LABORATORY THERMAL EXPANSION MEASURING TECHNIQUES APPLIED TO BITUMINOUS CONCRETE

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by

C. C. HOOKS

W. H. GOETZ

Joint
Highway
Research
Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Informational Report

LABORATORY THERMAL EXPANSION MEASURING TECHNIQUES APPLIED TO BITUMINOUS CONCRETE

TO: K. B. Woods, Director
Joint Highway Research Project

September 18, 1964

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 2-4

The attached report entitled "Laboratory Thermal Expansion Measuring Techniques Applied to Bituminous Concrete" is presented to the Board as information. The project was performed under a contract with the U. S. Army Engineer Waterways Experiment Station, Corps of Engineers. Mr. C. C. Hooks, Graduate Assistant, and Professor W. H. Goetz, Research Engineer, are the authors of the report.

The report is presented to the Board in line with the policy of the School of Civil Engineering to make available to the Indiana State Highway Commission pertinent reports of research performed in the School of Civil Engineering.

Respectfully submitted,

Harold L Michael
Harold L. Michael, Secretary

HLM:bc

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Informational Report

LABORATORY THERMAL EXPANSION MEASURING TECHNIQUES APPLIED TO BITUMINOUS CONCRETE

by

C. C. Hooks

Graduate Assistant

and

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Joint Highway Research Project

File: 2-4

(Research performed under contract
with US Army Engineer Waterways
Experiment Station, Corps of Engineers)

Purdue University
Lafayette, Indiana
September 18, 1964

PREFACE

This report presents results of work accomplished under contract DA-22-079-CIVENG-62-77 between the Corps of Engineers, U. S. Army, and the Purdue Research Foundation, Purdue University, The work was performed by Mr. Collis C. Hooks, graduate assistant, in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering. The work was directed by Professor W. H. Goetz, and was performed using the facilities of the School of Civil Engineering, Purdue University, K. B. Woods, Head. Dr. W. L. Dolch contributed valuable assistance throughout this investigation and aided in the review of the final manuscript.

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ABSTRACT

Hooks, Collis C., MSCE, Purdue University, January 1965. Laboratory Thermal Expansion Measuring Techniques Applied to Bituminous Concrete. Major Professor: William H. Goetz.

A laboratory study was conducted to investigate several methods of measurement applicable to determining the thermal expansion and contraction of bituminous concrete. The primary objective was to select the test methods which would measure most adequately thermal expansion and contraction. Both linear as well as volumetric techniques were investigated over the temperature range of - 30 to 40°C.

Three volumetric and three linear techniques were investigated in the course of this investigation. The best of the volumetric techniques was found to be a mercury-filled dilatometer, constructed of stainless steel and accommodating a standard size Marshall specimen. The best of the linear techniques investigated was an optical one, composed of two microscopes separated by a 10-inch gage length and mounted on a chassis which provided accurate positioning along two perpendicular lines in the horizontal plane. The linear specimens were 12-inch by 2 1/2-inch by approximately 2-inch beams.

In an attempt to evaluate these methods more completely, variables were introduced into the linear and volumetric test specimens for the purpose of observing whether the measuring technique could distinguish adequately any change in the expansion resulting from the addition of

these variables. The variables introduced included: type of aggregate, grade of asphalt cement, asphalt content and method of compaction.

Although the variables were not introduced intentionally for the purpose of evaluating the effects they produced on the resulting mixture, certain general trends were observed. In most cases there existed a reasonable correlation between volumetric and linear coefficients of expansion for specimens of similar composition tested with the respective techniques.

The results from both the volumetric and linear techniques demonstrated that a linear relationship existed between temperature and expansion over the temperature range of - 30 to 15°C. Above 15°C, inconsistencies were observed in the expansion rates of replicate specimens, indicating an inadequacy in the establishment of a consistent temperature-expansion trend for higher temperatures.

After subjecting specimens to a cyclic temperature change, the linear specimens exhibited differences between their original and final lengths which were subject to the conditions and limitations of the test technique involved.

The coefficients of expansion for the mixes were found to increase with increasing asphalt content.

On the basis of overall results, there was no appreciable difference in the measured coefficient of expansion between individual mixes composed of a single type aggregate mixed with the two different grades of asphalt cement used in this study. On the basis of the overall results, there was no appreciable difference in the measured thermal coefficient of expansion for individual mixes composed of the same grade asphalt and two different types of aggregate, a limestone and a gravel.

The measured coefficients of expansion for one of the mixes tested in this study was shown to vary approximately in proportion to the thermal coefficient and volume of the respective components in the mixtures.

The average linear coefficient of thermal expansion for all the mixes tested in this report was of the order of 2.0×10^{-5} in/in/°C. The average volumetric coefficient of thermal expansion for all the mixes tested was of the order of 7.0×10^{-5} $in^3/in^3/°C$.

INTRODUCTION

Discussion of the Problem

When a material is subjected to a temperature gradient or temperature change, or when a composite material consisting of two or more materials having different rates of expansion is heated either uniformly or nonuniformly, the various elements tend to expand different amounts in accordance with their individual temperatures and thermal rates of expansion. To enable the body to remain continuous, rather than allowing each element to expand individually, a system of thermal strain and associated stresses may be introduced depending upon the shape of the body and the temperature distribution. If the material cannot withstand the stresses and strains, rupture may occur.

Brittle and ductile materials react in considerably different manners to thermal stress. Brittle materials can endure only a very small amount of strain before rupture; ductile materials can undergo appreciable strain without rupture. Since thermal stress behavior depends essentially on the ability of the material to absorb the induced strains necessary to maintain a continuous body upon the application of a thermal gradient, brittle materials cannot readily withstand these superimposed strains without inducing enough stress to cause rupture. Ductile materials, on the other hand, can usually withstand these additional strains, but may ultimately fail if subjected to a number of cycles of imposed temperature.

Considerable research has been carried on in the field of thermal properties of materials and, in particular, in the field of thermal expansion. One of the first accounts known to us of the observance of thermal volume change was demonstrated by Galileo's attempt to construct a thermometer using the expansive properties of air. Since Galileo's time, science has come to recognize and investigate many aspects of the thermal expansion of materials. The uses to which this phenomenon has been advanced are quite numerous, but along with these advantages are many problems that have also resulted. One of the major sources of difficulty occurring from the thermal expansion of materials is in the construction field. This problem is quite evident when an examination of current design procedures for major bridges, buildings, portland cement concrete highways, and runways is made. In the design of these structures, consideration is given to the effects of temperature change which can induce considerable stresses and resulting strains in these brittle materials which, if not allowed for, can cause surficial failure if not a complete structural failure.

With the advent of construction in the arctic and the increasing use of asphaltic concrete as a building material for airfields and roads in these severe weather conditions, consideration must now be given to the thermal expansion properties of this material. In the past, asphaltic concrete being considered somewhat ductile and plastic, little concern was developed for this property under ordinary operating environments. Because this material is being used more and more in areas of low temperature conditions, an investigation of the expansive properties is desirable. Based on information regarding the thermal expansion and contraction of this material, some means of adaptation of this property to design procedures may subsequently be developed. It is toward this ultimate goal that this research has been conducted.

Purpose of the Investigation

The purpose of this investigation has been to measure the linear and volumetric thermal expansion of laboratory specimens of various bituminous mixes over a broad range of temperatures. The temperature ranges investigated are those representative of arctic, subarctic, and temperate geographical areas.

The primary purpose of the study has been to investigate several methods of measuring the thermal expansion. Then by a comparison of the methods, by means of results, ease of technique, degree of accuracy, and cost, the most desirable method was selected for use in further studies. Investigation of volumetric as well as linear expansion was conducted. In order to afford some means of comparison of the various test methods, mixes were varied by changing asphalt content, grade of asphalt, means of compaction, and type of aggregate. The effects of these variables on the expansive characteristics of the resulting mixes was also investigated.

REVIEW OF LITERATURE

Definition of Terms

Before proceeding any further with this discussion, it would be advantageous to define the terms and concepts to be used in the ensuing discussion.

Thermal expansion, defined in its broadest sense, is that change in length, or volume, of a body resulting from a temperature change. One of the most important concepts involved in thermal expansion is that of cohesion. The molecules of any substance attract one another with a force called cohesion. It is cohesion that is the resisting force that prevents a wire from breaking when supporting a heavy weight. Another factor adding to cohesion in keeping the molecules of a body together is atmospheric pressure. However, opposed to both of these forces is the effect produced by heat. The resulting effect of the agitation of the molecules of the body being heated is to make them jostle one another apart. Thus, in general, an increase in temperature results in expansion. In solids, in which the cohesion is relatively large, the expansion for a given increase of temperature is very slight, especially when the test is made at low temperature (26).

The change in length that takes place when a solid body is heated depends upon the original length of the body and the temperature range over which it is heated. The observation of this change is meaningless unless it is related to the length of the body and the temperature range.

The relation between these factors is known as the coefficient of linear thermal expansion and has been defined in a number of ways.

1) The average coefficient of linear expansion, a, is defined as:

$$_{t_1}a_{t_2} = \frac{L_2 - L_1}{L_o(t_2 - t_1)} = \frac{\Delta L}{L_o \Delta t}$$

where $_{t_1}a_{t_2}$ is the average coefficient of expansion between temperatures t_1 and t_2, L_1 and L_2 are the lengths at t_1 and t_2, respectively, and L_o is the length at some reference temperature. This reference temperature may be any convenient temperature. The difference introduced in using room temperature instead of 0^oC is negligible for the average coefficient of linear expansion.

If L_o is the initial length of a solid body at 0^oC, then its length, L_t, at any temperature, t^oC, may be represented by the empirical equation:

$$L_t = L_o(1 + at + bt^2 + ---)$$

where a and b are constants dependent upon the material. In most cases, these constants, a and b, are positive, for bodies usually expand at a faster rate as the temperature increases. For a short range of temperature, the linear equation $L_t = L_o(1 + at)$ may be used instead of the curvelinear form.

When a molecular change, or transformation, occurs on heating or cooling a body, the length of the body may not be accurately represented in all cases by a first, second, or third degree equation. In some cases, it may be desirable to obtain two equations, one for the range below the transformation temperature or point of inflection, and the other equation for the range above the transformation temperature.

2) A change in volume that takes place when a solid body is heated may be treated in a similar manner. The following volumetric equations correspond to the previous equations relating to linear thermal expansion:

Average:

$$_{t_1}\alpha_{t_2} = \frac{V_2 - V_1}{V_o(t_2 - t_1)} = \frac{\Delta V}{V_o \Delta t}$$

Empirical:

$$V_t = V_o(1 + \alpha t + \beta t^2 + \text{---})$$

where $_{t_1}\alpha_{t_2}$ is the average coefficient of cubical thermal expansion between temperatures t_1 and t_2, V_1 is the volume at t_1, V_2 is the volume at t_2, and V_o is the volume at a reference temperature. V_t is the volume at any temperature, t^o; α and β are constants dependent on the material.

For an isotropic body, in the temperature range from 0^oC to t^oC, the volumetric coefficient of expansion is three times the linear coefficient.

The above equations and definitions are adapted from a National Bureau of Standards circular (33). Other terms that are of interest include specific heat, conductivity, and diffusivity of heat.

3) Specific heat is the ratio of the quantity of heat required to raise the temperature of a body one degree centigrade to that

required to raise an equal mass of water one degree centigrade. Specific heat may be expressed by the equation:

$$s = \frac{H}{m(t_1 - t_2)}$$

where s is specific heat, H is units of heat added or removed, m is the mass of material involved, and $t_1 - t_2$ is the temperature change in degrees.

4) Conductivity denotes time rate of transfer of heat through unit thickness across unit area for a unit temperature difference. Conductivity may be expressed by the equation:

$$R = \frac{Hd}{(t_2 - t_1)aT}$$

where H is units of heat transferred, R is specific heat conductivity in units of heat per unit time per unit area for unit thickness and unit temperature change, $t_2 - t_1$ is temperature difference in degrees, a is cross sectional area, T is elapsed time, and d is the thickness.

5) Diffusivity of heat denotes rate of advancement of temperature change across a unit thickness of material for a unit initial temperature difference. It is a function of the thermal conductivity of the material, its specific heat, and its density. Diffusivity of heat may be expressed by the equation:

$$\frac{dH}{dt} = -Dsd\,\frac{dT}{dx}\,dy\,dz$$

where dH is quantity of heat transferred in time dt, dT is temperature difference, D is diffusivity, s is specific heat, d is density of material, dt is elasped time, x is line of variation of temperature, and dy dz is area.

The above equations and definitions are adapted from the Handbook of Chemistry and Physics, 43rd Edition, 1961, Chemical Rubber Publishing Company; Webster's New Collegiate Dictionary, Text Edition, 1961, G. and C. Merriam Company; and Highway Engineering Handbook, K. B. Woods Editor-in-Chief, McGraw-Hill Book Company, Inc., 1960.

General Concepts

There are many factors which have a marked effect upon the performance of compacted bituminous mixtures (109). One of these factors that has received considerable attention is discussed by Rader (70) as follows:

> "It is important that bituminous pavements be designed to resist cracking. This is especially true for pavements laid in the northern part of the United States. One of the strong competitive advantages of properly designed and constructed bituminous pavements is the ability to resist cracking, making it unnecessary to install joints to provide for expansion and contraction."

and

> "Cracks in asphalt pavements may be due 1) to the characteristics of the asphalt paving mixtures or 2) to structural defects in the pavement. Cracks of the first class are due primarily to failure of the asphalt pavements to resist stresses caused by contraction produced by temperature reduction."

In the past, work has been done on the relationship between temperature and strength properties and resistance to cracking, but very little has been done regarding the thermal expansion and contraction involved. Rader (71, 72, 73, 74), and Rashig and Doyle (75) have done work in relating strength parameters to low temperature cracking. Rader advances the following conclusions: 1) Asphalts of high susceptibility to temperature change produce mixtures that are least resistant to cracking at low temperatures, as indicated by their high modulus of elasticity, low modulus of rupture and low toughness, 2) Source and method of refining and consistency appeared to have little relation to cracking of sheet asphalt paving mixtures, 3) Other factors being equal, it would appear that those mixtures containing the highest penetration asphalt and the highest percentage of asphalt consistent with the necessary stability should prove most resistant to cracking at low temperature.

Rashig and Doyle, using test methods similar to Rader, agree with the latter's findings and add that the standard penetration of the asphalt is reduced after a freezing period by 4 to 10 points, thus showing some physical change in the structure of the material. It was also pointed out in their study that, based on field inspection, the concrete base course should be smooth instead of roughened due to the difference in expansion ratios, as the top is subjected to much more rapid changes in the temperature than the base.

Thelen (92) has the following to say regarding the cold flow of asphalts:

> 1) "The specific volume of an asphalt decreases as the temperature is lowered. If the strains thus introduced cannot be relieved by cold flow, the material will crack, usually at its boundaries."
>
> 2) "In applications where the asphalt must be able to restore itself after penetration, displacement, or other deformation, it must be capable of relatively great cold flow."

Skidmore (84) feels that, based on shear strengths of mixes, the inherent characteristics and quantity of the bitumen in the mixture are more important at low temperatures than at normal and higher temperatures.

Lee (45) says the following in reference to the function of the binder in mixes:

> "In dense surfacing the tar or bitumen, in connection with the fine aggregate, is acting as a dense, plastic mortar or matrix. This mortar may act as a bond between the coarse aggregate or it may constitute the main structure of the surfacing in which particles of coarse aggregate are distributed."
>
> "Whether these binders are acting as simple adhesives or as mortars they are required to remain in a plastic condition so that the surfacing can accommodate itself, without cracking, to small movements in the road induced by temperature, moisture changes, and traffic."

Wood (109) agrees with Lee and adds that bituminous materials show properties which differ widely from those of elastic materials. He says the deformation which bituminous materials undergo is thought to be made up of two distinct parts: 1) plastic, and 2) elastic. These two components may vary widely under different conditions of loading and temperature. Wood reviews several methods of testing involving temperature as one of the prime variables.

Jording (96), conducted thermal expansion studies on Marshall cores, and stated that when samples were subjected to temperatures below $0^{\circ}F$, elastic properties were apparent. It was assumed that above $0^{\circ}F$, the cores had plastic properties.

Goetz, McLaughlin, and Wood (20) sum up the present condition of strength parameters and test temperature as follows:

> "In the strength evaluation of bituminous-aggregate mixtures by present-day design methods, there appears to be a general lack of knowledge regarding the fundamental relationship involved among the variables of temperature, rate of deformation, and strength. This lack is apparent when one considers the wide variations in rate of deformation and temperature used in the various test procedures."

It is evident from past experience that of the major building materials, Portland cement concrete is the one in which the problem of temperature expansion and contraction has presented the most problems. Mullen (55), on the subject of concrete thermal expansion, says that some researchers allege that certain combinations of aggregate having different thermal properties tend to lower the durability of the concrete when subjected to temperature changes. It is suggested that internal stresses of sufficient magnitude to disrupt the mortar matrix or the bond between matrix and aggregate could be developed with temperature change, provided the thermal properties of the coarse aggregate and mortar matrix are sufficiently different. Mullen proposes the following combinations of thermal properties that could account for lack of durability: 1) The thermal coefficient of expansion of an aggregate is approximately constant for ordinary atmospheric temperature variations but is either much higher or much lower than the thermal coefficient of expansion of the mortar matrix; 2) The coefficients of expansion of the components are the same, but their diffusivity rates are greatly different, thus resulting in a condition of different temperatures in the body if subjected to cycles of heating and cooling; 3) A condition may exist in which, with low diffusivity rate mortar and coarse aggregate, the resulting concrete would inherit the property of low diffusivity also. In this case then, the concrete would be very susceptible to thermal shock, with a large temperature gradient possibly existing from one boundary to another, requiring a considerable length of time before a condition of thermal equilibrium developed. Of less consequence is the opposite case, a condition of high rate of diffusivity, where the advance of a temperature front would cause stresses to be of shorter duration than in low diffusivity concrete; 4) Either the aggregate or mortar matrix has a varying coefficient of expansion; 5) There are several variations and combinations of the above mentioned items within an aggregate that could tend to produce a poor durability concrete. Examples of this would be an aggregate containing fractions having widely different thermal properties, and having different coefficients of expansion along different crystal axes.

Walker, Bloem and Mullen (100) investigated the influence of aggregate properties on temperature effects in concrete. The principal findings of the test were: 1) Thermal coefficients of expansion of concrete and mortar containing different aggregates varied approximately in proportion to the thermal coefficient and quantity of aggregate in the mixture; 2) An approximation of the thermal coefficient of expansion of aggregate may be made from determinations of the thermal coefficients of concrete of varying proportions; 3) Changes in temperature were destructive to the concrete with sudden changes being much more severe than slower ones; 4) Concretes having higher coefficients of expansion were less resistant to temperature changes than concretes with lower coefficients.

It is hypothesized that many of the problems that account for poor durability in concrete may also be responsible for similar effects in asphaltic concrete mixes. It is because of this similarity that much of the following work has been directed along similar lines to methods and test procedures used in the investigation of thermal effects as related to Portland cement concrete.

Review of Procedures and Equipment

General

Since man first became aware of the phenomenon of thermal expansion, he has tried several methods in his attempt to measure this property. The methods employed depend primarily on the desired accuracy, various properties of the specimen to be tested and the temperature range in which the investigation is to take place. The basic specimen properties to be considered are: size, the larger the specimen the nearer the approach to structural conditions but the greater the handling difficulties and the more likelihood of internal stresses (13); possible reactions with surroundings and thus the necessity of an inert atmosphere for measuring purposes; strength, the weaker the specimen, the more delicate the procedure needs to be; various thermal properties such as conductivity, diffusivity, and specific heat; as well as homogeneity, isotropy, and absorptive properties.

In general, the majority of work done in the field of thermal expansion has been done by means of linear measuring techniques. Davis (13) in a report describing various methods used to determine volume changes in plain concrete, in an attempt to establish an ASTM standard method of test, says:

> "With few exceptions investigators have determined 'volume change' in terms of length change, ----. Length changes are of direct use to engineers."

In regards to the relationship between actual field conditions and laboratory tests, Davis (13) says:

> "As the amount of volume change depends greatly upon the size and type of specimen, such tests do not render absolute values; but the comparative values they afford are entirely satisfactory for comparisons as between cements, aggregates, mixes, and other variable factors."

There is generally considered to be three components of an adequate thermal expansion measuring system. The first is the temperature unit into which the specimen is placed in order to obtain the desired test temperature. The second is the means of determining the temperature of the specimen during the test. The third component, and the one of most concern in this investigation, is the actual measuring instrument. To be quite general, the latter category can be subdivided into the following: optical methods, including measuring microscopes, telescopes, cathetometers, light levers, and interferometer techniques; mechanical methods, including dial gages, calipers, micrometers, extensometers, dilatometers, and density measurement; electrical methods, including resistance strain gages, capacitance strain gages, and various other circuits. Besides this simple break down, many of the methods are composed of combinations of several of these methods in order to obtain more desirable characteristics for a particular investigation.

Before proceeding into a review of the individual test procedures it is important to realize that, among the factors already mentioned in choosing a system, the rate of temperature change is also very important. Two methods of temperature change are generally considered; one is the attainment of an equilibrium temperature throughout the system before the length measurement is taken; the second is a continuous transition during which readings are taken at predetermined temperature increments before an equilibrium condition is reached.

Hidnert and Souder (33) have this to say about these methods:

> "Dilatometric methods have an advantage over the thermal method (temperature-time cooling curves) in investigating transformations, for the temperatures may be passed through for any length of time in order to attain equilibrium and the heating or cooling then resumed."

Merritt (50) adds the following:

> "The results obtained by the two procedures are not always the same and it is necessary for the experimenter to consider carefully which procedure is the one which will yield the information he desires."
>
> "The point to be emphasized here is that neither the 'equilibrium' nor the mobile procedure should be used indiscriminately, but that each problem should be analyzed and a decision reached as to the type of information desired so that the more appropriate procedure may be selected."

Optical Linear Techniques

In reviewing the literature many measuring methods were encountered that were used in investigations for other properties than thermal expansion. Some of these may have potential as thermal expansion measuring systems. It was felt, however, that the review should be limited in scope to only those methods which have actually been used in thermal expansion studies. For the most part this objective has been carried out in the following review.

Of the many linear techniques used in the past to measure the thermal expansion of materials, none have found as much favor as optical techniques. Tuckerman (94) in a paper describing an optical strain gage he designed, says the following about optical methods:

> "For many years optical methods have furnished the most sensitive and most accurate means of measuring small distances, including small displacements or deformations. For this reason they have been chosen where extreme sensibility or extreme accuracy was desired."

He adds the following disadvantages:

> "Unfortunately, optical devices, although precise and sensitive, have been cumbersome and difficult to maintain in adjustment. This has limited their usefulness in great measure, confining them largely to well-equipped laboratories with a highly trained personnel."

One of the agencies possessing these well-equipped laboratories and employing highly trained personnel is the National Bureau of Standards. This agency has long been a leader in the use of optical techniques for the measurement of thermal expansion. They have also worked with other measuring techniques and their facilities include four or more laboratories equipped for as many types of determinations. They include the volumetric and density laboratory, the length laboratory, the interferometry laboratory and the thermal expansivity laboratory. Of the many methods used by the National Bureau of Standards, the interferometric method has been used quite extensively when considerable accuracy has been necessary. One of the main advantages of the interference methods is that they carry their own calibration with them, making them useful in standardization (94).

Griffith (21), in an investigation on the thermal expansion of typical American rocks, says the following about the interferometer:

> " ---, physicists, ceramists, and petrologists attach great scientific importance to measurements with an interferometer which gives precise measurements on small specimens, or over a limited area, but does not integrate effects as in the case of a long-gauge extensometer or a dial gauge."

Most of the interferometers that have been used for thermal expansion measurements are based on the Fizeau (16) interferometer. The principle is dependent on the interference of the wave lengths of monochromatic light. Hidnert and Souder (33) give a description of the technique. The sample is placed vertically between two transparent fused-quartz plates, each about 4-mm thick and reasonably free from bubbles and other imperfections. The surfaces of each plate should be flat within one-fifth of a fringe, and should be inclined to each other at an angle of about 20' of arc. The sample with the two fused-quartz plates is set in an electric furnace or cooling chamber for heating or cooling. When the plates are illuminated, normally with the monochromatic light, a set of interference fringes is produced by the interference of the light reflected between the lower surface of the upper plate and the upper surface of the lower plate, when the angle between these surfaces is slight. The fringes are observed by means of a viewing device. Changing the temperature of the sample brings about a change in length which causes the distance between the plates to change with a corresponding movement of the interference fringes past a reference mark on the lower surface of the upper plate. From the observed displacement of the fringes, the change in length, or linear thermal expansion, can be determined.

The specimen size varies from 5- to 10-mm in height and is generally in the shape of a tripod, although rings, cones, tetrahedrons, and sometimes three separate pieces, have been used. Merritt (50) gives a description of the apparatus used by the National Bureau of Standards as well as a detailed account of their test procedure. Wood and Bekkedahl (110), using this method to investigate dimensional changes in rubber specimens, comment on the test method:

> "In spite of the small size of the specimens, the sensitivity of the method is quite great, since measurements of the changes of length are made by comparison with the wave length of light."

The interferometer method has been used in the investigation of all sorts of materials, and about the only requirement necessary is that the material lend itself to the required shaping, in order to obtain the proper size and shape. Peters and Cragoe (67) used the method to investigate optical glass. Souder and Peters (90) investigated the expansion of dental materials and found that the technique had an error of about 0.0000002 inch. Merritt (51) used the method to investigate fused quartz. Peters and Boyd (66) used the interferometer to measure, to the nearest 0.000001 inch, gage blocks that were used to calibrate other instruments. Merritt (49), used the technique to investigate ceramic materials, including glaze, terra cotta, tile, porcelain, and clay. Hidnert and Sweeny (35) investigated the expansion of magnesium and some of its alloys by the interferometer and by two other methods. Ingberg and Foster (38) reported thermal expansion measurements, obtained by this technique, on specimens from hollow clay tile over the temperature range of $0^{\circ}C$ to $300^{\circ}C$. Saunders and Tool (80) measured the expansion of pyrex tubing in an investigation to determine the effect of heat treatment on the coefficient of expansion. Johnson and Parsons (40, 63) used the interferometer method to investigate the expansion of over 100 specimens of aggregate commonly used in Portland cement. Saunders (79) investigated the expansion of iron using the interferometer technique.

As with any measuring system there is always need for improvement and need to eliminate possible sources of error. Saunders (78) conducted an investigation to improve the Fizeau interferometric method and in this report he gives detailed causes and effects of various errors in the technique and recommends methods of improvements. Willey and Fink (104) made some modifications, in their investigation on aluminum, and developed a technique that makes it unnecessary to count the number of fringes passing the fiducial mark. Nix (58) made some modifications also and placed the samples in a vacuum during the test to avoid oxidation. He also added a 16-mm motion picture camera to photograph the fringes passing the fiducial mark. A fairly recent publication by Hidnert and Souder (33) lists the present condition of the interferometer technique as used by the National Bureau of Standards. This same paper lists nine other techniques used by that Bureau in thermal expansion studies, some of which will be discussed later in this review.

Although the interferometric method has been used quite extensively to obtain very precise information, a method that has received even more favor, although generally not as accurate, is the use of micrometer microscopes. Griffith (21) says the following about the comparison of the interferometric and other techniques:

> "Two groups of observers at the National Bureau of Standards (85), working independently and simultaneously on the same materials, found the resulting curves were practically identical by either gauge or interferometer. Certain advantages in one case are compensated by those in the other."

The gauge technique referred to in this quote was an apparatus consisting of two micrometer microscopes. This apparatus will be described later. Peters (67) expressed his views on this type of measuring system as follows:

> "The greater part of the measurements of thermal expansion have been made, by direct observation of the elongation, with micrometer microscopes focused upon lines ruled near the ends of a rod of the material."

Norton (59, 60) used two telescopes, one being provided with a micrometer eyepiece having a least reading of 0.0001 inch, to investigate the thermal expansion of 6 inch and 10 inch concrete cubes. He sighted through holes that were placed in the double gas muffle furnace, the furnace being used to heat the specimens. Houldsworth (36) used a telescoping arrangement of two brass tubes containing the specimen, each tube being connected to opposite ends of the specimen, to measure the thermal expansion of refractory materials. By observing the relative movements of two fine lines scratched on small glass plates carried by each tube, Houldsworth was able to make his measurements with only one micrometer microscope. Booze (8) also developed a technique that required only one micrometer microscope. To each end of his specimens, which were fire clay refractories, he connected fused silica rods which extended out of the furnace. One of the rods was U-shaped and bent up and over the furnace and was maintained in a parallel position slightly above the other rod. By measuring the relative movement of fine index marks ruled on each rod the specimen expansion was obtained. The microscope used in this investigation possessed a filar micrometer eyepiece and was capable of observing a length change of 0.0001 inch.

Kohlmeyer (43), in an investigation on fire brick, used a surveyors transit to measure the thermal expansion. He sighted, through two holes in the furnace, on two orton cones which he used as reference points. The cones had been securely fastened to the specimen prior to the test. The transit was carefully leveled and the intersection of the cross hairs was brought to focus on one of the orton cones. Then the telescope was inverted in the vertical plane and focused on a steel scale mounted at such a distance from the transit to give a suitable maltiplication factor to the distance between the cones. The same procedure was then followed for the other reference point and the length change, increased by the multiplication factor, was then the difference in the scale reading of successive observations at various temperatures.

Norton (61) used telescopes, provided with filar micrometer eyepieces, in measuring the expansion of 1 inch square by 9 inch refractory specimens. The specimen ends were accurately ground and were used as the reference points. The method was believed to be precise to ± 0.01 percent of the length of the specimen. Dawley (14) used the two microscope apparatus developed by Scholer and Dawley (82) to investigate the thermal expansion of concrete beams 4 by 6 by 24 inches. The reference points were two 7-mm glass tubes located 20 inches apart and placed in the beam after mixing.

Griffith (21), conducting work at Iowa State College on the expansion of typical American rocks, gives a very detailed description of his test and procedure. He used two Gaertner filar micrometer microscopes, having 6 inch working distances and reading correctly to 0.0001 inch, for the investigation from room temperature to 500°F. The calibration of the microscopes was conducted by using a Leitz microscope and micrometer scale, which was checked against an American scale, and rechecked against a Starrett scale and a Brown-Sharpe screw micrometer, which all gave results concordant with the first. The size of his specimens ranged from 3 1/2-to 5-inches in length, with an average of 4 inches, and 1/4-to 3/4-of an inch square in cross section. Concerning the selection of the microscopes used in his investigation, Griffith states:

> "The first problem presenting itself in the selection of suitable microscopes was the proper selection of easily adapted graticules for observation points and suitable cross wires and recticle framework since, for the short-length specimens, finer measurements were required."

He investigated sheet brass (0.002 inch) for the reference points but found it difficult to secure repetitive check readings to 0.0001 inch. A more successful method was to rub fine graphite crystals into the specimen terminals, this required sketches of the "constellations" of brightly illuminated crystals otherwise the reference point could be lost to mind during the succession of readings. Griffith tried to create a "black body" by drilling the specimens with a No. 54 drill and then mounting a bright thin platinum wire across the tops of the black "caverns". Griffith found this latter method worked best but considered it far from the desired expediency because the settings had to be done with a magnifier, the wires were difficult to cement securely, and they were easily lost by springing into space. He finally settled on using the tips of Rodgers English sewing needles which usually had sharp parabolic points that could easily be whetted on a fine carborundum stone to a diameter of the order of the cross wires. These points were then secured to the specimen by potter's plaster and were carbonized in a flame so as to be sharply silhouetted on a white asbestos background placed in the rear of the furnace.

Lang and Thomas (44) conducting an investigation on the thermal expansion of sheet asphalt used beams 2 by 2 by 10 inches. They used two telescopes equipped with cross hairs and mounted in a vertical position on a movable bar. The telescopes read directly down on the glass capillary tubes embedded on 8-inch centers in the sheet asphalt beams. The movement of the bar supporting the telescopes was in a horizontal direction and was controlled by a screw mechanism attached to a micrometer scale. The readings were always compared to readings on a standard bar. The beams were placed in an alcohol bath and were covered by a thin coating of liquid rubber preparation to protect them from any action of the alcohol bath. The desired temperatures were obtained by adding bits of solid carbon dioxide to the bath. Two procedures were used in varying the temperature of the beams. In one, the beams were cooled to - 10°F and then allowed to warm up slowly in the bath, readings being taken at intervals. The other method consisted of putting the beams through a number of more rapid cycles of temperature change. In this case, the temperature was varied from room temperature of 33°F to - 20°F and back to 33°F during one day.

Philleo (68), in connection with an investigation of the fire resistance of concrete conducted at the Portland Cement Association Research and Development Laboratories, determined the expansion of 2-by 2 3/4-by 6-inch specimens in the temperature range of 75 to 1500°F. He used a pair of micrometer microscopes to focus on No. 30 gage Chromax wires that had placed in vertical grooves sawed near the ends of the specimen. The wires extended over the groove in the specimen and out through holes in the bottom of the furnace. Weights were hung on the wires to maintain tension and then the weights and a portion of the wire were suspended in an oil bath to dampen vibrations and swaying of the wire. The microscopes had a readability of 1-micron and an increment of length change equal to 7×10^{-6} of the specimen length could be detected (33).

The National Bureau of Standards has done a considerable amount of work with microscope measuring systems in the investigation of thermal expansion of various materials. In essence, they have used two systems.

The first of these, reported in a paper by Schad and Hidnert (81), was used to investigate the expansion of molybdenum. This paper does not give an adequate description of the apparatus but a later paper by Hidnert (30), who investigated the expansive properties of copper, gives the description in great detail. This method employs an invar tube, the same length as the specimen, 20-cm long. This tube is placed above the furnace and from each end of the tube are suspended 1-mil wires which pass into the furnace and are held in contact with the ends of the specimens. Tension in these wires is maintained by means of a pulley system from which is suspended suitable-size weights. The gage points are established on the 1-mile wires at a distance up from the specimen equal to 1/10 of the distance between the specimen and invar tube. These "points" on the wires then establish the reference points for a set of micrometer microscopes. These microscopes are rigidly clamped on an invar bar and are spaced apart a distance equal to the specimen length of 20 cm. The measured displacement of the gage points, due to a length change of the specimen, is only 9/10 of the actual movement of the specimen and hence the deformation must be multiplied by a factor of 10/9 to obtain the true expansion. This arrangement eliminates the necessity of observing the specimen directly while in the furnace. The arrangement is also a means of compensating for changes in room temperature and the effects these changes would produce on the invar bar. The coefficient of expansion of the invar is quite small to begin with, and because of the location of the gage points, any movement in the invar tube would only cause 1/10 of that movement in the gage points. Hidnert (32), in another paper uses the same method to investigate the expansion of columbium.

The other system used by the Bureau is similar to the one just reviewed. It consisted of hanging 1-mil wires from the ends of the specimens and passing the wires through holes in the furnace where weights were attached. The weights and wires were suspended in an oil bath to dampen vibrations. The measurements were made by means of two micrometer microscopes rigidly clamped on an invar bar at a distance from each other equal to the length of the specimen, which was 30-cm long and 1-cm square. The microscopes were arranged so that they could first be sighted on a standard-length bar kept at constant temperature, and then on the vertically suspended wires which were in contact with the ends of the specimens. In the case of some specimens, when the wires were suspended from the ends, an unknown factor of corrosion added to the length change. To avoid this problem, the wires were placed in V-notch grooves cut near the ends of the specimen.

The investigations conducted using this apparatus have been quite extensive. Souder (87) used the method to investigate the expansion of insulating materials. Souder and Hidnert (88) used the method to investigate the expansion of several metals including nickel and stainless steel.

They also used it to investigate other steels (86). Hidnert (28) used the method in the investigation of aluminum and some of its alloys. Souder and Hidnert (85), gave a very detailed description of the technique used in investigating the expansion of fused silica. In this paper they stated that the accuracy of the method was 0.01 percent in the determination of the coefficient of expansion. Hidnert and Sweeney (34) investigated the expansion of graphite, over the temperature range of 20 to 600°C, with the method. Hidnert and Sweeney (35) used this method, as well as two others, in an investigation of the expansion of magnesium and some of its alloys. Hidnert (29, 31) conducted separate investigations of the expansive properties of artificial graphite and carbon and on heat resisting alloys.

Another division of instruments in the optical category uses the principle of the light-lever. In general, a light-lever involves a light source that is reflected by a mirror, located on the specimen, so that it reflects onto a scale at a known distance from the mirror. The mirror is arranged so that when the sample moves, the tilt of the mirror is altered and consequently the reflection on the scale moves. Depending on the value of the lever arm, a large multiplication factor can be obtained with the result that very small changes in length appear quite large on the scale and can be easily measured.

Pence (65), conducting an investigation of the expansion of concrete, used a method involving the principle of the light lever. His specimens were columns 4-inches in diameter by 36-inches high. A mirror, fastened to a small tripod base was placed on top of the concrete column. Two legs of the tripod were placed on the column and the third on a rod of either steel or copper, the same height as the column. Individual tests were made with the steel and copper rods for comparisons, with the coefficient of expansion of each bar being accurately determined beforehand. As the temperature changed there was a differential movement between the concrete column and metal rod causing the mirror to tilt. The measurement of this differential movement was obtained by the use of an engineers level. The level was maintained at the same location and always leveled before an observation. A sighting made on the mirror actually reflected the reading of a level rod held in a vertical position and in the same location for all tests. Readings were taken at various temperatures to give successive increments of relative movements of the two materials. By knowing the expansion of the metal rod and the multiplication factor of the light lever, the expansion of the concrete was determined.

The National Bureau of Standards (33) describes a method of thermal expansion measurement they have used which involves the light-lever method. The apparatus is quite involved but a detailed description is given by Souder and Hidnert (89). The apparatus can be used to measure visually the expansion of the sample, or it can be modified so that continuous expansion curves can be obtained photographically during the progress of the test. The method is estimated to give results with an error of about 6 percent.

Thomas (93), conducting an investigation on the expansion of building stone during freezing and thawing, tried a volumetric as well as a linear technique. He made his most satisfactory determinations by an optical-lever, linear extensometer method. The relative movement of the specimen, in relation to the frame of the apparatus, was determined by a two-mirror system with a third mirror being employed as a check. One mirror was securely fastened to the frame of the apparatus and was considered fixed. The second mirror was attached to a movable rod which was connected to the specimen. The mirror was also attached to the frame by means of a ball and socket, or roller, joint. This arrangement caused the mirror to move when there was a differential movement between the rod and frame. A light from a projector impinged on the mirrors and the images were focused sharply on a screen in such a way that they were in a vertical plane. The lower image, used as the reference point, was that produced by the fixed mirror. The edges of the images were sharply defined, and their positions could be marked accurately on the screen with a fine pencil. The intercepts from the lower image were measured with a finely graduated narrow steel tape, estimating to 0.1 mm. The magnification for the roller mirrors was about 3,240 times and for a movement of 1 cm on the screen, this corresponded to a movement of the sample equal to about 0.174×10^{-4} cm/cm. The check mirror was not as accurate as the main mirror set and was mounted by a spring mechanism which resulted in a magnification of about 2/3 of the roller attached mirror.

Willis and DeReus (105) used a light lever arrangement to investigate the expansion of aggregates. The specimens were 1-inch in diameter and 2-inches long. The temperature range investigated was 37°F to 140°F. The movement was observed by sighting on a scale reflected in a mirror that was simultaneously connected to the specimen, indirectly, and connected to a fixed point. The instrument used in sighting on this scale was a precise level, and the scale was located 20 feet from the specimen. Consideration of the possible errors involved in the measurement showed that the calculated coefficients are probably accurate to plus or minus 2.0×10^{-7} inch/inch/$^{\circ}$F.

Tuckerman (4) devised a gage which employs the light-lever principle and is now commercially available. In his paper, Tuckerman gives a detailed introduction to his gage and describes the principle involved in the operation of the gage. The instrument uses a separate auto-collimater, an instrument performing the same duty as a telescope with cross hairs, as well as containing the measuring scale, and a 0.2-inch Martens lozenge on a 2-inch gage length. One division on the scale represents a deformation of 0.00004 inches and it is quite easy to read tenths of a division. Therefore a least reading of 0.000002 inch per inch of gage length is obtained. The gage has found great favor as a measuring devise because of its portability and ease of operation. However, not much work has been conducted using the gage for thermal expansion measurements.

Ross (77), investigating the thermal expansion of clay building bricks, employed the Tuckerman gage. He calibrated the gage by conducting a test with it using a metal bar whose thermal coefficient of expansion had been previously determined. The difference in the experimental values and the standardized values was the error introduced by the gage expansion. For many of his tests a 4-inch extension bar was added to the gage, giving a 6-inch gage length. He also describes the method of mounting used to maintain the gage on the specimen in the same position. He used iron plates, cemented to the specimen with cellulose nitrate cement, about 0.1-inch in width on which to rest the delicate knife edges of the gage. The actual readings consisted of only two per specimen, one being made at each extreme of the temperature range of - 10^{o}C to 40^{o}C. Ross states that the chief limit on the accuracy of the thermal expansion measurements was the lack of precision in the determination of the length of the portion of the brick within the gage length.

A bulletin by the American Instrument Company (95) describes various uses for the Tuckerman gage as well as its principles. In the report, a method of using the gage for high temperature measurements is mentioned, however, not much detail is given about the procedure.

Wilson (106) investigated the properties of the Tuckerman gage. He comments on the gage as follows:

> "Because of the sensitivity, the small size, and the light weight of the Tuckerman strain gage, it is well adapted to measuring deformations of specimens and structures over short gage lengths. It is now being applied in the laboratories of the National Bureau of Standards and elsewhere to a large variety of problems. ----."

By means of an interferometric calibration device used at the National Bureau of Standards for calibrating gages and autocollimators, experimental results were secured which indicated the variations of the gage calibration factor with different conditions of use. The results indicated that 1) the change in autocollimator reading is accurately proportional to the change in length of the gage length of the strain gage, 2) the calibration factor is not greatly influenced by the material of the specimen provided the gage is properly attached, 3) the calibration factor is practically independent of the position of the gage in space, and 4) the calibration factor is almost independent of the temperature within the range of 70 to 100°F.

Mechanical Linear Techniques

Mechanical strain gages have found a wide usage in measuring thermal expansion as well as in investigations of deformations due to other causes. Geller and Heindl (19), investigating the thermal expansion of some clays, used dial gages for their purpose. The specimens were about 1-inch square and 7-inches long. They were placed vertically in an electric muffle furnace and fused quartz rods were inserted in holes which had been drilled in each end of the specimen. The specimen rested on the bottom quartz rod and the top rod extended out of the furance and was connected to a dial gage. The gage had a least reading of 0.0002 inch. A correction factor was introduced to account for the quartz expansion. The apparatus was arranged so three samples could be tested at a time over the temperature range of 25 to 1000°C. The length between the ends of the two quartz rods, the actual gage length, was measured to 0.001 inch by means of an end standard comparator.

Westman (103) used a method similar to that used by Geller and Heindl in an investigation of expansion of fireclay bricks. The specimens were 1-inch in diameter and 9-inches long. The specimen was placed vertically between two fused silica rods which previously had been calibrated for their expansion. The specimen and rods were placed in a furnace and arranged so that they were the only things to be heated. The dial gage, having a least reading of 0.0001 inch, was protected by a radiation shield of copper tubing through which water circulated. The expansion of the silica rods was incorporated in a correction factor that accounted for 10 percent of the dial readings.

Myers (57) investigated thermal volume change, under field conditions, of concrete slabs 81 feet long, 24 inches wide, and 6 inches thick. The measurements were made with Ames dials having a least reading of 0.001 inch. The purpose of the test was primarily to determine the effects of different curing methods upon volume changes. He could not, however, obtain a true coefficient of thermal expansion because of moisture changes and restraint offered by the subgrade. He did show, however, that of the two aggregates investigated, a gravel and a limestone, the gravel had the higher expansion.

Griffith (21) used a different method for his investigation in the temperature range from freezing to room temperature than he used in the range from room temperature to 500°F. In this low temperature range he used a mechanical strain gage rather than an optical comparometer. He securely fastened 1/4-inch steel cylinders, which had been drilled with a No. 54 drill (0.06-inch diameter), to his specimens at an 8-inch gage length. The specimen was then placed in an ice bath, wrapped in a protective coating to prevent absorption, and the strain gage inserted in the small gage holes. The difference in dial readings between this condition and that existing at room temperature gave the expansion for that temperature interval.

Koenitzer (42), investigating the effects of aggregate expansion properties, used a mechanical lever-arm device employing an Ames dial. The least reading of the dial was 0.0001 inch, and with the lever arm providing a ratio of 5 to 1, the actual value of one division of the gage was 0.00002 inch. He was interested in determining the effects of the aggregate thermal expansion on the expansion of concrete. He carried out this investigation on stone cores, 5-inches in length and 2-inches in diameter, and on concrete cylinders, 6-inches long and 3-inches in diameter. The desired temperature was obtained by placing the sample in individual baths maintained at 9°F, 80°F, and 190°F. In making an observation the samples were placed in the desired temperature bath long enough to reach equilibrium conditions and then the reading was obtained immediately upon removal.

Hveem (37) used a device he called a "spider" in an investigation on concrete expansion. The device was a specially designed frame which consisted of two metal bars that were perpendicular to each other. On the end of each bar was mounted a dial gage. The least reading of the two gages was not mentioned in the paper. On the other ends of these perpendicular bars were fixed supports so that an 8-inch gage length was the resulting distance between the gage and the fixed supports. The specimens were sawed from concrete cylinders to give a disk 8-inches in diameter and 1/4-inch thick. The specimen was placed in the frame and the entire apparatus was placed in a temperature bath. With this arrangement, measurements were possible along two gage lines perpendicular to each other. The paper makes no mention of calibration technique.

Callan (11), investigating the expansion of concrete aggregates, used a dial gage comparator for investigating the expansion of mortar mixtures. The specimens were bars 1 inch by 1 inch by 11.5 inches and contained invar inserts embedded in the ends, giving an effective axial gage length of 10 inches. When the bars were 7 days old, they were placed in a constant temperature bath maintained at 135°F. The bars were maintained at this temperature for 15 minutes, long enough to allow them to come to equilibrium. They were then removed individually from the bath and placed in the dial gage comparator, for which no least reading was given, and a reading taken. The entire measuring operation was completed within 15 seconds after removal from the bath, which was rapid enough that no appreciable loss of temperature occurred along the major axis of the bar. This procedure is repeated at a temperature of 35°F and the difference in the readings at these two temperatures is the thermal expansion. The coefficients obtained for at least five cycles were averaged and then averaged for three bars of the same mortar to give the thermal coefficient of expansion of the mortar.

Witte and Backstrom (107) ran a series of tests on barite (barium sulfate) to determine its use as a concrete aggregate. Thermal expansion measurements were obtained on both 4-by 4-by 30-inch prisms as well as 8-by 8-by 48-inch prisms of concrete, made with barite as an aggregate. The thermal expansion measurements were made on the beams after they had been investigated for drying shrinkage and autogenous length changes. The length change measurements were obtained on the 30-inch beams by means of a horizontal-type invar steel comparator equipped with a dial gage sensitive to 0.0001 inch. A fulcrum plate strain gage of equivalent sensitivity was used to measure length changes of the 48-inch beams. The beams, completely sealed in soldered copper foil, were subjected to three repeated temperature cycles of 43°F, 73°F, and 103°F. The beams were held at these temperatures for approximately 20 hours and then measured and subjected to the next temperature change.

Lewis (47) studied the thermal expansion of light-weight concrete made from expanded blast furnace slag. He used specimens 3-by 3-by 19-inches long with stainless steel studs molded in the ends for reference points. These studs resulted in an effective gage length of 17 1/4 inches. The length measurements were made on a laboratory built comparator consisting of a channel frame with one fixed gage point and an Ames dial secured at the other end. An invar reference bar standard was used to compensate for temperature effects on the comparator. The desired temperatures were obtained by placing the specimens in water baths maintained at 35°F, 72°F, and 145°F. When equilibrium conditions had been reached, the beam was removed and measured and placed in the next desired temperature bath.

Fontana (17) describes a "dilatometer" he constructed which is capable of measuring the thermal expansion of solid materials accurately to within $\pm$ 2 percent or $\pm$ 1.0 x 10^{-7} inch/°C, whichever is greater, in less than an hour. The sample is 1/4-inch in diameter by 4-inches long and is rounded on the ends. Measurements are made by a Federal dial gage having an invar steel rack and a 0.1-inch total travel. The least reading of the gage is 0.0001 inch. The gage is connected to the specimen by means of a hollow-ground, fused-silica push rod. Readings are taken at only two temperatures in the range of 25 to 300°C.

