VOLUME CHANGES IN UNRESTRAINED STRUCTURAL LIGHTWEIGHT CONCRETE

by

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Determination of Critical Mechanical Properties of Structural Lightweight Concrete and the Effects of these Properties upon the Design of the Pavement Structure

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PREFACE

This is the second report in a series of three reports to be written covering the work of this project. The reports are:

Report No. 1 - "Relationship Between Critical Mechanical Properties and Age for Structural Lightweight Concrete" by W. B. Ledbetter and J. Neils Thompson; this report was concerned with the development of a technique to measure the tensile stress-strain characteristics of lightweight aggregate concrete and how this property is affected by restraint from volume change.

Report No. 2 - "Volume Changes in Unrestrained Structural Lightweight Concrete" by James T. Houston and J. Neils Thompson; the current report is concerned with the development of a method to accurately determine the coefficient of linear thermal expansion as well as the unrestrained shrinkage characteristics of structural lightweight concrete.

Report No. 3 (Final Report) - "Critical Mechanical Properties of Structural Lightweight Concrete and the Effects of the Properties Upon the Design of the Pavement Structure" by W. B. Ledbetter, Ervin S. Perry, James T. Houston and J. Neils Thompson; this report will summarize the findings of the first two reports, and provide some interpretation of the effect of environment and restraint upon the design of the pavement structure.

ABSTRACT

In this study a comparator-type measuring system was developed to accurately determine volume change characteristics of one structural lightweight concrete. The specific properties studied were the coefficient of linear thermal expansion and unrestrained shrinkage.

One finding of this report was that the coefficient of expansion of the type of lightweight concrete studied was only slightly less than that of normal-weight concrete of similar air content and cement factor. Another finding was that an increase in air content of the lightweight concrete resulted in a slight reduction in its value of coefficient of expansion.

The use of the aggregate studied in this report resulted in a concrete that, in general, had a low unrestrained shrinkage as compared with concrete made with other lightweight aggregates (particularly those with higher absorption characteristics) as reported by other investigators.

A study of the effect of curing conditions on the unrestrained shrinkage properties of this lightweight concrete indicated that curing procedures might be developed which could minimize destructive volume changes during the curing period.

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1. INTRODUCTION

1.1 Purpose

The effective use of concrete for structural purposes requires a thorough understanding of its material properties. This is especially true with regard to the use of "synthetic" aggregate concretes of which many types and varieties have been introduced.

The purpose of this report is to present the results of a partial investigation of one type of structural lightweight concrete. This study was conducted in three phases. First, a method of accurately and reliably measuring small dimensional changes in concrete specimens was developed. Secondly, the system developed was used to determine the coefficient of linear thermal expansion of lightweight and regular-weight concretes. Lastly, the measurement system was used also to study the unrestrained shrinkage characteristics of lightweight concrete.

1.2 Scope and Limitations

The coefficient of linear thermal expansion was determined with regard to the following parameters

1. Coarse aggregate type -- one structural lightweight, semicoated, expanded shale coarse aggregate and one regular-weight river-run coarse aggregate were chosen for comparison purposes.

2. Air content -- 2 air contents, 2 per cent (no air entrainment) and 6 per cent (using an air-entrainment additive), were

used in the lightweight concrete. No air-entrainment additive was used in the regular-weight concrete.

Unrestrained shrinkage characteristics were determined for the lightweight concrete only, with regard to the following parameters:

1. Cement factor -- 4 sacks per cubic yard and 5 sacks per cubic yard were chosen as representative of current values being used for pavement structures in Texas.

2. Curing conditions -- two curing methods were chosen to represent the extreme conditions which could be expected to occur in Texas. They are oven dried at low humidity and 110F, and bag cured at essentially 100 per cent relative humidity and 75F.

For the determination of the effect of the parameters listed previously, the following conditions were held constant.

1. Mixing time and sequence
2. Cement type
3. Batch size
4. Air-entrainment type
5. Consistency
6. Fine aggregate

1.3 Conclusions

1. Small changes in length of concrete specimens due to temperature variation or shrinkage were reliably determined with a comparator device which utilized mechanical and electrical measurement principles.

2. The coefficient of linear thermal expansion of one expanded shale and sand aggregate lightweight concrete was determined to be 5.3×10^{-6} in./in. per ^{o}F as compared to 5.6×10^{-6} in./in. per ^{o}F for normal-weight concrete of similar cement factor and air content.

3. Entrainment of air in lightweight concrete resulted in a reduction in the coefficient of expansion. An increase in air content from 2.8 to 7.4 per cent resulted in a decrease in the coefficient of expansion of from 5.3 to 5.2×10^{-6} in./in. per ^{o}F.

4. Lightweight concrete left in forms in the laboratory during the first day after pouring consistently expanded during this interval.

5. On the basis of the results of other investigators on a wide variety of lightweight aggregates, this particular aggregate used in conjunction with ordinary sand showed low shrinkage characteristics.

6. The results of volume change observations on continuously moist cured specimen at 75F and on oven cured specimen at 110F indicate that when suitable curing procedures are followed, concrete with lightweight aggregate can be produced without being subjected to destructive volume change.

1.4 Recommendations

1. Additional tests for the determination of the coefficient of expansion should be made with regard for the following parameters:

   a. Age of concrete

   b. Cement factor (Particularly at higher cement factors than used in this study - 5 1/2 to 8 sk/c.y.)

   c. Air content

d. Aggregate type

Also testing of several specimens of each mix investigated would minimize error due to experimental inconsistencies.

2. Additional tests for unrestrained shrinkage characteristics should include normal-weight concrete specimens for comparison purposes.

3. A more complete investigation of unrestrained shrinkage characteristics should also include air content as a test parameter as well as a wider range of cement factors.

4. Future investigations of unrestrained shrinkage properties of oven-cured specimens should require a minimum of one measurement every four hours during the first day or two of oven curing.

5. Future use of polyethylene bags for 100 per cent humidity curing requires the development of an effective method of sealing the bags.

6. Future tests of lightweight concrete should include concretes made solely from lightweight aggregates.

2. TEST FOR THE DETERMINATION OF LENGTH CHANGES IN CONCRETE SPECIMEN.

2.1 General

Many devices have been developed which serve the purpose of measuring changes in length of various specimens, several specifically for concrete. These methods, in general, derive their usefulness from either mechanical, electrical, or optical principles. Since in this investigation it was desired to determine the coefficient of linear thermal expansion and to investigate unrestrained shrinkage characteristics of concrete, extreme accuracy was required in the measuring method selected.

To fulfill the basic requirements of accuracy, a method was selected which utilized both mechanical and electrical principles in a comparator-type system. However, even a well-designed system can lose much of its value if poor test procedures are used. With this consideration in mind, techniques were devised which minimized the human factor in experimental error. With the exception of minor modifications, the comparator used in this work was developed by Professor Hudson Matlock at The University of Texas.

2.2 Measurement System

In general, a comparator-type system compares the measurement of a specimen with that of a standard bar. The main advantage of the

standard bar is that it compensates for any changes in length of the comparator due to temperature variations. The basic components are the framework, micrometer, strain-gage-instrumented aluminum cantilever, and an invar standard bar. A schematic drawing of the basic unit of the comparator is shown in Fig. 2-1. A picture of the comparator with strain-reading equipment is shown in Fig. 2-2.

Framework. The steel framework of the comparator was composed of a wide flange section and stand. One flange had been replaced by a machined rail which allowed the measurement of specimens with various gage lengths, (0 to 16 inches). The adjustment was accomplished by moving the lower cantilever up or down along the rail. The lower cantilever (steel) also housed one of the machined and polished gage points between which measurements were made. Note also in Fig. 2-2 that insulation material was wrapped around the lower cantilever and wide flange section. This helped stabilize the framework dimensionally with temperature variations.

Micrometer. The micrometer was mounted on the upper cantilever as shown in Figs. 2-1 and 2-2. A close-up view of the micrometer showing front and side views is pictured in Figs. 2-3 and 2-4 respectively. Each complete revolution of the micrometer dial represented a movement of the gage point of 0.025 in., and its standard scale could be read directly to the nearest 0.001 in. with estimation to the nearest 0.0001 inch. The total range of travel of the micrometer gage point was 1 inch.

To increase the accuracy of measurements, a modified scale with 250 divisions per revolution was added. This scale was positioned

