #1,Y$,W
Ø44Ø REM
Ø45Ø REM NOW FOR DATA BLOCKS
Ø46Ø REM
Ø47Ø LET Y=USER(L7)
Ø49Ø LET L3=PEEK(2)*256+PEEK(3)
Ø5ØØ IF PEEK(8)=Ø THEN 53Ø
Ø51Ø IF PEEK(8)=8 THEN 7ØØ
Ø511 PRINT "I/O ERROR #";PEEK(8)
Ø52Ø PRINT "CONITNUE WITH NEXT BLOCK ";
     :INPUT A$:IF LEFT$(A$,1)="Y" THEN 47Ø
Ø521 END
Ø53Ø IF L3=L2 THEN 63Ø
Ø535 LET L=L2-1
Ø54Ø GOSUB 9ØØ
Ø545 LET C1=VAL(Z$)
Ø55Ø GOSUB 9ØØ
Ø554 IF Z$="" THEN Z$="Ø"
Ø555 LET C2=VAL(Z$)
Ø557 LET L=L2+9
Ø56Ø GOSUB 9ØØ
Ø565 LET C3=VAL(Z$)
Ø575 LET L=L+1
Ø577 LET L4=L3-L+1
Ø58Ø LET F1=FNF(L)
Ø585 LET D1=FND(L)
Ø59Ø LET E=F1*D1
Ø595 FOR I=1 TO 2ØØØ
Ø597 LET L=L+2
Ø6ØØ LET F=FNF(L)
Ø6Ø5 LET D=FND(L)
Ø6Ø7 IF F>Ø THEN 61Ø
Ø6Ø8 IF I>6Ø THEN 635
Ø61Ø LET E=E+(F+F1)*(D-D1)
Ø615 LET F1=F
Ø62Ø LET D1=D
Ø63Ø NEXT I
Ø635 LET E=.5*(E+F1*(FND(L)-D1))
```

REDUCTION OF AUTOMATICALLY ENTERED TEST DATA

(Continued)

```
Ø640 LET C=.5*(C1+C2)
Ø641 LET N=C3:IF N<N1 THEN N=N*1Ø
Ø646 PRINT "CYC =";N,"E = ";E,"C = ";C
Ø647 IF E<=Ø. THEN E=1
Ø650 LET X=LOG(N)
Ø651 IF C<>Ø THEN 655
Ø652 LET C=.ØØ1
Ø655 LET Y=LOG(C)
Ø660 LET Z=LOG(E)
Ø665 WRITE #1,E,C,N,X,Y,Z
Ø666 LET N1=N
Ø670 GOTO 47Ø
Ø700 PRINT "END CONVERSION FOR SAMPLE ";Y$
Ø705 CLOSE #1
Ø710 PRINT "DO YOU WANT SINGLE OR MULTIPLE LINE REGRESSION";:INPUT A$
Ø711 IF LEFT$(A$,1)="S" THEN CHAIN REGRES
Ø712 IF LEFT$(A$,1)="M" THEN CHAIN REG2
Ø713 GOTO 71Ø
Ø715 END
Ø795 REM
Ø800 REM USER ADD ROUTINE
Ø810 REM
Ø820 POKE( 4Ø,INT(L7/256))
Ø830 POKE( 41,IMOD(L7,256))
Ø840 RETURN
Ø850 REM
Ø900 REM FIELD READ
Ø910 REM
Ø920 LET Z$=""
Ø925 LET L=L+1:X$=CHR$(PEEK(L)):IF X$="O" THEN X$="Ø"
Ø930 IF X$="," THEN RETURN
Ø940 LET Z$=Z$+X$:GOTO 925

BASIC
#
```

# COMPUTER PROGRAM FOR SINGLE REGRESSION ANALYSIS AND CALCULATION OF STRAIN ENERGY RELEASE RATE

```
0010 REM OVERLAY DATA REGRESSION
0011 PRINT ""
0060 DIGITS= 2:STRING=10:LINE=80:P=1:REM P=PASS NUMBER
0100 REM EQERY FOR DATA DELETIONS
0120 PRINT "DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ";:INPUT A$
0160 IF LEFT$(A$,1)="N" THEN 280
0180 LET N5=VAL(A$)
0200 FOR N=1 TO N5
0220 PRINT "CYCLE ";
0240 INPUT C(N):NEXT N
0280 PRINT "DROP OUT ANY ENERGY POINTS (N OR TOTAL) ";
0300 INPUT A$:IF LEFT$(A$,1)="N" THEN 440
0340 LET N6=VAL(A$)
0360 FOR N=1 TO N6
0380 PRINT "CYCLE ";:INPUT E(N):NEXT N
0440 REM OPENING THE FILE
0441 OPEN #1,"OVLDAT"
0460 READ #1,Z$,W
0480 PRINT
0500 PRINT "REGRESSION RESULTS FOR DATA ";Z$
0660 FOR I=1 TO 200
0680 IF STATUS #1=6 THEN 1080
0700 READ #1,E,C,N,X,Y,Z
0740 FOR N1=1 TO N5
0760 IF N=C(N1) THEN 900
0780 NEXT N1
0800 LET X1=X1+X
0820 LET Y1=Y1+Y
0840 LET S3=S3+X*Y
0860 LET S2=S2+X↑2
0900 FOR N1=1 TO N6
0920 IF N=E(N1) THEN 1040
0940 NEXT N1
0960 LET X2=X2+X
0980 LET Z1=Z1+Z
1000 LET T2=T2+X↑2
1020 LET T3=T3+X*Z
1040 NEXT I
1080 LET I1=I-1-N5
1100 LET X3=X1/I1
1120 LET Y3=Y1/I1
1160 LET S5=S3-(X1*Y1)/I1
1180 LET S6=S2-(X1↑2)/I1
1200 LET S9=Y3
1220 GOSUB 6000
```

SINGLE REGRESSION ANALYSIS AND CALCULATION

OF STRAIN ENERGY RELEASE RATE

(continued)

```
124Ø LET A1=EXP(S7)
126Ø LET B1=S8
128Ø PRINT
13ØØ PRINT "A= ";A1,"B= ";B1
134Ø LET I1=I-1-N6
136Ø LET X3=X2/I1
138Ø LET Z3=Z1/I1
14ØØ LET S5=T3-(X2*Z1)/I1
142Ø LET S6=T2-(X2↑2)/I1
144Ø LET S9=Z3
146Ø GOSUB 6ØØØ
148Ø LET C1=EXP(S7)
149Ø LET D1=S8
15ØØ PRINT "C= ";C1,"D= ";D1
154Ø PRINT
156Ø PRINT "FRACTURE TOUGHNESS = ";(C1*D1)/(2*W*A1*B1)
1561 CLOSE #1
157Ø SKIP 2
1575 PRINT "DO YOU WISH TO REPEAT THE REGRESSION ON THE SAME SAMPLE ";
1576 INPUT A$:IF LEFT$(A$,1)="Y" THEN 12Ø
158Ø PRINT
1585 PRINT "ANOTHER TEST TO ANALYSE ";:INPUT A$
159Ø IF LEFT$(A$,1)<>"Y" THEN END
16ØØ CHAIN ADBAS
6ØØØ REM
6Ø8Ø LET S8=S5/S6
612Ø LET S7=S9-S8*X3:RETURN

BASIC
#
```

COMPUTER PROGRAM

FOR

MULTIPLE REGRESSION ANALYSIS AND CALCULATION

OF STRAIN ENERGY RELEASE RATE

```
0010 REM OVERLAY DATA REGRESSION
0011 PRINT ""
0060 DIGITS= 2:STRING=10:LINE=80:P=1:REM P=PASS NUMBER
0100 REM EQERY FOR DATA DELETIONS
0120 PRINT "DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ";:INPUT A$
0160 IF LEFT$(A$,1)="N" THEN 280
0180 LET N5=VAL(A$)
0200 FOR N=1 TO N5
0220 PRINT "CYCLE ";
0240 INPUT C(N):NEXT N
0280 PRINT "DROP OUT ANY ENERGY POINTS (N OR TOTAL) ";
0300 INPUT A$:IF LEFT$(A$,1)="N" THEN 440
0340 LET N6=VAL(A$)
0360 FOR N=1 TO N6
0380 PRINT "CYCLE ";:INPUT E(N):NEXT N
0440 PRINT "ENTER FABRIC HEIGHT ";:INPUT M
0441 OPEN #1,"OVLDAT"
0460 READ #1,Z$,W
0480 PRINT
0485 IF P>1 THEN 660
0500 PRINT "REGRESSION RESULTS FOR DATA ";Z$
0660 FOR I=1 TO 200
0680 IF STATUS #1=6 THEN 1080
0700 READ #1,E,C,N,X,Y,Z
0701 IF P<>1 THEN 703
0702 IF C>=M THEN 1080
0703 IF P<>2 THEN 740
0704 IF C<=M THEN 680
0740 FOR N1=1 TO N5
0760 IF N=C(N1) THEN 900
0780 NEXT N1
0800 LET X1=X1+X
0820 LET Y1=Y1+Y
0840 LET S3=S3+X*Y
0860 LET S2=S2+X↑2
0900 FOR N1=1 TO N6
0920 IF N=E(N1) THEN 1040
0940 NEXT N1
0960 LET X2=X2+X
0980 LET Z1=Z1+Z
1000 LET T2=T2+X↑2
1020 LET T3=T3+X*Z
```

MULTIPLE REGRESSION ANALYSIS AND CALCULATION
OF STRAIN ENERGY RELEASE RATE
(continued)

```
1040 NEXT I
1080 LET I1=I-1-N5
1100 LET X3=X1/I1
1120 LET Y3=Y1/I1
1160 LET S5=S3-(X1*Y1)/I1
1180 LET S6=S2-(X1↑2)/I1
1200 LET S9=Y3
1220 GOSUB 6000
1240 LET A1=EXP(S7)
1260 LET B1=S8
1280 PRINT
1290 IF P=1 THEN PRINT"REGRESSION RESULTS BELOW THE FABRIC "
1291 IF P=2 THEN PRINT"REGRESSION RESULTS ABOVE THE FABRIC "
1292 IF P=3 THEN PRINT"OVERALL REGRESSION RESULTS "
1300 PRINT "A= ";A1,"B= ";B1
1340 LET I1=I-1-N6
1360 LET X3=X2/I1
1380 LET Z3=Z1/I1
1400 LET S5=T3-(X2*Z1)/I1
1420 LET S6=T2-(X2↑2)/I1
1440 LET S9=Z3
1460 GOSUB 6000
1480 LET C1=EXP(S7)
1490 LET D1=S8
1500 PRINT "C= ";C1,"D= ";D1
1540 PRINT
1560 PRINT "FRACTURE TOUGHNESS = ";(C1*D1)/(2*W*A1*B1)
1561 LET P=P+1:IF P<4 THEN CLOSE #1:GOTO 441
1570 SKIP 2
1575 PRINT "DO YOU WISH TO REPEAT THE REGRESSION ON THE SAME SAMPLE ";
1576 INPUT A$:IF LEFT$(A$,1)="Y" THEN 120
1580 PRINT
1585 PRINT "ANOTHER TEST TO ANALYSE ";:INPUT A$
1590 IF LEFT$(A$,1)<>"Y" THEN END
1600 CHAIN ADBAS
6000 REM
6080 LET S8=S5/S6
6120 LET S7=S9-S8*X3:RETURN

BASIC
#
```

## COMPUTER PROGRAM FOR CACULATION OF FRACTURE PROPERTIES

```
//REFC JOB   (W188,505A,S02,001,KT),'CRACK'
//*XBM WATFIV
      DIMENSION CLC(30),CRL(30),FMX(30),SK(30),DCN(30),EK(30),E(30)
     +,FTO(35),FFB(35),SLU(35)
      DIMENSION CD(30),PK(30),X01(65),Y01(65),X02(65),Y02(65)
      DIMENSION TITLE1(20),TITLE2(20),DL(30)
      DATA X01/0.,.04,.06,.08,.10,.12,.135,.14,.15,.16,.17,.18,.19,.2,
     +.22,.24,.26,.28,.30,.325,.35,.375,.4,.425,.45,.475,.5,.51,.52,.53,
     +.54,.55,.56,.57,.58,.59,.6,.61,.62,.63,.65,.675,.7,.725,.75,.775,
     +.80,.81,.82,.84,.86,.87,.88,.89,.9,.91,.92,.93,.94,.95,.96,.97,
     +.98,.99,.994/
      DATA Y01/.19,.19,.125,.075,.045,.0335,.0318,.0319,.0322,.0326,
     +.033,.0338,.0345,.0355,.0368,.0384,.04,.041,.0428,.0448,.0473,
     +.0488,.0518,.054,.056,.0589,.062,.063,.064,.065,.066,.067,.0677,
     +.0695,.0707,.0725,.074,.0748,.076,.077,.0802,.0838,.088,.0925,
     +.0966,.1018,.1078,.1085,.1118,.1168,.1202,.1224,.122,.1208,
     +.1189,.1149,.1109,.106,.101,.094,.085,.0735,.0598,.0377,.0/
      DATA X02/0.,.045,.06,.08,.10,.1205,.14,.16,.17,.18,.19,.2,.225,
     +.25,.275,.3,.325,.35,.375,.4,.425,.45,.475,.5,.525,.55,.56,.57,
     +.58,.59,.6,.61,.62,.63,.64,.65,.67,.68,.69,.70,.72,.74,.76,
     +.78,.79,.8,.81,.82,.84,.85,.86,.87,.88,.89,.9,.91,.92,.93,.94,
     +.95,.96,.97,.98,.99,.994/
      DATA Y02/.273,.273,.232,.172,.112,.0429,.0377,.0371,.0372,.0373,.0
     +374,.0375,.0377,.038,.0382,.0385,.0386,.0387,.0388,.039,.0391,.039
     +2,.03925,.0393,.0394,.0395,.0395,.0395,.0395,.0395,.0395,.0395,.03
     +95,.0395,.0395,.0395,.0395,.0395,.0395,.0395,.0395,.0395,.0393,.03
     +9,.0389,.0387,.03826,.03782,.03694,.0365,.0363,.0359,.0352,.0343,
     +.033,.032,.031,.029,.027,.024,.021,.018,.012,.0055,.0/
      READ(5,1)TITLE1,TITLE2
    1 FORMAT(20A4,/,20A4)
      WRITE(6,2) TITLE1, TITLE2
    2 FORMAT(1H1,///,120('*'),///,10X,'PROJECT   : ',20A4,
     +//,10X,'FILE NAME : ',20A4,///)
      READ(5,9)SB,SD,SL,CK,DOV,DUN,FM,NC
    9 FORMAT(7F10.3,I10)
      READ(5,12)AFM,FL,FCL,LL1,LL2
   12 FORMAT(F10.1,2F10.2,2I5)
      WRITE(6,15)
   15 FORMAT(25X,'INPUT DATA',//)
      WRITE(6,17)SB,SD,SL,CK,DOV,DUN,FM,FL
   17 FORMAT(10X,'THE WIDTH OF SPECIMEN =',F7.1,1X,'IN',/,
     C        10X,'THE DEPTH OF SPECIMEN =',F7.1,1X,'IN',/,
     C        10X,'THE LENGTH OF SPECIMEN=',F7.1,1X,'IN',/,
     C        10X,'THE CRACK OPENING     =',F7.3,1X,'IN',/,
     C        10X,'THE HEIGHT OF OVERLAY =',F7.1,1X,'IN',/,
     C        10X,'THE HEIGHT OF UNDERLAY=',F7.1,1X,'IN',/,
     C        10X,'THE FABRIC MODULUS    =',F7.1,1X,'LB/IN*2',/,
     C        10X,'THE FABRIC LENGTH     =',F7.1,1X,'IN',//)
```

```
      WRITE(6,18)
   18 FORMAT(10X,'NO. OF CYCLE',8X,'CRACK',14X,'FMAX',17X,'DL',/,
     C       30X,'LENGTH',13X,'(LB)',16X,'(IN)',/)
      DO 20 I=1,NC
      READ(5,30)CLC(I),CRL(I),FMX(I),DL(I)
      CD(I)=CRL(I)/FCL
      N=CLC(I)
   20 WRITE(6,25)  N,CRL(I),FMX(I),DL(I)
   25 FORMAT(10X,I5,10X,F10.3,10X,F10.3,10X,F10.4)
   30 FORMAT(F5.1,3F10.3)
      IF(LL1.EQ.1)GO TO 31
      UU=CK/2.
      CALL INTERP(X01,Y01,CD,PK,NC,NO)
      CALL INTERP(X02,Y02,CD,EK,NC,NO)
      CALL REGR(CLC,CRL,NC,A,B)
      DO 36 I=1,NO
      SK(I)=(FMX(I)/SB)*PK(I)
      DCN(I)=A*B*CLC(I)**(B-1.0)
      E(I)=SK(I)/(UU*EK(I))
   36 CONTINUE
      WRITE(6,40)
   40 FORMAT(///,25X,'OUTPUT DATA',///,14X,'N',9X,'C',8X,'FMX',11X,'C/D'
     +,9X,'K/P',9X,'K',8X,'DC/DN',8X,'2K/EU',9X,'E',//)
      DO 59 J=1,NC
      N=CLC(J)
      IF(CD(J).GT.0.994 ) GO TO 55
      WRITE(6,45)    N,CRL(J),FMX(J),CD(J),PK(J),SK(J),DCN(J),EK(J),
     +E(J)
   45 FORMAT(9X,I5,5F12.3,E12.2,F12.4,F12.3)
      GO TO 59
   55 WRITE(6,58)     N,CRL(J),FMX(J),CD(J)
   58 FORMAT(9X,I5,3F12.3)
   59 CONTINUE
      CALL REGR(SK,DCN,NO,AA,BN)
      WRITE(6,65)AA,BN
   65 FORMAT(//,65X,'A = ',E10.3,/,65X,'N = ',E10.3)
      GO TO 999
C
C     CALCULATION OF MINIMUM SHEAR STRESS AND MODULUS OF UNDERLAY
C     FROM THE LAST CYCLE
C
   31 SSMIN=2.0*FMX(NC)/(SB*SL)
        EU =0.125*SL*SL*SSMIN/(CK*DUN)
      WRITE(6,32)
   32 FORMAT(//,25X,'OUTPUT DATA')
       WRITE (6,35)SSMIN,EU
   35 FORMAT(//,10X,'MINIMUM SHEAR STRESS =',F10.4,1X,'LB/IN*2',//,
     C       10X,'MODULUS OF UNDERLAY  =',F10.4,1X,'LB/IN*2',//)
C
C     CALCULATION OF KO BY TRY AND ERROR FROM THE FIRST CYCLE
C
```

```
       FBTA=1./SL
      ESP  =0.001
      J=0
   50 AA   =0.5*FBTA*SL
      J=J+1
      IF(J.GT.500)STOP
      SKO   =FMX(1)*FBTA*SINH(AA)/(SB*CK*(COSH(AA)-1))
      SBTA=SQRT(SKO/EU*DUN)
      IF(ABS(SBTA-FBTA).LE.ESP) GO TO 60
      FBTA=SBTA
      GO TO 50
   60 WRITE(6,70) SKO
   70 FORMAT(10X,'STIFFNESS KO          =',F10.4,//)
      SLU(NC)=0.5*FL
      IF(LL2.EQ.1) GO TO 75
      FTLC = 0.5*AFM*CK*SB/SLU(NC)
      WRITE(6,78) FTLC
   78 FORMAT(10X,'FABRIC FORCE          =',F10.4,//)
      GO TO 999
   75 WRITE(6,38)
   38 FORMAT(23X,'NO. OF CYCLE',3X,'OVERLAY STRESS',6X,'FABRIC FORCE/WID
     CTH',10X,'LU',/,40X,'(LB/IN*2)',14X,'(LB/IN)',16X,'(IN)',/)
C     ******************************************************************
C     CALCULATE THE FABRIC FORCE, OVERLAY FORCE, AND LU
C     FOR ALL CYCLES
C     ******************************************************************
      DO 100 I=1,NC
      FTO(I)=EU*DL(I)/SL
  100 FFB(I)=FMX(I)/SB-FTO(I)*DOV
      RFM=2.*SLU(NC)*FFB(NC)/(CK*SB)
      NN=NC-1
      DO 200 J=1,NN
  200 SLU(J)=0.5*RFM*CK*SB/FFB(J)
      WRITE(6,80)(CLC(I),FTO(I),FFB(I),SLU(I),I=1,NC)
   80 FORMAT(10X,I18,3F20.4)
      WRITE(6,90)RFM
   90 FORMAT(//,10X,'RE-FABRIC MODULUS    =',F10.4,//)
  999 STOP
      END
      SUBROUTINE INTERP(XO,YO,CD,Y,NC,NO)
      DIMENSION XO(65),YO(65),CD(30),Y(30)
      NO=0
      DO 60 K=1,NC
      IF(CD(K).GT.0.994) GO TO 60
      NO=NO+1
   23 I=1
   24 IF(CD(K)-XO(I)) 27,26,25
   25 I=I+1
      GO TO 24
   26 Y(K)=YO(I)
      GO TO 60
```