Several mechanical strain gages have been marketed which employ standard-type dial gages with or without previous lever multiplication. The Berry gage and Whittemore gage are examples of this type. The Berry strain gage multiplies the displacement five times before transmitting the movement to the dial gage. Durelli (15) says the following about the 10-inch Berry gage:

> "When a dial gage graduated to 0.0001 inch is used and experienced operator can measure strain to the nearest 0.00001 inch per inch; however, the most common application is in field work, where the gage is used on large structures (reinforced-concrete bridges, for example) and at several locations instead of being fixed at one station. Here the errors introduced by the removals between readings reduce the accuracy."
>
> "In such applications small holes are drilled and countersunk, according to the manufacturer's specifications, at each end of the base lengths being studied; and it is necessary to exercise extreme care in the preparation of the holes and in the insertion of the gage contact points."

The Whittemore gage employs a dial gage without additional multiplication, thus, making it basically a fixture designed for hand holding a dial gage. As in the case of the Berry gage, drilled and countersunk holes are prepared for insertion of the gage contact points at the locations where the strain is to be measured, and the gage is inserted and removed between readings. Durelli adds:

> "Like the Berry gage, its advantages lie primarily in its ruggedness, and hence suitability for field work. Its high strain sensitivity and large base length make it unsuitable for most laboratory strain analysis."

Hatt (23), investigating the effects of moisture on concrete, made thermal expansion determinations with a 20-inch Berry strain gage. He used beams 2 by 2 by 24 inches for investigating the expansion of the neat cement, and beams 4 by 7 by 48 inches for investigating the expansion of the concrete. The specimens were heated in an oven at 150°F until equilibrium had been obtained, and then they were removed and allowed to cool to room temperature while readings were taken at 20°F increments. The temperature of the specimen was determined by placing a thermometer in a temperature well consisting of steel pipes and containing light paraffin oil. Another set of beams was kept in various water baths at a constant temperature for 2 hours before observation. The specimens each contained 6 gage lines, three being on one face and the other three on the opposite face. The gage was checked against a standard invar steel bar, kept at a constant temperature, to allow for temperature effects on the gage.

Camp and Shelburne (12) conducted field studies on the expansion and contraction of concrete using a 20-inch Berry gage. The investigations were conducted on pavements that were actually in use and not just slabs constructed for the investigation. The main objective of the study was to observe seasonal variations in the length of the pavements due to temperature and moisture changes. The investigation included transverse as well as longitudinal observations. The gage points were brass plugs 1/4-inch in diameter by 3/8-inch in length. The plugs contained five No. 54 drill holes, one being placed in the center of the plug and the remaining four being placed off center and 90° apart. The plugs were grouted into drill holes in the pavement and when in place, they formed a square 20 inches on a side. Observations were then taken on all four sides of the square using all of the gage holes.

Palmer (62) reported tests on six types of clay and shale and two types of fire-clay bricks. A 20-inch Whittemore strain gage was used to measure the length changes in specimens consisting of three bricks cemented together with litharge-glycerin cement. The bricks were measured at only two temperatures, - 3°C and 25°C.

Walker, Bloem and Mullen (100) used a Whittemore strain gage for their work on concrete expansion. Brass inserts, spaced on 10-inch gage lengths, were used as reference points. The specimens were beams 3 by 4 by 16 inches with the measurements being taken on the 3-by 16-inch faces. The results of these tests have been mentioned previously.

Another means of measurement employing mechanical methods is the use of micrometers. Micrometers have been used quite extensively in determining length changes from causes other than temperature change, particularly changes in concrete, but they have found little use in thermal expansion determinations. Meyers (52, 53) investigated volume changes, due to temperature change, of mortar specimens by means of an invar micrometer, having a least reading of 0.0001 inch. The specimens were 1-inch square and 13 1/2-inches long. The specimens were sealed in soldered copper foil to eliminate effects of moisture change. Other methods of sealing were investigated including paints, waxes, shellac, and rubber membranes, but none of these completely sealed the pores of the test pieces. The reference points were brass posts located 12 inches apart in one face of the beam and protruding above the specimen to allow measurements to be made on the inner face of the posts. The micrometer was held in a constant position relative to the brass plugs throughout the test and was subjected to the same temperature conditions as the specimen. The micrometer was calibrated by two methods to determine the effect of temperature change on the gage itself. The first method used was to place the micrometer on a glass slide ruled in microns and then to observe the movement of one end of the micrometer by means of a microscope. The second method involved comparing the expansion values of a fused quartz rod which had been measured by the micrometer and by another method.

Another mechanical method is what Souder and Hidnert (33) call the 'fused-quartz tube and dial-indicator' method. The National Bureau of Standards uses the method for determination of linear thermal expansion for various temperature ranges between - 190 and 1000°C. It consists of a fused-quartz tube closed at the bottom and capable of containing a specimen 20-cm long and about 1 1/2-cm in diameter. A movable fused-quartz rod rests on top of the sample and extends above the open end of the tube. The bottom of the tube and the movable rod are ground concave, and the ends of the sample convex, in order to secure satisfactory contact. The top of the movable rod on which a dial indicator rests, is flat. The tube containing the sample is placed in the desired temperature apparatus so that the entire sample is subjected to the same temperature conditions.

The dial indicator, fastened near the top of the tube, registers the differential expansion between the sample and an equivalent length (20 cm) of fused quartz. A small correction for the expansion of the fused quartz is made.

Hidnert and Sweeney (35) used the quartz tube apparatus in an investigation of the thermal expansion of magnesium and some of its alloys. Walters and Gensamer (101) modified this type of apparatus so that the expansion of a sample could be determined in a vacuum or an inert gas between - 200 and 1000°C. Kingston (41) modified the apparatus to a recording dilatometer by means of a contact mechanism, transmission shaft, recorder, and electronic relay. He also made provision to use various atmospheres in which to conduct the tests.

Heindl (27) used an apparatus, similar to the one just reviewed, to investigate the expansion of refractories. His samples were about 6-inches long and 1-inch square. The dial indicator was an Ames dial with a least reading of 0.0001 inch. The sample, placed in a cylindrical graphite muffle, was aligned, both top and bottom, by two graphite rods. This setup formed a continuous system which expanded and contracted independently of the furnace. A fused-quartz rod, resting on the top graphite rod, conveyed the expansion of the sample to the dial gage. The dial readings represented the difference between the total expansion of the built-up column and the vertical expansion of the outer framework and dial support. The actual specimen expansion was obtained by adding a correction factor determined by calibrating the equipment against the previously determined expansion of a fused-quartz rod. This method is also one of those described in the N. B. S. Circular No. 486 (33).

Boyer and Spencer (9) performed linear thermal expansion measurements on rods of polymer about 2-to 4-inches long. The apparatus used was a quartz tube dilatometer and Ames dial micrometer according to the ASTM Standard Method of Test for Linear Expansion of Plastics, ASTM Designation D 696-42T. This method is now designated D 696-44. A detailed description of the recommended type of equipment is given in ASTM Standard Method of Test for Linear Expansion of Metal, ASTM Designation B 95-39.

Lifanov and Strelkov (46) developed an apparatus similar to the quartz tube method. The equipment was used for measuring dimensional changes of specimens under variable temperature and humidity conditions. A quartz push rod, resting on top of the specimen, transfers the specimen movement to a steel roller which is held in contact with the rod. The specimen is supported on a small table which is suspended by quartz rods which are connected to the top of a quartz bulb surrounding the specimen and supporting rods. As the specimen expands, the rotation angle of the steel roller is measured by means of an autocollimation tube. The apparatus accommodates specimens 10-to 40-mm in length and 8-to 15-mm in diameter. It is designed so that the temperature change effect on the apparatus is quite small because all parts are either quartz or invar. The apparatus is capable of measuring individual length changes on the order of 1.7×10^{-5} to 2.5×10^{-5} mm of the push rod displacement. The authors give a detailed decription of the equipment.

Another mechanical method that has been used in studies of thermal expansion is one which utilizes a diaphragm constituting one side of a vessel which contains a liquid. The specimen, as it expands, applies pressure to the diaphragm which then forces the liquid into a tube whereby the specimen length change can be determined from the movement of the liquid. The apparatus is referred to as a liquid micrometer.

Andrew (2) devised a very sensitive apparatus of this sort. A colored liquid was forced, by the diaphragm movement, into a narrow capillary tube and the liquid movement then became an exaggerated counterpart of the specimen movement. The capillary tube was then calibrated to give a corresponding length change of the sample and the final arrangement resulted in a ratio of about 2,000 to 1. This same apparatus was used by Haugton and Griffiths (25) with some modifications. They substituted mercury for the indicating liquid, the movement of which shortened the effective length of a fine resistance wire placed in the capillary tube. The changes in the electrical resistance of the wire were recorded and these correspond to the changes in the length of the specimens. Prytherch (69) comments on this apparatus:

> "The apparatus used by Andrew and modified by Haughton and Griffiths is open to the criticism that the specimen is under considerable pressure, and is liable to become deformed at high temperatures, thus giving rise to a serious source of error."

The apparatus used by Andrew is the same as the one described by Hidnert and Souder (33). Both references give a detailed description of the equipment involved.

Electrical Linear Techniques

Of the various types of electrical strain gages, the resistance type has found the largest usage in measuring strains induced by various causes. However, the electric circuit type of strain gage has not found much use in thermal expansion measurements. This is primarily due to the temperature effects on the gages as well as the effects on the bonding material.

Even so, some investigators have successfully used techniques involving electrical gages and these are reviewed in the following discussion.

Callan (10, 11) developed a rapid method for determining the thermal coefficients of expansion of coarse aggregate using an application of the familiar SR-4 strain gage technique. Its advantages are: the large number of determinations which may be made simultaneously; the relatively simple preparation of the specimens; the degree of accuracy (sufficient for all practical purposes); applicability to many rocks, which because of crumbly or fractured structure are difficult to handle by other means. Resistance-wire strain gages are attached to slabs of rock, the specimens are placed in a controlled-temperature cabinet, and strain readings are taken at two temperatures with an SR-4 indicator. A compensating gage and an active gage are attached to a specimen of known thermal coefficient of expansion. The difference in readings between these two gages and the expected expansion values for the known specimens are applied as a correction to the readings of the gages attached to the test specimens to compensate for temperature effect on the gages. A complete description of the apparatus and procedure is given in the references.

Prytherch (69) describes an apparatus for determining the temperature at which any abnormal change in length occurs in a body. The apparatus consists of an oscillatory circuit and the specimen, upon expanding, is made to actuate the moving plate of a small capacitor which constitutes part of the series grid capacitance of the circuit. Small changes in the capacitance bring about relatively large changes in the mean steady anode current of the tube. A continuous record of the anode current of the tube is made on a thread recorder which also simultaneously records the temperature of the specimen. The specimens are 1-to 2-cm in length and 7-mm in diameter. Haugton and Adcock (24) made some modifications of this equipment which included provisions for working in an inert atmosphere at temperatures up to 1300°C. This apparatus is also reviewed by Hidnert and Souder (33).

Hidnert and Souder (33) review an X-ray method for determining the coefficients of expansion of crystals in different directions over large temperature ranges. A very small amount of the material is sufficient for a sample. The procedure is outlined and the apparatus is described in detail.

Volumetric Techniques

One of the oldest techniques used in determining the volumetric thermal expansion of a material is the density method. In this method the material under investigation is weighed in a liquid of known density at various temperatures. The density of the liquid has previously been determined for the temperature range over which the unknown material is to be investigated. The sample is placed in the liquid, which is maintained at the desired temperature, and accurately weighed when equilibrium is obtained. An early account of this method is given by Matthiessen (18). He determined the densities of water and mercury at various temperatures so he could use these liquids as a means for obtaining the volumetric expansion of other materials. In order to calibrate these liquids, he first determined the linear thermal expansion of a glass rod by means of a micrometer screw mechanism, the least reading of which was 0.001 mm. After calculating the expansion of the glass rod it was cut into smaller pieces and used to calibrate the water in which the glass was weighed by means of an analytical balance reading directly to 0.0001 gm. The mercury was calibrated in the same manner. Then these liquids were in turn used to determine the expansion of other materials.

Binnie (6) describes a crude early attempt to determine the volume change of a concrete block. The block, 1-foot on a side, was hung from the end of a steel-yardarm projecting through the wall of a small building. The block, being exposed to the atmosphere on all sides, was weighed in this suspended condition. It was found that the weight varied as much as 2 pounds within a 24 hour period.

The National Bureau of Standards (33) includes the density method as one of the ten methods used in thermal expansion studies. One of the advantages of the density method is that it is possible to make determinations with small irregular pieces of the material.

The main apparatus used in thermal volume expansion studies is some type of dilatometer. Furst (18) describes the average dilatometer as follows:

> "It is possible to follow reactions that are accompanied by a change in volume by means of a dilatometer. This instrument is essentially a bulb to which is sealed a capillary tube, and it is by the rise or fall of the liquid level in the tube that the volume change can be noted."

In selecting a dilatometer technique, the main problem in the selection of the apparatus is the determination of the best confining liquid. Bekkedahl (5), in a paper on volume dilatometry, says:

> "A confining liquid to be used in the dilatometer in order to be entirely suitable for the purpose, must satisfy certain requirements. It must exist in the liquid state over the entire range of temperature in which measurements are desired. It must have a vapor pressure sufficiently low that none of the liquid is lost by evaporation during the course of experiment. Its viscosity must not become unduly high at the lower temperatures.

> It must have little or no swelling action on the specimen. Its expansivity must be known accurately over the entire range of temperature for which it is to be used."

Bekkedahl (4) obtained temperature-volume measurements on rubber hydrocarbon and three soft rubber-sulpher compounds using a bulb-type dilatometer. The temperature range investigated was from - 85 to 85°C and the confining liquids used were alcohol, acetone, water, and mercury. The dilatometers were patterned after liquid-in-glass thermometers and consisted of bulbs sealed to capillary tubes. The volume of each capillary tube was previously calibrated by measuring various lengths of mercury threads, of known weights, occupying various positions of the tube. In making the dilatometers the capillaries, with an inside diameter of 2 mm, were sealed to tubes about 2-cm in diameter, leaving the end opposite the capillary open. Weighed samples of rubber, about 27 grams or approximately 30 ml, were then placed inside the tubes and the ends quickly sealed, without scorching the rubber. The dilatometer containing the sample was weighed, filled to a mark on the capillary with a confining liquid at a given temperature, and again weighed. The volume of the dilatometer was found from the weights and densities of the sample and confining liquid at the given temperature. The volume of the dilatometer at other temperatures was computed using the coefficient of volume expansion for the type of glass used in the dilatometer construction.

In some other work Bekkedahl (3, 5) used the same technique with a small modification. In these studies, after he inserted the specimen, he inserted a glass bulb of the same material as the dilatometer. The bulb was about 40-or 50-mm long and its purpose was to avoid possible heating of the specimen during the sealing operation. The effect of this hollow bulb was equivalent to a mere reduction of the net volume of the dilatometer bulb and its expansivity did not enter directly into any calculations. In these studies mercury was used as the confining liquid and the dilatometer was evacuated, before and after the addition of the mercury, to remove any entrapped air.

Bekkedahl (5), in an attempt to eliminate the process of heat-sealing the glass bulb, tried a slightly different technique on one of the tests. The experimental dilatometer used for this test was prepared in two parts with the bottom and top halves joined to each other by means of a ground joint held together by springs. Although this bulb gave no real trouble, the author felt it required considerable care to keep it tightly closed and less confidence was felt in the ground-glass joints through which there was always the possibility of a leak. In this reference the author also gives a detailed account of the necessary calculations and demonstrates their significance with an example.

Thomas (43) used a bulb type dilatometer of the same sort as Bekkedahl. He was investigating the expansion of partially saturated building stones and found the dilatometer unreliable for this work. It appeared that the physical properties of the petroleum ether, the confining liquid, were such that the liquid readily entered, to an undetermined extent, the pore spaces not filled with water.

Patnode and Scheiber (64) conducted volumetric expansion studies on styrene and polystyrene with a mercury-filled dilatometer. However, no description of the apparatus was given.

Boyer and Spencer (9) used an apparatus identical to Bekkedahl's with a single modification. They obtained their capillary tubes pre-calibrated from the Corning Glass Company.

Verbeck and Hass (99) developed a dilatometer method for determining the thermal coefficient of expansion of fine and coarse aggregate. The apparatus consists of a 1-liter dilatometer flask to which was attached a capillary-bulb arrangement containing electrical contacts spaced over a calibrated volume. The flask was filled with aggregate and water and the apparatus allowed to come to equilibrium at one of the controlling electrical contacts. The equilibrium temperature was then noted and the procedure repeated at the other electrical contact. After proper calibration, the only measurements required are the weight of the water placed in the flask and the temperature needed to produce an expansion equivalent to the volume between the electrical contacts.

Valore (97, 98) used a mercury displacement dilatometer for measuring the changes in bulk volume of small concrete cylinders during freezing and thawing. The temperature range investigated was 40 to - 20°F. He, like Bekkedahl, also mentions the problem of selecting a suitable confining medium:

> "The initial problem in the development of a satisfactory dilatometer involved the choice of a suitable displacement medium."
>
> "For the present work, mercury was chosen as the displacement medium, because of several advantages it appeared to show over liquids in the hydrocarbon group. These advantages included (1) a uniform and relatively low coefficient of thermal expansion, (2) a relatively high coefficient of thermal conductivity, (3) a low specific heat, and (4) the nonwetting property."

The vertical cylindrical chamber was constructed from 0.15-inch thick seamless mild-steel tubing 2.05-inches in internal diameter and 7.25-inches high. The top and bottom were formed from 1 inch steel plate. The bottom plate was machined to fit the tubing and then welded into place. The steel cover was machined to fit the top of the cylinder, and the inner surface of the cover was funnel-shaped to facilitate the removal of air extrapped in the dilatometer during the liquid-filling process. A glass measuring pipette was fastened to a threaded steel tube which screwed into the top plate, resulting in a detachable and interchangeable pipette assembly. The cover was attached to the cylinder by means of four 1/4 inch bolts, which extended through the bottom plate, and was secured by wing nuts. A compressible organic plastic gasket 0.002-inch thick was placed between the top of the cylinder and the cover to prevent the loss of mercury.

The size of pipettes used were one-, two-, and five-ml capacity, with the one-ml being generally satisfactory. The pipettes were calibrated by the Metrology Division of the National Bureau of Standards. Only those pipettes for which the mean error of marking was less than one percent were used. Readings were estimated to 0.001 ml for the one- and two-ml pipettes. Therefore, changes in volume as small as 0.0003 percent could be discerned for specimens with bulk volumes ranging between 335 and 340 ml.

A detailed calibration procedure is described in the paper. It consisted of determining the linear expansion of a steel calibration specimen, the same size as the concrete samples, by means of a Tuckerman optical-lever extensometer and autocollimator. The temperature correction for the Tuckerman gage had previously been obtained. The steel specimen was then placed in the dilatometer and the dilatometer filled. It was held at various temperatures until equilibrium resulted and the pipette readings were then noted. The total volume change per degree for the dilatometer chamber was the burette change per degree subtracted from the computed volume change per degree for the steel specimen and mercury. To provide an approximate but independent check, the linear thermal expansion of the dilatometer chamber was measured with the Tuckerman gage and the coefficient multiplied by three.

All observations were made under conditions of temperature equilibrium and the final volume change of the specimen was equal to the burette reading change plus the volume change of the dilatometer chamber, minus the volume change of the mercury. The specimens tested were 1.92-inches in diameter and 7.20-inches long and the surfaces were rendered impermeable to mercury by rubbing a 1:1 cement-fine sand mortar into the surface to fill exposed voids.

In the most recent study conducted on the expansion of bituminous concrete (96), and the beginning of this present investigation, a brief description of work that has been done by the Waterways Experiment Station is given. They tried SR-4 strain gages bonded to Marshall cores and then subjected them to temperature changes to determine suitability of the strain gages for measuring changes in volume. The cores were too soft at high temperatures and did not return to their original dimensions. An asphalt swell apparatus was tried but changes were too small to be measured with dial gages. It was stated that when Marshall cores were subjected to temperatures below 0^{o}F, the cores apparently had elastic properties, it was assumed that above 0^{o}F, the cores had plastic properties. It appeared, therefore, that SR-4 strain gages were suitable for measuring expansion and contraction in low temperature ranges at which the cores were stable. The sample size was discussed and it was felt that Marshall cores were too small for linear tests and that linear and cubical coefficients of expansion are not the same. The main advantage and desirability of using Marshall cores was that of cost and convenience. A possible measuring technique was suggested and it entailed using a metal bar of known coefficient of expansion and then comparing changes in the bar with changes in pavement samples.

This last reference reviews the present condition of the investigation of the thermal expansion properties of asphaltic concrete. This reference has shown many of the problems and questions that have arisen in the measurements of thermal expansion of bituminous concrete. It is the intent of this present investigation to conduct further research into these problems.

MATERIALS

The bituminous mixtures used for this study were selected to be representative of those currently used by the Corps of Engineers for flexible airfield pavements. The gradation selected is an average one recommended for use as a surface course. A description of the materials used in the research follows.

Mineral Aggregates

The types of aggregates and the sources from which they were obtained are as follows:

1. Limestone	Greencastle, Indiana
2. Natural gravel	West Lafayette, Indiana
3. Natural sand	West Lafayette, Indiana
4. Limestone filler	Greencastle, Indiana

St. Genevieve limestone was obtained from deposits of the Mississippian period in west central Indiana near Greencastle. The natural gravel and sand were obtained from a gravel terrace along the Wabash river in West Lafayette, Indiana. The limestone, natural gravel, and natural sand were all obtained from commercial sources. The filler material used was a commercially-produced filler crushed from Greencastle limestone.

A single gradation was used in this investigation but two aggregate mixes were investigated. The first mixture consisted completely of limestone constituents and the second of a gravel-sand combination. The latter mixture employed limestone as the filler.

This single aggregate concept was employed in an attempt to determine the effects of various aggregates on the thermal expansion of the resulting mixture. Rather than mix various types of aggregates in one mixture, with the result that the contributions of the separate constituents would become obscured, it was felt that mixes composed essentially of a single aggregate type would yield more of the desired information. Aggregate materials were tested for specific gravity and absorption according to ASTM methods C 127 and C 128. The results of these tests are shown in Tables 1 and 2.

The commercially produced and washed aggregates, after being brought to the laboratory, were sieved into the required sizes and then washed again before storage prior to blending.

Gradations

The gradation used in this study is shown in Figure 1. The sieve size fractions of the aggregates used, listed in Table 3, corresponded to the sizes specified by the Corps of Engineers for asphalt-mixture surface course, gradation 3-b (1). Table 3 also lists the specifications of gradation 3-b as well as the final batch proportions used. The Fuller's maximum density gradation for these sizes was calculated from the Fuller and Thompson empirical formula:

$$P_i = P_o \left(\frac{D_i}{D_o}\right)^{1/2}$$

where: D_i = sieve size being considered

P_i = percent smaller than D_i

P_o = percent smaller than D_o

D_o = maximum particle size in gradation

TABLE 1

RESULTS OF TESTS ON LIMESTONE AGGREGATES

Size	Material	Bulk Specific Gravity	Apparent Specific Gravity	% Absorption
3/4"-1/2"	Limestone	2.66	2.71	1.05
1/2"-3/8"	Limestone	2.66	2.71	1.12
3/8"-#4	Limestone	2.66	2.72	1.18
#4-#10	Limestone	2.64	2.72	1.57
#10-#20	Limestone	2.64	2.73	1.88
#20-#40	Limestone	2.64	2.73	1.99
#40-#80	Limestone	2.65	2.74	2.15
#80-#200	Limestone	2.65	2.74	2.20
Passing #200	Limestone	2.71	--	--

All results are the average of three determinations.

TABLE 2

RESULTS OF TESTS ON GRAVEL-SAND AGGREGATES

Size	Material	Bulk Specific Gravity	Apparent Specific Gravity	% Absorption
3/4"-1/2"	Natural Gravel	2.71	2.78	1.42
1/2"-3/8"	Natural Gravel	2.70	2.78	1.75
3/8"-#4	Natural Gravel	2.64	2.73	1.85
#4-#10	Natural Sand	2.63	2.74	2.14
#10-#20	Natural Sand	2.64	2.72	2.28
#20-#40	Natural Sand	2.64	2.70	1.46
#40-#80	Natural Sand	2.64	2.69	0.83
#80-#200	Natural Sand	2.67	2.71	0.81

All results are the average of three determinations.

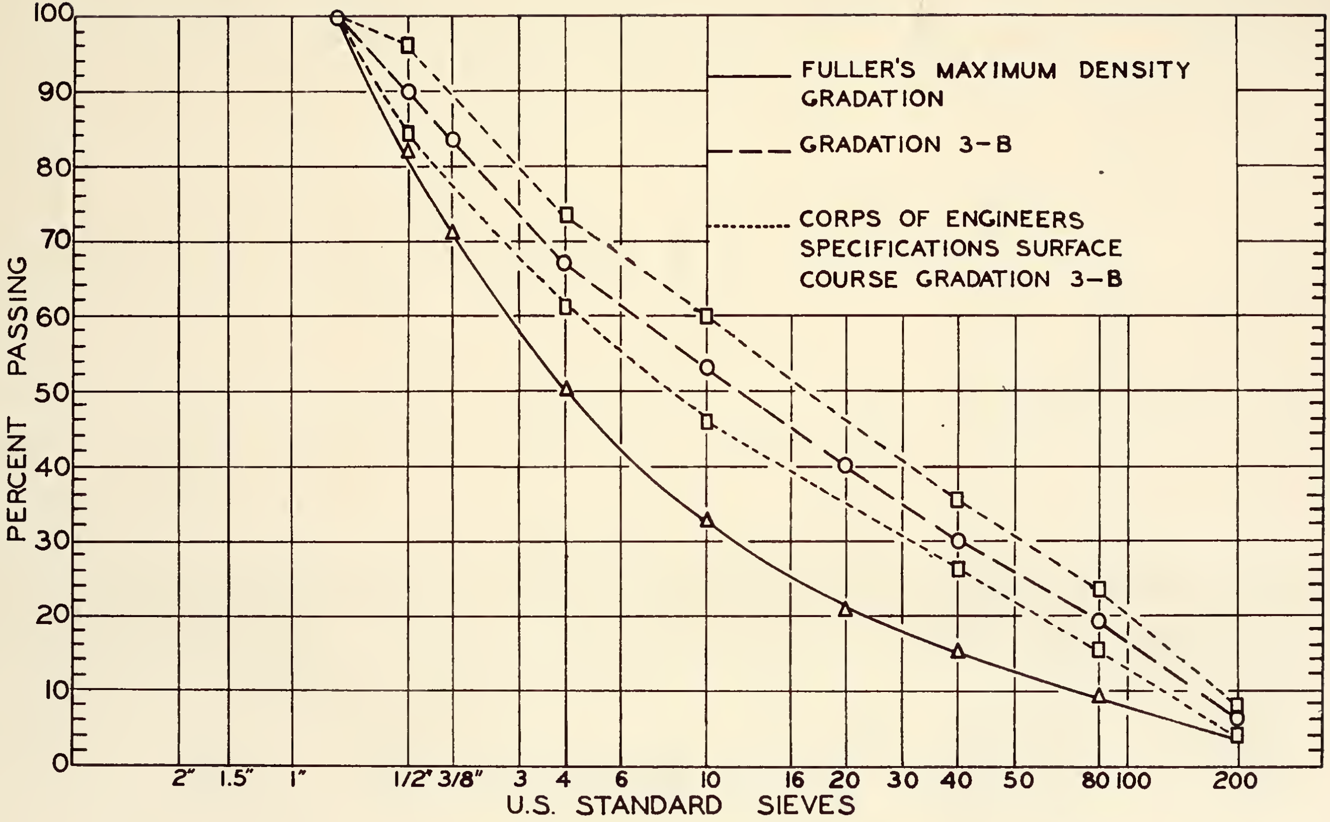

FIG. 1 AGGREGATE GRADATION CURVES

TABLE 3

BATCHING SPECIFICATIONS AND FORMULA FOR GRADATION 3-b

U.S. Standard Sieve No.	Size of Opening in Microns	Gradation Specifications Percent by Weight (passing)	Batch Formula Percent by weight (passing)	Batch Formula Percent by weight (retained)
3/4"	19000	100	100	0
1/2"	12700	84-96	90	10
3/8"	9520	---	83	7
# 4	4760	61-74	67	16
# 10	2000	46-60	53	14
# 20	841	---	40	13
# 40	420	26-35	30	10
# 80	177	15-23	19	11
#200	74	3.5-7.5	6	13
#200-	74-			6

Asphalt

Two penetration grades of asphalt were used in this study, a 60-70 penetration and an 85-100 penetration. These penetration grades were chosen to be representative of those used by the Corps of Engineers in the various temperature ranges to be investigated in this study. Results of tests on these asphalts are presented in Table 4.

TABLE 4

RESULTS OF TESTS ON ASPHALT CEMENTS

Asphalt Property	Results	
	60-70	85-100
Specific Gravity @ 77°F	1.007	1.006
Softening Point, Ring and Ball, °F	130	122
Ductility @ 77°F, 5 cm/min., cm.	100+	100+
Penetration, 100 g., 5 sec., 77°F	62	88
Penetration, 200 g., 60 sec., 32°F	28	33
Loss on Heating, 50 g., 5 hr., 325°F., percent	0.003	0.012
Penetration of Residue from Loss on Heating, percent of original	89	92
Flash Point, Cleveland Open Cup, °F	600	583
Solubility in CCl_4, percent	99.27	99.51
Thin Film Oven Test, Penetration after Test 77°F., 100 g., 5 sec., percent of original	73	69

SAMPLE PREPARATION

This section describes all phases of the study connected with the fabrication and preliminary preparation of the bituminous specimens. In the course of this investigation two types of specimens were used. For the volumetric determinations a standard Marshall specimen was used, while for the linear determinations, a laboratory fabricated beam specimen was used. The preparation of the two types of specimens is discussed separately in the ensuing section. Procedures and equipment for the following operations are described:

Batching and mixing
Marshall design procedure
Compaction
Gage point location
Specific gravity measurements
Securing of gage plugs

Batching and Mixing

Aggregates separated into component sieve-size fractions were blended, according to the batch formula given in Table 3, into 1150 gram samples. The aggregate batching was accomplished by using a Toledo scale, with a sensitivity of one gram, while the aggregate was in a cold, dry condition. The size of the beam specimens were such that they required twice the amount of dry aggregate as the Marshall specimens. Therefore, when preparing to produce a beam, two of the 1150 gram aggregate batches were used.

Prior to mixing with asphalt, the aggregate batches were placed in a Peerless gas oven and heated to a temperature of 345 ± 5°F. These temperatures were used to obtain the required mixing and compaction temperatures as set forth in ASTM D 1559-62T (91). The mixing bowl, paddle and other utensils were heated to approximately 370 ± 5°F to prevent excessive heat loss during mixing. The hot aggregate was placed in the mixing bowl and mixed by hand while still in the dry condition to insure proper distribution of fractions. The mixing bowl was then placed on the Toledo scale and the specified percentage (by weight of dry aggregate) of heated asphalt was added. The mixing was accomplished with a Hobart (Model A-200) electric mixer, modified with a special mixing paddle and a scraper. In the case of a 1150 gram charge of aggregate, mechanical mixing was employed for one minute, then approximately one minute of mixing by hand was used followed by another minute of mechanical mixing. In the case of the 2300 gram charge of aggregate, an initial mixing time of one and one-half minutes of mechanical mixing was employed followed by one minute of hand mixing and then one minute of mechanical mixing.

Marshall Design Procedure

The Marshall test is a compression test in which a cylindrical specimen, 4-inches in diameter by 2 1/2-inches high, is compressed in a special cylindrical test-head, with a constant rate of compression of 2 inches per minute. During manufacture, specimens are compacted by impact employing a special hammer of 10 pounds falling through 18 inches, the number of blows on each of the two faces being 75 for this investigation. The normal test temperature is 140°F (7).

The asphalt contents used in this study were based on the results of the Marshall design procedure as applied to 85-100 penetration grade asphalt cement and the Greencastle limestone mixture. The design procedure was undertaken for this combination of variables only and the results are shown in Figure 2. The procedure followed was the same as that outlined in ASTM 1559-62T (91).

It was felt that only one design investigation was necessary to establish the asphalt contents to be studied for the thermal expansion properties. Selecting and maintaining constant asphalt contents for all mixes allowed a comparison of the effects of other variables.

Compaction

Two methods of compaction were employed in this study. For the volumetric determinations, standard Marshall specimens were used. The compaction procedure used to produce these specimens was the same as that outlined in ASTM 1559-62T (91). The molds were heated to a temperature of 260 ± 5°F previous to mixing, while the compaction hammer was heated in a pan of boiling water. The compactive effort used was 75 blows per face of each specimen. After the specimen had been compacted, it was removed from the mold while still warm and then placed on a level surface and allowed to come to room temperature over night before further testing.

For the linear determinations, laboratory compacted beams, 12 by 2 1/2 by approximately 2 inches, were used. The beams were fabricated using a procedure similar to one used by Monismith (54), which required a modification of the California Kneading Compactor. The unmodified equipment is a mechanical compactor which produces densification by a kneading action

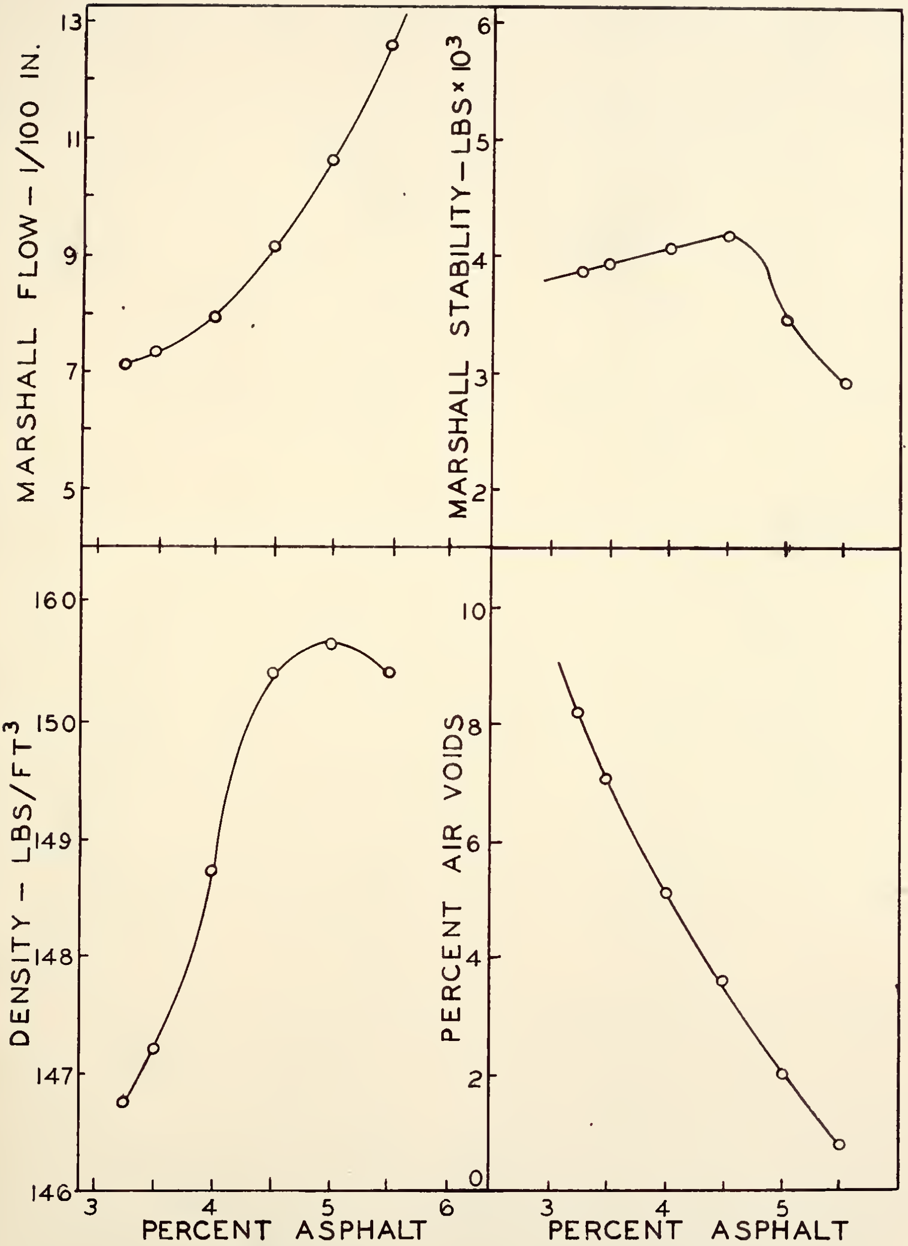

FIG. 2 MARSHALL METHOD DESIGN DATA

imparted through a series of individual impressions made with a ram having a face shaped as a sector of a 4-inch diameter circle. This equipment was modified so that the ram had a square face, 2.5 inches on a side. Since the tamping foot of the compactor moves up and down in a fixed vertical position, it was necessary to move the mold back and forth in a horizontal plane to compact the beam specimens. This movement was accomplished by means of a rack and pinion. The beam mold, in a dissembled condition, is shown in Figure 3. Figure 4 shows the assembled mold in position on the Kneading Compactor and shows the rack and pinion as well as the modified tamping foot.

In order to provide a legitimate basis for comparison between the linear and volumetric determinations, it was decided that it was necessary to produce essentially equal densities between linear and volumetric specimens composed of similar constituents. The Marshall method, being an established procedure, has a specified input energy. It was necessary to vary the beam compaction technique in an attempt to obtain the desired densities in corresponding beam specimens. The compaction procedure outlined below was the result of this investigation and the density of resulting beam specimens compared quite favorably with the corresponding Marshall specimens.

Prior to mixing of aggregate and asphalt, the assembled beam mold and a large metal spoon were heated to a temperature of $370^{\circ}F \pm 5^{\circ}F$. At the completion of the mixing operation, the mold and spoon were removed from the oven. The entire inner surface of the mold was then coated with a thin layer of SAE 20 motor oil. The contents of the mixing bowl were then spooned into the beam mold and proportioned evenly throughout the length

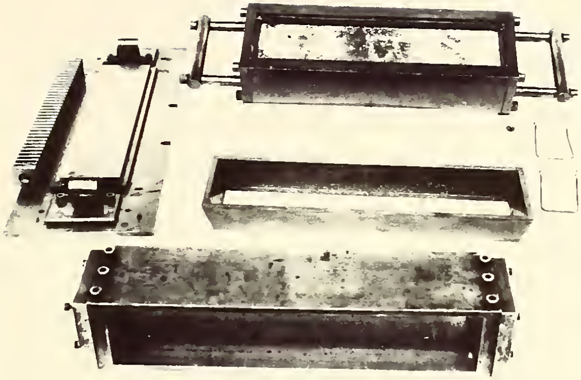

FIG. 3 BEAM MOLD

FIG. 4 BEAM MOLD IN PLACE ON COMPACTOR

of the mold. The mixture was then spaded with a hot spatula around the entire perimeter and then 15 times over the interior. The mixture was then leveled off with the spatula to help insure a level face upon the completion of compaction.

The mold and contents were next placed on the guide channel which was fastened to the Kneading Compactor. Metal stops were then placed at each end of the rack to limit the length of travel to the equivalent length of the beam. The entire assembly, ready for compaction, is shown in Figure 3.

The initial compaction consisted of four complete cyclic movements of the mold, with one cycle beginning and ending at the center of the beam. The initial compaction pressure was about 50 psi. The final compaction consisted of 150 tamping blows spread out evenly over the length of the beam. A pressure of 250 psi was used for the limestone mixtures, while a pressure of 200 psi was used for the gravel mixtures. In the entire compaction procedure the mold was moved a sufficient amount, after each tamp, to maintain a level surface.

After the final compaction, the mold was removed from the Kneading Compactor and placed in a Riehle universal testing machine. A piece of waxed wrapping paper, cut to fit the mold, was placed on top of the compacted mixture and on top of this was placed an I-beam designed to fit into the mold. At this time a leveling load of 1000 psi was applied at a loading rate of 0.05 inches per minute. This leveling load was applied for a period of one minute, after which the specimen was unloaded at the same rate. By this process the variation in height, from one end of the beam to the other, was held to a minimum.

After removal of the leveling load, the base plate was removed from the mold and the remaining part, still containing the specimen, was placed in a cold water bath for a period of at least one-half hour. At the end of this time the specimen (still in the mold) was removed from the water, dried, and stored at room temperature until ready for the next operation.

Gage Point Location

After the beam had cured over night at room temperature, the next step was that of locating and drilling the gage plug holes. The holes were located on the top of the compacted beam, which was still in the mold, by using a template. The template, shown in Figure 3, consisted of a 1/8 inch piece of masonite 2 1/2-inches wide by 12-inches long. The holes in the masonite were accurately located with a steel ruler and then drilled to allow a small tack to fit snuggly into them. Two lines of four holes each were used to obtain two 10-inch and two 5-inch gage lines per specimen. The gage lines were located 3/4 inches from the edge of the beam with the 10-inch gage line holes being located 1 inch from each end. The 5-inch gage line holes were located along the 10-inch lines and were located symmetrically with respect to the center of the beam. The outside set of holes shown in the template in Figure 3 was an early attempt at locating the holes closer to the edge. This resulted in cracking of the sides of the beam at the hole locations.

The masonite template was placed on the compacted beam and held firmly in place. The tack was then inserted in the proper hole and tapped lightly to give a small impression on the surface of the beam. This same procedure was followed for each of the eight holes. The template was then removed and the beam was placed on the table of a drill press. The drilling was accomplished using a 1/4-inch masonary drill bit, shown in Figure 3. Before drilling, the beam was properly positioned under the bit, using the tack impressions as guides. The mold was then securely fastened in place by means of C-clamps. The drilling progressed at a moderate rate, taking care not to force the bit into the material and also allowing sufficient time to bore through individual pieces of aggregate. The depth of drilling was about 3/8 inch. This drilling procedure resulted in vertical holes, properly located, and of a diameter slightly larger than that of the gage plugs.

The gage point plugs were 1/4-inch brass rods that were cut to a length of 1/2 inch. One end of the plug was drilled in the center of the diameter with a No. 52 drill bit. This drill hole was countersunk a slight depth with a 1/4-inch bit. The purpose of the countersinking was to provide a better contact for the mechanical strain gage points. The gage plugs are shown in Figure 5.

After the beam had been drilled, the accuracy of the hole locations was checked by inserting the plugs and checking them with the standard jig. The 5- and 10-inch standard jigs are shown in Figure 5. The loose gage plugs were then removed and the mold was placed on the extraction box, shown in the foreground of Figure 3. A piece of waxed wrapping paper was placed on the top of the beam and on this was placed the I-beam. The asphalt beam was then pushed out of the mold using the Riehle testing machine, after which it was removed from the extraction box and placed on a level surface at room temperature.

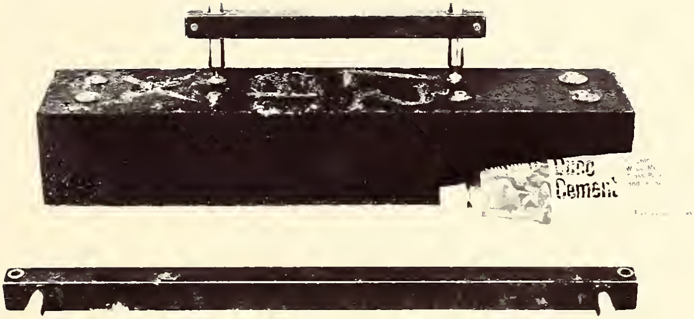

FIG. 5 SECURING OF GAGE PLUGS

Specific Gravity Measurements

Two types of specific gravity measurements were used in the testing of the mixture specimens: bulk specific gravity and Rice specific gravity. After the beams had been drilled and removed from the mold, they were wiped free of any loose aggregate and weighed in air. The specimens were then submerged in water for a one-half hour absorption period. At the end of this absorption period the specimens were then weighed in water and saturated-surface-dry in air. The same procedure was followed for the Marshall specimens after they had cooled to room temperature. For the bulk specific gravity determinations the following formula was used:

$$S.G._{bulk} = \frac{W_a}{W_{ssd} - W_w}$$

where:

W_a = weight of specimen in air

W_{ssd} = saturated-surface-dry weight in air

W_w = weight of saturated specimen in water

Rice specific gravity was obtained for those specimens in the Marshall design procedure for which voids were to be computed. The Rice specific gravity determination is a vacuum saturation procedure used for determining the maximum specific gravity of bituminous paving mixtures. Details of the Rice procedure may be found in ASTM Special Technical Publication No. 191 (76).

Securing of Gage Plugs

The plug holes in the beams were first thoroughly cleaned of all loose material. This was accomplished during the half-hour soaking period in the course of the specific gravity determinations. With the beam completely submerged in water, a 1/4-inch rod was inserted into each hole in turn. By moving the rod up and down a flushing action resulted which removed the accumulated drilling dust.

At the completion of the saturated-surface-dry weighing phase, the beams were again placed on a level surface, at room temperature, and allowed to dry. The plugs were then glued in place, two at a time, using Du Pont Duco Cement. The hole was filled about half way with the cement and the plugs were then inserted with a twisting motion to insure uniform distribution of the cement. There was sufficient clearance between the plug and the edge of the hole to allow a good bond for the cement. Enough cement was used so that some was squeezed out of the hole and formed a ring around the top of the plug. The plugs were then held in place with the 5- and 10-inch jigs as shown in Figure 5. The jigs were supported in place until the cement set, at which time the next set of plugs was cemented in place.

The depth to which the plug holes had been drilled was 3/8 inch. This allowed 1/8 inch of the plug to protrude above the beam to facilitate removal of the plugs after the test. Removal was accomplished by heating the plugs with an electric soldering gun until hot, and then removing them with a pair of pliers. The plugs were then cleaned by sanding with a fine sand paper and reused in the next beam.

Using this method of securing, the plugs were held in place without any noticeable drift during the test. At temperatures of 35°C and higher, some movement of the plugs was detected and this is attributed to the softening of the cement. This movement was very slight, however, and no effect on the results obtained at the lower temperatures could be detected. An early attempt using asphalt to seal the plugs in place met with the same resulting drift at an appreciably lower temperature.

Near the completion of this investigation an attempt was made to reduce the drift produced by the softening of the Duco cement at elevated temperatures. An epoxy cement* was used in several of the tests to determine if it was better suited to resist softening at high temperatures. The epoxy was a composition of three constituents in the following formulation: Epon Resin 828, 55 percent; Epon Resin 871, 36 percent; Diethylenetriamine, 9 percent.

The resulting mixture was quite fluid and easy to apply. The same cementing technique developed with the Duco cement was used with this epoxy. The material was found to set in approximately two hours, requiring that a new batch of epoxy be mixed for each set of plugs glued.

The results obtained with this product indicate that it is more resistent to softening at elevated temperatures than the Duco cement. The increased difficulty in removing the cemented plugs also indicated that a considerably better bond had been obtained. The removal procedure was the same as previously described, with more heat being required to loosen the plugs.

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* Shell Oil Company, New York, N. Y.

Although the epoxy was more troublesome to use than the Duco cement, it produced more consistent results and is recommended as the cementing agent in further testing.

THERMAL EXPANSION MEASURING TECHNIQUES

This section describes the equipment and testing techniques developed for this investigation. The primary purpose is to describe the apparatus and to present the general techniques used with each piece of equipment. Because of a need for comparisons in the various aspects of the techniques, modifications in the procedure were introduced throughout the investigations. These individual modifications are discussed separately in reviewing the results of the appropriate tests. The final evaluation of the different methods are presented in the results section. The aspects of this section are discussed under the following headings:

- Constant temperature equipment
- Volumetric techniques
    - Dilatometer I
    - Dilatometer II
    - Dilatometer III
- Linear techniques
    - Stainless steel strain gages
    - Whittemore strain gages
    - Dual microscope apparatus
- Sealing of specimens

Constant Temperature Equipment

The equipment used to obtain the desired temperatures for this investigation is shown in Figure 6. The equipment* a "Precision" Lo-Temptrol Bath

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*Precision Scientific Company, Chicago, Illinois

FIG. 6 CONSTANT TEMPERATURE BATH

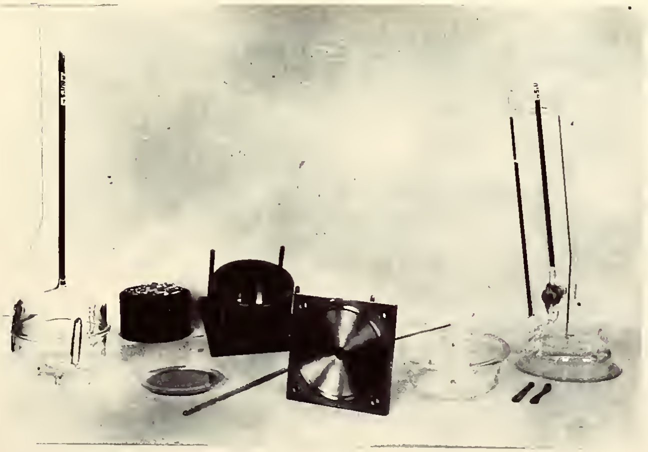

FIG. 7 DILATOMETERS

and Circulating System, has a temperature range of from - 30 to + 70°C. The manufacturer states the controllable sensitivity and uniformity as being ± 0.2°C. The bath is a circulating liquid medium type having a 15 gallon capacity, with a 50 percent mixture of ethylene glycol and water being used as the liquid medium. The bath possesses one cooling rate and three heating rates. All tests were conducted using the medium heating rate.