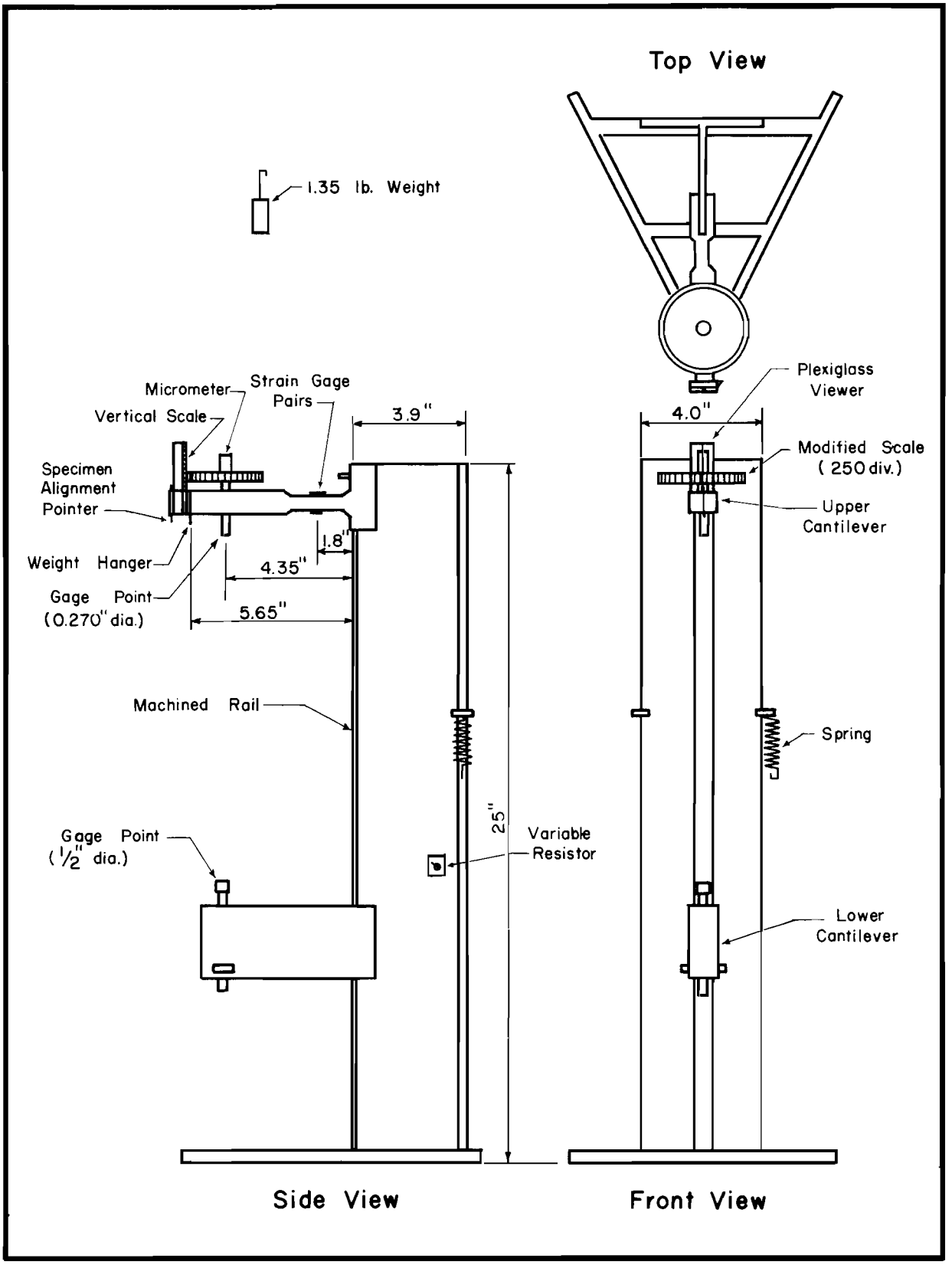


Figure 2-1. Comparator Measuring System

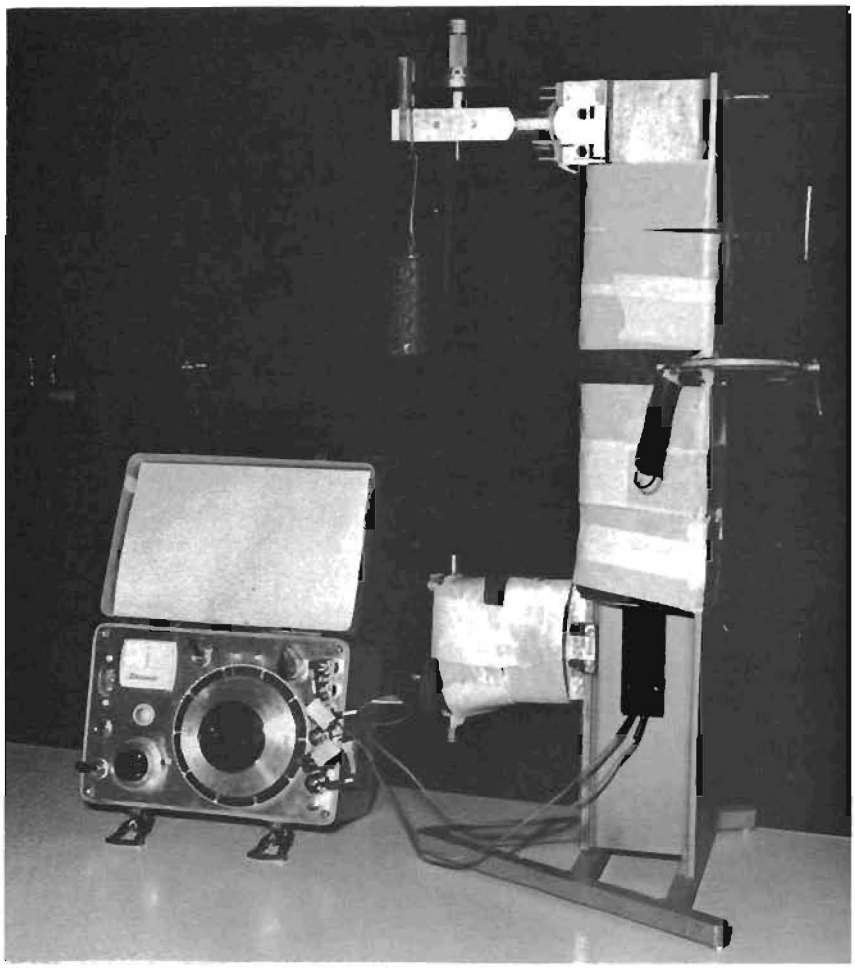


Fig. 2-2. Over-All View of Comparator and Strain Indicator

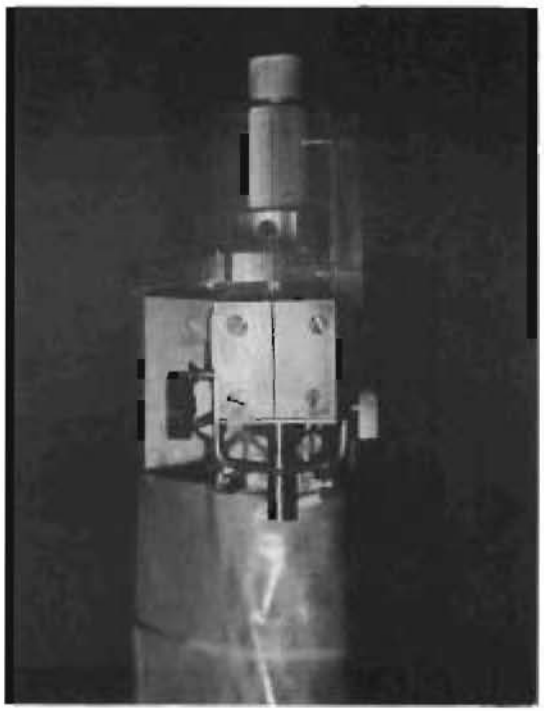


Fig. 2-3. Front View of Upper Cantilever Showing Modified Scale

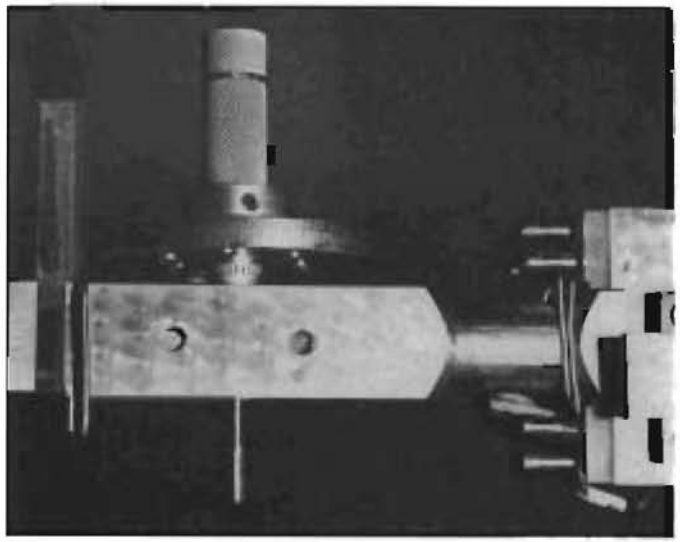


Fig. 2-4. Side View of Upper Cantilever Showing Vertical Scale

horizontally and was located just below the knurled knob used to adjust the gage point of the micrometer. With the modified scale, direct readings could be taken to the nearest 0.0001 in. with estimation to the nearest 0.00001 in., (one-tenth of a division).

A reading was made with the aid of a vertical hairline etched on the frontside of the plexiglass viewer shown in Fig. 2-3. A second hairline on the inside face of the viewer was positioned parallel to and directly behind the first. The purpose of this arrangement was to minimize the reading error caused by parallax.

A vertical scale calibrated in 0.025-in. increments was located at one side of the plexiglass viewer. This vertical scale augmented the modified scale by indicating the number of revolutions turned in relation to any previous reading.

Strain-gage instrumented cantilever. The upper cantilever shown in Fig. 2-4 was instrumented with four SR-4 strain gages which formed a self-temperature-compensated Wheatstone-bridge circuit. The gages were mounted in pairs on the upper and lower side of the cantilever with all grids parallel to its longitudinal axis. This, in effect, placed the gages in either tension or compression when a vertical force was applied to the cantilever.

A schematic drawing of the strain-gage bridge is shown in Fig. 2-5. Also shown is a variable resistor which allowed the adjustment of an initial reading on the strain-indicating instrument. Use of the variable resistor simplified the procedures involved when using this measuring system.

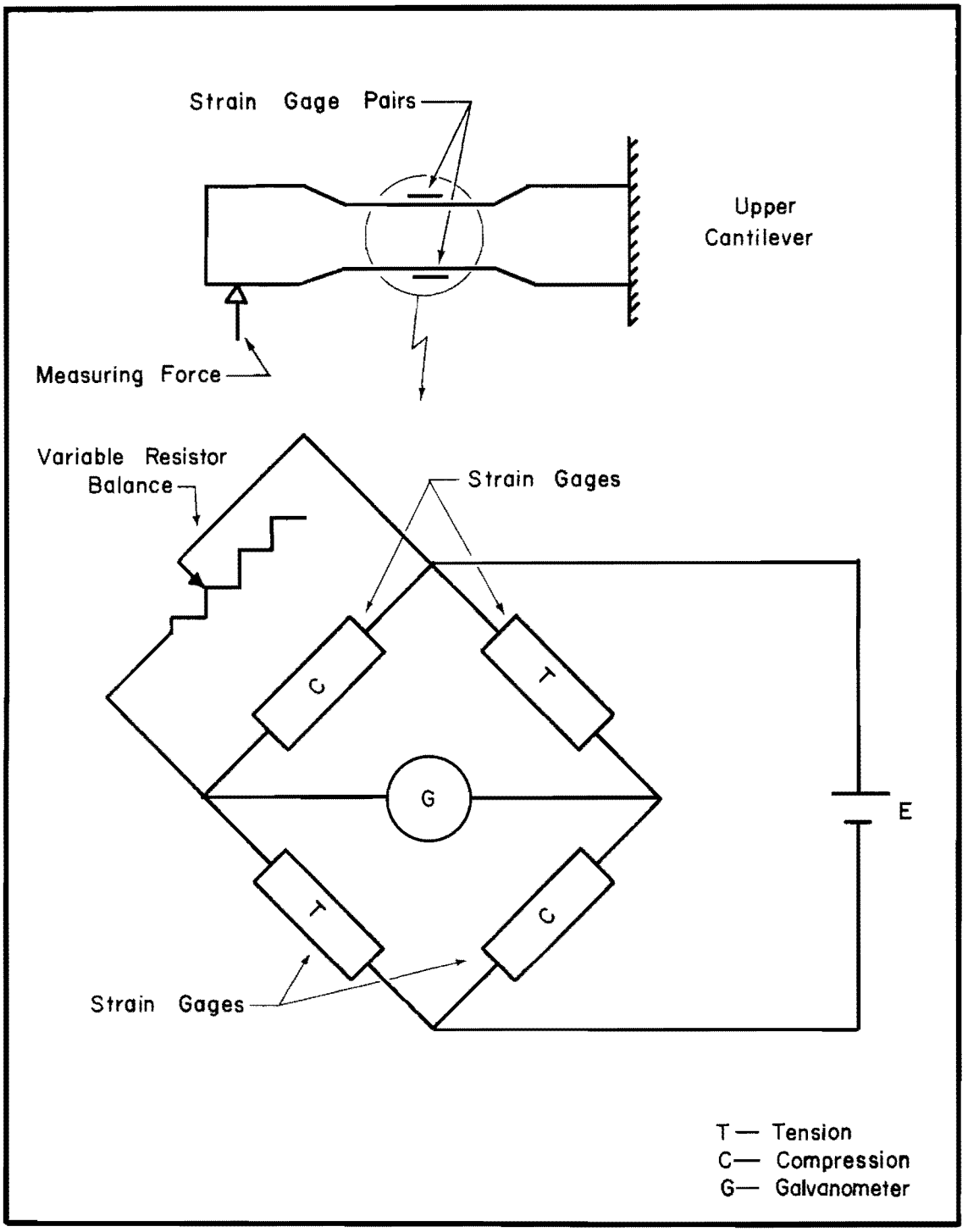


Figure 2–5. Constant Pressure Indication System--Electrical Circuitry

The purpose of the instrumented cantilever was to enable the experimenter to place the same pressure on the specimen gage plugs for each comparator reading taken, and thereby reduce error. A complete description of the specimen and gage plugs is found in Section 5.1.