```
   27 Y(K)=(YO(I)-YO(I-1))/(XO(I)-XO(I-1))*(CD(K)-XO(I-1))+YO(I-1)
   60 CONTINUE
      RETURN
      END
      SUBROUTINE REGR(X,Y,N,A,B)
      DIMENSION X(30),Y(30)
      AX=0.0
      BY=0.0
      AA=0.0
      ASX=0.
      RN=FLOAT(N)
      DO 10 I=1,N
      XX=ALOG(X(I))
      YY=ALOG(Y(I))
      AX=AX+XX
      BY=BY+YY
      AA=AA+XX*YY
      ASX=ASX+XX*XX
   10 CONTINUE
      A1=AA/RN
      XM=AX/RN
      YM=BY/RN
      SX=ASX/RN
      BN=A1-XM*YM
      DN=SX-XM*XM
      B=BN/DN
      AR=YM-B*XM
      A=EXP(AR)
      RETURN
      END
```

## APPENDIX B

## ORIGINAL TEST DATA

As explained in Chapter IV, selected loading cycles were monitored by the TTI data collection microcomputer during testing of each specimen. Electronic voltages representing load and displacement were received by the microcomputer and stored on magnetic tape. These data were later used to calculate the crack opening energy, E, for each loading cycle. The load versus displacement data for each test specimen were also graphically recorded by means of the X-Y recorder. Copies of these original graphs are included on pages 121 through 156 .

The crack length was also recorded for each of the selected loading cycles. Crack length measurements were made from the base plates to the crack's longest vertical extension on each side of the specimen. (The average of the two crack lengths was then used in all data reduction calculations.) These measurements were made visually using an engineer's scale when the sample reached its maximum "open" position during the loading cycle. Crack length data were manually entered into the TTI microcomputer and then stored on magnetic tape. The cycle number and crack langth data were also recorded on test data sheets. These original data sheets have been transcribed and copies for each test specimen are included on pages 157 through 192 . An illustration showing the approximate cracking pattern at failure is also included on these data sheets. This cracking pattern information is useful in evaluating the additional test data as described in Chapter VI.

The peak load, P, required to produce the 0.070 inches gap opening was determined for selected loading cycles from the load versus displacement graphs. The relationship between log P and log N is shown for each sample on pages 193 through 228 . Analysis of these graphs is discussed in Chapter VI, page 58 .

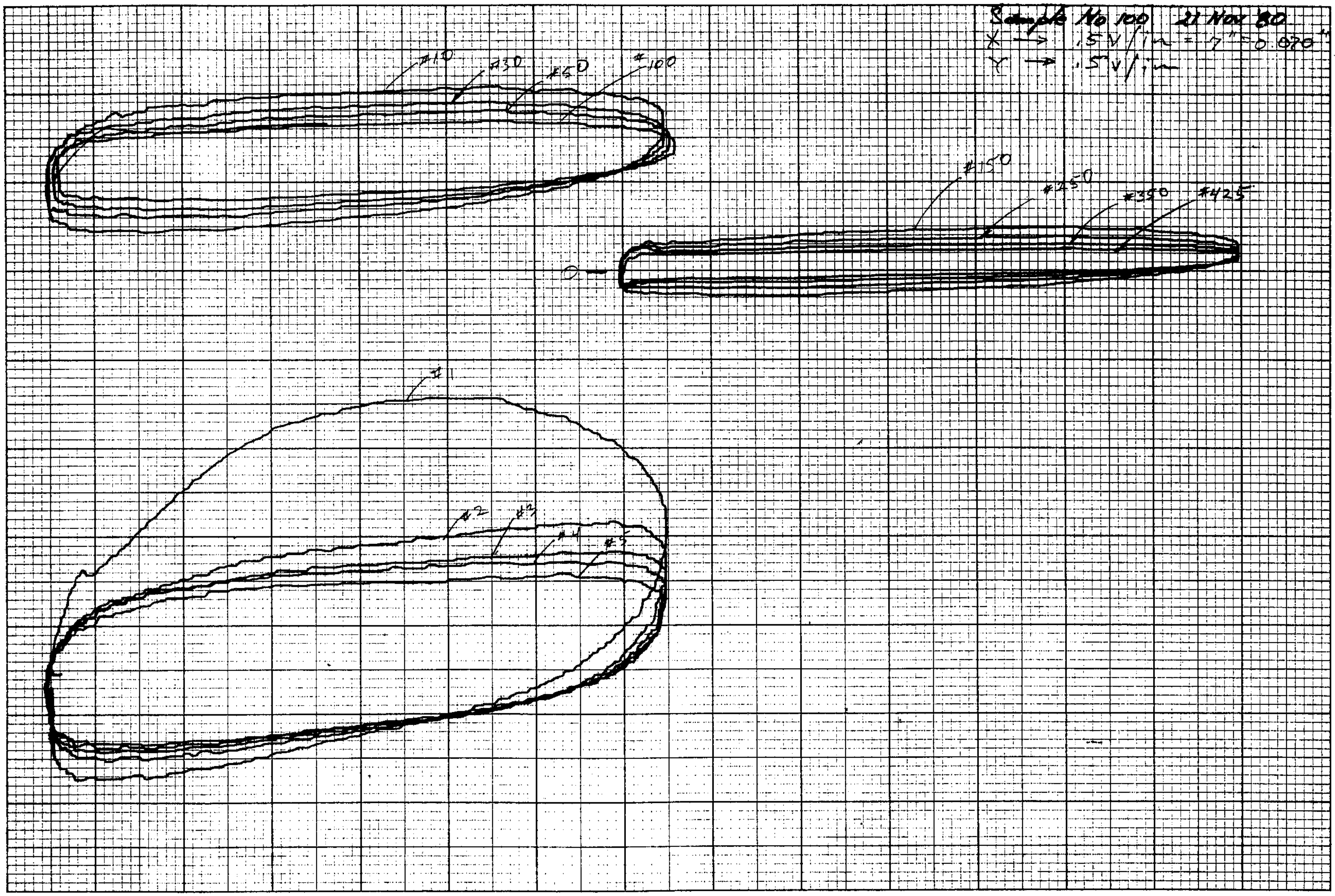



Figure 1B. Load versus Displacement for Sample 100.

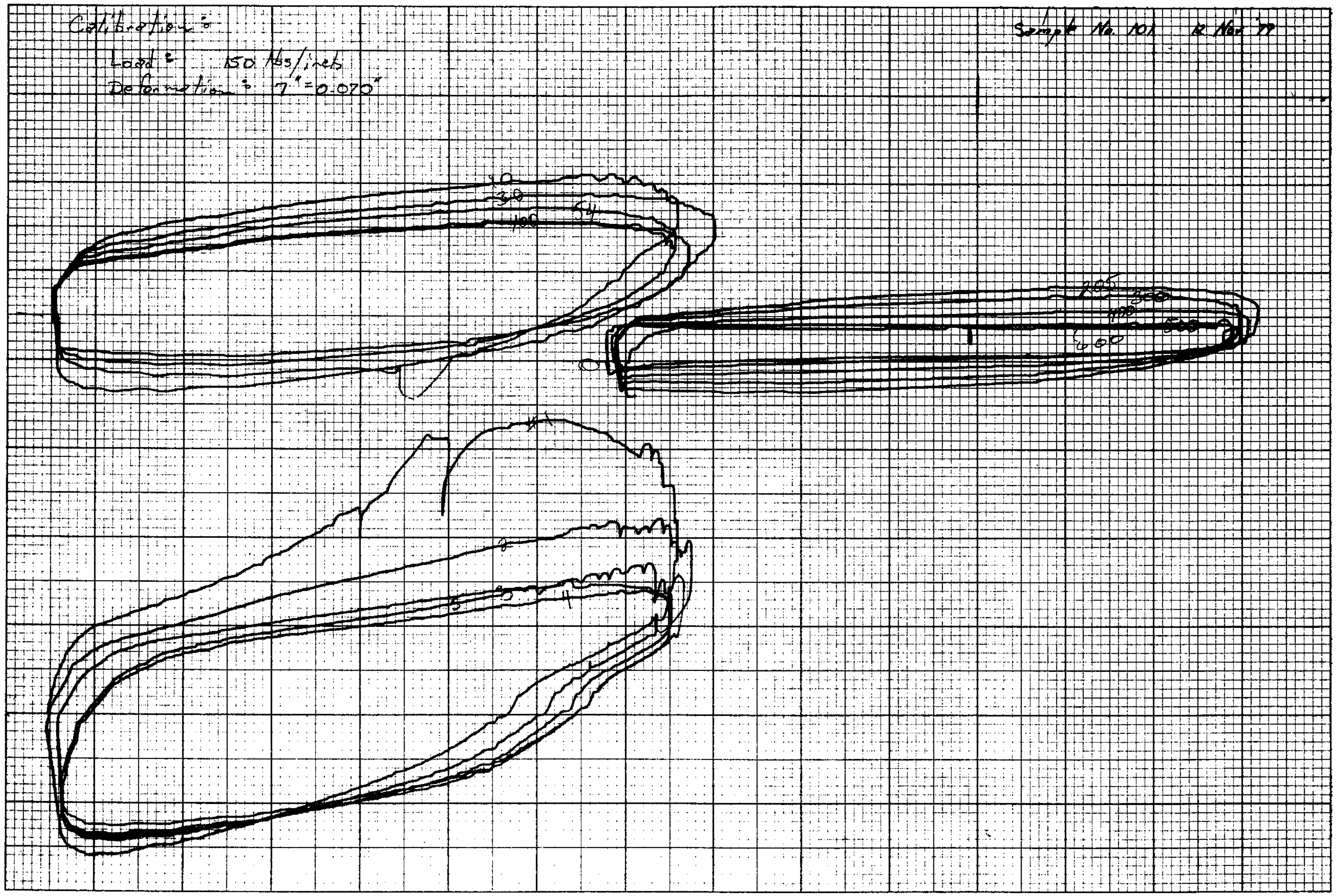



Figure 2B. Load versus Displacement for Sample 101.

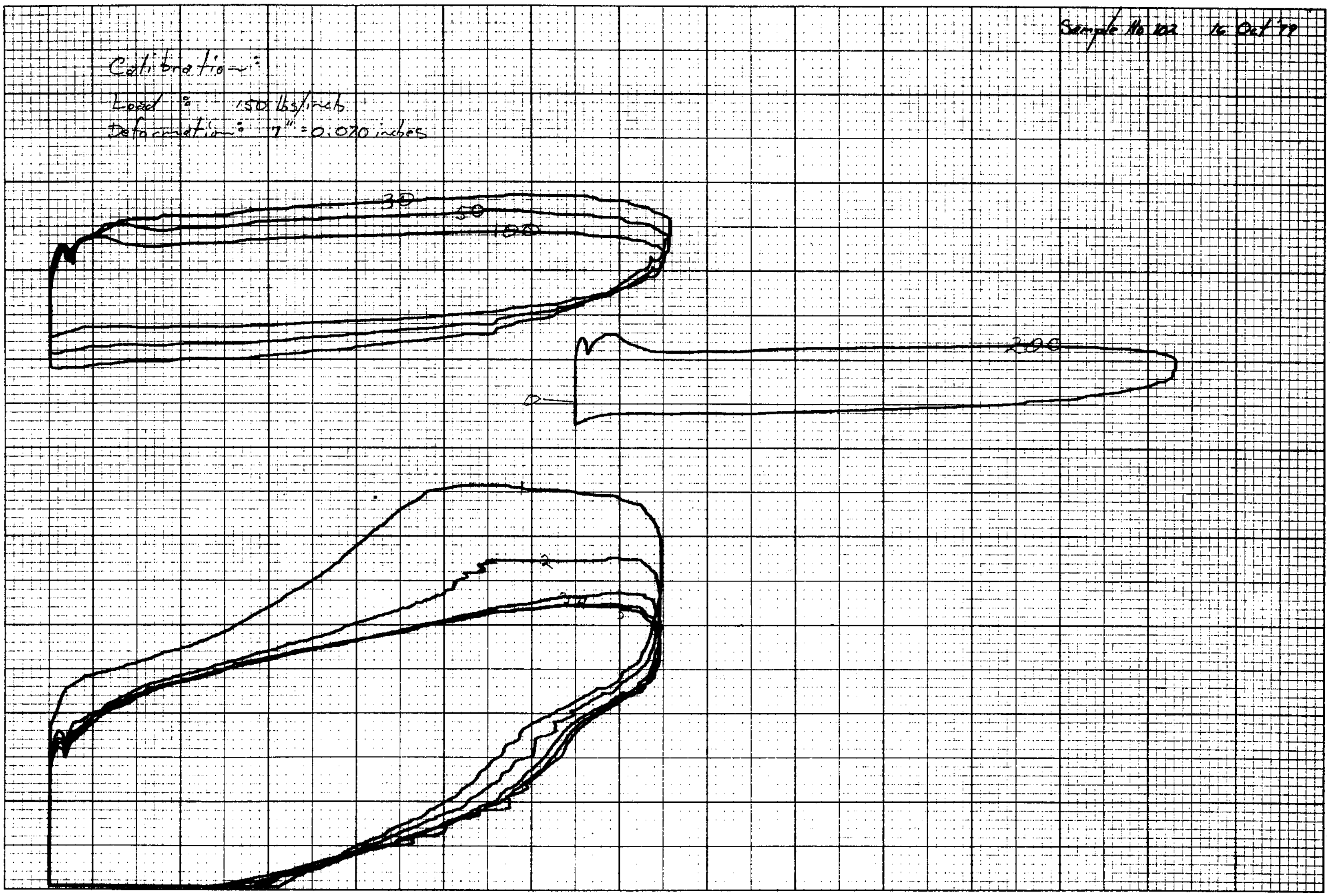



Figure 3B. Load versus Displacement for Sample 102.

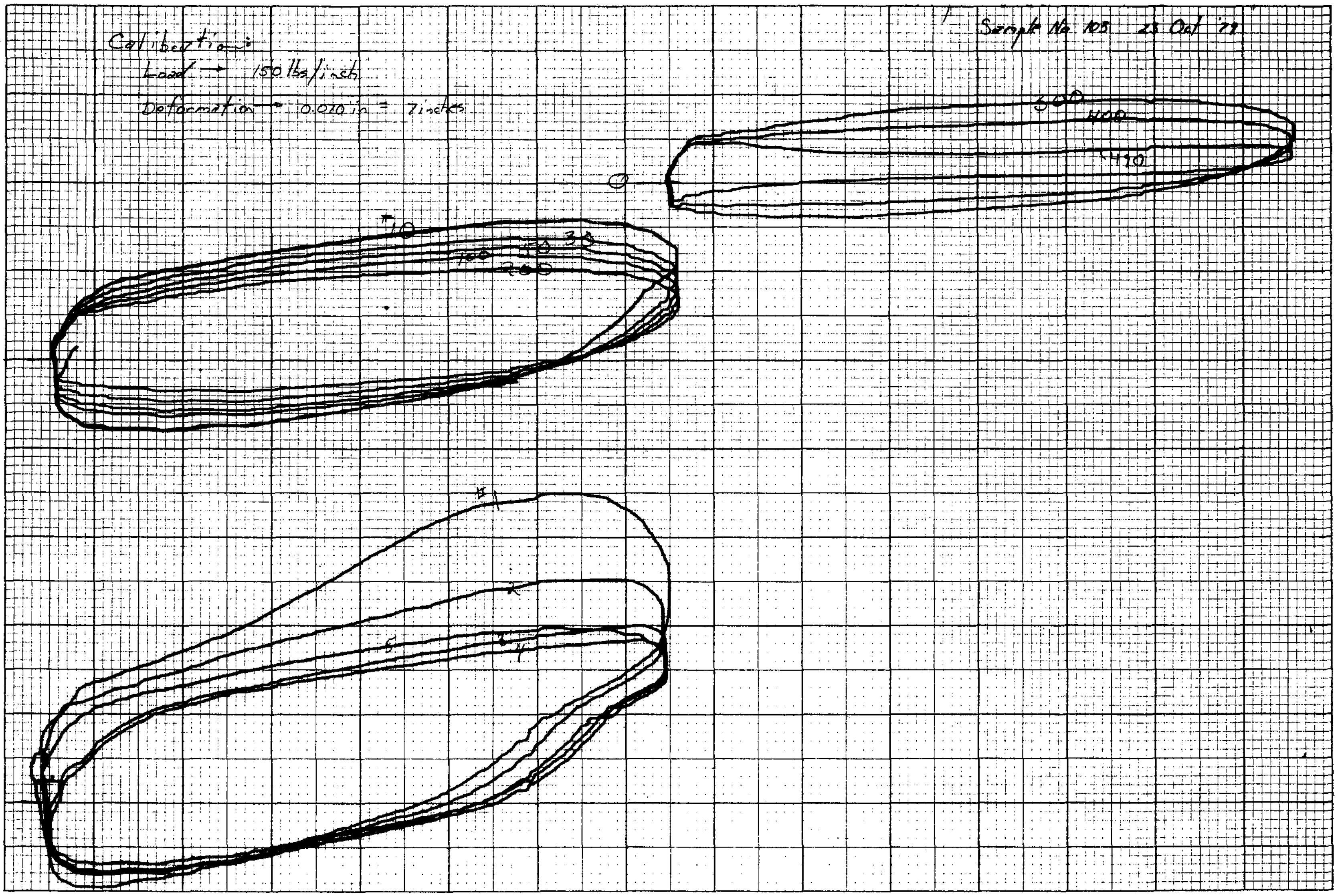



Figure 4B. Load versus Displacement for Sample 103.

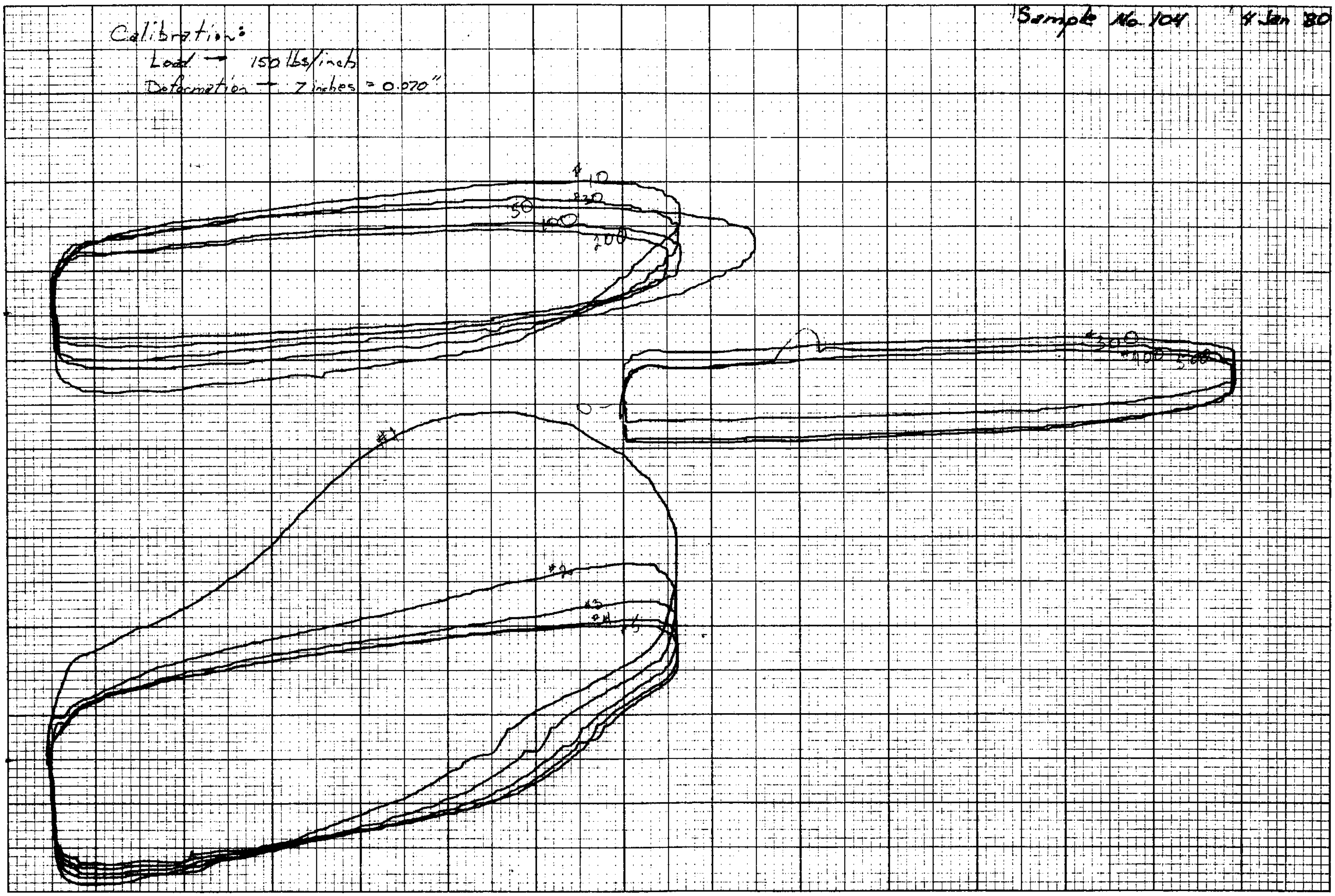



Figure 5B. Load versus Displacement for Sample 104.

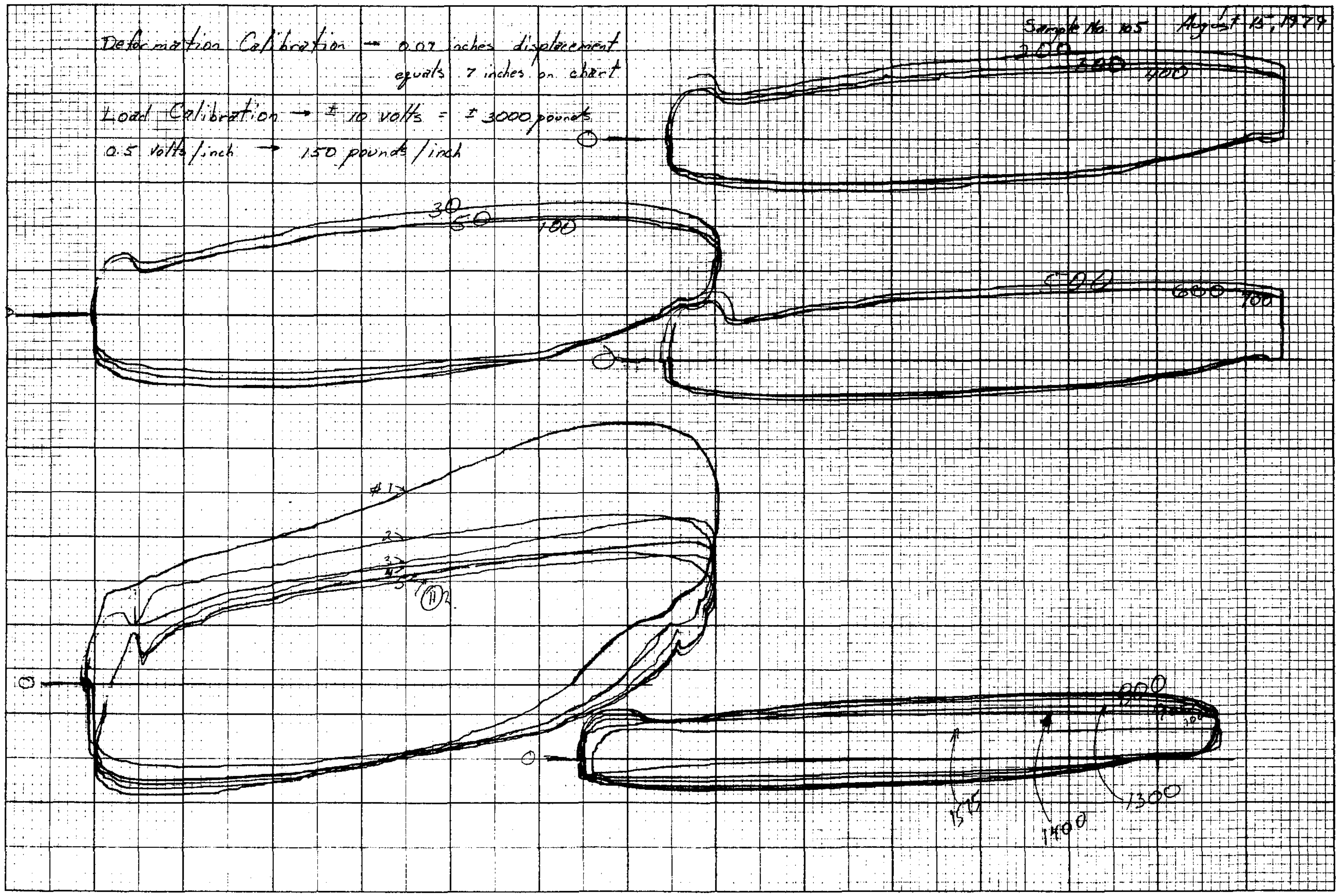



Figure 6B. Load versus Displacement for Sample 105.

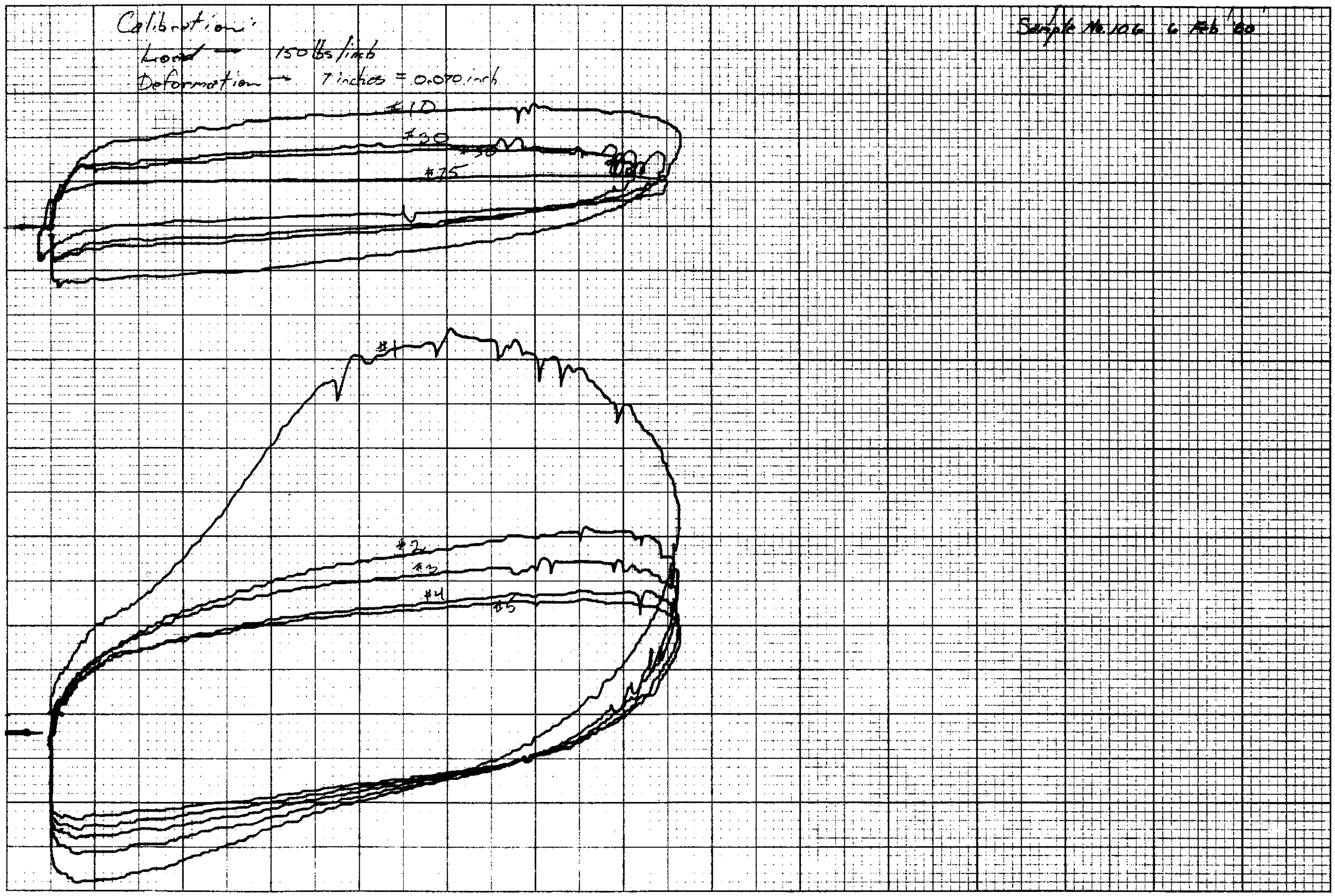



Figure 7B. Load versus Displacement for Sample 106.

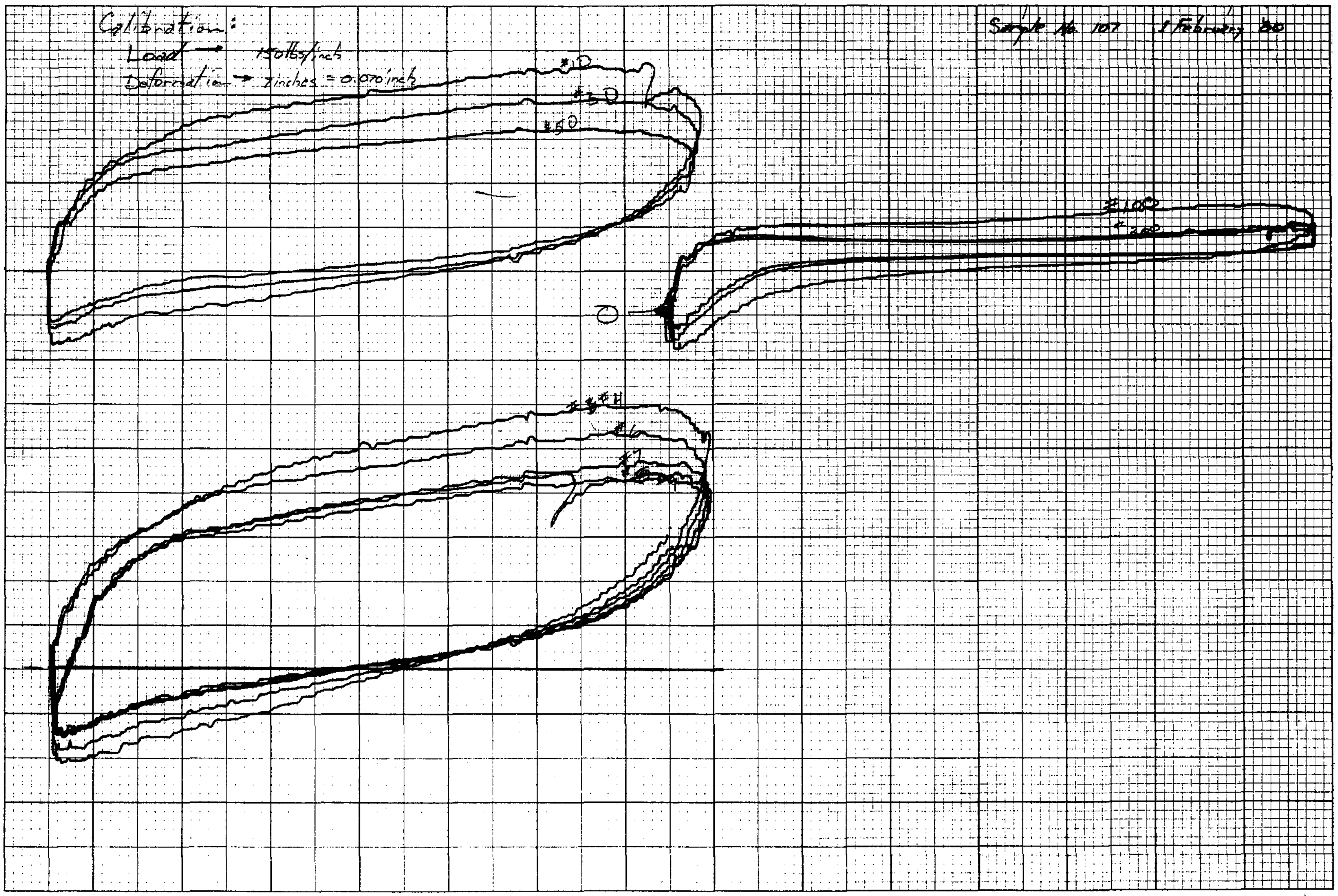



Figure 8B. Load versus Displacement for Sample 107.

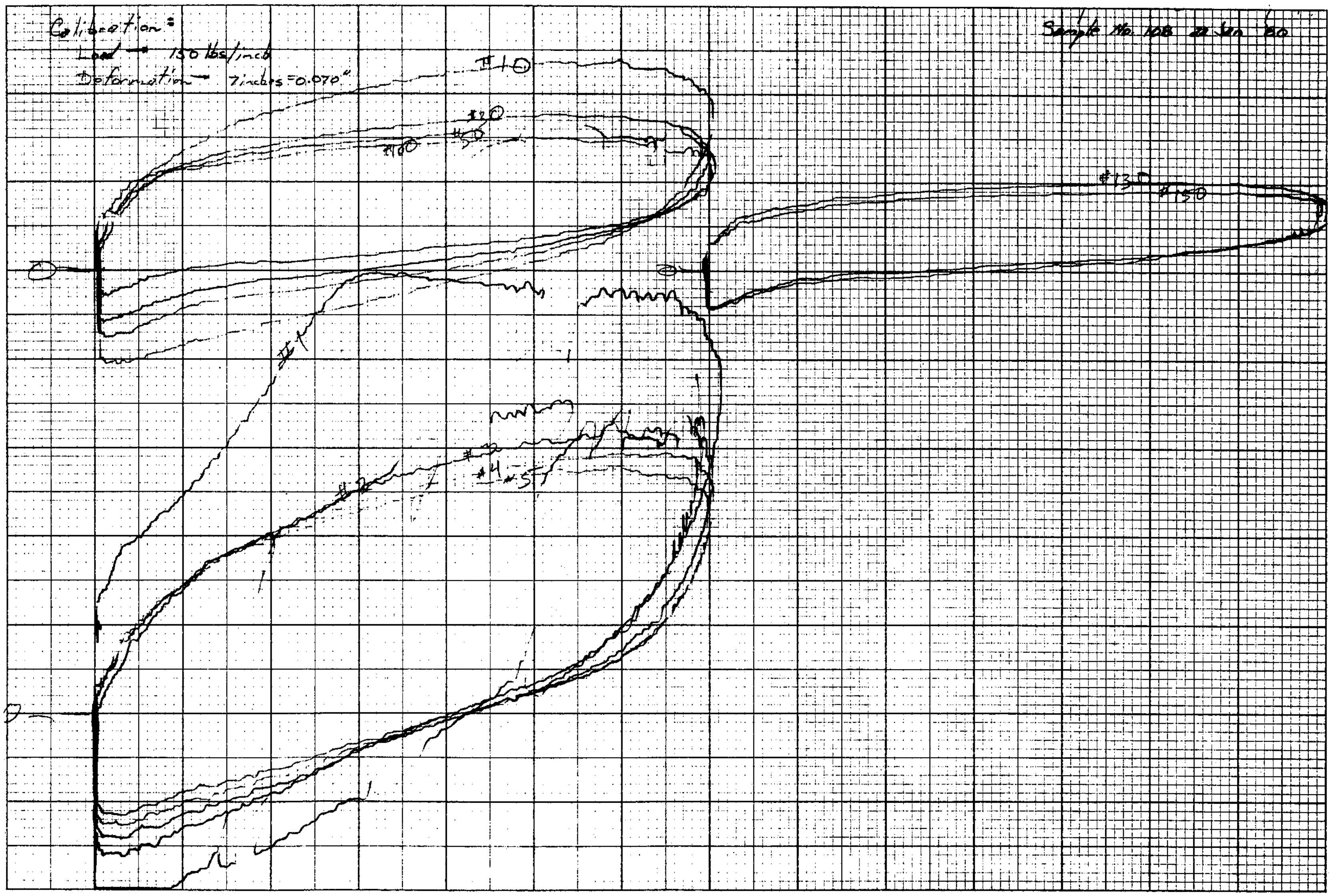



Figure 9B. Load versus Displacement for Sample 108.

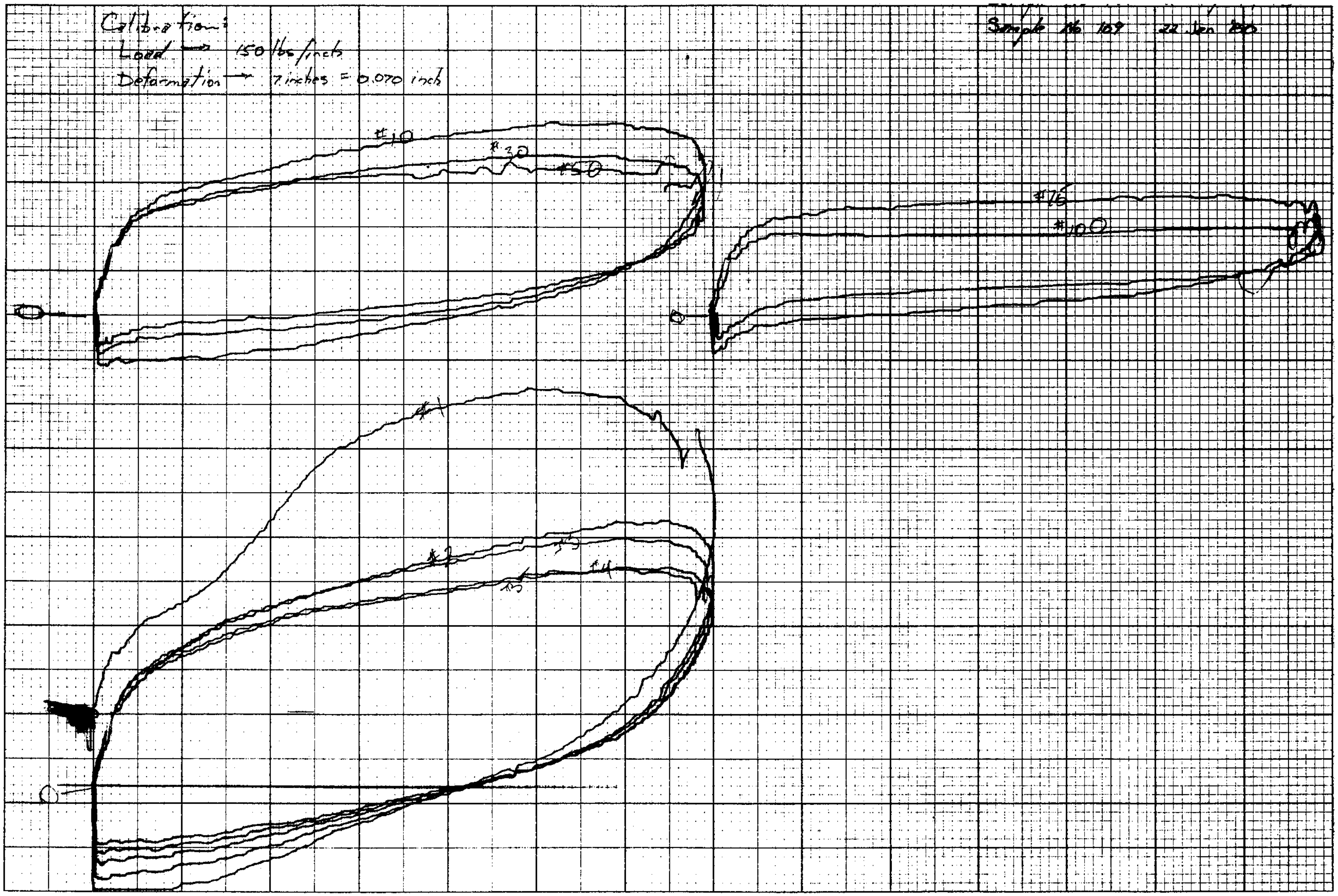



Figure 10B. Load versus Displacement for Sample 109.

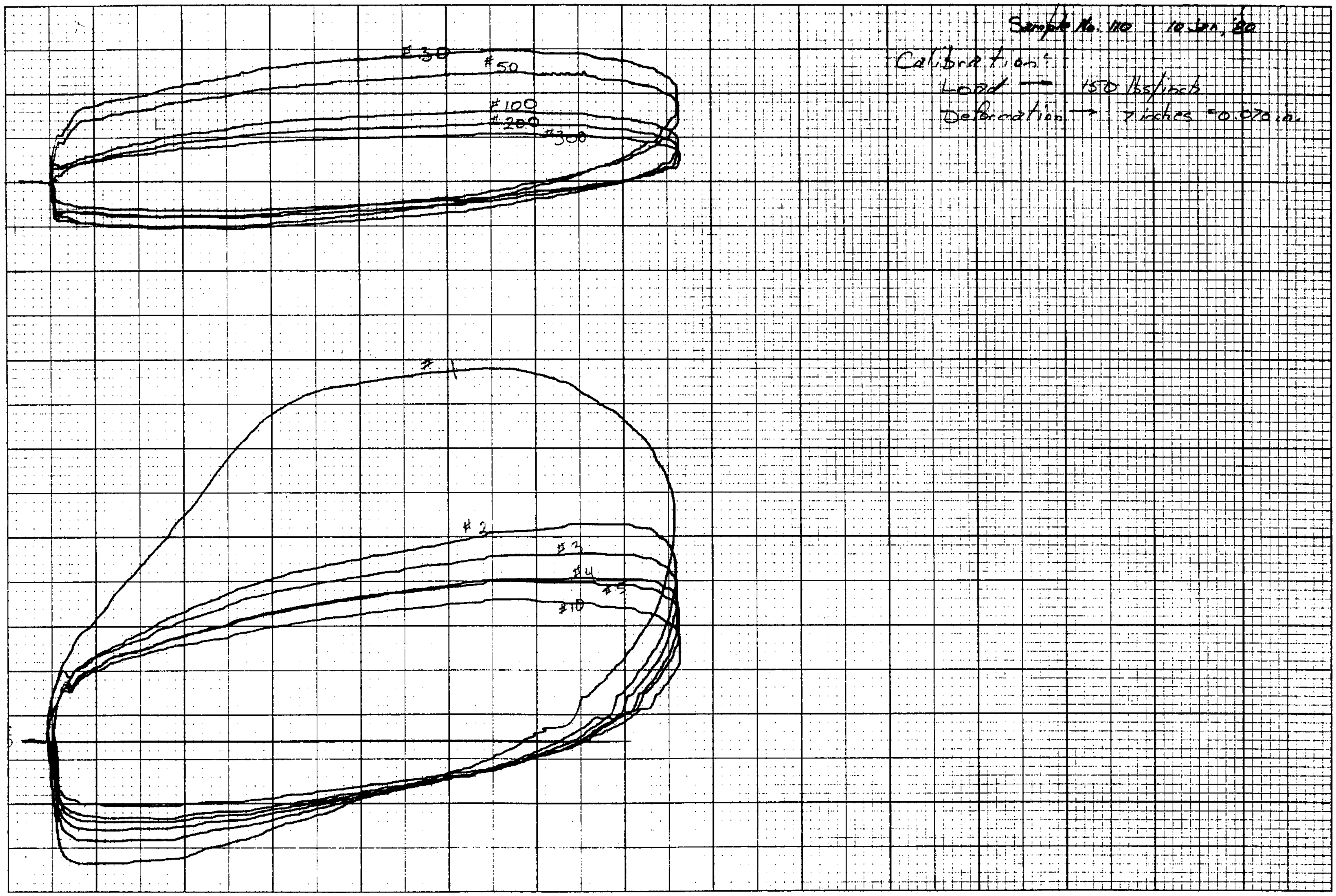



Figure 11B. Load versus Displacement for Sample 110.

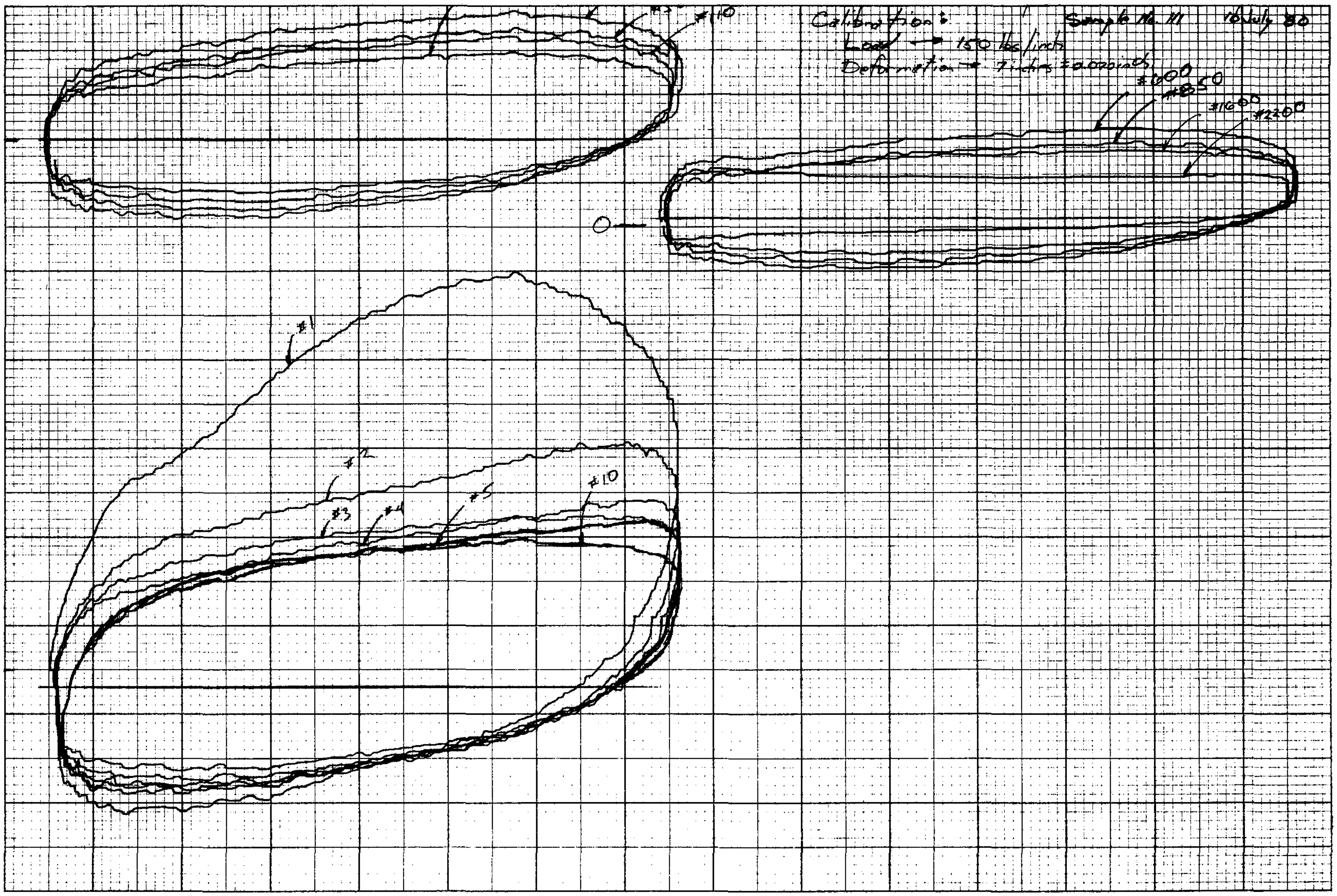



Figure 12B. Load versus Displacement for Sample 111.

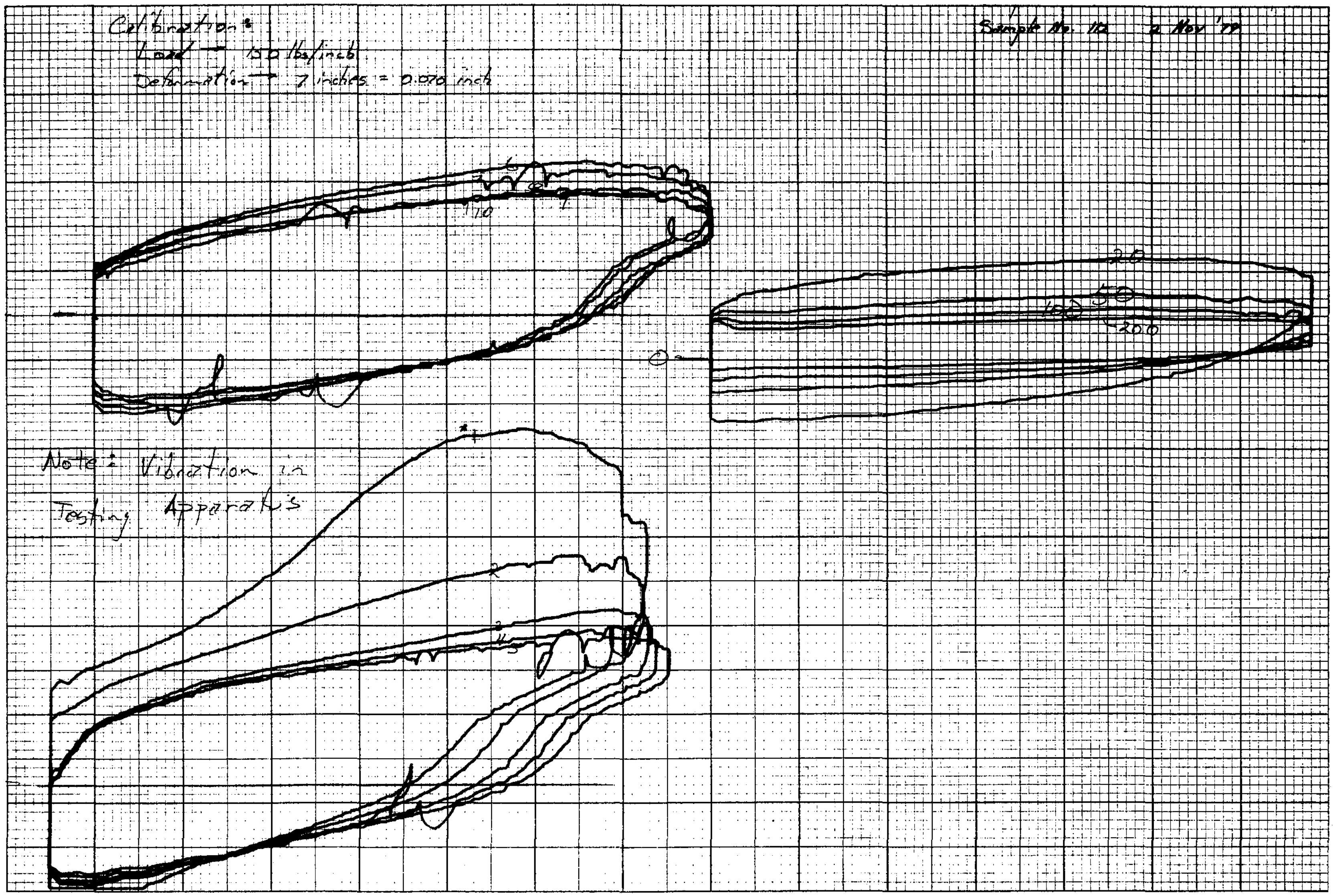



Figure 13B. Load versus Displacement for Sample 112.

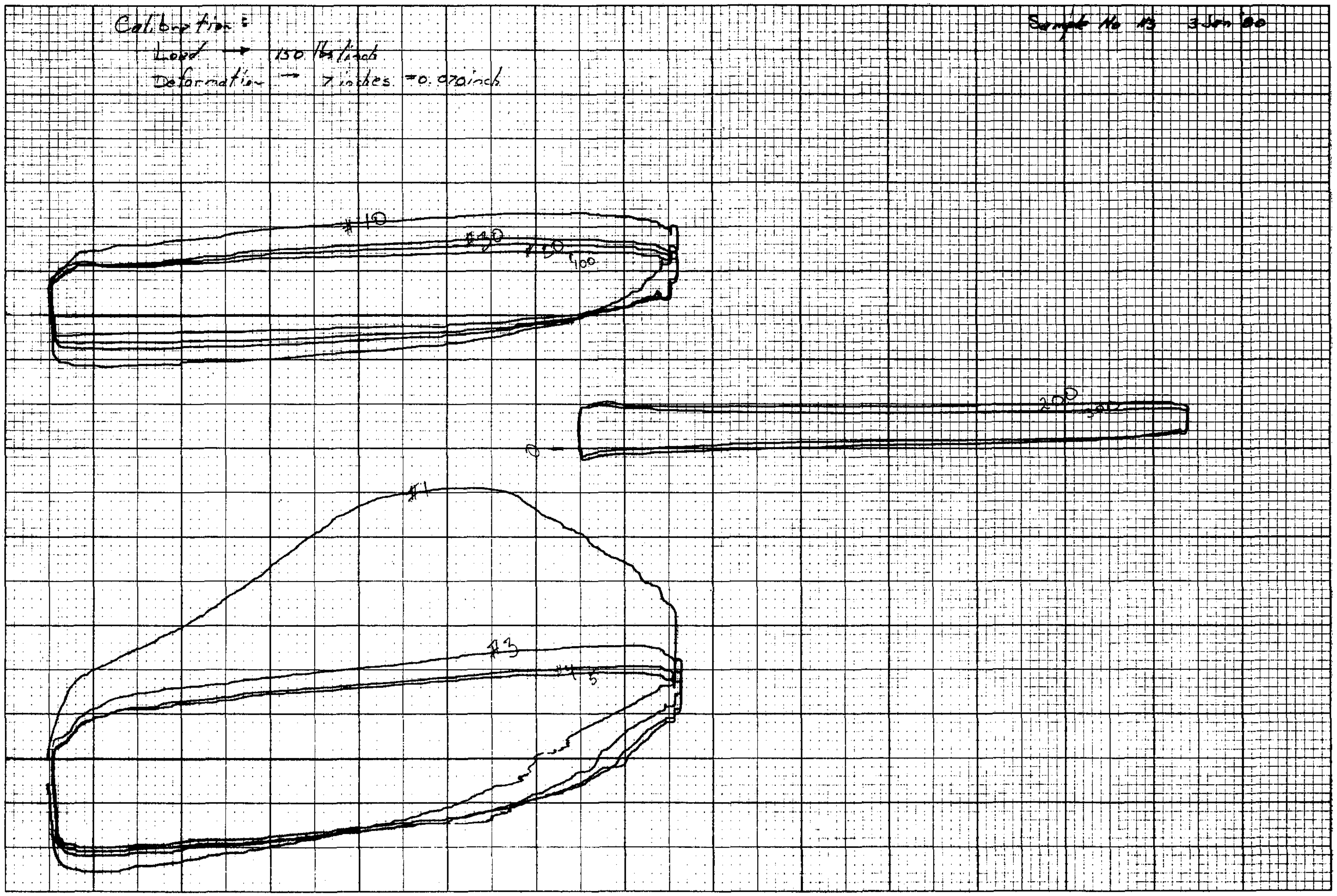



Figure 14B. Load versus Displacement for Sample 113.

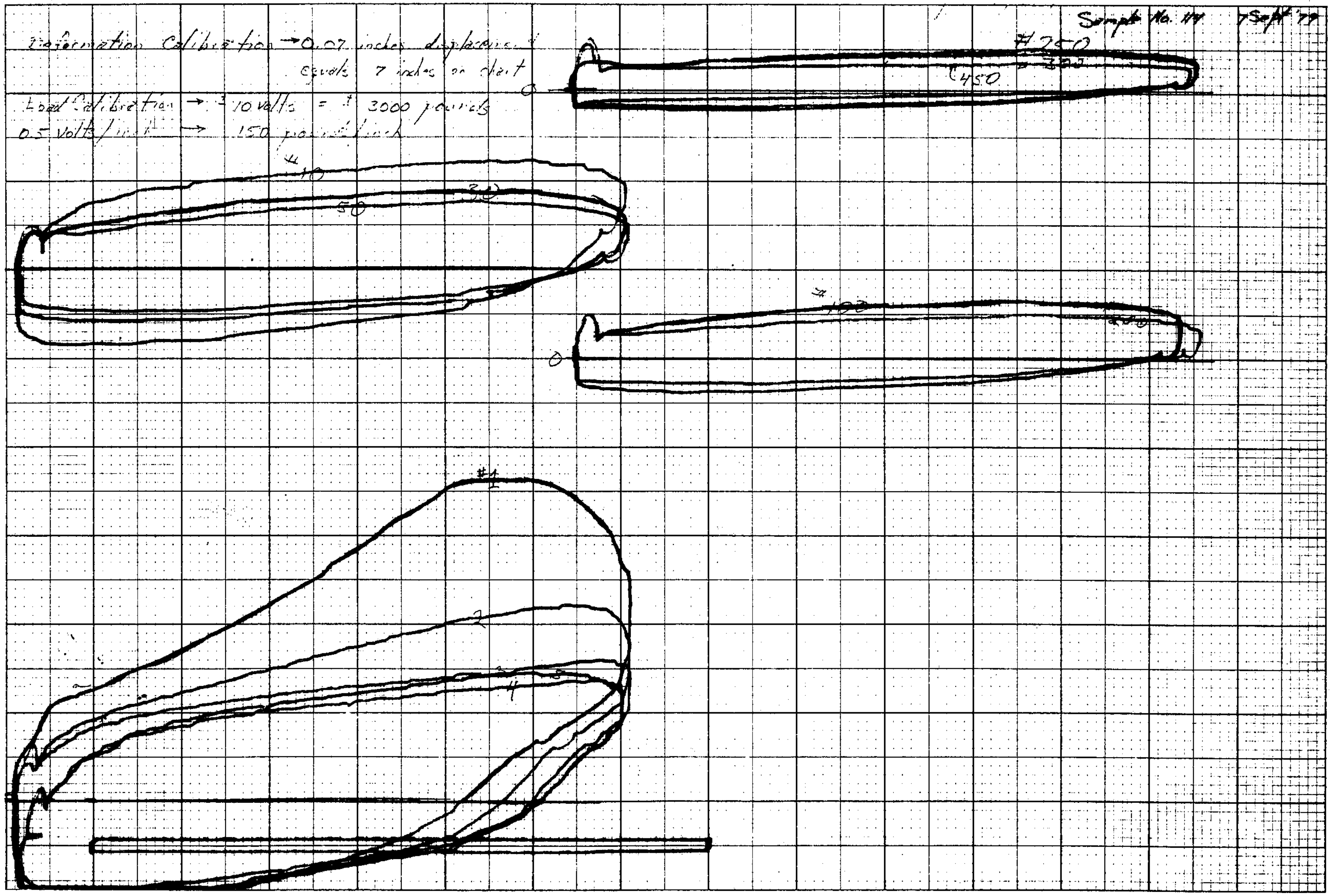


Figure 15B. Load versus Displacement for Sample 114.

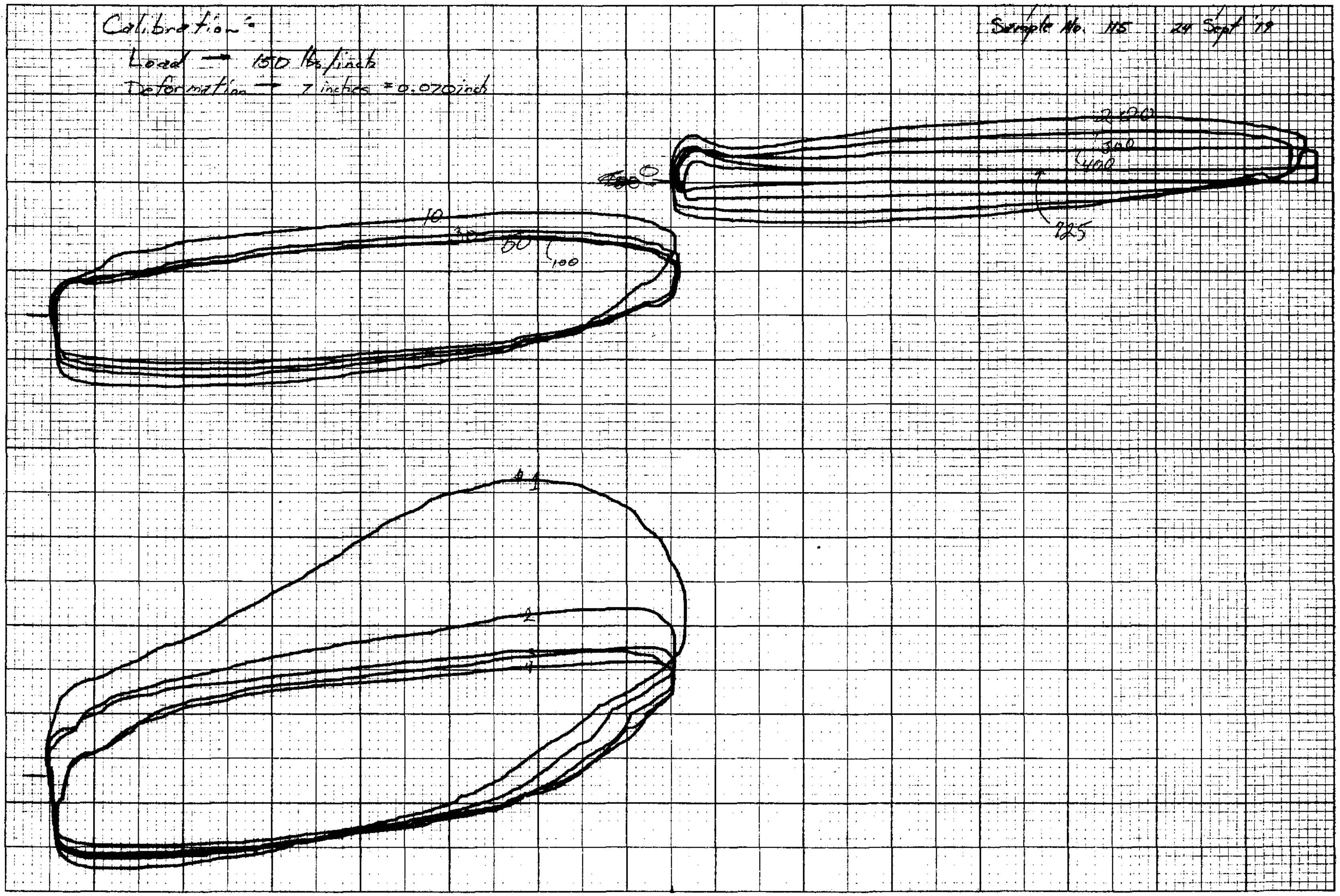



Figure 16B. Load versus Displacement for Sample 115.

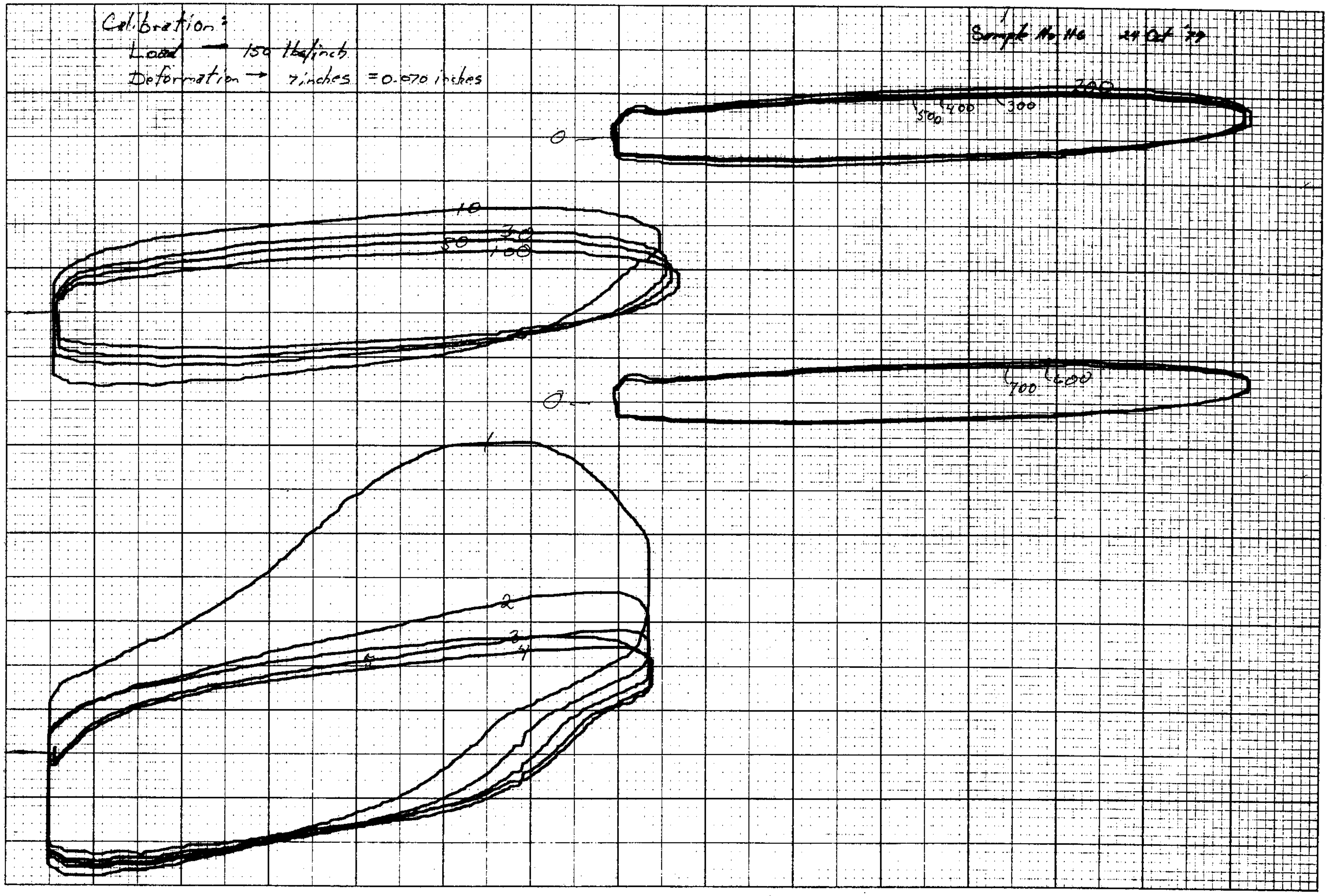



Figure 17B. Load versus Displacement for Sample 116.

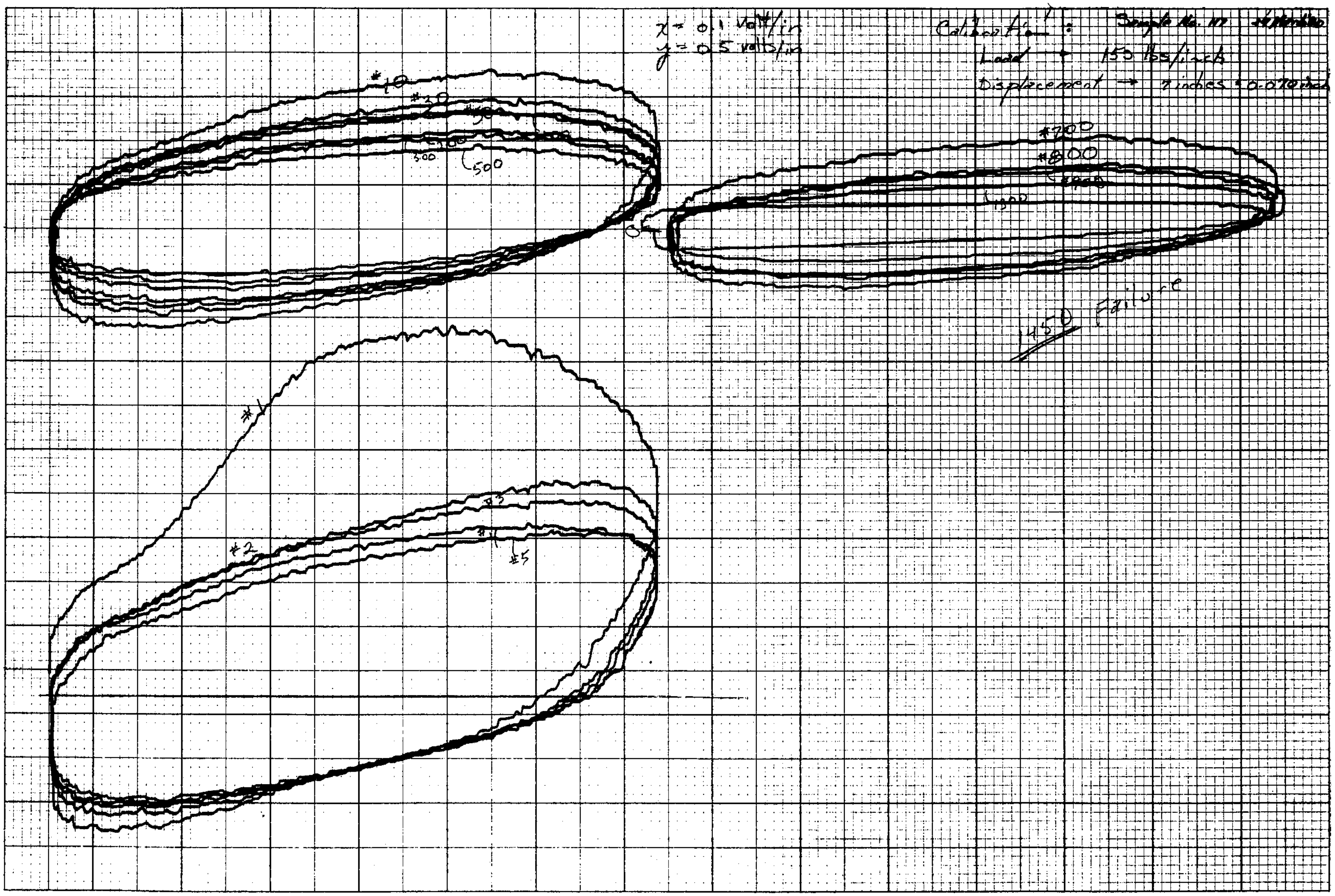



Figure 18B. Load versus Displacement for Sample 117.

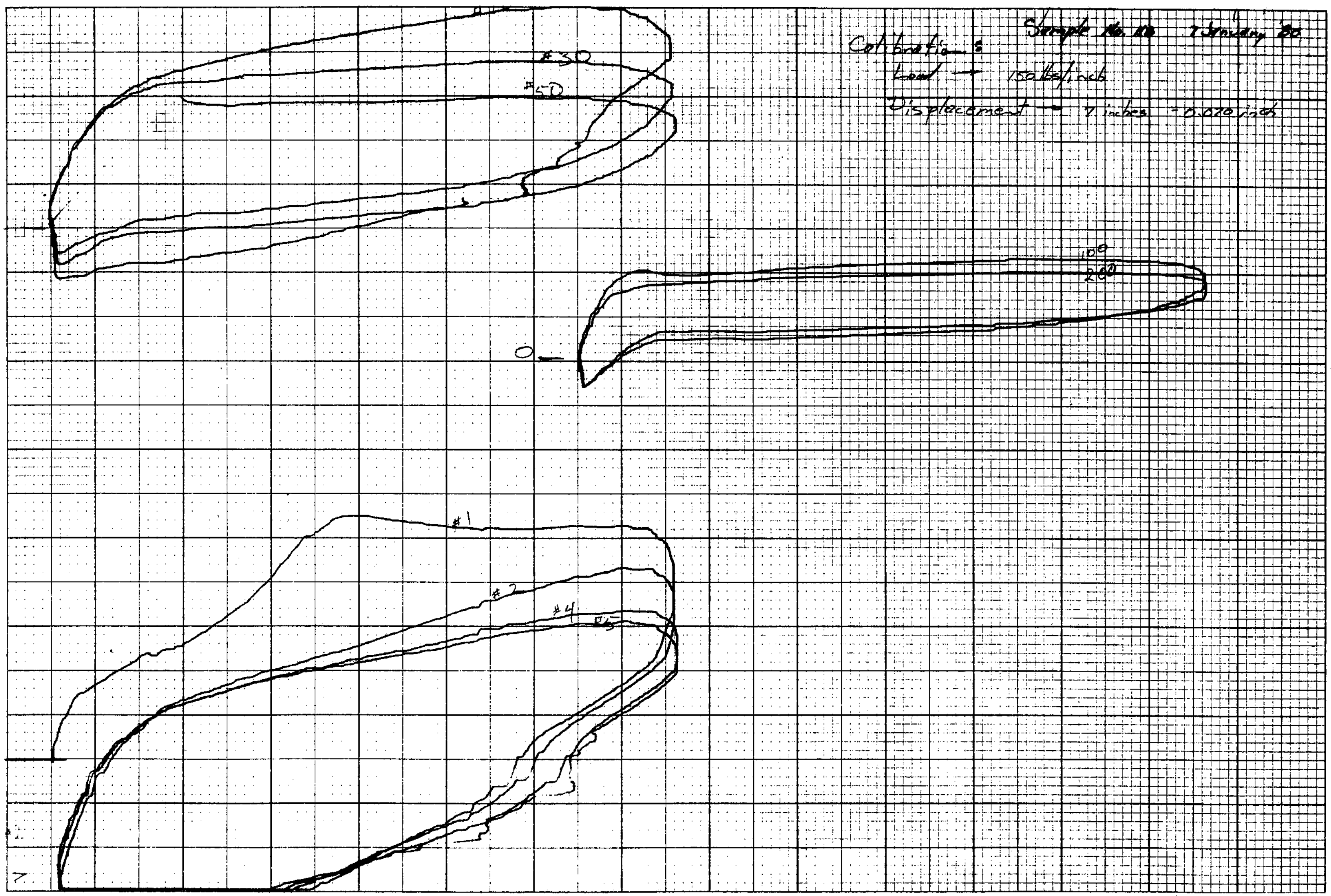



Figure 19B. Load versus Displacement for Sample 118.

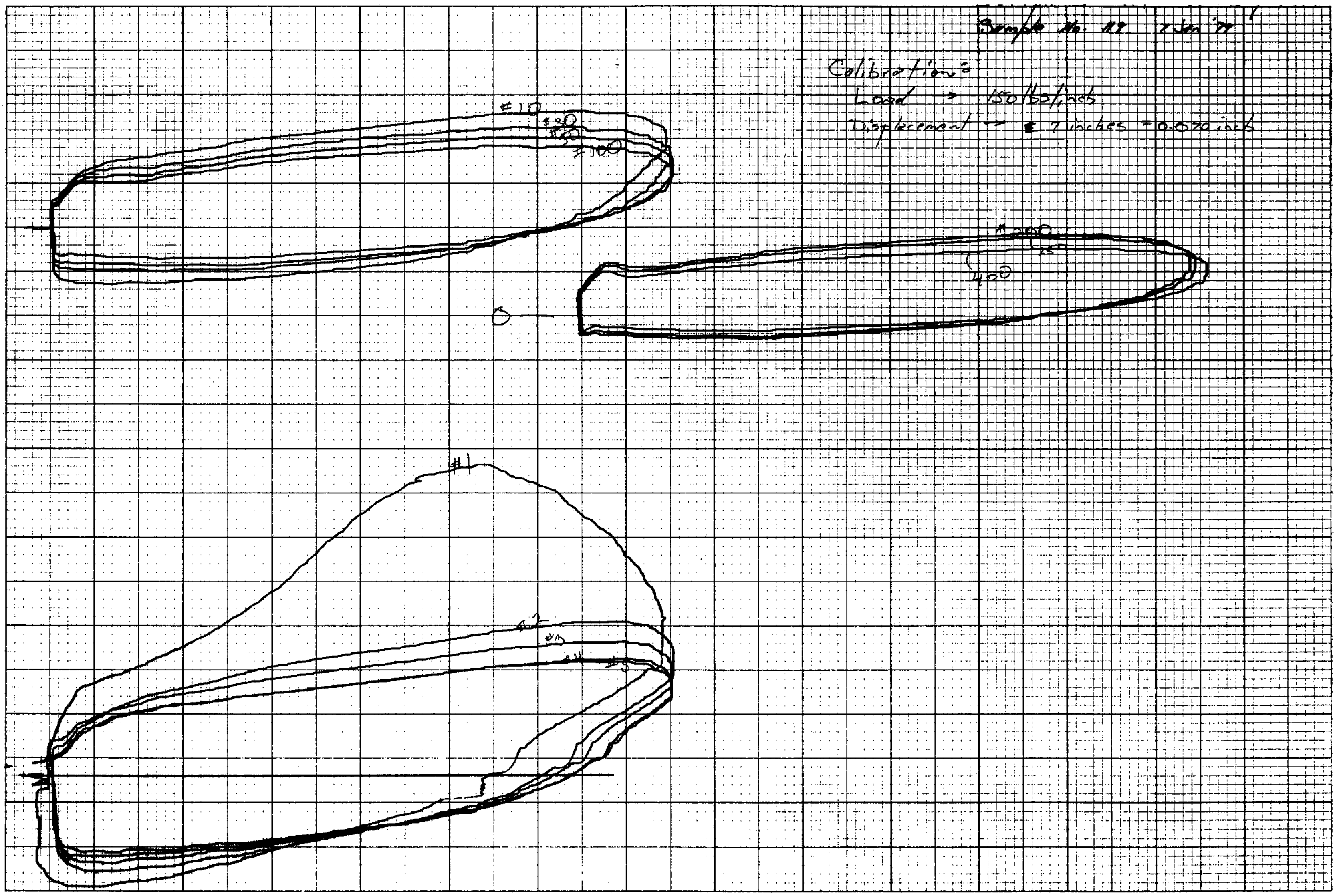



Figure 20B. Load versus Displacement for Sample 119.

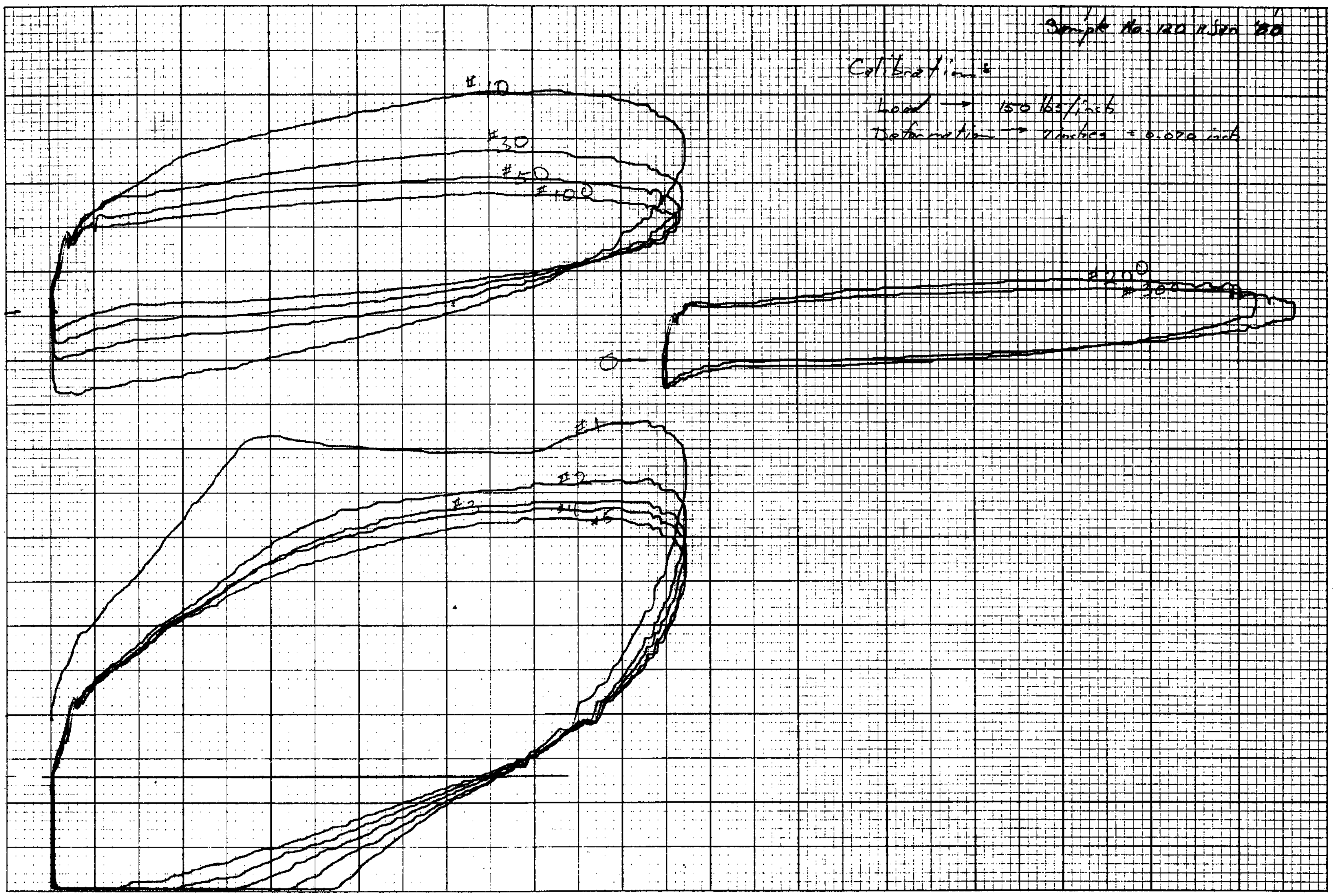



Figure 21B. Load versus Displacement for Sample 120.

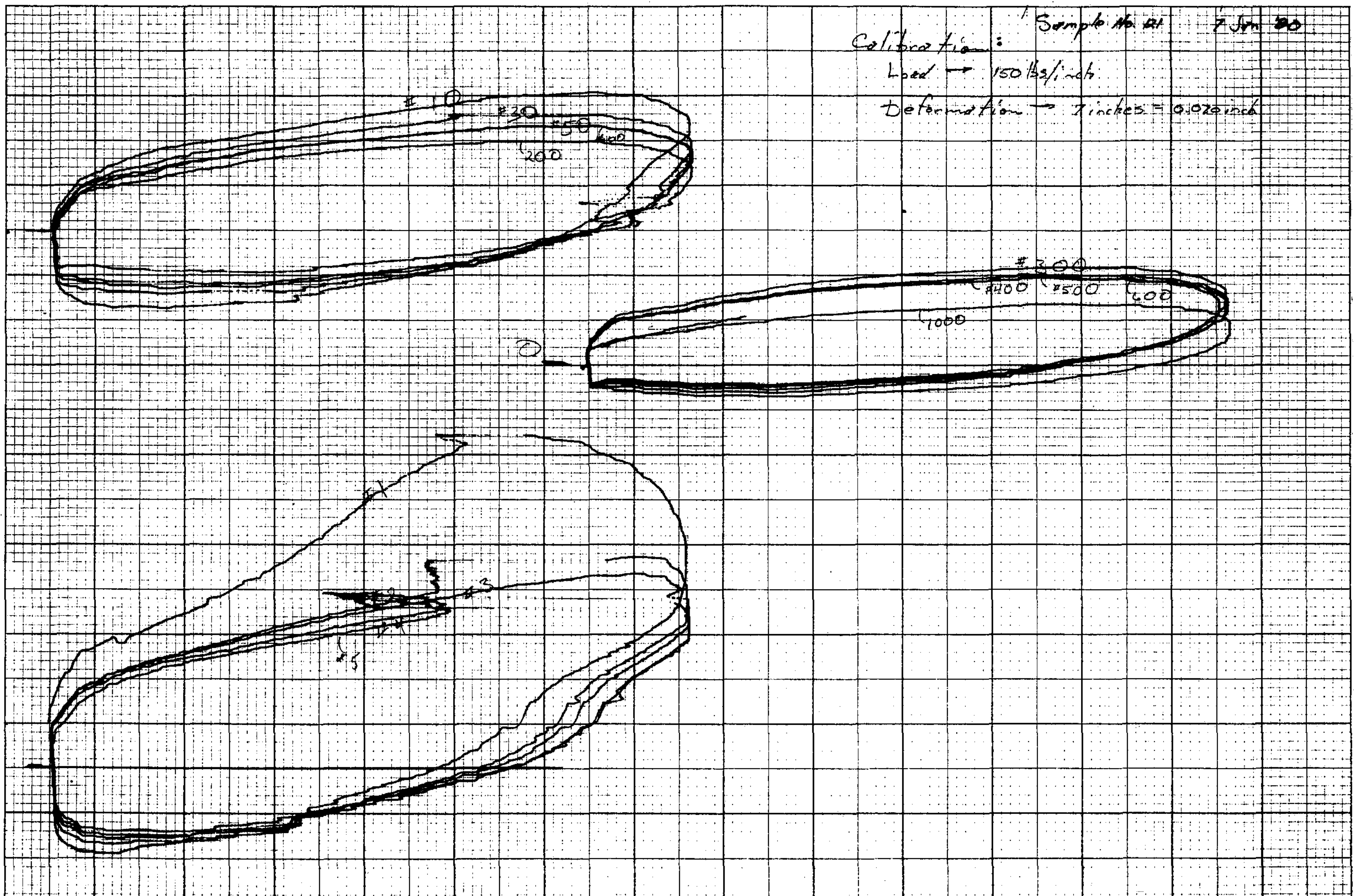



Figure 22B. Load versus Displacement for Sample 121.

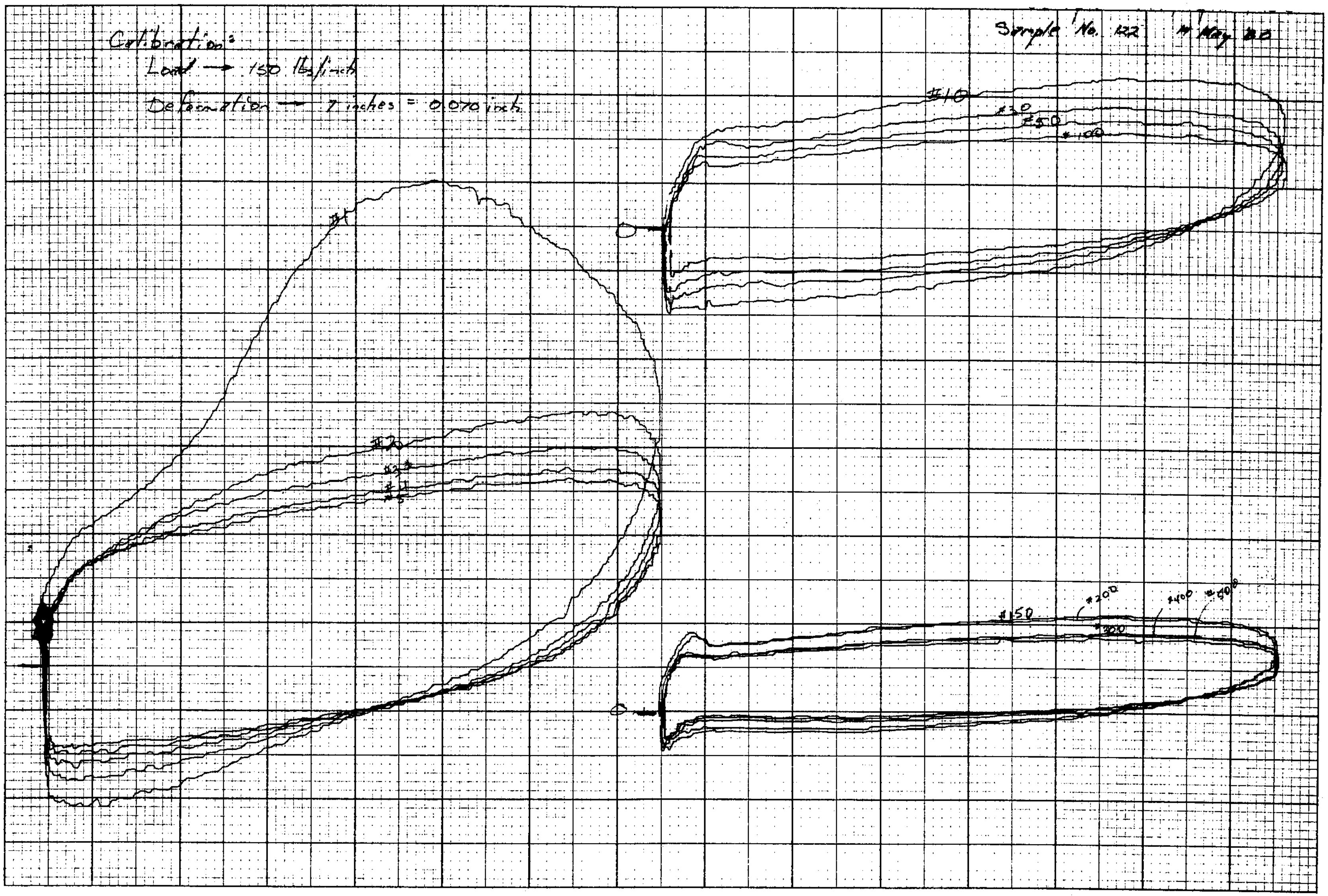



Figure 23B. Load versus Displacement for Sample 122.

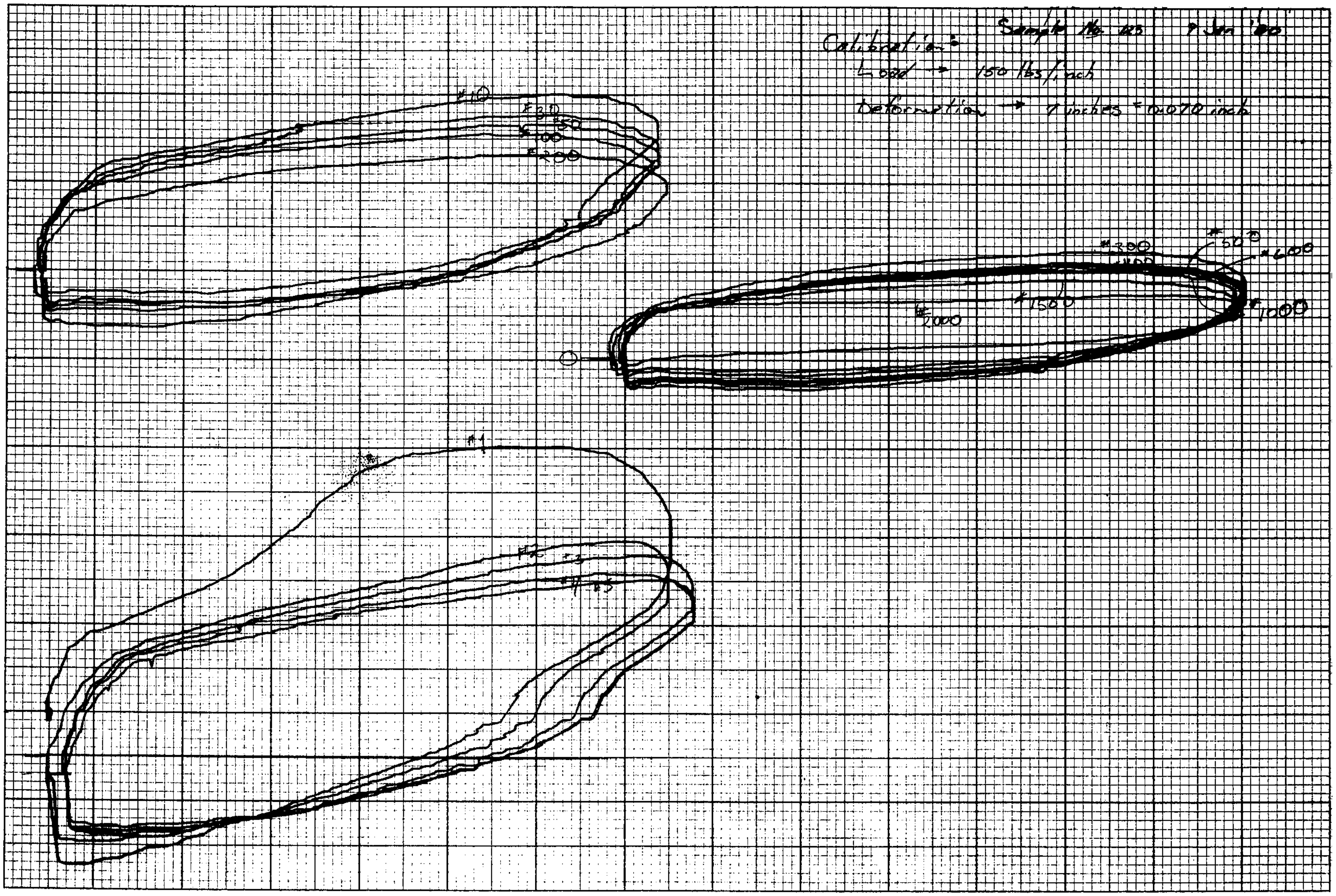



Figure 24B. Load versus Displacement for Sample 123.

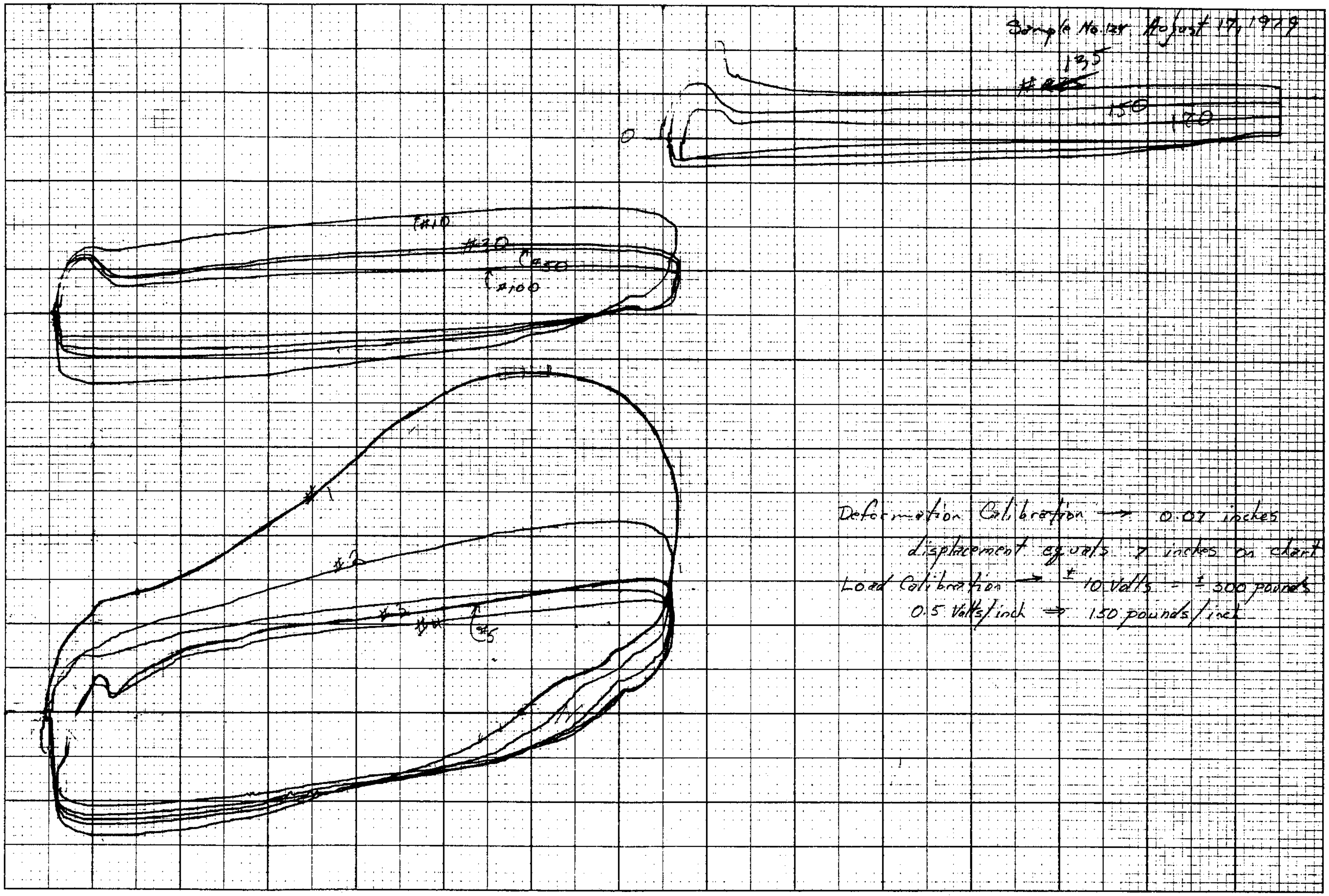



Figure 25B. Load versus Displacement for Sample 124.

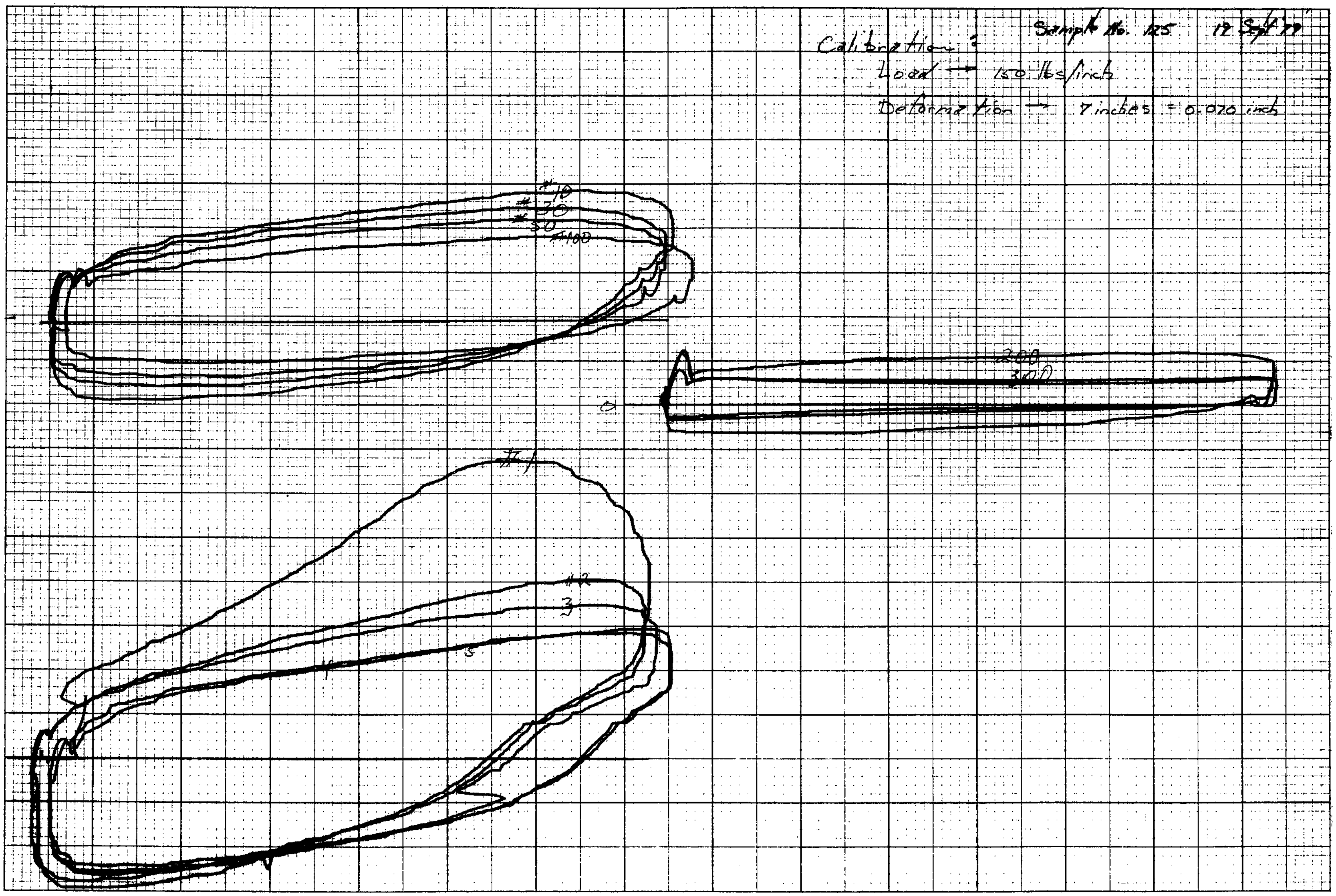



Figure 26B. Load versus Displacement for Sample 125.

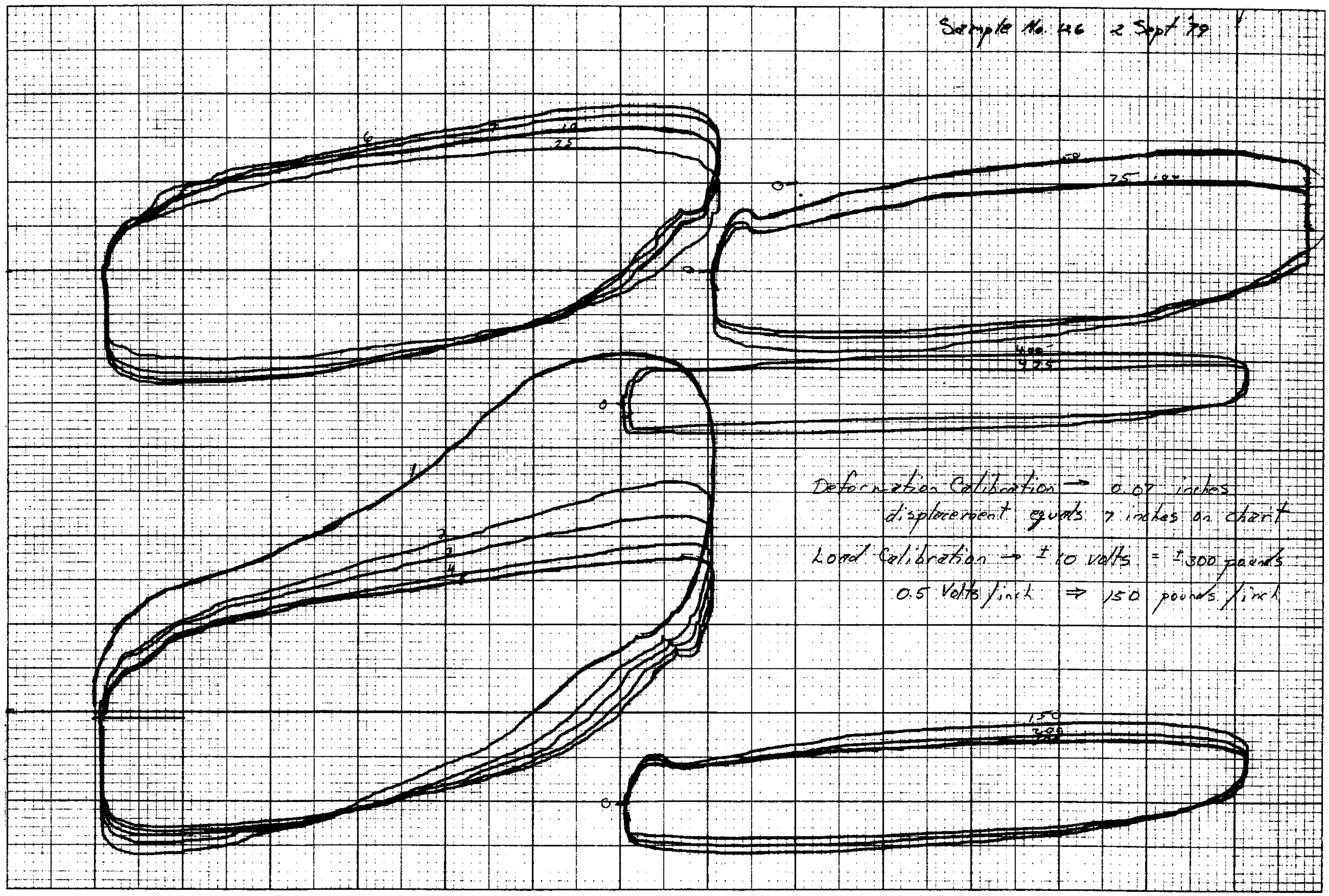



Figure 27B. Load versus Displacement for Sample 126.

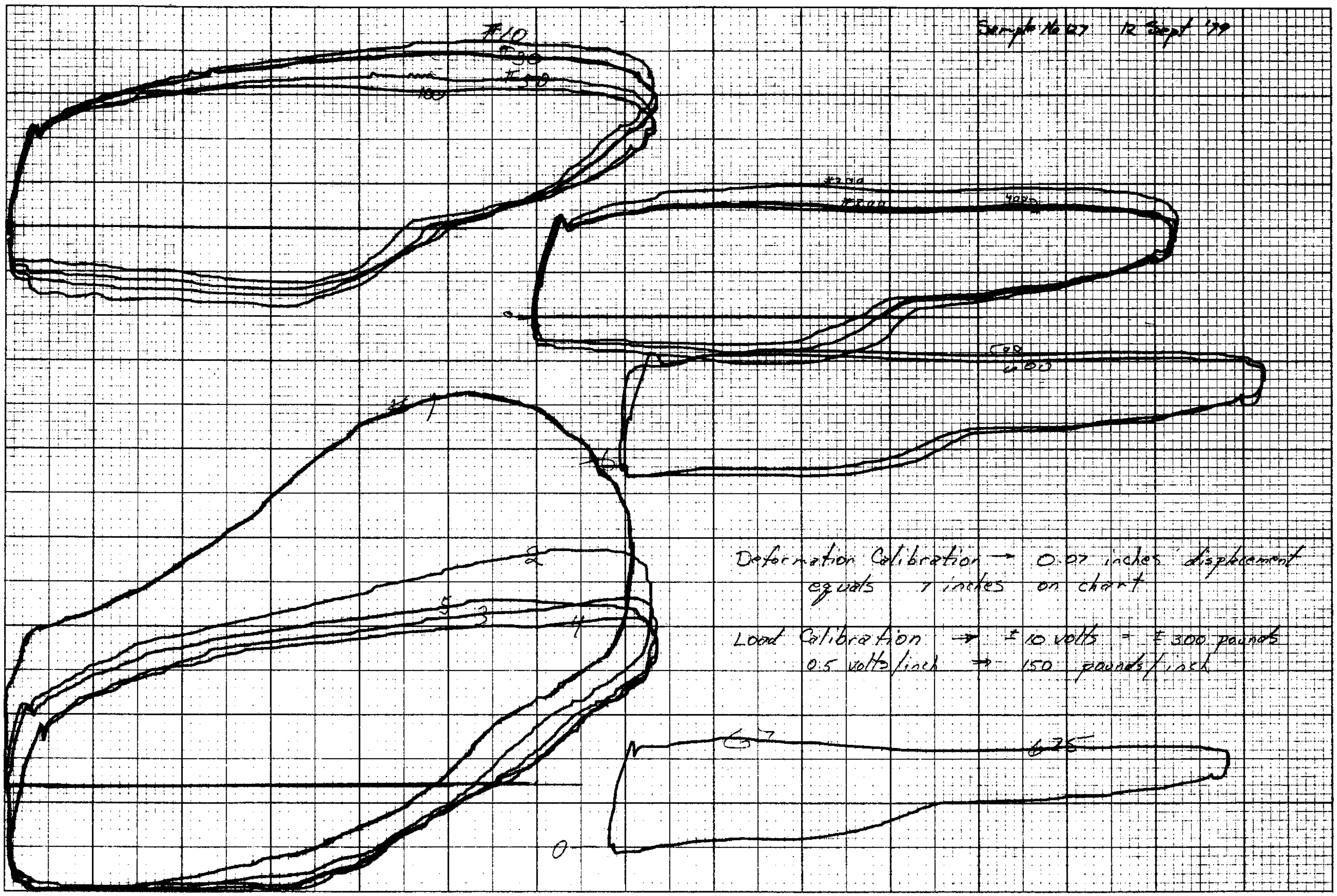



Figure 28B. Load versus Displacement for Sample 127.

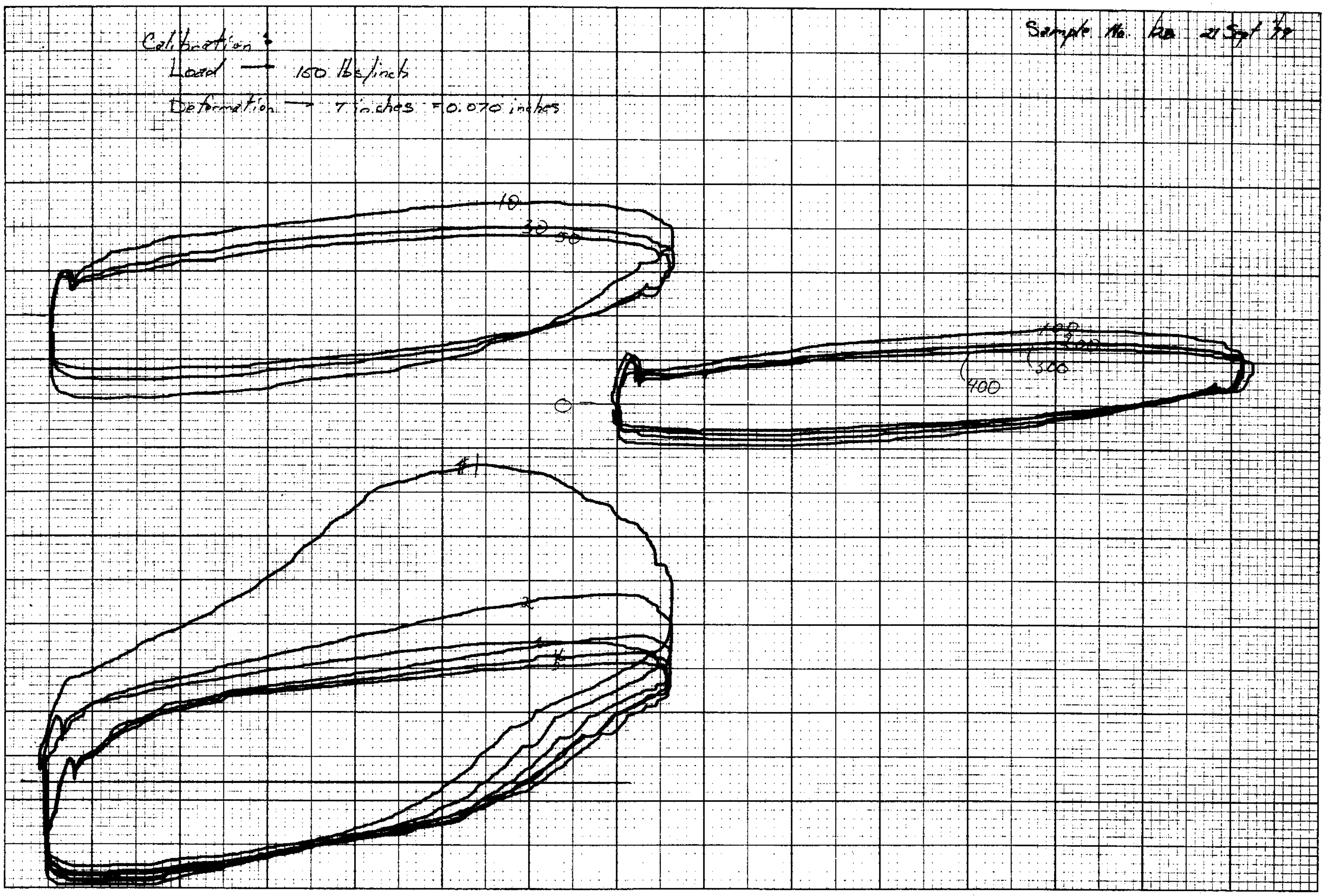



Figure 29B. Load versus Displacement for Sample 128.

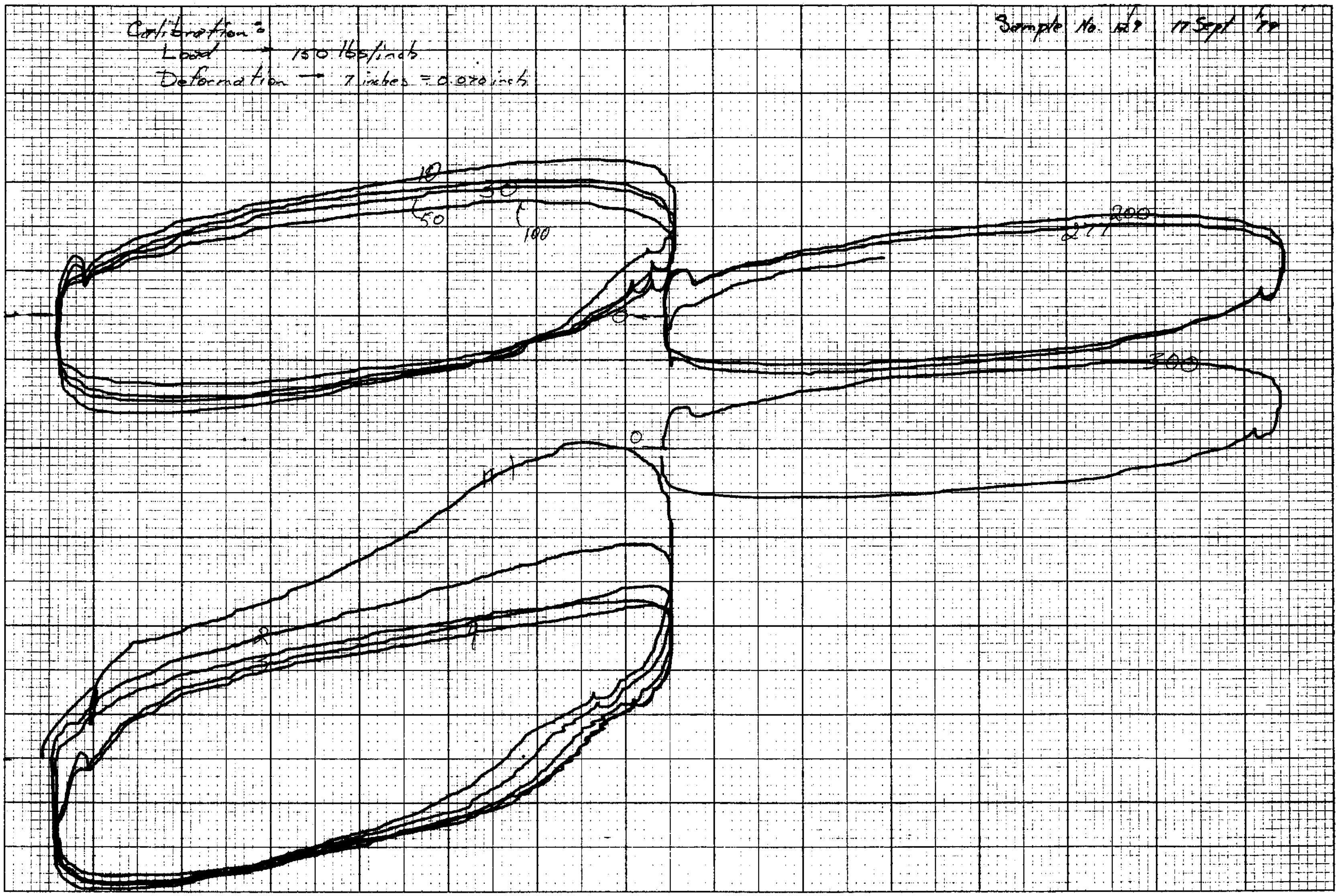



Figure 30B. Load versus Displacement for Sample 129.

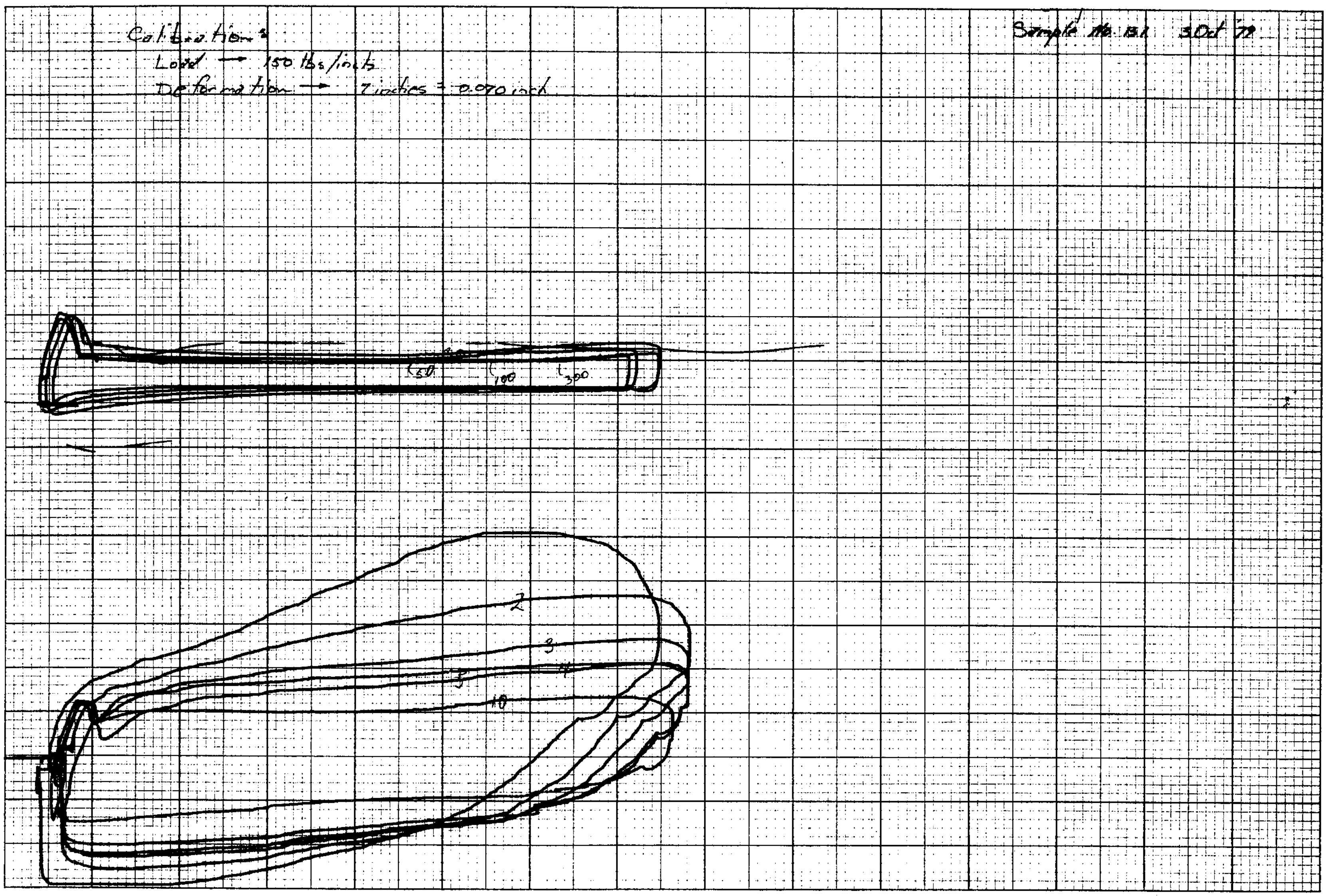



Figure 31B. Load versus Displacement for Sample 131.

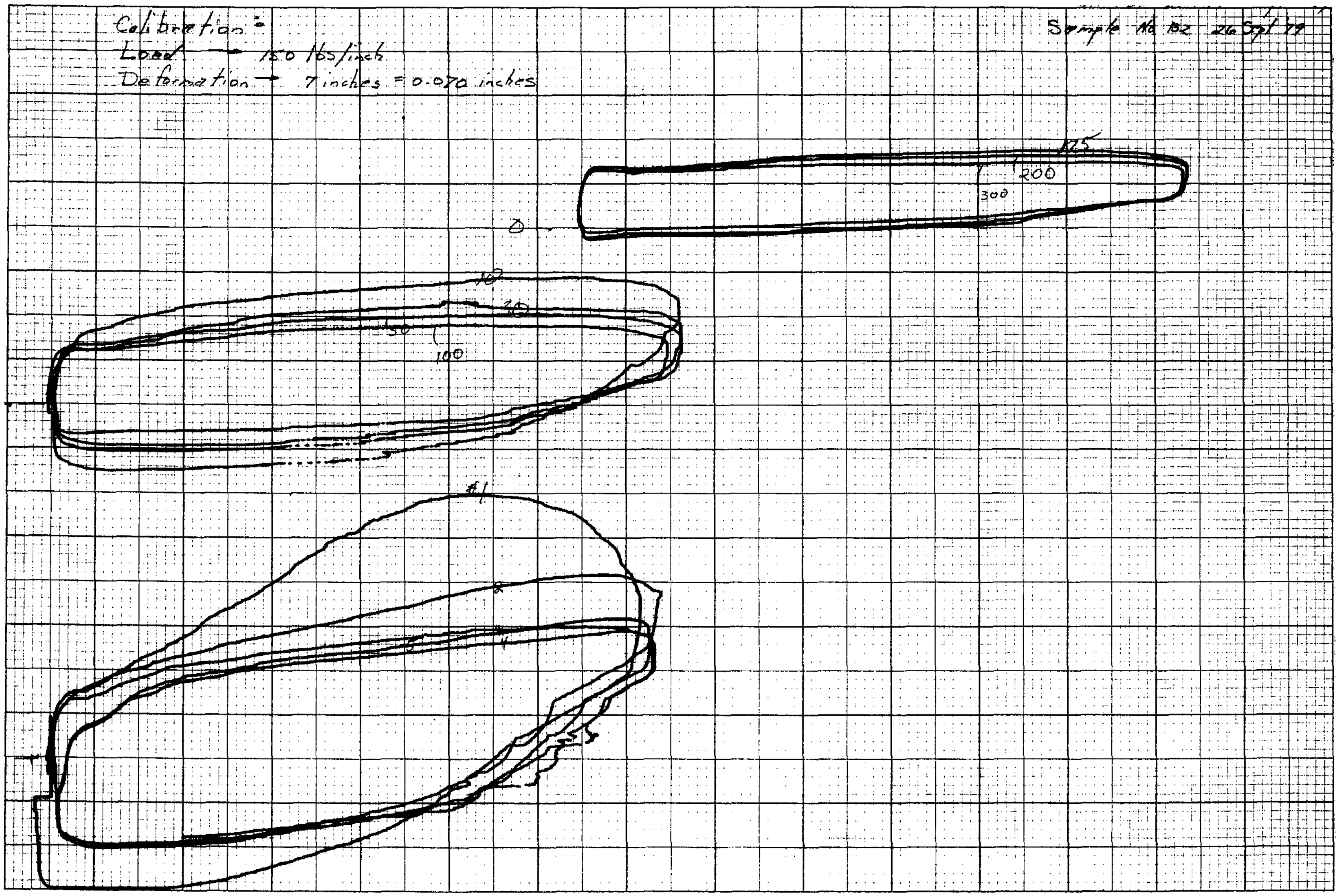



Figure 32B. Load versus Displacement for Sample 132.

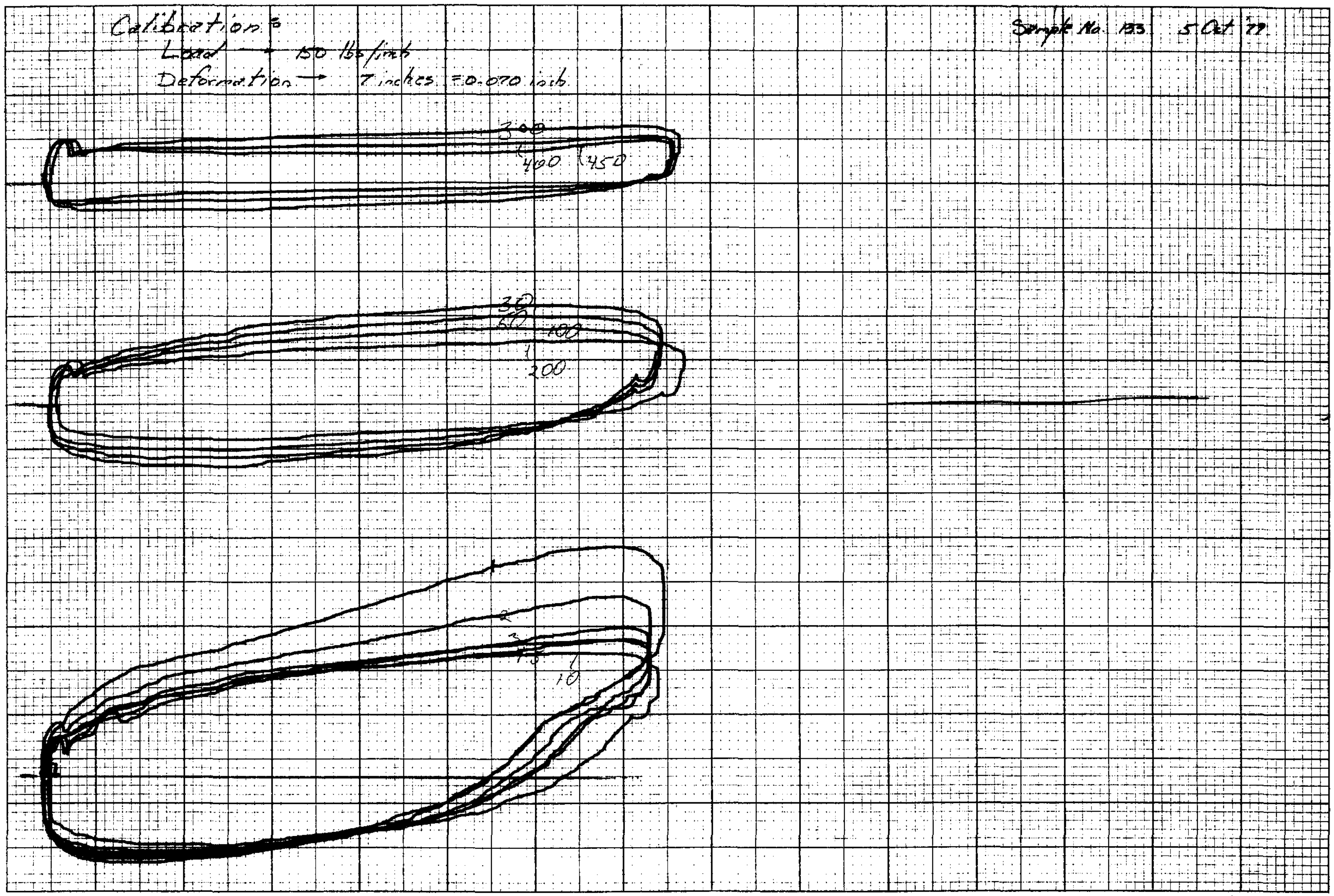



Figure 33B. Load versus Displacement for Sample 133.

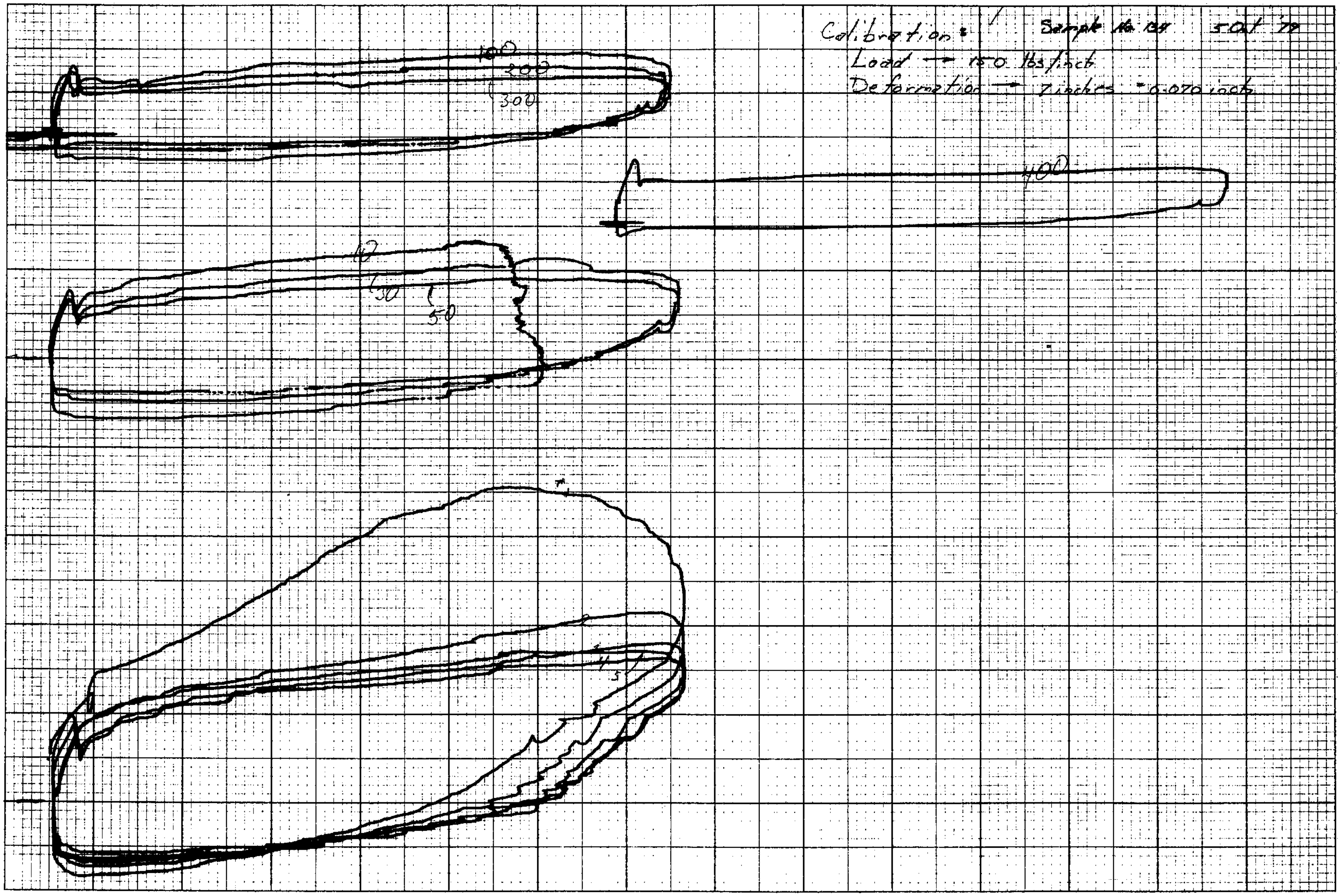



Figure 34B. Load versus Displacement for Sample 134.

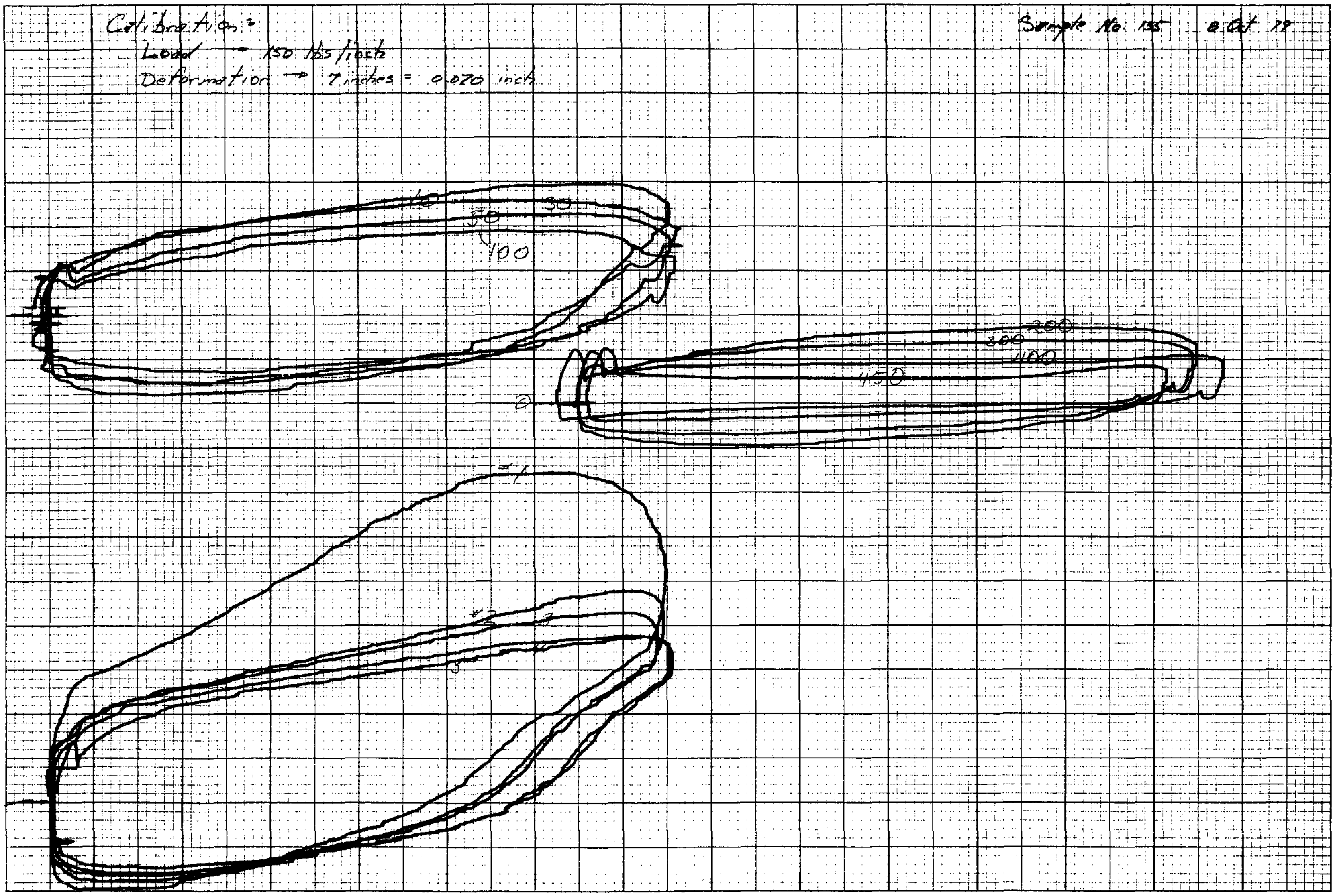



Figure 35B. Load versus Displacement for Sample 135.

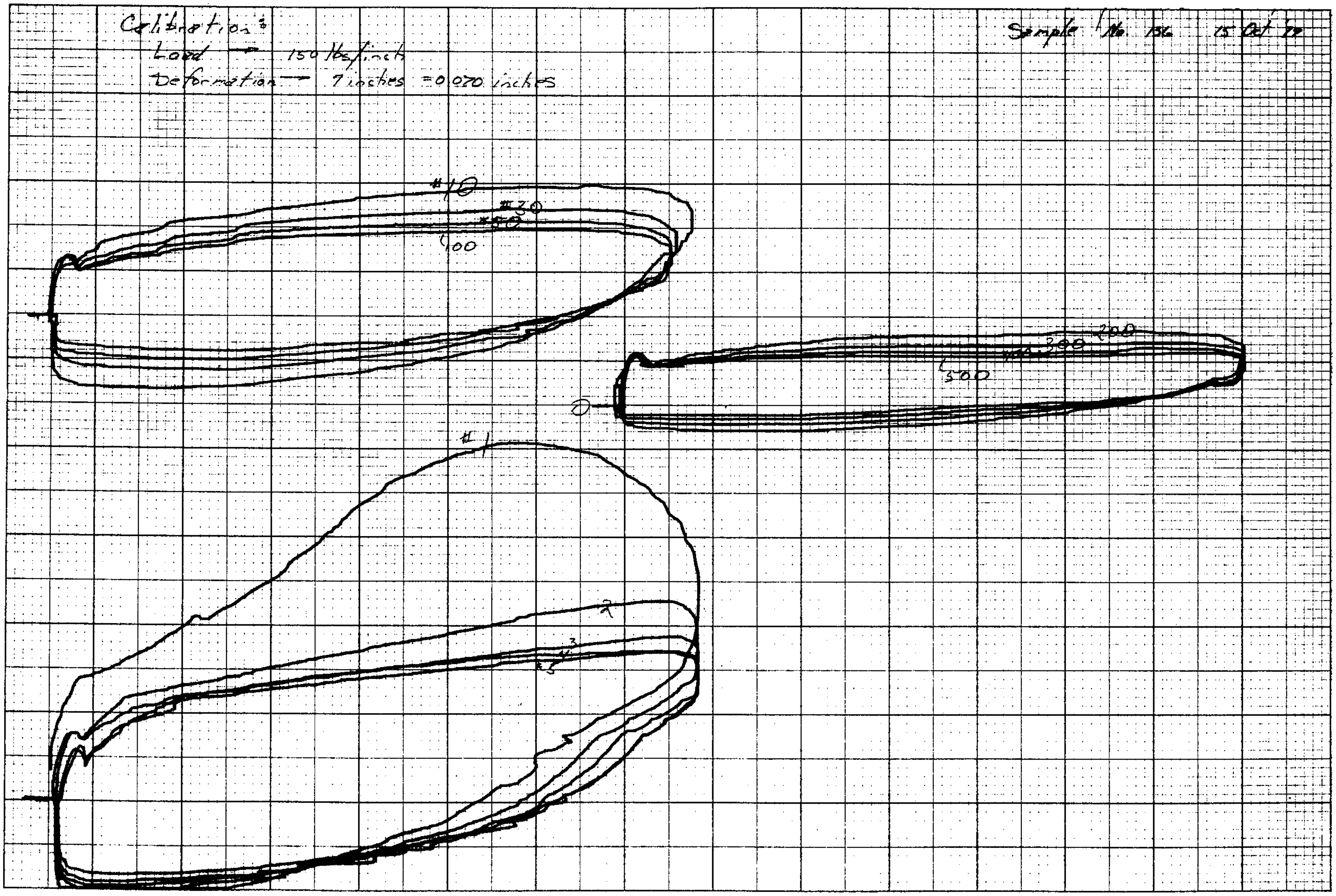



Figure 36B. Load versus Displacement for Sample 136.

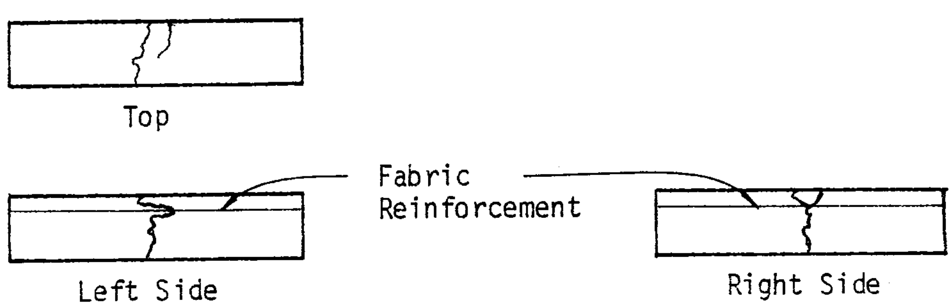
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 100 Test Date: Nov. 21, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 3 | 0.75 | 1.00 |
| 5 | 1.00 | 1.10 |
| 10 | 1.25 | 1.25 |
| 30 | 1.40 | 1.30 |
| 50 | 1.50 | 1.30 |
| 100 | 1.50 | 1.60 |
| 150 | 1.75 | 1.75 |
| 200 | 1.80 | 1.90 |
| 250 | 2.25 | 2.25 |
| 300 | 3.00 | 2.25 |
| 350 | 3.00 | 3.00 |
| 425 | 3.00 | 3.00 |
| 550 | 3.00 | 3.00 |
| 675 | 3.00 | 3.00 |

Note: "Hinge" effect developed on top of sample at cycle 400.




SAMPLE AT FAILURE

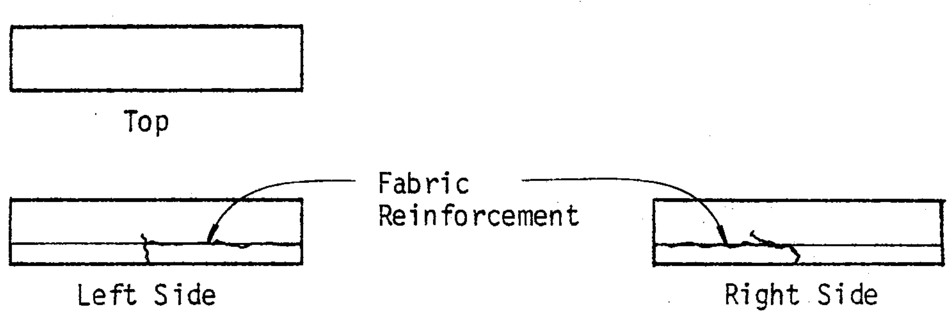
OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 101 Test Date: Nov. 12, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.75 | 0.75 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 54 | 1.00 | 1.00 |
| 100 | 1.50 | 1.00 |
| 205 | 1.50 | 1.75 |
| 300 | 1.50 | 1.75 |
| 400 | 1.50 | 1.75 |
| 500 | 1.50 | 1.75 |
| 600 | 1.50 | 1.75 |

Note: Slippage along the fabric layer was evident at cycle 30. Excessive slippage prevented the crack from penetrating the remainder of the sample.




SAMPLE AT FAILURE

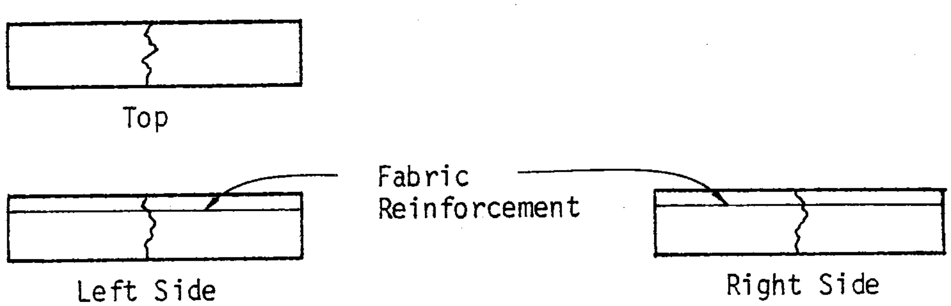
OVERLAY TEST DATA

Test Temperature: $77^{o}F$

Sample Number 102

Test Date: Oct. 16, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.10 | 0.10 |
| 5 | 0.25 | 0.25 |
| 10 | 0.90 | 0.75 |
| 30 | 1.40 | 1.50 |
| 50 | 2.25 | 2.25 |
| 100 | 2.25 | 2.25 |
| 200 | 3.00 | 3.00 |



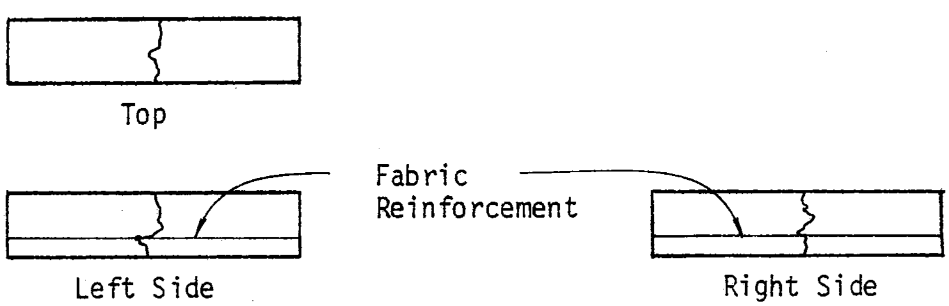

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 103 Test Date: Oct. 23, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 5 | 0.75 | 0.75 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.10 | 1.00 |
| 200 | 1.25 | 1.25 |
| 300 | 1.25 | 1.80 |
| 400 | 2.00 | 2.00 |
| 490 | 3.00 | 3.00 |



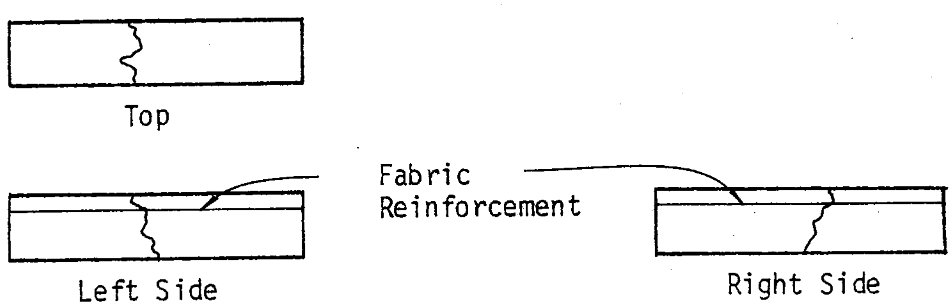