During testing the bath was used with the insulated top removed. In order to obtain the stated performance it was necessary to place the unit in a temperature controlled environment. A forced-air controlled temperature chamber* was used for this purpose. The temperature of this unit was held at 23.5°C ±0.5°C throughout the investigation.

The temperature measurements throughout the investigation were made by means of a total immersion mercury thermometer calibrated in increments of 0.1°C and having a range of - 35 to + 50°C. The calibration of the thermometer was checked at 0°C and + 25°C. The error in the thermometer calibration at these temperatures was less than one-half of the least graduation. Using this thermometer, and with the temperature bath in the constant temperature room, the sensitivity and uniformity of the bath were checked and found to be within the manufacturer's stated performance except at the extreme end of the cooling range. At the lower temperatures the sensitivity varied considerably from the stated performance, and to compensate for this the specimen temperature was assumed to be the average temperature attained during the cyclic operation of the bath. In order to help assure consistent temperature readings, the thermometer was maintained at a constant position in the bath throughout the entire investigation.

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* Electric Hot Pack Company, Philadelphia, Pennsylvania

Volumetric Techniques

In essence only one volumetric technique was employed in this study. The method investigated was that of a liquid-medium displacement dilatometer. A dilatometer consists of a bulb of some sort into which the specimen fits. To this bulb is attached a graduated glass tube. The remainder of the bulb is sealed and a liquid medium is added to some mark on the tube. The dilatometer and contents are then subjected to various temperatures and the level of the liquid in the tube is read. Knowing the expansion of the dilatometer and that of the liquid medium, the expansion of the sample can be determined.

There are various desirable characteristics for both the dilatometer and displacement liquid. The requirements for this liquid, as given by Bekkedahl (5) and Valore (97, 98), have been mentioned in the Review of Literature. The characteristics considered desirable for the dilatometer include the following: it should be as simple as possible and be reusable for each test in order to minimize calibration; the material from which the dilatometer is constructed should have a low coefficient of expansion and high conductivity; the volume of the dilatometer bulb should be as small as possible, and yet accommodate the specimen, in order to reduce the amount of required displacement liquid; the seal at the bulb joint, permitting the specimens to be replaced, should allow no loss of liquid during the test as well as cause no difference in the calibrated expansion of the dilatometer with each usage; there should be no reaction between the dilatometer and the displacement liquid; visual observation of the specimen should be possible to permit detection of any discrepancy in the course of the test, such as entrapped air; and the dilatometer should lend itself to easy handling and cleaning.

Three pieces of equipment employing these principles were designed and constructed for this investigation. The first two were made of Pyrex glass and the last was constructed of stainless steel. All three dilatometers were designed to accommodate the standard-size Marshall specimen. The following discussion describes this equipment and the measuring techniques developed.

Dilatometer I

The first dilatometer constructed is shown in the left of Figure 7. The bulb was constructed from 110-mm Pyrex tubing with the top and bottom being rounded to facilitate the removal of entrapped air. The bulb was in two pieces, being connected by means of a flat-ground glass-joint held in place by rubber bands and sealed with vacuum grease. To the top of the bulb was attached a 5-ml capacity pipette which was graduated in 0.1-ml divisions.

The original concept in the use of this dilatometer was to calibrate it using mercury and then make actual test observations using a 50-percent solution of ethylene glycol and water. The glycol-water solution possessed all of the desirable characteristics except that its thermal expansion properties were not known. This drawback was to be overcome by calibrating the liquid in the dilatometer, which had previously been calibrated with mercury.

This procedure was never accomplished because the dilatometer seal would not contain the head of mercury developed during the calibration procedure. In order to obtain some information concerning the feasibility of the apparatus and displacement liquid, a different calibration technique was used. In this case a volume of mercury, measured by weight, equal to the volume of an average Marshall specimen was introduced into the sealed dilatometer. This volume occupied somewhat less than two-thirds the volume of the dilatometer with a considerable reduction in the force acting on the seal. The remainder of the dilatometer volume was filled with the glycol-water solution, the amount being determined by weight. The filled dilatometer was then placed in the temperature bath and held at constant temperature until equilibrium conditions resulted. The liquid level and temperature were noted after equilibrium and the dilatometer was then subjected to another temperature. The procedure was then continued over the entire range of - 30°C to + 30°C, with the upper temperature being established by the melting point of the silicon stopcock grease used to seal the bulb. This calibration procedure overcame the initial sealing problem encountered when using only the mercury as the calibrating liquid.

A calibration curve was obtained by subtracting the calculated expansion of the mercury, for the appropriate test temperature, from the dilatometer reading at the same temperature. This curve represented the combined expansion of the dilatometer and a specified volume of ethylene glycol-water solution. This calibration technique necessitated a constant specimen volume, equal to the volume of mercury used during calibration, in order to be valid. Due to the normal change in density with varying asphalt content, everything else remaining constant, this requirement could not be met. Therefore the dilatometer was actually calibrated for a single asphalt content which gave the desired specimen volume. To measure the expansion of specimens having other asphalt contents the dilatometer would have to be calibrated for the specimen volumes resulting from the various asphalt contents.

This technique involved an unnecessary amount of calibration and because this was only a preliminary investigation of the technique, the dilatometer was calibrated for only one specimen volume. A series of tests were undertaken on specimens containing the asphalt content for which the dilatometer had been calibrated. From this investigation many additional undesirable characteristics of the apparatus and technique were discovered.

The ideal condition in any measuring system is to make direct observations on the desired property. If this is not possible then the next best procedure is to minimize the influence of extraneous factors. For this measuring technique, although the specimen volume amounted to almost twice the volume of the displacement liquid, the actual specimen expansion was about one-tenth of the differential dilatometer reading, indicating an extreme influence due to the displacement liquid. The cause for this difficulty was thought to be due to two factors. In the construction of the dilatometer, for the convenience of the glass blower and to facilitate the removal of air, the top and bottom of the bulb were rounded. This increased the amount of displacement liquid necessary to fill the dilatometer and thereby increased the total thermal expansion of the liquid. The second factor was the coefficient of expansion of the displacement liquid. The 50-percent solution of glycol and water had a considerably higher coefficient than plain water, also acting to increase the total expansion of the system.

Another difficulty encountered with this apparatus was removal of entrapped air. The first attempt to remove this air was by subjecting the filled dilatometer to a vacuum. This procedure not only removed the air, but removed air from suspension in the displacement liquid as well as removing air from the specimen and thus saturating it to an undetermined extent. Although the vacuum removed most of the entrapped air, the resulting side effects were considered undesirable. In a further attempt to find a solution to this problem, a vibrating table was used in conjunction with a vacuum. The nearly-filled dilatometer was placed on the vibrating table and subjected to a slight vacuum while the table was vibrating. This technique aided little in removing the air. To increase the efficiency of this last technique, a small percentage of wetting agent was added to the displacement liquid. This addition increased the air removal but changed the characteristics of the displacement liquid as well as increasing the degree of saturation of the specimen. The final solution consisted in partially filling the dilatometer at a very slow rate. The dilatometer was then tipped and rotated until all the surface air had been removed. This procedure was continued in stages until the dilatometer was filled.

In designing this dilatometer the smallest tubing available, which would still accommodate the specimen, was chosen for the construction of the bulb. This choice was made in order to minimize the volume of the bulb. However, in selecting this tubing the resulting diameter was not large enough to accommodate coated specimens. This removed the opportunity to compare coated and uncoated specimens in order to determine the effects of absorption, greatly reducing the value of the apparatus.

The first dilatometer was an experimental model and was constructed with the thought that many improvements would subsequently be necessary. The primary purpose was to investigate the apparatus and determine the faults of the design so the proper improvements could be included in a revised apparatus. To this extent the initial dilatometer served its purpose and subsequently a second dilatometer was designed and constructed.

Dilatometer II

The second dilatometer to be constructed was to include the appropriate corrections found necessary in the first apparatus. The initial design of this dilatometer incorporated a slightly different concept than the first. The dilatometer was made from Pyrex glass and is shown in the right of Figure 7. The bulb was constructed from 120-mm diameter tubing and although the top and bottom had been designed flat, for convenience in fabrication they were rounded. The bulb was again constructed in two pieces, being connected by a flat-ground glass-joint of larger surface area than that of the first dilatometer. The joint was secured by rubber bands and sealed with a high temperature Apiezon* vacuum grease. The entire bulb was tilted about 10° to facilitate air removal. The measuring pipette was of 1-ml capacity with graduations of 0.01 ml, making estimation to 0.001 ml possible. By increasing the accuracy of the readings the capacity of the pipette was reduced. Because the total expansion of the system, as calculated for the entire temperature range, was expected to be more than 1 ml, some allowance had to be made to maintain the liquid level on scale. This was accomplished by attaching a 5-ml pipette to the 1-ml pipette by means of a stopcock, as shown in Figure 7. With the stopcock closed, the liquid level would rise in the 1-ml pipette and appropriate readings were then taken. When the liquid level reached the capacity of the pipette, the stopcock was opened and a measured amount of the liquid transferred to the 5-ml pipette. The stopcock was then closed when the

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* Apiezon 'T' Grease, Associated Electrical Industries, Ltd.

liquid level reached the desired point on the 1-ml scale. This procedure allowed the removal of a known amount of the displacement liquid, maintaining the level of the liquid on the scale at all times during the test, with considerable ease and efficiency.

This dilatometer was designed with the idea of using mercury as both the calibrating liquid as well as the displacement liquid. However, again a sealing problem developed and the use of mercury was discontinued with this dilatometer. Instead, distilled de-aired water was used both as the displacement liquid as well as calibration liquid. This limited the range of testing to temperatures above $0^{\circ}C$, but did not rule out the use of another liquid for the lower temperature range. However, an initial investigation of the equipment, using water, was undertaken while searching for an appropriate liquid for use at lower temperatures.

The volume of the bulb was first investigated by placing a specimen in the dilatometer, sealing it, and determining the amount of water necessary to fill it to an appropriate point on the scale. The amount of water required to fill the dilatometer was less than that needed for the first dilatometer, but considerable "dead space" was still incorporated into this volume. To reduce this, a glass plate was cut and ground to fit the bottom of the bulb. The bottom of this plate was rounded while the top, on which the specimen rested, was flat. The plate was removable and is shown in Figure 7. Considerable space remained at the top of the dilatometer and rather than risk entrapping unnecessary air by using another plate in this location, a different solution was attempted. This space was filled with glass rods and beads, held in place on top of the specimen by a 1/4-inch rubber O-ring, 3 1/2-inches in diameter. After these modifications the volume of liquid necessary to fill this dilatometer, when containing a specimen, was less than half the amount required to fill the first dilatometer.

In calibrating the dilatometer, the glass plate, rods, beads, and O-ring were inserted and the dilatometer sealed. The dilatometer was then evacuated to seal the vacuum-bulb stopcock, after which the vacuum was released. To aid in the filling process a long-stem funnel was inserted into the 5-ml pipette. The distilled water, which had previously been de-aired by means of an aspirator, was introduced into the dilatometer through the funnel and open stopcock. The amount of water required to fill the apparatus was determined by weight. The entrapped air was removed by tilting and rotating the dilatometer at various stages in the filling process.

The dilatometer was then placed in the temperature bath and allowed to come to equilibrium conditions at a temperature slightly higher than 0°C. If necessary a small amount of water was added to the system in order to locate the liquid level on the pipette scale. This procedure was accomplished by using the funnel and slowly adding the required amount. A very small amount of air pressure was then applied to force all of the water out of the 5-ml pipette. Care was exercised so as not to entrap air in the dilatometer before the stopcock was closed.

When the system had again reached equilibrium conditions a few drops of a colored light oil were allowed to run down the inside of the 1-ml pipette to prevent evaporation. The temperature and liquid level, at the bottom of the oil miniscus, were then noted. A new temperature was then established and the readings again taken after equilibrium conditions had become established. This procedure was continued over the desired temperature range, transferring liquid to the 5-ml pipette when necessary. These data were then transformed into a calibration curve for the dilatometer by subtracting the calculated expansion of the water for the various test temperatures. This curve and accompanying calculations may be found in APPENDIX A. The specific volume data for water, used in making these calculations, can also be found in APPENDIX A.

The procedure followed in testing a specimen was quite similar to the calibration technique. The dilatometer and accessories were first thoroughly cleaned with a chromic acid cleaning solution, as described by Shoemaker and Garland (83). The bottom plate was positioned in the dilatometer and the specimen was placed on top of the plate. The O-ring was then centered on top of the specimen and the glass rods and beads positioned. The ground joint was then greased, the dilatometer sealed, and the rubber bands put in place. The stopcock, which had previously been greased, was positioned to allow evacuation of its sealing bulb. A vacuum was then applied to the 1-ml pipette evacuating the stopcock bulb. The stopcock was then turned to release the vacuum, sealing the vacuum bulb, and leaving the dilatometer ready for filling.

Figure 8 shows the dilatometer at this stage of preparation. The water, previously de-aired, was introduced through the funnel and entrapped air was removed in the same manner as used in the calibration procedure. The amount of water required to fill the dilatometer was determined by weight. The funnel was then removed and the dilatometer, held in its proper position by the white base shown in Figure 8, was placed in the temperature bath. The remainder of the procedure was identical to that used during calibration.

FIG. 8 FILLING PROCESS-DILATOMETER II

FIG. 9 FILLING PROCESS-DILATOMETER III

In this technique there was one modification introduced that was different from the methods used for the other techniques. The temperature of the bath, prior to the addition of the specimen, was not at room temperature, but slightly more than 0°C. After the filling operation the specimen was introduced directly into this temperature environment which had been reached in the normal progression of another test series. Introducing the water filled dilatometer at this point allowed the simultaneous testing of the various methods without waiting for the completion of one test series before the commencement of another.

This apparatus and technique solved many of the problems encountered with the first dilatometer. A complete series of tests on various specimens was run using this procedure and the results are presented later in this report. The usefulness of this dilatometer for investigation of the low temperature range was never studied because a suitable displacement liquid was not found. In order to investigate samples in the lower temperature range, a third dilatometer was designed and constructed.

Dilatometer III

The third dilatometer was designed to be used with mercury as the displacement liquid. It was made of stainless steel and is shown in the center of Figure 7. It consisted of a tube brazed onto a flat plate to form the bulb of the dilatometer. The top was a removable flat plate held in position by four wing nuts. The underside of the top plate was machined to fit over the tube as well as having a slight conical slope toward the center to facilitate air removal. The inside dimensions of the bulb were large enough to accommodate a coated specimen, and with the sample in place, the amount of liquid necessary to fill the dilatometer was about half that necessary to fill the second dilatometer. The dilatometer seal was precision machined to insure a good metal to metal contact. When sealing the apparatus, a small amount of the high melting point Apiezon vacuum grease was spread around the top of the tube. With this combination, no trouble was encountered in sealing the dilatometer to withstand the force exerted by the mercury.

The measuring system was comprised of an arrangement similar to that used on the second dilatometer, and included a provision for removing the expanded liquid necessary to maintain the liquid level on the pipette scale. The measuring pipette was of 1-ml capacity and graduated in 0.01 ml divisions. The pipette was connected to a glass tube, used for storing the expanded mercury, by means of a three-way stopcock. This stopcock allowed the dilatometer to be evacuated and then filled while under evacuated conditions. This entire arrangement was then fastened to a 1/2-inch Kovar tube. The metal tube was fastened to the top plate of the dilatometer by means of an epoxy, forming a permanent seal.

Previous to any use, the glass portion of the dilatometer was first cleaned with a ten percent solution of nitric acid and then thoroughly washed with distilled water. It was then recleaned with the same chromic acid cleaning solution as used to clean the glass dilatometers, and thoroughly washed with distilled water. Extreme care was exercised to prevent any of the acid from contacting the metal portions of the dilatometer.

There was no difference between the calibration technique and the procedure used for conducting an actual test, except for the presence of of the specimen. Previous to the sealing process, the top of the metal tube forming the dilatometer bulb was greased with the Apiezon vacuum grease. In the case of an actual test, the specimen was then carefully placed in the bulb, whereas for the calibration procedure the bulb was left empty. The top was then set in the proper position on top of the bulb and fastened by the four wing nuts.

Figure 9 shows the dilatometer ready for filling. To aid in the filling process, a glass container was attached to the top of the reservoir tube by means of a small piece of rubber tubing. A vacuum tube, connected to an aspirator, was attached to the 1-ml pipette as shown in the figure. The stopcock was then positioned to allow the dilatometer to be evacuated while a weighed amount of mercury was placed in the glass reservoir tube. The stopcock was then readjusted to allow the mercury to enter the bulb of the dilatometer, which was now evacuated. During this process the vacuum on the 1-ml pipette was released so that mercury would not be sucked up into the pipette when the stopcock was again adjusted to that position. To ensure complete removal of air, the evacuation and filling operation was done in stages. This entailed evacuating the system, allowing a portion of the mercury to fill the dilatometer, and then evacuating again. This procedure was followed until the dilatometer was filled. The vacuum tubing and glass container were then removed.

The dilatometer was then placed in the temperature bath, which was originally maintained at room temperature. The initial testing temperature was then set by adjusting the thermostat on the bath and sufficient time allowed for equilibrium conditions to become established. The initial test temperature selected was always at the lower end of the temperature range and thus it became necessary to add more mercury to the system before starting the actual test. This was accomplished by placing the glass container on top of the 1-ml pipette and adding a sufficient amount of mercury to the system to bring the liquid level to the desired position on the pipette scale. In performing this last operation, it was found helpful to insert a long piece of enameled copper wire into the pipette to remove air which was entrapped by the addition of this mercury. The quantity of mercury added was again determined by weight.

The calibration curve, shown in APPENDIX B, was obtained in the same manner as the curve for the second dilatometer. The calculated expansion of the mercury was subtracted from the dilatometer readings for the respective temperatures, resulting in the expansion of the dilatometer. In order to obtain the specimen expansion, the dilatometer correction was added to the dilatometer reading and from this was subtracted the calculated expansion of the mercury.

This apparatus, although it possessed a rather large correction factor, satisfactorily fulfilled its purpose. There were not any difficulties encountered with the apparatus itself and it could be used with any other desirable displacement liquid besides the mercury. The function for which the original dilatometer had been designed was fulfilled in this dilatometer and the results obtained are discussed herein.

Linear Techniques

In the course of this study there were three linear techniques investigated. They consisted of a combination optical-mechanical method, a mechanical method, and an optical method. All three techniques were adapted for measuring the expansion of the laboratory compacted beams. The different methods are discussed under appropriate headings.

Before proceeding with the actual measuring techniques, a brief description of the means for supporting the beams during testing is in order. Figure 10 shows the apparatus used for this purpose. The specimen was supported in the horizontal plane on a set of rollers, made from glass tubing with an outside diameter of 12 mm. It was aligned in the longitudinal direction by the four corner posts, each containing a brass roller. By this means the beam was supported over its entire length in a manner allowing it to expand and contract freely. During a test, the entire stand was placed in the temperature bath and the liquid level maintained about 1/4 inch above the top of the beam. Two separate stands were constructed and used during the investigation, allowing a set of two beams to be tested under identical test conditions.

Stainless Steel Strain Gages

The original concept of this method of length change measurement is credited to Mullen (56). He used the technique to measure the creep of portland cement paste under conditions of constant temperature. His equipment possessed some characteristics that lent themselves for use in the present investigation, and the technique was incorporated into this investigation with slight modifications.

The gage consisted of two sizes of stainless steel hypodermic needle tubing arranged to form a telescoping extensometer. The gage shown in the extreme left of Figure 11 is an original one of Mullen's. Next to this is shown the modified gage before completion, while next to this are three completed gages. A completed gage is shown in position on the specimen in the background. Figure 12 shows a drawing of the gage.

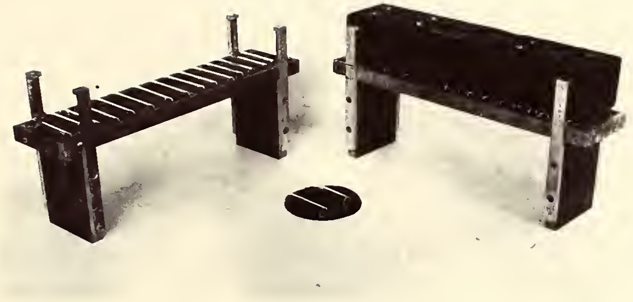

FIG. 10 BEAM SUPPORTS

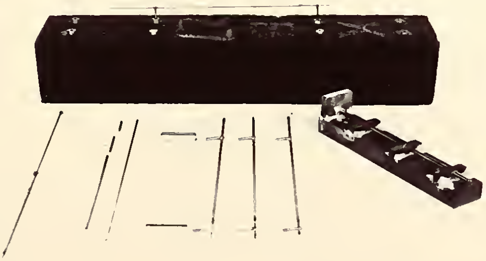

FIG. 11 STAINLESS STEEL STRAIN GAGES

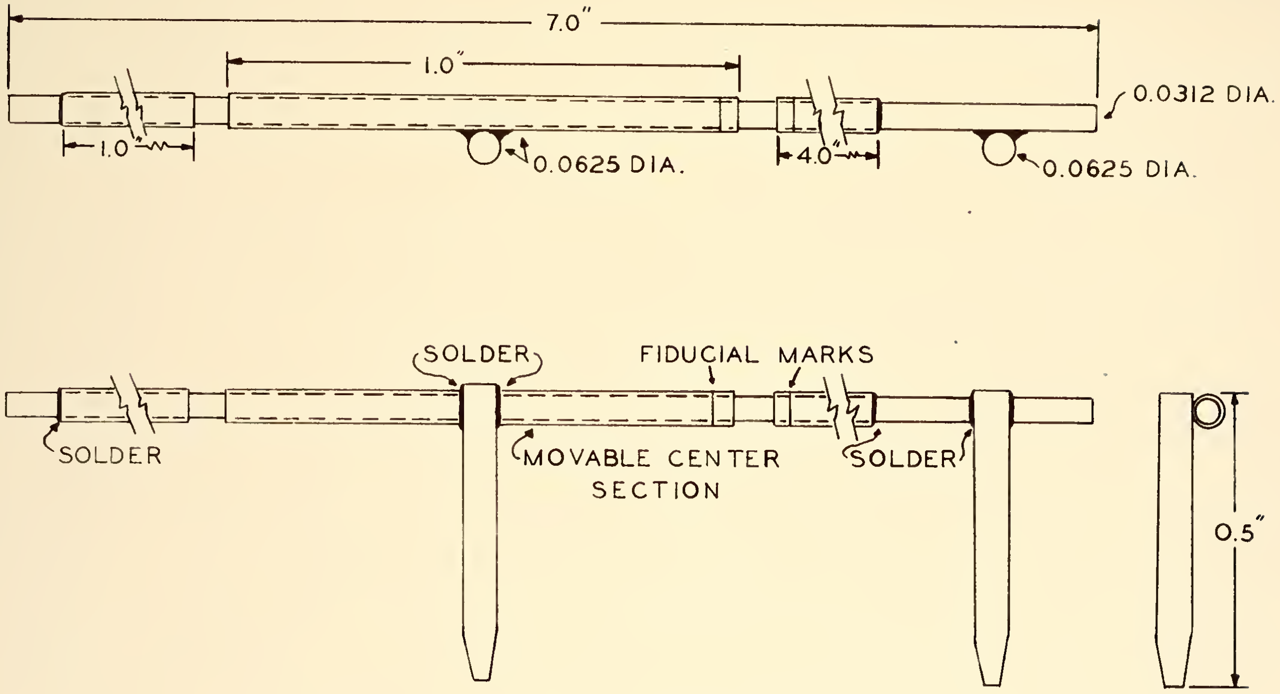

FIG. 12 STAINLESS STEEL STRAIN GAGE

The differential movement of the gage was observed with a portable bifilar linear traverse microscope* with a range of 0.08 inch, drum calibration of 20 microinches, a magnification of 50, and a working distance of 1 1/2 inches.

In the assembly of the gage, referring to Figure 12, three sleeves of large tubing (0.0625 inch outside diameter) were placed over a long piece of small tubing (0.0312 inch outside diameter). The short sleeve, at the left end of the gage, was soldered to the inside tube; the long sleeve on the right end of the gage was soldered to the inside tube; the left stud was soldered onto the middle tube, which was left movable; and the right stud was attached to the long inside tube. The studs were made from the larger size tubing and tapered slightly by grinding to allow driving them into the drilled holes in the brass plugs where they were held securely by friction. The studs, perpendicular to the shaft, were located to give a 5-inch gage length when the movable center section was located in the middle of its field of travel.

Fiducial gage marks were scribed around the right end of the movable center section and around the left end of the long outer sleeve. The fiducial mark was formed by cutting a narrow sharp groove around the tubes on a lathe. The cutting tool was a single-edge safety razor blade which was barely touched to the tube surface. These grooves were located as near the ends of the tube as possible so that when the tubes were in place, the grooves on the two adjacent tubes were in close proximity. By sidelighting the groove, a black line was visible which could be intercepted between the bifilar cross hairs. Fixed sidelighting, visible across the top of Figure 6 and partially visible across the top of Figure 13, was

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* Gaertner Scientific Corporation, Chicago, Illinois

FIG. 13 MEASURING TECHNIQUE-STAINLESS STEEL GAGES

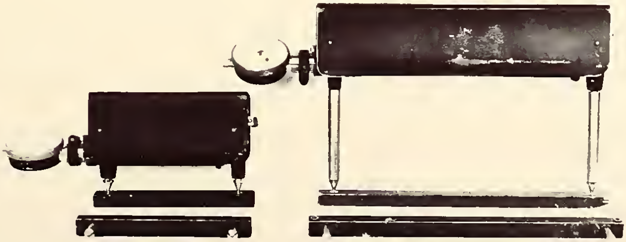

FIG. 14 WHITTEMORE STRAIN GAGES

accomplished by the installation of two fluorescent lights above and in back of the test specimens. Irregularities were often observed in the fiducial marks and in these cases it was necessary to map the mark and to use the same segment for all determinations.

Figure 13 shows the gages in position on a specimen in the bath ready for observation. The gages were constructed so that the fiducial marks would be above the bath medium, eliminating the chance of error due to refraction. However, this arrangement presented problems in determining the proper correction factor to be applied to the gages to account for their thermal expansion. Under this condition the only parts of the gage that were directly subjected to the bath medium were the contact studs, with the body of the gage being above the temperature environment. This made it difficult to determine the actual temperature of the gage relative to the bath medium.

In an attempt to evaluate the necessary correction factor, the brass block, shown in the right of Figure 11, was constructed. A length of 1/8-inch diameter Invar rod was inscribed with a fiducial mark as described above and in like manner a length of the large diameter hypodermic needle tubing was inscribed. The rod and tube were then placed in the brass block and soldered at the back only. The lengths of the rod and tube were adjusted, previous to soldering, to give a 5-inch gage length from the point of soldering to the fiducial marks.

With this arrangement, the fiducial marks were located side by side. The block allowed free expansion and contraction of the rod and tube over the 5-inch gage length, with the three center sections acting only as guides. The block was placed in the temperature bath and adjusted so the height of the rods above the liquid level equaled that for test conditions. Readings were then taken with the microscope on the differential movement of the stainless steel tube relative to the Invar rod for various bath temperatures. By knowing the expansion of the Invar rod (39), the expansion of the stainless steel tube was obtained.

The results obtained by this method agreed quite favorably with the thermal coefficient of expansion of the tubes given by the manufacturer. It had been anticipated that this correction would be different from the actual coefficient of expansion for the tubing because the body of the gage was exposed to a different temperature environment than the bath medium. The resulting agreement in these two values may be due to the conductivity afforded by the brass block which may have resulted in equalizing the temperature of the tube to that of the bath. For lack of more conclusive information, and in order to obtain a preliminary evaluation of the technique, the correction factor applied to actual test results was based on the thermal coefficient of expansion of the tubing as given by the manufacturer.

In performing a test, the studs of the gages were first tapped into the holes located in the center of the brass plugs. Two beams were tested at a time with two gage lines being observed per specimen. After the gages had been positioned, the specimens were then placed on the beam supports and positioned in the temperature bath. The bath thermostat was set for the desired temperature and after equilibrium conditions had been reached the initial readings were taken on each specimen. In making strain determinations for a single specimen, it was necessary to read two separate gages that were mounted on 5-inch gage lines, parallel to each other, and 1 1/2 inches apart.

To observe the strain of a single gage, the bifilar cross hairs were set upon one fiducial mark, and the reading recorded. The cross hairs were then moved to the second mark by means of the micrometer eyepiece drum, and that reading was then recorded. The difference between these two readings was the total distance between the gage marks at that temperature. Three such readings were obtained and averaged. The microscope was then shifted along the metal shelf and focused on the second gage of the specimen. The procedure was repeated for this gage and then the two gages of the remaining specimen. Three observations were taken on each of the gages. The bath was then adjusted to a different temperature and the procedure repeated after equilibrium conditions had again become established.

The difference between the average initial reading and the average reading obtained for each successive temperature gave the movement for that particular gage. This movement was comprised of two parts, that of the specimen expansion and the expansion of the gage itself. Because of the position of the fiducial marks, the expansion of the gage itself produced a shorting of the enclosed distance. This meant that had there been no temperature correction necessary for the gage, the distance between the fiducial marks would have been greater than that actually measured at each temperature. To account for this, the calculated gage expansion was added to each reading for the appropriate temperature change. Then the difference between the initial reading and each successive corrected reading was the expansion of the beam under that particular gage. The sample expansion was then obtained by averaging the results for the two gage lines.

The results obtained with this apparatus and technique, including an evaluation, are presented later in this report.

Whittemore Strain Gages

The Whittemore strain gage is a mechanical strain gage employing a dial gage and having no internal multiplication of the measured deformation. For this investigation two gages were used, one possessing a 5-inch gage length and the other a 10-inch gage length. The least reading of both gages was 0.0001 inch, resulting in a strain sensitivity of 0.00002 inch/inch for the 5-inch gage and 0.00001 inch/inch for the 10-inch gage.

The gages and accessories are shown in Figure 14. Standard bars, on which the gages are mounted in the figure, are used as a reference between readings. The standard jigs, used for establishing the correct gage length on the specimens, as well as the brass plugs and No. 52 drill bit are also shown. The drill bit was used in drilling the center holes in the brass plugs.

At the outset of this phase of the investigation, the initial concern was the effect of the temperature environment on the gages. In an attempt to overcome any temperature effect on the gage, the 10-inch Whittemore was modified as shown in the figure. The extensions, machined from 1/2-inch diameter stainless steel, were 3 1/2-inches long. When they were securely screwed in place no loss in accuracy could be detected. The extensions allowed the bulk of the gage to be well above the specimen and temperature environment when making measurements. A comparison between the unmodified 5-inch gage and the modified 10-inch gage showed no temperature effect on the 5-inch gage even though it was closer to the temperature environment. This was due primarily to the short length of time in which the gage was in contact with the specimen. The modification of the 10-inch Whittemore proved useful in another respect however. It allowed simultaneous testing with the dual microscope apparatus. For this reason, the extensions on the 10-inch gage were left in place throughout the investigation even though none were used on the 5-inch gage.

The testing technique was very simple and easy to perform and was identical for both gages. The standard bars and the two gages were stored in the constant temperature room, thus maintaining them at a uniform temperature throughout the investigation. In obtaining a measurement, the gage was first checked against the appropriate standard bar and a series of three readings obtained. The gage points were then gently inserted into a set of the brass gage plugs and the reading taken. This procedure was repeated three times for each gage line, removing and replacing the gage for each consecutive reading.

It was found necessary to hold the gage vertically and gently tap the dial gage to assure that the proper reading was obtained. With this technique the gage could be removed and replaced with a variation of only two dial divisions in any set of readings. After the four gage lines had been measured, the gage was again checked against the standard bar. Any difference between this set of readings and the initial set indicated a change in the base length of the gage during this time interval. However, throughout the investigation this comparison showed no need for any compensation to be applied to the gage readings.

The entire procedure was repeated at the desired temperatures and the difference between the initial reading and the consecutive readings was the length change of the specimen. The results were then plotted in graphical form and are presented later in this report accompanied by an evaluation of this technique.

Dual Microscope Apparatus

A large percentage of the thermal expansion measurements that have been conducted used some sort of a dual microscope measuring system. Therefore, an apparatus of this sort was designed and constructed for use in this investigation. The equipment, in its final form, appears in Figure 15.

The apparatus was essentially two microscopes rigidly fixed apart at a 10-inch gage length and mounted on a chassis which provided movement in two horizontal directions. The movement was controlled by two screw mechanisms, each providing continuous parallel movement. The screw elements were 5/8-inch diameter stainless steel rods which possessed eighteen threads to the inch, allowing accurate positioning with fairly rapid motion. All components of the apparatus were made from stainless steel, aluminum, or brass in order to minimize corrosion. The parts were precision machined to provide smooth effortless movement with a minimum of deviation along the line of travel.

The microscopes used with this apparatus are shown in Figure 15. The measuring microscope was the portable bifilar linear traverse microscope used for the phase of this investigation involving the stainless steel strain gages. The other microscope* possessed a magnification of 10, a working distance of 2 inches and a filar cross hair. Both microscopes were equipped with a rack and pinion focusing arrangement.

Prior to observing a specimen, the entire assembly was placed on top of the temperature bath and securely fastened by tighting three thumbscrews against the inside walls of the bath. The microscopes were then adjusted to align the cross hairs parallel to the respective lines of

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* Gaertner Scientific Corporation, Chicago, Illinois

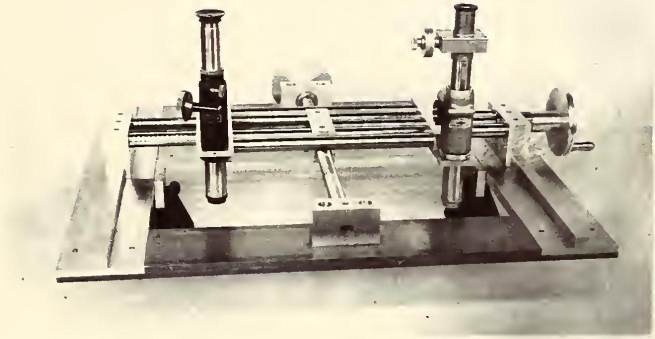

FIG. 15 DUAL MICROSCOPE APPARATUS

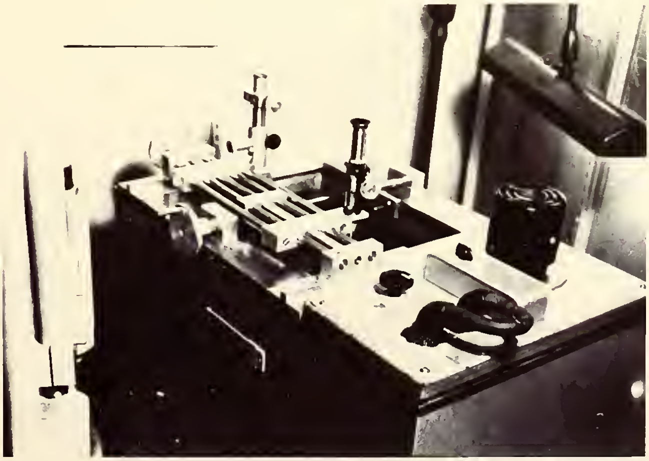

FIG. 16 DUAL MICROSCOPE APPARATUS IN POSITION

travel provided by the positioning screws. Both microscopes were then securely fastened in position by lock nuts. At this time all the moving parts of the apparatus were oiled to reduce wear and increase the freedom of movement. The apparatus in position and ready for observation is shown in Figure 16.

This apparatus conveniently measured the expansion of two specimens, which allowed a comparison to be made of specimens under identical conditions. The specimens were placed on the beam supports and positioned side by side in the temperature bath with the 10-inch gage lines being parallel to the microscopes. The microscopes were then positioned and focused over each gage line in turn and the position of the beams adjusted so that the two brass plugs were in the field of view of the respective microscopes. The bath thermostat was then set for the initial temperature and after sufficient time was allotted for equilibrium conditions to become established, the beams were ready for observation.

By sidelighting the brass plugs, using two fluorescent lights partially visible in Figure 16, a shadow was cast across the hole in the center of the brass plugs. This shadow created a black circle which was accentuated by the counter-sinking of the hole. When viewed under the microscopes, the edge of this circle made an excellent index mark for the microscope cross hairs. Either side of the hole, the side being parallel to the gage lines, could be used as the index mark. When first selecting the side to be used as the index mark, primary consideration was given to the best side observed under the bifilar microscope. The side was selected which would give the finest and sharpest image on which the cross hairs could be focused. Once having selected this side, the same side was used as the index mark for the filar microscope. That is to say, if the left side of the plug under the bifilar microscope was selected, then the left side of the plug under the filar microscope would also be used as the index mark for that plug. The same index mark was then used throughout the entire test when sighting on that particular gage line. In order to reduce vibrations and increase the accuracy of the readings all observations were made with the temperature bath turned off during this period.

For the first reading, the microscopes were positioned over the brass plugs of the first gage line. The microscopes were adjusted by the two positioning screws until both brass plugs appeared in the field of view of the respective nicroscopes. The index marks were selected and mapped to assure ease in relocation. The cross hair on the filar microscope, that microscope on the left side of Figure 15, was then set on the index mark of the plug on which it was focused. The setting of this cross hair was accomplished by adjusting the positioning screw which controlled the direction of travel parallel to the gage lines. After this cross hair had been set in place no further movement of the positioning screws was done until the observation of this gage line was completed.

The bifilar cross hairs of the measuring microscope were then focused on the selected index mark. This was accomplished by adjusting the micrometer eyepiece drum until the index mark was centered between the cross hairs. The micrometer eyepiece drum was then observed and recorded. The bifilar cross hairs were then moved and reset on the index mark and a second reading taken. The procedure was again repeated a third time, with the cross hair relocation being accomplished only by moving the micrometer eyepiece drum. During a set of readings, the bifilar cross hairs could be removed and reset on the index mark with an average variation of about three of the micrometer eyepiece drum divisions. The average of these values represented the initial reading for that gage line.

The same procedure was followed for the remaining three gage lines, with three observations being made on each line. When all four lines had been observed, the bath was again turned on and the thermostat adjusted to the next temperature setting. After equilibrium conditions had been reached, the procedure was repeated at the new temperature and then at other desired temperatures.

The expansion of a particular gage line was the difference between the initial and subsequent readings for that line. The sample expansion was obtained by averaging the values obtained from its two gage lines. These data, as well as an evaluation of the apparatus and technique, are presented later in this report.

Sealing of Specimens

Early in the investigation it was found necessary to coat the specimens in order to reduce absorption effects. Several materials were investigated in an attempt to find one that would adequately fulfill the necessary requirements. Besides the ability to seal the specimen, the material should possess the following characteristics: it should remain plastic over the desired temperature range so as not to crack, run or introduce excessive confining pressures; it should not react with the sample; it should not react with the displacement liquid in the case of the volumetric determinations; the material should be easy to apply in thin coats sufficient to seal the specimen; the application should be done at room temperature so as not to change the sample characteristics; the material should be securely attached to the sample in order to represent the actual sample expansion and not the entrapped air, in the case of the volumetric determination; and the coating should be easily removable at the end of the test.

This last requirement was found to be impractical and subsequently dropped from this list. Initially, the idea of testing the same sample by various methods had been contemplated. This would have eliminated the variables involved in sample preparation and would have given a better basis for comparison of the various techniques. However, this idea was found impractical for bituminous concrete samples. Initial tests showed that the linear specimens did not always return to their original length, indicating a permanent length change had taken place. This information agreed with the findings of Lang and Thomas (44). Therefore the idea of testing the same sample by the various techniques in both the coated and uncoated state was discontinued.

The materials investigated for this purpose included the following: a petroleum wax; rubber cement; several latexes; asphalt emulsions; and hot asphalt cement of the same grade as that used in the specimens. The primary need for the seal coat was for use with the volumetric determinations. Although some work was done on sealing the linear specimens, by far the most critical problems resulted in sealing the volumetric specimens and the bulk of this discussion is concerned with this phase of the sealing operation. All of these materials met with varying degrees of success and each one had its own characteristic disadvantages.

The wax was applied by partially dipping the specimen in the melted material. When the material solidified, the remainder of the specimen was coated in the same manner. Although this method proved to be an easy means of application and quite adequate in sealing the surface voids of the specimen, it was difficult to obtain the desired thickness. When the material solidified, the surface became quite smooth, assisting the removal of entrapped air. However, at low temperatures the material cracked, allowing liquid to enter the specimen.

A rubber cement was tried, but with little success. The material was applied with a brush and a fairly uniform coat of the desired thickness could be obtained. The material formed a good bond and sealed the specimen quite adequately. However the material remained sticky even after it had dried a considerable length of time. This made handling and removal of entrapped air difficult. In an attempt to overcome this problem, the rubber cement was thinned with benzene and then applied to the surface. This served only to dissolve the asphalt on the surface of the specimen and mix it with the rubber cement, disrupting the surface and still maintaining the stickiness.

Two types of latex were tried, one a synthetic latex of the Dow Chemical Company*, and the other a natural latex of the J. G. Milligan Company**. The Dow Chemical product was a thinner latex than the Milligan product. The Milligan product required a fixer, a solution of ethyl alcohol and acetic acid, to be sprayed on after the latex application. Both latexes were easy to apply and formed a good seal with a minimum thickness. The latexes set in less than a day and formed a clear plastic coating. However when the coated samples were immersed in water both latexes turned a milky color, indicating that the emulsions had not completely broken.

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* Dow Chemical Company, Midland, Michigan
** J. G. Milligan Company, Milwaukee, Wisconsin

The latex, in order to set properly, should have been cured at temperatures higher than room temperature. However, if the coated specimens were immersed in the water for only a few days, the coating sill appeared intact and upon drying it returned to its original clear color. This problem was not encountered in the metal dilatometer where mercury was used as the displacement liquid. For this case the latex coating worked quite well.

Two SS-type emulsions were also investigated in an effort to find an adequate solution to this problem. The emulsions were made of an 85-100 penetration asphalt cement and a 60-70 penetration asphalt cement respectively. The emulsion that was composed of the same grade asphalt as that used in the sample, was used to seal the specimen. The emulsion was applied by a brush with considerable ease, resulting in the desired thickness and adequately sealing the surface voids. Upon drying however, the material was quite sticky and required careful handling to keep from peeling off small portions. The stickiness again impeded the removal of entrapped air, as well as sometimes causing the material to stick to the sides of the dilatometer. The concept of using this type of material, which would have properties similar to the asphalt used in the specimen, was quite sound and a good idea. However, the resulting disadvantages impaired its usefulness.

The use of hot asphalt to seal the specimens resulted in much the same disadvantages as the emulsions. The same grade asphalt as used in the specimen was heated and then brushed on the specimen. The material cooled rather rapidly upon coming in contact with the specimen and made it extremely difficult to obtain the desired thickness. The material was also sticky and required extreme care in handling. For these reasons no further attempt to use this technique was tried.

Of the various methods tested, the two that gave the best overall results were the asphalt emulsions and the Dow latex. The Milligan latex apparently increased the expansion of the sample considerably. Of these two methods, the emulsions produced the best protection against absorption. For this reason, the asphalt emulsions are the recommended materials to be used in sealing the specimens. However, if a latex could be obtained that would completely break at room temperatures it would certainly be easier to work with than the asphalt emulsions and it would probably seal the specimens as adequately.

RESULTS

The primary concern of this study was the investigation of a number of techniques for the purpose of determining those best suited for measuring the thermal expansion of bituminous concrete. The general techniques employed with each method have been previously presented. Some variations were introduced into these techniques in an attempt to evaluate the apparatus more completely. A description of these variations is included with the discussion of the respective technique.

In this section results are presented graphically and accompanied by a written discussion. The numerical data obtained for this investigation appear in APPENDIX C and APPENDIX D. The data are catalogued according to type of measuring technique employed. The volumetric determinations are contained in APPENDIX C and the linear determinations are given in APPENDIX D. The results are presented under the following headings:

- Discussion of Volumetric Apparatus
    - Dilatometer I
    - Dilatometer II
    - Dilatometer III
    - Volumetric Apparatus Evaluation
- Discussion of Linear Apparatus
    - Stainless Steel Strain Gages
    - Whittemore Gages
    - Dual Microscope Apparatus
    - Linear Apparatus Evaluation

Thermal Expansion Trends

60-70 Asphalt Cement-Greencastle Limestone
85-100 Asphalt Cement-Greencastle Limestone
85-100 Asphalt Cement-Lafayette Gravel

Comparison of Asphalt-Aggregate Contributions

Discussion of Volumetric Apparatus

In this section a discussion of the volumetric apparatus used in this study is presented. Typical trends obtained with the different pieces of equipment are discussed in arriving at an evaluation of the respective techniques. Before proceeding with this discussion the reader should know that neither of the glass dilatometers nor the metal dilatometer had been designed to incorporate means for inserting a thermocouple to obtain the temperature of the specimen. This eliminated any direct means of determining when the sample had reached the same temperature as that of the bath. A method was then devised to obtain an indirect indication of when the specimen had reached constant temperature, and consequently when the dilatometric system had reached equilibrium conditions. When the temperature of the system was changed, the liquid level in the pipette rose to a higher position than it originally occupied. Theoretically, when the liquid level no longer changed position for an appreciable period of time, the system had reached a state of equilibrium. At this time, the level of the liquid was recorded and it was assumed that this condition represented a state of equilibrium for the respective components of the system.

Dilatometer I

Most of the disadvantages of the original dilatometer have been mentioned previously when describing the technique. The questionable calibration procedure and the relative inaccuracy of the 5-ml. pipette combine to make the results uncertain. Another undesirable factor was the large volume of displacement liquid necessary to fill the dilatometer. This factor, coupled with the relatively large coefficient of expansion of the ethylene glycol-water solution, resulted in the sample expansion being only one-tenth of the differential dilatometer reading. This influence of the displacement liquid was more than desired and added to the uncertainty of the results obtained with this dilatometer. For these reasons no test results using this dilatometer are presented. The main purpose served by this piece of equipment was to provide information about the technique and thereby provide a basis for corrections that could be incorporated into a modified apparatus. This dilatometer did adequately fulfill this purpose.

Dilatometer II

The second dilatometer was a direct result of the changes found necessary in the first dilatometer. Although many of the original problems were solved with this apparatus, many more were encountered. These problems are discussed in this section.

A few of the equipment difficulties have been previously mentioned when describing the technique. The problem concerning the volume reduction of the displacement liquid was solved by the addition of the glass plate and beads. With this arrangement the sample expansion was about three-quarters of the differential dilatometer reading, considerably better than the one-tenth value obtained with the first dilatometer. However, although the glass plate was easy to handle and place in the dilatometer, considerable difficulty was encountered with the glass beads. The placement of the beads was quite time consuming and tedious and considerable care had to be exercised to keep from losing some of the beads during handling.

Another problem encountered was that of unsealing the dilatometer after a specimen had been tested. There was not enough clearance between the specimen and bulb walls to allow the bottom half to be slid free of the top half. The solution involved twisting and sliding the joint while applying tension, necessitating care to prevent breakage.

The problem of air removal was continually encountered throughout the investigation, not only with this dilatometer but with all of the volumetric techniques. However, more trouble was encountered with this dilatometer than with the metal one. Although as much of the surface air as possible was removed before the test, on several occasions during the course of the test small air bubbles were emitted from the dilatometer bulb. The source of this air is not definitely known, indicating uncertainty in the thoroughness of the air removal procedure. This air may have been released from a small pocket between the specimen and glass plate. It may have been air escaping from voids in the specimen, either due to slight absorption or differential expansion of the asphalt and aggregate. Whatever the reason, the phenomenon was not consistent and served only to invalidate the test.

The second dilatometer required a relatively long time to reach equilibrium conditions. This was due to several factors, among which are the relatively low rates of thermal conductivity of the glass and water. The large volume of water also increased the total time to reach equilibrium conditions.

The dilatometer was constructed of glass for reasons previously given. However, because of this it was quite fragile and required care in handling. This property reduced the practicality of the apparatus.

The calibration curve for this dilatometer appears in APPENDIX A, Figure 47. The expansion of the dilatometer itself is relatively small, a factor which should increase the accuracy of the sample expansion determination. However because the dilatometer expansion is so small, the accuracy of the calibration technique could be questioned. The calibration procedure for this dilatometer was performed several times, with this being the most consistent set of results obtained.