To obtain a constant pressure, a weight was hung from a fixed point on the upper cantilever as shown in Figs. 2-1 and 2-2, and a strain reading was taken. Then, with the weight removed and a specimen placed between gage points, a force was applied to the cantilever by turning the micrometer to bear on the specimen gage plugs. If the micrometer was adjusted so that the same value of strain was obtained as that given by the weight, a reproducible, constant pressure had been applied to the specimen. The magnitude of the weight and the corresponding force applied through the micrometer are inconsequential except that weights of approximately 1 lb give the best results, as shown by previous work with this comparator. Of course, the weight used must be constant throughout the test period.

Two types of strain indicators, Budd Model HW-1 and Baldwin Type N, were used in the experimental work. The use of two indicators on any given test series presented no problem from instrument variation since they were used essentially as null indicators. Also the fact that the constant weight was used prior to each set of readings eliminated any error which might have been caused by strain-gage creep occurring over the entire test period.

Standard bar. As mentioned previously, a standard bar was an integral part of the comparator system of measurement since it served to compensate for any changes in length of the comparator framework. An ideal standard bar would be one that has precisely the same length at all times during the test period. Therefore, a bar and associated techniques were selected which approached, as nearly as possible, the ideal condition.

The bar used was made of free-cut invar. A schematic drawing of the bar is shown in Fig. 2-6, and a pictorial representation is shown in Fig. 2-7. Free-cut invar was selected for two reasons. First, it was relatively stable dimensionally with temperature since its thermal coefficient of expansion was low, (0.89×10^{-6} in./in. per ^{o}F as supplied by the manufacturer). Secondly, it was easily machined. Machineability was important since gage plugs had to be bored into each end of the bar.

Note in Fig. 2-6 that a slightly deeper cut was made on the circumference of the measuring surfaces. This was done to prevent measuring errors caused by a binding action which could have occurred between the edges of the gage points and the bottom of the gage plugs. Also, to provide positive contact between the surfaces of the gage points and gage plugs, all such surfaces were polished in addition to machining.

Even though the thermal coefficient of expansion of invar is relatively low, provisions were made to keep the bar at as near a constant temperature as possible in order that its length be kept constant.

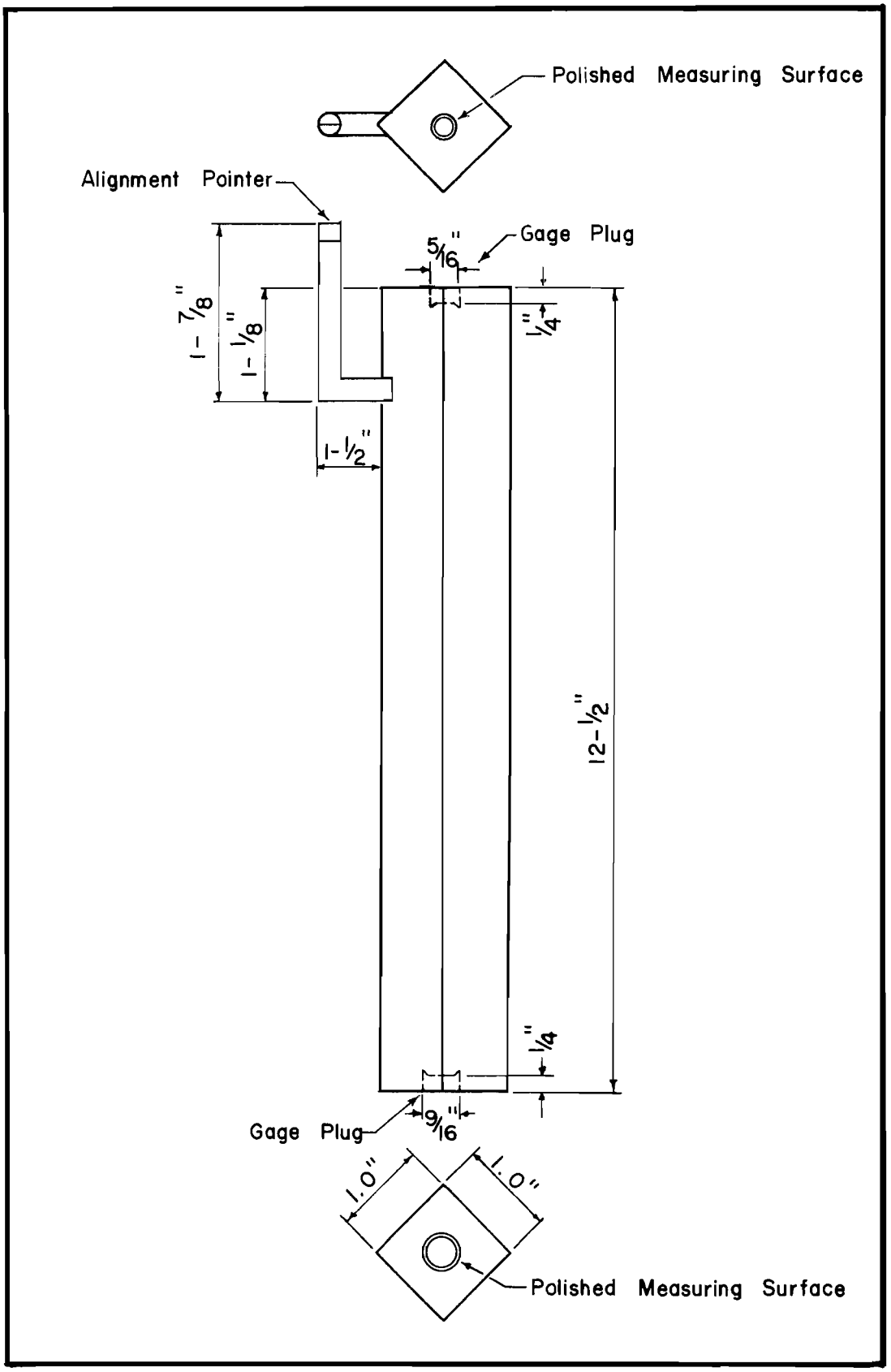


Figure 2-6. Standard Bar with Alignment Device

Fig. 2-7. View of Standard Bar Showing Polished Gage Plug

Fig. 2-8. Fiberglass Insulation of Standard Bar

This was done by first wrapping the bar with 3/4-in. -thick fiberglass insulation material (see Fig. 2-8) and second, by keeping the bar in an insulated box when it was not being used. The box containing the insulated bar was stored in a room with a temperature of 75F ±3F until it was necessary to move the box and bar into the laboratory for a measurement.

Despite the use of insulation, the temperature of the standard bar varied over a 5F range. The temperature of the standard bar was measured with a calibrated thermometer inserted between the insulation and the bar. This variation in temperature was sufficient to change the length of the standard bar by a measurable amount. As a result, the use of the bar for temperature compensation would have been limited. To eliminate this problem, all standard bar readings were corrected to correspond to the temperature of the bar on the initial reading. A sample data sheet included in Section 2.3 shows how this correction was made.

Preliminary readings taken with the standard bar showed that rotation of the bar on the comparator caused deviations in the strain reading. This meant that either the gage plugs or the gage points were not exactly plane and perpendicular to the longitudinal axis of the bar. For this reason an error in the standard bar reading would have resulted unless the bar was placed on the comparator in exactly the same position at each measurement. To eliminate this error, a steel pointer was affixed to the bar as shown in Figs. 2-6 and 2-8. The proper position of the standard bar was obtained on each measurement

by aligning the pointer with a vertical line on the upper cantilever of the comparator as shown in Fig. 2-9.

During the early part of the testing period, it was noticed that variations in strain readings could be obtained by applying various magnitudes of horizontal pressure to the standard bar. It was therefore necessary to develop a method of applying a constant horizontal pressure to the bar throughout the entire testing period.

The method selected, pictured in Fig. 2-10, consisted of an aluminum band and spring. One end of the band was fixed to the frame of the comparator while the other end could be placed around the bar and then attached to the spring which was also fixed to the frame. The positioning of the band around the bar was kept constant by the use of alignment marks placed at the midheight of the bar.

It should be noted that the methods of obtaining alignment and constant pressure, as described above, were also applicable to the measurement of a test specimen. A complete description of the procedure used in a test measurement is given in the following section.

2.3 Measurement Procedure

In order to more easily relate the various aspects of the comparator discussed in the previous sections, a complete description of a test measurement is included. It is helpful to refer to Fig. 2-11 which pictorially shows the sequence of steps used.

Also included in this section is a sample data sheet shown in Fig. 2-12 with data from the unrestrained shrinkage series. Inclusion