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 104 Test Date: Jan. 4, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 1.25 | 1.25 |
| 5 | 1.25 | 1.40 |
| 10 | 1.30 | 1.45 |
| 30 | 1.30 | 1.45 |
| 50 | 1.50 | 1.80 |
| 100 | 1.75 | 2.25 |
| 200 | 2.25 | 2.25 |
| 300 | 3.00 | 2.25 |
| 400 | 3.00 | 3.00 |
| 500 | 3.00 | 3.00 |




SAMPLE AT FAILURE

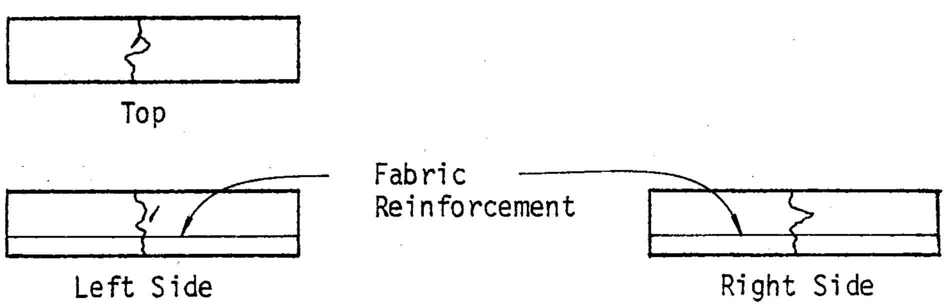
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 105 Test Date: Aug. 16, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.37 | 0.38 |
| 11 | 0.40 | 0.40 |
| 30 | 0.60 | 0.75 |
| 50 | 0.65 | 0.80 |
| 100 | 0.70 | 0.88 |
| 200 | 0.75 | 0.90 |
| 300 | 0.90 | 1.00 |
| 400 | 1.00 | 1.00 |
| 500 | 1.10 | 1.40 |
| 600 | 1.10 | 2.10 |
| 700 | 1.25 | 2.20 |
| 800 | 1.25 | 2.20 |
| 1000 | 1.25 | 2.20 |
| 1300 | 2.25 | 2.50 |
| 1400 | 2.25 | 3.00 |
| 1440 | 3.00 | 3.00 |

Note: Multiple fine cracks formed prior to failure.



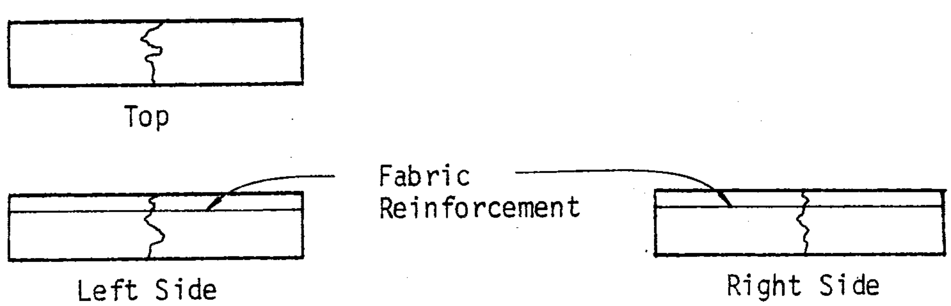

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 106 | Test Date: Feb. 6, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 1.00 | 1.00 |
| 5 | 1.50 | 1.50 |
| 10 | 2.25 | 2.25 |
| 30 | 2.25 | 2.25 |
| 50 | 2.25 | 3.00 |
| 75 | 3.00 | 3.00 |
| 100 | 3.00 | 3.00 |




SAMPLE AT FAILURE

OVERLAY TEST DATA

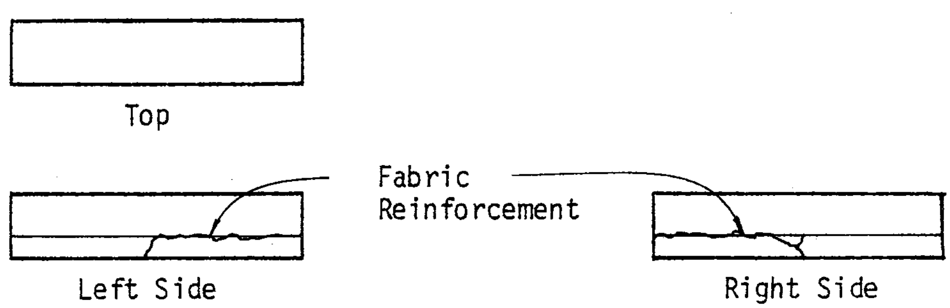
Test Temperature: 77$^{o}$F

<u>Sample Number 107</u>

Test Date: Feb 1, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 2 | 0.75 | 0.75 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.00 | 1.00 |
| 300 | 1.00 | 1.00 |

Note: Slippage along the fabric layer was evident at cycle 50. Excessive slippage prevented the crack from penetrating the remainder of the sample.



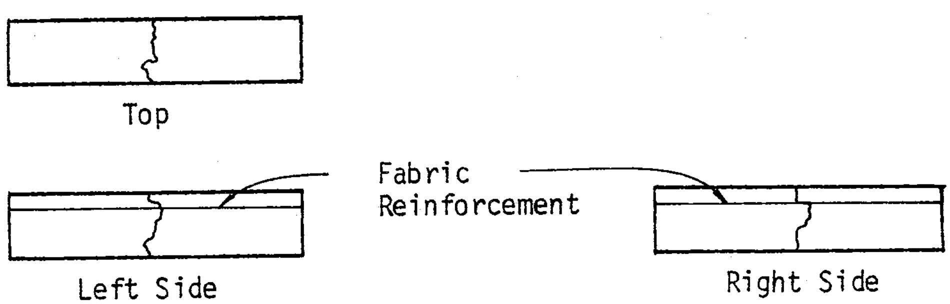

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 108 Test Date: Jan. 22, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 1.00 | 1.00 |
| 10 | 1.50 | 1.25 |
| 30 | 1.75 | 1.50 |
| 50 | 2.25 | 1.75 |
| 100 | 2.25 | 2.25 |
| 130 | 3.00 | 3.00 |
| 150 | 3.00 | 3.00 |



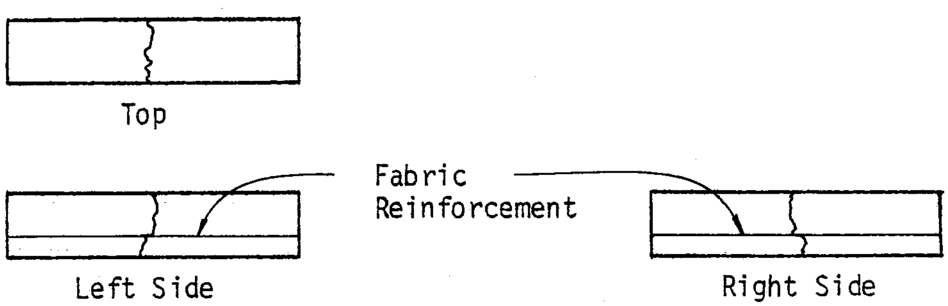

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 109 Test Date: Jan. 22, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.30 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 30 | 1.25 | 1.50 |
| 50 | 1.75 | 1.75 |
| 75 | 2.25 | 3.00 |
| 100 | 3.00 | 3.00 |



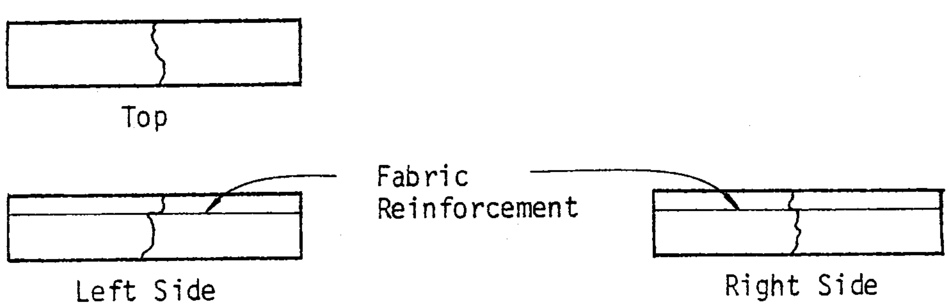

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 110 — Test Date: Jan. 10, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 0.75 |
| 5 | 1.50 | 1.25 |
| 10 | 1.75 | 1.50 |
| 30 | 1.80 | 1.80 |
| 50 | 2.00 | 2.00 |
| 100 | 2.10 | 2.25 |
| 200 | 3.00 | 3.00 |
| 300 | 3.00 | 3.00 |




SAMPLE AT FAILURE

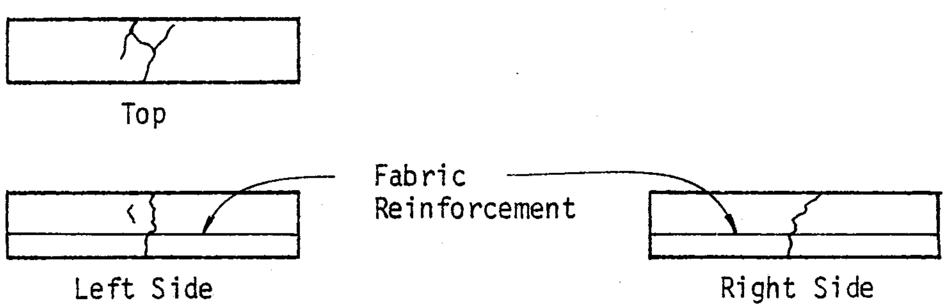
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 111 Test Date: Jul. 10, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.50 | 0.50 |
| 10 | 0.75 | 0.75 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 110 | 1.00 | 1.00 |
| 300 | 1.00 | 1.00 |
| 600 | 1.00 | 1.00 |
| 850 | 1.25 | 2.00 |
| 1100 | 2.00 | 3.00 |
| 1600 | 2.25 | 3.00 |
| 1835 | 2.25 | 3.00 |
| 2200 | 3.00 | 3.00 |

Note: Multiple cracking occurred on both the sides and top of the sample prior to failure.



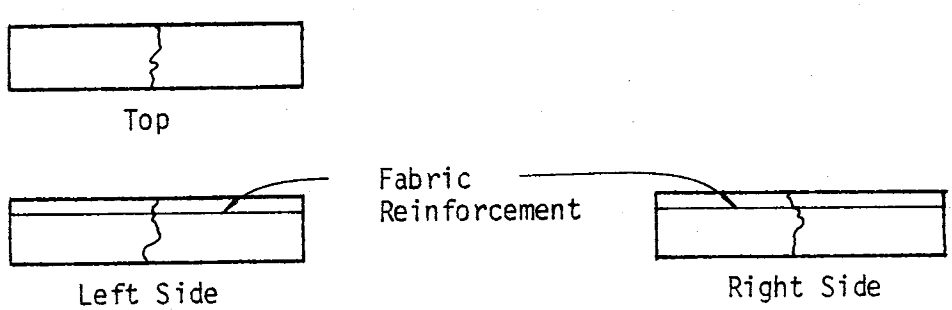

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: $77^{o}F$

Sample Number 112 | Test Date: Nov. 2, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 0.75 |
| 6 | 1.00 | 1.00 |
| 10 | 1.25 | 1.25 |
| 20 | 1.75 | 1.75 |
| 30 | 2.25 | 2.25 |
| 50 | 2.25 | 2.25 |
| 100 | 2.25 | 2.25 |
| 150 | 3.00 | 3.00 |
| 200 | 3.00 | 3.00 |
| 300 | 3.00 | 3.00 |
| 400 | 3.00 | 3.00 |




SAMPLE AT FAILURE

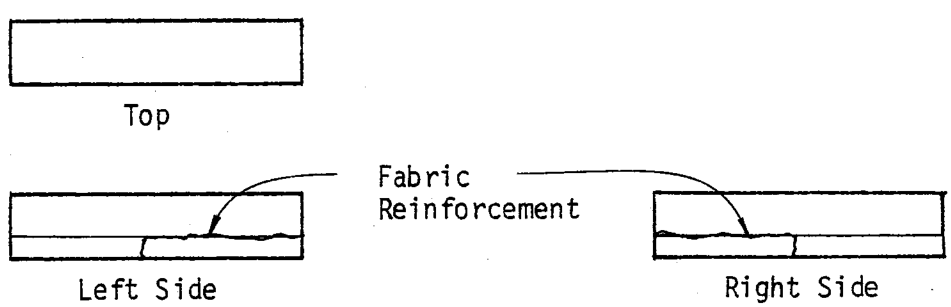
OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 113 Test Date: Jan. 3, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 1.00 | 1.00 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.00 | 1.00 |
| 300 | 1.00 | 1.00 |

Note: Crack progressed to fabric layer on the first cycle. Slippage along fabric layer then prohibited the crack from extending upward through the sample.




SAMPLE AT FAILURE

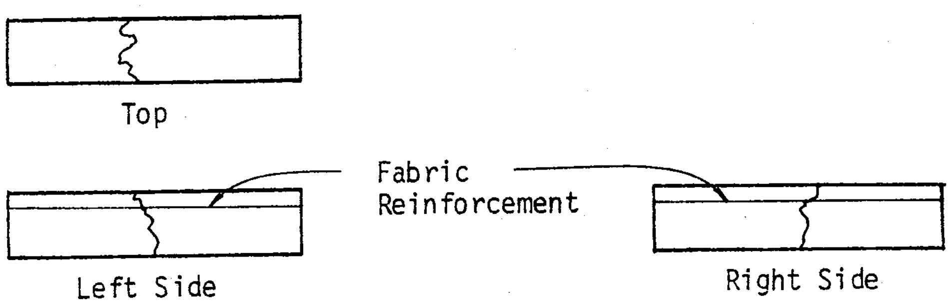
OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 114

Test Date: Sept. 7, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.15 | 0.15 |
| 5 | 1.00 | 1.25 |
| 10 | 1.25 | 1.50 |
| 30 | 1.50 | 2.00 |
| 50 | 1.75 | 2.15 |
| 100 | 2.25 | 2.25 |
| 200 | 2.40 | 2.40 |
| 250 | 2.50 | 3.00 |
| 300 | 2.50 | 3.00 |
| 450 | 2.90 | 3.00 |




SAMPLE AT FAILURE

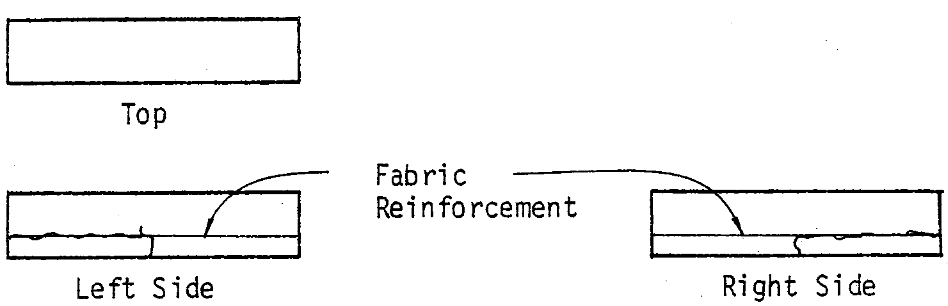
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 115 Test Date: Sept. 24, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.25 | 1.00 |
| 300 | 1.25 | 1.00 |
| 400 | 1.25 | 1.00 |
| 725 | 1.25 | 1.00 |

Note: Slippage along the fabric layer was evident at cycle 10. Excessive slippage prevented the crack from penetrating beyond the fabric.




SAMPLE AT FAILURE

OVERLAY TEST DATA

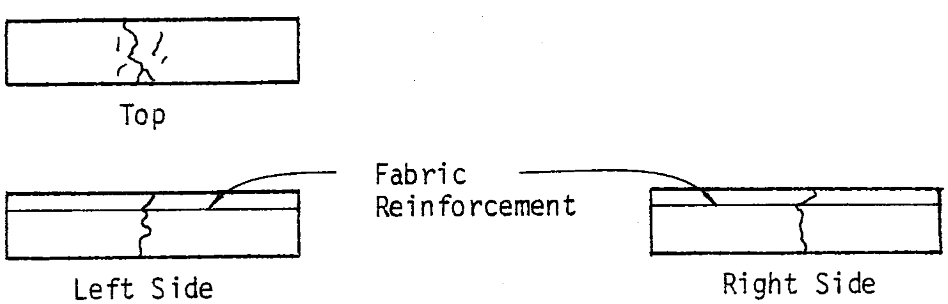
Test Temperature: 77°F

Sample Number 116

Test Date: Oct. 24, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.75 | 0.75 |
| 10 | 1.00 | 1.00 |
| 30 | 1.50 | 1.50 |
| 50 | 1.75 | 1.50 |
| 100 | 1.80 | 1.75 |
| 200 | 2.25 | 2.25 |
| 300 | 2.25 | 2.25 |
| 400 | 2.25 | 2.25 |
| 500 | 2.25 | 2.25 |
| 600 | 2.25 | 2.25 |
| 700 | 3.00 | 3.00 |

Note: Multiple fine cracks formed on the top of the sample prior to failure.




SAMPLE AT FAILURE

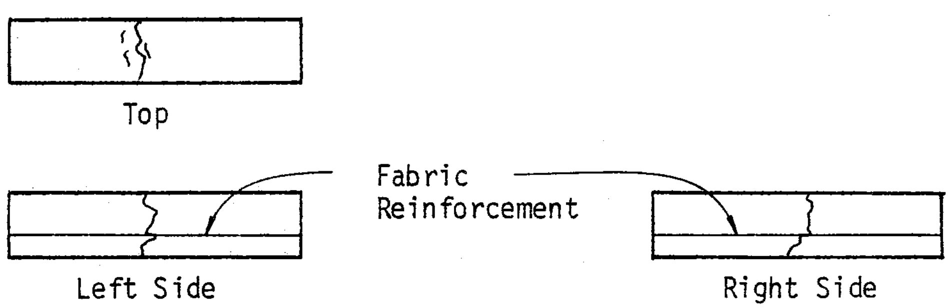
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 117 Test Date: Mar. 24, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.75 | 0.75 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.00 | 1.00 |
| 300 | 1.00 | 1.00 |
| 400 | 1.00 | 1.00 |
| 500 | 1.00 | 1.00 |
| 600 | 1.00 | 1.00 |
| 700 | 1.50 | 3.00 |
| 800 | 1.50 | 3.00 |
| 900 | 2.00 | 3.00 |
| 1000 | 2.00 | 3.00 |
| 1100 | 3.00 | 3.00 |
| 1200 | 3.00 | 3.00 |
| 1300 | 3.00 | 3.00 |
| 1400 | 3.00 | 3.00 |

Note: Some slippage occurred along fabric layer and multiple fine cracks formed prior to failure.




SAMPLE AT FAILURE

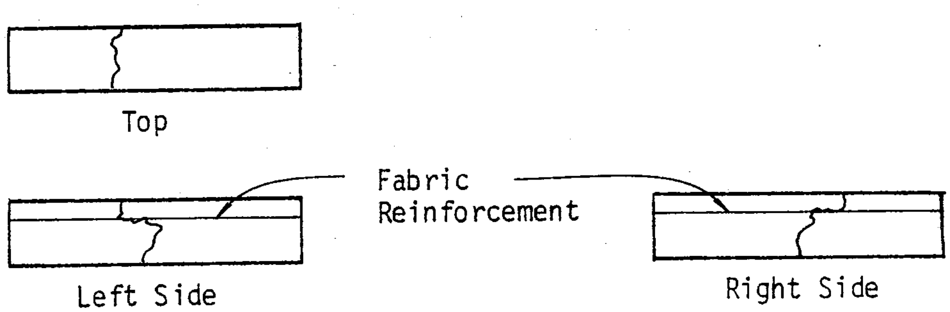
OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 118 | Test Date: Jan. 7, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.25 |
| 5 | 0.75 | 0.50 |
| 10 | 1.00 | 0.75 |
| 30 | 2.00 | 1.75 |
| 50 | 2.25 | 2.25 |
| 100 | 2.25 | 2.25 |
| 200 | 3.00 | 3.00 |

Note: A crack appeared on the top of the sample at about cycle 150. (Cracks on sides were still at the fabric layer.) The crack then progressed from the top of the sample down both sides to the fabric layer.




SAMPLE AT FAILURE

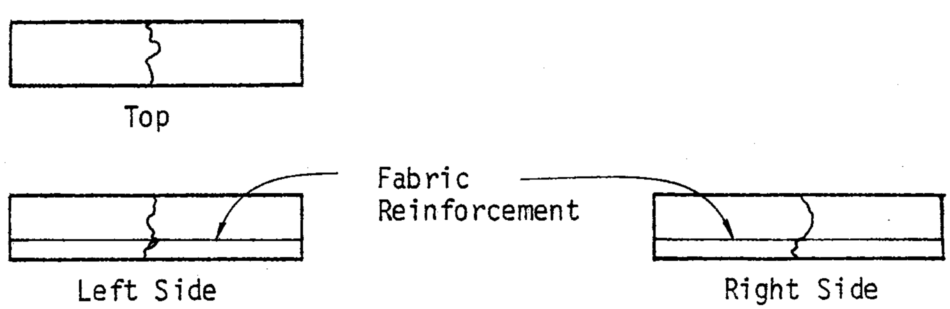
OVERLAY TEST DATA

Test Temperature: 77°F

<u>Sample Number 119</u> Test Date: Jan. 7, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 0.75 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.00 | 1.00 |
| 250 | 2.25 | 1.75 |
| 400 | 3.00 | 3.00 |

Note: Slippage along the fabric layer was evident at cycle 20. The crack progressed up the left side, across the top, then down the right side.




SAMPLE AT FAILURE

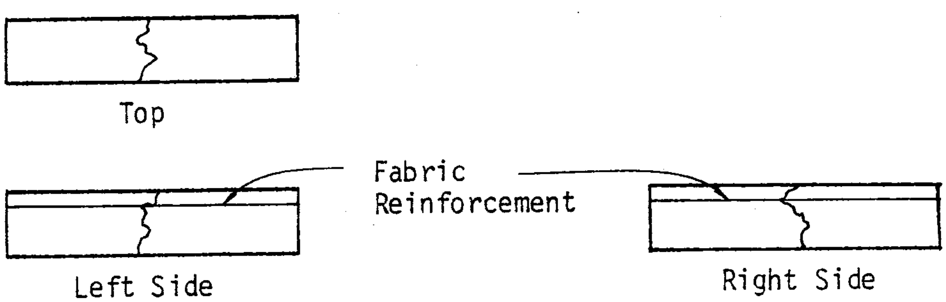
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 120

Test Date: Jan. 11, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.50 |
| 5 | 0.90 | 1.00 |
| 10 | 1.00 | 1.20 |
| 30 | 1.75 | 2.00 |
| 50 | 2.25 | 2.25 |
| 100 | 2.25 | 2.25 |
| 200 | 2.25 | 2.25 |
| 300 | 3.00 | 3.00 |




SAMPLE AT FAILURE

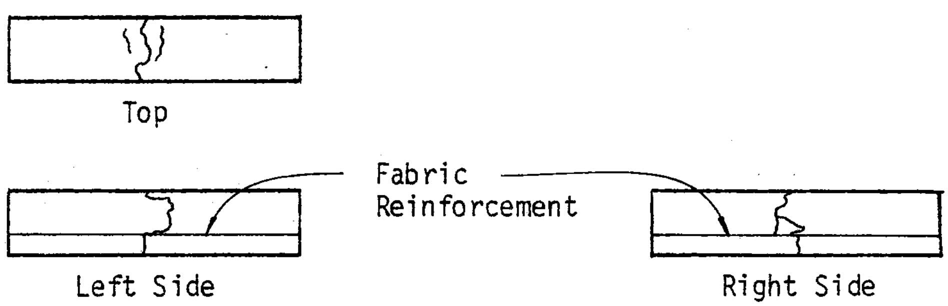
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 121 Test Date: Jan. 7 '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 5 | 0.75 | 0.75 |
| 10 | 0.90 | 1.00 |
| 30 | 0.90 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.00 | 1.00 |
| 300 | 1.00 | 1.00 |