Figures 17 and 18 show test data for dilatometer II. Figure 17 shows a series of typical test readings obtained with this dilatometer. The sample represented by this figure was composed of the Greencastle limestone and 4.5 percent of the 85-100 penetration asphalt cement. The solid line represents the actual dilatometer readings for the various temperatures indicated. Since the specimen was uncoated, the reductions in the readings are most easily explained by considering them a result of absorption of the displacement medium. The time intervals shown on the figure represent the intervals in which this assumed absorption took place. The dashed line represents the dilatometer readings assuming no absorption and was obtained by adding the volume assumed due to absorption to each successive

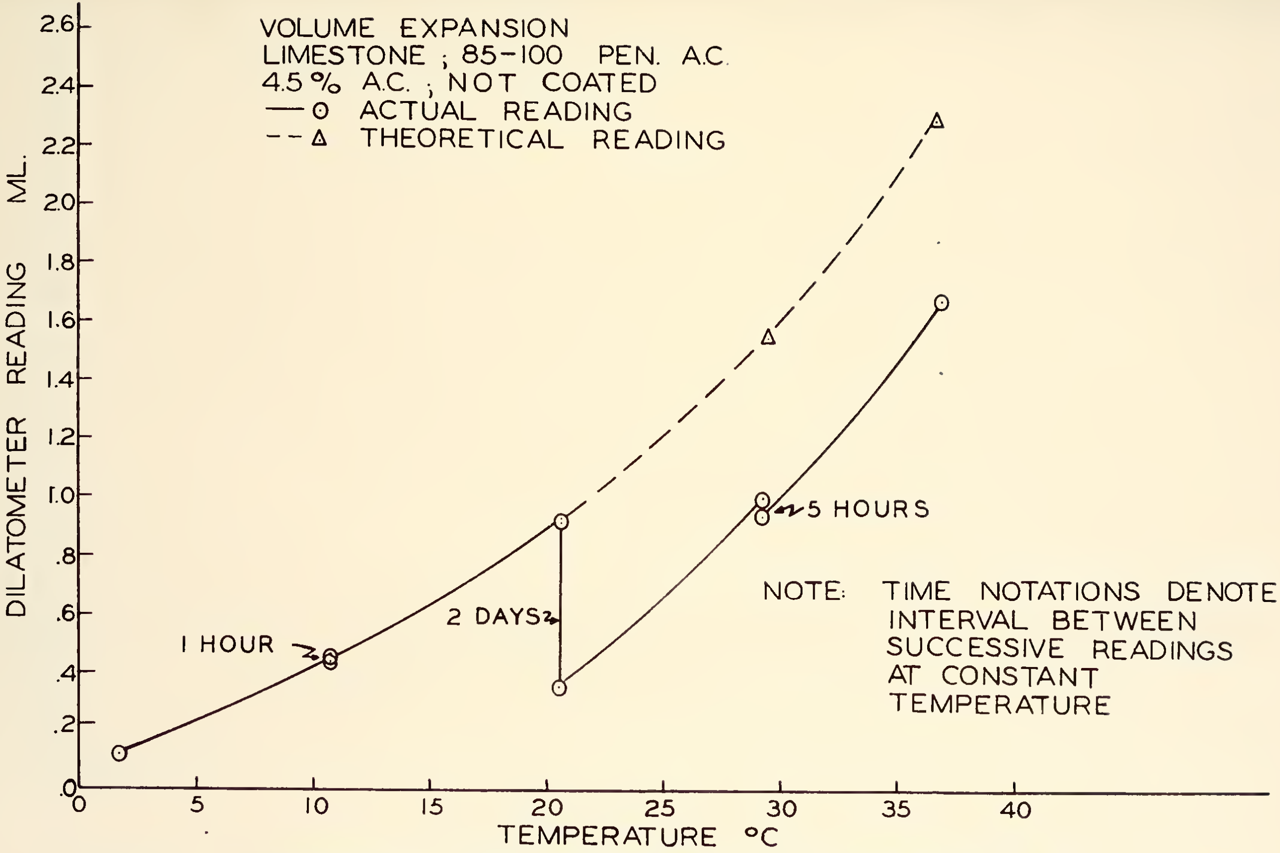


FIG. 17 TYPICAL TEST READINGS-DILATOMETER II

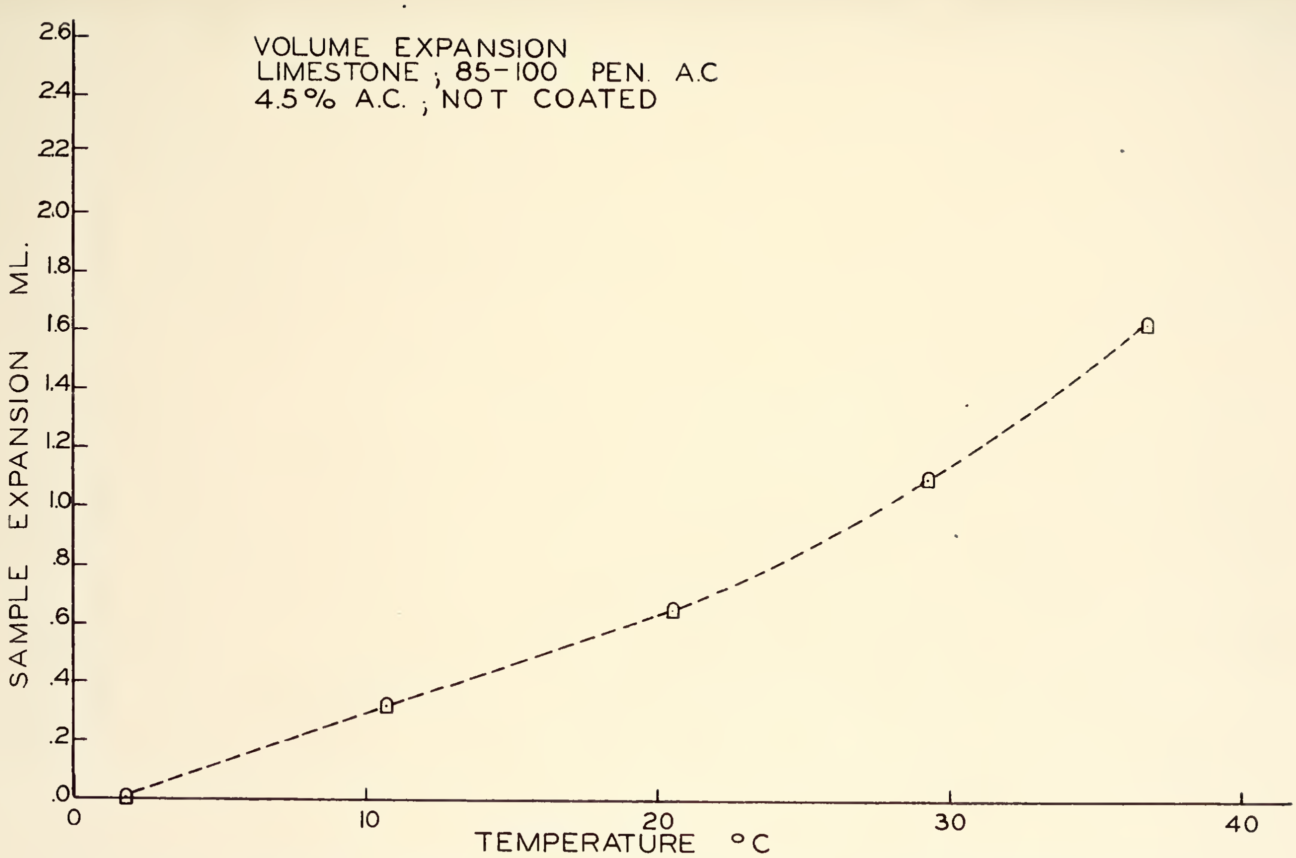


FIG. 18 TYPICAL VOLUMETRIC RESULTS - DILATOMETER II

reading. The final curve, represented by the dashed line, is not completely accurate because the amount of liquid presumably absorbed while changing temperature is not included. However, this amount would be small because of the relatively slow rate of absorption and the required length of time to reach equilibrium conditions. The time interval required to reach equilibrium conditions after making a 10°C temperature change was on the order of 3 hours. Figure 17 shows a reduction of 0.042 ml. in a 5-hour period at 28.5°C for the 4.5 percent sample. Assuming this to be a standard rate for all temperatures, which it is not, then approximately 0.02 ml. would be absorbed while reaching equilibrium conditions after a 10°C temperature change. For a 30°C temperature change this assumed absorption could account for an error of about 3 percent for this particular test. However, this rate is not consistent for all specimens and the absorption rate would also be temperature dependent. Because the effects of these factors were extremely difficult to measure, the computed sample expansion was based on the theoretical dashed curve neglecting the possible absorption during the temperature change.

Figure 18 shows the computed sample expansion for the same specimen represented in Figure 17. The calculations used in obtaining this curve, as well as those for all the specimens tested with this dilatometer, appear in APPENDIX C. Figure 18 is typical of all of the tests conducted with this dilatometer. The expansion curves all have the same characteristic shape. The first portion of the curve is essentially a straight line up to approximately 20°C, where the expansion appears to increase at an increasing rate. Additional results obtained with this dilatometer are presented later in this report when discussing the trends produced by different variables.

A final evaluation of this test technique and apparatus is presented by means of a comparison between the second and third dilatometers. A discussion of the information learned from the third dilatometer is presented first.

Dilatometer III

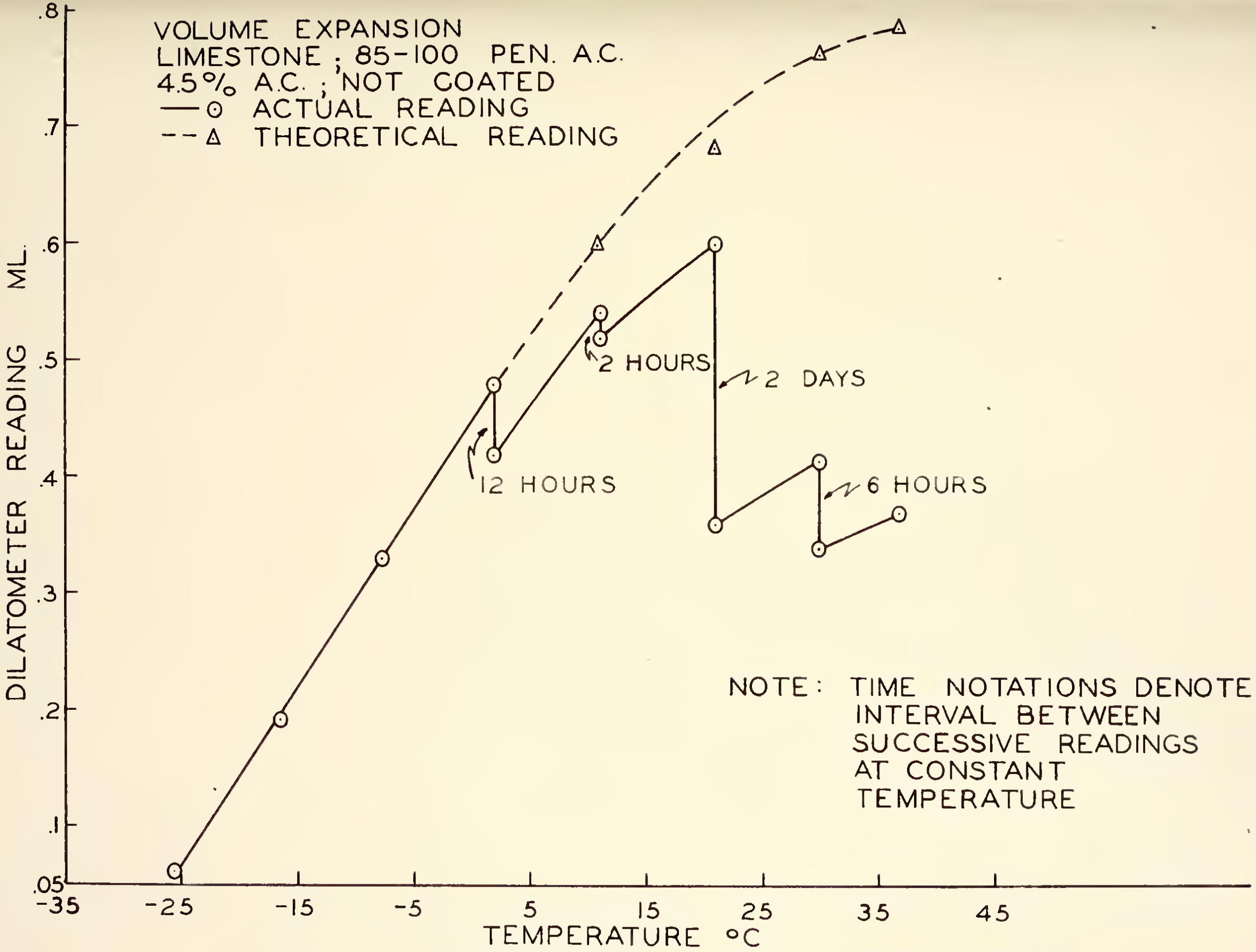
In using Dilatometer III there were relatively few problems encountered with the apparatus itself. It was rugged and easy to handle. It adequately held the head of mercury developed during a test. The time required for the system to reach equilibrium conditions was considerably shorter than that required for the second dilatometer, resulting from the relatively high conductivity of the stainless steel and mercury as compared to glass and water. This dilatometer was not as easy to clean as the glass dilatometer and required care to keep from corroding the metal with the cleaning agents. Another disadvantage of this dilatometer was the inability to observe the specimen and determine if entrapped air was present.

A portion of the tests with this dilatometer were conducted by introducing the displacement liquid under a vacuum. This procedure almost guaranteed the removal of entrapped air. However, after comparing the weight of specimens before and after subjection to this test method, a large change in weight was noted. This change was due to absorption of the mercury by the specimen while under vacuum. This phenomenon was encountered in both coated and uncoated specimens, indicating that a rupturing of the coating had taken place. The greatest amount of mercury absorbed was by the uncoated specimens of low asphalt content.

In an attempt to reduce this problem, several tests were conducted by filling the apparatus without the aid of evacuation. This reduced the amount of absorption that occurred during filling, but made the filling process more tedious. The three-way stopcock allowed no air to escape during the filling. Therefore, only a small portion of mercury could be added to the dilatometer bulb at a time before it was necessary to relieve the pressure developed by the displaced air.

The data for tests made with Dilatometer III are presented in Figures 19 through 22. Typical test readings obtained with this dilatometer are shown in Figure 19. The specimen represented by this figure was uncoated and was fabricated from Greencastle limestone and 4.5 percent of the 85-100 penetration grade asphalt cement. The problem of absorption during the test was also encountered with this technique. Figure 19 represents a test in which the dilatometer was filled while under vacuum. Figure 20, showing typical dilatometer readings for an uncoated specimen which consisted of Greencastle limestone and 5.0 percent of the 60-70 penetration grade asphalt cement, represents a test in which no evacuation was employed during filling. Similar absorption trends resulted with both filling techniques during the test, with a slightly lower absorption rate resulting from the process using evacuation. In both cases, however, this absorbed amount was small compared to the total sample expansion.

In an attempt to reduce this absorption, the dilatometer was tipped to reduce the head of mercury and the test was conducted while the dilatometer was in this position. Because of the design, the dilatometer could not be tipped to any great extent and the loss in head was not a considerable amount. This modification however, seemed to reduce the absorption at lower temperatures but aided little at elevated temperatures.



NOTE: TIME NOTATIONS DENOTE INTERVAL BETWEEN SUCCESSIVE READINGS AT CONSTANT TEMPERATURE

FIG. 19 TYPICAL TEST READINGS-DILATOMETER III

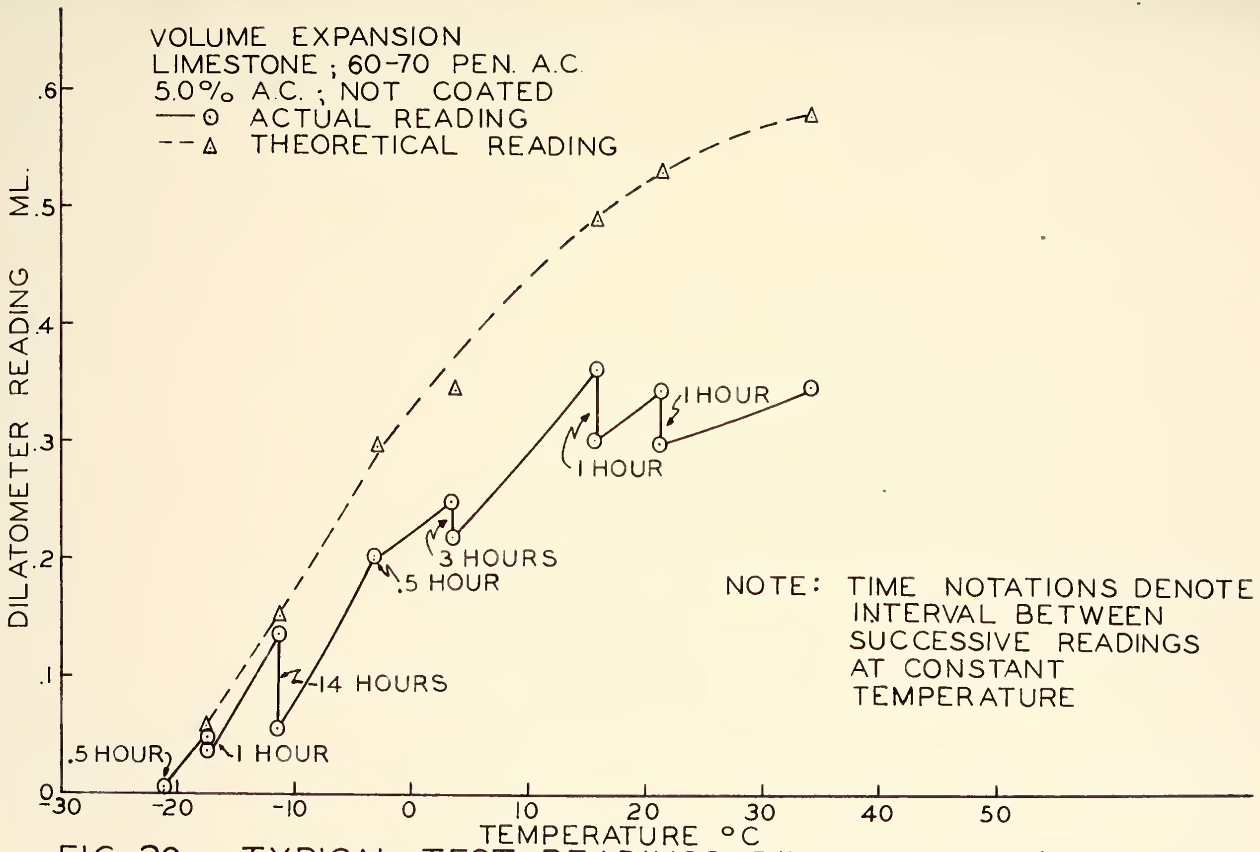


FIG. 20 TYPICAL TEST READINGS-DILATOMETER III
NON-EVACUATED TECHNIQUE

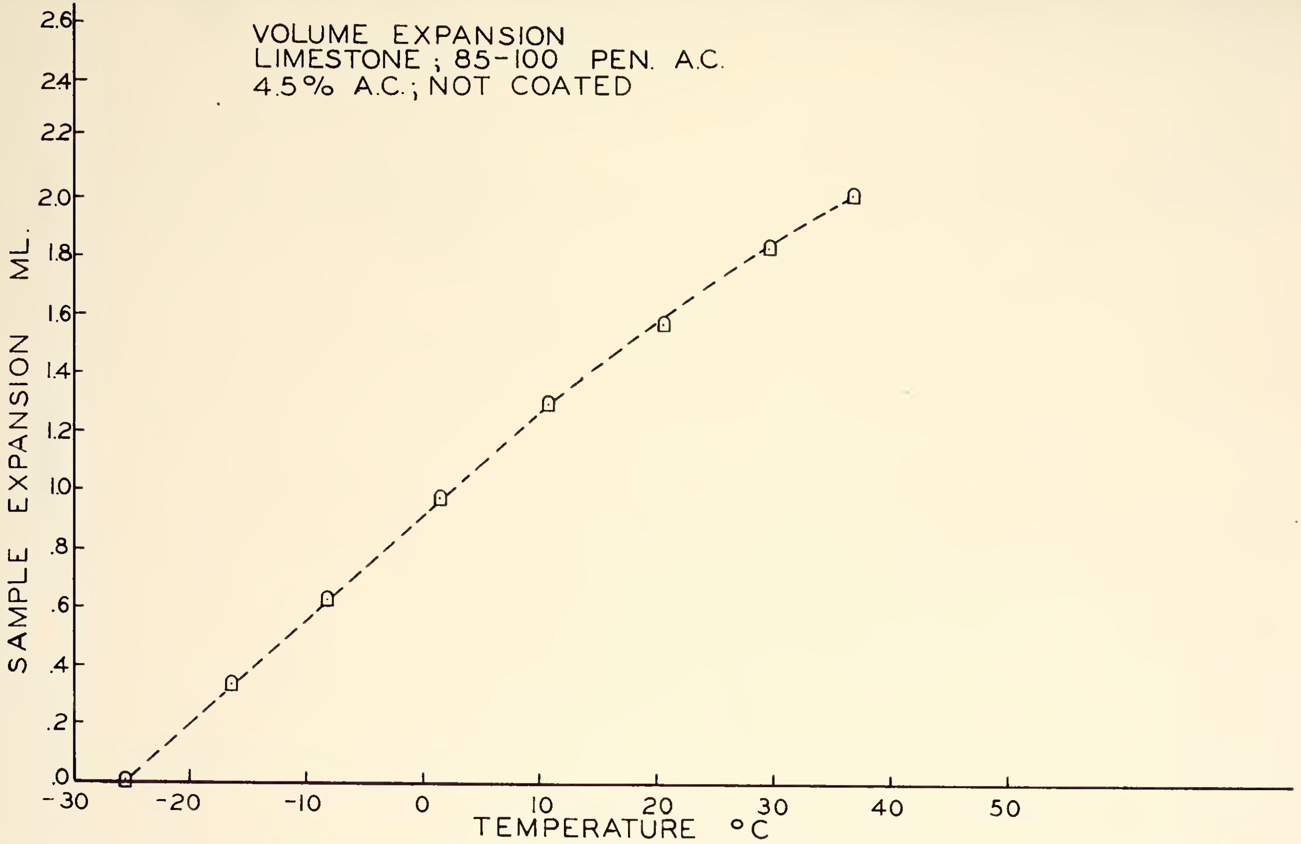


FIG. 21 TYPICAL VOLUMETRIC RESULTS - DILATOMETER III

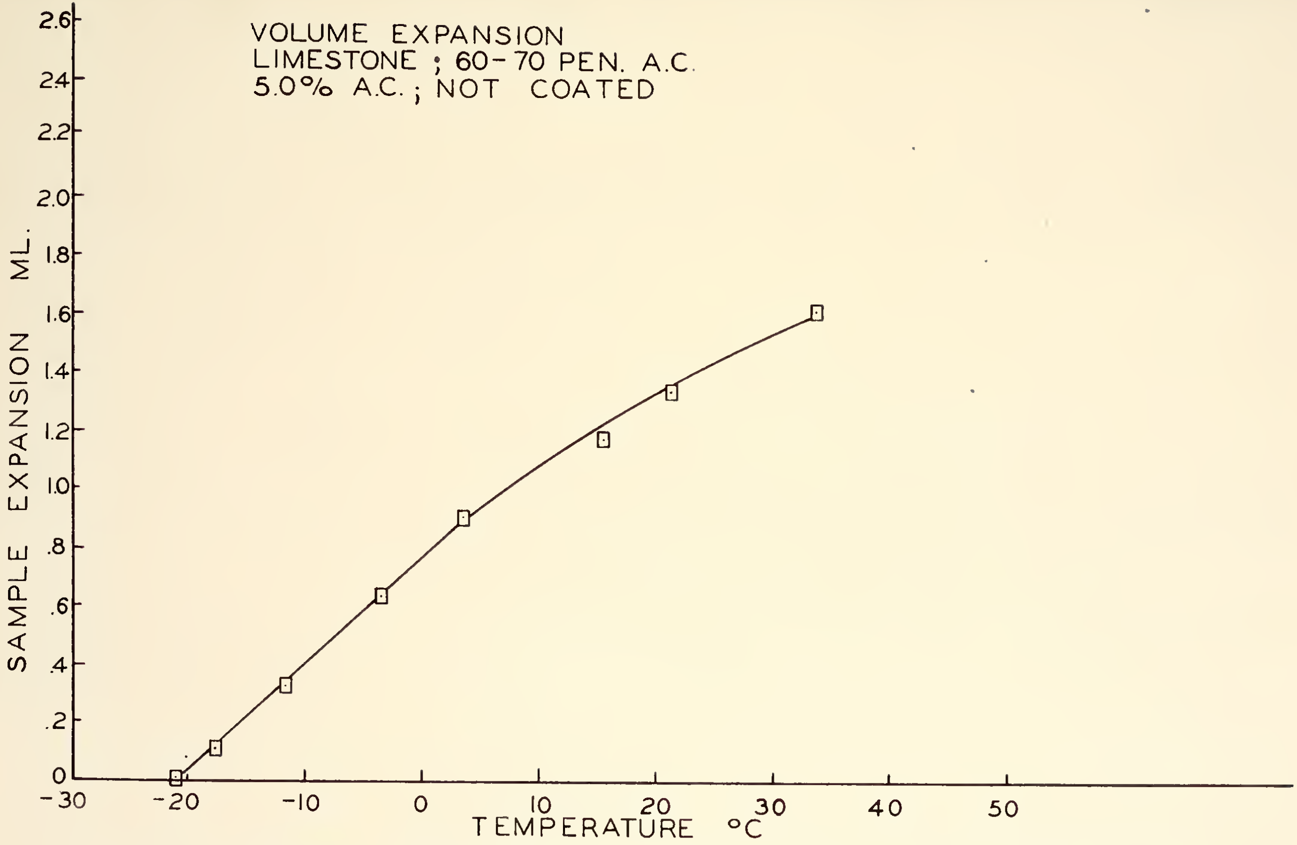


FIG. 22 TYPICAL VOLUMETRIC RESULTS-DILATOMETER III
NON-EVACUATED TECHNIQUE

Because the absorbed amount was relatively small, the final procedure established was to observe the reduction in the liquid level after equilibrium conditions had become established. This reduction was then accounted for by adding it to each successive reading, producing the dashed curves shown in Figures 19 and 20. These curves are the theoretical readings of the dilatometer assuming no liquid level reduction due to absorption has taken place.

This correction procedure was the same as that used for the second dilatometer and suffered from the same inadequacies. Figures 19 and 20 show the variation of the reduction with time and temperature, greatly complicating any attempt to accurately establish a rate for the liquid level reduction during the heating interval.

Figures 21 and 22 show the calculated sample expansion for the specimens represented by Figures 19 and 20 respectively. The general trend obtained with this dilatometer was the same for all the specimens tested, regardless of filling process. The resulting expansion curve showed a linear relationship between volume expansion and temperature in the low temperature range, while increasing at decreasing rates for the temperature range above 10°C.

Although the volume of displacement liquid was held to a minimum in this dilatometer, the expansion of the dilatometer itself was larger than desired. The specimen expansion, as determined using this dilatometer, was more than twice the differential dilatometer reading. Although this was a large difference, it was not thought to be very detrimental because of the accurate calibration achieved for this dilatometer. This large expansion of the dilatometer was advantageous to the extent that it reduced the amount of expanded displacement liquid that would otherwise have to be removed, thereby reducing calculations and possible sources of error. The data and calculations used in computing the expansion of specimens tested with this dilatometer appear in APPENDIX C.

The expansion trends produced by the different variables incorporated into the specimens tested with this dilatometer are presented later in this report. An evaluation of this dilatometer and the second glass dilatometer are presented in the following section.

Volumetric Apparatus Evaluation

Figures 23 and 24 present a comparison of the results obtained with the glass dilatometer and the metal dilatometer. Figure 23 shows the results for two replicate specimens, one being tested by each of the two dilatometers, composed of Greencastle limestone and 5.0 percent of the 85-100 penetration grade asphalt cement. Both of these specimens were coated with the synthetic latex. Figure 24 shows the results for two additional replicate samples, each composed of Greencastle limestone and 4.0 percent of the 60-70 penetration grade asphalt cement. These two specimens were coated with the 60-70 penetration grade asphalt emulsion. One of the latter specimens was tested with the metal dilatometer, while the other was tested with the glass dilatometer. The two replicate specimens of Figure 23 gave almost identical values for the volumetric coefficient of expansion as determined by the different dilatometric methods, while the two replicate specimens of Figure 24 gave values which were considerably different for the two methods. The comparison of the calculated volumetric coefficient of expansion of replicate specimens by the two dilatometric methods is based on the slope of the straight line portion

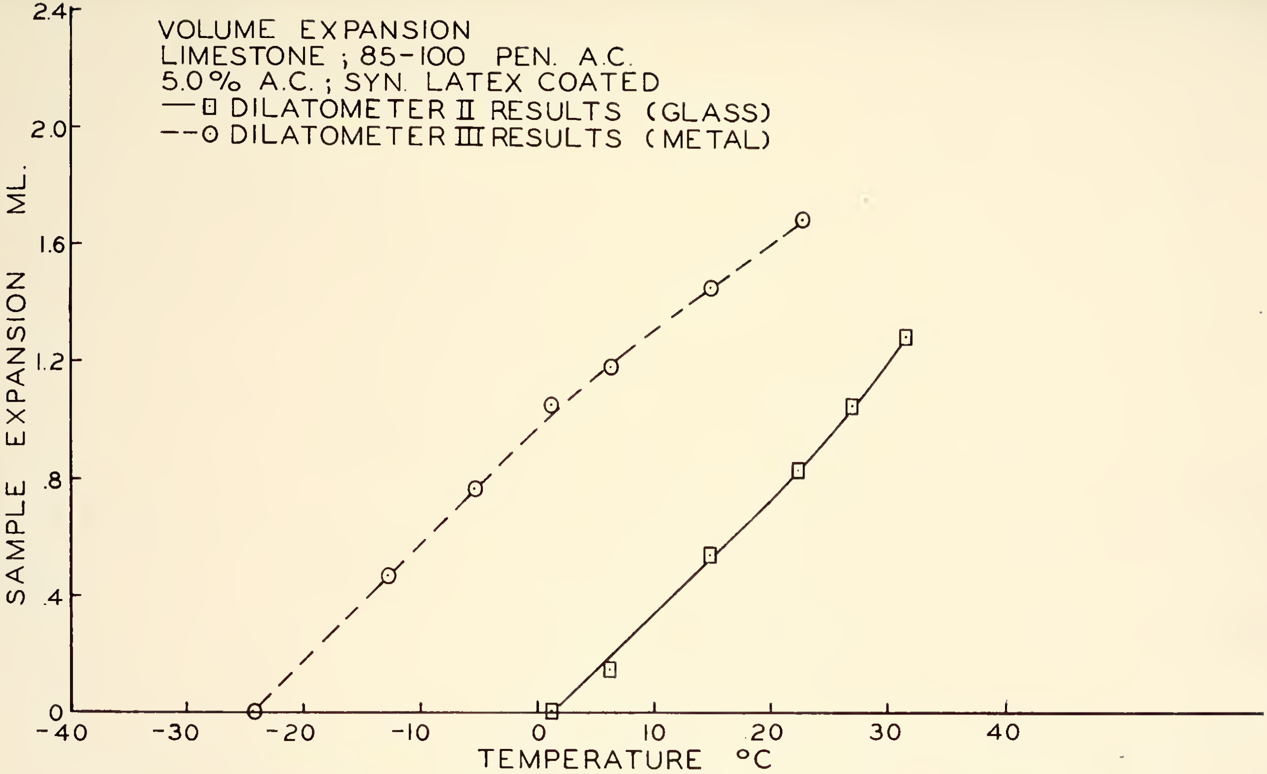


FIG. 23 COMPARISON OF RESULTS — DILATOMETERS II & III

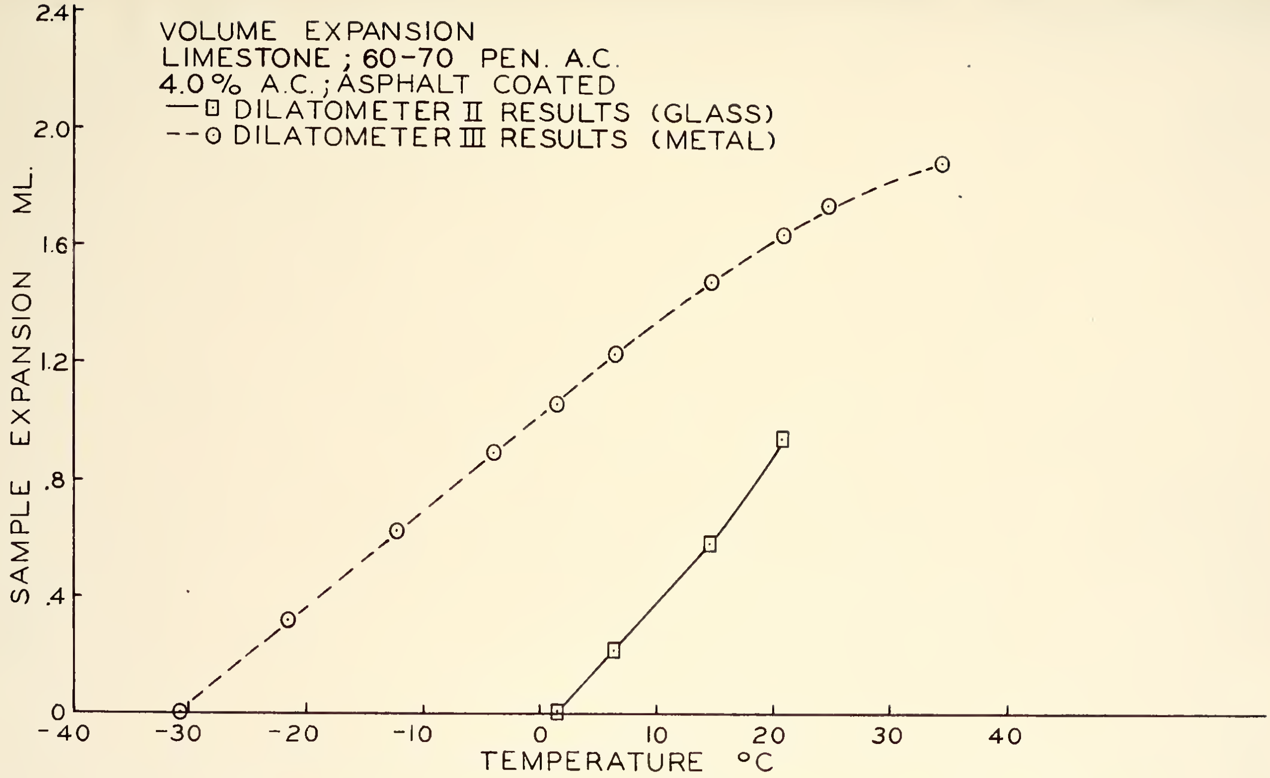


FIG. 24 COMPARISON OF RESULTS – DILATOMETERS II & III

of the expansion curve and the uncoated bulk volume of the specimen. The calculated coefficients for the specimens of Figure 23 were 8.20 and 8.10×10^{-5} in^3/in^3/°C for the water- and mercury-filled dilatometers respectively. The volumetric coefficient of expansion for the specimens represented by Figure 24 were 8.47 and 6.45×10^{-5} in^3/in^3/°C for the water- and mercury-displacement liquids respectively.

The coefficients determined from the curves of Figures 23 and 24 show the extremes obtained for replicate specimens tested with the different dilatometers. Because of the different temperature ranges of the two dilatometers, the coefficients for the specimens tested in the glass dilatometer were obtained from the slope of the straight line portion of the expansion curve above 0°C. The coefficients for the metal dilatometer were obtained from the straight line portion of the expansion curve above - 25°C. This difference in the respective temperature ranges could be part of the reason for any discrepancy in the coefficients of replicate specimens tested by the two different techniques. However, this method of obtaining the coefficient was the only one available which allowed a direct comparison of results obtained from the two dilatometers.

Figures 17 through 24 have shown various aspects of each technique. With both techniques some absorption occurs during the course of the test. Both techniques give a linear relationship for the lower temperature range, but show different expansion rates for the temperature range above 20°C. The results obtained from the water-filled dilatometer indicate that the expansion above 20°C increases at an increasing rate, while the results from the mercury filled dilatometer show the expansion increasing at a decreasing rate above this temperature. The difference at elevated temperatures could be partially due to the added confinement provided by the mercury. The effect of this confinement might become more pronounced at elevated temperatures because of the reduction in the strength of the bituminous concrete with increasing temperature.

Although the time required to reach equilibrium conditions is considerably less for the metal dilatometer, it has an extremely large calibration correction in comparison to the glass dilatometer. However this was offset by the accurate establishment of the required correction factor. The glass dilatometer furnished information on the specimen for only half the desired temperature range and required considerable care in handling. It did however allow visual observation of the specimen during the progression of the test with more assurance of complete air removal. Both techniques suffered from problems with absorption, but by noting the amount absorbed after equilibrium conditions had become established, an appropriate correction could be incorporated into the calculations.

In general the metal dilatometer was easier to work with and handle than the glass dilatometer. It was more practical than the glass dilatometer because it was usable over the entire temperature range. Once having been accurately calibrated, it could be used with other displacement liquids if desired. Some question arose concerning the accuracy of the calibration of the glass dilatometer. This was exemplified by the scattering of data points along the calibration curve. The use of mercury, as the displacement liquid, required more caution than the use of the water; however, the initial volume determination by weighing was more accurate for the mercury. Although both pieces of apparatus allowed filling under evacuation, the procedure was considerably easier with the metal dilatometer and also reduced the fear of breakage during evacuation. The cost of the two dilatometers was approximately the same.

Based on this evaluation, the metal dilatometer, employing the filling process without evacuation, is the recommended volumetric equipment and technique. This technique and apparatus yields the greatest amount of desirable information for the required amount of preparation. The glass dilatometer does not yield as much information as the metal dilatometer because of the smaller temperature range over which the glass dilatometer is applicable. This latter characteristic greatly reduces the practicality of the glass dilatometer. It is also believed that more reliability can be placed on the results obtained with the metal dilatometer. This recommendation, however, does not eliminate the use of the glass dilatometer to obtain a check on the results of the metal dilatometer. The use of both pieces of equipment to obtain check values would not involve much additional work now that both dilatometers are available for further testing.

Discussion of Linear Apparatus

In this section a discussion of the linear apparatus used in this phase of the investigation is presented. Typical trends obtained with the different pieces of equipment are discussed in arriving at an evaluation of the respective techniques.

Stainless Steel Strain Gages

Figure 25 shows a set of typical readings obtained by using the stainless steel strain gages. This figure presents only the microscope readings and does not represent the sample expansion. The two lines represent the results for two replicate specimens composed of Greencastle limestone and 4.5 percent of the 85-100 penetration grade asphalt cement. The plotted values were obtained by averaging the two gage lines for each specimen. The technique provided advantages not possible with other methods. The gage was light and offered little resistance to expansion of the sample. Once it was positioned, there was no further need for disturbing the sample. The gages were easy and economical to make and they were reusable.

However, a considerable number of problems were encountered. One of the main disadvantages was the problem of accurately calibrating the gage for temperature effects. This has been previously discussed in the description of the technique employed with this gage.

Another disadvantage was the inconsistency in readings taken at subsequent temperatures. This inconsistency is apparent when comparing the expansion curves of the two replicate specimens shown in Figure 25. The scattering of the data points and the difference in the shapes of the two curves can be attributed to this inconsistency. The individual differences in the replicate specimens may also have accounted for some of the difference in the shape of the curves.

The inconsistency which was characteristic of this technique may be attributed to many causes. Because of the small amount of material involved in the construction of the gage, temperature changes in the surrounding environment affected the gage rapidly. Because of its location, the gage was exposed to an indeterminable environment that was influenced by changes in air currents moving across the gages. These changes could very easily affect the consistency of the results. Another possible reason was the

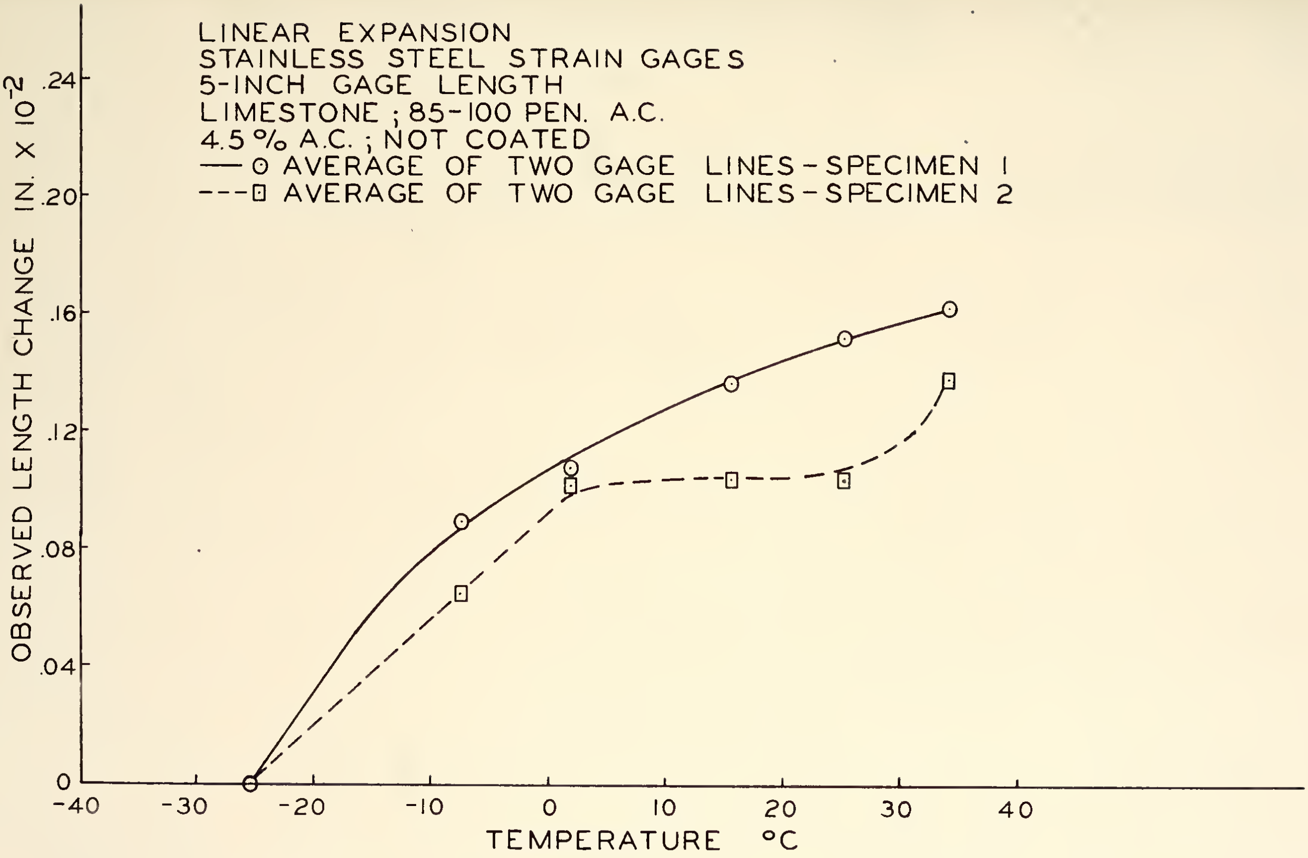


FIG. 25 TYPICAL READINGS—STAINLESS STEEL STRAIN GAGES

difficulty in aligning the microscope over each gage to assure that the line of travel of the cross hairs was parallel to the gage. The problem of alignment was also aggravated by the small field of view possessed by the microscope as well as the fact that the instrument had to be positioned by sliding. These factors also resulted in a considerable loss of time when moving the microscope from one location to another.

Another factor that might possibly have affected the consistency of the results was the combined effect of vibrations of the bath and friction developed in the gage. The gage was constructed to minimize the effects of friction by providing sufficient freedom of movement for the movable center section. No lubricant was used on the gage in order to eliminate restriction of movement resulting from changes in the viscosity of the lubricant. Although the temperature bath was turned off during observation of the gages, the normal cyclic action of the compressor operation caused some vibrations. These vibrations coupled with possible friction in the gage may also have resulted in inconsistent readings.

Another disadvantage to this system was the difficulty of removing the gages after a test. To insure secure fastening to the specimen, the gage studs had been driven into the holes of the brass plugs where they were firmly held in position throughout the test. After completion of the test it was necessary to remove the gages with pliers. It was quite difficult to perform this operation without damaging the gage.

Figure 26 shows the final sample expansion for the specimen readings presented in Figure 25. The expansion value for these specimens were obtained by adding the calculated expansion of the stainless steel, based on the manufacturer's stated value of 17.25×10^{-6} in/in/°C. The extreme

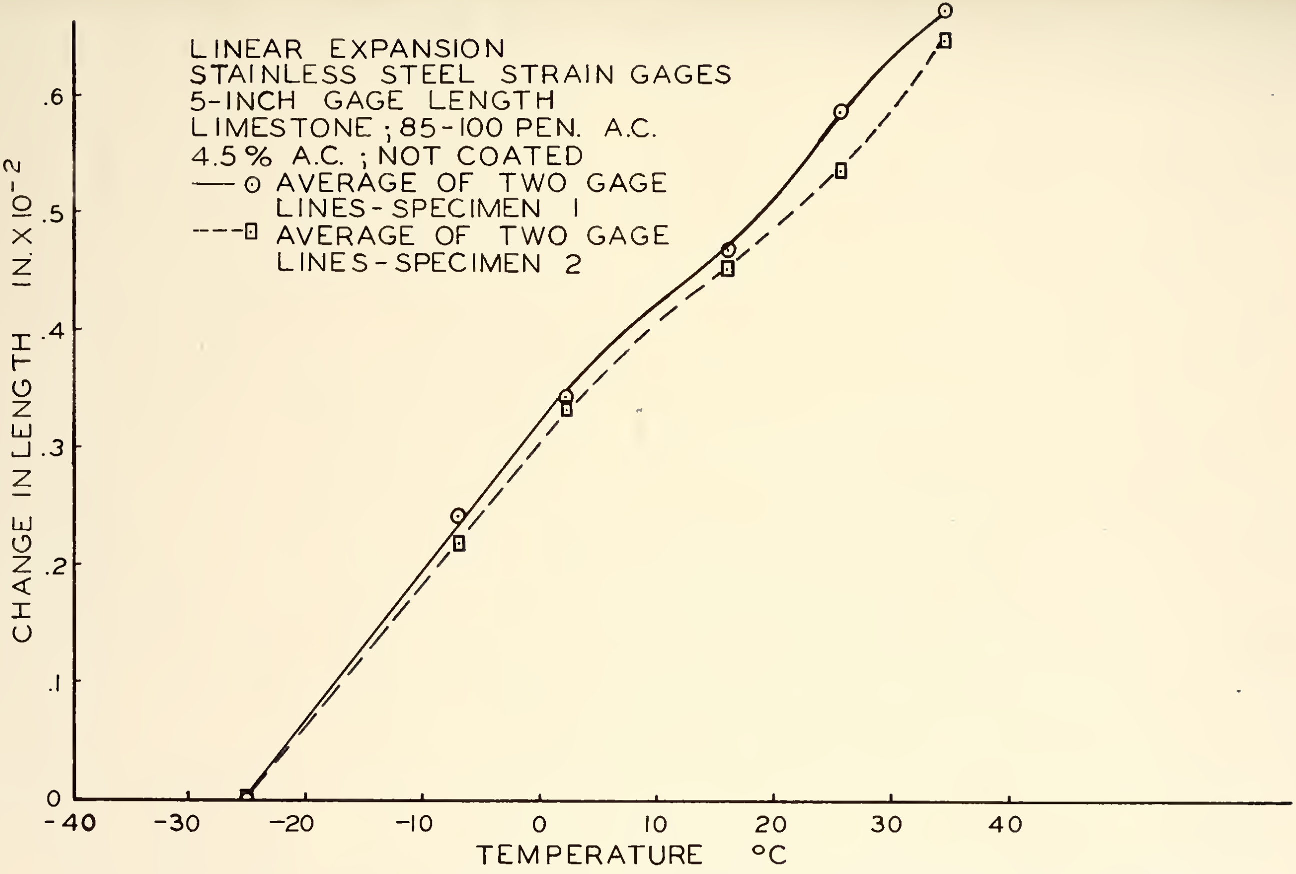


FIG. 26 TYPICAL LINEAR RESULTS — STAINLESS STEEL STRAIN GAGES

influence of this correction is quite apparent. The correction was more than twice the observed reading, resulting in a calculated sample expansion considerably higher than that obtained by other methods for duplicate specimens. The average coefficient of expansion for the two beams represented in Figure 26 was determined to be 2.45×10^{-5} in/in/°C, somewhat higher than the average 1.95×10^{-5} in/in/°C obtained by other methods.

Based on these results, the inconsistency of readings, and the extreme amount of uncertainty concerning this technique, it was concluded that the technique was not applicable to this investigation without modifications. Before attempting to modify the equipment, other techniques were investigated and found to be more applicable to this investigation. Rather than attempting to make a workable system incorporating the stainless steel strain gage, the entire idea was abandoned.