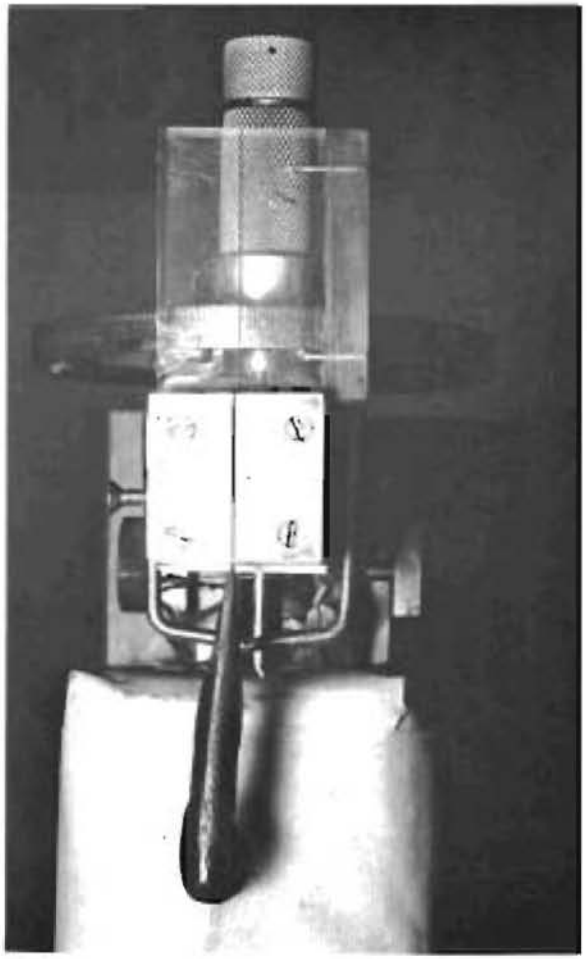


Fig. 2-9. Alignment of Standard Bar

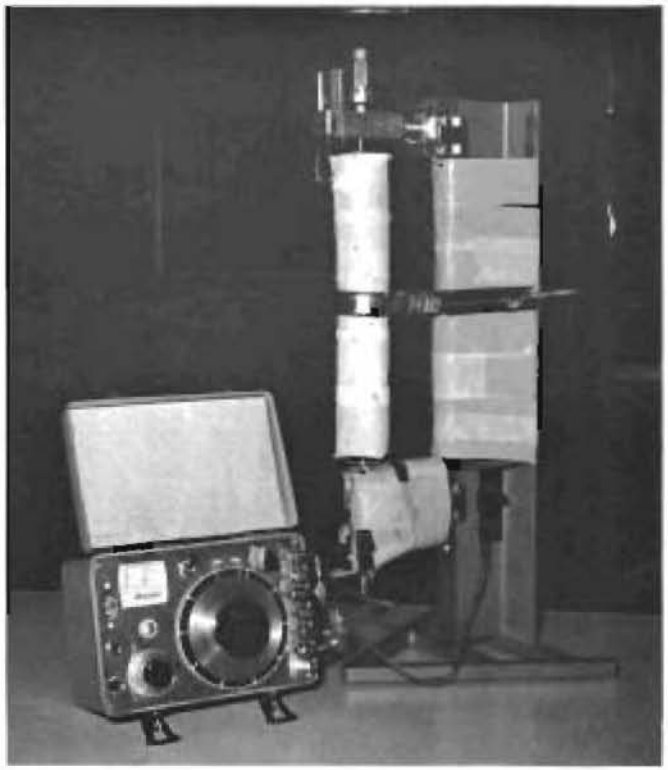
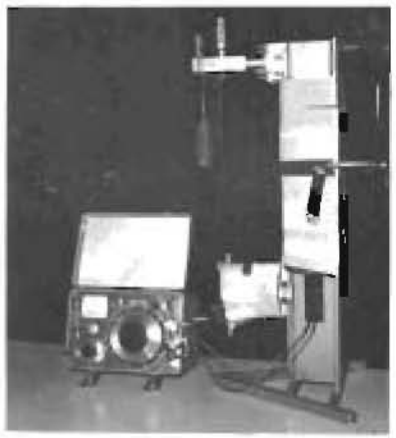
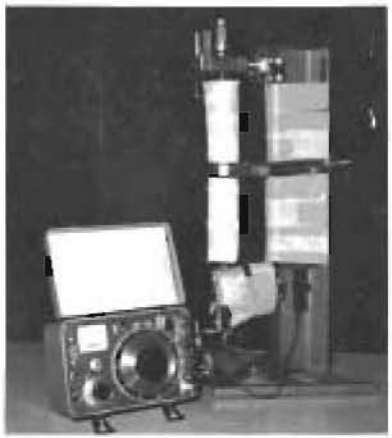


Fig. 2-10. Band-Spring Method of Applying Constant Horizontal Pressure to Standard Bar



a



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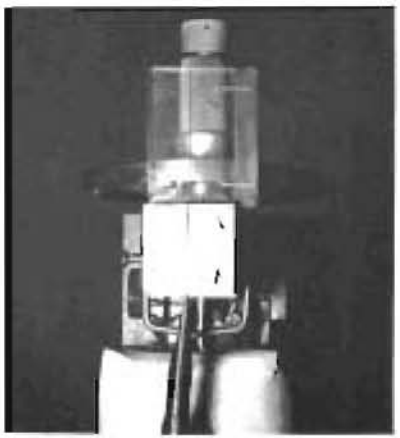

c

d

e

Fig. 2-11. Steps Used in the Comparator Measurement Procedure

$$\text{Correction to Standard Bar Reading} = \frac{(T_o - T)(0.89 \times 10^{-6})(12)}{1 \times 10^{-4}} \text{ divisions}$$

$$\text{Units} = \frac{(°F)(\text{in./in.}/°F)(\text{in.})}{(\text{in./div.})} = \text{"}$$

Date Time	Air Temperature °F	Standard Bar Temperature (T)- °F	Standard Bar Reading No. 1 - div.	Standard Bor Reading No. 2- div.	Standard Bar Average (A) - div.	Corrected Standard Bar Reading (A_c) - div.	Specimen Reading (B) - div.	Difference $B - A_c = C$ - div.	Change in Length $\Delta L = C - C_o$ div.	Unit Strain $= \frac{\Delta L}{12 \times 10^{-2}}$ micro-inch per inch
4-10-64 1125	76.5	76.5 T_o	86.2	86.2	86.2	86.2	117.5	+31.3 C_o	—	—
5-1-64 0900	77.0	76.0	80.6	80.8	80.7	80.8	107.7	+26.9	-4.4	-36.7*

* (-) sign denotes contraction

Figure 2-12. Sample Data Sheet for Comparator Readings

of this data sheet helps to explain the use of the standard bar.

The description of the measurement procedure is given in five steps as follows.

Step 1. The strain-gage wiring was connected to the strain indicator, and approximately five minutes was allowed for "warm-up." Next, the indicator was zeroed at a convenient value by use of the variable resistor. The weight was then hung from a fixed point on the cantilever and a strain reading was noted, (see Fig. 2-11a). The weight was then removed and the indicator was adjusted to deviate from zero by the same magnitude of strain but of opposite sign as that noted above.

Step 2. The standard bar was removed from the insulated box, and the bar temperature was recorded on the data sheet. The gage points of the comparator and the gage plugs of the bar were then wiped clean and the bar was placed, on the comparator with the gage points fitting into the plugs of the bar. After the upper gage point of the micrometer was adjusted to just enter the upper plug of the bar, the constant pressure band was placed around the bar at the midheight and attached to the spring. (See Fig. 2-11b). Next the pointer on the bar was aligned with the vertical line on the upper cantilever as shown in Fig. 2-11c. All alignment procedures now being completed, the micrometer was adjusted until the strain indicator galvanometer showed no deflection. This corresponds to the proper force as indicated by the use of the constant weight in Step 1. Finally, the horizontal scale of the micrometer was read with aid of the antiparallax hairlines. This value was recorded as standard bar reading No. 1. The bar was then returned to the insulated

box.

Step 3. With only a few minor modifications, the measurement procedures for the specimen were the same as those for the standard bar. First, the specimen was taken from its respective curing condition and placed on the comparator. The specimen shown in Fig. 2-11d is of the oven-cured series and has been wrapped in an insulating jacket before removal from the oven. The pressure band was again used and alignment of the specimen was accomplished with the aid of a pointer inserted through a vertical hole in the face of the upper cantilever. Figure 2-11e shows that the tip of the pointer was placed on a radial line on top of the specimen for alignment. The measurement was then made as described previously, and the specimen reading "B" was recorded as shown on the sample data sheet.

Step 4. The final step of the measuring process is a second measurement of the standard bar. The procedure was the same as that of Step 2 except that no second bar temperature was taken.

The purpose of making two bar measurements was that the use of their average minimized the error which might have been caused by a change in the length of the comparator during the interval between the first bar reading and the specimen reading. This was especially important for relatively hot or cold cured specimens.

Also, it was important that the measuring time interval be as short as possible. With practice, one could make a measurement of either the bar or specimen in approximately one minute.

Step 5 - Calculation methods. A second series of readings is included in Fig. 2-12 for the purpose of illustrating the technique involved in the use of the standard bar. This includes the correction of the standard bar reading and the comparison of the bar and specimen readings.

The correction to the standard bar reading was necessary for complete temperature compensation. This correction was made by the use of the formula shown at the top of Fig. 2-12, and was applied to the average bar reading A. Corrections were made to the nearest 0.1 divisions.

In the second set of readings of Fig. 2-12, it is seen that a bar temperature variation of 0.5F results in a correction of 0.1 divisions. It is interesting to note that only in 7 out of approximately 90 observations did the correction exceed 0.1 divisions. Also in over one-half of the observations no correction was necessary.

A primary advantage of the comparator is the elimination of the effects of frame movement and is shown in Fig. 2-12 by the calculation of C. The term C represents the difference between the length of the bar and specimen. Note that C is not affected by a change in the length of the frame because the values of the corrected standard bar reading A_c and the specimen reading B would either be increased or decreased by a constant.

It is evident that since A_c represents the constant length of the standard bar, any change in the quantity C must be due to a change in the specimen length represented by B. It follows that the difference in

C terms is the change in length of the specimen over a particular time interval. A final calculation was made in the last column of Fig. 2-12 which converts the change in length for a 12-inch gage length to strain with units of μin./inch.

2.4 Accuracy of Results

Since techniques were devised to eliminate most procedural errors, the main limitations in the use of the comparator were the physical aspects of the micrometer. These include the scale, the threaded screw within the micrometer, and the surface of the micrometer gage point.

As mentioned previously, the horizontal scale of the micrometer was read to the nearest 0.1 ±0.05 divisions. This corresponds to 0.833 ±0.425 μin./in. strain for a 12-in. gage length. Therefore the maximum error due to reading on any 2 observations was 0.833 μin./inch.

The final two aspects to be mentioned are related and are discussed as one error source. This is because it was difficult to differentiate between the errors caused by uneven threading of the micrometer screw and those caused by uneven surfaces of the micrometer gage point. If either or both of these conditions existed, a random error of varying magnitude would have been produced as the micrometer dial was turned.

From the calibration of this comparator by Matlock at The University of Texas, it was concluded that such errors were present in the micrometer. Precision gage blocks were used to check points

along the entire range of the micrometer including checks on sample revolutions. The results of Matlock's calibration is shown in Fig. 2-13.

Note that the first revolution of the micrometer dial (0.000 to 0.025 on the horizontal scale of the lower left curve of Fig. 2-13) encompassed the total range of readings of all tests of this investigation. Also, the maximum error over this range is shown to be approximately 30 μin. or 2.5 μin./in. strain.

It can now be said that strain values obtained by the use of this comparator have a maximum possible error of between 3 and 4 μin./in. considering all sources previously mentioned. It is therefore felt that, with this error analysis and the measurement techniques used, the test results reported in Sections 3.1 and 3.2 are within the limits of accuracy of the testing equipment.