| 400 | 1.00 | 1.00 |
| 500 | 1.00 | 1.00 |
| 600 | 1.00 | 1.00 |
| 700 | 1.00 | 1.00 |
| 800 | 1.00 | 1.00 |
| 900 | 1.50 | 1.50 |
| 1000 | 1.75 | 1.50 |
| 1300 | 3.00 | 3.00 |

Note: Some slippage occurred along fabric layer, but continued loading eventually caused failure.




SAMPLE AT FAILURE

OVERLAY TEST DATA

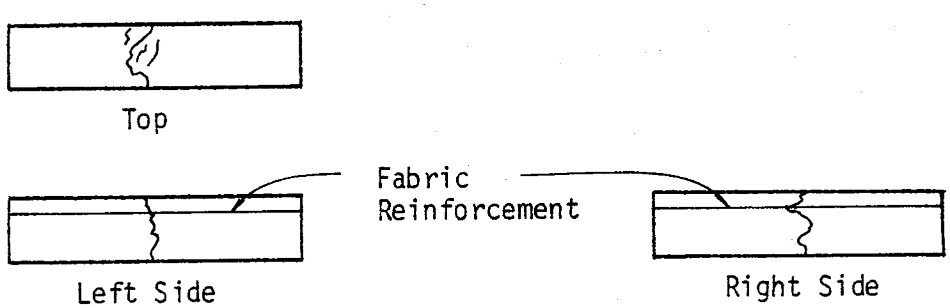
Test Temperature: 77$^{o}$F

Sample Number 122

Test Date: May 14, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 1.00 |
| 5 | 1.25 | 1.50 |
| 10 | 1.50 | 1.75 |
| 100 | 2.00 | 2.25 |
| 150 | 2.25 | 2.25 |
| 200 | 2.25 | 2.25 |
| 300 | 2.25 | 2.25 |
| 400 | 2.25 | 2.25 |
| 500 | 2.25 | 2.25 |
| 700 | 3.00 | 3.00 |
| 900 | 3.00 | 3.00 |

Note: Multiple fine cracks formed on the top of the sample prior to failure.




SAMPLE AT FAILURE

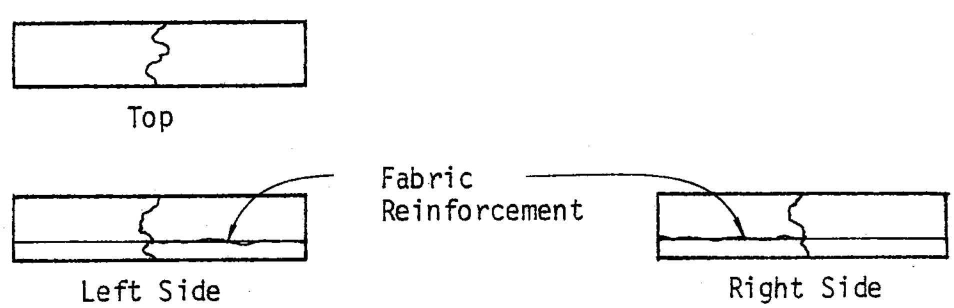
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 123 Test Date: Jan. 9, '80

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.50 | 0.50 |
| 10 | 0.75 | 0.75 |
| 30 | 0.75 | 0.75 |
| 50 | 0.80 | 0.80 |
| 100 | 0.90 | 1.00 |
| 200 | 1.00 | 1.00 |
| 300 | 1.00 | 1.10 |
| 400 | 1.10 | 1.10 |
| 500 | 1.10 | 1.10 |
| 600 | 1.10 | 1.10 |
| 700 | 1.10 | 1.10 |
| 800 | 1.10 | 1.10 |
| 900 | 1.25 | 1.20 |
| 1000 | 1.25 | 1.20 |
| 1200 | 1.25 | 1.50 |
| 1500 | 2.25 | 2.00 |
| 2000 | 3.00 | 2.90 |

Note: Some slippage occurred along the fabric layer.




SAMPLE AT FAILURE

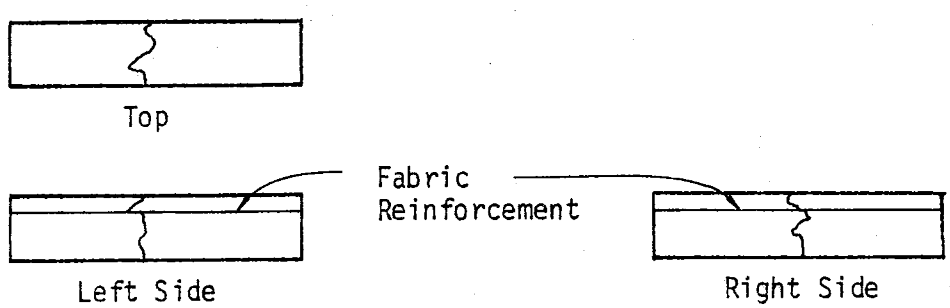
## OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 124

Test Date: Aug. 17, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 5 | 1.50 | 1.75 |
| 10 | 1.75 | 2.00 |
| 30 | 2.25 | 2.25 |
| 50 | 2.25 | 2.25 |
| 100 | 2.25 | 2.25 |
| 135 | 2.75 | 3.00 |
| 150 | 2.90 | 3.00 |
| 175 | 3.00 | 3.00 |




SAMPLE AT FAILURE

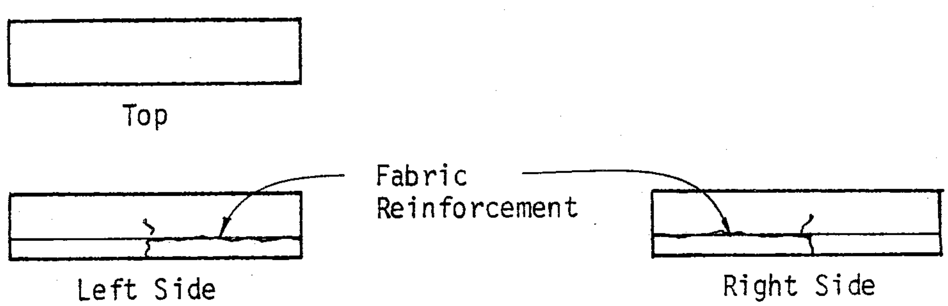
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 125      Test Date: Sept. 19, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 0.75 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.10 |
| 30 | 1.00 | 1.10 |
| 50 | 1.00 | 1.10 |
| 100 | 1.00 | 1.10 |
| 200 | 1.40 | 1.50 |
| 300 | 1.50 | 1.60 |
| 400 | 1.50 | 1.60 |
| 700 | 1.50 | 1.60 |
| 850 | 1.50 | 1.60 |
| 1000 | 1.50 | 1.60 |

Note: Excessive slippage along the fabric layer prevented the crack from completly penetrating the sample.



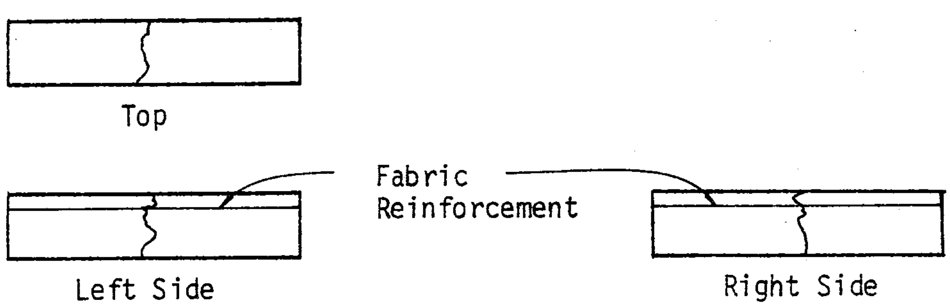

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 126 Test Date: Sept. 2, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.25 |
| 7 | 0.75 | 0.50 |
| 10 | 0.80 | 0.60 |
| 25 | 1.50 | 1.20 |
| 50 | 1.80 | 1.20 |
| 75 | 2.00 | 1.50 |
| 100 | 2.20 | 1.75 |
| 150 | 2.00 | 2.00 |
| 200 | 2.00 | 2.00 |
| 300 | 2.50 | 2.50 |
| 400 | 3.00 | 2.50 |
| 475 | 3.00 | 3.00 |




SAMPLE AT FAILURE

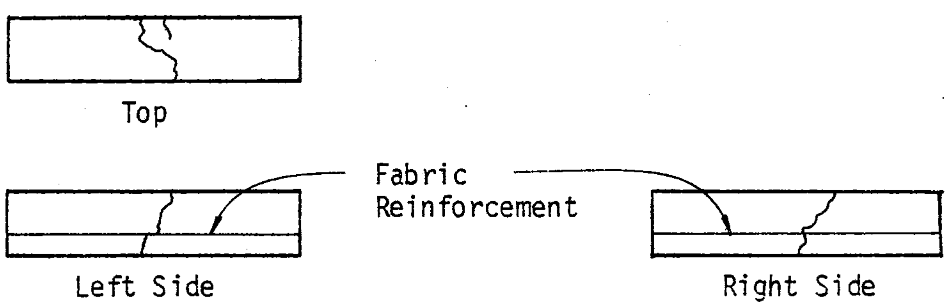
OVERLAY TEST DATA

Test Temperature: 77$^{o}$F

Sample Number 127 Test Date: Sept. 12, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 0.75 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.10 |
| 50 | 1.00 | 1.10 |
| 100 | 1.00 | 1.10 |
| 200 | 1.10 | 1.10 |
| 300 | 1.87 | 1.20 |
| 400 | 2.20 | 1.20 |
| 500 | 2.25 | 1.20 |
| 600 | 3.00 | 1.20 |
| 675 | 3.00 | 3.00 |

Note: A "hinge" effect developed, but continued cycling resulted in failure.




SAMPLE AT FAILURE

OVERLAY TEST DATA

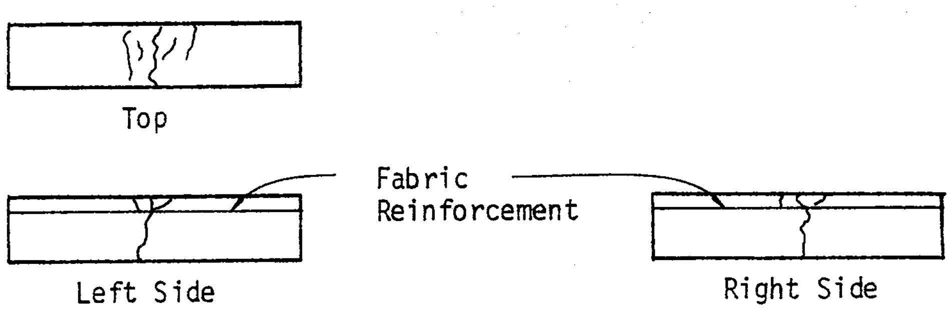
Test Temperature: 77°F

Sample Number 128

Test Date: Sept. 21, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 6 | 0.90 | 0.90 |
| 10 | 1.25 | 1.25 |
| 30 | 1.50 | 1.50 |
| 50 | 1.75 | 1.90 |
| 100 | 1.90 | 2.00 |
| 200 | 2.00 | 2.20 |
| 300 | 2.25 | 2.25 |
| 400 | 2.25 | 2.25 |
| 500 | 3.00 | 3.00 |
| 600 | 3.00 | 3.00 |

Note: Multiple fine cracks formed on both the sides and top of the sample prior to failure.



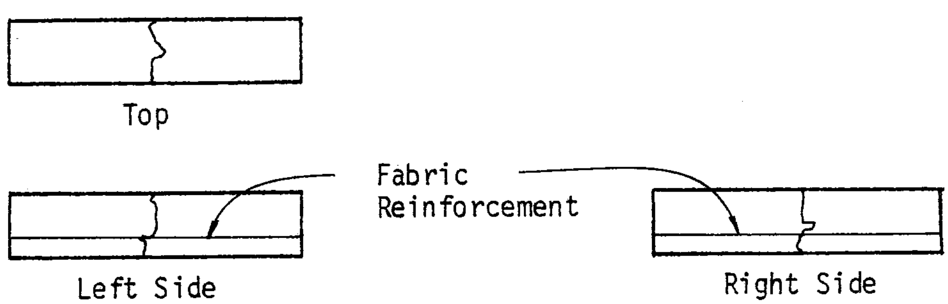

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 129 Test Date: Sept. 17, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.15 | 0.15 |
| 5 | 0.50 | 0.50 |
| 10 | 0.75 | 0.90 |
| 30 | 0.90 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |
| 200 | 1.10 | 1.10 |
| 277 | 3.00 | 3.00 |
| 300 | 3.00 | 3.00 |




SAMPLE AT FAILURE

OVERLAY TEST DATA

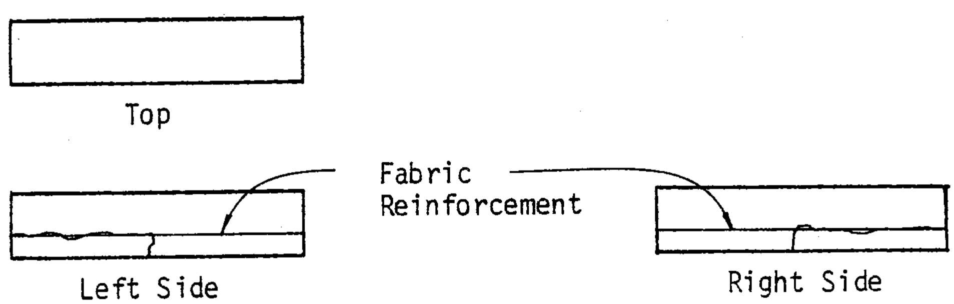
Test Temperature: 77$^{O}$F

Sample Number 131

Test Date: Oct. 3, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 2 | 0.50 | 0.50 |
| 5 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.00 |
| 50 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 |

Note: Complete slippage at fabric layer prevented the crack from penetrating the remainder of the sample.




SAMPLE AT FAILURE

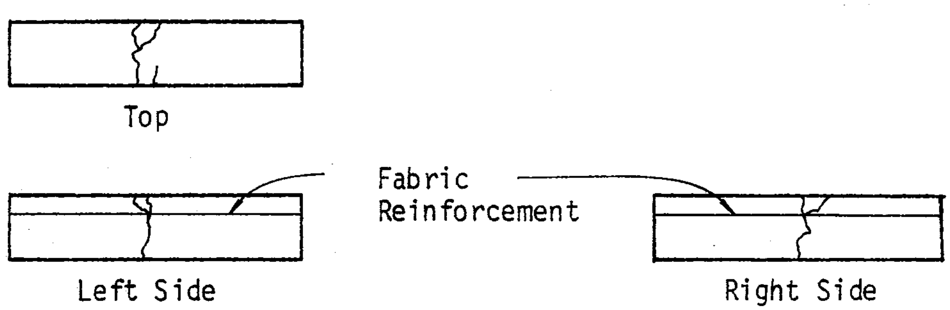
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 132 Test Date: Sept. 26, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 5 | 1.00 | 0.75 |
| 10 | 1.50 | 1.00 |
| 30 | 1.50 | 1.25 |
| 50 | 1.75 | 1.75 |
| 100 | 2.25 | 2.00 |
| 175 | 3.00 | 2.50 |
| 200 | 3.00 | 3.00 |
| 300 | 3.00 | 3.00 |
| 400 | 3.00 | 3.00 |
| 450 | 3.00 | 3.00 |

Note: Multiple fine cracks formed on both the sides and top of the sample prior to failure.



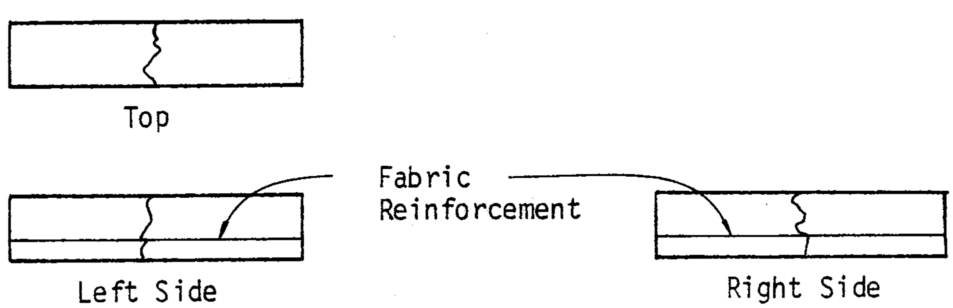

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 133 Test Date: Oct. 5, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 5 | 0.90 | 0.90 |
| 10 | 1.00 | 1.00 |
| 30 | 1.00 | 1.10 |
| 50 | 1.00 | 1.10 |
| 100 | 1.00 | 1.50 |
| 200 | 1.00 | 1.90 |
| 300 | 1.50 | 2.50 |
| 400 | 3.00 | 3.00 |
| 450 | 3.00 | 3.00 |




SAMPLE AT FAILURE

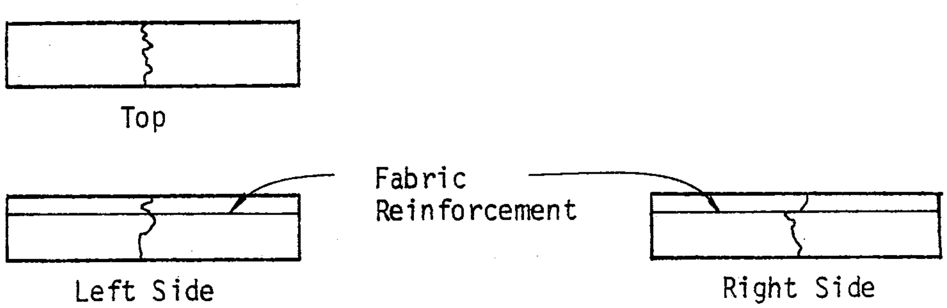
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 134

Test Date: Oct. 5, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.75 | 0.75 |
| 5 | 1.00 | 1.00 |
| 10 | 1.25 | 1.10 |
| 30 | 1.75 | 1.50 |
| 50 | 2.00 | 2.25 |
| 100 | 2.25 | 2.25 |
| 200 | 2.50 | 2.50 |
| 300 | 2.50 | 3.00 |
| 400 | 2.75 | 3.00 |
| 450 | 3.00 | 3.00 |




SAMPLE AT FAILURE

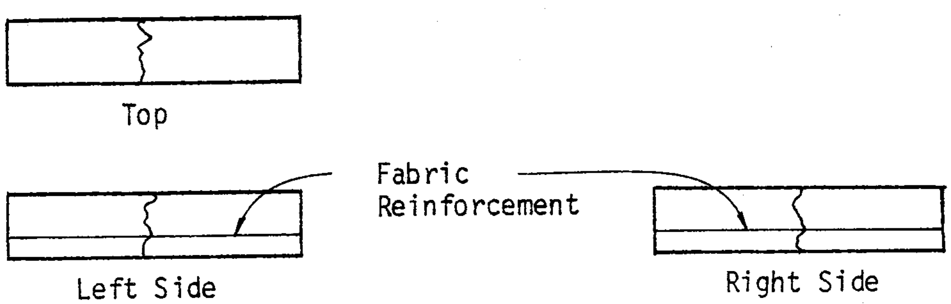
OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 135

Test Date: Oct. 8, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.25 | 0.25 |
| 5 | 0.50 | 0.50 |
| 10 | 0.70 | 0.70 |
| 30 | 0.75 | 0.75 |
| 50 | 0.80 | 0.90 |
| 100 | 1.00 | 1.00 |
| 200 | 2.00 | 2.00 |
| 300 | 2.25 | 2.50 |
| 400 | 3.00 | 3.00 |
| 450 | 3.00 | 3.00 |



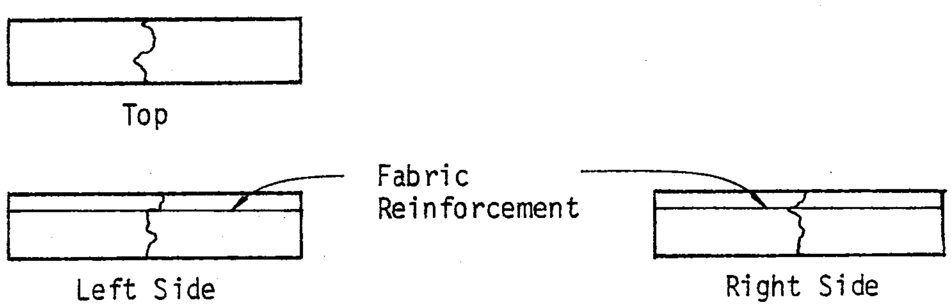

SAMPLE AT FAILURE

OVERLAY TEST DATA

Test Temperature: 77°F

Sample Number 136 — Test Date: Oct. 15, '79

| Cycle Number | Left Crack Length | Right Crack Length |
|---|---|---|
| 1 | 0.50 | 0.50 |
| 5 | 0.75 | 1.00 |
| 10 | 0.75 | 1.10 |
| 30 | 1.50 | 1.75 |
| 50 | 1.70 | 1.75 |
| 100 | 2.00 | 1.90 |
| 200 | 2.25 | 2.25 |
| 300 | 2.25 | 2.90 |
| 400 | 2.25 | 3.00 |
| 500 | 3.00 | 3.00 |




SAMPLE AT FAILURE

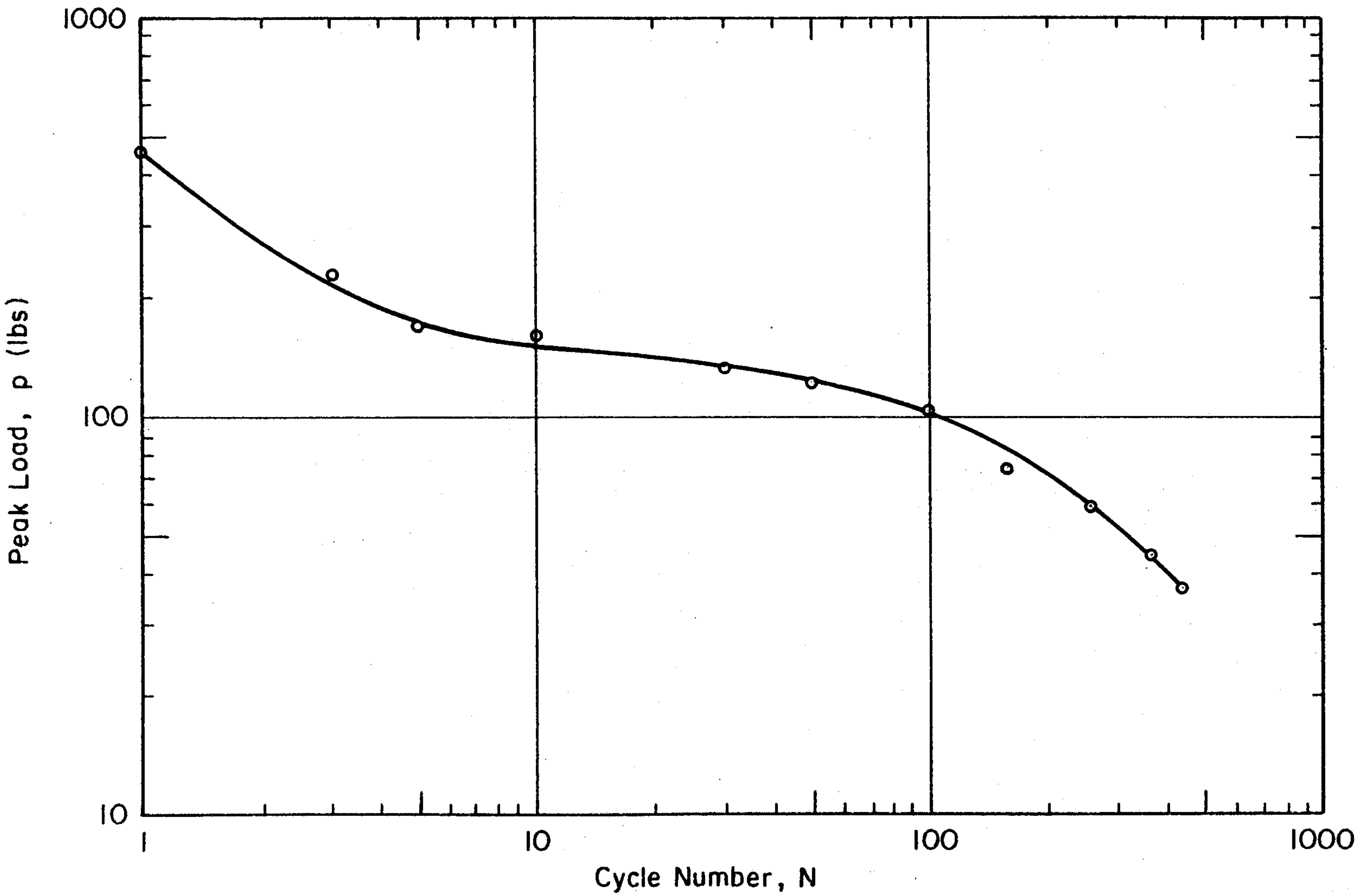



FIGURE 37B. Peak Load versus Cycle Number for Sample 100

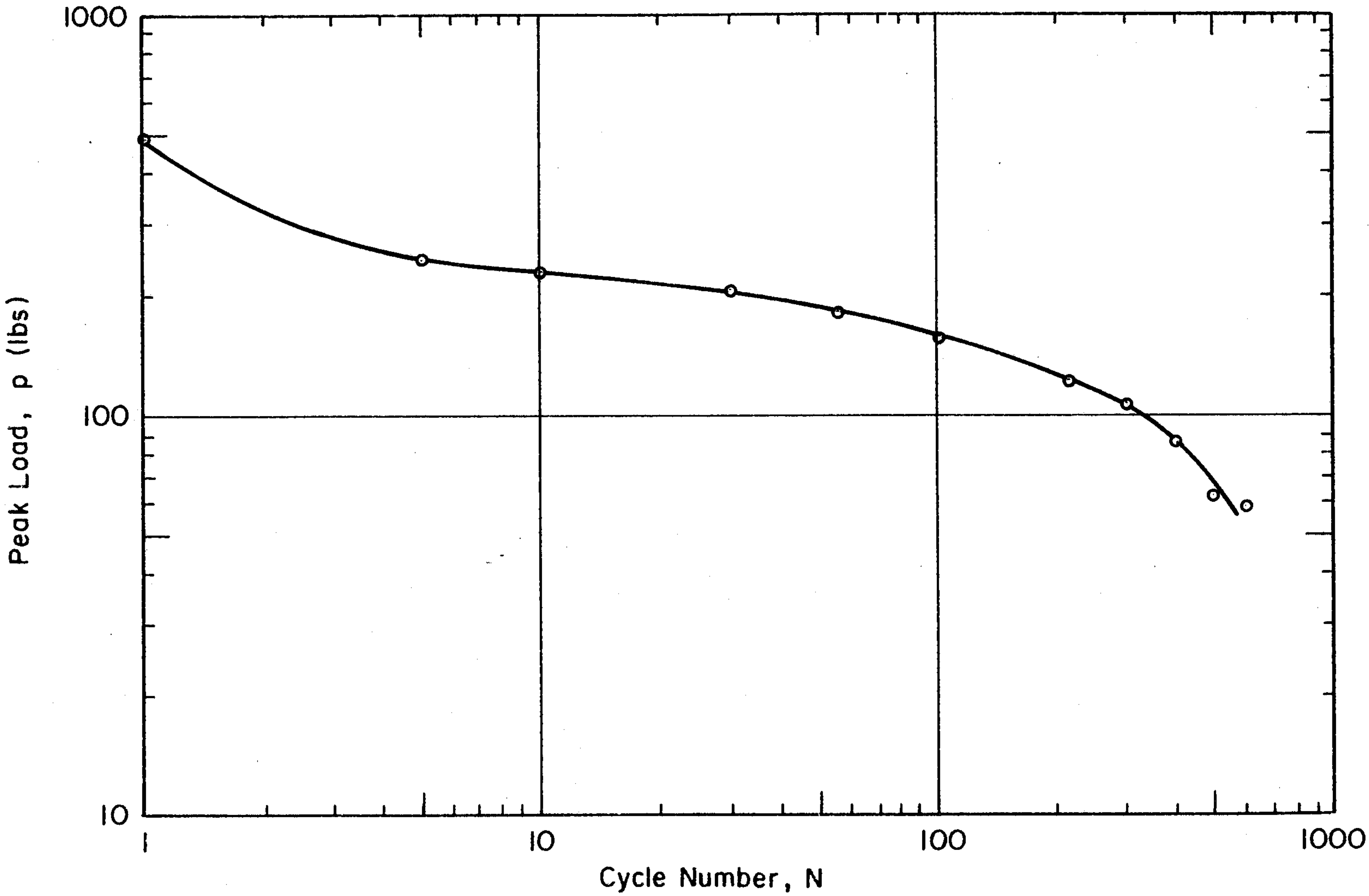



FIGURE 38B. Peak Load versus Cycle Number for Sample 101

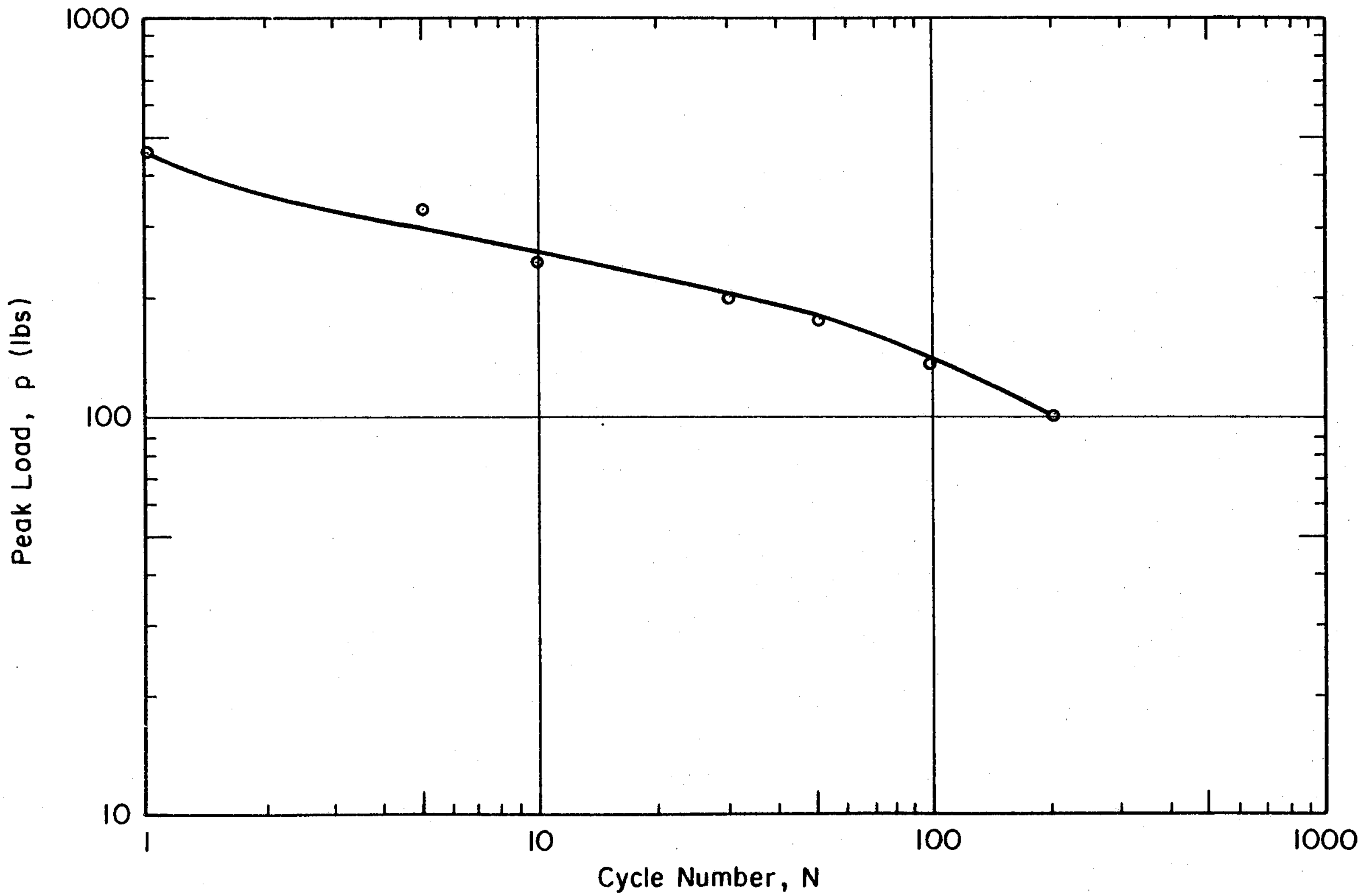



FIGURE 39B. Peak Load versus Cycle Number for Sample 102

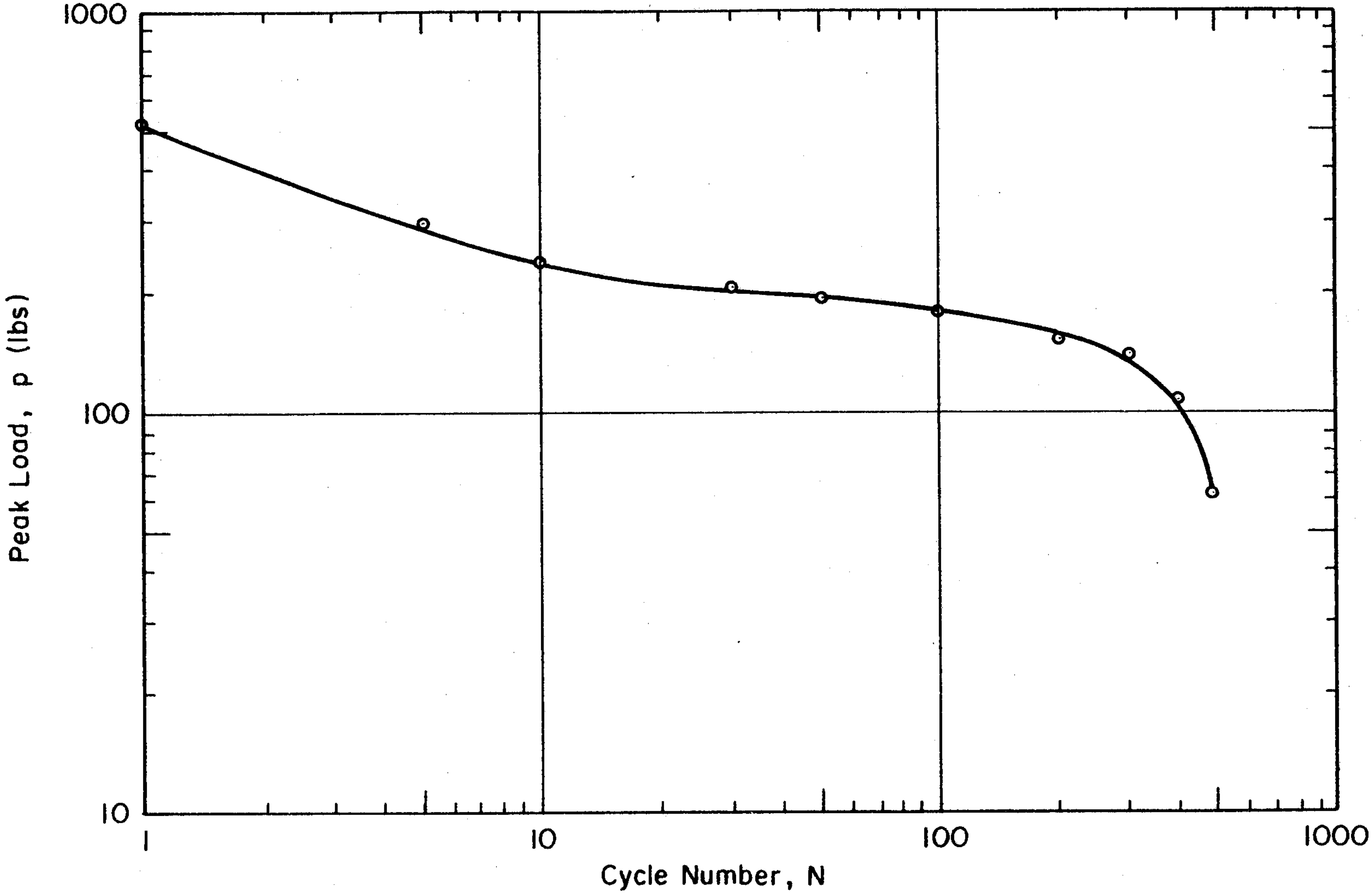



FIGURE 40B. Peak Load versus Cycle Number for Sample 103

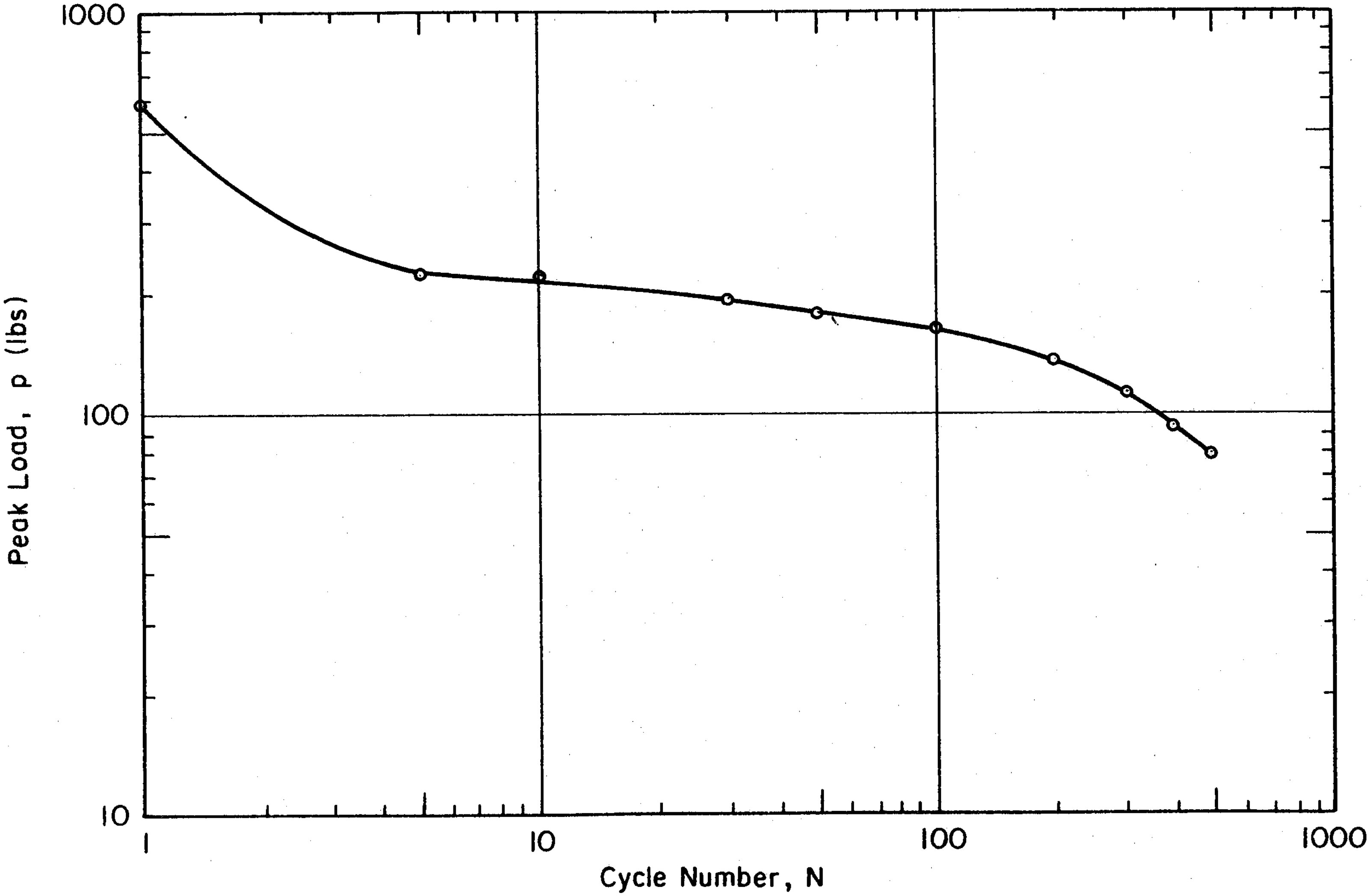



FIGURE 41B. Peak Load versus Cycle Number for Sample 104

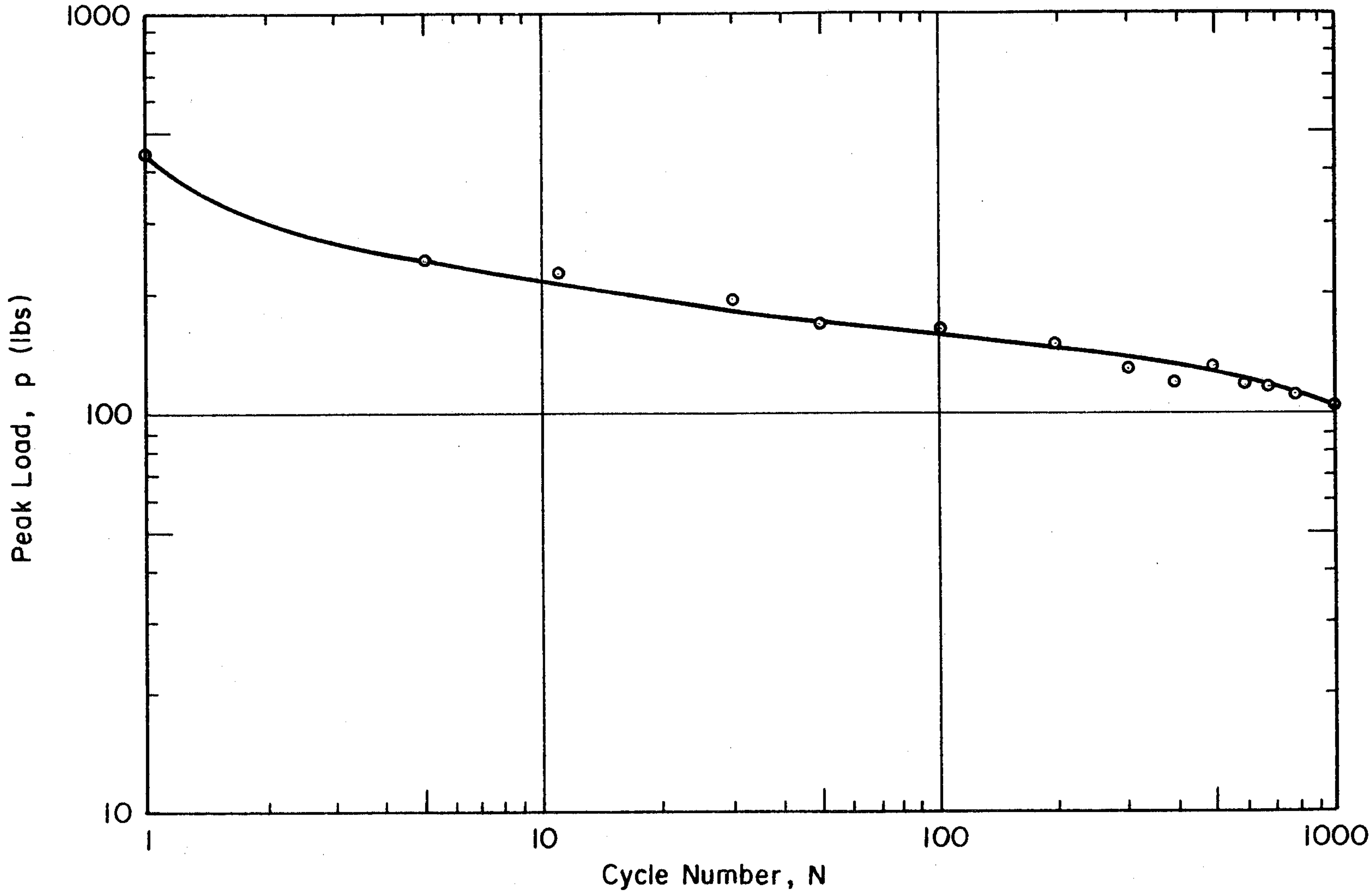



FIGURE 42B. Peak Load versus Cycle Number for Sample 105

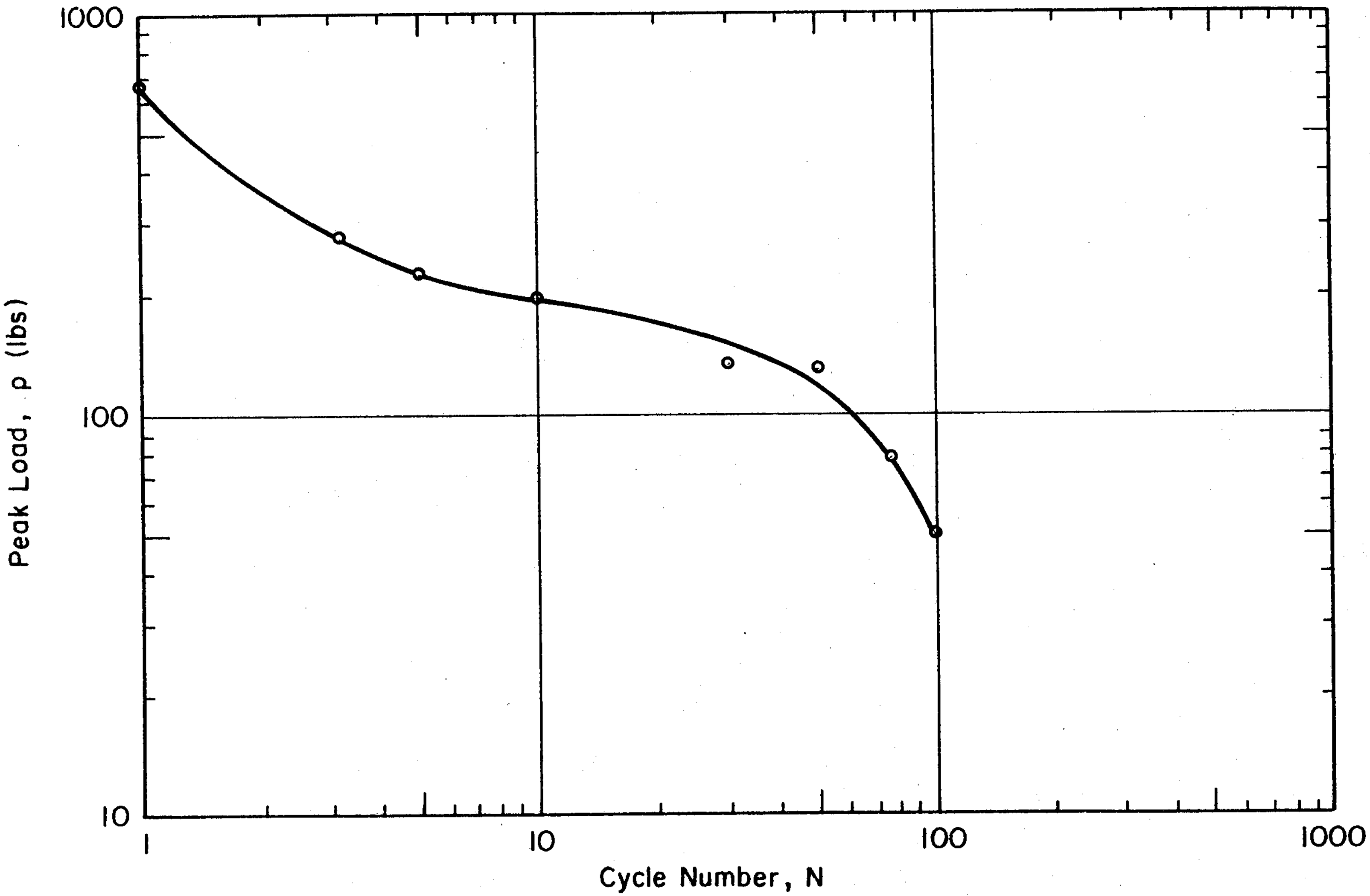



FIGURE 43B. Peak Load versus Cycle Number for Sample 106

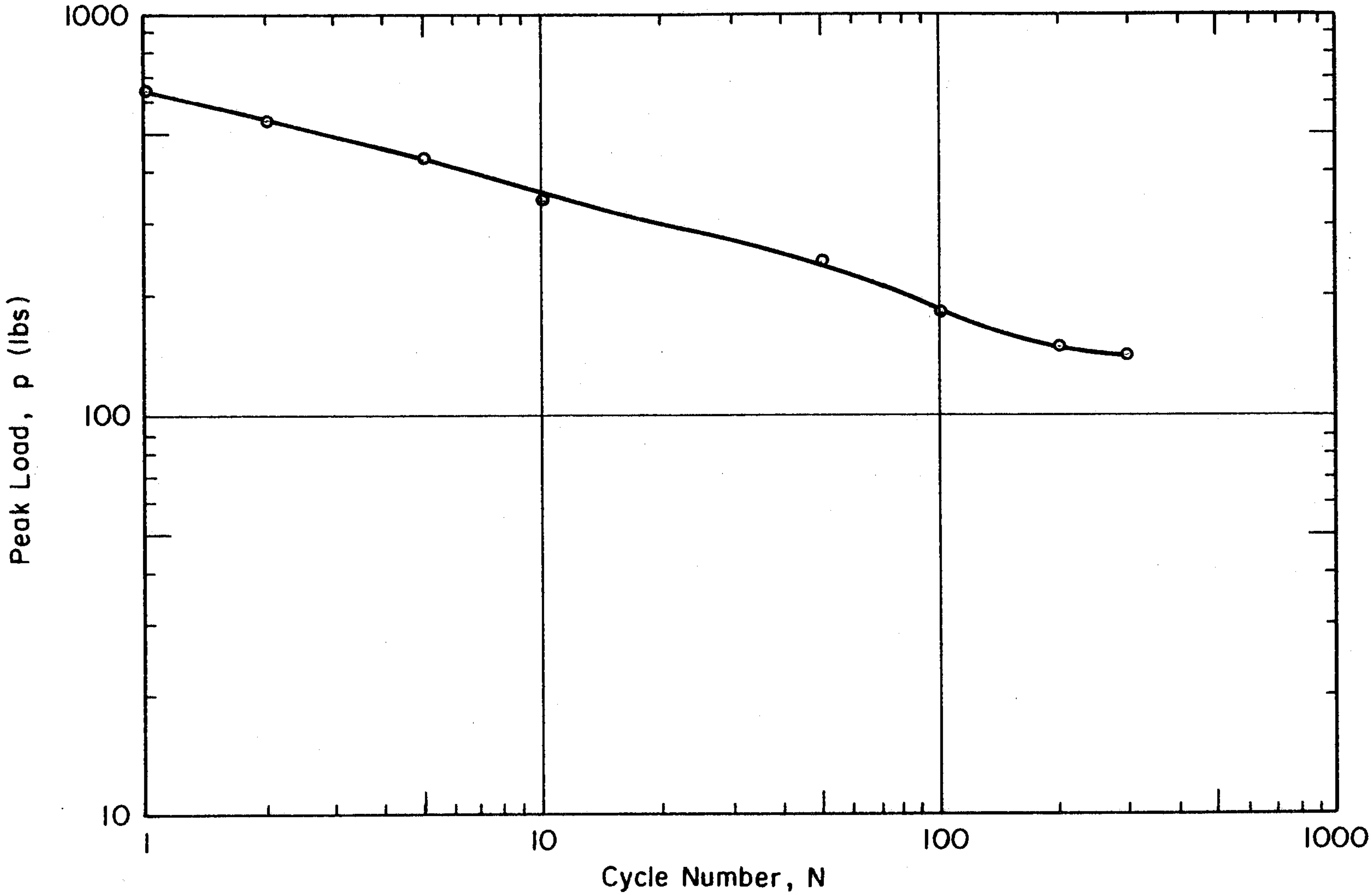



FIGURE 44B. Peak Load versus Cycle Number for Sample 107

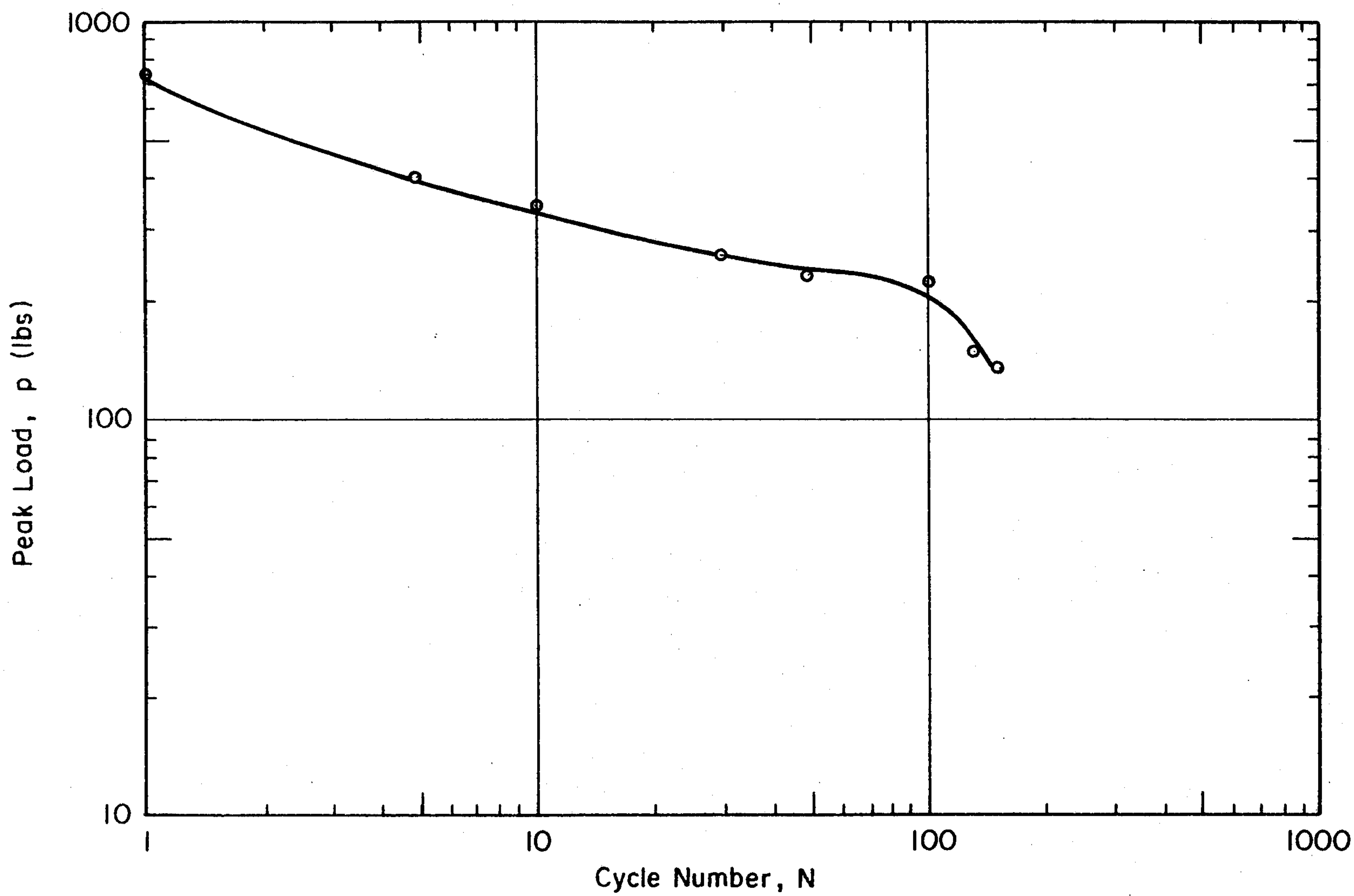



FIGURE 45B. Peak Load versus Cycle Number for Sample 108

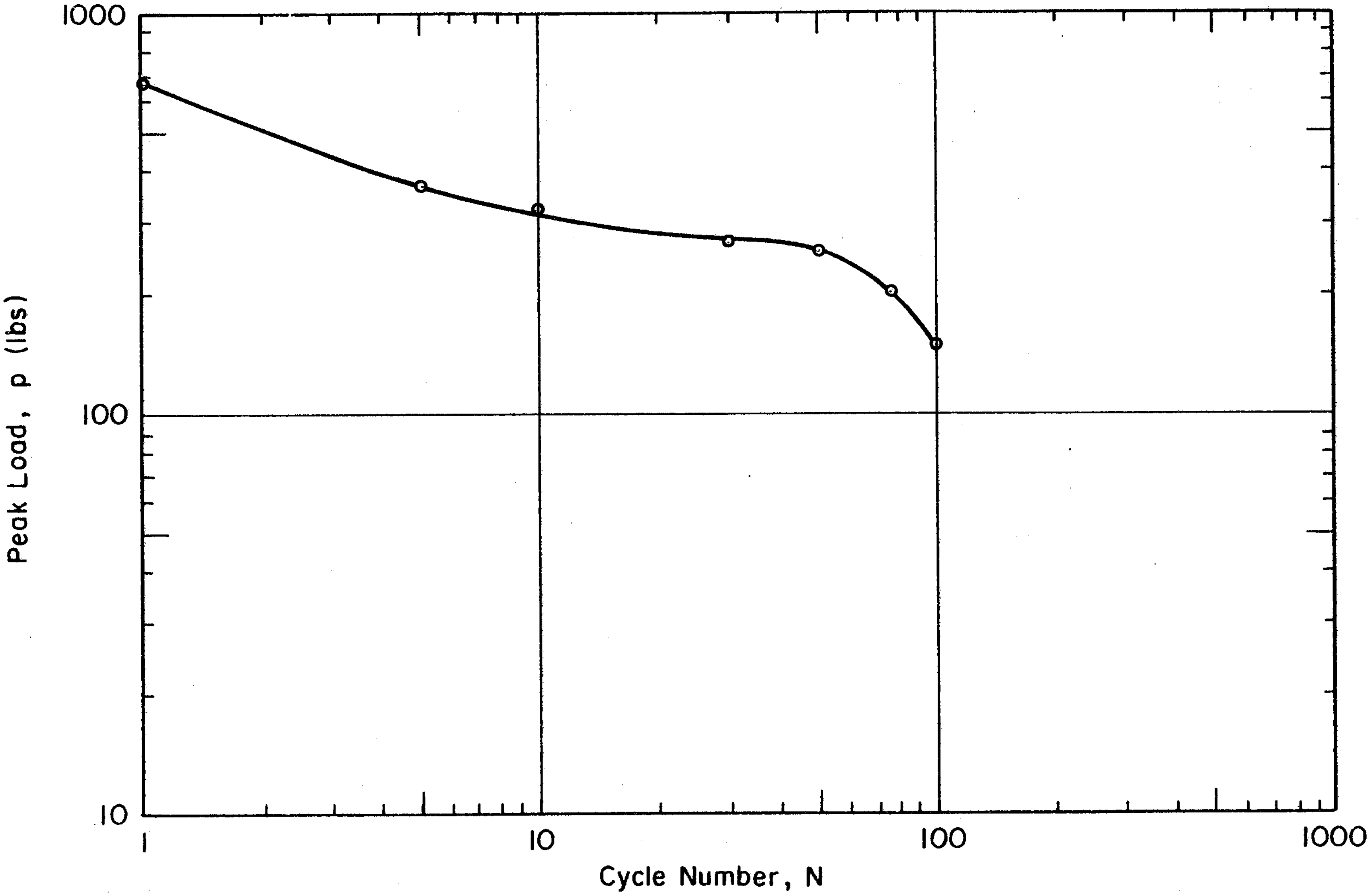



FIGURE 46B. Peak Load versus Cycle Number for Sample 109