Whittemore Strain Gage

The Whittemore gage proved to be very useful and practical in this investigation. It was easy to operate and required only a little experience before reproducible results could be obtained. Throughout the investigation there was no need for a correction factor to be applied to the gage readings. This meant that the specimen expansion was being read directly by the gage, eliminating a possible source of error.

The possible sources of error resulting from the use of this gage are those associated with the repeated placement and removal of the gage, as well as the weight effects of the gage. In removing and replacing the gage for consecutive readings at the same temperature, a maximum difference of two gage divisions was obtained, a difference amounting to 0.0002 inches. This difference was not extreme and was averaged by obtaining three consecutive readings. In the higher temperature range, above 20°C, considerable movement of the plugs was detected when the gage was positioned and allowed to rest for a short time. This problem was partially due to the softening of the cementing agent used on the plugs and partially due to the plastic properties of the asphaltic concrete. The problem was reduced by the use of the epoxy cement as the gage plug cementing agent. No movement was detected in this case until temperatures were higher than 40°C, at which point it was speculated that the movement was due primarily to softening of the asphaltic concrete. Figures 27, 28 and 29 shows results obtained with the Whittemore gages.

Figures 27 and 28 show typical results obtained with the 5- and 10-inch Whittemore gages respectively. The same specimens are represented in both figures. The use of both gages allowed a comparison and check to be made on the same specimen and often proved to be worthwhile. A single line in the figures represents the average of two gage lines. The average values determined for the thermal coefficient of expansion for this set of beams were 2.46×10^{-5} in/in/°C and 2.59×10^{-5} in/in/°C for the 5- and 10-inch Whittemore gage readings respectively. These coefficients were obtained from the slope of the straight line portion of the curve. The gage length used was the standard gage length at room temperature, established when the plugs were originally secured.

The curves represented by Figures 27 and 28 are typical of the results obtained with the Whittemore gages. The temperature-length change curve is linear over the lower temperature range. At temperatures above 20°C, the rate of expansion differs from a linear relationship. According to the results for replicate specimens shown in Figure 27, the expansion rate at

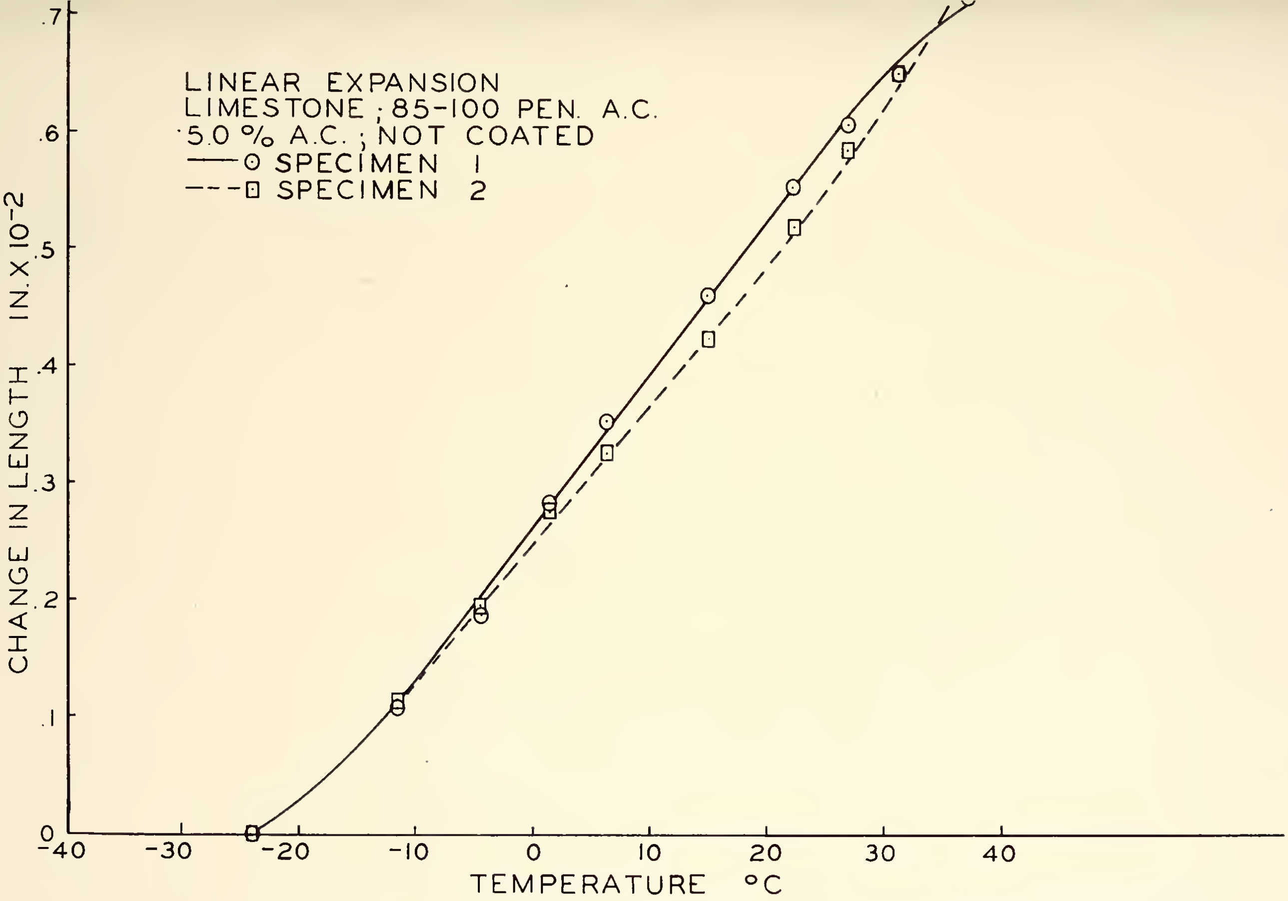


FIG. 27 TYPICAL LINEAR RESULTS — 5-IN. WHITTEMORE STRAIN GAGE

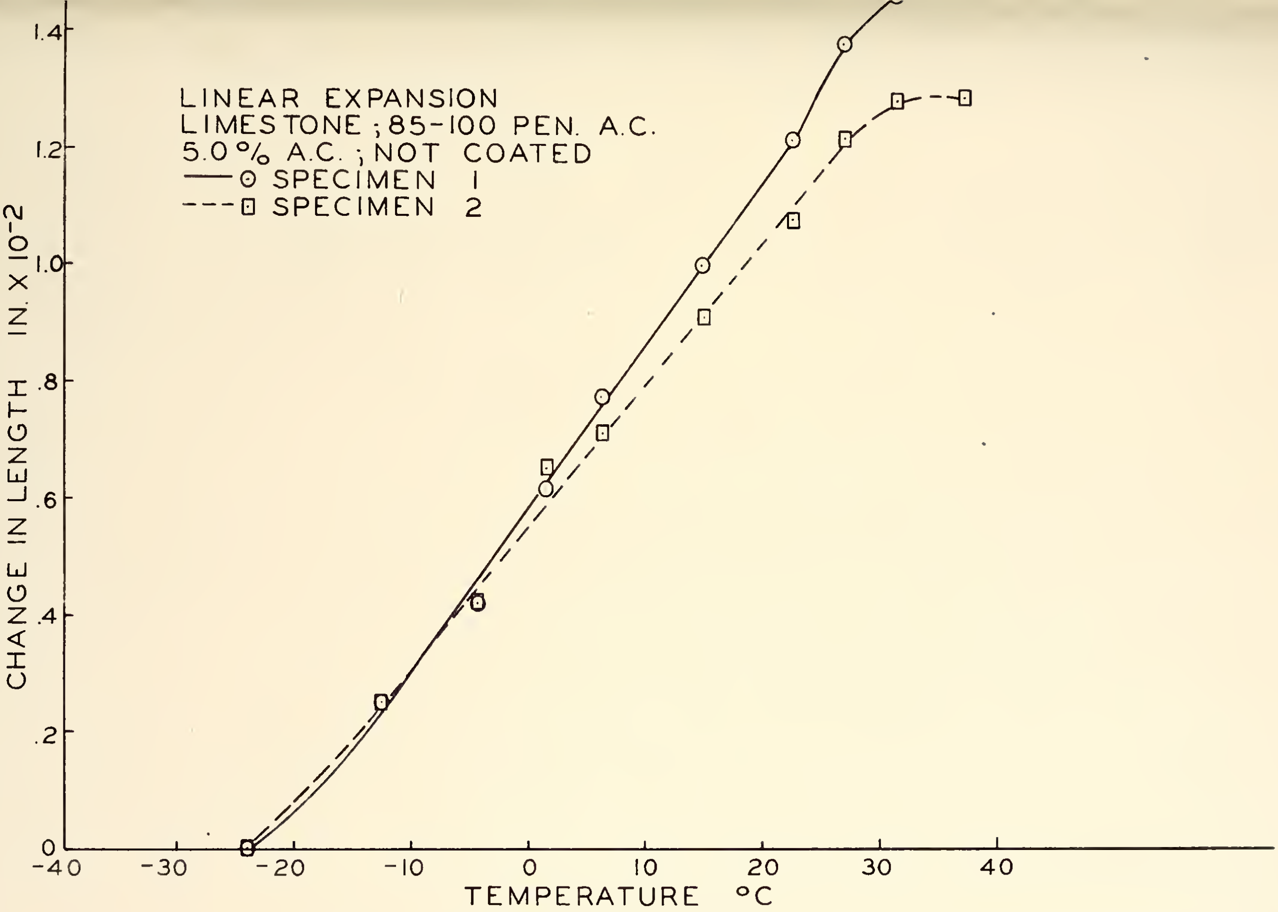


FIG. 28 TYPICAL LINEAR RESULTS — 10-IN. WHITTEMORE STRAIN GAGE

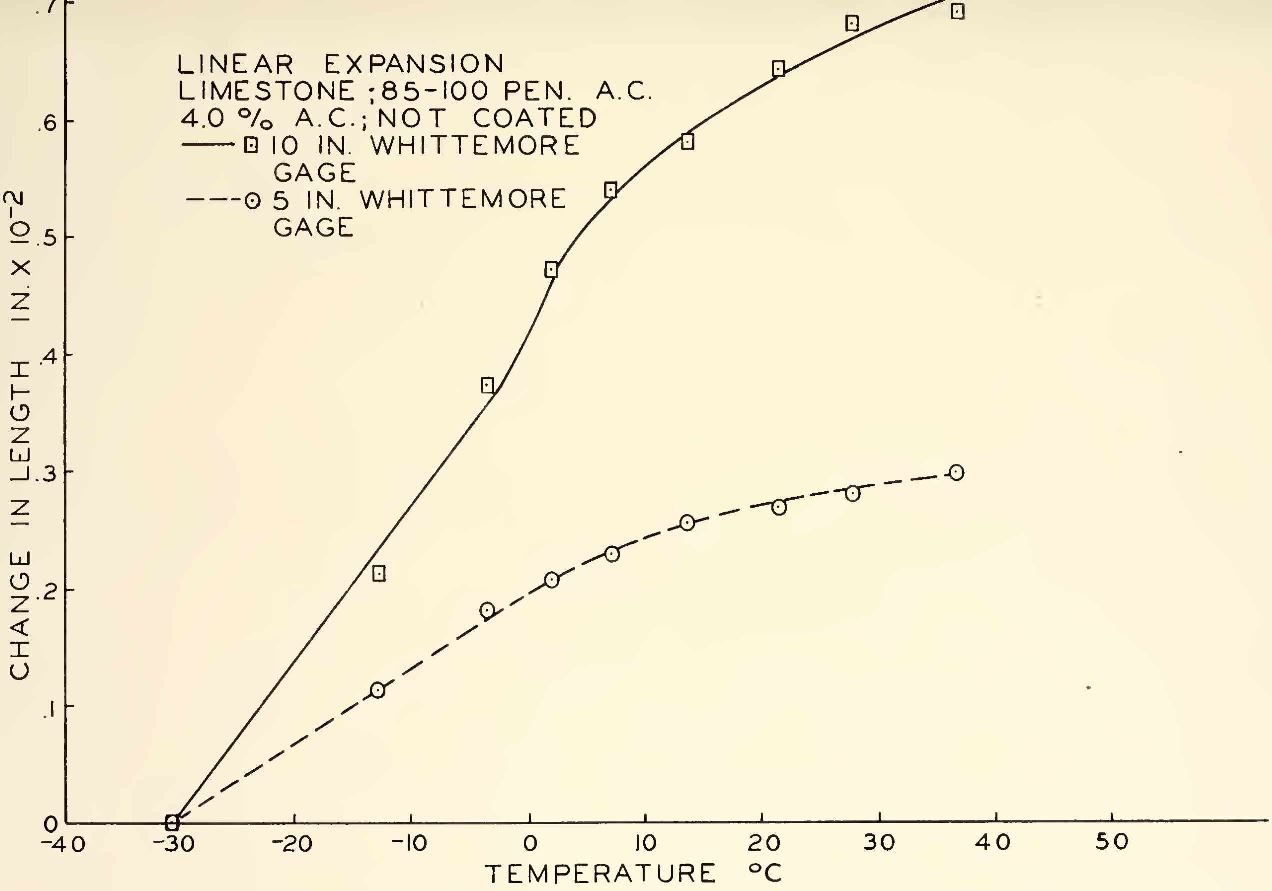


FIG. 29 COMPARISON OF 5-IN. AND 10-IN. WHITTEMORE STRAIN GAGES

these elevated temperatures can be either increasing or decreasing. Figure 28 shows a decreasing expansion rate at these elevated temperatures for replicate specimens. The results of specimen No. 2 (Figure 28) show a rather sudden change in the expansion rate above 30°C. Thus, a comparison of the expansion trends obtained at these high temperatures shows a contradiction. This leads to the conclusion that above a temperature of 15°C the results no longer reliably represent the general expansion trends of the respective specimens.

Figure 29 shows a comparison of the length change of the same specimen obtained by both the 5- and 10-inch Whittemore gages. It gives an indication that although both gages are measuring along the same axis of the beam, a uniform distribution of the expansion does not take place. Part of the difference between the results obtained with the separate gages, referring to the jump in the expansion of the 10-inch gage line, is possibly due to the effects of the free ends, wherein the ends of the beams are permitted to expand more per unit length than the interior section. It is also hypothesized that the method of supporting the beams may have some effect on the results. If a section of the beam was not completely supported initially, then as the temperature increased the beam could sag under its own weight a sufficient amount to cause a noticeable irregularity. This latter hypothesis may be a possible explanation for the irregularities observed in the expansion rates of specimens at elevated temperatures. It is also a possibility that part of this difference between the expansion determined by the respective gages results from the inconsistencies of the gages themselves.

A comparison of the results obtained using Whittemore gages with those of the dual microscope apparatus are made in a later section along with a final evaluation of the two techniques. Typical results, accompanied by a discussion of the technique, for the dual microscope apparatus are presented first.

Dual Microscope Apparatus

The dual microscope apparatus was a very efficient addition to this investigation. By means of the apparatus it was possible to position rapidly and accurately the two microscopes over the desired gage point locations. Once the beam had been properly positioned under the microscope there was no further need to disturb the specimen. The positioning screws for the microscopes allowed the horizontal cross hairs to be positioned in the same location for successive observations, assuring that the same segment of the beam was always being observed.

The entire apparatus was mounted on top of the temperature bath and was subjected to the environment of the constant temperature room. The spacing bars, which established the 10-inch gage length of the microscopes, were subjected to this constant temperature and were far enough above the temperature bath that no correction was found necessary for temperature effects on the apparatus itself. The apparatus possessed the highest potential accuracy of those investigated. The average error in a set of three readings was found to be on the order of three micrometer drum divisions, or 0.00006 inch. The apparatus provided for the simultaneous testing of at least two specimens, allowing replicate specimens to be investigated under identical test conditions. The system also permitted simultaneous testing of specimens by other methods, in this case the 10-inch Whittemore gage, so that a legitimate comparison of the two methods could be made.

The only difficulty encountered with this apparatus was that of obtaining an adequate reference system that would remain consistent throughout the test. This required selecting index marks that were permanent and would not be affected by other testing techniques. On several occasions, when obtaining readings with this apparatus as well as the 10-inch Whittemore gage, the metal points of the latter would alter the reference point chosen for the microscopes. Another characteristic that complicated this selection was the oxidation of the brass gage plugs during the course of the test, which darkened their color and sometimes impeded the relocation of the initial reference point. However, these problems were reduced after obtaining experience in the selection of the best reference points.

Figure 30 presents results for two specimens that were tested using this apparatus. Each line is the average of two gage lines per specimen. The solid line represents a specimen with an asphalt content of 5.0 percent while the dashed line is for a 3.6 percent specimen. Both specimens were made from Lafayette gravel and 85-100 penetration grade asphalt cement. The same general trends are apparent with this technique that were observed with the other measuring systems. The expansion curve is generally linear over the initial temperature range, but a deviation from the original linearity occurs at elevated temperatures. Since the figure clearly shows variable expansion rates for two specimens at the higher temperatures, the unreliability of the expansion trends at temperatures above 15°C is again verified.

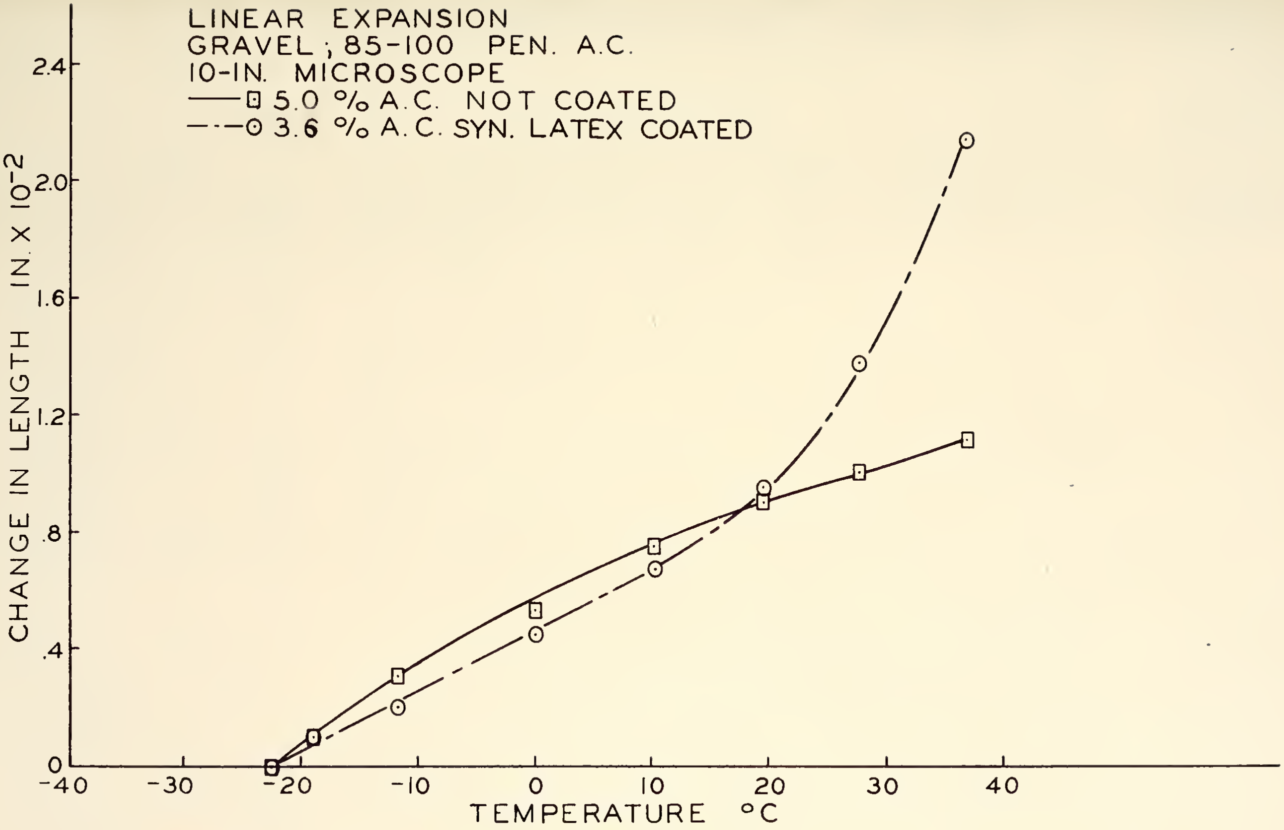


FIG. 30 TYPICAL LINEAR RESULTS — DUAL MICROSCOPE APPARATUS

The remainder of the data obtained with this technique are presented later in this report. Selection of a linear technique through a comparison of those investigated is made in the following section.

Linear Apparatus Evaluation

Figures 31 and 32 show a comparison of results obtained with the dual microscope apparatus and the 10-inch Whittemore gage. In each case readings were taken on the same specimen consecutively while at constant temperature with the microscope readings being obtained first. Figure 31 represents the results obtained from a specimen composed of Greencastle limestone and 4.5 percent of the 60-70 penetration grade asphalt cement. The specimen was coated with an asphalt emulsion produced from a 60-70 grade asphalt cement. Figure 32 represents a specimen composed of Greencastle limestone and 4.0 percent of the 60-70 penetration grade asphalt cement. This specimen was also coated with the 60-70 grade asphalt emulsion. The curves are an average of two gage lines for each specimen. These figures show that the specimen expansion data obtained by each method were quite similar. The results obtained by these two methods were not always as consistent as shown in these figures, but differences are attributed to causes other than those associated with the measuring system.

The calculated coefficients of expansion for the curves of Figure 31 were 1.95×10^{-5} in/in/°C and 2.30×10^{-5} in/in/°C for the 10-inch Whittemore gage and the dual microscopes respectively. The values for Figure 32 were 2.13×10^{-5} in/in/°C and 2.00×10^{-5} in/in/°C for the Whittemore gage and dual microscopes respectively. These values were obtained from the straight line portion of the curves, disregarding the

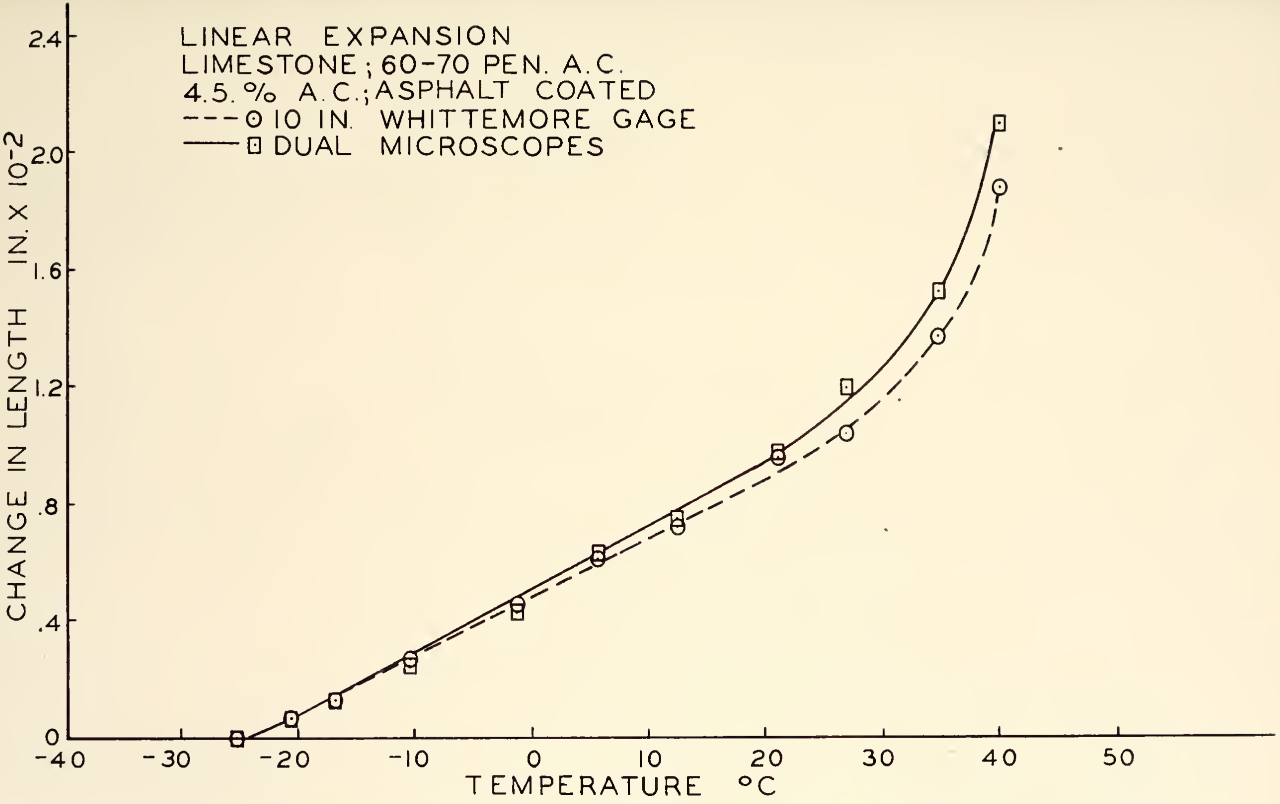


FIG. 31 COMPARISON OF DUAL MICROSCOPES AND 10-IN. WHITTEMORE GAGE

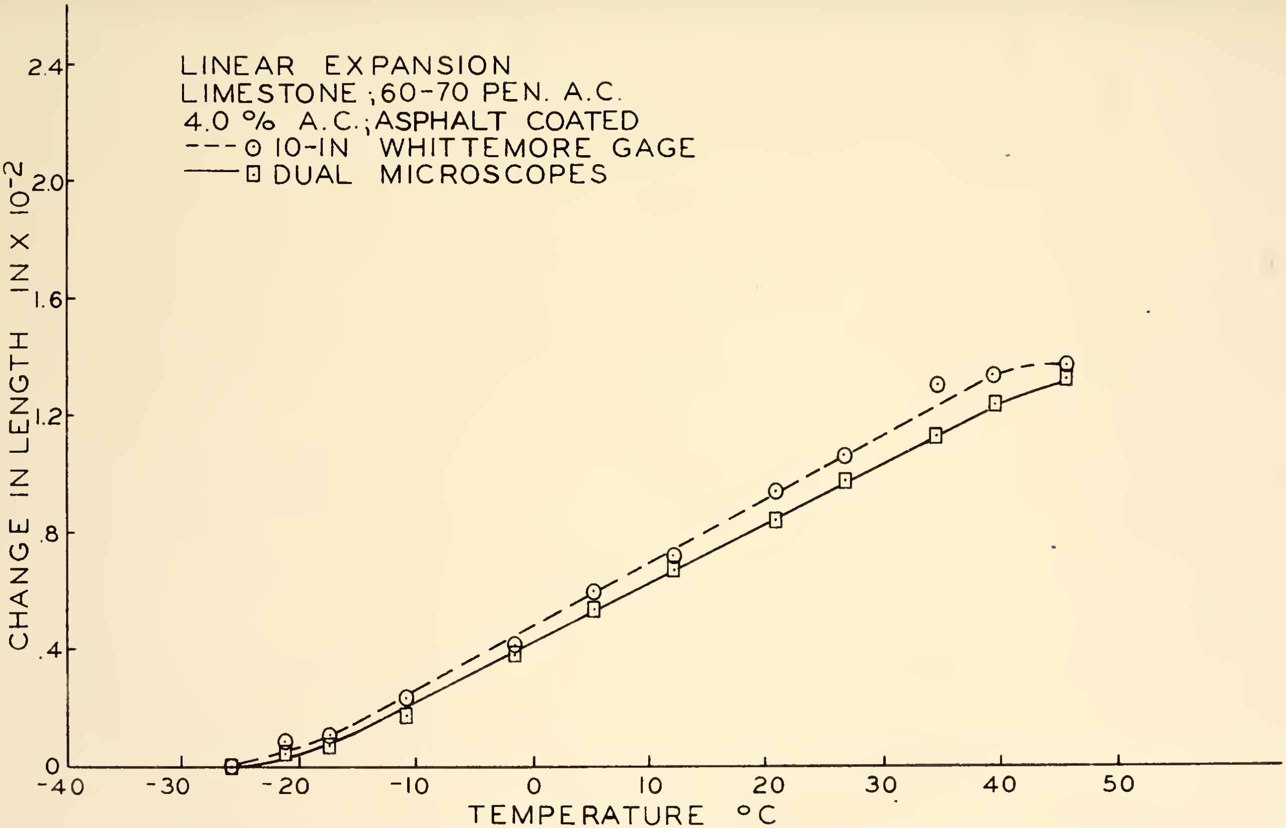


FIG. 32 COMPARISON OF DUAL MICROSCOPES AND 10-IN WHITTEMORE GAGE

effects at elevated temperatures. Although the two specimens differ by only 0.5 percent asphalt content, there is a noticeable difference in the expansion rates of the two samples above 20°C. The exact reason for this difference is not known, but it is hypothesized that it could possibly be a result of the two beams not being supported identically, causing the beam in Figure 31 to sag more than the other beam. It may also be due to regional disturbance around the gage plugs which resulted from the drilling process, with the material in the 4.5 percent sample being more susceptible to flow under the weight of the Whittemore gage. It is doubtful that the gage plug movement could be traced to the cement used to secure the plugs because the epoxy was used as the cementing agent for both beams. The actual reason for the difference at elevated temperatures may be a combination of several of these factors, or may have been just characteristic of the two specimens tested.

These data show the similarity in the results obtained by the two methods. The Whittemore gages have the disadvantage of having to be removed and replaced in direct contact with the specimen. This manipulation did disturb the specimen to some extent, but the effects can be greatly reduced by careful handling of the gages and by use of epoxy cement to secure the gage plugs. The 5-inch Whittemore gage has the added disadvantage of possessing a small gage length, thereby reading less of the total specimen change. Both techniques, the Whittemore gages and the dual microscopes, require no temperature correction. The dual microscope apparatus possesses the disadvantage of a more complicated measuring system, thereby increasing the chance of error. With experience however, this latter disadvantage can be minimized.

When considering the potential accuracy and mechanical advantages and disadvantages of the two techniques, the dual microscope apparatus would be the recommended equipment. However, the specially designed microscope apparatus was considerably more expensive to obtain than the commercial Whittemore gages. The Whittemore gage could also be used for field correlation studies if desired. The total specimen expansion in all cases was sufficient to be easily read with the Whittemore gage and the correlation between it and the microscope system has been shown to be good.

The opinion is therefore expressed that either of these techniques could be used to obtain reasonable results of the linear expansion trends of bituminous concrete. The dual microscope apparatus is recommended for exacting laboratory work, while the Whittemore gage could be used in connection with a correlation of field and laboratory work as well as an independent and quick check on the results obtained with the microscope apparatus.

Thermal Expansion Trends

The primary objective of this study was to investigate several possible methods of measuring the thermal coefficient of expansion of bituminous concrete. The methods were to be employed in testing samples of variable composition for the purpose of evaluating the technique and not, per se, to study effects of composition of the specimen on expansion characteristics. Strictly speaking, then, the results obtained from the various samples should be compared only for the purpose of evaluating the measuring techniques in relation to ability to detect differences in specimen expansion caused by variable composition. However, the following information is presented to demonstrate the general trends obtained from different combinations that were incorporated into these specimens. It is also presented to complement the discussions of the different techniques previously given in this report.

This information is presented in graphical and tabular form, accompanied by a description of the various aspects considered pertinent to this investigation. The data used in plotting the graphs can be found in the APPENDIX, catalogued according to the type of measuring technique employed. All of the curves for the linear techniques were obtained by averaging the results of two gage lines for each specimen. The volumetric results were obtained from single specimens. The coefficientsof expansion for the linear techniques were based on the straight line portion of the expansion curves and the standard gage length. The volumetric coefficient was based on the straight line portion of the curve and the bulk volume of the uncoated specimen.

The techniques employed did distinguish differences in the expansion properties of the specimens that were due to various combinations of constituents. However, the variation in results between specimens of the same composition cause inconsistencies in the observed general trends. These inconsistencies are not extreme but they do make it difficult to establish adequately the effects of the different variables. These inconsistencies may be due to slight differences in fabrication, coating materials, and variables purposely introduced in an attempt to further evaluate the test techniques.

Figure 33 shows the effects of temperature reversal on the length change of an uncoated specimen composed of Greencastle limestone and 4.5 percent of the 85-100 penetration grade asphalt cement. The solid line represents the sample contraction during the lowering of the temperature. The dashed line represents the expansion of the sample during the heating phase of this test. Both curves were obtained by averaging the results of the specimen's two gage lines. The figure clearly shows that after the temperature cycle, the distance between the gage plugs is not the same as when the test was started. This variation with direction of temperature change indicated that inconsistent results would be obtained if readings were taken on both the heating and cooling cycles, either successively or independently. Therefore, in order to produce consistent testing conditions, measurements were made by first placing the specimens in the temperature bath which was maintained at room temperature. The bath was then lowered to the initial test temperature and readings taken during the heating phase. In this manner it was hoped that the irreversibility would not affect the consistency of the results.

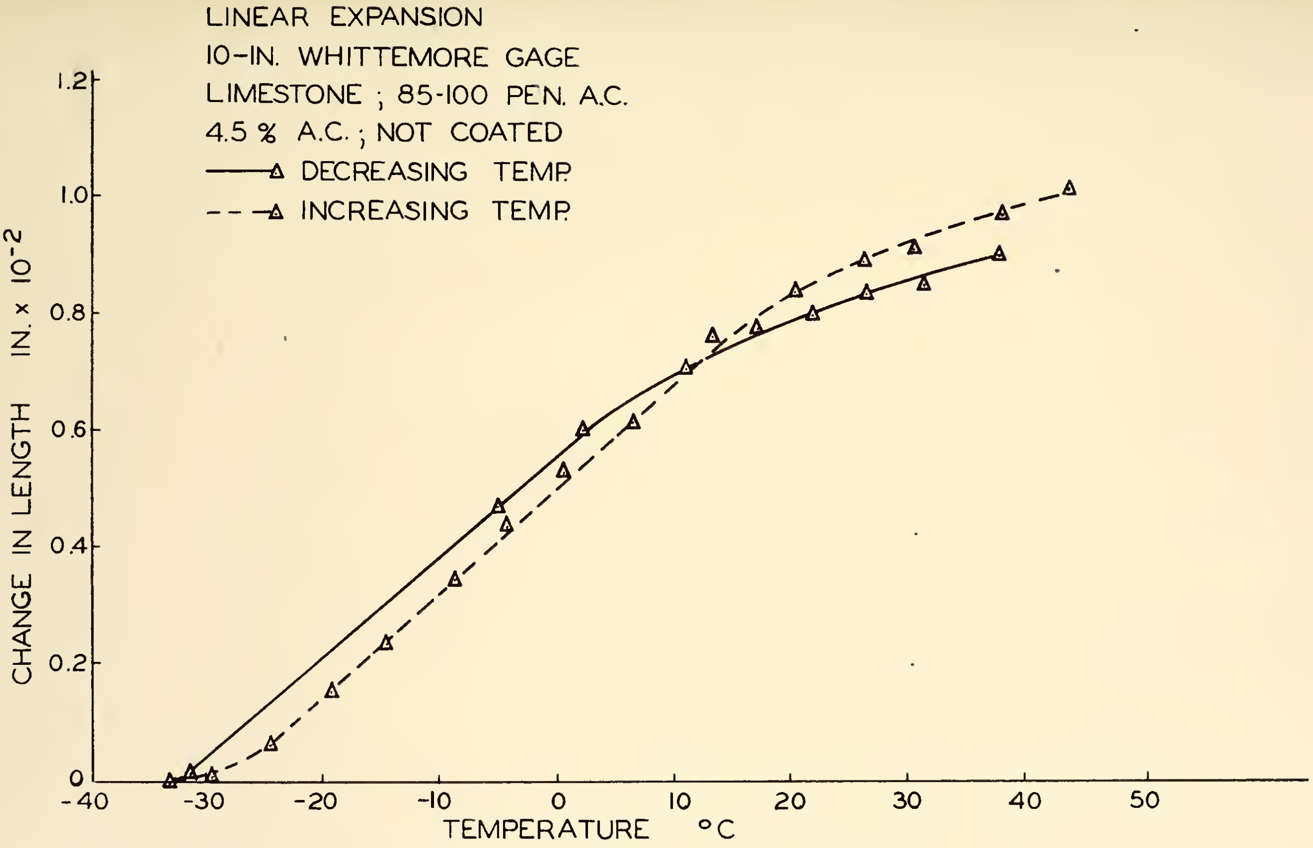


FIG. 33 EFFECTS OF TEMPERATURE REVERSAL

The following discussion is subdivided into divisions based on the variables to be discussed.

60-70 Asphalt Cement-Greencastle Limestone

Figures 34 through 36 present a graphical representation of the results obtained on specimens composed of Greencastle limestone and 60-70 penetration grade asphalt cement. Figure 34 represents the volume expansion of three separate specimens composed of Greencastle limestone and 60-70 penetration asphalt cement. Two of the specimens were tested by means of the metal dilatometer, while the glass dilatometer was used for the other specimen. The specimens represent two different asphalt contents. Both of the 4.0 percent specimens were coated with an asphalt emulsion, while the 5.0 percent specimen was not coated. The figure shows the different characteristics of the two dilatometric techniques. First, the limited temperature range inherent with the glass dilatometer is evident. The figure also shows that for replicate samples, the two volumetric techniques give different expansion rates at elevated temperatures. This is indicated by the direction of curvature at temperatures above 15°C, where the metal dilatometer shows a decreasing rate of expansion and the glass dilatometer shows an increasing rate.

Figure 35 represents the linear expansion obtained by the 10-inch Whittemore gage. Four specimens are represented in the figure, each composed of Greencastle limestone and varying percentages of 60-70 penetration grade asphalt cement. The asphalt percentages tested were 4.0, 4.5, 5.0, and 5.5. The 4.0 and 4.5 asphalt content specimens were coated with asphalt and synthetic latex, respectively, while the other two were not coated. The linear expansion curves obtained with this gage for these

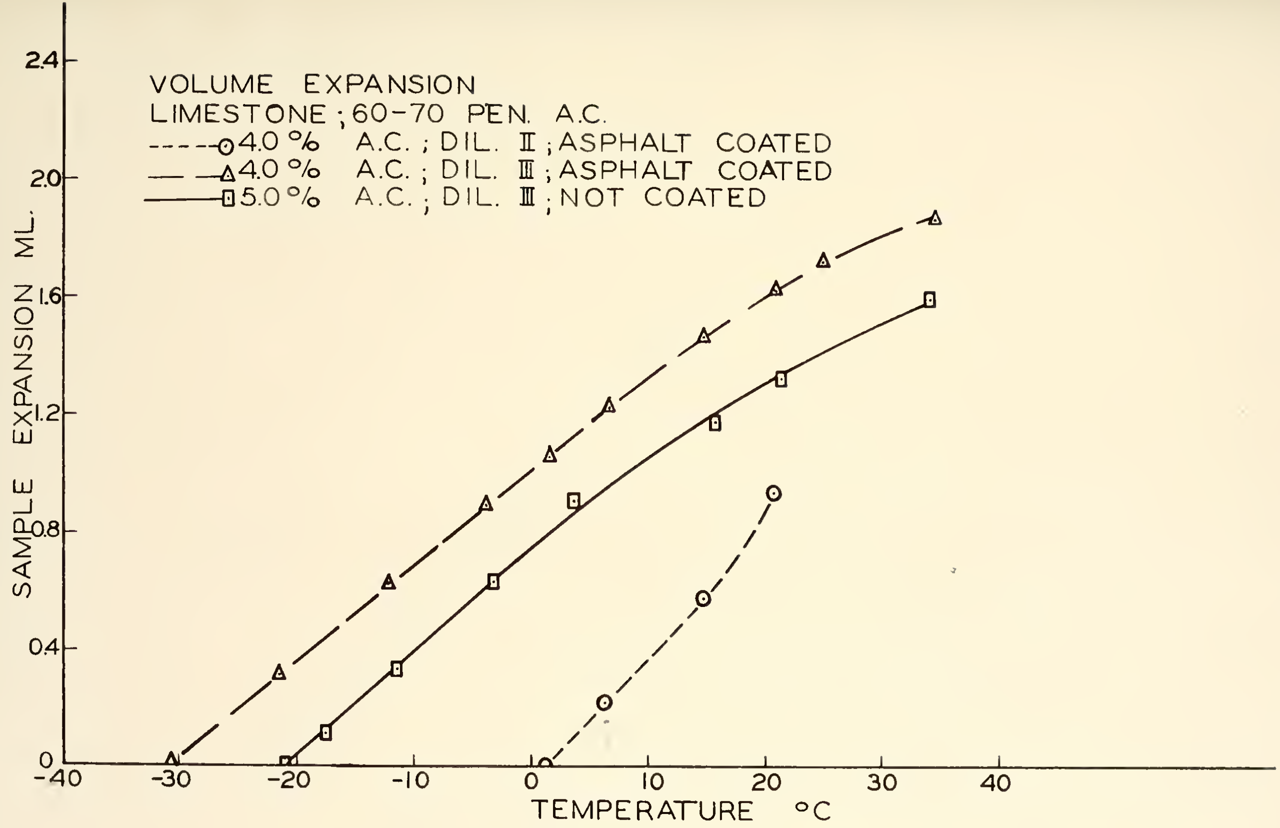


FIG. 34 VOLUMETRIC EXPANSION VS. TEMPERATURE
DILATOMETER II & III; LIMESTONE; 60-70 PEN. A.C.

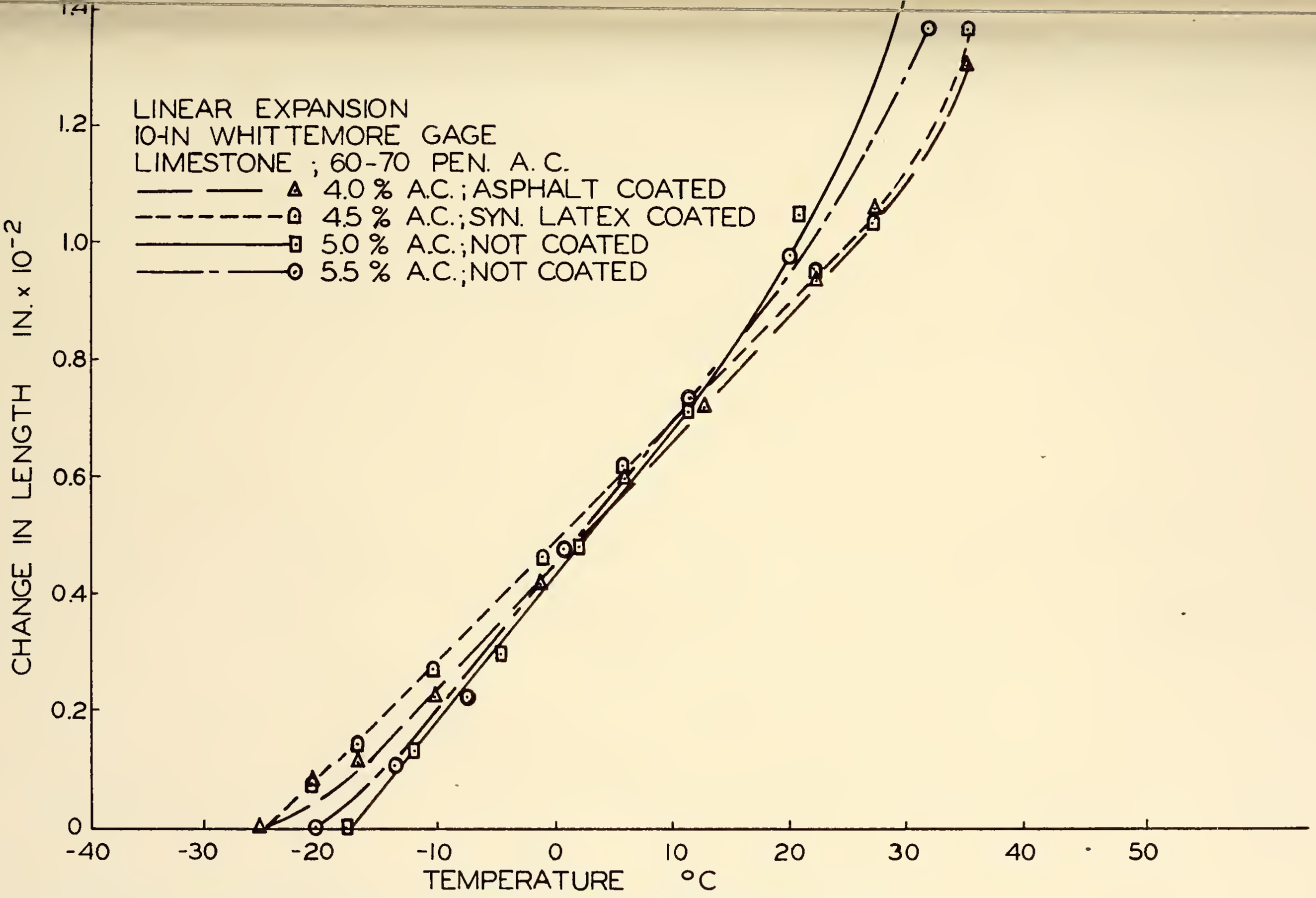


FIG. 35 LINEAR EXPANSION VS. TEMPERATURE

10-IN. WHITTEMORE GAGE; LIMESTONE ; 60-70 PEN. A. C.

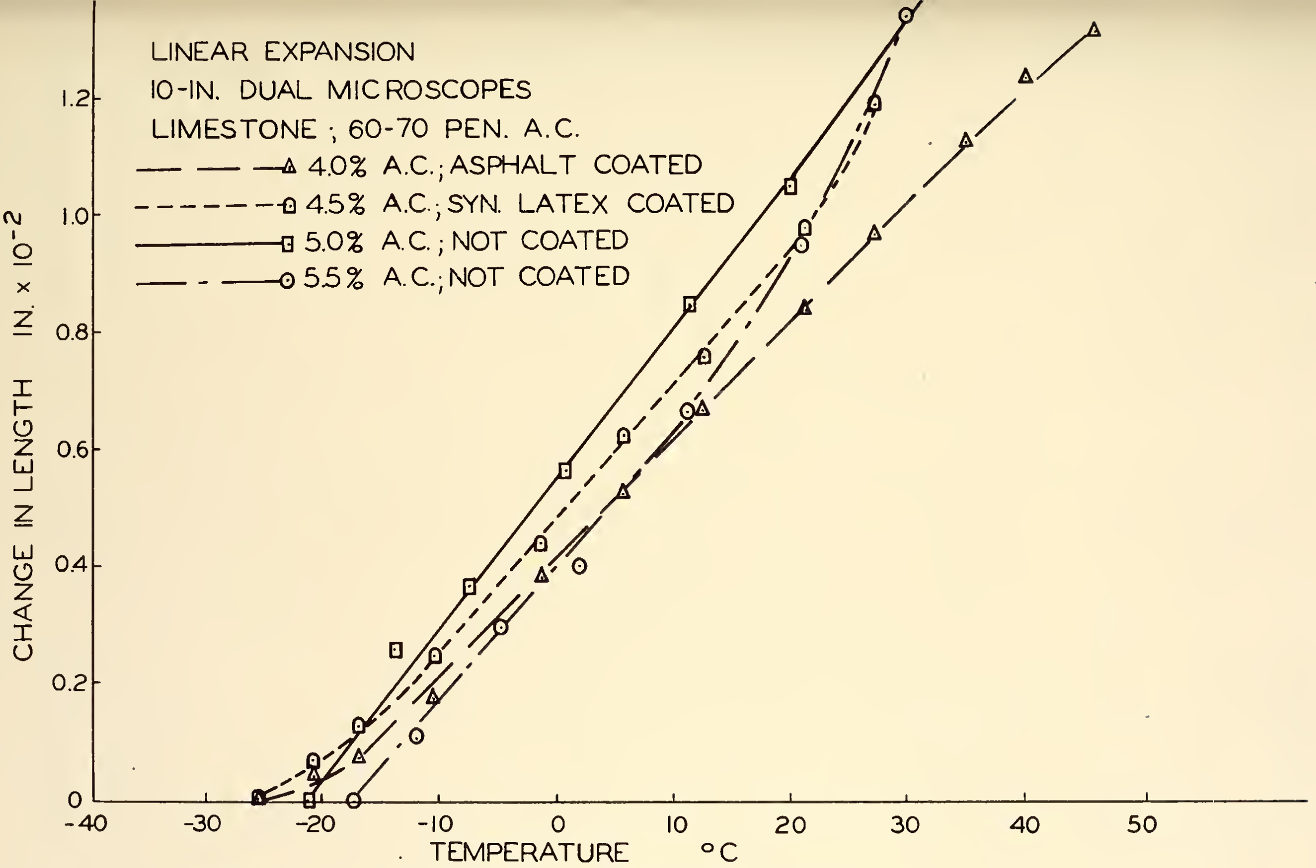


FIG. 36 LINEAR EXPANSION VS. TEMPERATURE
10-IN. DUAL MICROSCOPES; LIMESTONE ; 60-70 PEN. A.C.

asphalt contents were all characteristic and possessed linearity over the lower temperature range. The linear slopes of the curves vary with the asphalt content of the respective specimens and in general show an increase in the slope with increasing asphalt content. All the curves of this figure show an increase in the expansion rates for the temperature range above 20°C.