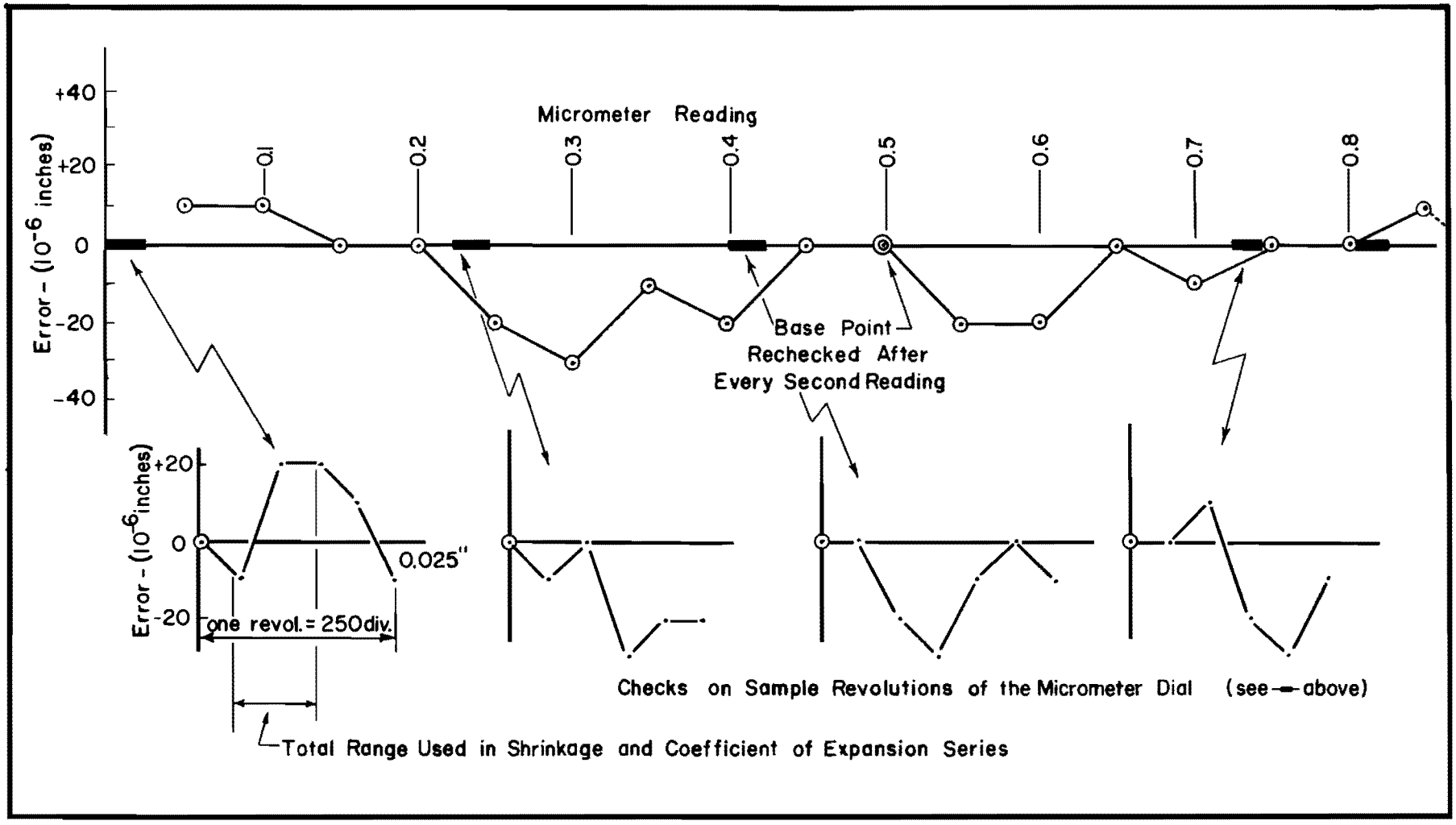

Figure 2-13. Micrometer Calibration Curves by Matlock

3. EXPERIMENTAL RESULTS

3.1 Coefficient of Linear Thermal Expansion

General. The determination of the coefficient of linear thermal expansion, hereafter called coefficient of expansion (K_T), is an important design factor as well as a factor related to the performance of a concrete in regard to its durability. For these reasons, and the fact that little information is available on the coefficient of expansion of the type of lightweight concrete studied in this investigation, the comparator device was used to compare the coefficient of expansion of one lightweight concrete with that of normal-weight sand and gravel concrete. Temperature measurements were made with embedded thermocouples and a portable potentiometer.

Curing of test specimens. In general, a total of 3 coefficient-of-expansion specimens (6 in. diam x 12 in. long) were moist cured in sealed polyethylene bags at 75F for 7 days, followed by 21 days of oven curing in air at 110F. At this time, the specimens were sealed and subjected to the initial temperature of the test series. The purpose of this curing procedure was to eliminate the effect that humidity changes would have produced on the concrete during the coefficient-of-expansion testing period. Table 5-2 in the Appendix contains a summary of the mix properties of each concrete tested. Note also in this table that a set of compression test cylinders was subjected to the same curing conditions as that of the coefficient-of-expansion specimens. This gave some information as to the actual strength of the expansion specimens. A

complete description of test specimens, sealing techniques, use of thermocouples, and laboratory procedures is found in Sections 5.1 and 5.2.

Discussion of data. Values of K_T in this and the following sections are reported as $\times 10^{-6}$ in./in. per ^{o}F.

The results of the coefficient-of-expansion series shown in Fig. 3-1 indicate that this property does not vary greatly between the regular-weight concrete and the lightweight concrete studied in this project. Note that the data points shown fall very near to a straight line in all three cases. In fact, values of K_T obtained by a straight line through the end points and those obtained by the use of a least squares fit differ by a maximum of only one unit in the third decimal place. However, as a matter of practicality, results are reported only to the second place.

Control specimen. The value of K_T of 5.6 for regular-weight concrete compares favorably with published values when the aggregate type is considered. The aggregates used were natural sands and gravels of the siliceous limestone type. Parsons and Johnson[1] report the coefficient of expansion of siliceous limestone aggregate to vary from 2.0 to 5.4 while Callan[2] reports a range of 5.8 to 7.0 for siliceous mortars. A combination of the two would approach the type of concrete used here as well as its value of K_T.

Lightweight results. In comparison, it is seen that the values of K_T of both lightweight specimens are slightly lower than that of the regular-weight mix. This relationship between normal-weight and lightweight concretes has also been reported by Monfore and Lentz,[3]

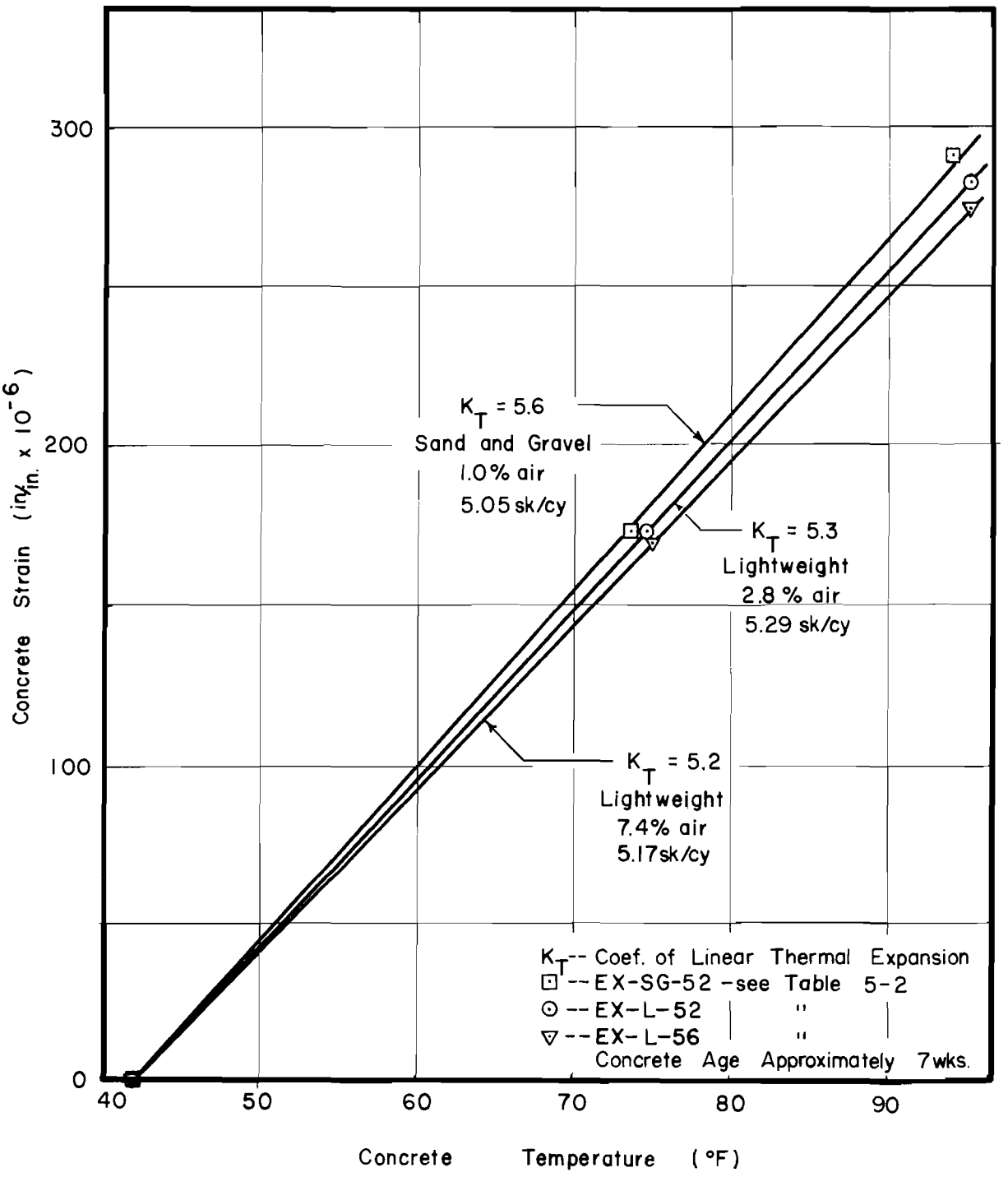

Figure 3-1. Concrete Strain — Temperature Properties of Normal Weight and Lightweight Concretes

and Philleo.[4]

A value of 4.5 for K_T has been reported for concrete containing all expanded shale aggregate.[5] When it is considered that the lightweight concrete used in this report contained a natural sand as fine aggregate, the higher values of 5.2 and 5.3 seem reasonable.

Effect of air content. In general, the addition of air-entraining agents decreases the value of the coefficient of expansion of concrete. Petersen[6] reports a reduction in the value of K_T of 0.4 for expanded shale concrete containing 13.9 per cent air over that of the same concrete with no entrained air. The reduction in K_T of 0.1 reported here therefore seems logical when the magnitudes of the air contents are noted, (see Fig. 3-1).

Although the data obtained in this test series was apparently quite good, additional series should be completed to investigate the effect of age on the coefficient of expansion of this type of lightweight concrete. Also, more specimens of each concrete type would help minimize any error due to experimental inconsistencies.

3.2 Unrestrained Shrinkage

General. The comparator device was used to determine the unrestrained shrinkage characteristics of four lightweight concrete specimens. Mix properties of these specimens are given in Table 5-3 of the Appendix. The test parameters were cement factor and curing condition. The curing conditions (bag at 75F and, oven at 110F) were chosen to represent the extreme cases which might be encountered in concrete usage. A complete

description of the specimen and laboratory procedures is found in Sections 5.1 and 5.3.

Early shrinkage characteristics. An attempt was made to measure the strain occurring prior to the initial comparator reading which was taken at a concrete age of about one day. This was accomplished by the use of embedment strain gages placed in the specimens at the time of pouring. The initial strain-gage reading was taken one to two hours after the cement was added to the mix. See Section 5.3 of the Appendix for a description of the type and placement of the strain gages.

The strains occurring in this initial period of about one day are shown in Table 3-1. The "Concrete Age" column gives the age of the concrete at which the final strain-gage reading and the initial comparator reading were taken, (with the exception of Shacklock).[7] Also included in Table 3-1 are values found by this experimenter in previous work with this type of concrete as well as one value for crushed granite and sand concrete reported by Shacklock.

Note that all mixes show expansion for the time period indicated; and that, in general, the lightweight concretes exhibit the greatest expansion. The expansion in all cases was probably due to bulking of the aggregate and complicated chemical reactions.