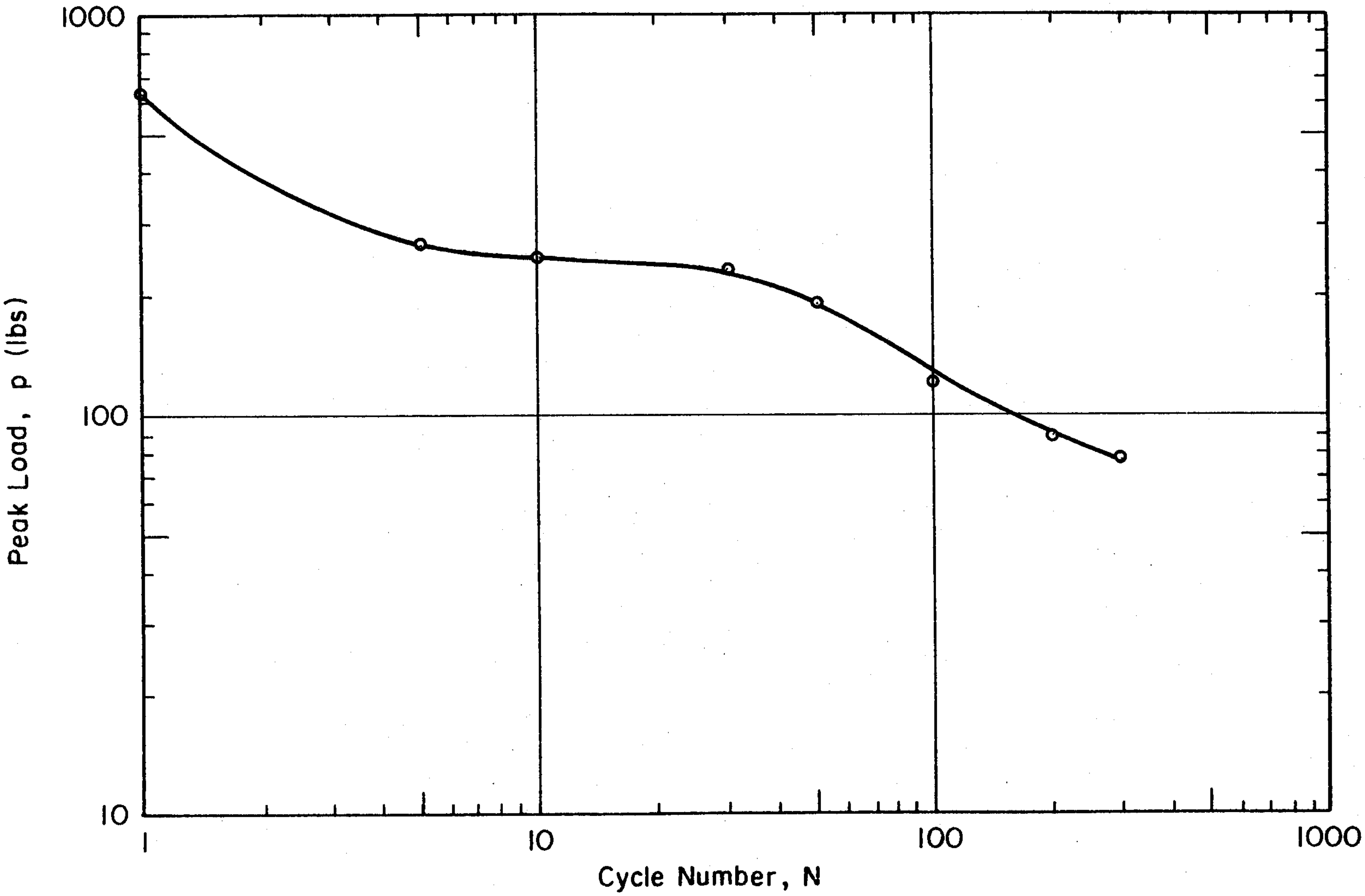



FIGURE 47B. Peak Load versus Cycle Number for Sample 110

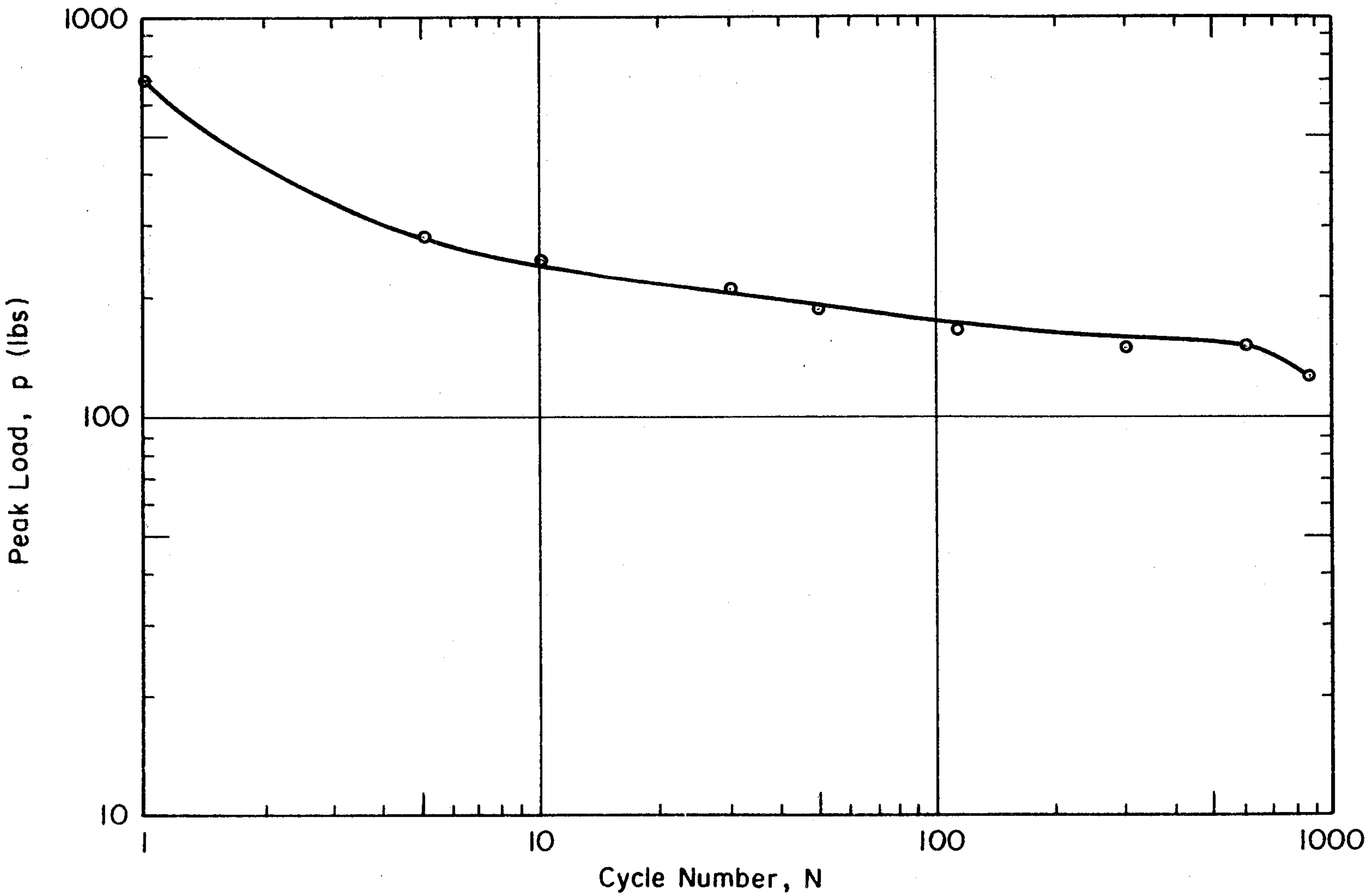



FIGURE 48B. Peak Load versus Cycle Number for Sample 111

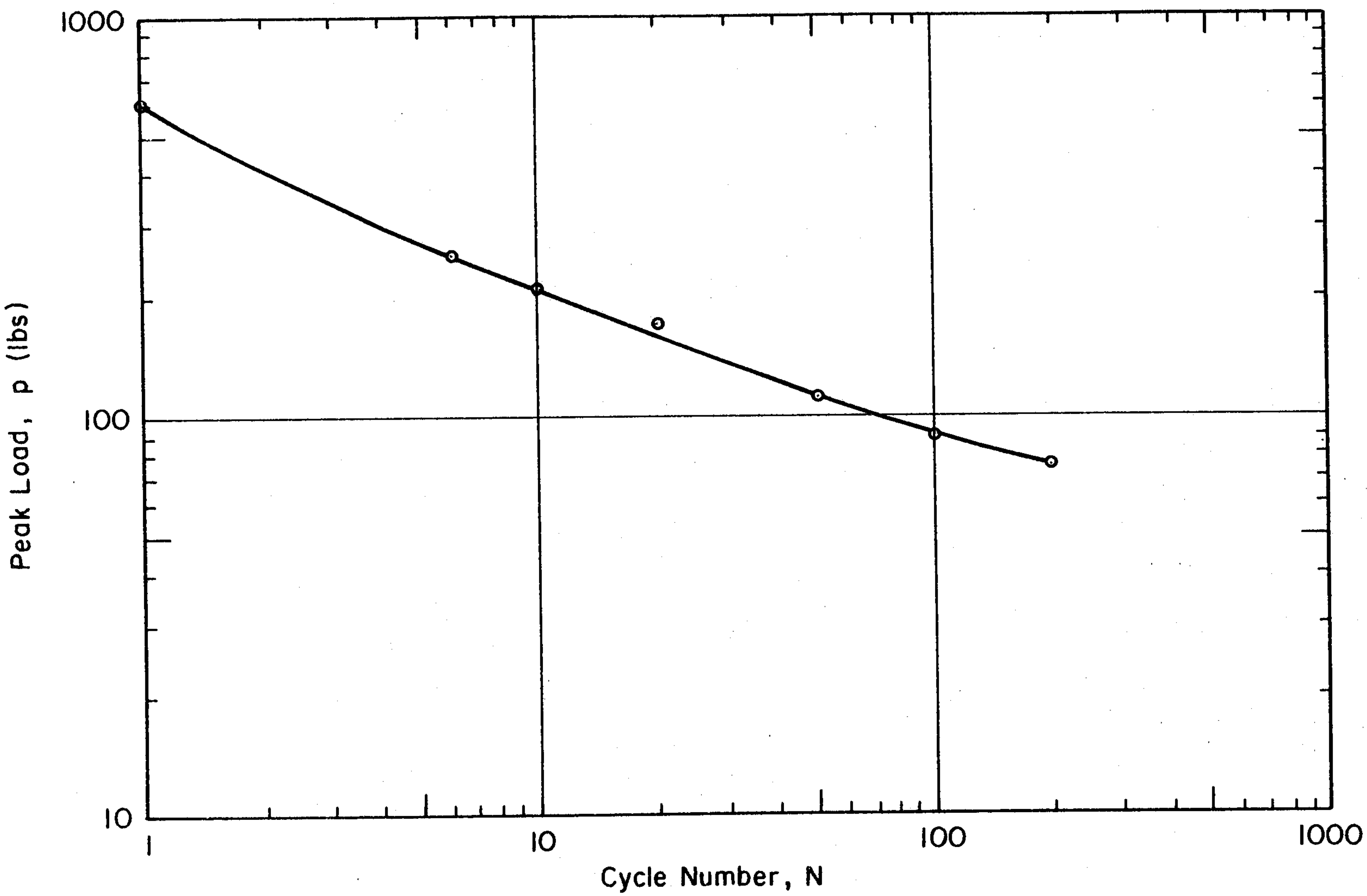



FIGURE 49B. Peak Load versus Cycle Number for Sample 112

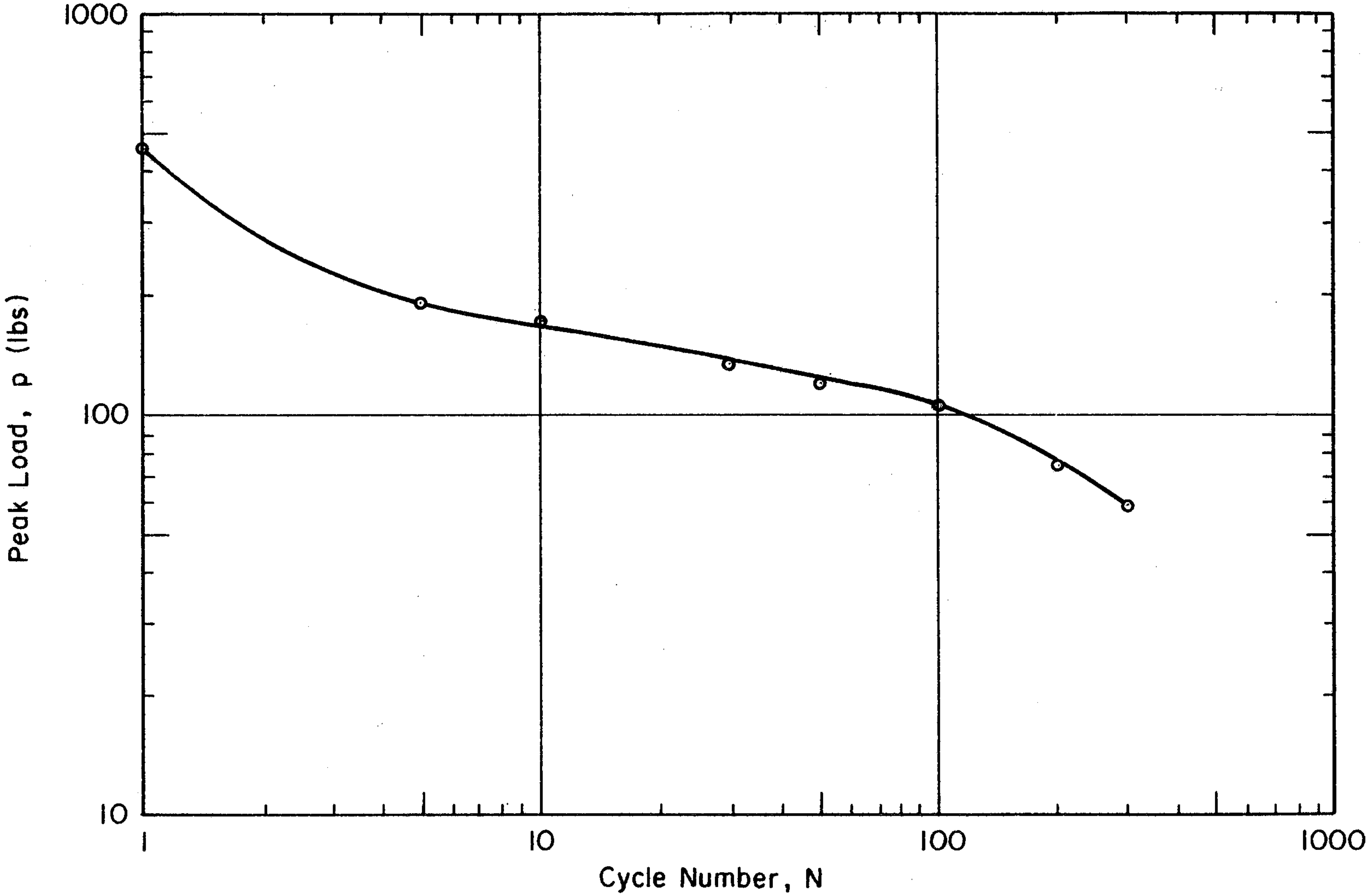



FIGURE 50B. Peak Load versus Cycle Number for Sample 113

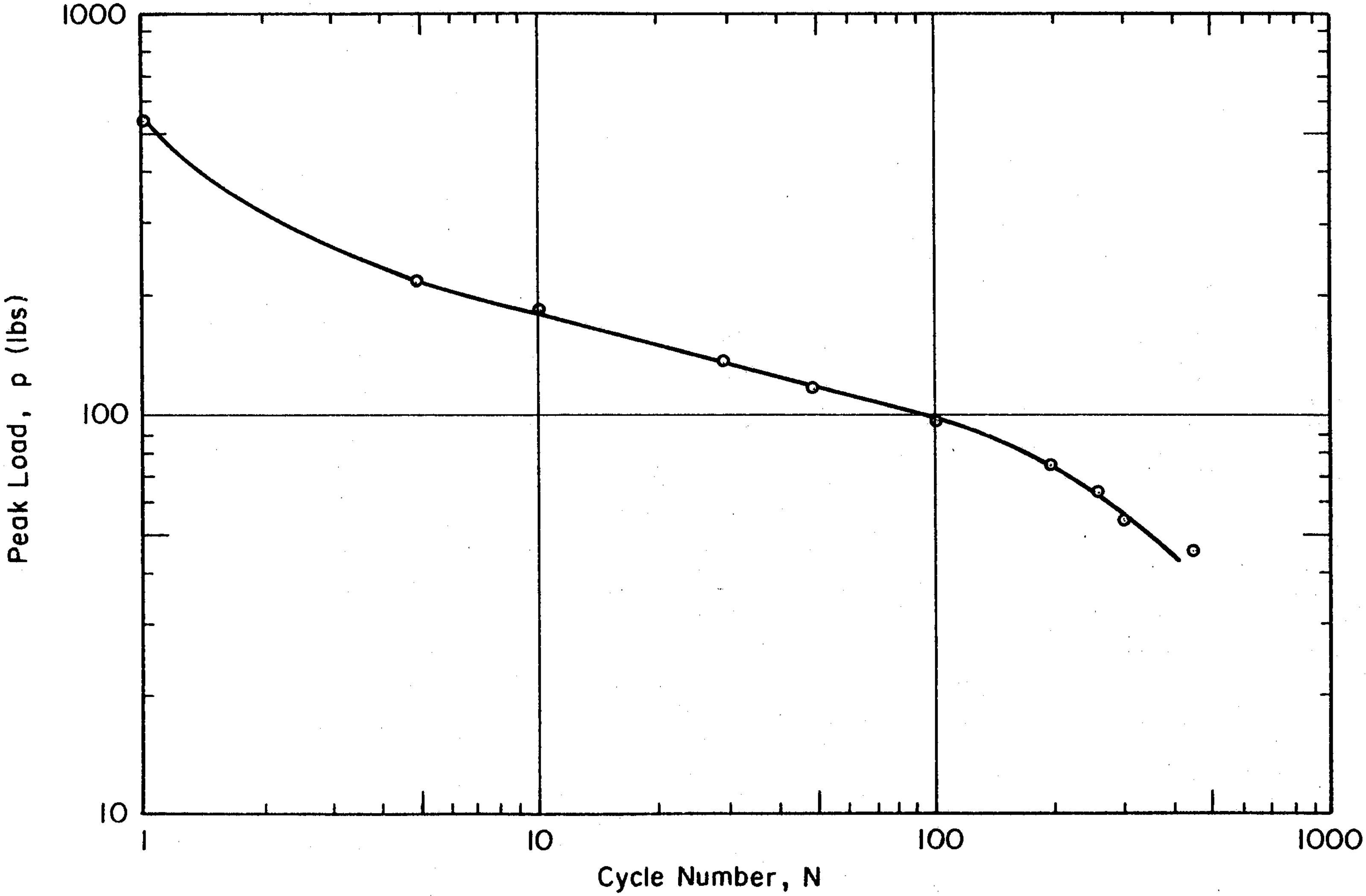



FIGURE 51B. Peak Load versus Cycle Number for Sample 114

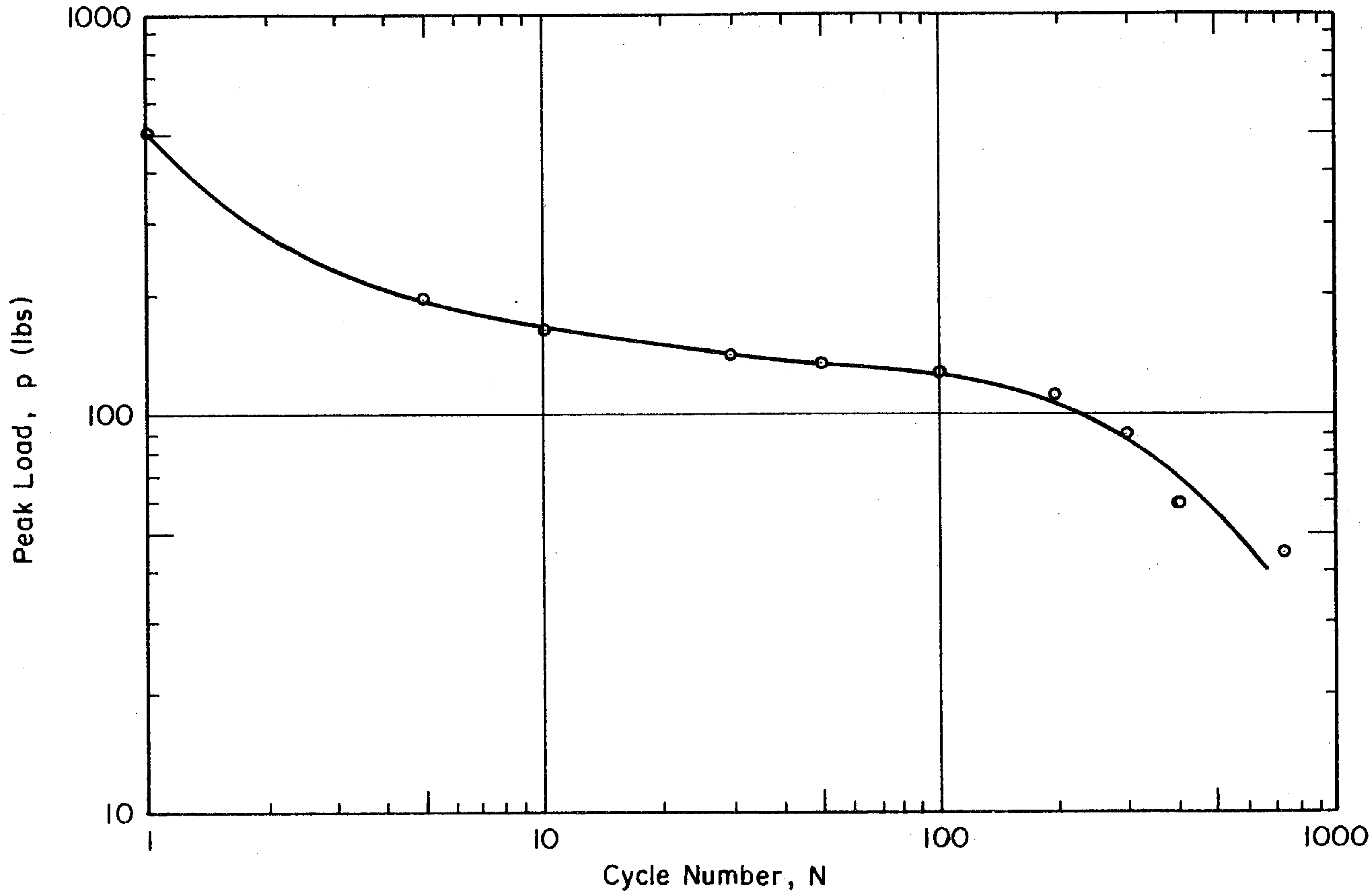



FIGURE 52B. Peak Load versus Cycle Number for Sample 115

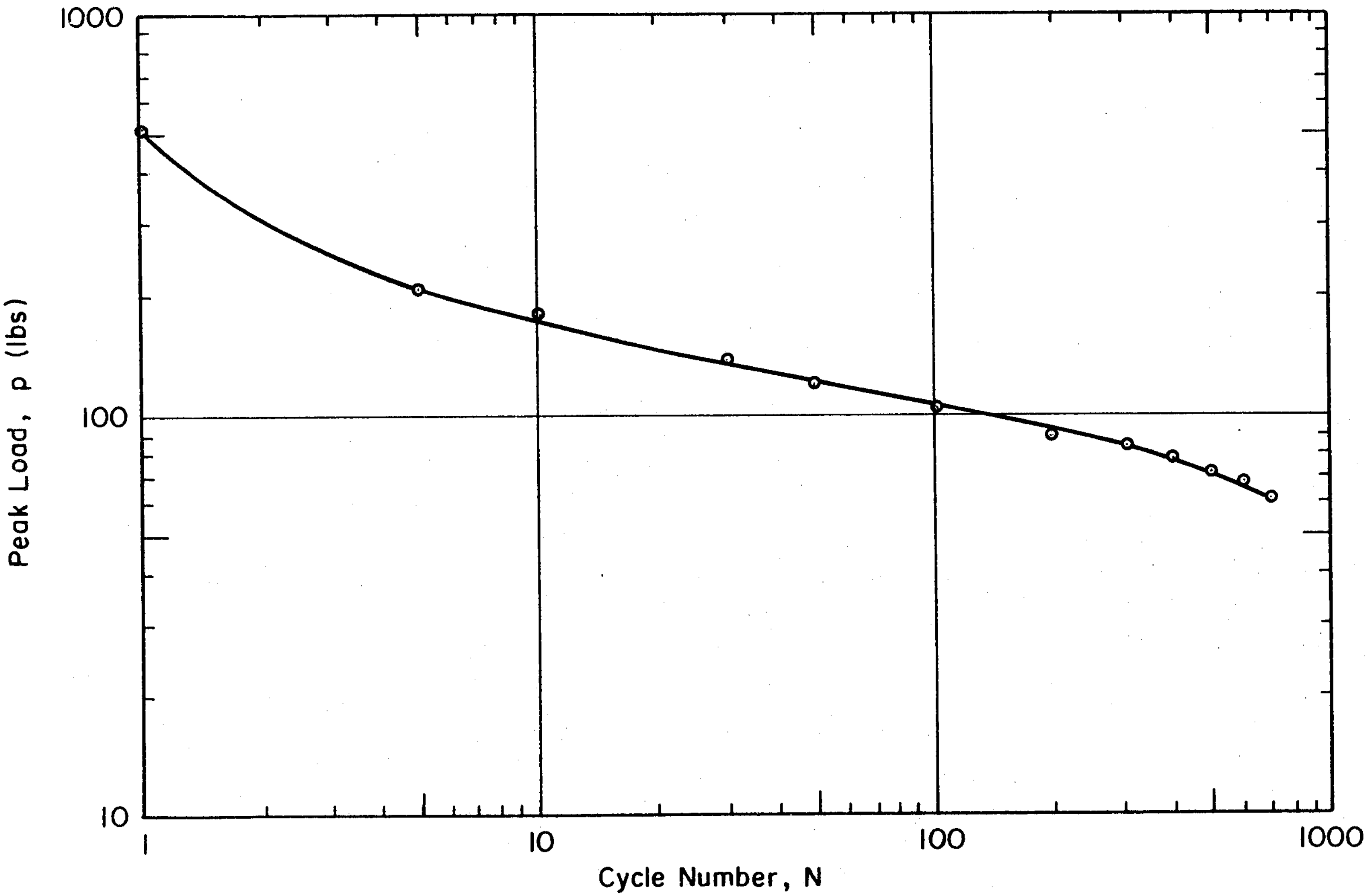



FIGURE 53B. Peak Load versus Cycle Number for Sample 116

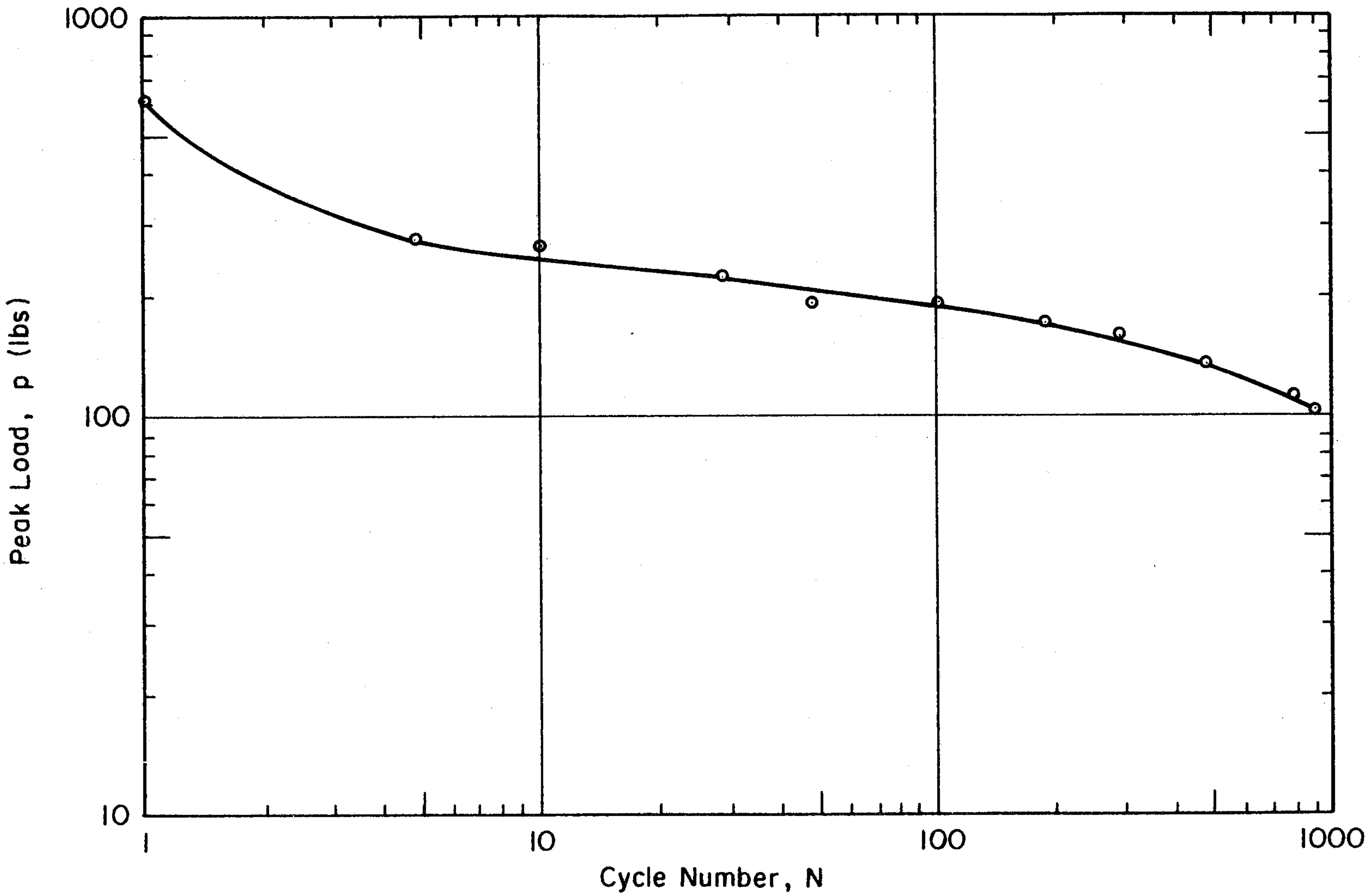



FIGURE 54B. Peak Load versus Cycle Number for Sample 117

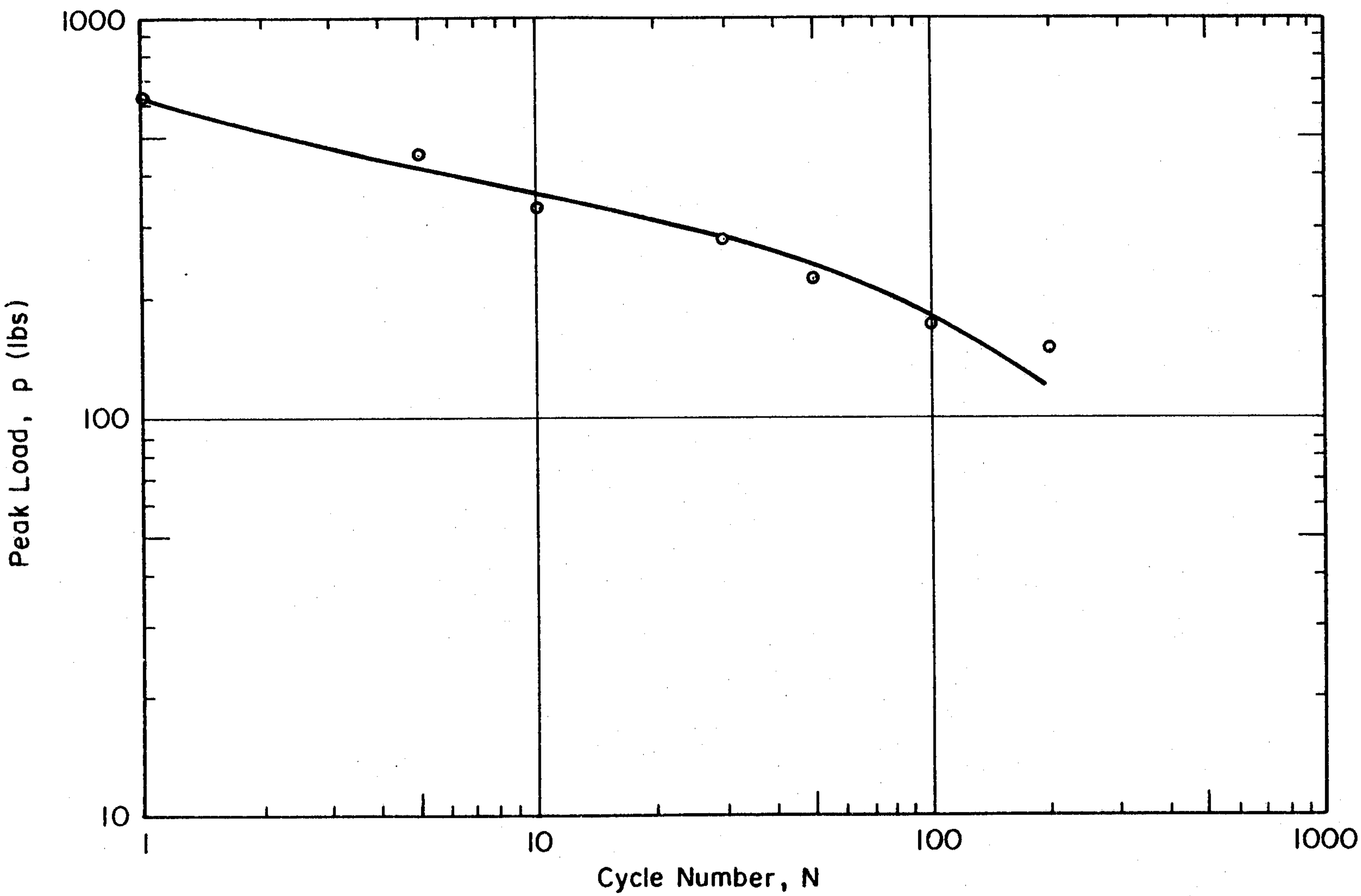



FIGURE 55B. Peak Load versus Cycle Number for Sample 118

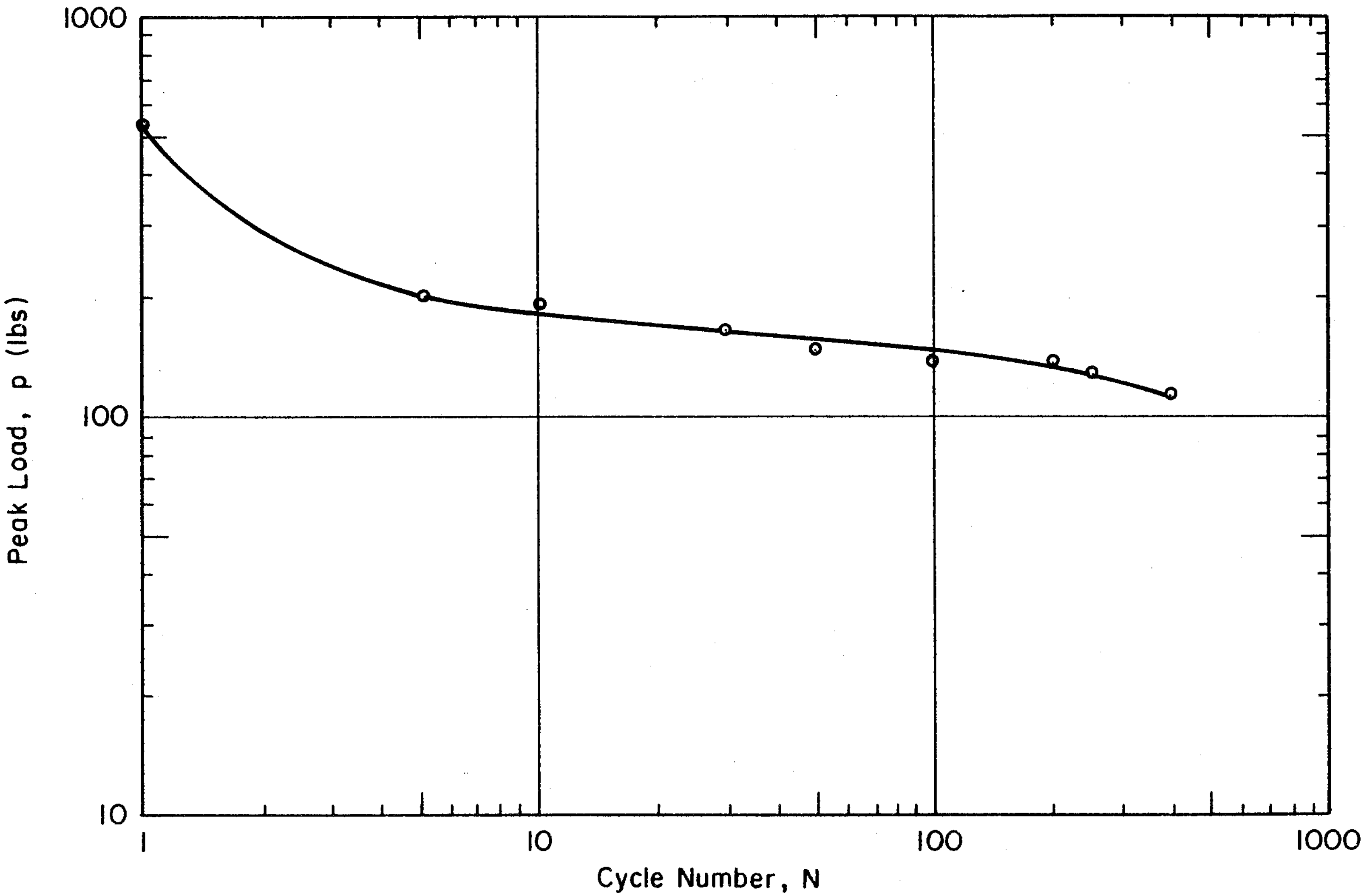



FIGURE 56B. Peak Load versus Cycle Number for Sample 119

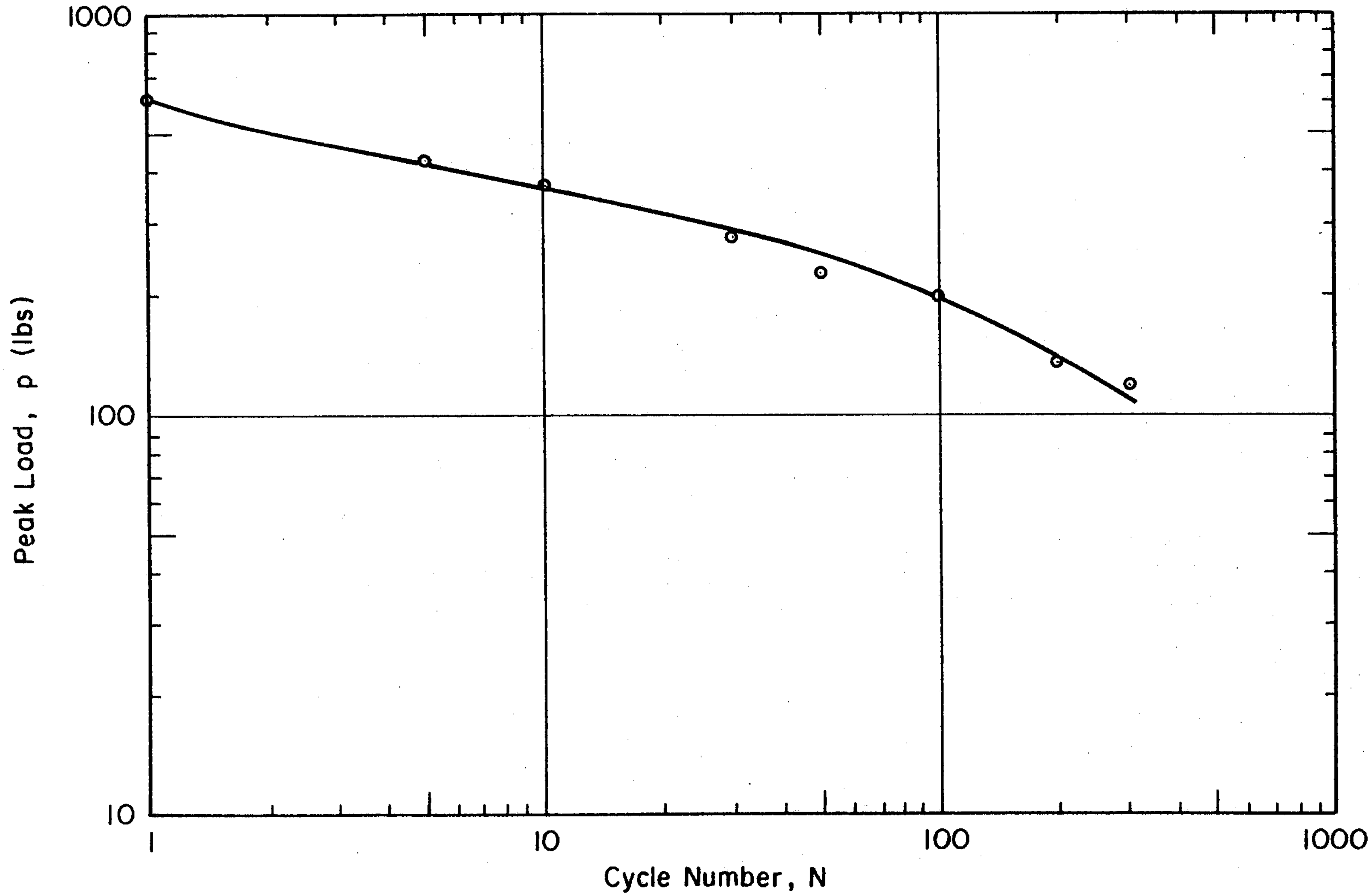



FIGURE 57B. Peak Load versus Cycle Number for Sample 120

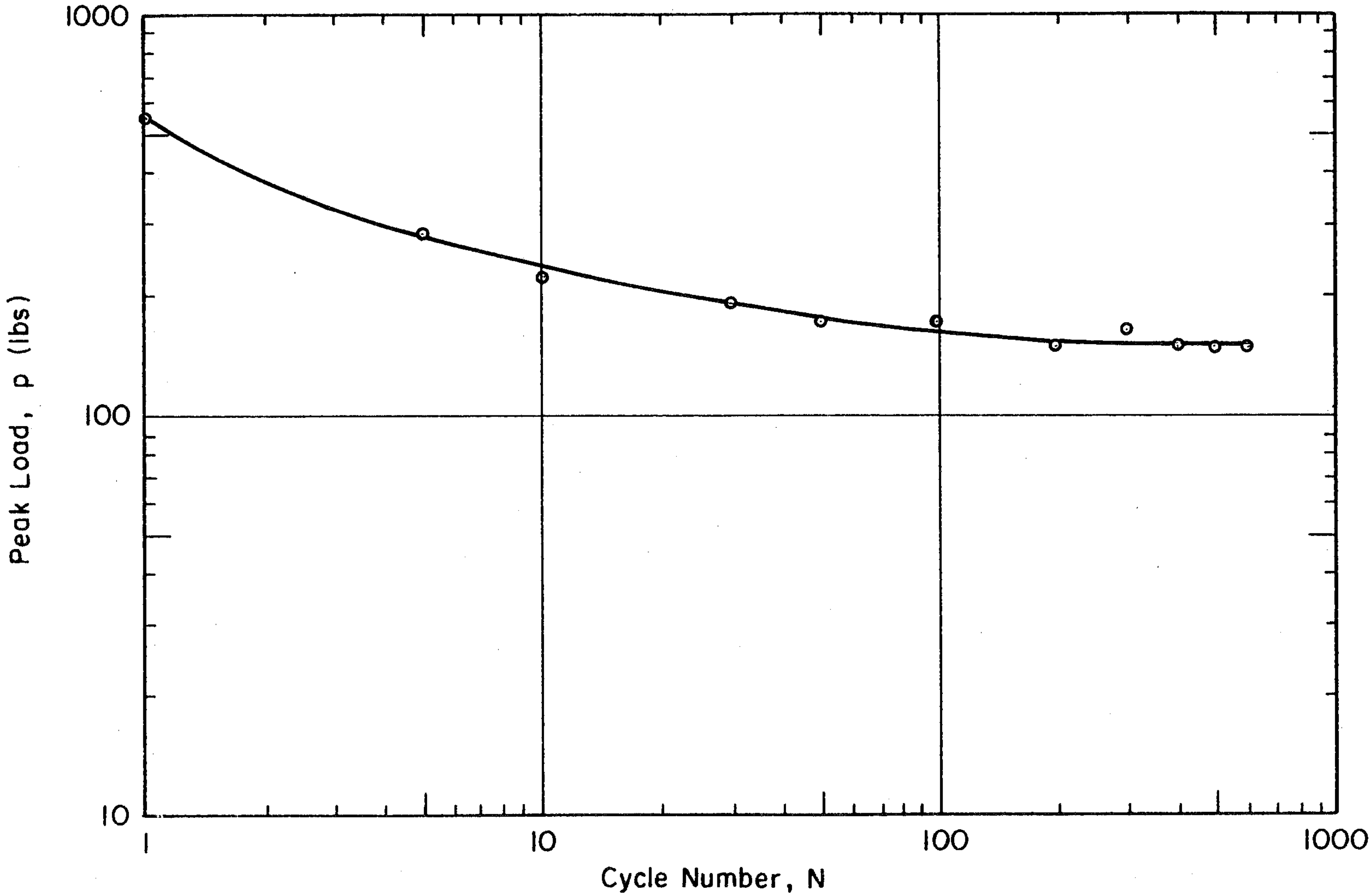



FIGURE 58B. Peak Load versus Cycle Number for Sample 121

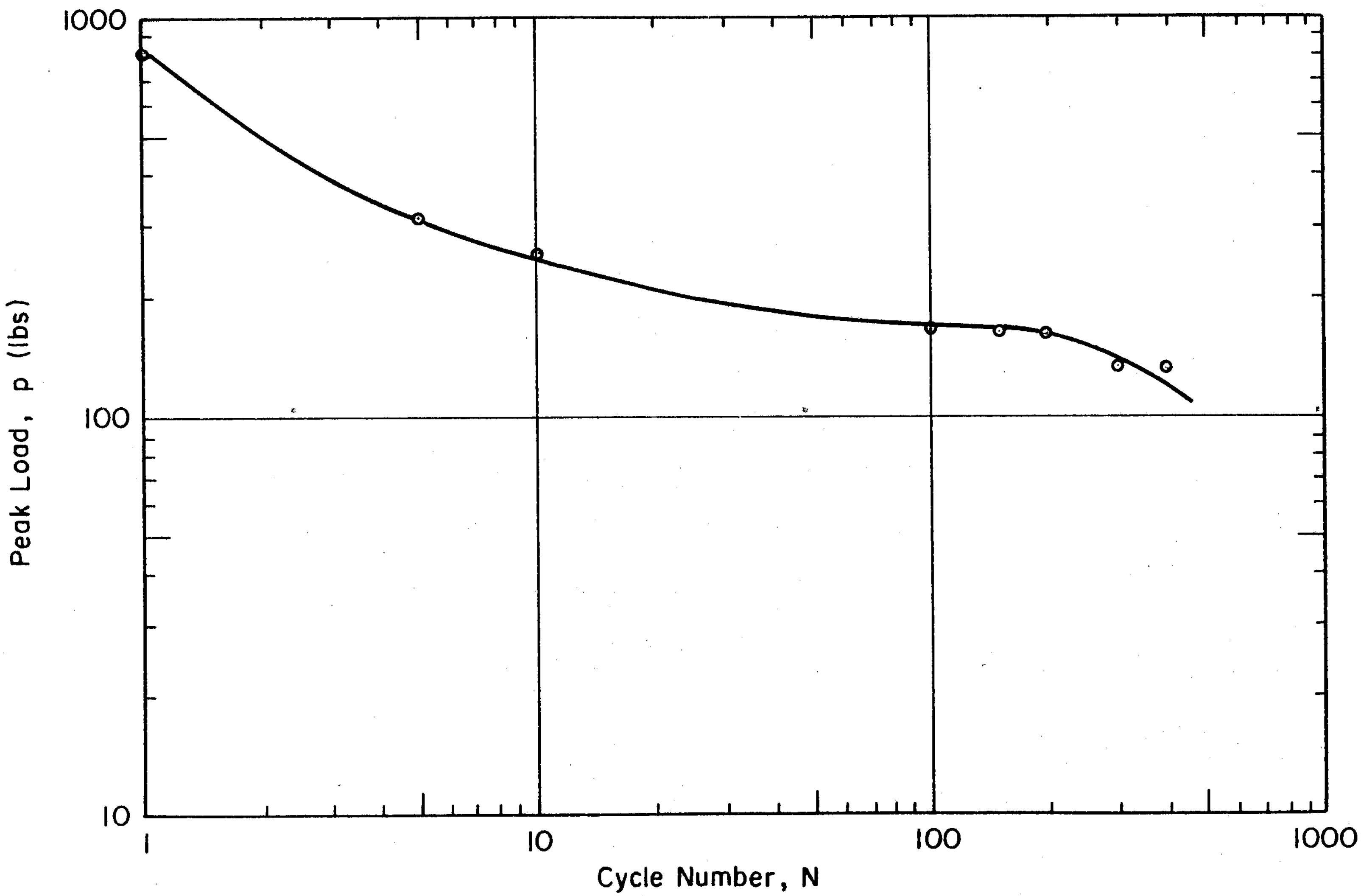



FIGURE 59B. Peak Load versus Cycle Number for Sample 122

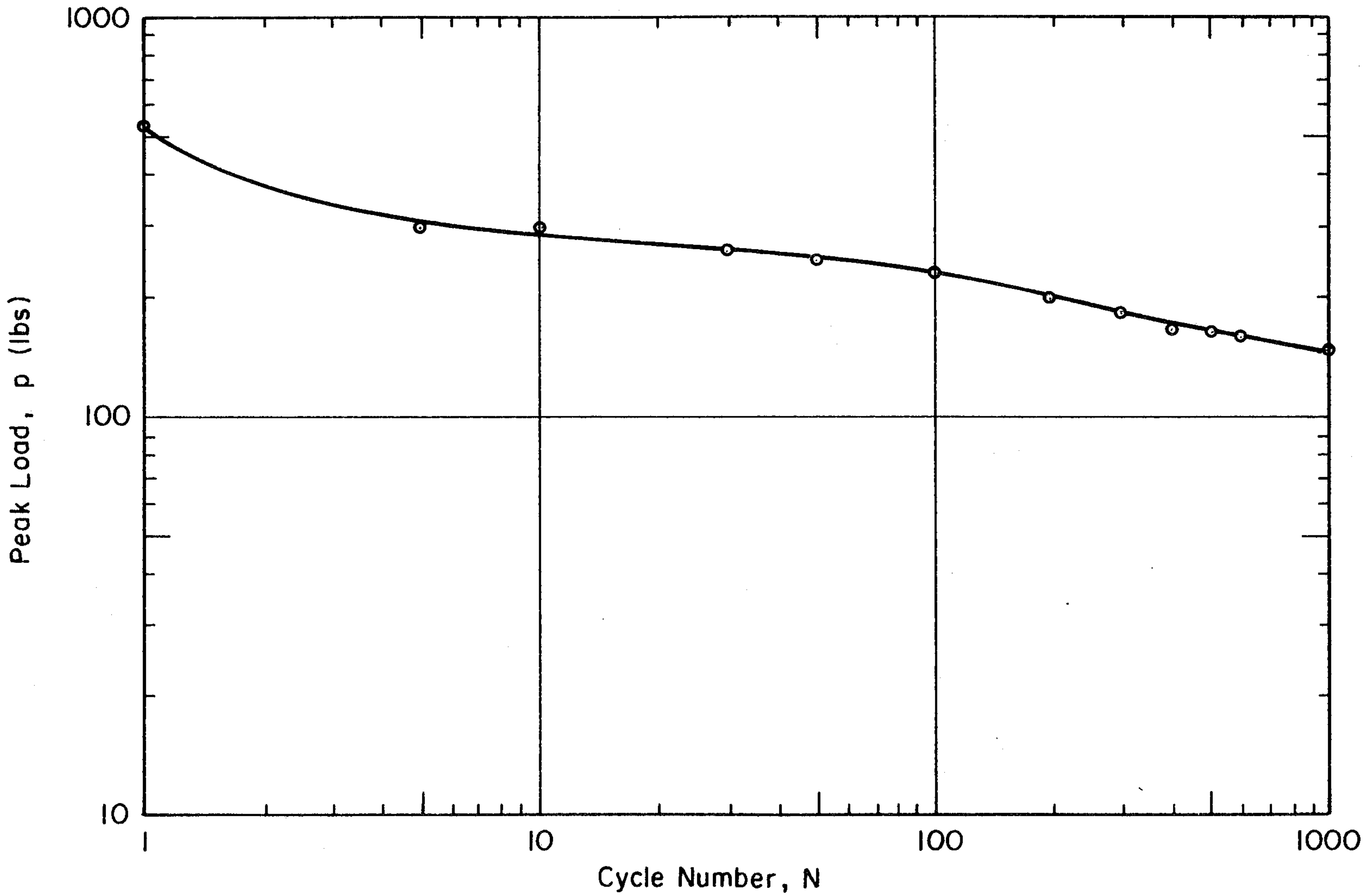



FIGURE 60B. Peak Load versus Cycle Number for Sample 123

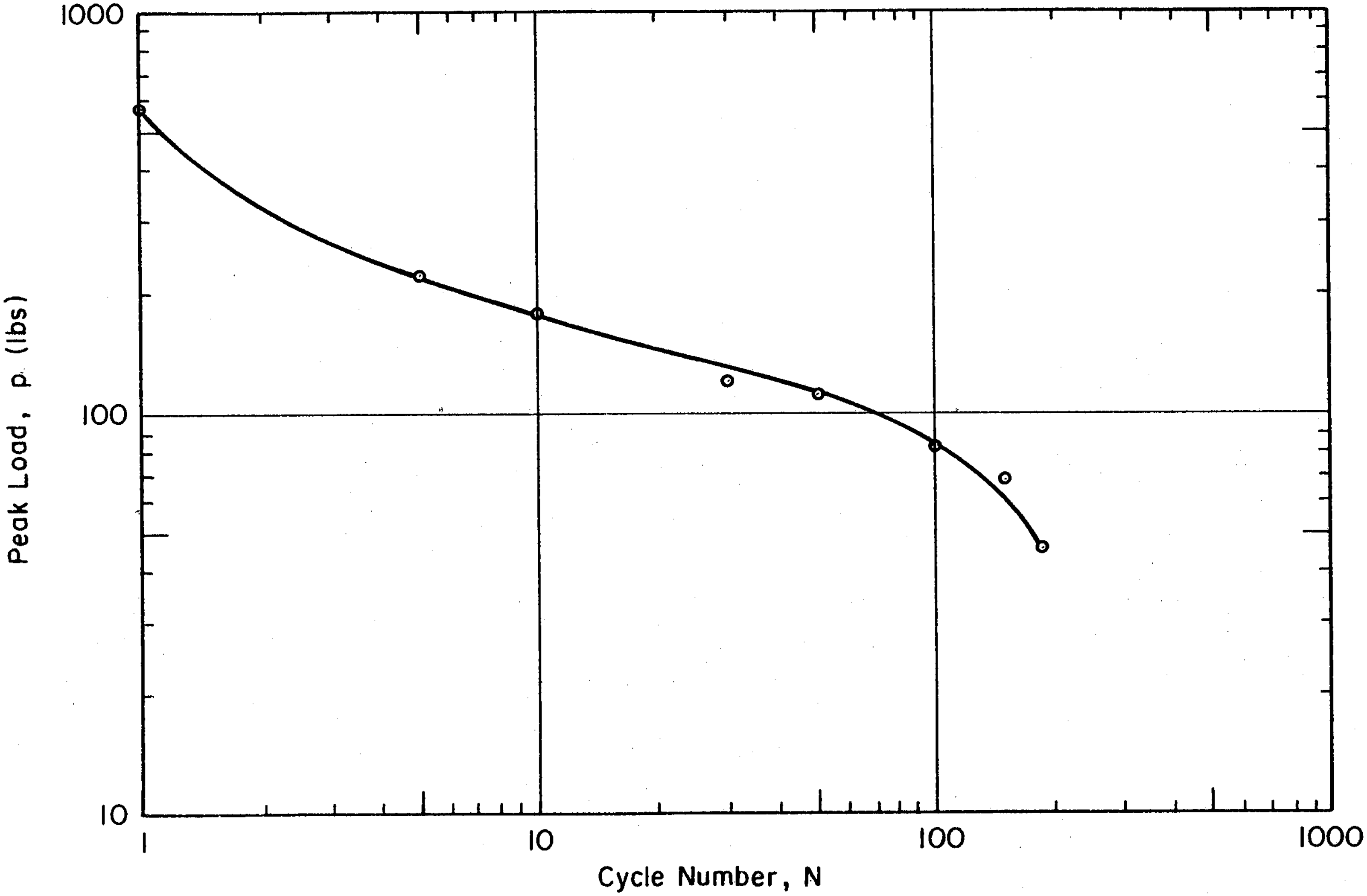



FIGURE 61B. Peak Load versus Cycle Number for Sample 124

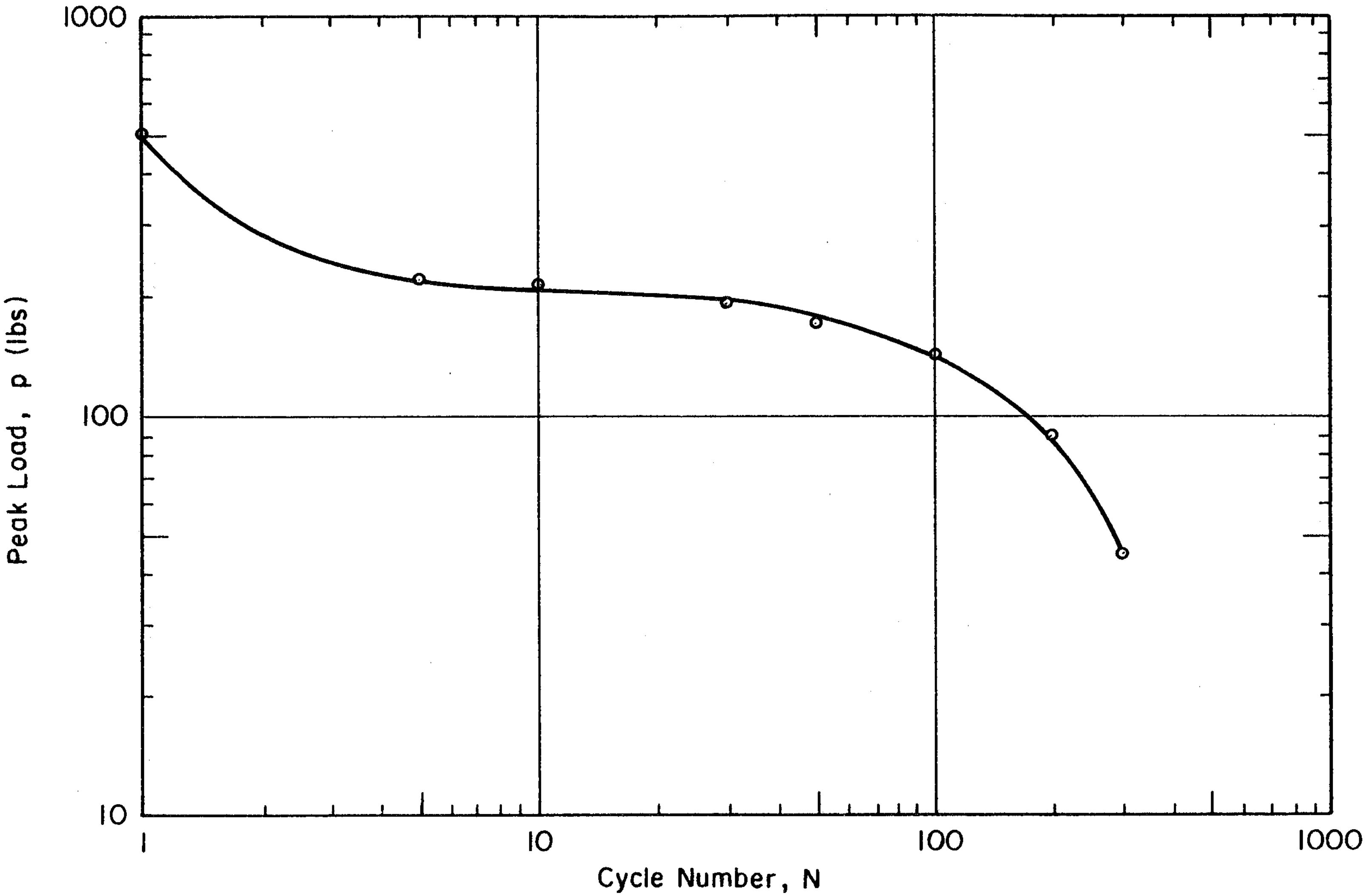



FIGURE 62B. Peak Load versus Cycle Number for Sample 125

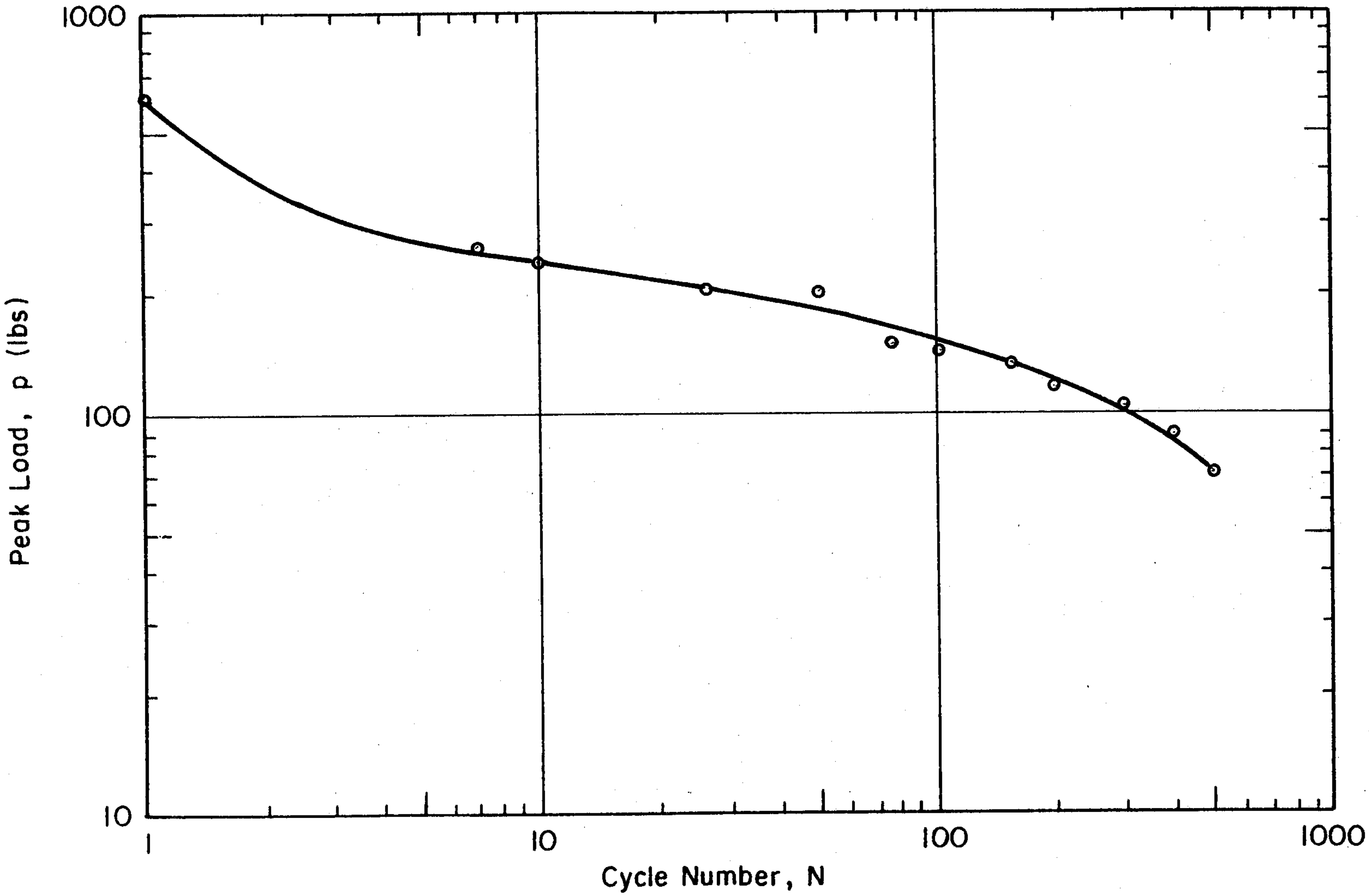



FIGURE 63B. Peak Load versus Cycle Number for Sample 126

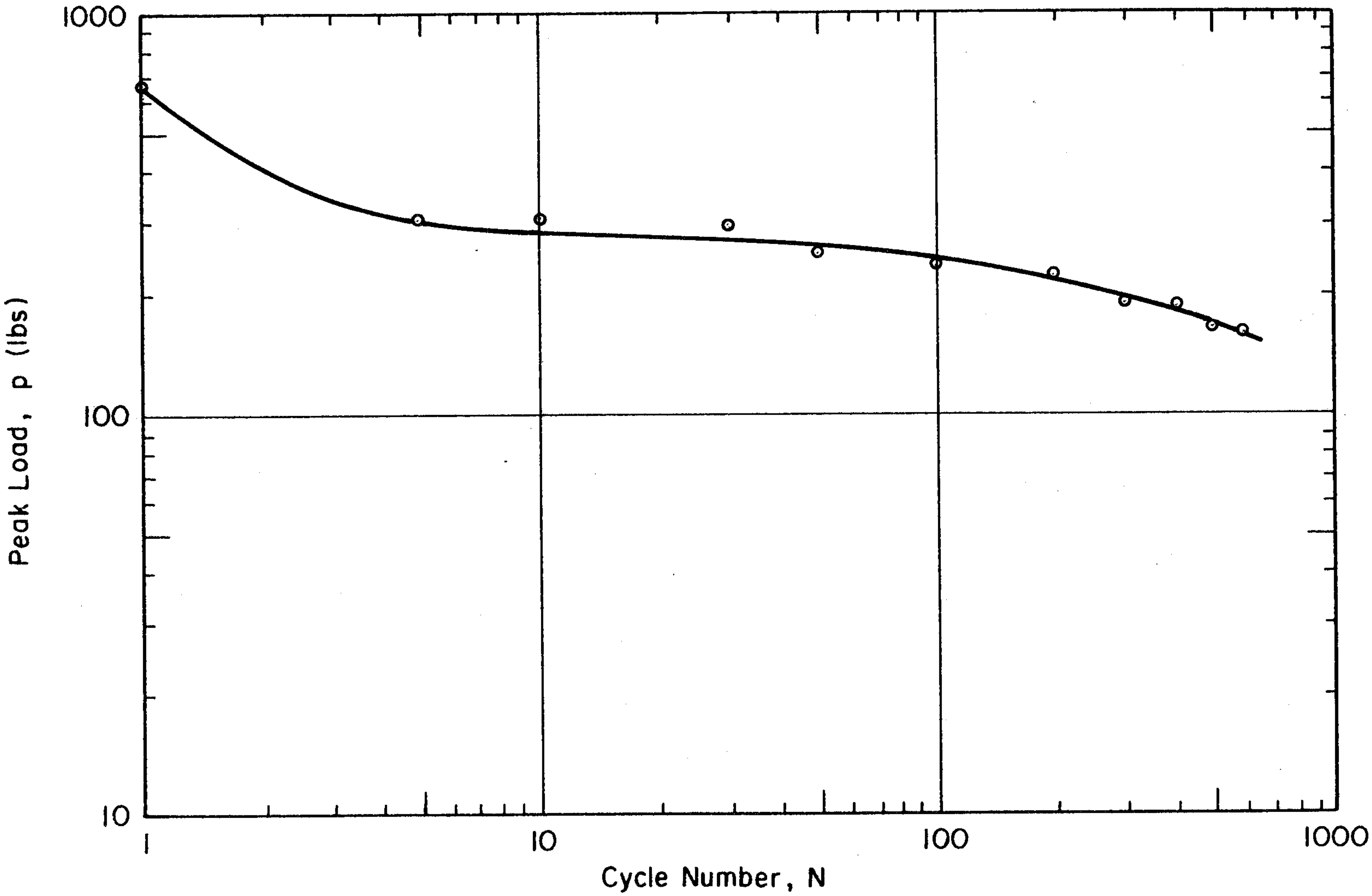



FIGURE 64B. Peak Load versus Cycle Number for Sample 127

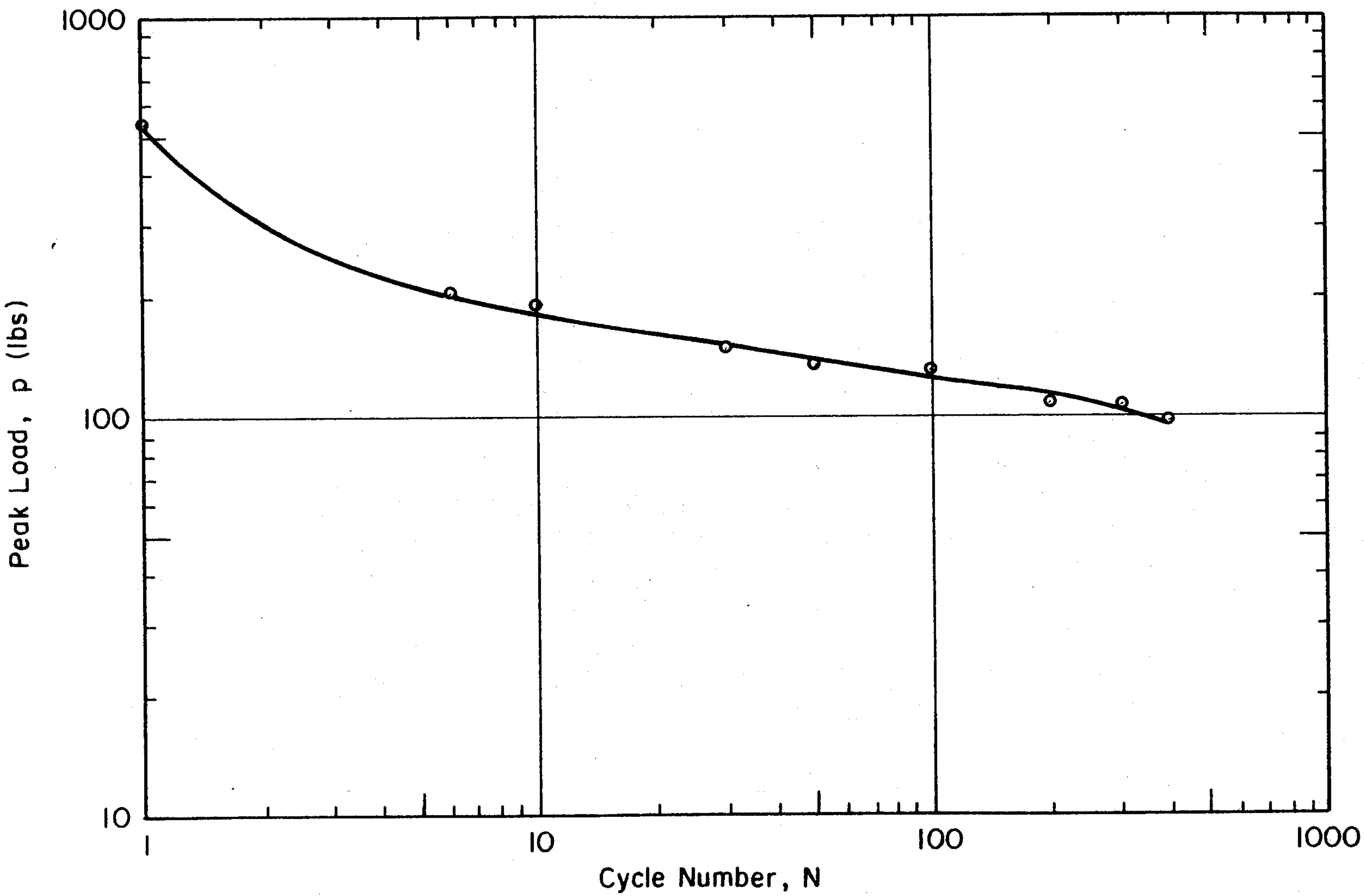



FIGURE 65B. Peak Load versus Cycle Number for Sample 128

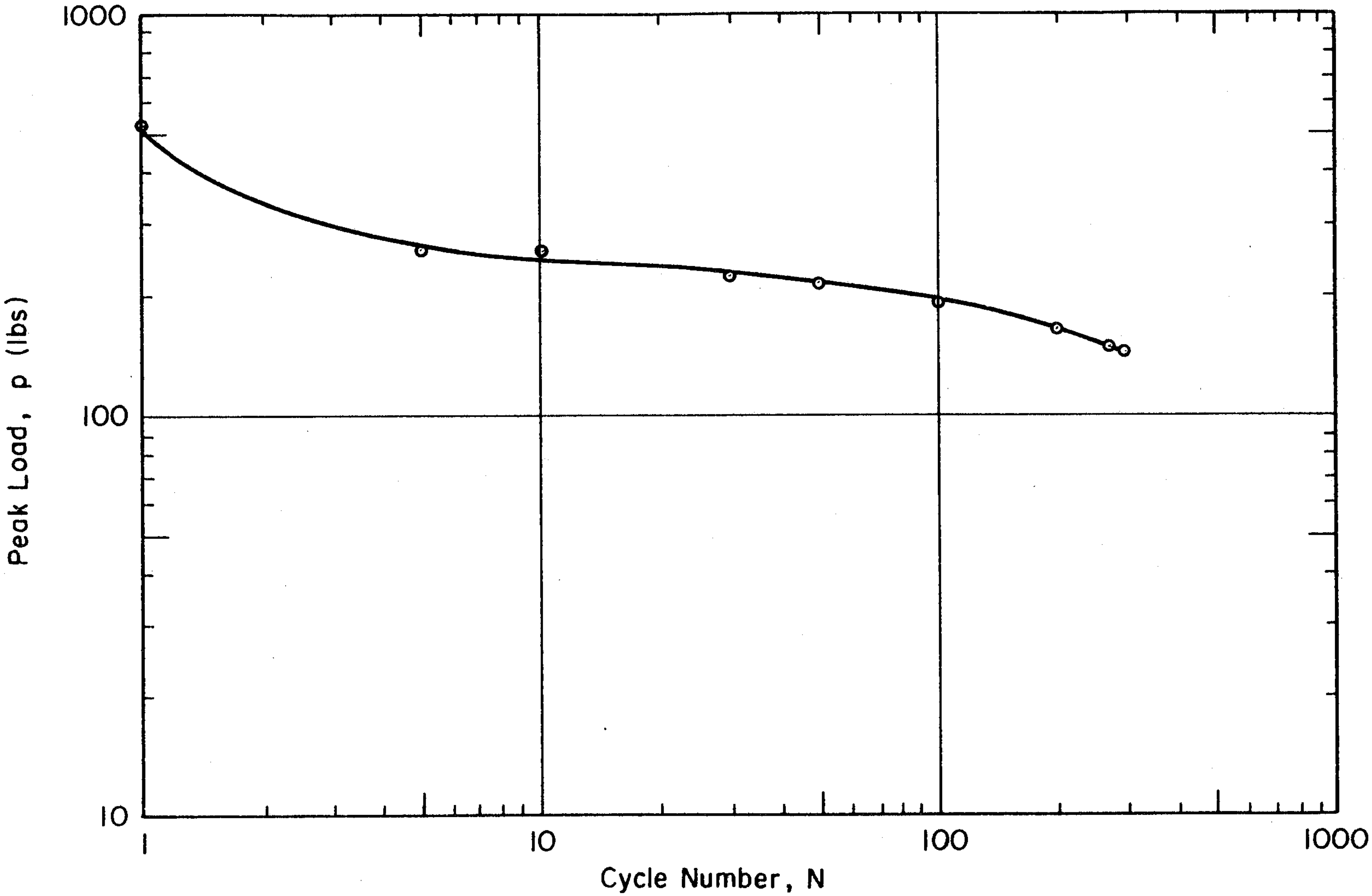



FIGURE 66B. Peak Load versus Cycle Number for Sample 129

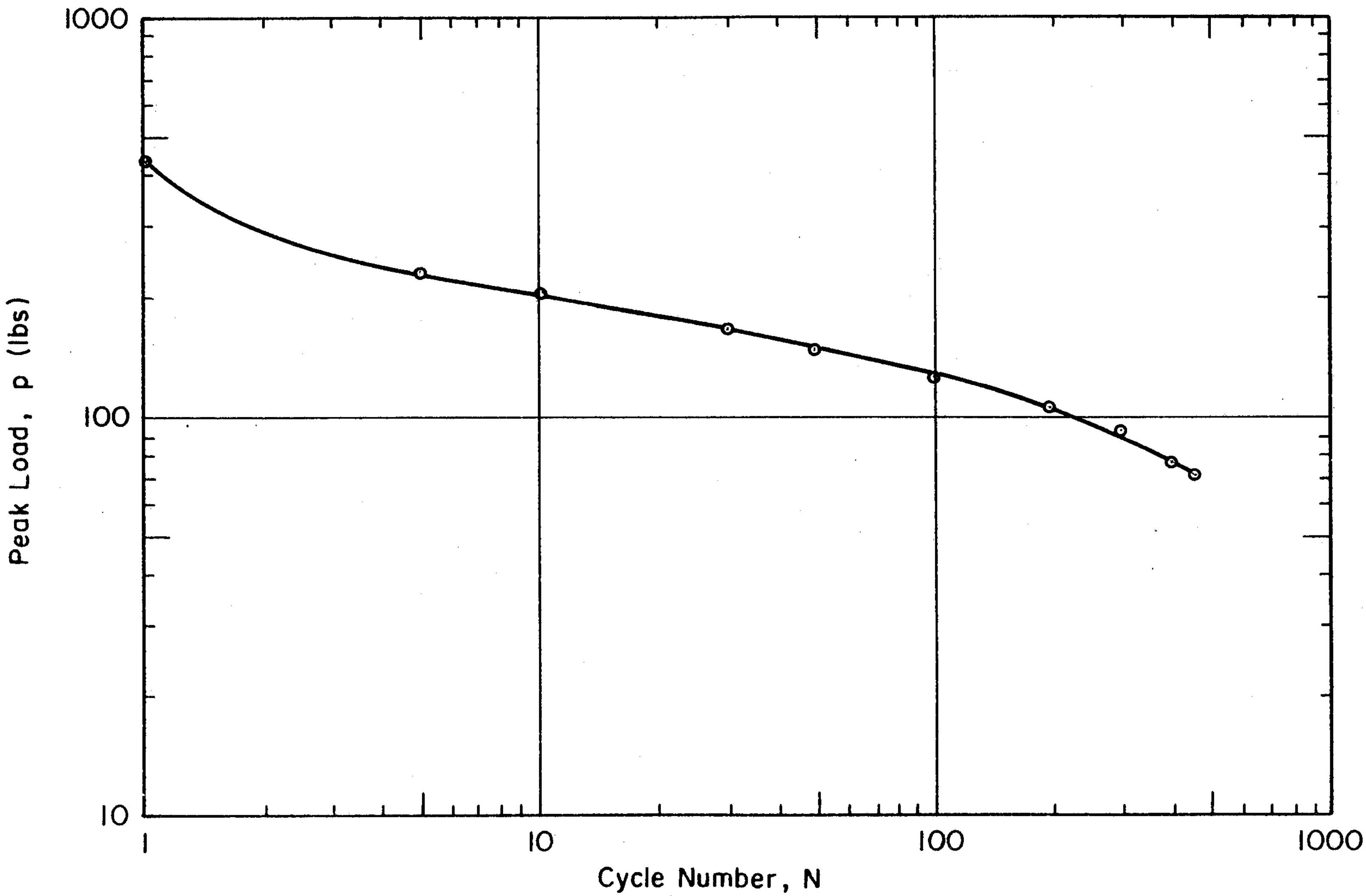



FIGURE 68B. Peak Load versus Cycle Number for Sample 132

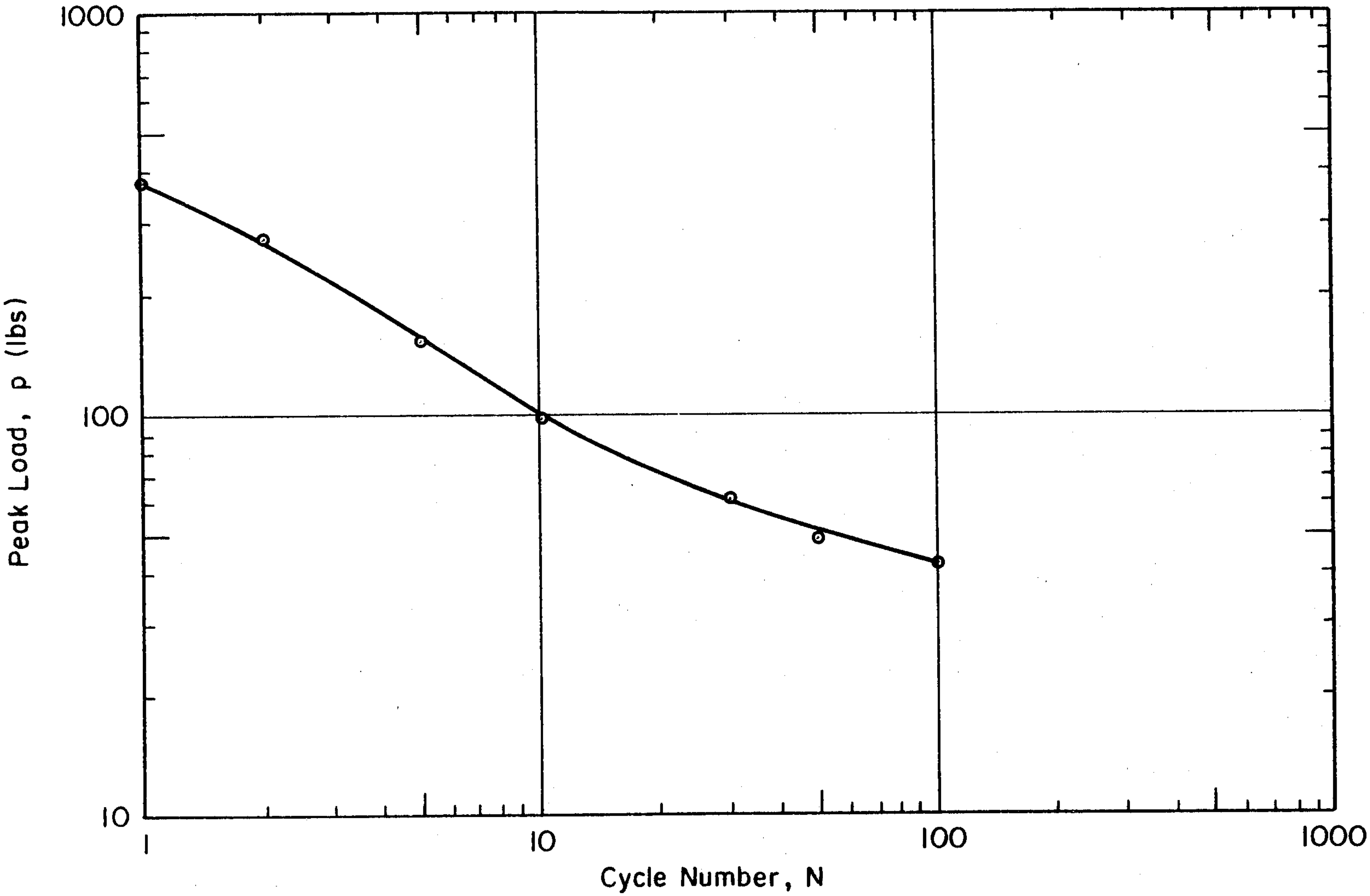



FIGURE 67B. Peak Load versus Cycle Number for Sample 131

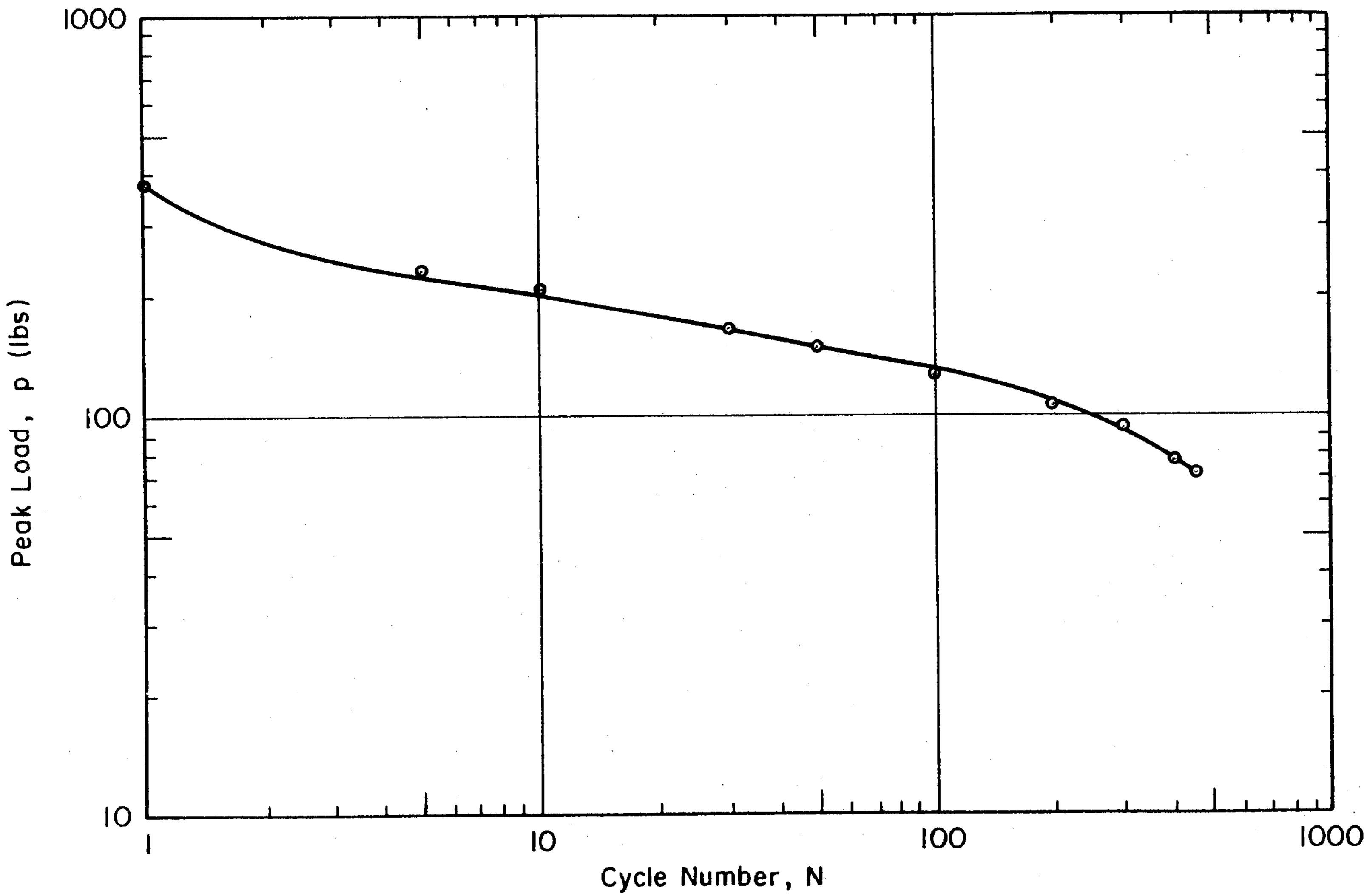



FIGURE 69B. Peak Load versus Cycle Number for Sample 133

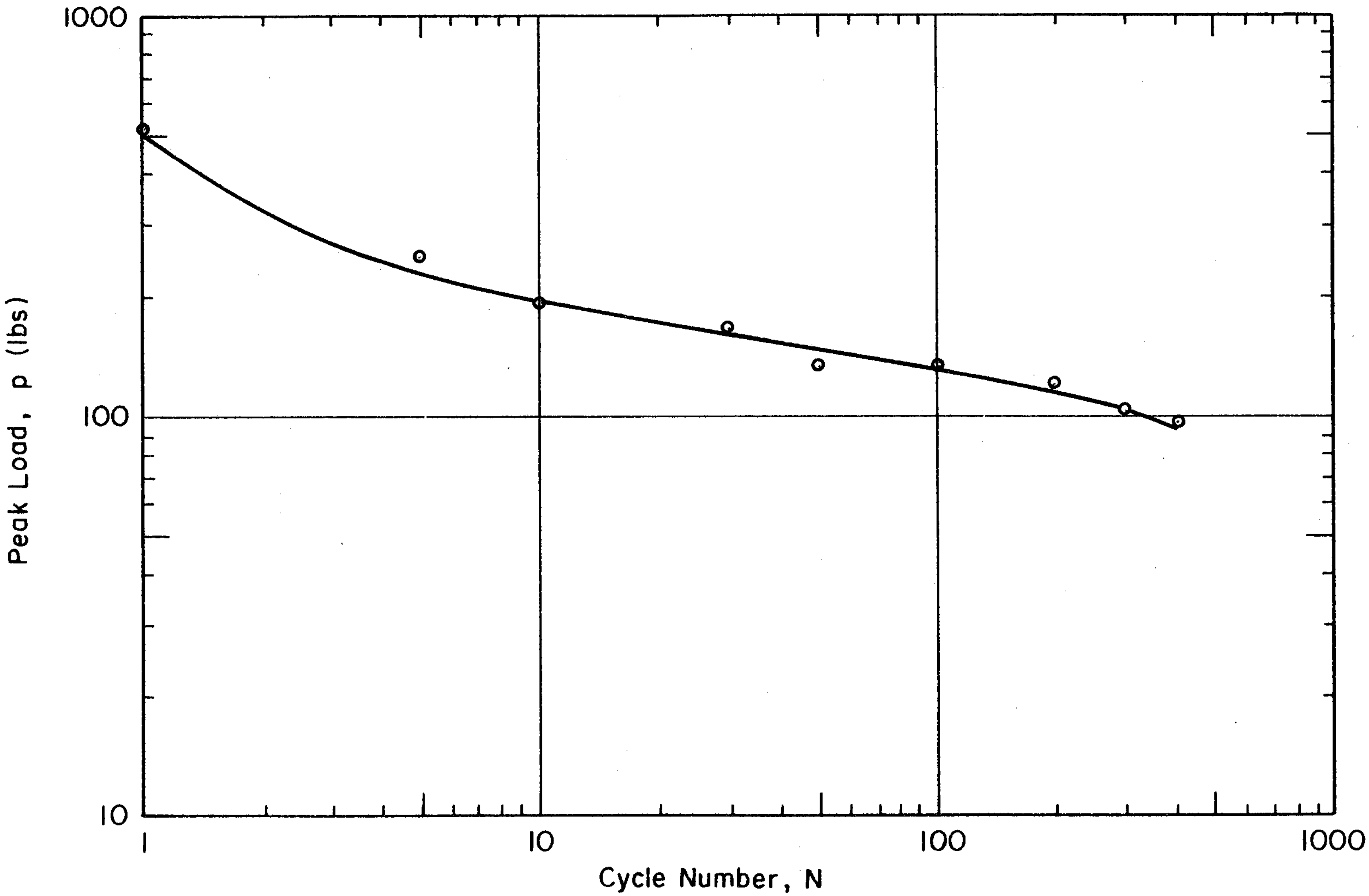



FIGURE 70B. Peak Load versus Cycle Number for Sample 134

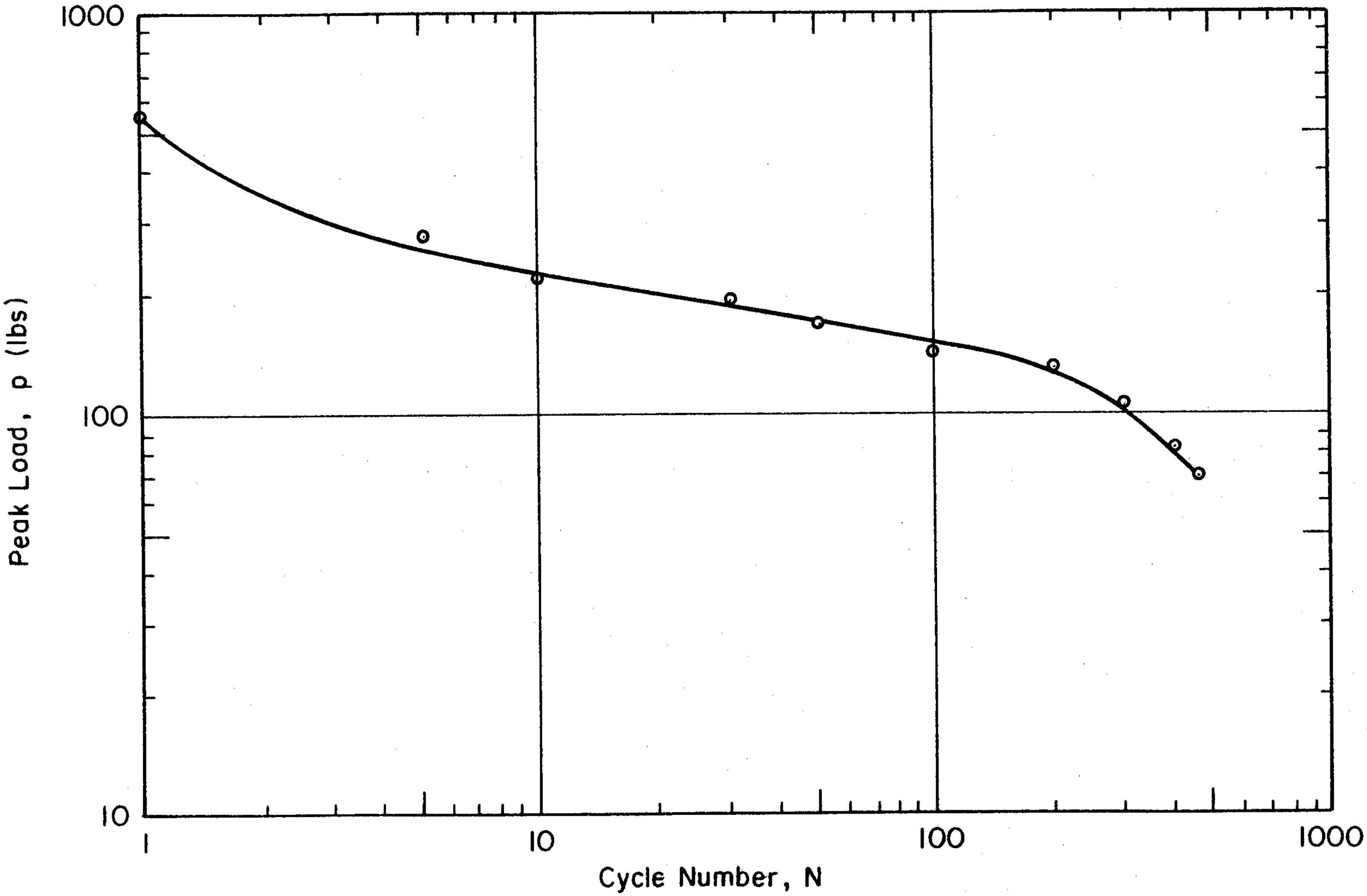



FIGURE 71B. Peak Load versus Cycle Number for Sample 135

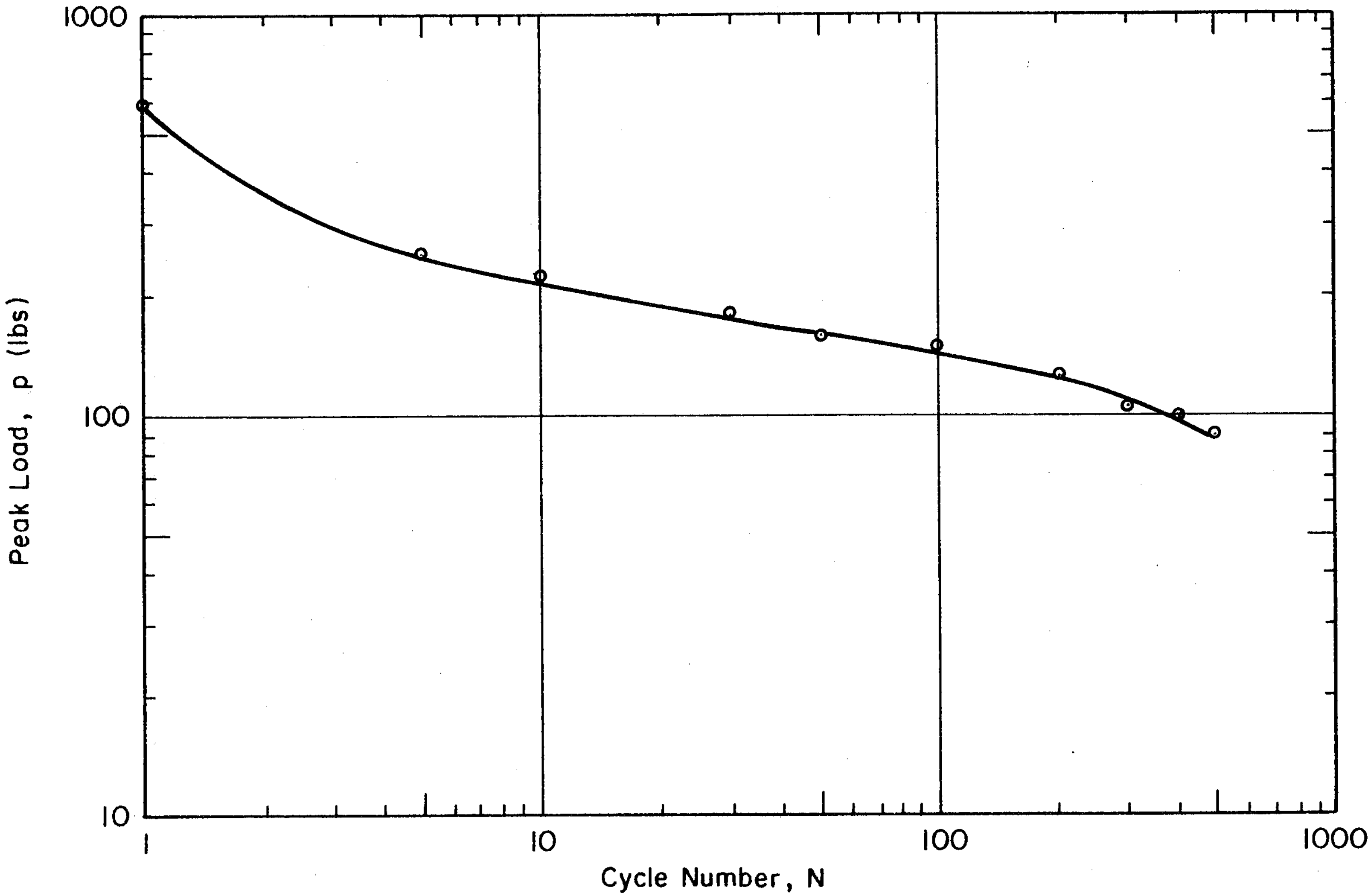



FIGURE 72B. Peak Load versus Cycle Number for Sample 136

## APPENDIX C

### SAMPLE CONSTRUCTION PROCEDURE AND SAMPLE IDENTIFICATION

Each sample tested on the TTI "Overlay Tester" consisted of a dense graded asphaltic concrete "beam" measuring 3 in. X 3 in. X 15 in. and reinforced with a selected engineering fabric applied with a tack coat of asphalt cement. A viscosity graded AC-10 petroleum asphalt cement produced by the American Petrofina Company was used for both the fabric tack coat and the asphaltic concrete mixture. The aggregate consisted of a washed, rounded, siliceous gravel obtained from a Gifford-Hill plant at the Brazos River near College Station, Texas.

The mixture design of the asphaltic concrete used in constructing each of the samples conforms to the laboratory standard established by the Materials Division of The Texas Transportation Institute (44). The aggregate gradation used in preparing the samples is shown in Table 1C on the following page. This gradation also meets the grading specifications established by ASTM D 1663-5A, shown in Table 2C, page 231 , for dense graded asphaltic concrete (45). The project gradation design as well as the upper and lower limits of the ASTM specifications are shown in Figure 1C, page 232 .

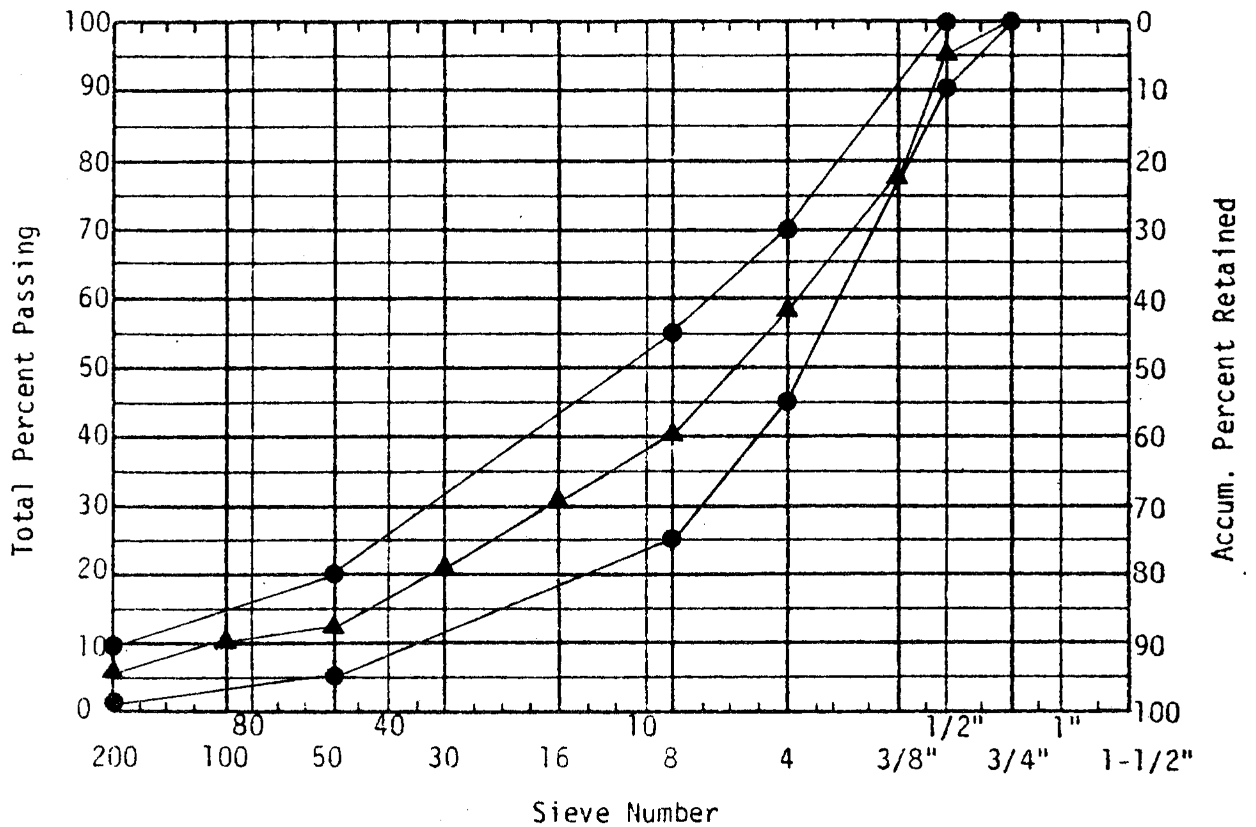
The aggregate was separated into various fractions by a combination of mechanical and manual sieving methods (46, 47). Then prior to mixing, the aggregate was recombined in appropriate quantities to meet the grading specifications shown in Table 1C, page 230 and Figure 1C , page 232. Both the AC-10 asphalt and the aggregate were heated to

TABLE 1C. Gifford-Hill river gravel gradation and sample weights.

| Sieve Size | | Percent (by Weight) | Aggregate Weight (grams) |
|---|---|---|---|
| Passing | Retained On | | |
| 3/4 in. | 1/2 in. | 5.00 | 260.0 |
| 1/2 in. | 3/8 in. | 18.75 | 975.0 |
| 3/8 in. | No. 4 | 18.75 | 975.0 |
| No. 4 | No. 8 | 17.50 | 910.0 |
| No. 8 | No. 16 | 9.10 | 473.2 |
| No. 16 | No. 30 | 9.20 | 478.4 |
| No. 30 | No. 50 | 9.20 | 478.4 |
| No. 50 | No. 100 | 3.50 | 182.0 |
| No. 100 | No. 200 | 3.50 | 182.0 |
| No. 200 | --- | 5.50 | 286.0 |
| | TOTAL | 100.00 | 5200.0 |

TABLE 2C. ASTM D 1663 - 5A aggregate gradation (45).

| Sieve Size | Percent (by Weight) Finer Than Sieve Size |
|---|---|
| 3/4 in. | 100 |
| 1/2 in. | 90 to 100 |
| 3/8 in. | ---- |
| No. 4 | 45 to 70 |
| No. 8 | 25 to 55 |
| No. 16 | ---- |
| No. 30 | ---- |
| No. 50 | 5 to 20 |
| No. 100 | ---- |
| No. 200 | 2 to 9 |




▲ Project Design Gradation

● ASTM D 1663-5A Specification Limits

Figure 1C . ASTM D 1663 aggregate gradation specification 5A and project gradation design.

305 ± 5°F in an oven; then the aggregate (5200 grams) and the asphalt (198 grams) were blended in a mechanical mixer. Combining the materials in these proportions produces an asphaltic concrete with 3.8 percent asphalt (by weight of aggregate).

When the blending of the asphalt and aggregate was completed, the mixture was then divided into three portions. For those samples with fabric reinforcement located one inch from the bottom of the sample, three equal portions of 1760 grams each were used to construct the beam in three equal layers. Material for samples with reinforcement to be located 3/4 inches from the top of the sample was divided into portions weighing 1975 grams, 1975 grams and 1320 grams for the bottom, middle, and top layers, respectively. After dividing the mixture into the appropriate proportions, the material was again placed in an oven and reheated to 250 ± 5°F for compaction purposes.

Compaction of the test samples was accomplished in three layers by use of a Soiltest, Inc. Model CN-425A pneumatic static compactor. Refer to Figure 3, page 29. Reinforcing fabric measuring 3 in. X 15 in. was located either between the first and second layers (one inch from the bottom of the sample) or between the second and third layers (3/4 inches from the top of the sample). A tack coat of liquid AC-10 asphalt (250 ± 5°F) was applied to the newly compacted asphaltic concrete, then the reinforcing fabric was applied and the final layer(s) of material was added and compacted. The first two layers of material received 35 compaction tamps each, while the final layer received 70 tamps. Each tamp applied approximately 40 psi pressure (500 psi ram pressure with a 3 in. X 4 in. compaction "foot") for a dwell time of 1.5 seconds. A leveling load of 12,000 pounds (approximately 270 psi) was then applied for five seconds to provide final compaction and remove surface irregularities. This leveling load was applied by means of a hydraulic universal testing machine manufactured by the Baldwin Southwark Corporation. A heated steel beam (3 in. X 4 in. X 15 in.) was used to distribute the leveling load uniformly over the surface of the sample. Figure 4 on page 31 of Chapter III illustrates a sample prepared for application of a leveling load.