Figure 36 presents the data obtained by the 10-inch dual microscopes. The specimens tested were the same as those presented in Figure 35 and they were tested simultaneously with the 10-inch dual microscopes and the 10-inch Whittemore gage. These results also show the general trends, with the expansion rate increasing with increasing asphalt content for most cases. The test procedure used in obtaining the data of Figures 35 and 36 was to first establish equilibrium conditions and then to read the gage lengths of the specimens first with the microscope apparatus and then with the 10-inch Whittemore gage. Therefore, this would imply that the results obtained by the microscopes and Whittemore gages should be identical because they were both measuring the same length under similar conditions.

However, a comparison of Figures 35 and 36 shows that both methods did not measure exactly the same. The results obtained with the 10-inch Whittemore gage indicate loss of a spread of the various asphalt content curves compared to the results obtained by the dual microscopes. This difference is possibly due to the different degrees of accuracy possessed by the two different pieces of apparatus, with the dual microscopes being more accurate and accordingly detecting the smaller differences. However, the general slopes of the respective curves, as obtained by the two measuring methods, are very similar and result in calculated linear coefficients which agree quite favorably with the respective replicate specimens.

Figures 35 and 36 illustrate another point that may be attributed to the differences in the 10-inch Whittemore gage and dual microscope measuring apparatus. Figure 36, the results obtained with the 10-inch dual microscope, shows that the expansion rate for the 4.0 percent asphalt content curve starts to decrease at 30°C. The results from the same specimen obtained with the 10-inch Whittemore gage show an increase in the expansion rate for temperatures higher than 30°C. The readings with the 10-inch Whittemore gage were made after the readings with the microscope had been obtained. It is therefore hypothesized that the increase measured by the 10-inch Whittemore gage may be due to movement of the brass plugs under the weight of the gage.

Table 5 gives a summary of the results obtained for the specimens fabricated from the Greencastle limestone and 60-70 penetration grade asphalt cement. The linear coefficients of expansion were all calculated from the slope of the linear portion of the temperature-length change curve for the respective specimens. The standard initial gage length, established at room temperature, was used as the base length. For the volumetric coefficients, the slope of the linear portion of the temperature-specimen expansion curve for the respective specimens was used. The bulk uncoated volume of the specimen at room temperature was selected as the base volume.

The results presented in Table 5 show fairly good correlation between the values obtained with the 10-inch Whittemore gage and the 10-inch dual microscopes. There is a considerable difference between the two volumetric values obtained for the 4.0 percent asphalt content specimens, with the

TABLE 5

COEFFICIENTS OF EXPANSION FOR 60-70 PEN.
A.C.-GREENCASTLE LIMESTONE SPECIMENS

Percent Asphalt Content (by weight of aggregate)	Linear Coefficient $\times 10^{-5}$ in/in/°C		Volumetric Coefficient $\times 10^{-5}$ in^3/in^3/°C	
	Whittemore Gage 10-inch	Dual Microscope 10-inch	Dilatometer II	Dilatometer III
4.0	2.13	2.00	8.47	6.45
4.5	1.95	2.30		
5.0	2.60	2.58		7.03
5.5	2.53	2.30		

value obtained by the metal, mercury-filled, dilatometer being in closer agreement with the linear results on the basis that the volumetric value obtained by the metal dilatometer is about three times the linear value for the 4.0 percent specimens. The volumetric value obtained for the 5.0 percent specimen is about 2.7 times the linear values. The correlation between linear and volumetric results is fairly good except for the results obtained by the glass dilatometer for the 4.0 percent specimen.

The two 4.0 percent specimens, tested by the two types of volumetric apparatus, were both coated with a slow-setting type asphalt emulsion containing 60-70 penetration grade asphalt cement. Therefore, the differences could not be due to variations resulting from different coatings. The difference could result from attempting to compare two specimens which had been tested over different temperature ranges. This lack of consistency could also be a result of the method of arriving at the initial test temperatures of the respective specimens. For the metal dilatometer, the specimen temperature was lowered gradually, while the specimen tested in the glass dilatometer was "shocked" from room temperature to 0°C.

The remainder of the data are fairly consistent and show a general increase in the coefficient of expansion with increasing asphalt content. This is true except for the 5.5 percent linear specimen, which appears to show a slight reduction in the coefficient compared to the 5.0 percent one. The volumetric result obtained for the 5.0 percent specimen is about 2.7 times the linear value, indicating that possibly the linear results obtained for the 5.0 percent sample are slightly high. A comparison of the slopes of the 5.0 and 5.5 percent samples presented in Figures 35 and 36 shows little difference between the two. It is therefore hypothesized that this inconsistency between the linear results of the 5.0 and 5.5 percent specimens is not characteristic of the normal trend, but rather resulted from the particular specimens tested.

85-100 Asphalt Cement-Greencastle Limestone

The majority of the specimens tested in this investigation were composed of Greencastle limestone and the 85-100 penetration grade asphalt cement. Figures 37 through 41 present the graphical representation of the data. Figures 37 and 38 show the values obtained with the metal and glass dilatometers respectively. Figures 39, 40 and 41 present the linear results as obtained for the 5-inch Whittemore gage, the 10-inch Whittemore gage and the 10-inch dual microscopes, respectively.

The volumetric data obtained for replicate specimens tested by the two dilatometric techniques appear in Figures 37 and 38. The results obtained by the two techniques agree quite favorably. Except for the 4.0 percent specimens, the linear portions of the curves of Figures 37 and 38 show an increase in slope for increasing asphalt content. In both figures, the 4.0 percent specimen produces a greater slope than any of the other specimens. The 4.0 percent specimens were coated with the natural latex while the 5.0 percent, and 3.6 percent specimens were coated with the synthetic latex. The 4.5 percent specimen was not coated. Since the 4.0 percent specimens were the only ones coated with the natural latex, it is assumed that the coating was responsible for the extreme increase in the expansion rates of these two specimens. For this reason, the natural latex was not used for coating any additional specimens.

Two 4.5 percent specimens were tested with the glass dilatometer. The graphical results appear in Figure 38. Both specimens were tested in

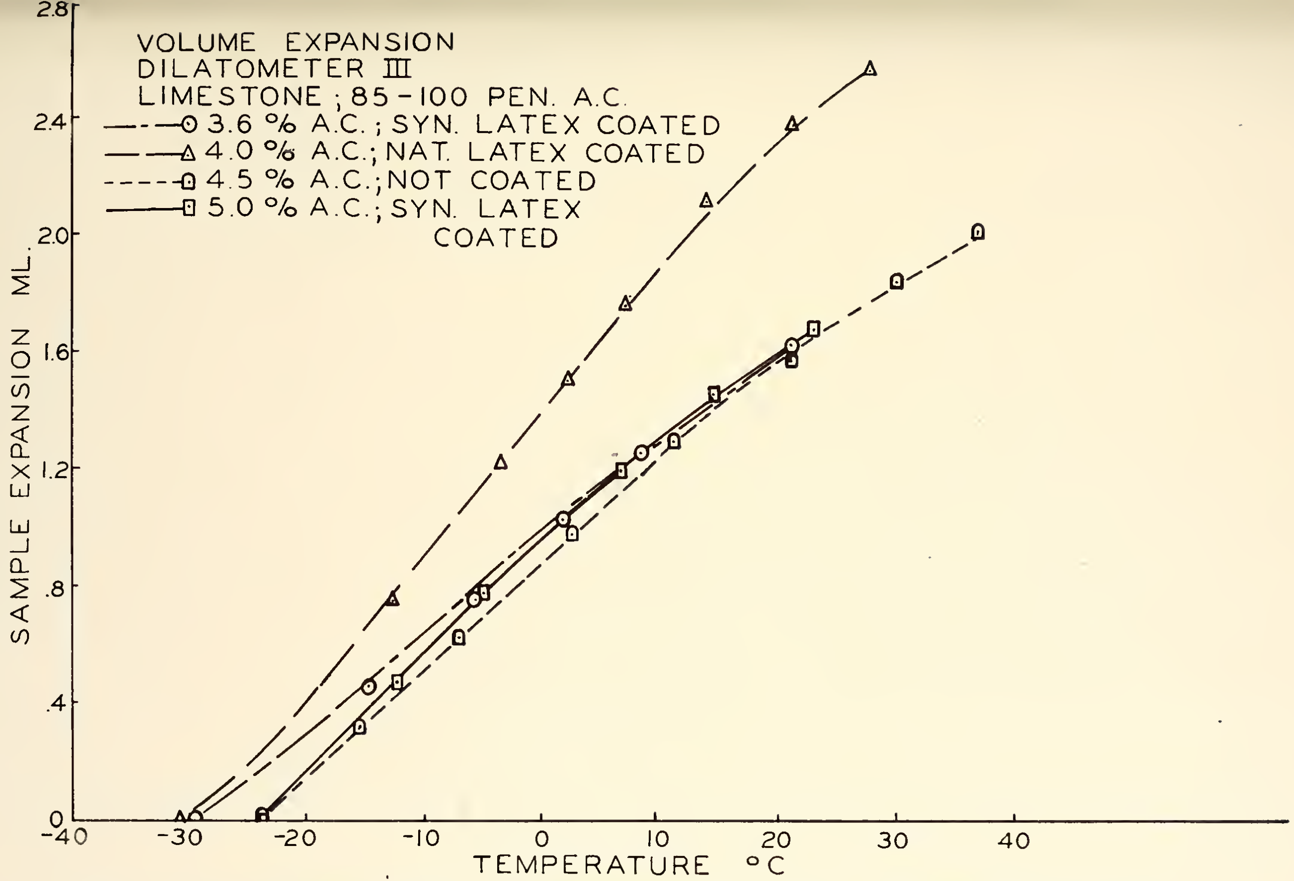


FIG. 37 VOLUMETRIC EXPANSION VS. TEMPERATURE
DILATOMETER III; LIMESTONE ; 85-100 PEN. A.C.

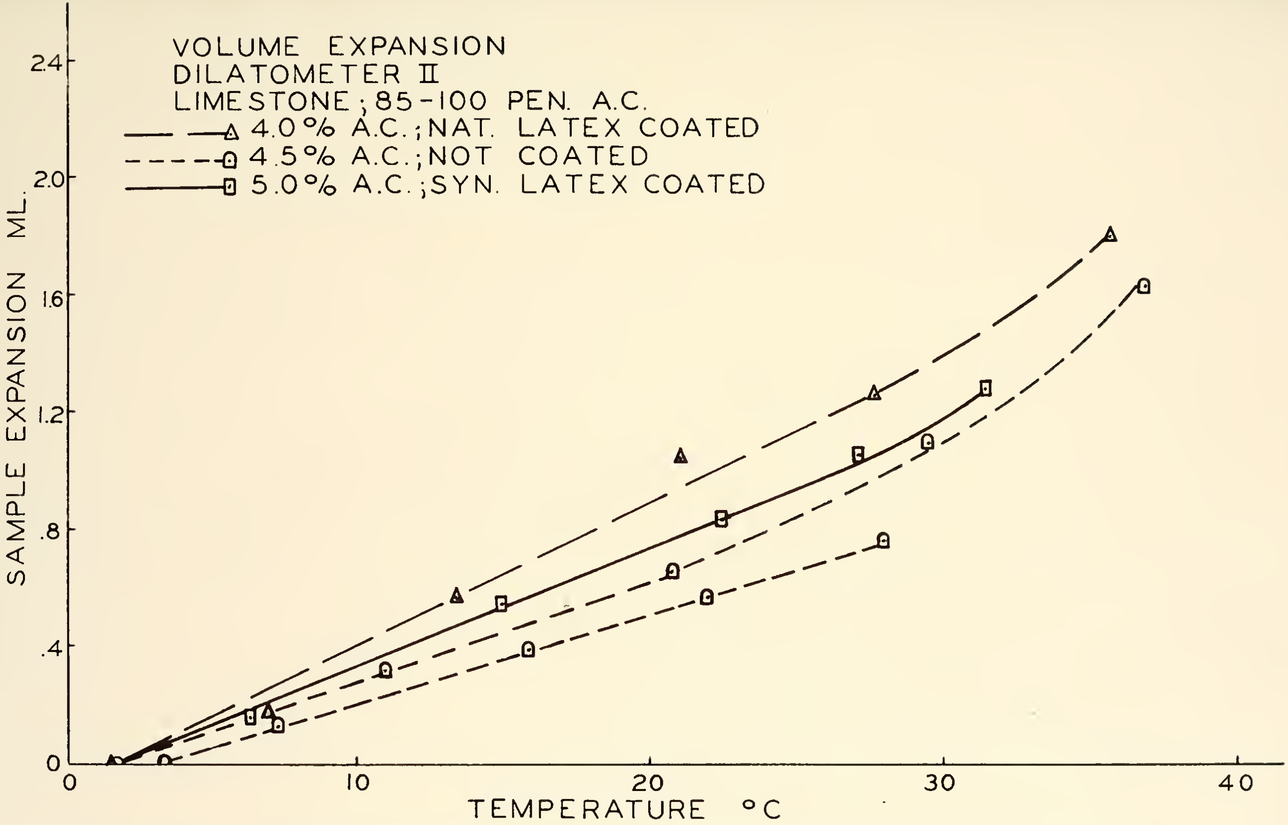


FIG. 38 VOLUMETRIC EXPANSION VS. TEMPERATURE
DILATOMETER II; LIMESTONE; 85-100 PEN. A.C.

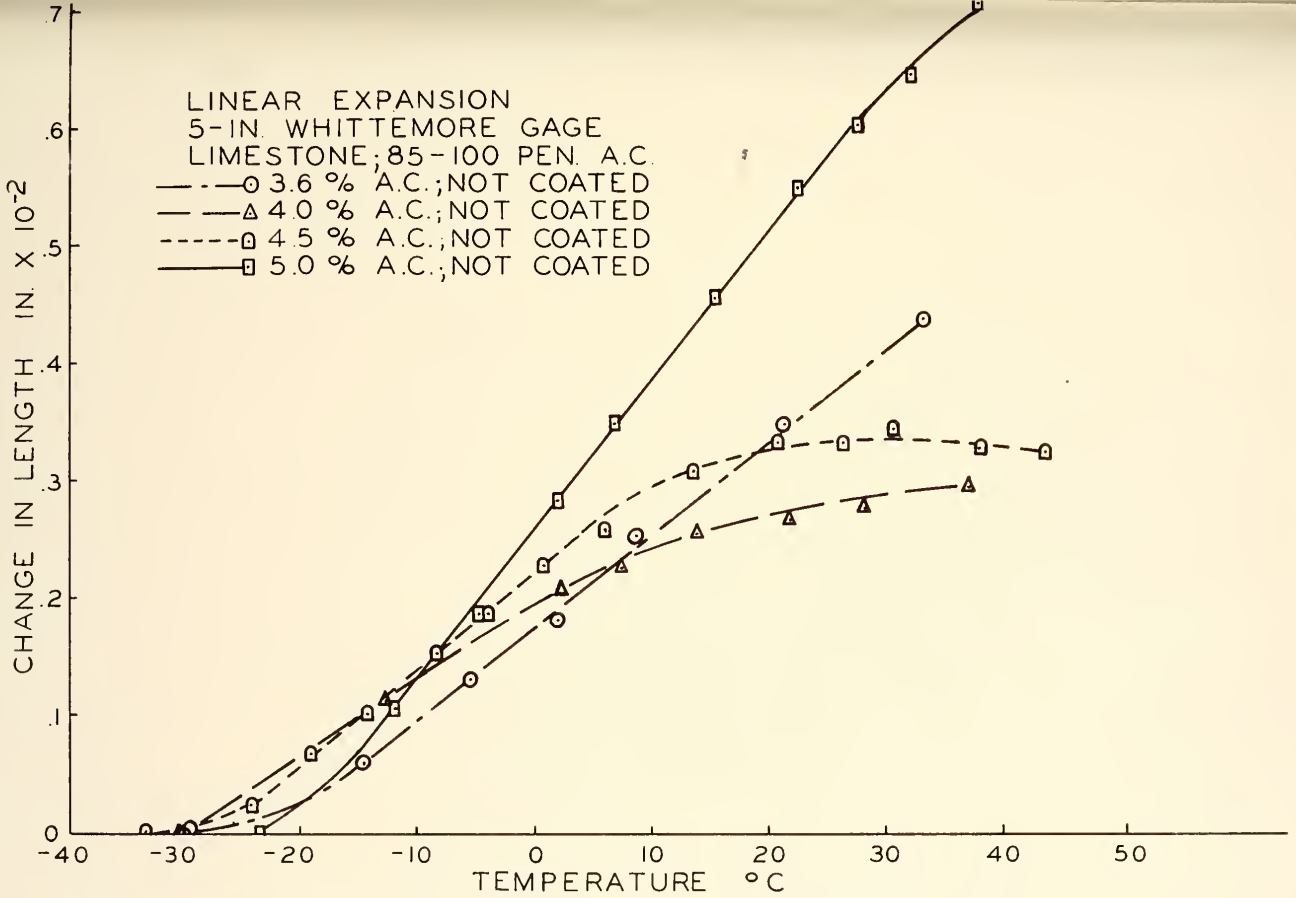


FIG. 39 LINEAR EXPANSION VS. TEMPERATURE
5-IN. WHITTEMORE GAGE; LIMESTONE; 85-100 PEN. A.C.

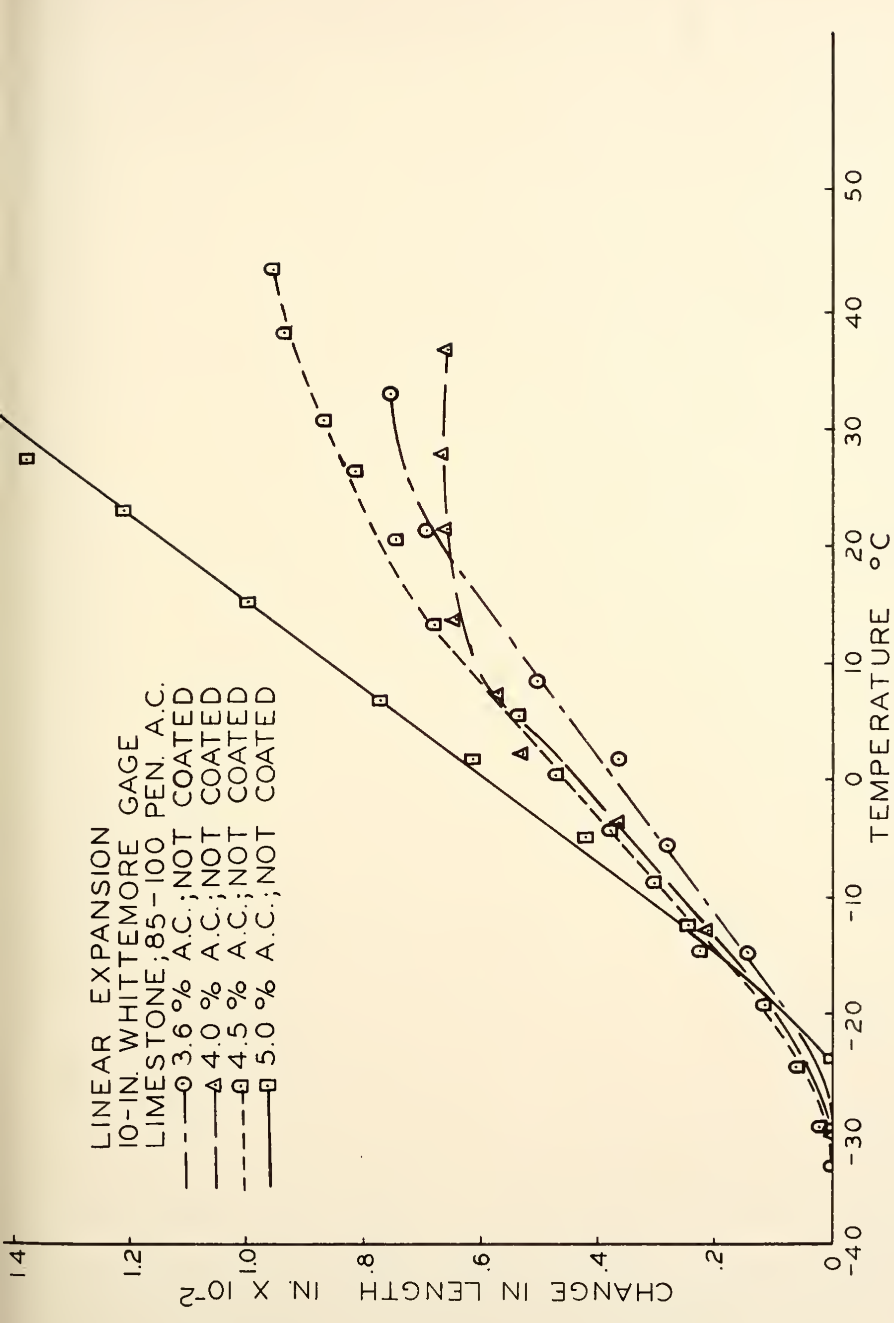


FIG. 40 LINEAR EXPANSION VS. TEMPERATURE
10-IN. WHITTEMORE GAGE; LIMESTONE; 85-100 PEN. A.C.

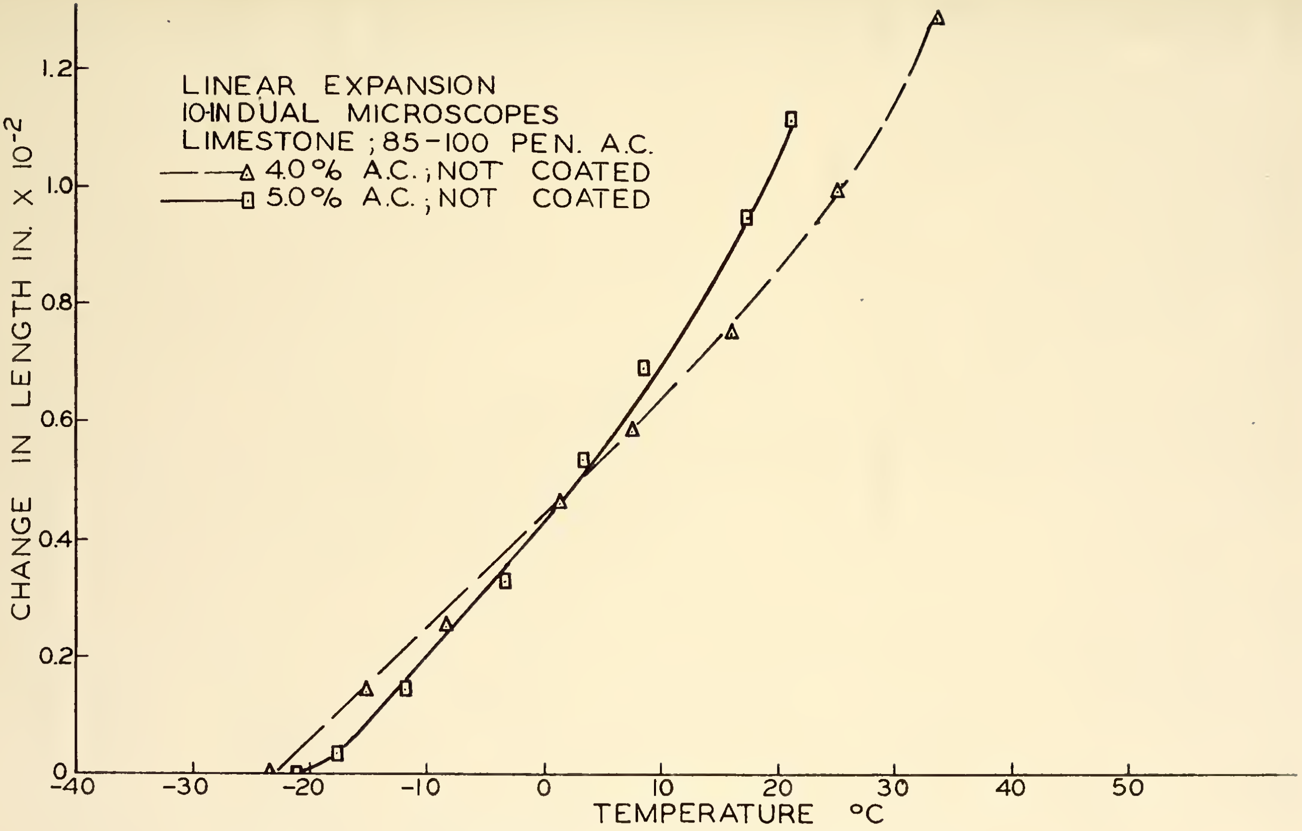


FIG. 41 LINEAR EXPANSION VS TEMPERATURE
10-IN. DUAL MICROSCOPES; LIMESTONE ; 85-100 PEN. A.C.

an uncoated condition. The slopes of the two curves are very similar and the resulting coefficient of expansion, based on the linear portion of the curve and the bulk uncoated volume of the specimen, were 6.89 and $7.48 \times 10^{-5} in^3/in^3/^\circ C$ respectively. This variation amounts to an 8 percent difference in the calculated coefficients of expansion. The reasons for this variation have not been definitely established. It is assumed that the main reason for this difference results from the inherent differences in the specimens due to the separate components and unavoidable differences in fabrication. Although the aggregate used in these specimens was obtained from a single source, this does not guarantee isotropic and homogeneous properties will be present in all, or any, of the individual sieve size fractions. Therefore, factors such as particle orientation, particle size, and degree of compaction may be factors responsible for differences obtained between replicate specimens. Another factor that may be responsible for the variation in the coefficients of these two specimens is the difference in density of the supposedly similar specimens. The 4.5 percent specimen possessing the higher coefficient of expansion had a density of 151.5 pcf, while the 4.5 percent specimen possessing the lower coefficient had a density of 150.3 pcf. The information obtained in this investigation was not sufficient to present a full analysis of the variation in the coefficient of expansion due to differences in the densities of replicate specimens. This particular comparison is presented only to point out the possible effects of this parameter.

The results obtained from the complementary linear expansion specimens are shown in Figures 38 through 40. All of the linear expansion curves were obtained by averaging the results of two gage lines for each specimen. The results of the 5- and 10-inch Whittemore gages were obtained simultaneously from the same specimens, while the results with the 10-inch dual microscopes were obtained on different specimens. In this manner a comparison could be made between replicate specimens tested by two different methods without the characteristics of one method affecting the results of the other.

The results obtained with the 5- and 10-inch Whittemore gages agree very favorably. Both gages apparently measured approximately the same unit length change, as indicated by the similarity of the curves of Figures 39 and 40. Slight differences are apparent in the higher temperature ranges, but unreliable information has been consistently obtained for this temperature range. The slopes of the expansion curves obtained by the two gages show the same general characteristics as obtained for all previous linear specimens. With one exception, the 4.0 percent specimen, the slopes of the expansion curves obtained by the two gages increase with increasing asphalt content. All four of the specimens were tested in an uncoated state and coating differences could not be the reason for the extreme increase in slope of the 4.0 percent specimen. This irregularity of the 4.0 percent specimen may possibly be due to the effects of such factors as different particle orientation from specimen to specimen or unintentional variations in compaction technique. These same reasons may be responsible for the rather high slope for the 5.0 percent specimen, which has a noticeably larger expansion rate than the other specimens.

Figure 41 shows the separate results obtained by the 10-inch microscope apparatus. The two specimens represented in the figure were fabricated from the Greencastle limestone and 5.0 percent and 4.0 percent asphalt contents, respectively. Neither of the specimens was tested in the coated condition. The results again show the characteristic expansion curve, being linear over the lower temperature range with a non-linear expansion rate above 10°C.

Table 6 presents a summary of the coefficients obtained for the Greencastle limestone and various percentages of the 85-100 penetration grade asphalt cement. Except for the small reduction of the coefficient of the 4.0 percent specimen, the linear results show an increase in the coefficient of expansion with increasing asphalt content. The same trend holds for the volumetric results, except for those at 4.0 percent asphalt content. This particular discrepancy was assumed to be a result of the natural latex coating placed on the specimen. The results obtained by the 10-inch dual microscopes are different from those obtained by the 5- and 10-inch Whittemore gages for the replicate specimens. The difference between the coefficients for these replicate specimens, tested by the two different methods, is again probably not characteristic of the measuring system. Instead it probably results from differences in the replicate specimens that occurred even though they were fabricated in the same manner. The nature of these differences include differences in particle orientation from specimen to specimen, degree of compaction and differences in the expansion characteristics of the individual pieces of aggregate. Also, there is a possibility of slight variations in support of the specimen.

For all of the asphalt contents used, except the 5.0 percent, the correlation between the linear and volumetric results is not very close. The poorest correlation is with the 4.0 percent specimens, for which the volumetric coefficients are high because of the natural latex coating

TABLE 6

COEFFICIENTS OF EXPANSION FOR 85-100 PEN. A.C.-GREENCASTLE LIMESTONE SPECIMENS

Percent Asphalt Content (by weight of aggregate)	Linear Coefficient x 10^{-5} in/in/°C			Volumetric Coefficient x 10^{-5} in^3/in^3/°C	
	Whittemore Gage 5-inch	Whittemore Gage 10-inch	Dual Microscope 10-inch	Dilatometer II	Dilatometer III
3.6	1.59	1.49			6.54
4.0	1.31	1.33	1.94	9.25	9.61
4.5	1.65	1.75		6.89 7.48	7.19
5.0	2.53	2.61	2.36	8.10	8.20

employed in sealing these particular specimens. The data for the 3.6 and 4.5 percent asphalt content specimens show that the volumetric coefficient is more than four times the linear coefficient in each case. For the 5.0 percent specimens, the volumetric coefficient is slightly more than three times the linear.

The poor correlation between volumetric and linear replicate specimens may be due to several causes. First, it could be a result of the different fabrication procedures used in making the beams and Marshall specimens respectively. The different compaction techniques could be responsible for different particle orientation, as well as differences in aggregate degradation of the respective specimens. Second, it appears the coefficients obtained by the Whittemore gages were lower than normal. This supposition is based on the comparison of the coefficients for the 4.0 percent linear specimens obtained by the Whittemore gages and the 10-inch microscope apparatus. The value obtained by the dual microscopes is higher than the values obtained by the 10-inch Whittemore gages. Another factor which tends to verify the supposition of subnormal coefficients obtained by the Whittemore gages is the inconsistency between the volumetric and linear results. In particular, the average volumetric coefficient is four times the linear coefficient for the 4.5 percent specimens. The comparison of the linear and volumetric coefficients for the 3.6 percent specimens also supports the hypothesis because the volumetric coefficient is more than four times the linear values. The large increase in the linear coefficient of the 5.0 percent asphalt content specimen over that for the 4.5 percent one also indicates that the linear results obtained with the Whittemore gages for the 3.6, 4.0, and 4.5 percent asphalt contents are possibly lower than normal.

For this set of parameters, the Greencastle limestone and the different percentages of the 85-100 penetration grade asphalt cement, more confidence was placed on the volumetric results and the linear results obtained with the 10-inch dual microscopes than on the results for the low asphalt contents as obtained by the Whittemore gages. It is felt that this is not primarily a result of inadequacies of the testing technique, but rather is due to differences between supposedly identical specimens.

85-100 Asphalt Cement - Lafayette Gravel

The information obtained on specimens made from the Lafayette gravel and 85-100 penetration grade asphalt cement is presented in Figures 42 through 44. The volumetric results obtained with the metal dilatometer are presented in Figure 42, while the linear results appear in Figures 43 and 44. Two linear specimens, composed of 4.0 and 4.5 percent asphalt respectively, were tested by both the 10-inch Whittemore gage and the 10-inch dual microscopes and the results appear in Figures 43 and 44 respectively. The 5.0 and 3.6 percent linear expansion specimens were tested only with the 10-inch dual microscope apparatus.

Figure 42 shows the results for two specimens tested with the metal dilatometer. The specimens were fabricated from Lafayette gravel and 3.6 and 5.0 percent of the 85-100 penetration grade asphalt cement respectively. The 5.0 percent sample was not coated, while the 3.6 percent sample was coated with the synthetic latex. The expansion curves are similar to all the results obtained with this dilatometer. The expansion is linear up to about 10°C and then increases at a decreasing rate. The two curves

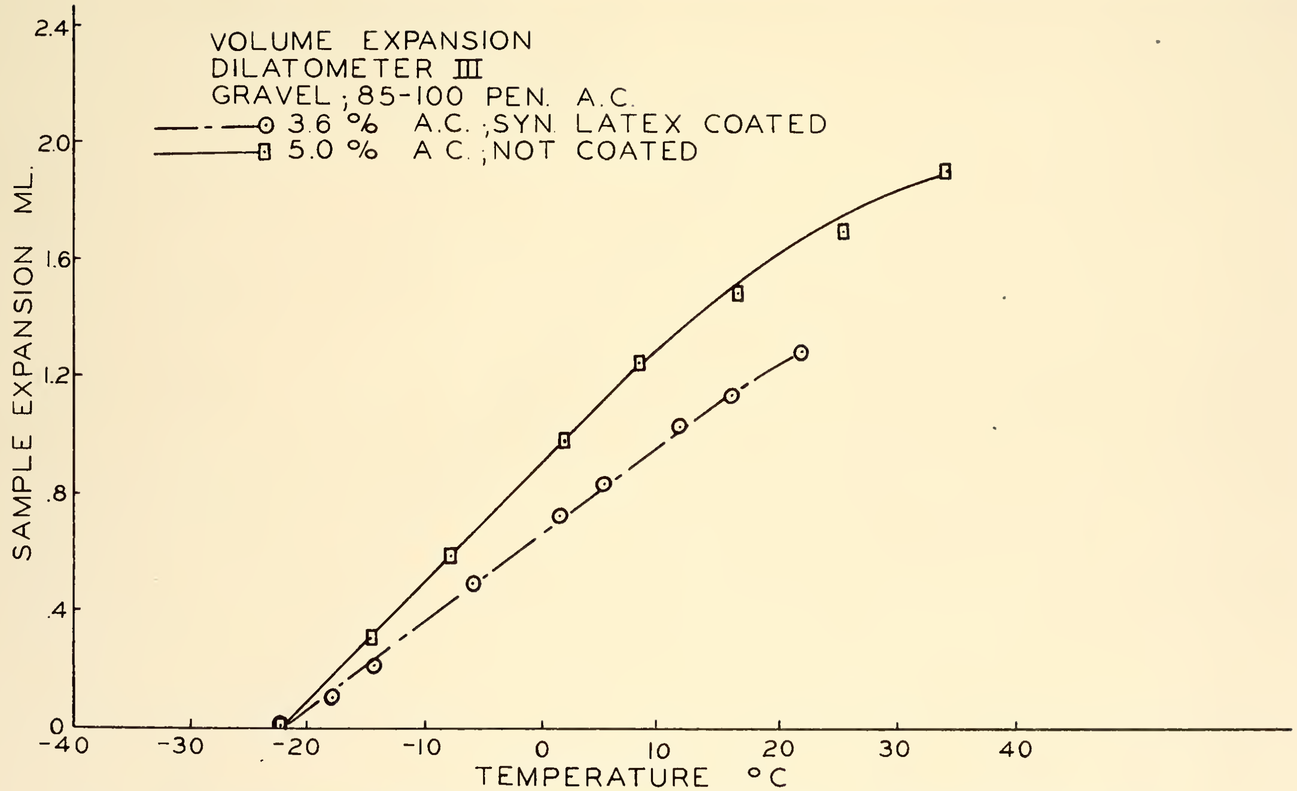


FIG. 42 VOLUMETRIC EXPANSION VS. TEMPERATURE
DILATOMETER III; GRAVEL ; 85-100 PEN. A.C.

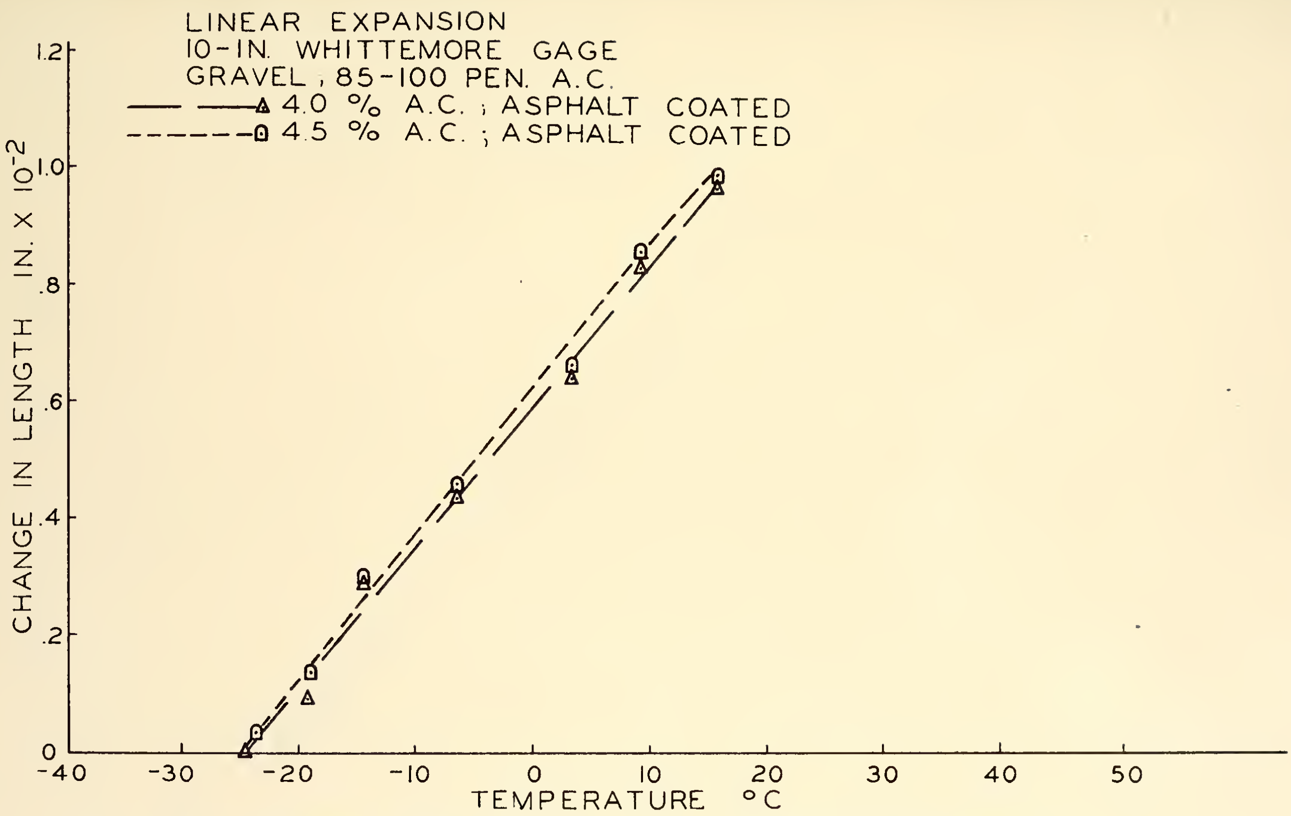


FIG. 43 LINEAR EXPANSION VS. TEMPERATURE
10-IN. WHITTEMORE GAGE; GRAVEL; 85-100 PEN. A.C.

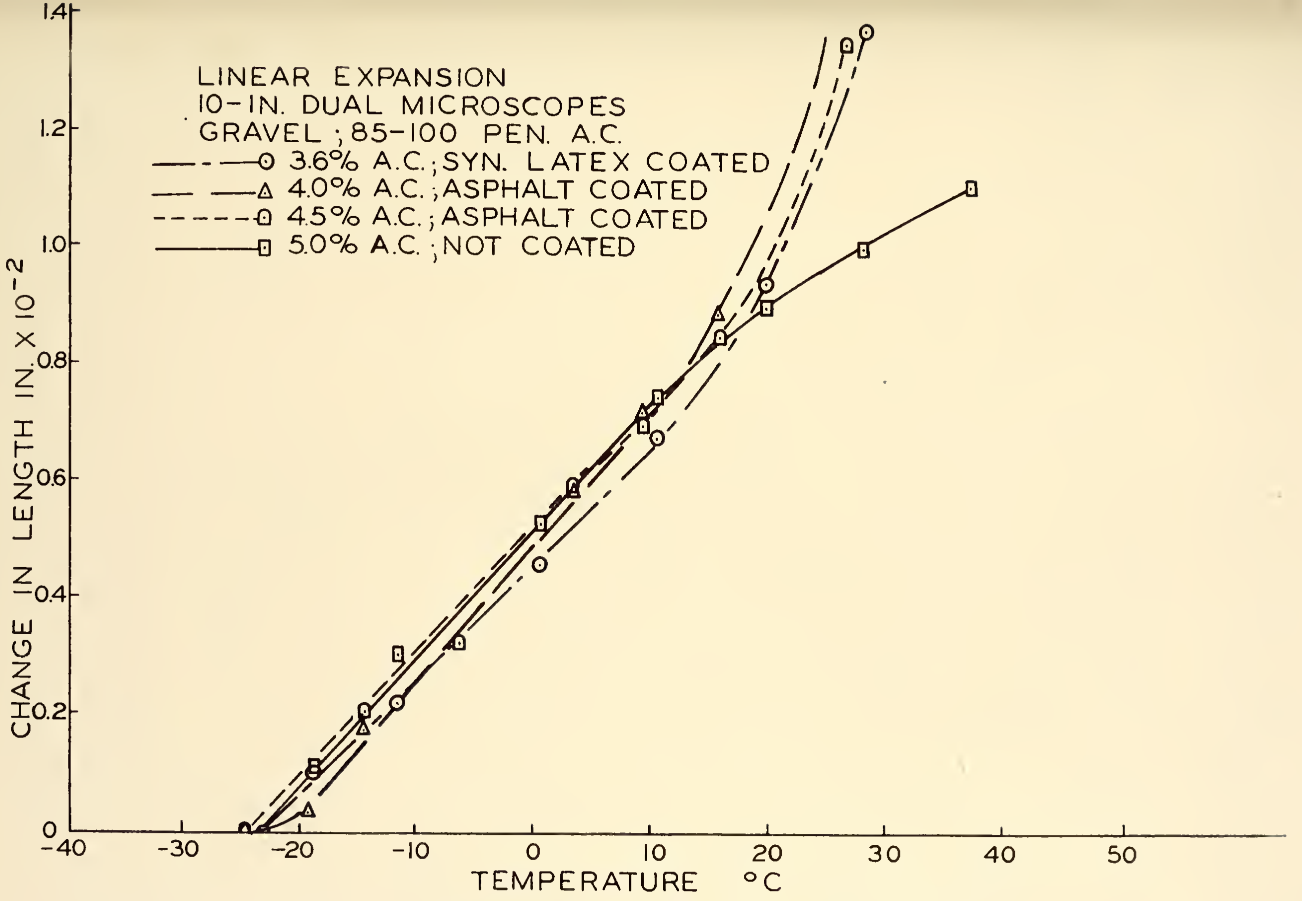


FIG. 44 LINEAR EXPANSION VS. TEMPERATURE
10-IN. DUAL MICROSCOPES; GRAVEL; 85-100 PEN A.C.

clearly show an increase in slope with increasing asphalt content. All the points fall on the curve, testifying to the consistency of the technique.

Figure 43 shows results for two specimens which were tested with the 10-inch Whittemore gage. Although the difference is only slight, the slope for the 4.5 percent specimen is higher than that for the 4.0 percent specimen. This also verifies the general trend of increasing rate of expansion with increasing asphalt content. Both specimens were coated with 85-100 penetration grade asphalt applied in emulsion form.

Figure 44 presents the results obtained with the 10-inch dual microscope apparatus. The specimens were composed of Lafayette gravel and 85-100 penetration grade asphalt cement. The asphalt contents tested were 3.6, 4.0, 4.5, and 5.0 percent. The 4.0 and 4.5 percent specimens were coated with asphalt emulsion, while the 5.0 percent specimen was not coated. The 3.6 percent specimen was coated with the synthetic latex. The slopes of the expansion curves are all grouped fairly close together and demonstrate the linear characteristic over the lower temperature range. There is not much difference in the slopes of the four curves, with the result that there is not much difference in the calculated coefficients of expansion. The difference in expansion rates at elevated temperatures, as shown when comparing the replicate specimens of Figures 43 and 44, again show the inconsistency in the shape of the expansion curve for temperatures above 15°C.

The calculated coefficients for these data are presented in Table 7. The linear coefficients were obtained from the linear portion of the respective expansion curves, using the standard gage length established at room

TABLE 7

COEFFICIENTS OF EXPANSION FOR 85-100 PEN. A.C.-LAFAYETTE GRAVEL SPECIMENS

Percent Asphalt Content (by weight of aggregate)	Linear Coefficient $\times 10^{-5}$ in/in/°C		Volumetric Coefficient $\times 10^{-5}$ in^3/in^3/°C
	Whittemore Gage 10-inch	Dual Microscope 10-inch	Dilatometer III
3.6		2.00	6.32
4.0	2.34	2.40	
4.5	2.55	2.06	
5.0		2.23	8.06

temperature as the base length. The volumetric coefficients were computed from the linear portion of the respective expansion curves, using the bulk uncoated volume at room temperature as the reference volume.

The calculated linear coefficients are inconsistent and show no apparent correlation with varying asphalt content. The correlation of volumetric and linear coefficients for the 3.6 percent asphalt content is good. However, the volumetric coefficient for the 5.0 percent specimen is more than 3.5 times the linear coefficient. This inconsistent relationship between expansion coefficients for the different asphalt contents is assumed to be due to the variation between specimens. The gravel was a composite of different minerals, with different coefficients for each respective mineral. Therefore, the coefficient of expansion for specimens fabricated from this aggregate could be expected to exhibit more variation between replicate specimens because of the increased effect that differences in particle orientation and distribution would produce. Another misleading factor is the narrow range in values of the linear coefficients obtained for the different asphalt contents. The linear coefficients presented for the 4.5 percent specimen are quite different, and yet they were obtained on the same specimen by two different methods. This shows the relative sensitivity of slight changes in the slope of the expansion curves which should have been similar for the results obtained with the 10-inch Whittemore gage and the 10-inch dual microscopes.

In general the results obtained for the gravel are not sufficient to establish trends for effect of variables and more specimens should be tested in order to establish these trends with more clarity.

Comparison of Asphalt-Aggregate Contributions

In comparing the results of Tables 5, 6, and 7, the following observations are noted. First, there appears to be a definite trend of increasing coefficient of expansion with increasing asphalt content. In comparing the results for Lafayette gravel and Greencastle limestone specimens containing the 85-100 penetration asphalt cement, the gravel specimens had considerably higher linear coefficients than the limestone ones, particularly for the low asphalt contents. However, the volumetric results did not show this difference. It was concluded earlier in this discussion that the linear values obtained with the Whittemore gages, for the 85-100 penetration asphalt cement and Greencastle limestone, were lower than expected. When initially choosing the two aggregate mixes, it was thought that the gravel would produce specimens with higher coefficients of expansion. However, the contributions of the aggregate constituents were possibly obscured by the large contribution to the expansion from the asphalt cement itself.

Comparing effects of the grade of asphalt, the 85-100 penetration grade seems to produce a slightly lower coefficient than the 60-70 penetration grade when comparing the linear results obtained with the limestone mixes. At the higher asphalt contents, the results for the two grades appear to agree more than at the lower asphalt contents. However, the volumetric results do not show much of a difference between specimens made with different grades of asphalt. This may be another indication that the linear results obtained for the 85-100 penetration asphalt cement limestone aggregate specimens are lower than the normal values.

In an attempt to determine the influence on the coefficient of expansion of the different mix components, separate volumetric determinations were conducted on the Greencastle limestone and 85-100 penetration grade asphalt cement. Figures 45 and 46 present the volume expansion curves for the asphalt cement and limestone, respectively.

The asphalt was heated a sufficient amount to allow easy pouring. Enough asphalt was then carefully poured into the metal dilatometer bulb to almost fill it and the entire bulb and contents heated to help insure air removal. The liquid asphalt was carefully stirred to eliminate any entrapped air and then allowed to cool to room temperature. The weight of the asphalt was obtained by weighing the dilatometer bulb before and after filling. The volumetric coefficient for the asphalt was obtained from the linear portion of the curve and the bulk volume of the asphalt at room temperature was taken as the reference volume. The resulting volumetric coefficient for the asphalt was $4.107 \times 10^{-4}/in^3/in^3/^\circ C$. This value is lower than the value given by the Handbook of Chemistry and Physics (22), which lists the volumetric coefficient of asphalt as ranging from 5 to $7 \times 10^{-4}/in^3/in^3/^\circ C$. The reference gave no temperature range for which these values were obtained.