It should be emphasized that these volume changes are occurring in the period when the concrete is changing from a viscous pseudo-fluid to the initial stages of a pseudo-crystalline solid. As a result, the strains occurring in the concrete in this period are not completely transmitted

Table 3-1
Unrestrained Shrinkage Strain From the Time of Mixing to a Concrete Age of Approximately One Day

(Expanded Shale and Sand Aggregate
Unless Indicated Otherwise)

Mix Design	Cement Factor sk/cy	Air Content %	Concrete Age-From Time Cement Added (hrs.)	Shrinkage Strain x 10^6 in./in.
US-56-1	5.17	5.7	26.7	+318 [1]
US-56-2	5.08	7.2	20.7	+79
US-46-1	4.01	7.1	25.0	+250
US-46-2	4.01	6.8	27.5	+296
R-56-U-1	5.29	— [2]	18.0	+269 [3]
R-56-U-H-1	5.04	7.1	21.0	+260 [4]
Shacklock granite - sand	— [5]	—	24	+100

1 - + Sign Denotes Expansion
2 - Approximately 6 %
3 - Average of 3 Specimen, 1 Gage Each
4 - Average of 5 Gages, 1 Specimen
5 - Aggregate - Cement Ratio = 3.0 by Weight

to reinforcing steel which might be encased by the concrete. In fact, at an age of about one day, less than 50 μin./in. of steel strain (expansion) is exhibited by an encased steel bar. This value is based on data taken from 20 direct-tension specimens of the first report of this study.

Oven curing. The unrestrained shrinkage characteristics of oven-cured specimens after an age of about one day are shown in Fig. 3-2. The exact age is shown in Table 3-1. These curves represent the least squares fit of the data points and were plotted by a computer using a modified least squares fit program, (See Section 5.3).

The oven-cured specimens show an expansion of between 170 and 200 x 10^{-6} in./in. during the first day of oven curing because of the heating from room temperature to approximately 110F. Since only two measurements were made in this interval, this portion of the curves was approximated with consideration of temperature, coefficient of expansion (recognizing its limitation in "green" concrete), and time. As a result, the peak point, where shrinkage began to exceed expansion, is quite limited.

After the peak expansion is reached, the concrete shows a high rate of shrinkage which continues for 10 to 15 days. At this point, the shrinkage rate decreases to a relatively constant value which remains through 70 days. It is interesting to note that laboratory air-cured specimens of this type concrete show continued shrinkage up to approximately 300 days.[8] However, it is believed that a peak shrinkage value for the oven-cured specimens would have been reached somewhat earlier than

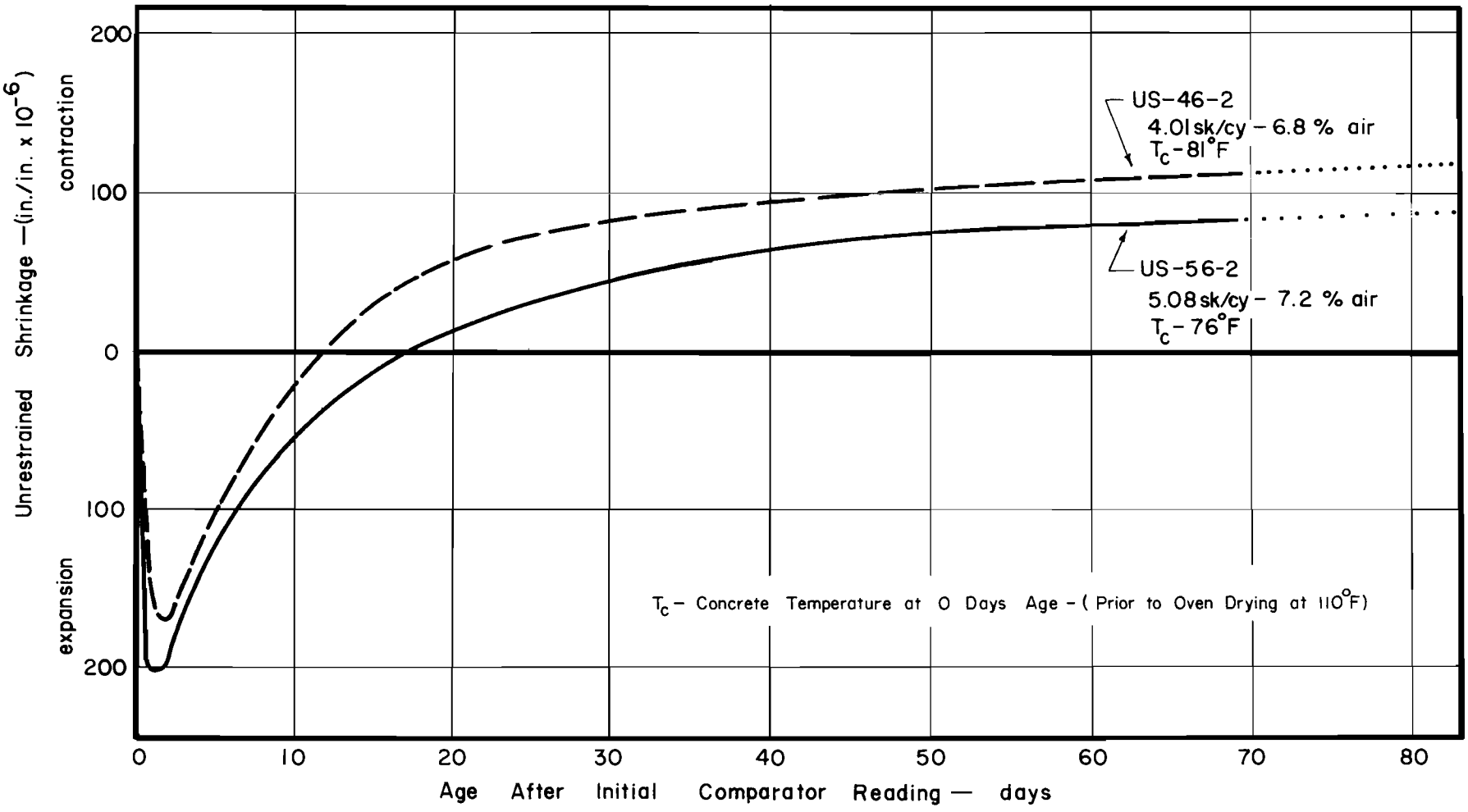

Figure 3–2. Unrestrained Shrinkage — Age After Approximately One Day for Oven Cured Lightweight Concrete

300 days had readings been continued.

Although the number of test specimens was limited, Fig. 3-2 can be used to show the effect of cement factor on shrinkage. Note that the 4 sk/cy mix exhibits the greater shrinkage, considering the portion of the curves above the horizontal axis. However, the total shrinkage of both specimens based on the initial peak points shows a smaller difference for the two mixes. In both cases the total shrinkage was approximately 280 x 10^{-6} in./in. at 65 days.

On the basis of Shideler's[9] results on a wide variety of lightweight aggregates, this particular aggregate used in conjunction with ordinary sand showed low shrinkage characteristics.

Bag curing. The unrestrained shrinkage characteristics of two bag-cured specimens after an age of about one day are shown in Fig. 3-3. Note that both specimens show similar expansion characteristics for the first few days. However, at this point both specimens began to shrink at different rates.

This type of concrete in this same curing condition has previously been shown to exhibit a relatively constant value of expansion over a 28-day period.[10] It is therefore believed that the shrinkage shown in both specimens of Fig. 3-3 was due to leakage of moisture from the polyethelene bags used to encase the specimens. A more realistic value for both specimens would be approximately 30 x 10^{-6} in./in. throughout the time period indicated.

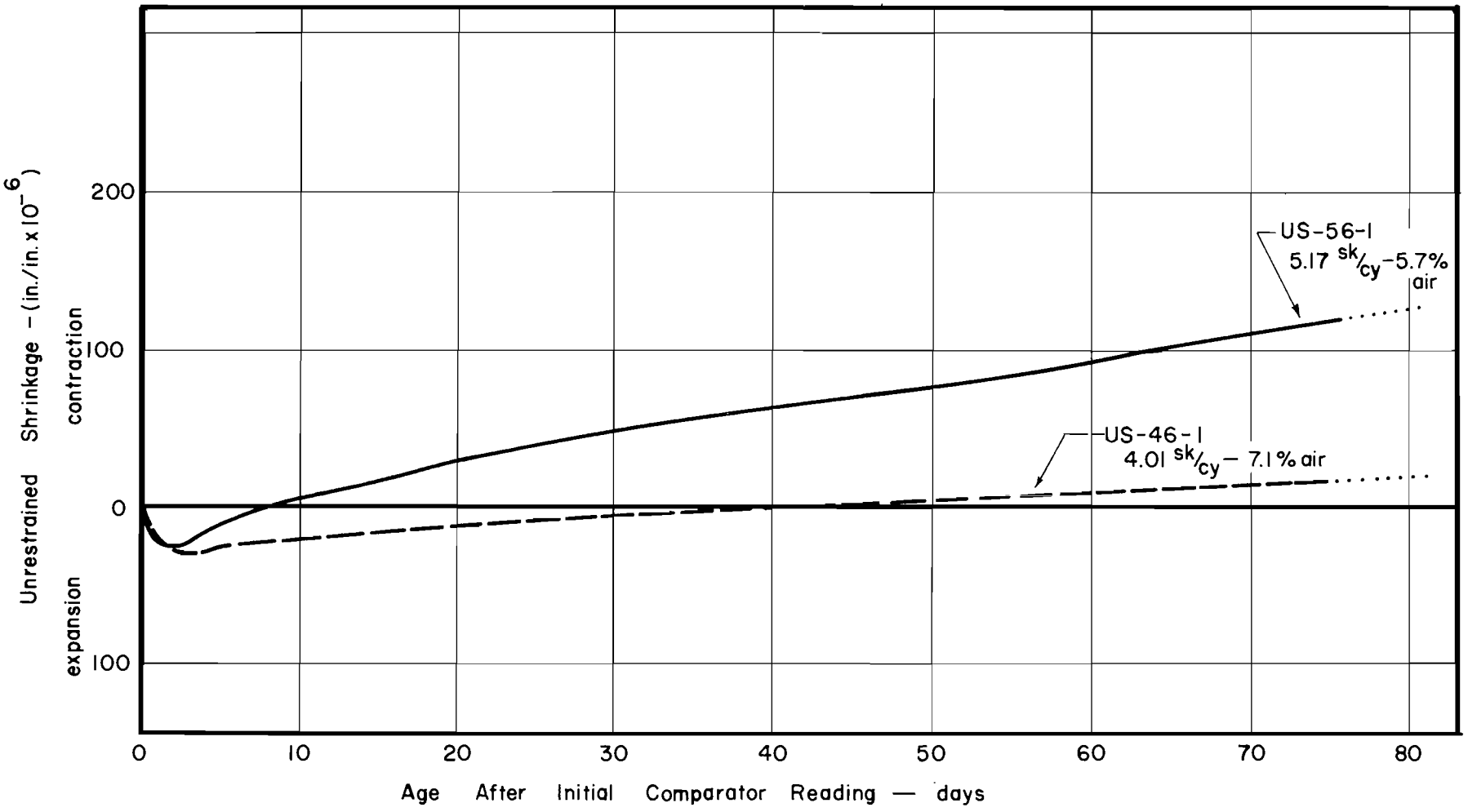

Figure 3-3. Unrestrained Shrinkage – Age After Approximately One Day for Bag Cured Lightweight Concrete

4. APPENDIX I - MATERIALS AND LABORATORY PROCEDURES

4.1 Concrete Materials

The materials used in this investigation include the concrete aggregates, cement, air-entraining agent, and water. A description of each is given as follows.