After the leveling load was applied, each beam was removed from the mold and allowed to "cure" at laboratory room temperature for approximately 24 hours. All samples were then stored in an environmentally controlled room (77$^{o}$F, 25% relative humidity) until tested. All samples were stored in this environment for at least 7 days prior to testing.

Table 3C on page 235 lists the samples tested, type and location of reinforcing fabric and fabric tack coat rate. Refer to Appendix D, page 237 for an explanation of the various tack coat rates. Appendix E, page 240 describes the various engineering fabrics used in the testing program.

TABLE 3C. Identification of fabric reinforced asphaltic concrete beams.

| Sample Number | Fabric* Position | Fabric Tack** Coat Rate | Fabric Type |
|---|---|---|---|
| 100 | A | Low | Old Petromat |
| 101 | B | Low | Old Petromat |
| 102 | A | Optimum | Old Petromat |
| 103 | B | Optimum | Old Petromat |
| 104 | A | High | Old Petromat |
| 105 | B | High | Old Petromat |
| 106 | A | Low | New Petromat |
| 107 | B | Low | New Petromat |
| 108 | A | Optimum | New Petromat |
| 109 | B | Optimum | New Petromat |
| 110 | A | High | New Petromat |
| 111 | B | High | New Petromat |
| 112 | A | Low | Mirafi 140 |
| 113 | B | Low | Mirafi 140 |
| 114 | A | Optimum | Mirafi 140 |
| 115 | B | Optimum | Mirafi 140 |
| 116 | A | High | Mirafi 140 |
| 117 | B | High | Mirafi 140 |
| 118 | A | Low | Bidim |
| 119 | B | Low | Bidim |
| 120 | A | Optimum | Bidim |
| 121 | B | Optimum | Bidim |

TABLE 3C. (Continued)

| Sample Number | Fabric* Position | Fabric Tack** Coat Rate | Fabric Type |
|---|---|---|---|
| 122 | A | High | Bidim |
| 123 | B | High | Bidim |
| 124 | A | Low | Woven Tape |
| 125 | B | Low | Woven Tape |
| 126 | A | Optimum | Woven Tape |
| 127 | B | Optimum | Woven Tape |
| 128 | A | High | Woven Tape |
| 129 | B | High | Woven Tape |
| 131 | B | Low | Burlington 2532 |
| 132 | A | Low | Burlington 2532 |
| 133 | B | Optimum | Burlington 2532 |
| 134 | A | Optimum | Burlington 2532 |
| 135 | B | High | Burlington 2532 |
| 136 | A | High | Burlington 2532 |

Notes:

* Fabric position "A" refers to the location 3/4 inches from the top of the sample. Fabric position "B" refers to the location one inch from the bottom of the sample.

** Refer to Table 1D, page 239, Appendix D for a list of the various tack coat quantities for each fabric type.

## APPENDIX D

## PROCEDURE FOR DETERMINING THE OPTIMUM FABRIC TACK COAT RATE

A viscosity graded AC-10 petroleum asphalt cement produced by the American Petrofina Company was used as a tack coat to bind a 3 in. X 15 in. fabric sample to the upper and lower layers of the asphaltic concrete. The "optimum" AC-10 tack coat requirement was determined for each fabric type by saturating fabric samples with liquid asphalt (heated to approximately 250$^{o}$F), then placing the samples between sheets of newspaper and pressing with a hot iron to remove excess asphalt. The optimum asphalt content is based on a visual observation and is defined as that amount (by weight) of AC-10 asphalt required to saturate a 3 in. X 15 in. fabric sample (plus a small adjustment for "surface hunger" of the asphaltic concrete). Fabrics with the proper amount of tack coat are thoroughly saturated, but do not contain an excess of asphalt as evidenced by a glossy appearance.

The "surface hunger" of the asphaltic concrete is defined as the amount of liquid asphalt that the asphaltic concrete surface will readily absorb when a tack coat is applied. Based on previous tests performed by personnel at the Texas Transportation Institute (48) approximately 10.5 grams (0.08 gallons per square yard) of AC-10 is required to satisfy the surface hunger of a 3 in. X 15 in. freshly compacted asphaltic concrete surface. This amount of AC-10 (10.5 grams) was added to the amount of asphalt required to saturate a 3 in. X 15 in. fabric sample to determine the optimum tack coat rate for each fabric type. This additional amount of asphalt was included in the determination of the optimum tack coat rate to ensure that sufficient asphalt was available to completely saturate the reinforcing fabric and to bond the fabric to the asphaltic concrete.

Tack coat rates of "low" and high were defined as one half and twice the optimum tack coat rate, respectively. One of these three tack coat rate types, low, optimum, or high, was used in the construction of each of the fabric reinforced beam samples. Table 1D, on the following page lists the various tack coat rates for each of the reinforcing fabrics. These variations in tack coat rates were used to simulate gross errors in the field application of liquid asphalt tack coats and to help clarify the role of the fabric tack coat in retarding reflection cracking.

TABLE 1D. Fabric tack coat rates.

| Fabric Name | Fabric Saturation Rate | | AC-10 Tack Coat Rates* gms/sample and (gals/sq.yd.) | | |
|---|---|---|---|---|---|
| | gms/ sample | gals/ sq.yd. | Low | Optimum | High |
| "Old" Petromat | 24.0 | 0.18 | 17.0 (0.13) | 34.0 (0.26) | 68.0 (0.52) |
| "New" Petromat | 18.0 | 0.14 | 14.0 (0.11) | 28.0 (0.22) | 56.0 (0.44) |
| Mirafi 140 | 17.0 | 0.12 | 13.5 (0.10) | 27.0 (0.20) | 54.0 (0.40) |
| Bidim | 43.0 | 0.32 | 26.5 (0.20) | 53.0 (0.40) | 106.0 (0.80) |
| Woven Tape | 9.0 | 0.06 | 9.5 (0.07) | 19.0 (0.14) | 38.0 (0.28) |
| Burlington 2532 | 10.0 | 0.08 | 10.0 (0.08) | 20.0 (0.16) | 40.0 (0.32) |

*Note:

Tack coat rates shown are those used in constructing 3 in. X 3 in. X 15 in. fabric reinforced asphaltic concrete beams. The "optimum" rate includes an allowance of 10 gms. per sample for "surface" hunger of the asphaltic concrete. "Low" and "High" rates are defined on the preceding page.

## APPENDIX E

## ENGINEERING FABRIC DESCRIPTIONS

As stated in Chapter I, six commerically produced engineering fabrics purported to reduce and/or delay the occurrence of reflection cracking in bituminous overlays were used to reinforce laboratory-prepared "overlay" test specimens. Samples of each of these fabrics were obtained from representatives of the various manufacturers. General descriptions of each of these fabrics are given below. These descriptions are based on information provided by the fabric manufacturers, and are included here to familiarize the reader with each of the fabrics. Due to the rapidly changing nature of the engineering fabrics manufacturing industry, these descriptions may not be entirely accurate for fabrics manufactured and marketed under the same trade names in the near future.

"Old" Petromat

Phillips Petroleum Company has been a leader in the production and marketing of engineering fabrics since the middle 1960's. "Petromat" is the manufacturer's name for a family of synthetic engineering fabrics produced for use as a waterproof barrier in reserviors and as a moisture barrier and reinforcement material in roadway maintenance and construction operations. The "Old" Petromat used in this study was received by the Texas Transportation Institute in 1975. Though this particular type of Petromat is no longer manufactured by Phillips Fibers Corporation, it was included in this study due to its widespread use in many field trials in the past.

"Old" Petromat is a nonwoven fabric composed primarily of polypropylene with strands of polyester filament fused into the primary material. The white polyester strands are spaced approximately ¼ in. apart, alligned in the long dimension of the fabric, and are fused into the "top" side of the black polypropylene fabric. The original paving grade petromat fabric was designed to absorb 0.25 to 0.30 gallons of asphalt per square yard of fabric. The following information was obtained from the manufacturer's product literature for paving grade Petromat (49):

| | |
|---|---|
| Tensile Strength, either direction, minimum, lbs | 50 |