The volumetric coefficient of expansion for the limestone was obtained from the linear portion of the curve of Figure 46. The amount of aggregate used was the exact weight of the individual sieve fractions above the #20 size sieve normally used in fabricating a standard Marshall specimen. A screen was soldered over the 1/2-inch hole in the dilatometer top in order to prevent any of the aggregate from floating up into the pipette. The volume of the aggregate used in calculating the limestone coefficient was

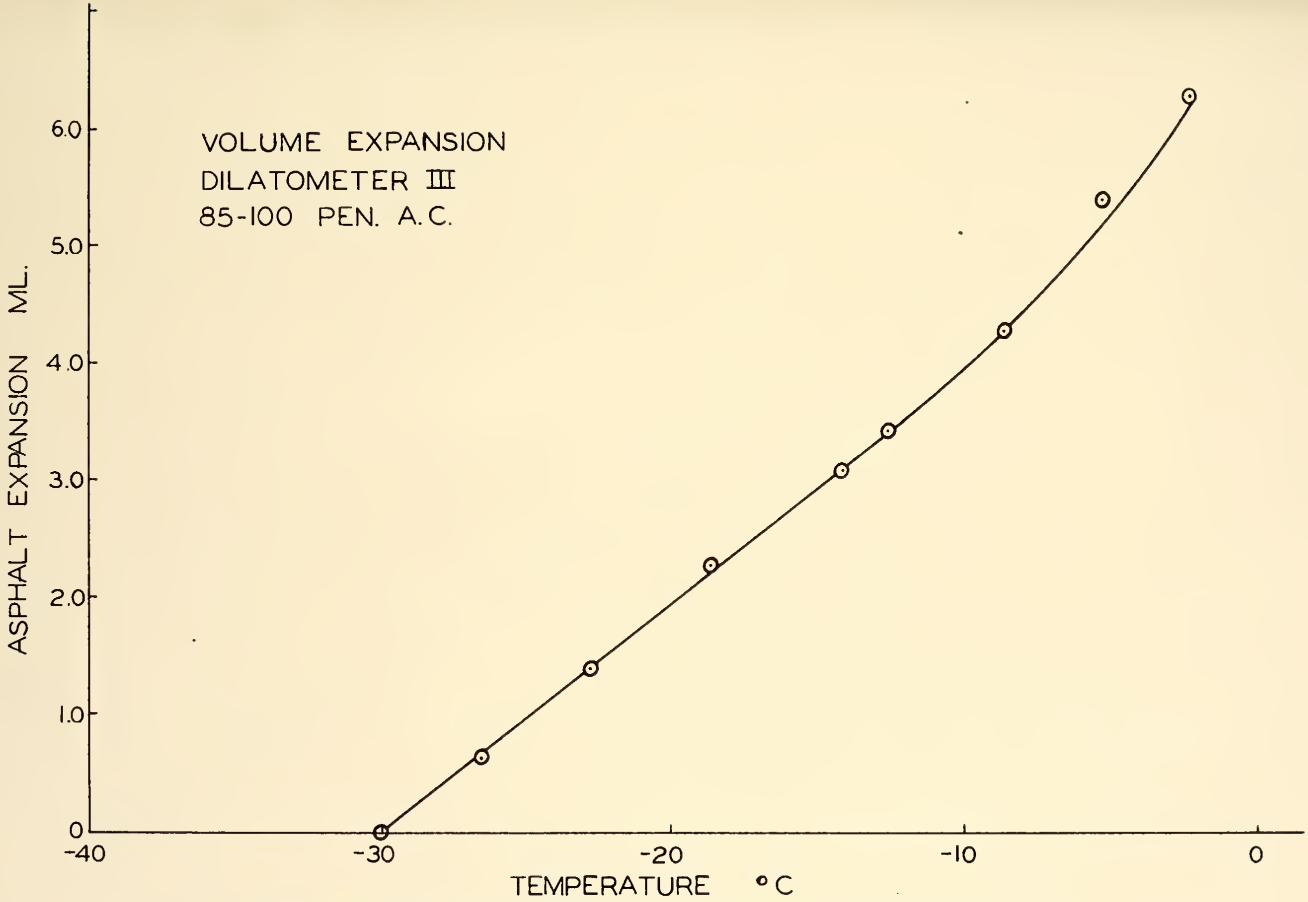


FIG. 45 VOLUMETRIC EXPANSION - 85-100 PEN. A.C.

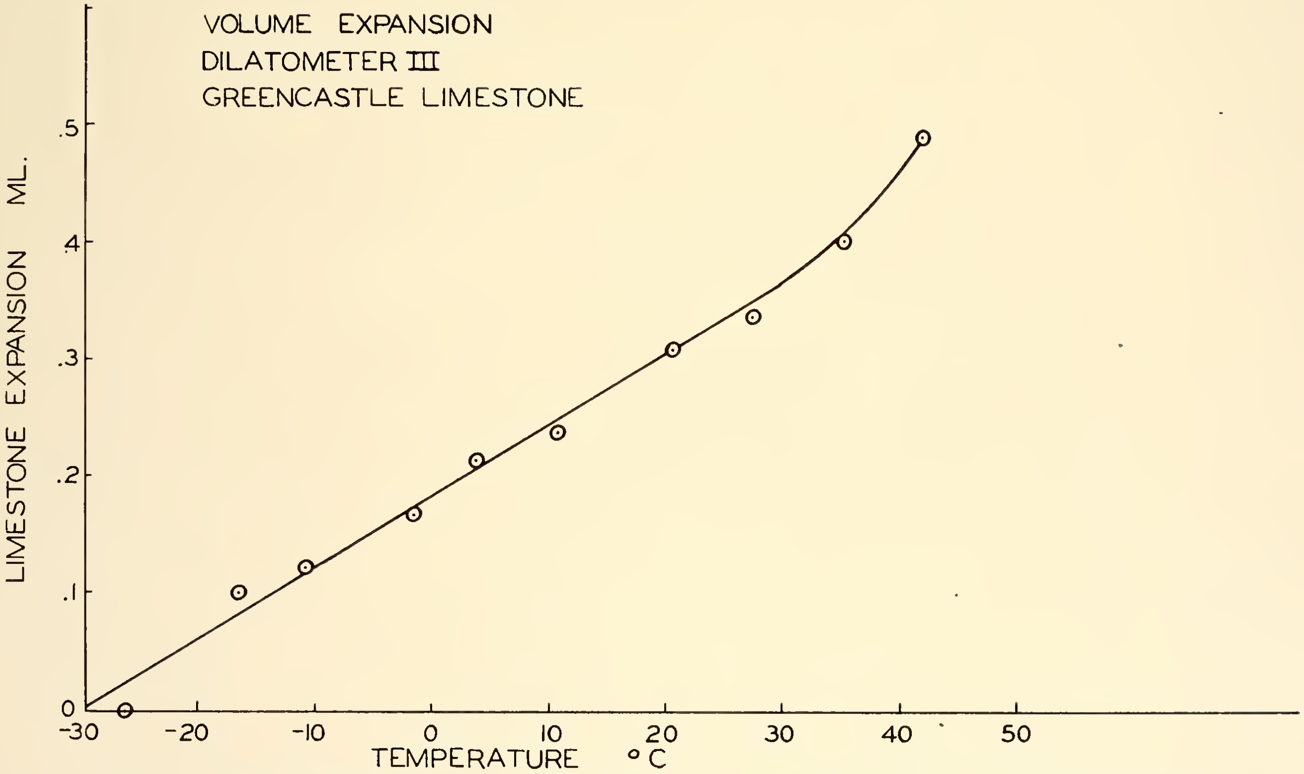


FIG. 46 VOLUMETRIC EXPANSION - GREENCASTLE LIMESTONE

obtained by dividing the weights of the various sieve-size fractions by their respective bulk specific gravities and then adding the total volume. The coefficient for the limestone as calculated in this manner was $23.30 \times 10^{-6}/in^3/in^3/^{\circ}C$.

Table 8 was prepared by assuming that the final coefficient of expansion of the Greencastle limestone - 85-100 penetration asphalt mix was in proportion to the thermal volumetric expansion contributed by the individual constituents of the mix. The ratio of the volume of asphalt in the mix to the total volume of the mix was multiplied by the experimental coefficient of expansion for the asphalt. This value was then added to the multiplication of the experimental coefficient of the limestone times the ratio of the volume of aggregate in the mix to the total mix volume. The linear values were obtained by dividing the volumetric values by three.

A comparison of Table 8 with Table 6 shows that the theoretical volumetric coefficients are lower than the measured volumetric coefficients for specimens containing respective asphalt contents. The difference between the two volumetric coefficients increases at the higher asphalt contents. The linear experimental results are lower than the theoretical ones and for the 3.6, 4.0 and 4.5 percent asphalt content specimens. This may indicate that these experimental linear coefficients are actually lower than normal, as previously mentioned. The experimental linear coefficient for the 5.0 percent specimen is larger than the theoretical.

The difference between the theoretical coefficients and the experimental coefficients are probably a result of the limited temperature range over which the volumetric coefficient of the asphalt was obtained. At higher temperatures, Figure 45 shows the asphalt expansion to be increasing at

TABLE 8

THEORECTICAL COEFFICIENTS OF EXPANSION
85-100 Pen. A.C.-Greencastle Limestone

Asphalt Content (by weight of aggregate)	Volumetric Coefficient $\times 10^{-5}$ in^3/in^3/°C	Linear Coefficient $\times 10^{-5}$ in/in/°C
3.6	5.71	1.90
4.0	6.05	2.02
4.5	6.46	2.15
5.0	6.86	2.29

an increasing rate. When mixed with the limestone and tested over the entire temperature range of - 30 to 30°C, the contribution to the total expansion made by the asphalt cement is probably more than was obtained from the linear segment of Figure 45. The same phenomenon occurs with the limestone as shown by Figure 46. At elevated temperatures, the expansion rate increases and the net effect of the aggregate expansion is probably more than the assumed contribution based on the measured coefficient of the limestone.

However, the theoretical calculated coefficients obtained by this method, particularly for the lower asphalt contents, agree well enough to indicate that the individual constituents do contribute to the expansion of the mix in approximate proportion to their respective volumes in the mix.

Based on a comparison of the two curves shown in Figures 45 and 46, the expansion trend for the asphalt and limestone seems to be increasing at an increasing rate for the higher temperatures. This may be an indication that the expansion of the resulting mix should also be increasing at an increasing rate at elevated temperatures.

This discussion on the general trends shows that the numerical results obtained in this investigation are not to be completely relied upon because an insufficient number of samples were tested to establish exact relationships. Only the apparent trends have been mentioned and considerably more tests should be conducted with the recommended equipment in order to establish these trends definitely.

SUMMARY OF RESULTS AND CONCLUSIONS

A laboratory investigation of the thermal expansion of bituminous concrete has been conducted. The primary objective of the study was to select and investigate appropriate test methods, both linear and volumetric, that would adequately measure the desired property. These techniques were to be compared with regards to accuracy, practicality, ease of operation, and cost. In an attempt to provide a means for a legitimate comparison of these testing techniques, asphaltic specimens of different compositions were tested. Variables introduced in the fabrication of the specimens included: type of aggregate, grade of asphalt cement, asphalt content, and method of compaction. No attempt was intentionally made to provide measuring techniques applicable for use under field conditions. Consequently, no attempt was made to correlate results from the laboratory with values obtained under field conditions.

Due to time and financial limitations, only a few of the many possible test techniques were investigated. It is not to be construed therefore, that the methods selected for study in this investigation are the only ones applicable, nor should they be considered final in respect to all details of procedure as applied to the measurement of the thermal expansion of bituminous concrete.

The following results and conclusions are applicable to the materials and test procedures of this specific research:

1. Of the three dilatometric techniques investigated, the mercury-filled metal dilatometer, used without evacuation during the filling process, proved to be the best and is recommended for any further investigation of the volumetric expansion of bituminous concrete.
2. Of the three linear techniques investigated, the specially designed dual microscope apparatus proved to be the best and is recommended for further linear expansion investigations. An alternative choice would be a 10-inch Whittemore strain gage, primarily for use in a possible laboratory-field correlation study.
3. In most cases there existed reasonable correlation between volumetric and linear coefficients of expansion for specimens of similar composition, as provided by the respective methods.
4. The results obtained by the methods used in this investigation show a linear relationship between expansion and temperature over the approximate range of - 30 to 15°C. Above 15°C, inconsistencies were observed between the expansion rates of replicate specimens. The data for this higher temperature range were inadequate to establish a consistent temperature-expansion trend.
5. The nature of the asphaltic concrete was such that when subjected to a cyclic temperature change, the linear specimens did not return to their original lengths. This conclusion is subject to the limitations of the test technique employed.
6. The effect of increasing asphalt content in a bituminous mixture was to produce an increase in both the measured linear and volumetric coefficients of thermal expansion of the mixture.

7. On the basis of average overall results, the use of two different grades of asphaltic cement, a 60-70 penetration grade and an 85-100 penetration grade, produced little difference in the coefficients of expansion of the respective mixes.
8. On the basis of average overall results, the use of two different types of aggregate, a limestone and a gravel, produced little difference in the coefficients of expansion of the respective mixes. This was presumably due to the large contribution from asphalt in the mix.
9. Determinations of the individual volumetric coefficients of expansion for the limestone and 85-100 penetration grade asphalt cement were made. The calculated theoretical coefficients for the mixtures composed of these ingredients varied approximately in proportion to the thermal coefficient and volume of the respective components in the mixture. This relationship was particularly valid for the low asphalt content specimens. At higher asphalt contents, the non-linearity of the asphalt expansion, increasing at an increasing rate for temperatures above $0^{\circ}C$, became predominant and the measured mixture coefficient was higher than the value predicted on the basis of a linear expansion curve.
10. The average linear coefficient of expansion for the various mixes tested in this investigation was of the order of 2.0×10^{-5} in/in/°C. The average volumetric coefficient of expansion was of the order of 7.0×10^{-5} $in^3/in^3/^{\circ}C$.

SUGGESTIONS FOR FURTHER RESEARCH

This study has presented an evaluation of different measuring techniques employed to find the linear and volumetric coefficients of expansion of bituminous concrete. Emphasis was placed primarily on developing adequate testing procedures and equipment. For this reason, only a minimum number of specimen variables were introduced into the study to help evaluate the sensitivity of the apparatus in measuring differences in the specimen expansion resulting from these variables. Therefore, an intensive investigation to evaluate effects of different mixture variables could be undertaken with the equipment and procedures recommended in this report. From the results of these tests, trends produced by the different variables could be developed to a greater extent and with more certainty than those mentioned in this report.

The recommended test techniques outlined in this report were not completely adequate in all aspects. One of the needed technique improvements is in the development of an adequate sealing coat for the specimens. The development of such a material would greatly increase the value of the respective techniques by reducing absorption effects. An investigation of this sort could readily be started on low-temperature-setting latexes, and if necessary, expanded to other materials not considered in this report.

This investigation was conducted under rigid laboratory control of the different test conditions. It would be very informative to conduct a field and laboratory correlation study of expansion trends for different conditions. Although laboratory testing techniques may provide reproducible results, these are meaningless unless they accurately represent actual field conditions. This correlation could be accomplished using the 10-inch Whittemore strain gage.

In connection with a field-laboratory correlation study, some additional variables besides those tested in this investigation which could profitably be introduced would be rate of temperature change and degree of confinement. Only one rate of temperature change was employed in this investigation and different rates could easily affect the expansion results. To obtain a true field-laboratory correlation, the laboratory technique should conform as closely as possible to the field conditions. This would entail providing some means of confinement for the linear specimens to simulate friction effects between base and surface as well as confinement offered by surrounding asphaltic concrete.

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APPENDIX A

Calibration Data for Dilatometer II

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Calibration Data for Dilatometer II

In this section, the calibration data obtained for the water-filled glass dilatometer are presented. Table 9 presents the specific volume data for water used in computing the dilatometer expansion and subsequently the expansion of specimens tested, using water as the displacement liquid. The calibration data appear in Table 10 and the resulting dilatometer expansion curve is presented in Figure 47. A description of the procedure used in arriving at the final dilatometer expansion curve is included to clarify the data presentation.

The first column of Table 10 is the temperature, in °C, of the dilatometer at equilibrium conditions. The second column is the actual dilatometer reading at equilibrium conditions, in ml. The next column is the amount of displacement liquid removed from the system in order to keep the liquid level on the 1-ml pipette scale. The amount removed does not affect the dilatometer reading for the temperature at which it was removed because the removal took place after equilibrium conditions had previously been established. Consequently, it affected only the subsequent readings. For this reason, the removed amount appears one temperature higher than that at which it was removed because this is the reading it first affects. The fourth column is the specific volume of the displacement liquid for the respective temperatures indicated.

The fifth column presents the calculated expansion of the amount removed. If this liquid had not been removed from the system, its expansion would have been included in the dilatometer reading and consequently it must be included in the calculations. The expansion, in ml, of the amount removed was computed by the following formula:

Expansion of amount removed =

$$[(1/d) - (1/d)'] \text{ (volume of amount removed) } [1/(1/d)']$$

where:

$(1/d)$ = the specific volume of the water at the new equilibrium temperature.

$(1/d)'$ = the specific volume of the water at the removal temperature.

After an amount of the displacement liquid has been removed from the system its hypothetical expansion is calculated for each of the successive equilibrium readings. Column six presents the theoretical dilatometer readings for the respective temperatures. The individual values in this column are obtained by adding the accumulated removed amount, the accumulated expansion of the removed amount, and the observed dilatometer reading for each of the respective temperatures. This theoretical dilatometer reading represents the reading that would be obtained if the dilatometer possessed a pipette of large enough capacity to accommodate the entire expansion of the system.

The seventh column is the differential theoretical dilatometer reading and was obtained by assigning a value of zero to the reading at the initial temperature. The eighth column is the differential expansion of the total amount of water initially in the dilatometer and was obtained by multiplying the total weight of the water by its specific volume for the appropriate temperature and then subtracting the calculated volume at the initial temperature from each succeeding value.

The final column gives the dilatometer expansion in ml and was obtained by subtracting the differential expansion of the water from the final differential dilatometer reading for the appropriate temperatures given in the table. This subtraction resulted in negative numbers, indicating that the dilatometer expands for increasing temperatures.

The final expansion curve for this dilatometer is shown in Figure 47. This curve represents the differential expansion of the dilatometer for the temperature range indicated in the figure. The zero point of the curve was arbitrarily selected at 1.8°C for convenience in performing the calculations. The zero point could be converted to any other temperature by subtracting the dilatometer expansion obtained for that temperature from the expansion value for each successive temperature.

TABLE 9

SPECIFIC VOLUME OF WATER*

T/T°C °C	0.0 ml/g	0.1 ml/g	0.2 ml/g	0.3 ml/g	0.4 ml/g	0.5 ml/g	0.6 ml/g	0.7 ml/g	0.8 ml/g	0.9 ml/g
0	1.0001322	1.0001255	1.0001190	1.0001127	1.0001065	1.0001005	1.0000948	1.0000892	1.0000837	1.0000785
1	0734	0685	0637	0592	0548	0506	0466	0427	0390	0355
2	0320	0289	0259	0230	0204	0179	0156	0134	0113	0095
3	0078	0063	0049	0038	0027	0019	0012	0006	0003	0000
4	0000	0001	0004	0008	0014	0022	0030	0040	0053	0067
5	0081	0098	0117	0137	0159	0182	0206	0232	0259	0288
6	0319	0351	0384	0419	0456	0494	0533	0574	0617	0661
7	0706	0753	0801	0851	0902	0954	1008	1064	1121	1179
8	1239	1300	1362	1426	1491	1558	1626	1696	1767	1839
9	1913	1988	2064	2142	2221	2302	2384	2467	2551	2637
10	2724	2813	2905	2993	3086	3181	3278	3374	3473	3573
11	3674	3776	3881	3985	4091	4199	4308	4417	4529	4641
12	4755	4871	4987	5105	5223	5343	5465	5588	5712	5837
13	5963	6091	6219	6349	6480	6613	6747	6882	7018	7155
14	7293	7433	7574	7716	7859	8003	8149	8296	8444	8592
15	8743	8895	9047	9201	9356	9512	9669	9828	9987	**0149
16	1.0010309	1.0010473	1.0010638	1.0010803	1.0010970	1.0011137	1.0011306	1.0011476	1.0011647	1.0011819
17	1993	2167	2343	2519	2697	2876	3056	3237	3419	3603
18	3787	3973	4160	4348	4537	4727	4918	5110	5303	5498
19	5694	5890	6088	6286	6487	6687	6889	7093	7296	7502
20	7708	7916	8124	8333	8544	8756	8968	9182	9397	9612

* Obtained from the International Critical Tables

TABLE 9 (con't)

T/T°C °C	0.0 ml/g	0.1 ml/g	0.2 ml/g	0.3 ml/g	0.4 ml/g	0.5 ml/g	0.6 ml/g	0.7 ml/g	0.8 ml/g	0.9 ml/g
21	1.0019830	1.0020048	1.0020266	1.0020486	1.0020708	1.0020930	1.0021153	1.0021377	1.0021603	1.0021828
22	2056	2285	2514	2744	2976	3208	3442	3676	3912	4148
23	4386	4624	4864	5104	5346	5589	5832	6077	6322	6569
24	6816	7065	7314	7565	7817	8069	8322	8577	8833	9089
25	1.0029346	1.0029605	1.0029864	1.0030124	1.0030387	1.0030649	1.0030912	1.0031176	1.0031442	1.0031708
26	1974	2243	2512	2782	3052	3325	3598	3871	4146	4422
27	4699	4976	5255	5535	5815	6097	6379	6662	6947	7232
28	7517	7804	8093	8381	8671	8962	9253	9546	8939	**0134
29	1.0040428	1.0040725	1.0041022	1.0041320	1.0041619	1.0041918	1.0042219	1.0042521	1.0042824	1.0043127
30	3432	3736	4043	4350	4658	4966	5277	5587	5898	6211
31	6523	6838	7153	7469	7786	8104	8422	8741	9062	9382
32	1.0049704	1.0050028	1.0050351	1.0050676	1.0051001	1.0051327	1.0051654	1.0051983	1.0052311	1.0052641
33	2972	3303	3636	3969	4303	4637	4973	5310	5647	5985
34	6324	6664	7005	7346	7688	8032	8376	8717	9067	9413
35	1.0059761	1.0060109	1.0060457	1.0060807	1.0061158	1.0061510	1.0061862	1.0062215	1.0062570	1.0062924
36	3279	3636	3993	4351	4710	5070	5430	5791	6153	6516
37	6879	7244	7609	7975	8341	8709	9077	9447	9817	** 0187
38	1.0070559	1.0070932	1.0071304	1.0071678	1.0072052	1.0072428	1.0072804	1.0073181	1.0073559	1.0073938
39	4317	4697	5077	5460	5841	6225	6609	6993	7379	7765
40	8152									

TABLE 10

VOLUMETRIC CALIBRATION DATA

Dilatometer II
Calibration Liquid: Water
Weight of Water: 629.0 g.

Temp. °C	Dil. Reading ml	Amt. Removed ml	Specific Volume of Water ml	Expansion of Removed Amt. ml	Acc. Amt. Removed ml	Final Δ Dil. Reading ml	Δ Exp. of Water ml	Dilatometer Expansion ml
1.8	0.390	0.0	1.0000390	0.0	0.0	0.0	0.0	0.0
4.2	0.360	0.0	1.0000004	0.0	0.0	-0.030	-0.024	-0.006
6.6	0.387	0.0	1.0000533	0.0	0.0	-0.003	0.009	-0.012
8.9	0.465	0.0	1.0001839	0.0	0.0	0.075	0.091	-0.016
11.5	0.598	0.0	1.0004199	0.0	0.0	0.208	0.240	-0.032
14.6	0.829	0.0	1.0008149	0.0	0.0	0.439	0.488	-0.049
17.1	0.443	0.639	1.0012167	0.0	0.639	0.692	0.741	-0.049
19.5	0.718	0.0	1.0016687	0.001	0.639	0.968	1.025	-0.057
21.0	0.907	0.0	1.0019830	0.001	0.639	1.157	1.223	-0.066
23.8	0.620	0.688	1.0026322	0.001	1.327	1.558	1.631	-0.073
25.7	0.900	0.0	1.0031176	0.002	1.327	1.839	1.937	-0.098
27.7	0.539	0.698	1.0036662	0.003	2.025	2.177	2.282	-0.105
29.4	0.829	0.0	1.0041619	0.004	2.025	2.468	2.593	-0.125
31.3	0.580	0.603	1.0047469	0.006	2.628	2.824	2.961	-0.137
33.4	0.971	0.0	1.0054303	0.008	2.628	3.217	3.391	-0.174
36.2	0.772	0.790	1.0063993	0.011	3.418	3.811	4.000	-0.189
38.7	0.742	0.580	1.0073181	0.015	3.998	4.365	4.578	-0.213

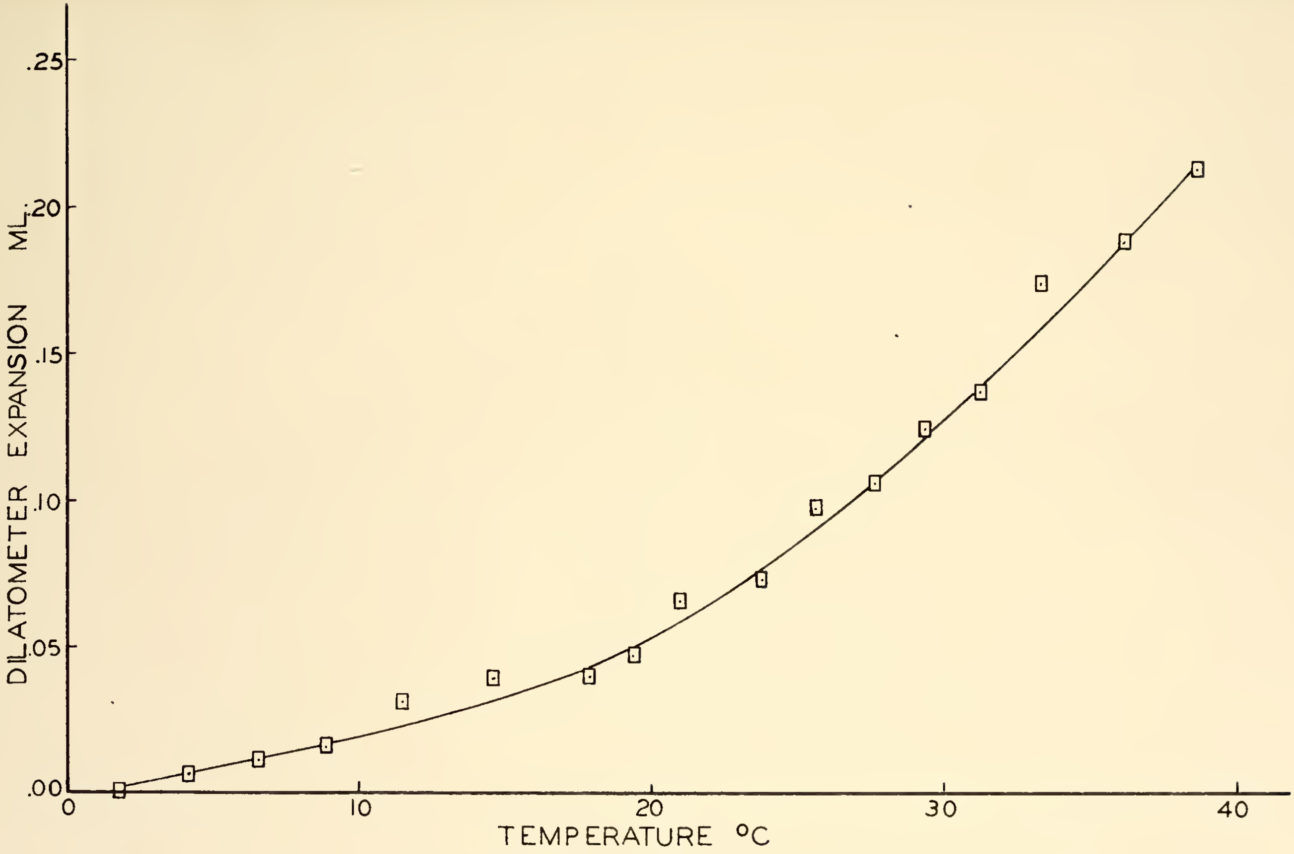

FIG. 47 FINAL CALIBRATION CURVE — DILATOMETER II

APPENDIX B

Calibration Data for Dilatometer III

APPENDIX B

Calibration Data for Dilatometer III

In this section the calibration data obtained for the mercury-filled metal dilatometer are presented. Table 11 contains the specific volume data for mercury that was used in computing the metal dilatometer expansion and subsequently the expansion of specimens tested when using the mercury as the displacement liquid. Table 12 contains the calibration data obtained for this dilatometer. The final dilatometer differential expansion curve appears in Figure 48.

The format of Table 12 is the same as that of Table 10. The same computation procedure as previously used was followed in arriving at the final differential expansion of this dilatometer. The only difference was the substitution of the specific volume values for the mercury in place of the values for the water.

The expansion curve, Figure 48, represents the differential expansion of the metal dilatometer for the temperature range indicated in the figure. The zero point of the curve was arbitrarily selected at - 25.6°C for convenience in performing the calculations. The zero point could be converted to any other temperature in this range by subtracting the reading obtained for that temperature from the expansion value for each successive temperature.

TABLE II

SPECIFIC VOLUME OF MERCURY

THIS TABLE WAS COMPILED FROM THE FOLLOWING FORMULA*

$$V_T = V_0 \left[1 + 10^{-6}\left(181.456T + 0.009205T^2 + 0.000006608T^3 + 0.000000067320T^4\right)\right]$$

WHERE V_T = VOLUME AT DESIRED TEMPERATURE T
V_0 = VOLUME AT 0°C $[V_0 = 0.073554]$
T = TEMPERATURE °C

T TEMP °C	V_T VOL. OF 1 GR IN ML.	T TEMP °C	V_T VOL. OF 1 GR. IN ML	T TEMP. °C	V_T VOL OF 1 GR. IN ML.	T TEMP °C	V_T VOL OF 1 GR IN ML	T TEMP °C	V_T VOL. OF 1 GR IN ML
-33.00	0.07311426	-28.50	0.07317414	-22.40	0.07325536	-16.30	0.07333662	-10.20	0.07341792
-32.90	0.07311559	-28.40	0.07317548	-22.30	0.07325669	-16.20	0.07333795	-10.10	0.07341926
-32.80	0.07311692	-28.30	0.07317680	-22.20	0.07325802	-16.10	0.07333928	-10.00	0.07342059
-32.70	0.07311825	-28.20	0.07317813	-22.10	0.07325935	-16.00	0.07334062	-9.90	0.07342193
-32.60	0.07311958	-28.10	0.07317947	-22.00	0.07326068	-15.90	0.07334195	-9.80	0.07342326
-32.50	0.07312091	-28.00	0.07318079	-21.90	0.07326201	-15.80	0.07334328	-9.70	0.07342459
-32.40	0.07312224	-27.90	0.07318213	-21.80	0.07326335	-15.70	0.07334461	-9.60	0.07342593
-32.30	0.07312357	-27.80	0.07318346	-21.70	0.07326468	-15.60	0.07334594	-9.50	0.07342726
-32.20	0.07312490	-27.70	0.07318479	-21.60	0.07326601	-15.50	0.07334728	-9.40	0.07342859
-32.10	0.07312623	-27.60	0.07318612	-21.50	0.07326734	-15.40	0.07334861	-9.30	0.07342993
-32.00	0.07312756	-27.50	0.07318746	-21.40	0.07326867	-15.30	0.07334995	-9.20	0.07343126
-31.90	0.07312889	-27.40	0.07318878	-21.30	0.07327001	-15.20	0.07335128	-9.10	0.07343259
-31.80	0.07313023	-27.30	0.07319012	-21.20	0.07327134	-15.10	0.07335261	-9.00	0.07343393
-31.70	0.07313155	-27.20	0.07319144	-21.10	0.07327267	-15.00	0.07335394	-8.90	0.07343526
-31.60	0.07313289	-27.10	0.07319278	-21.00	0.07327400	-14.90	0.07335527	-8.80	0.07343659
-31.50	0.07313421	-27.00	0.07319411	-20.90	0.07327534	-14.80	0.07335661	-8.70	0.07343793
-31.40	0.07313555	-26.90	0.07319544	-20.80	0.07327667	-14.70	0.07335794	-8.60	0.07343926
-31.30	0.07313688	-26.80	0.07319677	-20.70	0.07327799	-14.60	0.07335927	-8.50	0.07344060
-31.20	0.07313821	-26.70	0.07319810	-20.60	0.07327933	-14.50	0.07336061	-8.40	0.07344193
-31.10	0.07313954	-26.60	0.07319944	-20.50	0.07328066	-14.40	0.07336194	-8.30	0.07344326
-31.00	0.07314087	-26.50	0.07320076	-20.40	0.07328200	-14.30	0.07336327	-8.20	0.07344460
-30.90	0.07314220	-26.40	0.07320210	-20.30	0.07328332	-14.20	0.07336461	-8.10	0.07344593
-30.80	0.07314353	-26.30	0.07320343	-20.20	0.07328466	-14.10	0.07336593	-8.00	0.07344726
-30.70	0.07314486	-26.20	0.07320476	-20.10	0.07328599	-14.00	0.07336727	-7.90	0.07344860
-30.60	0.07314619	-26.10	0.07320609	-20.00	0.07328732	-13.90	0.07336860	-7.80	0.07344993
-30.50	0.07314752	-26.00	0.07320742	-19.90	0.07328866	-13.80	0.07336994	-7.70	0.07345127
-30.40	0.07314885	-25.90	0.07320875	-19.80	0.07328998	-13.70	0.07337127	-7.60	0.07345260
-30.30	0.07315019	-25.80	0.07321008	-19.70	0.07329132	-13.60	0.07337260	-7.50	0.07345393
-30.20	0.07315151	-25.70	0.07321142	-19.60	0.07329265	-13.50	0.07337394	-7.40	0.07345527
-30.10	0.07315285	-25.60	0.07321274	-19.50	0.07329398	-13.40	0.07337527	-7.30	0.07345660
-30.00	0.07315417	-25.50	0.07321408	-19.40	0.07329532	-13.30	0.07337660	-7.20	0.07345793
-29.90	0.07315551	-25.40	0.07321541	-19.30	0.07329664	-13.20	0.07337793	-7.10	0.07345927
-29.80	0.07315684	-25.30	0.07321674	-19.20	0.07329798	-13.10	0.07337926	-7.00	0.07346060
-29.70	0.07315817	-25.20	0.07321807	-19.10	0.07329931	-13.00	0.07338060	-6.90	0.07346193
-29.60	0.07315950	-25.10	0.07321940	-19.00	0.07330064	-12.90	0.07338193	-6.80	0.07346327
-29.50	0.07316083	-25.00	0.07322074	-18.90	0.07330198	-12.80	0.07338326	-6.70	0.07346460
-29.40	0.07316216	-24.90	0.07322206	-18.80	0.07330330	-12.70	0.07338460	-6.60	0.07346594
-29.30	0.07316349	-24.80	0.07322340	-18.70	0.07330464	-12.60	0.07338593	-6.50	0.07346727
-29.20	0.07316482	-24.70	0.07322473	-18.60	0.07330597	-12.50	0.07338727	-6.40	0.07346860
-29.10	0.07316615	-24.60	0.07322606	-18.50	0.07330731	-12.40	0.07338860	-6.30	0.07346994
-29.00	0.07316749	-24.50	0.07322739	-18.40	0.07330864	-12.30	0.07338993	-6.20	0.07347127
-28.90	0.07316881	-24.40	0.07322872	-18.30	0.07330997	-12.20	0.07339127	-6.10	0.07347260
-28.80	0.07317015	-24.30	0.07323006	-18.20	0.07331130	-12.10	0.07339260	-6.00	0.07347394
-28.70	0.07317148	-24.20	0.07323138	-18.10	0.07331263	-12.00	0.07339393	-5.90	0.07347527
-28.60	0.07317281	-24.10	0.07323272	-18.00	0.07331397	-11.90	0.07339526	-5.80	0.07347661
		-24.00	0.07323405	-17.90	0.07331530	-11.80	0.07339659	-5.70	0.07347794
		-23.90	0.07323538	-17.80	0.07331663	-11.70	0.07339793	-5.60	0.07347927
		-23.80	0.07323671	-17.70	0.07331796	-11.60	0.07339926	-5.50	0.07348061
		-23.70	0.07323804	-17.60	0.07331929	-11.50	0.07340059	-5.40	0.07348194
		-23.60	0.07323938	-17.50	0.07332063	-11.40	0.07340193	-5.30	0.07348327
		-23.50	0.07324070	-17.40	0.07332196	-11.30	0.07340326	-5.20	0.07348461
		-23.40	0.07324204	-17.30	0.07332329	-11.20	0.07340460	-5.10	0.07348594
		-23.30	0.07324337	-17.20	0.07332463	-11.10	0.07340593	-5.00	0.07348727
		-23.20	0.07324470	-17.10	0.07332595	-11.00	0.07340726	-4.90	0.07348861
		-23.10	0.07324603	-17.00	0.07332729	-10.90	0.07340860	-4.80	0.07348995
		-23.00	0.07324737	-16.90	0.07332862	-10.80	0.07340993	-4.70	0.07349128
		-22.90	0.07324870	-16.80	0.07332996	-10.70	0.07341126	-4.60	0.07349262
		-22.80	0.07325003	-16.70	0.07333129	-10.60	0.07341260	-4.50	0.07349395
		-22.70	0.07325136	-16.60	0.07333262	-10.50	0.07341393	-4.40	0.07349528
		-22.60	0.07325269	-16.50	0.07333395	-10.40	0.07341526	-4.30	0.07349662
		-22.50	0.07325403	-16.40	0.07333528	-10.30	0.07341659	-4.20	0.07349795

* OBTAINED FROM THE INTERNATIONAL CRITICAL TABLES.

TABLE II CON'T

T TEMP °C	V_T VOL OF I GR. IN ML	T TEMP °C	V_T VOL OF I GR IN ML	T TEMP. °C	V_T VOL OF I GR IN ML.	T TEMP °C	V_T VOL OF I GR IN ML	T TEMP °C	V_T VOL OF I GR IN ML
-4.10	0.07349928	2.00	0.07358069	8.10	0.07366215	14.20	0.07374366	20.30	0.07382523
-4.00	0.07350062	2.10	0.07358203	8.20	0.07366349	14.30	0.07374500	20.40	0.07382656
-3.90	0.07350195	2.20	0.07358336	8.30	0.07366482	14.40	0.07374633	20.50	0.07382790
-3.80	0.07350329	2.30	0.07358470	8.40	0.07366616	14.50	0.07374767	20.60	0.07382923
-3.70	0.07350462	2.40	0.07358603	8.50	0.07366749	14.60	0.07374901	20.70	0.07383057
-3.60	0.07350595	2.50	0.07358737	8.60	0.07366883	14.70	0.07375035	20.80	0.07383191
-3.50	0.07350729	2.60	0.07358870	8.70	0.07367016	14.80	0.07375168	20.90	0.07383325
-3.40	0.07350862	2.70	0.07359004	8.80	0.07367150	14.90	0.07375301	21.00	0.07383458
-3.30	0.07350995	2.80	0.07359137	8.90	0.07367284	15.00	0.07375436	21.10	0.07383592
-3.20	0.07351130	2.90	0.07359271	9.00	0.07367417	15.10	0.07375569	21.20	0.07383726
-3.10	0.07351263	3.00	0.07359404	9.10	0.07367551	15.20	0.07375702	21.30	0.07383860
-3.00	0.07351396	3.10	0.07359537	9.20	0.07367685	15.30	0.07375836	21.40	0.07383994
-2.90	0.07351530	3.20	0.07359672	9.30	0.07367818	15.40	0.07375970	21.50	0.07384127
-2.80	0.07351663	3.30	0.07359805	9.40	0.07367951	15.50	0.07376104	21.60	0.07384261
-2.70	0.07351796	3.40	0.07359938	9.50	0.07368085	15.60	0.07376237	21.70	0.07384395
-2.60	0.07351930	3.50	0.07360072	9.60	0.07368219	15.70	0.07376371	21.80	0.07384529
-2.50	0.07352063	3.60	0.07360205	9.70	0.07368352	15.80	0.07376505	21.90	0.07384662
-2.40	0.07352196	3.70	0.07360339	9.80	0.07368486	15.90	0.07376639	22.00	0.07384796
-2.30	0.07352330	3.80	0.07360473	9.90	0.07368620	16.00	0.07376772	22.10	0.07384931
-2.20	0.07352463	3.90	0.07360606	10.00	0.07368753	16.10	0.07376906	22.20	0.07385064
-2.10	0.07352597	4.00	0.07360739	10.10	0.07368887	16.20	0.07377040	22.30	0.07385198
-2.00	0.07352731	4.10	0.07360873	10.20	0.07369021	16.30	0.07377173	22.40	0.07385332
-1.90	0.07352864	4.20	0.07361007	10.30	0.07369154	16.40	0.07377307	22.50	0.07385466
-1.80	0.07352997	4.30	0.07361140	10.40	0.07369287	16.50	0.07377440	22.60	0.07385599
-1.70	0.07353131	4.40	0.07361273	10.50	0.07369421	16.60	0.07377575	22.70	0.07385733
-1.60	0.07353264	4.50	0.07361407	10.60	0.07369555	16.70	0.07377709	22.80	0.07385866
-1.50	0.07353397	4.60	0.07361540	10.70	0.07369689	16.80	0.07377842	22.90	0.07386000
-1.40	0.07353531	4.70	0.07361674	10.80	0.07369822	16.90	0.07377975	23.00	0.07386134
-1.30	0.07353664	4.80	0.07361808	10.90	0.07369956	17.00	0.07378110	23.10	0.07386268
-1.20	0.07353798	4.90	0.07361941	11.00	0.07370089	17.10	0.07378243	23.20	0.07386402
-1.10	0.07353932	5.00	0.07362074	11.10	0.07370223	17.20	0.07378376	23.30	0.07386536
-1.00	0.07354065	5.10	0.07362209	11.20	0.07370356	17.30	0.07378510	23.40	0.07386670
-0.90	0.07354198	5.20	0.07362342	11.30	0.07370490	17.40	0.07378644	23.50	0.07386804
-0.80	0.07354332	5.30	0.07362475	11.40	0.07370624	17.50	0.07378778	23.60	0.07386937
-0.70	0.07354465	5.40	0.07362609	11.50	0.07370757	17.60	0.07378911	23.70	0.07387071
-0.60	0.07354598	5.50	0.07362742	11.60	0.07370891	17.70	0.07379045	23.80	0.07387204
-0.50	0.07354732	5.60	0.07362876	11.70	0.07371025	17.80	0.07379179	23.90	0.07387338
-0.40	0.07354866	5.70	0.07363009	11.80	0.07371158	17.90	0.07379313	24.00	0.07387472
-0.30	0.07354999	5.80	0.07363143	11.90	0.07371292	18.00	0.07379446	24.10	0.07387606
-0.20	0.07355133	5.90	0.07363277	12.00	0.07371426	18.10	0.07379580	24.20	0.07387740
-0.10	0.07355266	6.00	0.07363410	12.10	0.07371559	18.20	0.07379714	24.30	0.07387874
0.	0.07355399	6.10	0.07363544	12.20	0.07371693	18.30	0.07379848	24.40	0.07388008
0.10	0.07355533	6.20	0.07363677	12.30	0.07371826	18.40	0.07379981	24.50	0.07388142
0.20	0.07355667	6.30	0.07363810	12.40	0.07371960	18.50	0.07380115	24.60	0.07388275
0.30	0.07355800	6.40	0.07363945	12.50	0.07372094	18.60	0.07380249	24.70	0.07388409
0.40	0.07355934	6.50	0.07364078	12.60	0.07372227	18.70	0.07380383	24.80	0.07388543
0.50	0.07356067	6.60	0.07364211	12.70	0.07372361	18.80	0.07380516	24.90	0.07388677
0.60	0.07356200	6.70	0.07364345	12.80	0.07372495	18.90	0.07380650	25.00	0.07388811
0.70	0.07356334	6.80	0.07364479	12.90	0.07372628	19.00	0.07380784	25.10	0.07388944
0.80	0.07356467	6.90	0.07364612	13.00	0.07372762	19.10	0.07380918	25.20	0.07389078
0.90	0.07356600	7.00	0.07364745	13.10	0.07372896	19.20	0.07381051	25.30	0.07389212
1.00	0.07356735	7.10	0.07364880	13.20	0.07373029	19.30	0.07381184	25.40	0.07389346
1.10	0.07356868	7.20	0.07365013	13.30	0.07373163	19.40	0.07381319	25.50	0.07389480
1.20	0.07357001	7.30	0.07365146	13.40	0.07373296	19.50	0.07381453	25.60	0.07389613
1.30	0.07357135	7.40	0.07365280	13.50	0.07373431	19.60	0.07381586	25.70	0.07389747
1.40	0.07357268	7.50	0.07365414	13.60	0.07373564	19.70	0.07381720	25.80	0.07389881
1.50	0.07357401	7.60	0.07365547	13.70	0.07373697	19.80	0.07381853	25.90	0.07390015
1.60	0.07357536	7.70	0.07365680	13.80	0.07373831	19.90	0.07381988	26.00	0.07390149
1.70	0.07357669	7.80	0.07365815	13.90	0.07373965	20.00	0.07382121	26.10	0.07390283
1.80	0.07357802	7.90	0.07365948	14.00	0.07374099	20.10	0.07382255	26.20	0.07390416
1.90	0.07357936	8.00	0.07366081	14.10	0.07374232	20.20	0.07382388	26.30	0.07390551

TABLE II CON'T

T TEMP °C	V_T VOL. OF 1 GR IN ML	T TEMP °C	V_T VOL. OF 1 GR IN ML	T TEMP. °C	V_T VOL OF 1 GR IN ML.	T TEMP °C	V_T VOL OF 1 GR IN ML	T TEMP °C	V_T VOL OF 1 GR IN ML
26.40	0.07390685	32.50	0.07398852	38.60	0.07407026	44.70	0.07415206		
26.50	0.07390818	32.60	0.07398986	38.70	0.07407160	44.80	0.07415340		
26.60	0.07390952	32.70	0.07399120	38.80	0.07407294	44.90	0.07415474		
26.70	0.07391086	32.80	0.07399254	38.90	0.07407428	45.00	0.07415608		
26.80	0.07391220	32.90	0.07399388	39.00	0.07407562	45.10	0.07415742		
26.90	0.07391354	33.00	0.07399522	39.10	0.07407696	45.20	0.07415877		
27.00	0.07391487	33.10	0.07399656	39.20	0.07407830	45.30	0.07416011		
27.10	0.07391621	33.20	0.07399790	39.30	0.07407964	45.40	0.07416145		
27.20	0.07391755	33.30	0.07399923	39.40	0.07408098	45.50	0.07416279		
27.30	0.07391889	33.40	0.07400057	39.50	0.07408232	45.60	0.07416413		
27.40	0.07392023	33.50	0.07400192	39.60	0.07408366	45.70	0.07416547		
27.50	0.07392157	33.60	0.07400326	39.70	0.07408500	45.80	0.07416681		
27.60	0.07392290	33.70	0.07400459	39.80	0.07408635	45.90	0.07416815		
27.70	0.07392424	33.80	0.07400593	39.90	0.07408769	46.00	0.07416949		
27.80	0.07392558	33.90	0.07400727	40.00	0.07408903	46.10	0.07417084		
27.90	0.07392692	34.00	0.07400861	40.10	0.07409037	46.20	0.07417218		
28.00	0.07392826	34.10	0.07400995	40.20	0.07409171	46.30	0.07417352		
28.10	0.07392960	34.20	0.07401130	40.30	0.07409305	46.40	0.07417487		
28.20	0.07393094	34.30	0.07401264	40.40	0.07409438	46.50	0.07417621		
28.30	0.07393228	34.40	0.07401397	40.50	0.07409573	46.60	0.07417755		
28.40	0.07393362	34.50	0.07401531	40.60	0.07409707	46.70	0.07417889		
28.50	0.07393496	34.60	0.07401665	40.70	0.07409841	46.80	0.07418023		
28.60	0.07393629	34.70	0.07401799	40.80	0.07409975	46.90	0.07418157		
28.70	0.07393763	34.80	0.07401934	40.90	0.07410109	47.00	0.07418291		
28.80	0.07393897	34.90	0.07402067	41.00	0.07410243	47.10	0.07418426		
28.90	0.07394031	35.00	0.07402201	41.10	0.07410377	47.20	0.07418560		
29.00	0.07394165	35.10	0.07402335	41.20	0.07410511	47.30	0.07418694		
29.10	0.07394299	35.20	0.07402469	41.30	0.07410645	47.40	0.07418828		
29.20	0.07394432	35.30	0.07402603	41.40	0.07410780	47.50	0.07418963		
29.30	0.07394566	35.40	0.07402737	41.50	0.07410914	47.60	0.07419097		
29.40	0.07394700	35.50	0.07402871	41.60	0.07411048	47.70	0.07419231		
29.50	0.07394835	35.60	0.07403005	41.70	0.07411182	47.80	0.07419365		
29.60	0.07394968	35.70	0.07403139	41.80	0.07411316	47.90	0.07419499		
29.70	0.07395102	35.80	0.07403273	41.90	0.07411450	48.00	0.07419634		
29.80	0.07395236	35.90	0.07403407	42.00	0.07411584	48.10	0.07419768		
29.90	0.07395370	36.00	0.07403541	42.10	0.07411718	48.20	0.07419902		
30.00	0.07395504	36.10	0.07403675	42.20	0.07411852	48.30	0.07420036		
30.10	0.07395638	36.20	0.07403809	42.30	0.07411987	48.40	0.07420170		
30.20	0.07395772	36.30	0.07403943	42.40	0.07412121	48.50	0.07420304		
30.30	0.07395906	36.40	0.07404077	42.50	0.07412255	48.60	0.07420439		
30.40	0.07396039	36.50	0.07404211	42.60	0.07412389	48.70	0.07420573		
30.50	0.07396173	36.60	0.07404345	42.70	0.07412523	48.80	0.07420707		
30.60	0.07396308	36.70	0.07404479	42.80	0.07412657	48.90	0.07420842		
30.70	0.07396441	36.80	0.07404613	42.90	0.07412791	49.00	0.07420976		
30.80	0.07396575	36.90	0.07404747	43.00	0.07412925	49.10	0.07421110		
30.90	0.07396709	37.00	0.07404881	43.10	0.07413059	49.20	0.07421244		
31.00	0.07396843	37.10	0.07405015	43.20	0.07413194	49.30	0.07421378		
31.10	0.07396977	37.20	0.07405149	43.30	0.07413328	49.40	0.07421513		
31.20	0.07397111	37.30	0.07405283	43.40	0.07413462	49.50	0.07421647		
31.30	0.07397245	37.40	0.07405417	43.50	0.07413596	49.60	0.07421781		
31.40	0.07397379	37.50	0.07405552	43.60	0.07413730	49.70	0.07421915		
31.50	0.07397512	37.60	0.07405686	43.70	0.07413864	49.80	0.07422049		
31.60	0.07397646	37.70	0.07405820	43.80	0.07413998	49.90	0.07422183		
31.70	0.07397781	37.80	0.07405953	43.90	0.07414132	50.00	0.07422318		
31.80	0.07397915	37.90	0.07406087	44.00	0.07414266				
31.90	0.07398048	38.00	0.07406221	44.10	0.07414401				
32.00	0.07398182	38.10	0.07406355	44.20	0.07414535				
32.10	0.07398316	38.20	0.07406490	44.30	0.07414669				
32.20	0.07398450	38.30	0.07406624	44.40	0.07414803				
32.30	0.07398584	38.40	0.07406758	44.50	0.07414937				
32.40	0.07398718	38.50	0.07406892	44.60	0.07415072				

TABLE 12

VOLUMETRIC CALIBRATION DATA

Dilatometer III
Calibration Liquid: Mercury
Weight of Mercury: 7757.5 g.