Aggregates. Properties of all aggregates used are shown in Table 4-1. A river-run sand obtained near the city of Austin was used as fine aggregate in both the regular-weight and lightweight mixes. The coarse aggregate used in the regular-weight concrete was of the same source as that of the fine aggregate and had a nominal maximum size of 1 inch. The coarse aggregate used in the lightweight concrete was a structural lightweight semicoated expanded shale with a nominal maximum size of 3/4 inch. The expanded shale aggregate was produced in Texas.

Cement. One brand of Type I portland cement conforming to ASTM designation C-150[11] was used throughout this study. The specific surface area of the cement was 1620 sq cm per gram as obtained from the Wagner Turbimeter test.

Air entraining agent. One brand of neutralized vinsol resin, meeting the Texas Highway Department 1962 Standard Item No. 437,[12] was used for the entrainment of air.

Water. City of Austin water was used throughout this study.

4.2 Laboratory Procedures

The procedures follwed in mixing and testing were the same as those used in a companion study by Ledbetter.[13] These procedures were held

TABLE 4-1

Aggregate Properties

Property	Lightweight Coarse Aggregate	Regular Wt. Coarse Aggregate	Regular Wt. Fine Aggregate
Sieve Analysis Cumulative % Retained			
1"	0	0	-
3/4"	1	9	-
3/8"	60	48	-
No. 4	98	93	0
No. 8	-	99	3
No. 16	-	-	20
No. 30	-	-	60
No. 50	-	-	92
No. 100	-	-	98
Pan	100	100	100
Specific Gravity (SSD)[1]	1.51	2.60	2.60
Absorption (% of SSD Wt)[2]	4.10	1.00	0.70
Unit Weight (pcf - dry loose)[3]	54.00	99.00	100.00

1. SSD - Saturated Surface Dry
2. Test made in accordance to ASTM Specifications C 128 and C 127
3. Test made in accordance to ASTM Specification C 29-42

constant, insofar as possible, throughout all phases of investigation.

Mixing. In selecting the proportions for the mix, ACI Standard 613A-59 was followed.[14] A 3 cu-ft-capacity, rotary, tilting drum mixer was used which permitted the mixing of many batches with consistent results. As the slump is generally considered to be the primary mix control device, a 3-in. slump was achieved on every mix made.* A rigidly fixed mixing procedure was used and is given briefly as follows:

1. The lightweight coarse aggregate was stored inside the laboratory and allowed to air dry thoroughly before use. In this way, the moisture condition of the aggregate was accurately known.

2. On the day the mix was to be made, the moisture content of the fine aggregate was closely determined by the drying method.

3. After coating the sides of the mixer with a small charge of concrete, the coarse aggregate was introduced into the mixer along with two-thirds of the mixing water. This was mixed slowly for ten minutes in order to allow sufficient time for the relatively pourous lightweight aggregate to absorb enough water to develop its "effective" moisture condition existent in the fresh concrete mixture.

4. The fine aggregate was then added and mixed briefly.

5. The cement was then added, together with almost all of the remaining water in which the air-entraining agent had been mixed (if used). The entire mixture was then thoroughly mixed.

6. The remaining design amount of water was slowly added

* Slump measurements were made in accordance to ASTM Specification C 143-52.

until the desired slump was reached. In any given mix, the total water used may vary slightly from the design total, depending upon the variations present in the amount water absorbed by the lightweight coarse aggregate, but this variation was usually insignificant and has been disregarded.

Air measurement. The air content of the fresh concrete was determined by averaging two measurements with an air meter meeting ASTM specification C-231. Because of the hardness and low absorption of the aggregate particles, it was concluded that this method was adequate without using a correction factor.

Initial curing condition. All test specimens, as well as control test cylinders, were poured in steel molds and left in the laboratory for the first 20-28 hours. The molds were then stripped and the specimens were placed in their respective curing conditions.

Control cylinder curing. Two curing conditions were used:

1. Bag cured - Moist cured at 100 per cent humidity in polyethylene bags at 75F.

2. Oven Cured - Oven cured at a low humidity at 110F.

Control cylinder testing. The basic control test used was a compressive test at 7 days on 3 bag-cured specimens from each mix. Also split-cylinder tests and additional compressive tests on cylinders of various curing conditions were included. All tests were static with loading rates of approximately 500 psi per minute. A Southwark-Emery 120,000-lb-capacity hydraulic testing machine was used in all tests within its capacity. Those cylinders above this machine's capacity were tested on one of two constant strain-rate testing machines available, (Riehle 400,000 lb and Young 200,000 lb).

5. APPENDIX II - MISCELLANEOUS

5.1 Test Specimens (Shrinkage and Thermal Coefficient Series

Specimens. All shrinkage and coefficient-of-expansion test specimens were 6-in.-diam by 12-in.-long cylinders formed in a special steel mold. A typical specimen is pictured in Fig. 5-1. The mold, shown is Fig. 5-2 was machined to allow precise placement of gage plugs.

Gage plugs. The gage plugs were machined from brass to prevent corrosion during the test period. A picture of the plugs is shown in Fig. 5-3 and a schematic drawing of the same is shown in Fig. 5-4. Note in Fig. 5-4 that the measuring surface of the plugs was recessed around its circumference to prevent binding with the measuring points during a test measurement. The distance between the measuring surfaces of the gage plugs was set initially at 12.0 in. in the mold.

Initial curing. All shrinkage and coefficient-of-expansion specimens as well as control test cylinders were left in the forms for 20 to 28 hours. At this time, the forms were stripped and the specimens were placed in their respective curing conditions.

5.2 Coefficient of Expansion Series - General

Temperature measurement. The method used to measure specimen temperature employed iron-constantan thermocouples and a Brown portable potentiometer, Model 126W2. Each thermocouple was calibrated individually over the range of temperatures used in the test series. Certified standard thermometers were used for the calibration. The results of

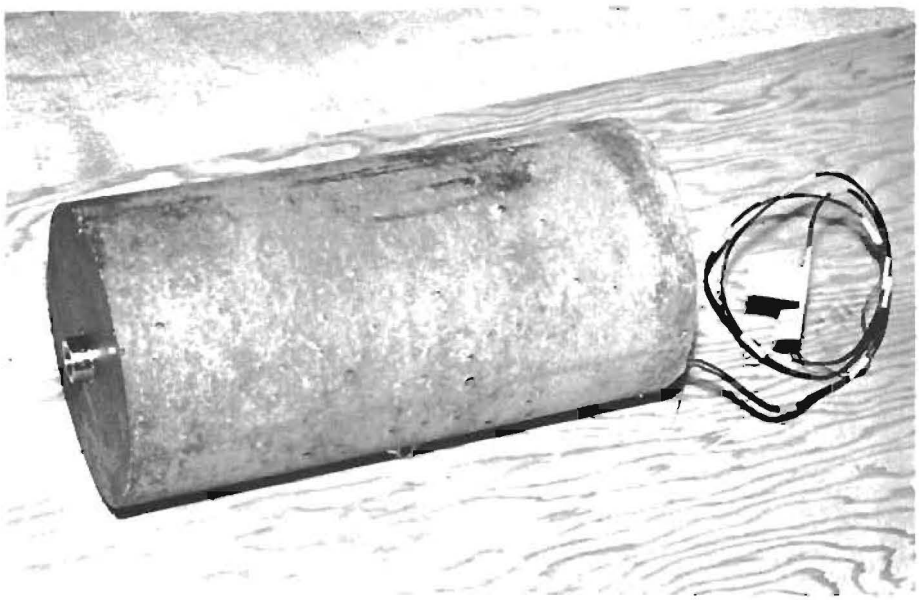

Fig. 5-1. Typical Shrinkage or Coefficient-of-Expansion Specimen

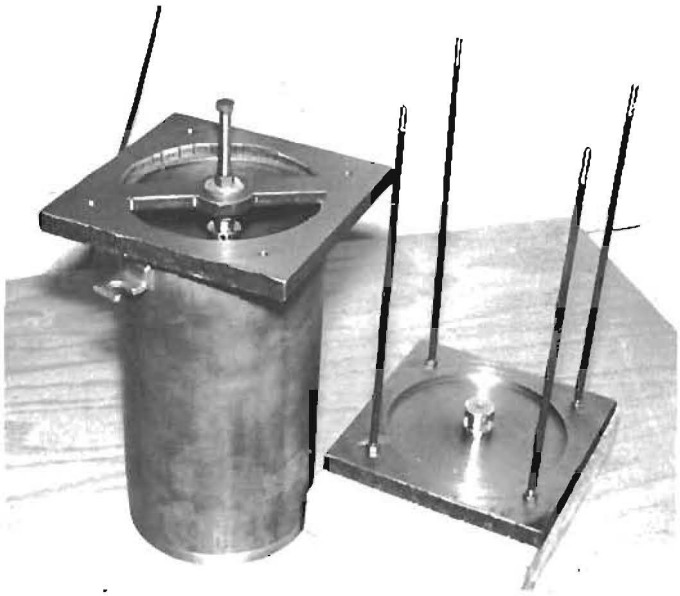

Fig. 5-2. Special Mold Used to Form Shrinkage and Coefficient-of-Expansion Specimen

Fig. 5-3. Brass Gage Plugs

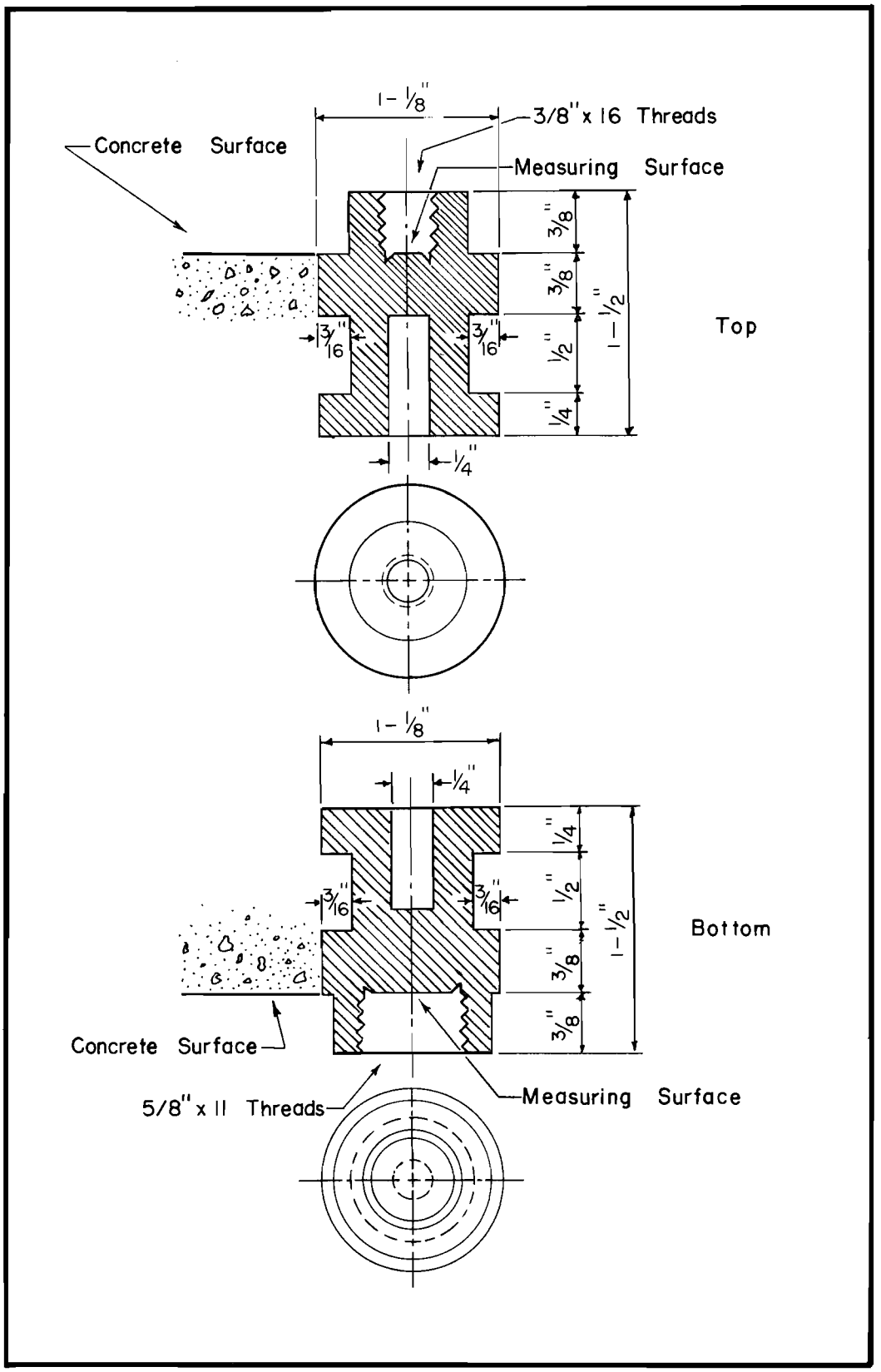

Figure 5-4. Embedment Gage Plugs - Brass

calibrations are shown in Table 5-1.