| Elongation, warp direction, maximum @ 20 lbs, inches/3 inches | 0.6 |
| Elongation, fill direction, maximum @ 30 lbs, inches/3 inches | 1.0 |
| Weight, (fused two sides), oz/sq yd | 3 to 5 |
| Width, inches | 75 & 150 |
| Length/Roll, (approximate), yds | 100 |

"New" Petromat

"New" Petromat is manufactured and marketed by Phillips Fibers Corporation, a subsidiary of Phillips Petroleum Company. The principal difference between the "Old" and "New" Petromat fabrics used in this study is the absence of the nylon strands in the "New" Petromat. Thus, "New" Petromat is a black, needle punched, nonwoven polypropylene fabric, having no machine direction or orientation. A second difference between the two fabrics is that "New" Petromat is designed to absorb 0.20 gallons of asphalt, while "Old" Petromat was designed to absorb 0.25 to 0.30 gallons of asphalt per square yard of fabric. The following information was obtained from the manufacturer's product literature for paving grade Petromat (50):

| Material Property | Typical | Minimum |
|---|---|---|
| Weight, oz/sq yd | 4.1 | 3.6 |
| Tensile Strength, lbs | 115 | 90 |
| Elongation at Break, % | 65 | 55 |
| Asphalt Retention, gals/sq yd | -- | 0.20 |
| Width, inches | 75 & 150 | -- |
| Length/Roll, yds | 100 | |

Additional product information may be obtained by contacting the manufacturers at the address shown below:

Phillips Fibers Corporation
Engineered Products Marketing
P. O. Box 66
Greenville, South Carolina 29602
Telephone: (803) 242-6600

Mirafi 140

Mirafi 140 fabric is a unique nonwoven fabric constructed from two types of continuous filament fibers. One is a polypropylene homofilament, and the other is a heterofilament comprised of a polypropylene core covered with a nylon sheath. A random mixture of these filaments is formed into a sheet that is heat-bonded or fused at the heterofilament contact points. The polypropylene filaments remain unaffected by the heat-bonding process. Thus, no bonding agent or resin is used in the manufacturing process and purely mechanical links operate to hold the filaments in position.

The following information was obtained from the manufacturer's product literature for Marafi 140 (51):

| | |
|---|---|
| Weight, oz/sq yd | 4 |
| Color | White |
| Length/Roll, meters | 100 |
| Width, meters | 4.5 |

Additional information may be obtained by contacting the manufacturer at the address shown below.

Celanese Fibers Marketing Company
P. O. Box 1414
Charlotte, North Carolina 28232
Telephone: (704) 554-2000

Bidim

"Bidim" is the name of a family of engineering fabrics manufactured by the Monsanto Textiles Company. Bidim engineering fabrics are made of continuous filament polyester fibers which are mechanically interlocked by a needle punching process. They are available in five different styles of thicknesses and weights and are designed for use in road construction and repair, railroad track stabilization, drainage systems, soil reinforcement, and erosion control. All Bidim fabrics are gray in color. The following information was obtained from the manufacturer's product literature for Bidim C34 (52):

| | |
|---|---|
| Weight, oz/sq yd | 8 |
| Grab Tensile Strength, lbs | 255 |
| Grab Elongation, % | 75 |
| Thickness, mils | 90 |
| Trapezoid Tear Strength, lbs | 125 |

| | |
|---|---|
| Mullen Burst Strength, psi | 400 |
| Heat Resistance, °F (at 50 psi loading) | 480 |
| Length/Roll, yds | 330 |
| Width, inches | 166 & 209 |

Additional product information may be obtained by contacting the manufacturer at the address shown below.

Monsanto Textiles Company
Nonwovens Business Group - G4WC
800 N. Lindbergh Blvd.
St. Louis, Missouri 63166
Telephone: (314) 694-7262

Woven Tape

The woven tape fabric used in this study is manufactured by Fiber Industries, Inc., a subsidiary of Celanese Corporation. The fabric consists of continuous polypropylene strands approximately 0.05 in. wide closely woven together. The fabric is black in color and weighs approximately 4.5 ounces per square yard. Additional product information may be obtained by contacting the Celanese Fibers Marketing Company at the address shown on page 243.

Burlington 2532

Burlington Glass Fabrics Company, a division of Burlington Industries, manufactures a variety of fiberglass fabrics. Style 2532 is a continuous filament, plain woven fabric manufactured from an electrical type fiberglass yarn. This fabric is manufactured by combining continuous fiberglass filaments into strands of yarn and mechanically weaving these strands together. The warp, or lengthwise direction of the fabric has sixteen strands per inch of width, while the fill, or crosswise direction has fourteen strands per inch. The following information was obtained from the manufacturer's representative (53):

| | |
|---|---|
| Style | 2532 |
| Color | White |
| Weight, oz/sq yd | 6.91 |
| Tensile Strength, lbs/inch | |
| warp direction | 405 |
| fill direction | 325 |

Additional information may be obtained by contacting the manufacturer at the address shown below:

Burlington Glass Fabrics Company
1345 Avenue of the Americas
New York, New York 10019
Telephone: (212) 333-5000

# APPENDIX F

## DATA REDUCTION RESULTS

The data reduction procedure is described in detail in Chapter V, page 44. Results of the crack opening energy, E, calculations are included on the following pages for reference purposes. The regression constants, a, b, c and d, as well as Strain Energy Release Rate, G, values for each test speciment are also included here. These results area summarized in Table 1, page 59.

FILE NAME IS NOV21-100

| | | |
|---|---|---|
| CYC= 1 | E= 23.814 | C= 0.5 |
| CYC= 3 | E= 8.946 | C= 0.875 |
| CYC= 5 | E= 7.055 | C= 1.05 |
| CYC= 10 | E= 5.525 | C= 1.25 |
| CYC= 30 | E= 3.796 | C= 1.35 |
| CYC= 50 | E= 2.768 | C= 1.4 |
| CYC= 100 | E= 1.657 | C= 1.6 |
| CYC= 150 | E= 1.23 | C= 1.75 |
| CYC= 200 | E= 0.749 | C= 1.85 |
| CYC= 250 | E= 0.484 | C= 2.25 |
| CYC= 300 | E= 0.299 | C= 2.625 |
| CYC= 350 | E= 0.091 | C= 3 |
| CYC= 425 | E= 0.105 | C= 3 |
| CYC= 550 | E= 0.01 | C= 3 |

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? 1
CYCLE ? 550

REGRESSION RESULTS FOR DATA NOV21-100

A= 0.59 B= 0.24
C= 12.32 D= -0.59

FRACTURE TOUGHNESS = -8.24

FILE NAME IS NOV12-1Ø1

| | | |
|---|---|---|
| CYC= 1 | E= 2Ø.651 | C= Ø.25 |
| CYC= 5 | E= 1Ø.175 | C= Ø.5 |
| CYC= 1Ø | E= 9.244 | C= 1 |
| CYC= 3Ø | E= 8.561 | C= 1 |
| CYC= 54 | E= 7.167 | C= 1 |
| CYC= 1ØØ | E= 5.82 | C= 1.25 |
| CYC= 2Ø5 | E= 4 | C= 1.625 |
| CYC= 3ØØ | E= 3.854 | C= 1.625 |
| CYC= 4ØØ | E= 2.799 | C= 1.625 |
| CYC= 5ØØ | E= 1.647 | C= 1.625 |
| CYC= 6ØØ | E= Ø.7Ø9 | C= 1.625 |

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA NOV12-1Ø1

A= Ø.35 B= Ø.26
C= 27.83 D= -Ø.44

FRACTURE TOUGHNESS = -22.2Ø

FILE NAME IS ØCT16-1Ø2

CYC= 1 E= 22.386 C= Ø.1

CYC= 5 E= 13.Ø58 C= Ø.25

CYC= 1Ø E= 1Ø.2Ø7 C= Ø.825

CYC= 3Ø E= 8.692 C= 1.45

CYC= 5Ø E= 6.595 C= 2.25

CYC= 1ØØ E= 4.412 C= 2.25

CYC= 2ØØ E= 3.38 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? NØ
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? NØ

REGRESSION RESULTS FOR DATA ØCT16-1Ø2

A= Ø.12 B= Ø.64
C= 23.73 D= -Ø.35

FRACTURE TOUGHNESS = -17.74

FILE NAME IS ØCT23-1Ø3

CYC= 1 E= 2Ø.325 C= Ø.5

CYC= 5 E= 11.451 C= Ø.75

CYC= 1Ø E= 1Ø.742 C= 1

CYC= 3Ø E= 8.776 C= 1

CYC= 5Ø E= 8.535 C= 1

CYC= 1ØØ E= 7.838 C= 1.Ø5

CYC= 2ØØ E= 6.744 C= 1.25

CYC= 3ØØ E= 6.933 C= 1.525

CYC= 4ØØ E= 5.182 C= 2

CYC= 49Ø E= 2.623 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? NØ
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? NØ
ENTER FABRIC HEIGHT ? 1.ØØ

REGRESSION RESULTS FOR DATA ØCT23-1Ø3

REGRESSION RESULTS BELOW THE FABRIC
A= Ø.5Ø B= Ø.25
C= 2Ø.32 D= -Ø.35

FRACTURE TOUGHNESS = -9.58