Temp. $^{\circ}$C	Dil. Reading ml	Amt. Removed ml	Specific Volume of Mercury ml	Expansion of Removed Amt. ml	Acc. Amt. Removed ml	Final Δ Dil. Reading ml	Δ Exp. of Mercury ml	Dilatometer Expansion ml
-25.6	0.081	0.0	0.07319810	0.0	0.0	0.0	0.0	0.0
-15.8	0.860	0.0	0.07333795	0.0	0.0	0.779	1.085	-0.306
- 8.9	0.541	0.818	0.07342993	0.001	0.818	1.279	1.799	-0.520
- 3.9	0.931	0.0	0.07350195	0.002	0.818	1.670	2.357	-0.687
6.4	0.781	0.891	0.07363945	0.005	1.709	2.414	2.357	-1.010
13.8	0.550	0.770	0.07373831	0.008	2.479	2.956	3.424	-1.235
19.9	1.000	0.0	0.07381988	0.010	2.479	3.408	4.824	-1.416
25.5	0.421	0.979	0.07389480	0.015	3.458	3.813	5.405	-1.592
31.7	0.859	0.0	0.07397781	0.019	3.458	4.255	6.049	-1.794
39.0	0.571	0.827	0.07407562	0.024	4.285	4.799	6.808	-2.009

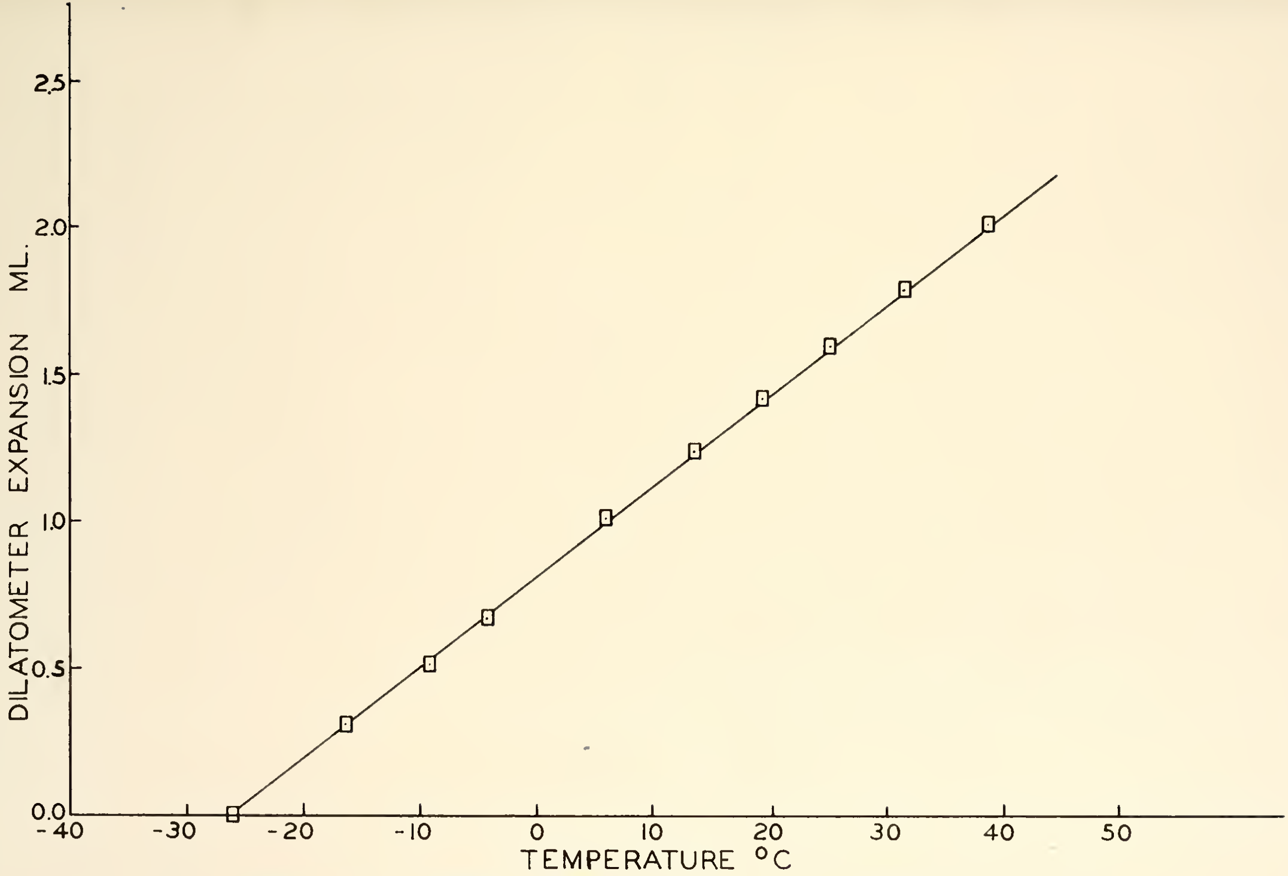

FIG. 48 FINAL CALIBRATION CURVE—DILATOMETER III

APPENDIX C

Volumetric Data

APPENDIX C

Volumetric Data

In this section is presented the data for the volumetric phase of this investigation. The data are catalogued according to measuring technique employed and according to the variables composing the different specimens.

The computation procedure used in obtaining the differential expansion of the specimens is similar to that used in computing the differential expansion of the respective dilatometers. The calculations and table format are the same for all the specimens tested by the two different volumetric methods. The following discussion is presented to clarify the calculations used in processing the volumetric data and reference is made to the form of the tables in this section.

The first three columns have previously been discussed while outlining the computational procedure used for the respective dilatometer calibrations. The fourth column contains the cumulative amount of liquid absorbed by the specimen after equilibrium conditions had been reached. The tabular location of this value, like the value for the removed amount, occurs one temperature reading higher than it was recorded because it affects all subsequent readings and not the reading at which it was absorbed.

The fifth column contains the specific volume of the appropriate displacement liquid. The sixth column contains the calculated expansion of the removed displacement liquid. The expansion of the removed amount of displacement liquid was calculated by the formula:

$$\text{Expansion of amount removed} = [(1/d) - (1/d)'] \text{ (volume of removed amount) } [1/(1/d)']$$

where:

$(1/d)$ = specific volume of the appropriate displacement liquid at the new equilibrium temperature.

$(1/d)'$ = specific volume of the appropriate displacement liquid at the removal temperature.

The seventh column presents the theoretical dilatometer readings which were obtained by adding the observed dilatometer reading to the cumulative amount removed, and the cumulative expansion of the amount removed for the respective temperatures. The eighth column is the differential theoretical dilatometer reading. The ninth column contains the differential expansion of the total weight of the displacement liquid. This was obtained by multiplying the total weight of liquid, initially placed in the dilatometer, by its specific volume for the respective temperatures and then subtracting the calculated volume for the initial temperature from each succeeding value.

The tenth column contains the differential dilatometer expansion values obtained from Figures 47 and 48 for the glass and metal dilatometers respectively. The last column contains the differential specimen expansion. These values were obtained by adding the differential dilatometer expansion to the differential theoretical dilatometer reading and then subtracting the differential expansion of the displacement liquid.

TABLE 13

VOLUMETRIC EXPANSION DATA

Dilatometer II
4.0% A.C.; 60-70 Pen.; Limestone
Coating: Asphalt
Density: 148.8 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume H_2O ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. H_2O ml	Δ Exp. Dil. ml	Sample Expansion ml
1.5	0.285	0.0	0.0	1.0000506	0.0	0.285	0.0	0.0	0.0	0.0
6.4	0.440	0.0	0.042	1.0000456	0.0	0.482	0.197	0.0	0.010	0.207
14.6	0.862	0.0	0.067	1.0008149	0.0	0.929	0.634	0.096	0.038	0.576
20.6	0.852	0.460	0.069	1.0018968	0.005	1.386	1.101	0.232	0.065	0.934

Volume of Specimen 502.0 ml   Weight of Water 125.5 gm

TABLE 14

VOLUMETRIC EXPANSION DATA

Dilatometer II
4.0% A.C.; 85-100 Pen.; Limestone
Coating: Nat. Latex
Density: 150.0 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume H_2O ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. H_2O ml	Δ Exp. Dil. ml	Sample Expansion ml
1.6	0.395	0.0	0.0	1.0000466	0.0	0.395	0.0	0.0	0.0	0.0
6.8	0.562	0.0	0.0	1.0000617	0.0	0.562	0.167	0.001	0.012	0.178
13.3	0.980	0.0	0.012	1.0006349	0.0	0.992	0.597	0.064	0.034	0.567
20.9	0.835	0.642	0.102	1.0019612	0.001	1.580	1.185	0.209	0.067	1.043
27.5	0.965	0.642	0.317	1.0036097	0.002	1.926	1.531	0.388	0.107	1.259
35.6	0.970	1.367	0.327	1.0061862	0.005	2.669	2.274	0.669	0.188	1.793

Volume of Specimen 514.5 ml   Weight of Water 109.0 gm

TABLE 15

VOLUMETRIC EXPANSION DATA

Dilatometer II
4.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.5 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume H_2O ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. H_2O ml	Δ Exp. Dil. ml	Sample Expansion ml
1.8	0.110	0.0	0.0	1.0000390	0.0	0.110	0.0	0.0	0.0	0.0
10.8	0.440	0.0	0.0	1.0003473	0.0	0.440	0.330	0.036	0.024	0.318
20.6	0.906	0.0	0.010	1.0018968	0.0	0.916	0.806	0.216	0.065	0.655
29.3	0.982	0.0	0.577	1.0041320	0.0	1.559	1.449	0.475	0.123	1.097
36.7	0.935	0.738	0.629	1.0065791	0.002	2.294	2.184	0.759	0.198	1.623

Volume of Specimen 509.0 ml   Weight of Water 116.0 gm

TABLE 16

VOLUMETRIC EXPANSION DATA

Dilatometer II
4.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 150.3 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume H_2O ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. H_2O ml	Δ Exp. Dil. ml	Sample Expansion ml
3.2	0.430	0.0	0.0	1.0000049	0.0	0.430	0.0	0.0	0.0	0.0
7.1	0.550	0.0	0.005	1.0000753	0.0	0.555	0.125	0.008	0.015	0.132
15.7	0.870	0.0	0.025	1.0009828	0.0	0.895	0.465	0.117	0.041	0.389
21.8	0.662	0.398	0.127	1.0021603	0.0	1.182	0.752	0.258	0.070	0.564
27.8	0.978	0.398	0.134	1.0036947	0.001	1.519	1.089	0.442	0.111	0.758

Volume of Specimen 502.5 ml   Weight of Water 120.0 gm

TABLE 17

VOLUMETRIC EXPANSION DATA

Dilatometer II
5.0% A.C.; 85-100 Pen.; Limestone
Coating: - Syn. Latex
Density: 151.5 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume H_2O ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. H_2O ml	Δ Exp. Dil. ml	Sample Expansion ml
1.4	0.579	0.0	0.0	1.0000548	0.0	0.579	0.0	0.0	0.0	0.0
6.2	0.725	0.0	0.0	1.0000384	0.0	0.725	0.146	-0.002	0.010	0.158
14.8	0.630	0.475	0.065	1.0008444	0.0	1.170	0.591	0.091	0.040	0.540
22.3	1.045	0.475	0.075	1.0022744	0.001	1.590	1.017	0.259	0.074	0.832
26.9	0.698	1.128	0.090	1.0034422	0.003	1.919	1.340	0.394	0.103	1.049
31.3	0.982	1.128	0.106	1.0047469	0.004	2.220	1.641	0.545	0.143	1.289

Volume of Specimen 510.0 ml   Weight of Water 115.0 gm

TABLE 18

VOLUMETRIC EXPANSION DATA

Dilatometer III
4.0% A.C.; 60-70 Pen.; Limestone
Coating: Asphalt
Density: 148.3 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-30.7	0.045	0.0	0.0	0.07314486	0.0	0.045	0.0	0.0	0.0	0.0
-21.5	0.188	0.0	0.0	0.07326734	0.0	0.188	0.143	0.116	0.287	0.314
-12.3	0.315	0.0	0.0	0.07338993	0.0	0.315	0.270	0.231	0.588	0.627
- 4.0	0.401	0.0	0.032	0.07350062	0.0	0.433	0.388	0.336	0.840	0.892
1.5	0.442	0.0	0.046	0.07357401	0.0	0.488	0.443	0.405	1.012	1.050
6.4	0.091	0.308	0.170	0.07363945	0.0	0.569	0.524	0.467	1.165	1.222
14.6	0.180	0.308	0.173	0.07374901	0.001	0.662	0.617	0.570	1.416	1.463
20.6	0.200	0.308	0.203	0.07382923	0.001	0.712	0.667	0.646	1.603	1.624
24.7	0.211	0.308	0.221	0.07388409	0.001	0.741	0.696	0.698	1.729	1.727
34.3	0.108	0.308	0.382	0.07401264	0.002	0.800	0.755	0.819	1.928	1.864

Volume of Specimen 503.5 ml   Weight of Mercury 943.5 gm

TABLE 19

VOLUMETRIC EXPANSION DATA

Dilatometer III
5.0% A.C.; 60-70 Pen.; Limestone
Coating: None
Density: 151.0 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-21.0	0.002	0.0	0.003	0.07327400	0.0	0.005	0.0	0.0	0.0	0.0
-17.5	0.050	0.0	0.003	0.07332063	0.0	0.053	0.048	0.043	0.109	0.114
-11.4	0.140	0.0	0.012	0.07340193	0.0	0.152	0.147	0.119	0.302	0.330
- 3.1	0.205	0.0	0.092	0.07351263	0.0	0.297	0.292	0.223	0.562	0.631
3.6	0.251	0.0	0.094	0.07360205	0.0	0.345	0.340	0.312	0.776	0.904
15.5	0.365	0.0	0.125	0.07376104	0.0	0.490	0.485	0.457	1.144	1.172
21.2	0.349	0.0	0.184	0.07383726	0.0	0.533	0.528	0.529	1.323	1.322
33.9	0.370	0.0	0.210	0.07400727	0.0	0.580	0.575	0.688	1.712	1.599

Volume of Specimen 498.0 ml   Weight of Mercury 937.5 gm

TABLE 20

VOLUMETRIC EXPANSION DATA

Dilatometer III
3.6% A.C.; 85-100 Pen.; Limestone
Coating: Syn. Latex
Density: 147.9 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-30.0	0.220	0.0	0.0	0.07315417	0.0	0.220	0.0	0.0	0.0	0.0
-15.6	0.405	0.0	0.0	0.07334594	0.0	0.405	0.185	0.187	0.456	0.454
- 6.0	0.520	0.0	0.017	0.07347394	0.0	0.537	0.317	0.301	0.743	0.759
1.4	0.143	0.505	0.017	0.07357268	0.001	0.660	0.446	0.389	0.968	1.025
8.0	0.208	0.505	0.032	0.07366081	0.001	0.746	0.526	0.467	1.187	1.246
20.8	0.182	0.505	0.175	0.07383191	0.002	0.864	0.644	0.619	1.587	1.612

Volume of Specimen 524.5 ml Weight of Mercury 889.5 gm

TABLE 21

VOLUMETRIC EXPANSION DATA

Dilatometer III
4.0% A.C.; 85-100 Pen.; Limestone
Coating: Nat. Latex
Density: 149.4 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-31.2	0.073	0.0	0.0	0.07313821	0.0	0.073	0.0	0.0	0.0	0.0
-13.2	0.406	0.0	0.0	0.07337793	0.0	0.406	0.333	0.190	0.607	0.750
- 4.0	0.295	0.377	0.0	0.07350062	0.001	0.673	0.600	0.289	0.907	1.218
1.7	0.450	0.377	0.017	0.07357669	0.001	0.845	0.772	0.348	1.072	1.496
6.8	0.350	0.377	0.277	0.07364479	0.001	1.005	0.932	0.400	1.224	1.756
13.5	0.518	0.377	0.297	0.07373431	0.002	1.194	1.121	0.469	1.449	2.101
20.9	0.182	0.752	0.375	0.07383325	0.003	1.309	1.236	0.545	1.674	2.365
27.5	0.070	0.752	0.535	0.07392157	0.003	1.357	1.284	0.614	1.887	2.557

Volume of Specimen 517.0 ml Weight of Mercury 778.7 gm

TABLE 22

VOLUMETRIC EXPANSION DATA

Dilatometer III
4.5% A.C.; 85-100 Pen. Limestone
Coating: None
Density: 151.5 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-25.3	0.061	0.0	0.0	0.07321674	0.0	0.061	0.0	0.0	0.0	0.0
-16.0	0.195	0.0	0.0	0.07334062	0.0	0.165	0.134	0.096	0.287	0.325
- 7.8	0.331	0.0	0.0	0.07344993	0.0	0.331	0.270	0.193	0.550	0.627
1.8	0.480	0.0	0.0	0.07357802	0.0	0.480	0.419	0.299	0.850	0.970
10.8	0.543	0.0	0.060	0.07369822	0.0	0.603	0.542	0.398	1.143	1.287
20.6	0.601	0.0	0.082	0.07382923	0.0	0.683	0.622	0.507	1.450	1.565
29.7	0.440	0.0	0.323	0.07395102	0.0	0.763	0.702	0.607	1.737	1.832
36.7	0.370	0.0	0.423	0.07404479	0.0	0.793	0.732	0.685	1.950	1.997

Volume of Specimen 508.0 ml   Weight of Mercury 827.5 gm

TABLE 23

VOLUMETRIC EXPANSION DATA

Dilatometer III
5.0% A.C.; 85-100 Pen.; Limestone
Coating: Syn. Latex
Density: 150.9 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-24.2	0.053	0.0	0.0	0.07323138	0.0	0.053	0.0	0.0	0.0	0.0
-12.7	0.272	0.0	0.0	0.07338460	0.0	0.272	0.219	0.119	0.363	0.463
- 5.3	0.422	0.0	0.0	0.07348327	0.0	0.422	0.369	0.194	0.600	0.775
1.4	0.552	0.0	0.0	0.07357268	0.0	0.552	0.499	0.261	0.813	1.051
6.2	0.591	0.0	0.0	0.07363677	0.0	0.591	0.538	0.308	0.956	1.186
14.8	0.169	0.500	0.0	0.07375168	0.001	0.670	0.617	0.392	1.233	1.458
22.6	0.160	0.500	0.071	0.07385599	0.001	0.732	0.679	0.468	1.475	1.686

Volume of Specimen 512.0 ml   Weight of Mercury 733.5 gm

TABLE 24

VOLUMETRIC EXPANSION DATA

Dilatometer III
3.6% A.C.; 85-100 Pen.; Gravel
Coating: Syn. Latex
Density: 149.8 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-23.2	0.191	0.0	0.0	0.07324470	0.0	0.191	0.0	0.0	0.0	0.0
-18.4	0.210	0.0	0.0	0.07330864	0.0	0.210	0.019	0.061	0.145	0.103
-14.7	0.219	0.0	0.029	0.07335794	0.0	0.248	0.057	0.109	0.270	0.218
- 6.2	0.335	0.0	0.033	0.07347127	0.0	0.368	0.177	0.218	0.538	0.497
1.2	0.415	0.0	0.048	0.07357001	0.0	0.463	0.272	0.313	0.775	0.734
4.9	0.289	0.0	0.219	0.07361941	0.0	0.498	0.307	0.360	0.890	0.837
11.3	0.352	0.0	0.228	0.07370490	0.0	0.580	0.389	0.442	1.085	1.032
15.6	0.340	0.0	0.270	0.07376237	0.0	0.610	0.419	0.498	1.215	1.136
21.6	0.291	0.0	0.358	0.07384261	0.0	0.649	0.458	0.575	1.402	1.285

Volume of Specimen 495.5 ml   Weight of Mercury 961.0 gm

TABLE 25

VOLUMETRIC EXPANSION DATA

Dilatometer III
5.0% A.C.; 85-100 Pen.; Gravel
Coating: None
Density: 151.0 pcf.

Temp. °C	Dil. Reading ml	Cum. Removed Amt. ml	Cum. Absorbed Amt. ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Sample Expansion ml
-22.6	0.310	0.0	0.0	0.07325269	0.0	0.310	0.0	0.0	0.0	0.0
-15.0	0.475	0.0	0.0	0.07335394	0.0	0.475	0.165	0.099	0.241	0.307
- 8.1	0.592	0.0	0.044	0.07344593	0.0	0.636	0.326	0.188	0.459	0.597
1.5	0.799	0.0	0.048	0.07357401	0.0	0.847	0.537	0.312	0.761	0.986
7.7	0.158	0.743	0.097	0.07365680	0.001	0.999	0.689	0.393	0.954	1.250
16.1	0.215	0.743	0.128	0.07376906	0.002	1.088	0.778	0.502	1.209	1.485
25.1	0.182	0.743	0.207	0.07388944	0.003	1.135	0.824	0.619	1.489	1.695
33.8	0.477	0.743	0.254	0.07400593	0.004	1.178	0.868	0.732	1.759	1.895

Volume of Specimen 496.0 ml   Weight of Mercury 972.0 gm

APPENDIX D

Linear Data

APPENDIX D

Linear Data

In this section is presented the data obtained from the linear specimens. The data are catalogued according to measuring technique employed and according to the variables composing the different specimens. The final linear expansion was obtained by averaging the results of two gage lines for each specimen.

TABLE 26

LINEAR EXPANSION DATA

5-inch Stainless Steel Strain Gage
4.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.5 pcf

Temp. °C	Reading Gage Line I (Drum Div.)	Δ Drum Div.	Reading Gage Line I (Drum Div.)	Δ Drum Div.	Avg. Δ in x 10^{-2}	Gage Correct. in x 10^{-2}	Specimen Expansion in x 10^{-2}
-25.1	32.691	0.0	33.550	0.0	0.0	0.0	0.0
- 7.1	33.021	0.330	34.100	0.550	0.089	0.155	0.244
2.1	33.104	0.413	34.154	0.604	0.107	0.235	0.342
15.7	33.189	0.498	34.214	0.664	0.116	0.352	0.468
25.4	33.415	0.724	34.338	0.788	0.151	0.436	0.587
34.4	33.506	0.815	34.342	0.792	0.161	0.513	0.674

NOTE: Gage correction based on manufacturer's stated thermal coefficient of expansion of 17.25×10^{-6} in/in/°C, and an expandable distance of 5.0 inches for each gage.

TABLE 27

LINEAR EXPANSION DATA

5-inch Stainless Steel Strain Gage
4.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 150.6 pcf.

Temp. °C	Reading Gage Line I (Drum Div.)	Δ Drum Div.	Reading Gage Line I (Drum Div.)	Δ Drum Div.	Avg. Δ in x 10^{-2}	Gage Correct. in x 10^{-2}	Specimen Expansion in x 10^{-2}
-25.1	41.760	0.0	35.198	0.0	0.0	0.0	0.0
- 7.1	42.104	0.349	35.495	0.297	0.065	0.155	0.220
2.1	42.227	0.467	35.743	0.545	0.101	0.235	0.336
15.7	42.267	0.507	35.720	0.522	0.103	0.352	0.455
25.4	42.292	0.532	35.690	0.492	0.102	0.436	0.538
34.4	42.416	0.656	35.914	0.716	0.137	0.513	0.650

NOTE: Gage correction based on manufacturer's stated thermal coefficient of expansion of 17.25 x 10^{-6} in/in/°C, and an expandable distance of 5.0 inches for each gage.

TABLE 28

LINEAR EXPANSION DATA

5-inch Whittemore Gage
3.6% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 147.3 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-30.1	6.300	0	6.155	0	0.0
-15.1	6.361	0.061	6.221	0.066	0.063
- 6.0	6.433	0.133	6.290	0.135	0.134
1.4	6.491	0.191	6.330	0.175	0.183
8.0	6.565	0.265	6.396	0.241	0.253
20.8	6.670	0.370	6.486	0.331	0.350
32.5	6.766	0.466	6.565	0.410	0.438

TABLE 29

LINEAR EXPANSION DATA

5-inch Whittemore Gage
4.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 149.8 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-30.7	5.213	0	5.418	0	0.0
-13.1	5.321	0.108	5.531	0.113	0.110
- 4.0	5.391	0.178	5.603	0.185	0.181
1.6	5.436	0.223	5.610	0.192	0.207
6.7	5.463	0.250	5.626	0.208	0.229
13.2	5.480	0.267	5.661	0.243	0.255
21.0	5.503	0.290	5.665	0.247	0.268
27.4	5.503	0.290	5.687	0.267	0.278
36.3	5.530	0.317	5.696	0.278	0.297

TABLE 30

LINEAR EXPANSION DATA

5-inch Whittemore Gage
4.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 150.9 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-33.9	6.522	0	6.610	0	0
-29.9	6.522	0	6.620	0.010	0.005
-24.7	6.548	0.026	6.632	0.022	0.024
-19.7	6.590	0.068	6.680	0.070	0.069
-14.9	6.625	0.103	6.710	0.100	0.102
- 9.1	6.680	0.158	6.762	0.152	0.155
- 4.9	6.715	0.193	6.792	0.182	0.188
0.0	6.755	0.233	6.835	0.225	0.229
5.2	6.790	0.268	6.860	0.250	0.259
12.8	6.840	0.318	6.905	0.295	0.307
20.0	6.865	0.343	6.935	0.325	0.334
25.6	6.865	0.343	6.935	0.325	0.334
29.9	6.877	0.355	6.947	0.337	0.346
37.3	6.852	0.330	6.938	0.328	0.329
42.9	6.847	0.325	6.935	0.325	0.325
49.4	6.843	0.321	6.923	0.313	0.317

TABLE 31

LINEAR EXPANSION DATA

5-inch Whittemore Gage
5.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.5 pcf.

Temp °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-24.2	5.820	0	5.825	0	0.0
-12.8	5.936	0.110	5.938	0.113	0.111
- 5.3	6.015	0.195	6.018	0.193	0.194
1.4	6.101	0.281	6.093	0.268	0.274
6.2	6.151	0.331	6.140	0.315	0.323
14.8	6.253	0.433	6.230	0.405	0.419
22.3	6.355	0.535	6.320	0.495	0.515
26.9	6.413	0.593	6.393	0.568	0.580
31.3	6.475	0.655	6.460	0.635	0.645
37.1	6.536	0.716	6.570	0.745	0.730

TABLE 32

LINEAR EXPANSION DATA

5-inch Whittemore Gage
5.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.4 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-24.2	5.625	0	5.690	0	0.0
-12.8	5.735	0.110	5.795	0.105	0.107
- 5.3	5.820	0.195	5.868	0.178	0.186
1.4	5.920	0.295	5.960	0.270	0.282
6.2	5.995	0.370	6.020	0.330	0.350
14.8	6.105	0.480	6.123	0.433	0.456
22.3	6.198	0.573	6.216	0.526	0.549
26.9	6.241	0.616	6.278	0.588	0.602
31.3	6.280	0.655	6.326	0.636	0.645
37.1	6.328	0.703	6.410	0.720	0.711

TABLE 33

LINEAR EXPANSION DATA

10-inch Whittemore Gage
4.0% A.C.; 60-70 Pen.; Limestone
Coating: Asphalt
Density: 147.6 pcf.

Temp. $^{\circ}$C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-25.7	6.057	0	5.837	0	0.0
-21.1	6.107	0.057	5.948	0.111	0.084
-17.4	6.150	0.093	5.973	0.136	0.114
-10.9	6.247	0.190	6.103	0.266	0.228
- 1.7	6.465	0.408	6.258	0.421	0.414
5.3	6.635	0.578	6.457	0.620	0.599
12.1	6.770	0.713	6.562	0.725	0.719
20.7	6.942	0.885	6.823	0.986	0.935
26.6	7.073	1.016	6.927	1.090	1.053
34.6	7.297	1.220	7.218	1.381	1.300

TABLE 34

LINEAR EXPANSION DATA

10-inch Whittemore Gage
4.5% A.C.; 60-70 Pen.; Limestone
Coating: Syn. Latex
Density: 150.6 pcf.

Temp. $^{\circ}$C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-25.7	5.435	0	5.677	0	0.0
-21.1	5.530	0.095	5.732	0.055	0.075
-17.4	5.583	0.148	5.813	0.136	0.142
-10.9	5.677	0.242	5.977	0.300	0.271
- 1.7	5.910	0.475	6.122	0.445	0.460
5.3	6.065	0.630	6.283	0.606	0.618
12.1	6.180	0.745	6.383	0.706	0.725
20.7	6.460	1.025	6.548	0.871	0.948
26.6	6.635	1.200	6.538	0.861	1.030
34.6	7.020	1.585	6.820	1.143	1.364

TABLE 35

LINEAR EXPANSION DATA

10-inch Whittemore Gage
5.0% A.C.; 60-70 Pen.; Limestone
Coating: None
Density: 151.0 pcf.

Temp. $^{\circ}$C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-20.8	4.743	0	4.753	0	0.0
-14.0	4.878	0.135	4.848	0.085	0.110
- 7.9	5.038	0.160	5.041	0.288	0.224
0.3	5.185	0.442	5.263	0.510	0.476
11.0	5.481	0.603	5.623	0.870	0.736
19.5	5.693	0.815	5.886	1.135	0.974
31.3	6.030	1.152	6.340	1.587	1.369

TABLE 36

LINEAR EXPANSION DATA

10-inch Whittemore Gage
5.5% A.C.; 60-70 Pen.; Limestone
Coating: None
Density: 151.5 pcf.

Temp. $^{\circ}$C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-17.8	4.970	0	6.345	0	0.0
-12.3	5.103	0.133	6.476	0.131	0.132
- 5.1	5.290	0.320	6.626	0.281	0.300
1.6	5.453	0.483	6.823	0.478	0.480
10.8	5.693	0.723	7.048	0.703	0.713
20.4	6.000	1.030	7.407	1.062	1.046
29.4	6.398	1.428	7.885	1.540	1.484

TABLE 37

LINEAR EXPANSION DATA

10-inch Whittemore Gage
3.6% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 147.3 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-30.1	5.100	0	5.580	0	0.0
-15.1	5.250	0.150	5.721	0.141	0.145
- 6.0	5.413	0.313	5.830	0.250	0.281
1.4	5.490	0.390	5.921	0.341	0.365
8.0	5.620	0.520	6.063	0.483	0.501
20.8	5.835	0.735	6.230	0.650	0.692
32.5	5.878	0.778	6.310	0.730	0.754

TABLE 38

LINEAR EXPANSION DATA

10-inch Whittemore Gage
4.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 149.8 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-30.7	4.490	0	3.955	0	0.0
-13.1	4.711	0.221	4.160	0.205	0.213
- 4.0	4.880	0.390	4.311	0.356	0.373
1.6	4.896	0.406	4.490	0.535	0.470
6.7	4.945	0.455	4.578	0.623	0.539
13.2	4.996	0.506	4.610	0.655	0.580
21.0	5.020	0.520	4.718	0.763	0.641
27.4	5.060	0.570	4.750	0.795	0.682
36.3	5.020	0.520	4.816	0.861	0.690

TABLE 39

LINEAR EXPANSION DATA

10-inch Whittemore Gage
4.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 150.9 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
37.2	6.118	0.898	6.122	0.892	0.895
30.8	6.072	0.842	6.078	0.848	0.845
25.7	6.060	0.830	6.063	0.833	0.832
21.1	6.025	0.795	6.025	0.795	0.795
16.5	6.001	0.771	6.000	0.770	0.771
10.5	5.937	0.707	5.927	0.697	0.702
1.7	5.832	0.602	5.827	0.597	0.599
- 5.5	5.692	0.462	5.700	0.470	0.466
-31.7	5.245	0.015	5.253	0.023	0.019
-33.9	5.230	0	5.230	0	0
-30.0	5.235	0.005	5.245	0.015	0.010
-25.0	5.290	0.060	5.292	0.062	0.061
-19.8	5.388	0.158	5.378	0.148	0.153
-15.0	5.470	0.240	5.465	0.235	0.238
- 9.1	5.577	0.347	5.580	0.350	0.348
- 4.9	5.663	0.433	5.667	0.437	0.435
0.0	5.763	0.533	5.757	0.527	0.530
5.1	5.843	0.613	5.840	0.610	0.611
12.8	5.993	0.763	5.987	0.757	0.760
20.0	6.070	0.840	6.067	0.837	0.838
25.7	6.122	0.892	6.113	0.883	0.888
30.0	6.150	0.920	6.127	0.897	0.909
37.5	6.205	0.975	6.190	0.960	0.967
43.1	6.248	1.018	6.223	1.003	1.010
49.5	6.397	1.167	6.308	1.078	1.123

TABLE 40

LINEAR EXPANSION DATA

10-inch Whittemore Gage
5.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.5 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-24.2	4.830	0	5.043	0	0.0
-12.8	5.061	0.231	5.305	0.262	0.246
- 5.3	5.243	0.413	5.471	0.428	0.420
1.4	5.463	0.633	5.650	0.607	0.650
6.2	5.521	0.691	5.773	0.730	0.710
14.8	5.753	0.923	5.928	0.885	0.904
22.3	5.916	1.086	6.100	1.057	1.071
26.9	6.043	1.213	6.240	1.197	1.205
31.3	6.081	1.251	6.335	1.292	1.271
37.1	6.023	1.193	6.410	1.367	1.280

TABLE 41

LINEAR EXPANSION DATA

10-inch Whittemore Gage
5.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.4 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-24.2	4.946	0	4.590	0	0.0
-12.8	5.181	0.235	4.850	0.260	0.247
- 5.3	5.383	0.437	4.996	0.406	0.421
1.4	5.563	0.617	5.203	0.613	0.615
6.2	5.730	0.784	5.351	0.761	0.772
14.8	5.941	0.995	5.590	1.000	0.997
22.3	6.156	1.210	5.800	1.210	1.210
26.9	6.313	1.367	5.976	1.386	1.376
31.3	6.380	1.434	6.076	1.486	1.460
37.1	6.423	1.477	6.216	1.626	1.551

TABLE 42

LINEAR EXPANSION DATA

10-inch Whittemore Gage
4.0% A.C.; 85-100 Pen.; Gravel
Coating: Asphalt
Density: 150.7 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-25.2	5.197	0	5.480	0	0.0
-24.3	5.225	0.028	5.503	0.023	0.025
-19.7	5.283	0.086	5.577	0.097	0.091
-15.0	5.507	0.310	5.755	0.275	0.292
- 7.0	5.640	0.443	5.902	0.422	0.432
2.7	5.890	0.693	6.065	0.585	0.639
8.8	6.133	0.936	6.187	0.707	0.821
15.1	6.228	1.031	6.378	0.898	0.964

TABLE 43

LINEAR EXPANSION DATA

10-inch Whittemore Gage
4.5% A.C.; 85-100 Pen.; Gravel
Coating: Asphalt
Density: 150.8 pcf.

Temp. °C	Ave. Reading Gage Line I (Dial Div.)	Δ in. x 10^{-2}	Ave. Reading Gage Line II (Dial Div.)	Δ in. x 10^{-2}	Ave. Δ in. x 10^{-2}
-25.2	6.260	0	6.223	0	0.0
-24.3	6.272	0.012	6.272	0.049	0.030
-19.7	6.375	0.155	6.385	0.162	0.138
-15.0	6.543	0.283	6.540	0.317	0.300
- 7.0	6.697	0.437	6.700	0.477	0.457
2.7	6.912	0.652	6.875	0.652	0.652
8.8	7.143	0.883	7.043	0.820	0.851
15.1	7.327	1.067	7.127	0.904	0.985

TABLE 44

LINEAR EXPANSION DATA

10-inch Dual Microscopes
4.0% A.C.; 60-70 Pen.; Limestone
Coating: Asphalt
Density: 147.6 pcf.

Temp. °C	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-25.7	26.018	0.	27.916	0	0.0	0.0
-21.2	26.130	0.122	28.209	0.293	0.207	0.041
-17.4	26.218	0.200	28.458	0.542	0.371	0.074
-10.9	26.585	0.567	29.083	1.167	0.867	0.173
- 1.7	27.737	1.719	30.003	2.081	1.903	0.380
5.3	28.481	2.463	30.709	2.793	2.628	0.525
12.1	29.153	3.135	31.476	3.560	3.347	0.669
20.7	29.952	3.934	32.364	4.448	4.191	0.838
26.6	30.591	4.573	33.015	5.099	4.836	0.967
34.6	31.267	5.249	33.891	5.975	5.612	1.122
39.7	31.819	5.801	34.415	6.499	6.150	1.230
45.5	32.259	6.241	34.789	6.873	6.552	1.310

TABLE 45

LINEAR EXPANSION DATA

10-inch Dual Microscopes
4.5% A.C.; 60-70 Pen.; Limestone
Coating: Syn. Latex
Density: 150.6 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-25.7	25.400	0	25.152	0	0.0	0.0
-21.1	25.742	0.342	25.463	0.311	0.326	0.065
-17.4	26.007	0.607	25.802	0.650	0.628	0.125
-10.9	26.724	1.324	26.313	1.161	1.242	0.248
- 1.7	27.799	2.399	27.133	1.981	2.190	0.438
5.3	28.582	3.182	28.211	3.059	3.120	0.624
12.1	29.267	3.865	28.795	3.647	3.756	0.751
20.7	30.465	5.065	29.940	4.688	4.876	0.975
26.6	31.625	6.225	30.800	5.648	5.936	1.187
34.6	33.052	7.625	32.679	7.527	7.576	1.515
39.7	35.963	10.563	35.432	10.280	10.421	2.084

TABLE 46

LINEAR EXPANSION DATA

10-inch Dual Microscopes
5.0% A.C.; 60-70 Pen.; Limestone
Coating: None
Density: 151.0 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-21.6	22.720	0	23.066	0	0.0	0.0
-14.3	23.983	1.263	24.382	1.316	1.289	0.258
- 7.9	24.440	1.720	25.044	1.978	1.849	0.370
0.3	25.304	2.584	26.092	3.026	2.805	0.561
11.0	26.507	3.787	27.719	4.653	4.230	0.844
19.5	27.454	4.734	28.830	5.764	5.249	1.050
31.3	28.993	6.273	30.709	7.643	6.958	1.392
41.0	30.412	7.692	32.593	9.527	8.605	1.721

TABLE 47

LINEAR EXPANSION DATA

10-inch Dual Microscopes
4.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 148.3 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-23.2	25.900	0	25.623	0	0.0	0.0
-15.0	26.612	0.712	26.337	0.714	0.713	0.142
- 8.1	27.023	1.123	27.001	1.378	1.251	0.250
1.5	28.197	2.297	27.933	2.310	2.303	0.460
7.7	28.707	2.807	28.648	3.025	2.916	0.583
16.2	29.748	3.848	29.283	3.660	3.759	0.751
25.2	30.979	5.079	30.482	4.859	4.969	0.993
33.8	32.339	6.439	32.041	6.418	6.428	1.285

TABLE 48

LINEAR EXPANSION DATA

10-inch Dual Microscopes
5.0% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 150.2 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-21.0	19.635	0	20.585	0	0.0	0.0
-17.6	19.848	0.213	20.761	0.176	0.194	0.038
-11.6	20.478	0.843	21.228	0.643	0.743	0.148
- 3.1	21.592	1.957	21.949	1.364	1.660	0.332
3.7	22.638	3.003	22.932	2.347	2.675	0.535
15.3	24.848	5.213	24.859	4.774	4.743	0.948
21.3	25.691	6.056	25.648	5.063	5.559	1.111

TABLE 49

LINEAR EXPANSION DATA

10-inch Dual Microscopes
5.5% A.C.; 85-100 Pen.; Limestone
Coating: None
Density: 151.5 pcf.

Temp. °C	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-17.8	25.629	0	31.509	0	0.0	0.0
-12.3	26.199	0.570	32.018	0.509	0.540	0.108
- 5.1	27.215	1.586	32.914	1.405	1.495	0.299
1.6	27.785	2.156	33.377	1.868	2.010	0.402
10.8	28.869	3.240	34.875	3.366	3.300	0.660
20.4	30.385	4.756	36.172	4.663	4.710	0.942
29.4	32.332	6.703	38.211	6.702	6.700	1.340

TABLE 50

LINEAR EXPANSION DATA

10-inch Dual Microscopes
3.6% A.C.; 85-100 Pen.; Gravel
Coating: Syn. Latex
Density: 149.1 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-23.5	24.223	0	29.916	0	0.0	0.0
-19.4	24.988	0.765	30.226	0.310	0.527	0.105
-12.0	25.368	1.145	30.975	1.059	1.102	0.220
- 0.3	26.671	2.448	32.060	2.144	2.296	0.459
10.0	27.669	3.446	33.226	3.310	3.378	0.675
19.4	29.023	4.800	34.513	4.597	4.698	0.939
27.3	31.270	7.047	36.555	6.649	6.848	1.369

TABLE 51

LINEAR EXPANSION DATA

10-inch Dual Microscopes
4.0% A.C.; 85-100 Pen.; Gravel
Coating: Asphalt
Density: 150.7 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-25.2	21.265	0	21.572	0	0.0	0.0
-19.7	21.539	0.274	21.686	0.114	0.194	0.038
-15.0	22.334	1.069	22.294	0.722	0.895	0.179
- 7.0	23.081	1.816	23.020	1.448	1.632	0.326
2.7	24.460	3.195	24.221	2.649	2.922	0.584
8.8	25.476	4.211	24.550	2.978	3.594	0.718
15.1	26.468	5.203	25.217	3.645	4.424	0.884
26.0	29.316	8.051	28.490	6.918	7.484	1.596

TABLE 52

LINEAR EXPANSION DATA

10-inch Dual Microscopes
4.5% A.C.; 85-100 Pen.; Gravel
Coating: Asphalt
Density: 150.8 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-25.2	24.767	0	25.285	0	0.0	0.0
-15.0	25.815	1.048	26.299	1.014	1.031	0.206
- 7.0	26.356	1.589	26.926	1.641	1.615	0.323
2.7	27.364	2.597	27.779	2.494	2.545	0.509
8.8	28.404	3.637	28.565	3.280	3.458	0.691
15.1	29.231	4.464	29.277	3.994	4.229	0.845
26.0	31.982	7.215	31.548	6.263	6.739	1.347

TABLE 53

LINEAR EXPANSION DATA

10-inch Dual Microscopes
5.0% A.C.; 85-100 Pen.; Gravel
Coating: None
Density: 152.1 pcf.

Temp. °C	Ave. Reading Gage Line I (Drum Div.)	Δ Drum Div.	Ave. Reading Gage Line II (Drum Div.)	Δ Drum Div.	Ave. Δ Drum Div.	Ave. Length Change in. x 10^{-2}
-23.5	22.796	0	24.517	0	0.0	0.0
-19.4	23.397	0.601	25.102	0.585	0.593	0.118
-12.0	24.362	1.566	26.016	1.499	1.533	0.306
- 0.3	25.566	2.770	27.043	2.526	2.648	0.529
10.0	26.660	3.864	28.102	3.585	3.725	0.745
19.4	27.545	4.749	28.734	4.217	4.483	0.896
27.3	28.262	5.466	28.944	4.427	4.947	0.999
36.7	28.635	5.839	29.702	5.185	5.512	1.102

APPENDIX E

Individual Component Expansions

APPENDIX E

Individual Component Expansions

This section contains the volumetric expansion data obtained from the individual expansion tests conducted on the Greencastle limestone and 85-100 penetration grade asphalt cement. The data for the limestone test is contained in Table 54 and the data for the asphalt cement is contained in Table 55. Both tests were conducted using the metal dilatometer and mercury. Filling while under vacuum was employed in the test on the limestone, while the air displacement method was used for the asphalt test.

TABLE 54

LIMESTONE EXPANSION DATA

Dilatometer III
Weight of Mercury: 4170.2 g
Volume of Sample: 260.0 ml.

Temp. °C	Cum. Dil. Reading ml	Amt. Removed ml	Specific Volume Hg ml/g	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Theo. Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Δ Sample Expansion ml
-26.7	0.063	0.0	0.07319810	0.0	0.063	0.0	0.0	0.0	0.0
-17.0	0.395	0.0	0.07332729	0.0	0.395	0.332	0.539	0.310	0.103
-11.3	0.560	0.0	0.07340326	0.0	0.560	0.497	0.856	0.480	0.119
- 2.2	0.843	0.520	0.07352463	0.0008	0.844	0.771	1.362	0.760	0.169
3.5	1.017	0.0	0.07360072	0.0014	1.018	0.955	1.679	0.940	0.216
10.1	1.210	0.0	0.07368887	0.0020	1.212	1.149	2.047	1.135	0.237
20.2	1.519	0.666	0.07382388	0.0042	1.523	1.460	2.610	1.460	0.310
27.1	1.719	0.0	0.07391621	0.0057	1.725	1.662	2.995	1.670	0.337
34.7	1.956	0.492	0.07401799	0.0083	1.964	1.901	3.419	1.920	0.402
42.5	2.292	0.0	0.07412255	0.0104	2.302	2.239	3.855	2.110	0.494

TABLE 55

85-100 PENETRATION ASPHALT CEMENT EXPANSION DATA

Dilatometer III
Weight of Mercury: 1350.0 g
Volume of Sample: 482.5 ml.

Temp. °C	Cum. Dil. Reading ml	Amt. Removed ml	Specific Volume Hg ml	Cum. Expansion Removed Amt. ml	Theo. Dil. Reading ml	Theo. Δ Dil. Reading ml	Δ Exp. Hg ml	Δ Exp. Dil. ml	Δ Sample Expansion ml
-30.0	0.070	0.0	0.07313555	0.0	0.070	0.0	0.0	0.0	0.0
-26.5	0.675	0.0	0.07320076	0.0	0.675	0.605	0.0880	0.130	0.647
-22.7	1.392	0.0	0.07325136	0.0	1.392	1.322	0.157	0.230	1.395
-18.6	2.221	1.687	0.07330597	0.0013	2.222	2.150	0.230	0.350	2.270
-14.1	2.930	0.870	0.07336593	0.0021	2.932	2.862	0.311	0.490	3.041
-12.6	3.267	0.645	0.07338593	0.0037	3.271	3.201	0.338	0.540	3.403
- 8.6	4.069	0.618	0.07343926	0.0037	4.076	4.006	0.410	0.670	4.266
- 5.2	5.072	0.812	0.07348461	0.0073	5.079	5.009	0.471	0.770	5.308
- 2.2	5.967	1.035	0.07352463	0.0129	5.980	5.910	0.525	0.860	6.245