TABLE 5-1

THERMOCOUPLE CALIBRATION DATA

Specimen	T_T	T_A	T_T	T_A	T_T*	T_A
EX - SG - 52	32.0	32.0	76.0	77.5	97.0	98.6
EX - L - 56	32.0	32.0	76.0	77.5	92.0	91.5
EX - L - 52	32.0	32.0	76.0	77.5	86.0	87.6

T_T - Temperature measured by thermocouple.

T_A - Temperature measured by standard thermometer.

* - Difficulty with the potentiometer at this temperature range made it necessary to use the vault temperature.

The thermocouples were embedded (one per specimen) such that the couple junction was at the quarter point of the specimen longitudinally and transversely. Placement in this position made the thermocouples useful as indicators of the time an equilibrium temperature was reached as well as the magnitude of the temperature of the specimen.

Sealing technique. To eliminate shrinkage strain in the coefficient-of-expansion series, each test specimen, after moist curing in bags for 7 days, was oven dried at 110F for 21 days and then sealed in 2 polyethylene bags. Since the specimens were to be insulated, it was convenient to place the end pieces of the fiberglass insulation material within the bags. The bags were then cut so that the gage plugs and lead

wires were accessible for measurements. The area around the plugs and thermocouple lead wires was sealed with applications of petrosene wax and epoxy cement as shown in Fig. 5-5.

Testing technique. After the specimens were sealed they were placed in the initial temperature of the test series. The test temperature range was 94F to 42F. At this time all specimens had been wrapped with a fiberglass insulation jacket. Insulation was necessary since the specimens were to be removed from controlled temperature vaults to the laboratory for comparator measurements. When the specimens had reache an equilibrium temperature, requiring a minimum of two days, a series of comparator measurements was taken.

Each series of measurements was comprised of three comparator readings taken over a 24-hour period at a constant specimen temperature; however, in a few instances only two were taken. The average of three readings was used to minimize the effects of experimental error. This procedure also served as a partial check on the elimination of shrinkage in the specimens. The test program involved three series of measurements They were taken at temperatures of 94F, 75F, and 42F.

5.3 Unrestrained Shrinkage Series - General

Embedment strain gages. A concrete SR-4 type embedment gage was placed in each of four shrinkage specimens at the time of pouring. The gages were positioned to measure longitudinal strain and were placed at the quarter point, longitudinally and transversely, of the specimens. The initial strain-gage reading was taken one to two hours after the

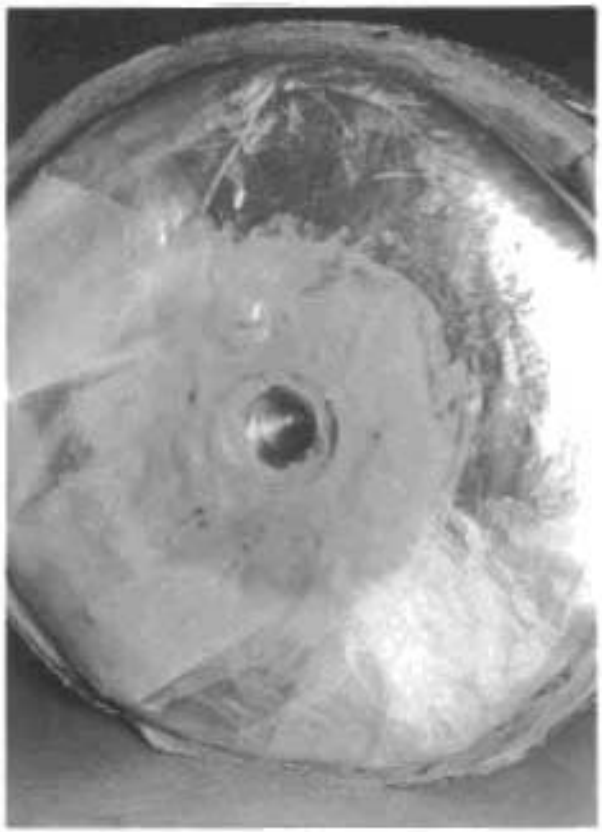

Fig. 5-5. Sealed Specimen of the Coefficient-of-Expansion Series

Fig. 5-6. Bag-Cured Unrestrained Shrinkage Specimen

cement was added to the mix in order to allow the temperature of the gage and concrete to become stable. A final reading was taken at the time of the initial comparator measurement, approximately one day after mixing.

It should be stressed that the strain indicated by these gages is not intended to be reported as an exact value. Previous work by this experimenter has indicated that these gages exhibit inconsistencies in indicated strain over a period of several weeks. As a result it was intended that these gages be used only as indicators of the "sign" and approximate value of the shrinkage strain.

Sealing technique - (Bag curing). At approximately one day of age, two shrinkage specimens were moistened and placed in polyethylene bags as shown in Fig. 5-6. It was necessary to cut the bags for access to the gage plugs and strain-gage lead wires. These openings were then sealed around the plugs and wires with a plastic mending tape.

Testing procedure. The testing procedure for all shrinkage specimens was the same with minor modifications for the oven-cured series. In that case the specimens were wrapped in an insulating jacket before removal from the oven for measurement. Comparator measurements were taken at the rate of five the first week, three the second week, and two or less per week for the remainder of the test period.*

Computer curve fitting. Although the data was generally quite good

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*Some variation in this schedule was necessary.

the shrinkage curves of Figs. 3-2 and 3-3 were plotted by a computer on the basis of the best least squares fit. A description of the computer program is given below.

> This program will compute by the method of least squares using orthogonal polynomials the polynomial of degree K, ($K \leq 100$), which best fits in the least squares sense M, ($M \leq 3000$) data points.[15]

5.4 Data Tabulation

This section contains data on concrete mixes as well as data used to prepare the curves of Section 5.3.

TABLE 5-2

CONCRETE PROPERTIES OF THE COEFFICIENT-OF-EXPANSION SERIES

Mix Design	Aggregate Type	Cement Factor sk/cy	Air Content %	Slump in.	f'_c - psi 7 Day Bag[1] Cured	f'_c - psi 7 Day Bag 21 Day Oven[2]	f_{sp} - psi 7 Day Bag Cured
EX-L-52	Exp. Shale and Sand	5.29	2.8	3	4020	5570	505
EX-L-56	Exp. Shale and Sand	5.17	7.4	3-1/2	3290	3930	457
EX-SG-52	Sand and Gravel	5.05	1.0	3-1/2	3760	4330	467

1. Moist cured in polyethylene bags at 75F.

2. Dry cured in air at 110F.

TABLE 5-3

CONCRETE PROPERTIES OF THE UNRESTRAINED SHRINKAGE SERIES
(All Expanded Shale and Sand Aggregate)

Shrinkage Curing	Mix Design	Cement Factor sk/cy	Air Content %	Slump in.	f'_c - psi 7-Day Bag[1] Cured	f_{sp}-psi, 7-Day Curing	
						Oven[2]	Bag
Bag 75F	US-56-1	5.17	5.7	3-1/2	2940	---	412
Oven 110F	US-56-2	5.08	7.2	3-1/2	3460	339	---
Bag 75F	US-46-1	4.01	7.1	3	2680	---	350
Oven 110F	US-46-2	4.01	6.8	3	2400	284	---

1. Moist cured in polyethylene bags at 75F.

2. Dry cured in air at 110F.

TABLE 5-4

UNRESTRAINED SHRINKAGE DATA

US-56-1[1] Bag Cured[2]		US-56-2 Oven Cured[5]		US-46-1 Bag Cured		US-46-2 Oven Cured	
Age[3] Days	Shrinkage[4] x 10^6 in./in.	Age Days	Shrinkage x 10^6 in./in.	Age Days	Shrinkage x 10^6 in./in.	Age Days	Shrinkage x 10^6 in./in.
0	0	0	0	0	0	0	0
0.9	+24.2	1.1	+200	2.0	+33.3	0.9	+152.4
2.9	+21.7	2.2	+181.7	4.0	+25.0	3.7	+124.2
4.9	-24.2	5.4	+101.6	7.0	+20.0	5.7	+ 85.8
6.0	- 3.3	7.0	+ 83.3	11.2	+23.3	6.8	+ 62.5
6.1	0	9.2	+ 47.5	12.9	+15.8	10.0	+ 15.8
10.1	- 9.2	12.9	+ 40.0	16.1	+20.0	12.9	- 10.8
12.0	- 9.2	14.9	+ 28.3	19.0	+15.8	17.0	- 49.1
14.9	-23.3	16.0	+ 0.8	23.1	+13.3	20.0	- 60.8
19.1	-20.8	19.2	- 21.7	26.0	+ 8.3	25.0	- 76.7
20.9	-36.7	22.0	- 24.2	31.1	+ 7.5	27.8	- 79.1
24.1	-34.2	26.1	- 45.8	33.9	0	45.8	-104.1
27.0	-45.0	29.1	- 51.7	51.9	- 4.2	60.8	-103.3
31.1	-58.3	34.1	- 48.3	66.9	-15.0		
34.0	-59.2	36.9	- 59.1				
39.1	-58.3	54.9	- 80.0				
41.9	-70.8	69.9	- 71.6				
59.9	-92.5						
74.9	-120.8						

1. Mix properties are given in Table 5-3.
2. Moist cured in polyethylene bags at 75F.
3. Zero days here corresponds to a concrete age of approximately one day. Exact ages are shown in Table 3-1.
4. (+) sign denotes expansion, (-) sign denotes contraction.
5. Dry cured in air at 110F.

5.5 List of Symbols

f'_c	Concrete compressive strength, psi
f_{sp}	Concrete split cylinder strength, psi
K_T	Coefficient of linear thermal expansion in./in. per ^oF.
μ	Micro unit (10^{-6})

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