```
FILE NAME IS JANØ4-1Ø4

CYC= 1          E= 26.145  C= 1.25

CYC= 5          E= 9.96    C= 1.325

CYC= 1Ø         E= 8.763   C= 1.375

CYC= 3Ø         E= 6.9Ø1   C= 1.375

CYC= 5Ø         E= 8.124   C= 1.65

CYC= 1ØØ        E= 5.162   C= 2

CYC= 2ØØ        E= 4.427   C= 2.25

CYC= 3ØØ        E= 4.44    C= 2.625

CYC= 4ØØ        E= 3.457   C= 3

CYC= 5ØØ        E= 3.138   C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? NO
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? 1
CYCLE  ? 3Ø

REGRESSION RESULTS FOR DATA JANØ4-1Ø4

A= 1.Ø1         B= Ø.16
C= 2Ø.87        D= -Ø.29

FRACTURE TOUGHNESS = -6.34
```

FILE NAME IS AUG16-1Ø5

| | | |
|---|---|---|
| CYC= 1 | E= 2Ø.5 | C= Ø.25 |
| CYC= 5 | E= 11.1 | C= Ø.375 |
| CYC= 11 | E= 1Ø.75 | C= Ø.4 |
| CYC= 3Ø | E= 1Ø.24 | C= Ø.675 |
| CYC= 5Ø | E= 1Ø | C= Ø.725 |
| CYC= 1ØØ | E= 9.75 | C= Ø.788 |
| CYC= 2ØØ | E= 8.52 | C= Ø.825 |
| CYC= 3ØØ | E= 8 | C= Ø.95 |
| CYC= 4ØØ | E= 7.9 | C= 1 |
| CYC= 5ØØ | E= 7.5 | C= 1.25 |
| CYC= 6ØØ | E= 7 | C= 1.6 |
| CYC= 7ØØ | E= 6.75 | C= 1.725 |
| CYC= 8ØØ | E= 6.62 | C= 1.725 |
| CYC= 1ØØØ | E= 6.5 | C= 1.725 |
| CYC= 13ØØ | E= 5 | C= 2.375 |
| CYC= 14ØØ | E= 4 | C= 2.625 |
| CYC= 144Ø | E= 3.5 | C= 3 |

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? NO
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? NO

REGRESSION RESULTS FOR DATA AUG16-1Ø5

A= Ø.2Ø B= Ø.32
C= 19.36 D= -Ø.18

FRACTURE TOUGHNESS = -8.96

```
FILE NAME IS FEBØ6-1Ø6

CYC= 1         E= 29.772  C= 1

CYC= 5         E= 6.868   C= 1.5

CYC= 1Ø        E= 7.285   C= 2.25

CYC= 3Ø        E= 6.243   C= 2.25

CYC= 5Ø        E= 5.75    C= 2.625

CYC= 75        E= 2.588   C= 3

CYC= 1ØØ       E= 1       C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? NO
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? NO

REGRESSION RESULTS FOR DATA FEBØ6-1Ø6

A= 1.Ø7          B= Ø.23
C= 29.2Ø         D= -Ø.61

FRACTURE TOUGHNESS = -12.ØØ
```

FILE NAME IS FEBØ1-1Ø7

CYC= 1 E= 2Ø.585 C= Ø.1

CYC= 2 E= 2Ø.41 C= Ø.25

CYC= 5 E= 15.384 C= Ø.75

CYC= 1Ø E= 12.324 C= 1

CYC= 5Ø E= 8.6Ø6 C= 1

CYC= 1ØØ E= 3.561 C= 1

CYC= 3ØØ E= 1 C= 1

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? NO
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? NO

REGRESSION RESULTS FOR DATA FEBØ1-1Ø7

A= Ø.23 B= Ø.31
C= 32.34 D= -Ø.53

FRACTURE TOUGHNESS = -39.51

FILE NAME IS JAN22-1Ø8

CYC= 1 E= 33.274 C= Ø.25

CYC= 5 E= 13.339 C= 1

CYC= 1Ø E= 13.274 C= 1.375

CYC= 3Ø E= 8.294 C= 1.5

CYC= 5Ø E= 7.1Ø2 C= 2

CYC= 1ØØ E= 6.438 C= 2.25

CYC= 13Ø E= 5.481 C= 3

CYC= 15Ø E= 4.687 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA JAN22-1Ø8

A= Ø.36 B= Ø.43
C= 29.2Ø D= -Ø.35

FRACTURE TOUGHNESS = -11.Ø7

FILE NAME IS JAN22-1Ø9

CYC= 1 E= 28.756 C= Ø.275

CYC= 5 E= 13.ØØ7 C= 1

CYC= 1Ø E= 11.516 C= 1

CYC= 3Ø E= 8.567 C= 1.375

CYC= 5Ø E= 8.131 C= 1.75

CYC= 75 E= 6.686 C= 2.625

CYC= 1ØØ E= 4.121 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA JAN22-1Ø9

A= Ø.32 B= Ø.47
C= 27.65 D= -Ø.37

FRACTURE TOUGHNESS = -11.Ø8

FILE NAME IS JAN10-110

| | | |
|---|---|---|
| CYC= 1 | E= 31.822 | C= 0.75 |
| CYC= 5 | E= 12.102 | C= 1.375 |
| CYC= 10 | E= 11.015 | C= 1.625 |
| CYC= 30 | E= 9.713 | C= 1.8 |
| CYC= 50 | E= 7.61 | C= 2 |
| CYC= 100 | E= 5.911 | C= 2.175 |
| CYC= 200 | E= 5.052 | C= 3 |
| CYC= 300 | E= 4.218 | C= 3 |

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA JAN10-110

A= 0.85 B= 0.22
C= 25.96 D= -0.31

FRACTURE TOUGHNESS = -7.21

```
FILE NAME IS JUL1Ø-111

CYC= 1        E= 35.6    C= Ø.25

CYC= 5        E= 14.43   C= Ø.5

CYC= 1Ø       E= 13.45   C= Ø.75

CYC= 3Ø       E= 12.22   C= 1

CYC= 5Ø       E= 1Ø.41   C= 1

CYC= 11Ø      E= 9.5     C= 1

CYC= 3ØØ      E= 8.Ø6    C= 1

CYC= 6ØØ      E= 9.Ø7    C= 1

CYC= 85Ø      E= 7.25    C= 1.625

CYC= 11ØØ     E= 7       C= 2.5

CYC= 16ØØ     E= 6.78    C= 2.625

CYC= 1835     E= 4.75    C= 2.625

CYC= 22ØØ     E= 4.68    C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N
ENTER FABRIC HEIGHT  ? 1.ØØ

REGRESSION RESULTS FOR DATA JUL1Ø-111

REGRESSION RESULTS BELOW THE FABRIC
A= Ø.24          B= Ø.46
C= 34.12         D= -Ø.44

FRACTURE TOUGHNESS = -21.99
```

```
FILE NAME IS NOV02-112

CYC= 1        E= 24.523  C= 0.75

CYC= 6        E= 13.237  C= 1

CYC= 10       E= 11.06   C= 1.25

CYC= 20       E= 9.883   C= 1.75

CYC= 30       E= 9.532   C= 2.25

CYC= 50       E= 5.986   C= 2.25

CYC= 100      E= 4.386   C= 2.25

CYC= 150      E= 3.903   C= 3

CYC= 200      E= 3.492   C= 3

CYC= 300      E= 2.705   C= 3

CYC= 400      E= 1.825   C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N

REGRESSION RESULTS FOR DATA NOV02-112

A= 0.76          B= 0.24
C= 30.29         D= -0.42

FRACTURE TOUGHNESS = -11.41
```

FILE NAME IS JANØ3-113

CYC= 1 E= 22.48 C= Ø.9

CYC= 5 E= 11.44 C= 1

CYC= 1Ø E= 9.74 C= 1

CYC= 3Ø E= 7.43 C= 1

CYC= 5Ø E= 6.9 C= 1

CYC= 1ØØ E= 6.5 C= 1

CYC= 2ØØ E= 3.75 C= 1

CYC= 3ØØ E= 3.49 C= 1.1

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA JANØ3-113

A= Ø.92 B= Ø.Ø2
C= 21.14 D= -Ø.3Ø

FRACTURE TOUGHNESS = -47.46

FILE NAME IS SEPTØ7114

| | | |
|---|---|---|
| CYC= 1 | E= 23.917 | C= Ø.15 |
| CYC= 5 | E= 1Ø.315 | C= 1.125 |
| CYC= 1Ø | E= 9.886 | C= 1.375 |
| CYC= 3Ø | E= 7.278 | C= 1.75 |
| CYC= 5Ø | E= 5.987 | C= 1.95 |
| CYC= 1ØØ | E= 5.332 | C= 2.25 |
| CYC= 2ØØ | E= 3.881 | C= 2.4 |
| CYC= 25Ø | E= 3.624 | C= 2.75 |
| CYC= 3ØØ | E= 3.55 | C= 2.75 |
| CYC= 45Ø | E= 2.54 | C= 2.95 |

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA SEPTØ7114

A= Ø.36 B= Ø.37
C= 21.71 D= -Ø.33

FRACTURE TOUGHNESS = -8.82

FILE NAME IS SEPT24-115

CYC= 1 E= 23.Ø33 C= Ø.25

CYC= 5 E= 1Ø.Ø58 C= 1

CYC= 1Ø E= 9.192 C= 1

CYC= 3Ø E= 7.272 C= 1

CYC= 5Ø E= 6.575 C= 1

CYC= 1ØØ E= 6.582 C= 1

CYC= 2ØØ E= 5.7Ø9 C= 1.125

CYC= 3ØØ E= 4.218 C= 1.125

CYC= 4ØØ E= 2.858 C= 1.125

CYC= 725 E= 1.Ø93 C= 1.125

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA SEPT24-115

A= Ø.5Ø B= Ø.14
C= 25.19 D= -Ø.38

FRACTURE TOUGHNESS = -21.82

FILE NAME IS OCT24-116

CYC= 1 E= 25.Ø85 C= Ø.25

CYC= 5 E= 11.676 C= Ø.75

CYC= 1Ø E= 9.354 C= 1

CYC= 3Ø E= 7.673 C= 1.5

CYC= 5Ø E= 6.853 C= 1.625

CYC= 1ØØ E= 5.57 C= 1.775

CYC= 2ØØ E= 4.882 C= 2.25

CYC= 3ØØ E= 4.683 C= 2.25

CYC= 4ØØ E= 4.24 C= 2.25

CYC= 5ØØ E= 4.286 C= 2.25

CYC= 6ØØ E= 4.392 C= 2.25

CYC= 7ØØ E= 3.671 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N
ENTER FABRIC HEIGHT ? 2.25

REGRESSION RESULTS FOR DATA OCT24-116

REGRESSION RESULTS BELOW THE FABRIC
A= Ø.31 B= Ø.42
C= 21.81 D= -Ø.3Ø

FRACTURE TOUGHNESS = -8.41

FILE NAME IS MAR24-117

| | | |
|---|---|---|
| CYC= 1 | E= 32.916 | C= Ø.25 |
| CYC= 5 | E= 17.337 | C= Ø.75 |
| CYC= 1Ø | E= 14.Ø75 | C= 1 |
| CYC= 3Ø | E= 12.682 | C= 1 |
| CYC= 5Ø | E= 1Ø.82 | C= 1 |
| CYC= 3ØØ | E= 8.971 | C= 1 |
| CYC= 6ØØ | E= 6.425 | C= 1 |
| CYC= 9ØØ | E= 5.794 | C= 2.5 |
| CYC= 11ØØ | E= 4.973 | C= 3 |
| CYC= 14ØØ | E= 2.285 | C= 3 |

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA MAR24-117

| | |
|---|---|
| A= Ø.36 | B= Ø.26 |
| C= 32.45 | D= -Ø.29 |

FRACTURE TOUGHNESS = -16.63

FILE NAME IS JAN07-118

CYC= 1 E= 20.93 C= 0.375

CYC= 5 E= 9.147 C= 0.625

CYC= 10 E= 9.303 C= 0.875

CYC= 30 E= 5.716 C= 1.875

CYC= 50 E= 6.751 C= 2.25

CYC= 100 E= 2.513 C= 2.25

CYC= 200 E= 1.21 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA JAN07-118

A= 0.36 B= 0.40
C= 25.79 D= -0.51

FRACTURE TOUGHNESS = -14.56

FILE NAME IS JAN07-119

CYC= 1 E= 21.438 C= 0.75

CYC= 5 E= 8.014 C= 1

CYC= 10 E= 7.304 C= 1

CYC= 30 E= 6.074 C= 1

CYC= 50 E= 5.143 C= 1

CYC= 100 E= 4.348 C= 1

CYC= 200 E= 4.303 C= 1

CYC= 250 E= 3.958 C= 2

CYC= 400 E= 3.196 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA JAN07-119

A= 0.62 B= 0.18
C= 15.80 D= -0.26

FRACTURE TOUGHNESS = -6.01

```
FILE NAME IS JAN11-120

CYC= 1          E= 28.32  C= 0.375

CYC= 5          E= 17.649 C= 0.95

CYC= 10         E= 14.765 C= 1.1

CYC= 30         E= 10.156 C= 1.875

CYC= 50         E= 7.005  C= 2.25

CYC= 100        E= 6.041  C= 2.25

CYC= 200        E= 4.537  C= 2.25

CYC= 300        E= 3.756  C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N

REGRESSION RESULTS FOR DATA JAN11-120

A= 0.49           B= 0.32
C= 31.16          D= -0.36

FRACTURE TOUGHNESS = -11.66
```

```
FILE NAME IS JAN07-121

CYC= 1          E= 20.644  C= 0.5

CYC= 5          E= 9.55    C= 0.75

CYC= 10         E= 8.717   C= 0.95

CYC= 30         E= 7.044   C= 0.95

CYC= 50         E= 6.412   C= 1

CYC= 100        E= 6.471   C= 1

CYC= 300        E= 5.078   C= 1

CYC= 500        E= 4.036   C= 1

CYC= 800        E= 3.45    C= 1

CYC= 900        E= 2.766   C= 1.5

CYC= 1000       E= 3.6     C= 1.625

CYC= 1300       E= 0.351   C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N
ENTER FABRIC HEIGHT  ? 1.00

REGRESSION RESULTS FOR DATA JAN07-121

REGRESSION RESULTS BELOW THE FABRIC
A= 0.52          B= 0.20
C= 18.73         D= -0.31

FRACTURE TOUGHNESS = -9.32
```

FILE NAME IS MAY14-122

CYC= 1 E= 37.727 C= 0.875

CYC= 5 E= 15.045 C= 1.375

CYC= 10 E= 15.333 C= 1.625

CYC= 100 E= 7.949 C= 2.125

CYC= 150 E= 7.897 C= 2.25

CYC= 200 E= 7.35 C= 2.25

CYC= 300 E= 5.761 C= 2.25

CYC= 400 E= 5.787 C= 2.25

CYC= 500 E= 5.41 C= 2.25

CYC= 700 E= 4.98 C= 3

CYC= 900 E= 4.576 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N
ENTER FABRIC HEIGHT ? 2.25

REGRESSION RESULTS FOR DATA MAY14-122

REGRESSION RESULTS BELOW THE FABRIC
A= 0.95 B= 0.18
C= 32.21 D= -0.32

FRACTURE TOUGHNESS = -9.59

```
FILE NAME IS JAN09-123

CYC= 1          E= 21.067 C= 0.25

CYC= 5          E= 10.768 C= 0.5

CYC= 10         E= 10.657 C= 0.75

CYC= 30         E= 8.945  C= 0.8

CYC= 50         E= 5.957  C= 0.95

CYC= 100        E= 7.363  C= 1

CYC= 200        E= 7.565  C= 1.05

CYC= 300        E= 6.848  C= 1.1

CYC= 500        E= 5.52   C= 1.1

CYC= 800        E= 5.097  C= 1.1

CYC= 900        E= 4.954  C= 1.225

CYC= 1000       E= 5.403  C= 1.225

CYC= 1200       E= 4.908  C= 1.375

CYC= 1500       E= 4.231  C= 2.125

CYC= 2000       E= 3.118  C= 2.95

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N
ENTER FABRIC HEIGHT  ? 1.00

REGRESSION RESULTS FOR DATA JAN09-123

REGRESSION RESULTS BELOW THE FABRIC
A= 0.27          B= 0.33
C= 19.86         D= -0.28

FRACTURE TOUGHNESS = -10.08
```

FILE NAME IS AUG17-124

CYC= 1 E= 26.06 C= 0.5

CYC= 5 E= 9.8 C= 1.625

CYC= 10 E= 8 C= 1.875

CYC= 30 E= 6.78 C= 2.25

CYC= 50 E= 6 C= 2.25

CYC= 100 E= 4.58 C= 2.25

CYC= 135 E= 4 C= 2.875

CYC= 150 E= 3.1 C= 2.95

CYC= 175 E= 3 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA AUG17-124

A= 0.74 B= 0.27
C= 22.21 D= -0.37

FRACTURE TOUGHNESS = -6.59

FILE NAME IS SEPT19-125

CYC= 1 E= 22.192 C= 0.75

CYC= 5 E= 10.72 C= 1

CYC= 10 E= 10.127 C= 1.05

CYC= 30 E= 9.029 C= 1.05

CYC= 50 E= 8.076 C= 1.05

CYC= 100 E= 6.524 C= 1.05

CYC= 200 E= 4.234 C= 1.45

CYC= 300 E= 1.981 C= 1.55

CYC= 400 E= 1.64 C= 1.55

CYC= 700 E= 1.129 C= 1.55

CYC= 850 E= 0.914 C= 1.55

CYC= 1000 E= 0.694 C= 1.55

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA SEPT19-125

A= 0.77 B= 0.10
C= 34.25 D= -0.50

FRACTURE TOUGHNESS = -35.50

FILE NAME IS SEPT02-126

CYC= 1 E= 27.692 C= 0.375

CYC= 7 E= 12.572 C= 0.625

CYC= 10 E= 12.785 C= 0.7

CYC= 25 E= 12.889 C= 1.35

CYC= 50 E= 11.966 C= 1.5

CYC= 75 E= 8.489 C= 1.75

CYC= 100 E= 7.477 C= 1.975

CYC= 150 E= 7.608 C= 2

CYC= 200 E= 5.852 C= 2

CYC= 300 E= 5.673 C= 2.5

CYC= 400 E= 5.198 C= 2.625

CYC= 475 E= 3.614 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA SEPT02-126

A= 0.36 B= 0.34
C= 28.18 D= -0.29

FRACTURE TOUGHNESS = -11.03

```
FILE NAME IS SEPT12-127

CYC= 1         E= 30.74  C= 0.75

CYC= 5         E= 16.72  C= 1

CYC= 10        E= 16.5   C= 1

CYC= 30        E= 16.46  C= 1.05

CYC= 50        E= 15     C= 1.05

CYC= 100       E= 14     C= 1.05

CYC= 200       E= 12.25  C= 1.1

CYC= 300       E= 10.94  C= 1.535

CYC= 400       E= 10.9   C= 1.7

CYC= 500       E= 10     C= 1.875

CYC= 600       E= 9.75   C= 2.1

CYC= 675       E= 8      C= 3

DROP  OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N

REGRESSION RESULTS FOR DATA SEPT12-127

A= 0.63          B= 0.17
C= 27.09         D= -0.16

FRACTURE TOUGHNESS = -6.63
```

FILE NAME IS SEPT21-128

CYC= 1 E= 24.Ø25 C= Ø.5

CYC= 6 E= 11.186 C= Ø.9

CYC= 1Ø E= 9.969 C= 1.25

CYC= 3Ø E= 7.845 C= 1.5

CYC= 5Ø E= 6.893 C= 1.825

CYC= 1ØØ E= 6.1Ø6 C= 1.95

CYC= 2ØØ E= 4.882 C= 2.1

CYC= 3ØØ E= 4.511 C= 2.25

CYC= 4ØØ E= 4.1Ø1 C= 2.25

CYC= 5ØØ E= 3.592 C= 3

CYC= 6ØØ E= 3.168 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA SEPT21-128

A= Ø.58 B= Ø.25
C= 21.2Ø D= -Ø.28

FRACTURE TOUGHNESS = -6.8Ø

FILE NAME IS SEPT17-129

CYC= 1 E= 22.864 C= Ø.15

CYC= 5 E= 12.598 C= Ø.5

CYC= 1Ø E= 12.2Ø6 C= Ø.825

CYC= 3Ø E= 1Ø.26 C= Ø.95

CYC= 5Ø E= 11.123 C= 1

CYC= 1ØØ E= 9.Ø35 C= 1

CYC= 2ØØ E= 7.988 C= 1.1

CYC= 277 E= 7.217 C= 3

CYC= 3ØØ E= 7.Ø88 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA SEPT17-129

A= Ø.19 B= Ø.43
C= 19.86 D= -Ø.17

FRACTURE TOUGHNESS = -6.78

```
FILE NAME IS OCTØ3-131

CYC= 1         E= 14.166 C= Ø.5

CYC= 2         E= 14.166 C= Ø.5

CYC= 5         E= 9.258  C= 1

CYC= 1Ø        E= 5.623  C= 1

CYC= 3Ø        E= 2.342  C= 1

CYC= 5Ø        E= 1.463  C= 1

CYC= 1ØØ       E= 1.194  C= 1

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? 1
CYCLE  ? 1
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? 1
CYCLE  ? 1

REGRESSION RESULTS FOR DATA OCTØ3-131

A= Ø.63          B= Ø.11
C= 24.36         D= -Ø.67

FRACTURE TOUGHNESS = -36.75
```

```
FILE NAME IS SEPT26-132

CYC= 1          E= 22.532 C= 0.5

CYC= 5          E= 10.08  C= 0.875

CYC= 10         E= 10.074 C= 1.25

CYC= 30         E= 7.421  C= 1.375

CYC= 50         E= 6.511  C= 1.75

CYC= 100        E= 5.511  C= 2.125

CYC= 175        E= 4.345  C= 2.75

CYC= 200        E= 3.864  C= 3

CYC= 300        E= 3.294  C= 3

CYC= 400        E= 2.223  C= 3

CYC= 450        E= 2.21   C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N

REGRESSION RESULTS FOR DATA SEPT26-132

A= 0.54          B= 0.29
C= 22.63         D= -0.35

FRACTURE TOUGHNESS = -8.26
```

```
FILE NAME IS OCTØ5-133

CYC= 1         E= 15.433 C= Ø.5

CYC= 5         E= 9.448  C= Ø.9

CYC= 1Ø        E= 9.Ø41  C= 1

CYC= 3Ø        E= 7.46   C= 1.Ø5

CYC= 5Ø        E= 6.489  C= 1.Ø5

CYC= 1ØØ       E= 5.367  C= 1.25

CYC= 2ØØ       E= 4.494  C= 1.45

CYC= 3ØØ       E= 3.786  C= 2

CYC= 4ØØ       E= 2.657  C= 3

CYC= 45Ø       E= 1.968  C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL)  ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL)  ? N

REGRESSION RESULTS FOR DATA OCTØ5-133

A= Ø.48          B= Ø.26
C= 17.86         D= -Ø.3Ø

FRACTURE TOUGHNESS = -7.15
```

FILE NAME IS OCTØ5-134

CYC= 1 E= 21.9Ø2 C= Ø.75

CYC= 5 E= 9.534 C= 1

CYC= 1Ø E= 8.398 C= 1.175

CYC= 3Ø E= 6.161 C= 1.625

CYC= 5Ø E= 4.914 C= 2.125

CYC= 1ØØ E= 5.229 C= 2.25

CYC= 2ØØ E= 3.956 C= 2.5

CYC= 3ØØ E= 2.716 C= 2.75

CYC= 4ØØ E= 2.519 C= 2.875

CYC= 45Ø E= 2.119 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA OCTØ5-134

A= Ø.73 B= Ø.23
C= 19.85 D= -Ø.34

FRACTURE TOUGHNESS = -6.66

FILE NAME IS OCT08-135

CYC= 1 E= 22.237 C= 0.25

CYC= 5 E= 9.737 C= 0.5

CYC= 10 E= 9.409 C= 0.7

CYC= 30 E= 8.832 C= 0.75

CYC= 50 E= 7.952 C= 0.85

CYC= 100 E= 6.384 C= 1

CYC= 200 E= 5.216 C= 2

CYC= 300 E= 4.317 C= 2.375

CYC= 400 E= 2.624 C= 3

CYC= 450 E= 1.528 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA OCT08-135

A= 0.23 B= 0.39
C= 23.97 D= -0.36

FRACTURE TOUGHNESS = -15.50

FILE NAME IS OCT15-136

CYC= 1 E= 27.341 C= Ø.5

CYC= 5 E= 1Ø.816 C= Ø.875

CYC= 1Ø E= 1Ø.386 C= Ø.925

CYC= 3Ø E= 8.Ø44 C= 1.625

CYC= 5Ø E= 6.549 C= 1.725

CYC= 1ØØ E= 5.755 C= 1.95

CYC= 2ØØ E= 4.749 C= 2.25

CYC= 3ØØ E= 3.698 C= 2.575

CYC= 4ØØ E= 3.115 C= 2.625

CYC= 5ØØ E= 2.685 C= 3

DROP OUT ANY CRACKING POIONTS (N OR TOTAL) ? N
DROP OUT ANY ENERGY POINTS (N OR TOTAL) ? N

REGRESSION RESULTS FOR DATA OCT15-136

A= Ø.53 B= Ø.27
C= 23.88 D= -Ø.33

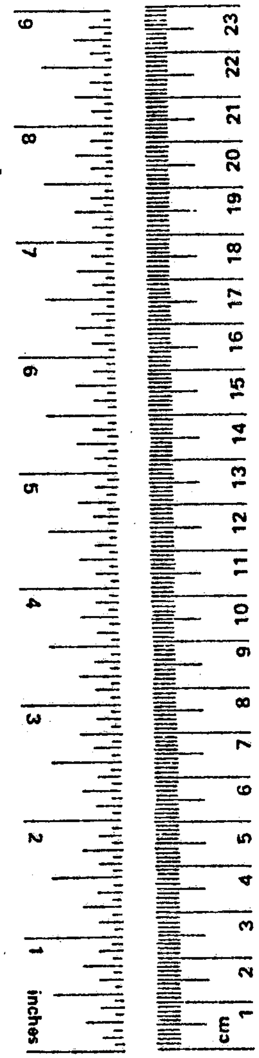
FRACTURE TOUGHNESS = -8.96

# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |