1969

Preliminary report on concrete strains in pretensioned structural members, May 1969

D. C. Frederickson

Ti Huang

Progress Report No. 2

LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

CONCRETE STRAINS IN PRE-TENSIONED CONCRETE STRUCTURAL MEMBERS — PRELIMINARY REPORT

by
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July 1969

Fritz Engineering Laboratory Report No. 339.3

Project 339

PRESTRESS LOSSES IN PRE-TENSIONED
CONCRETE STRUCTURAL MEMBERS

Progress Reports Completed to Date

Progress Report No.	
1	COMPARATIVE STUDY OF SEVERAL CONCRETES REGARDING THEIR POTENTIALS FOR CONTRIBUTING TO PRESTRESS LOSSES. Rokhshar, A. and Huang, T., F. L. Report 339.1, June 1968
2	CONCRETE STRAINS IN PRE-TENSIONED CONCRETE STRUCTURAL MEMBERS - PRELIMINARY REPORT. Huang, T. and Frederickson, D., F. L. Report 339.3, June 1969

CONCRETE STRAINS IN PRE-TENSIONED CONCRETE STRUCTURAL MEMBERS - PRELIMINARY REPORT

by

Ti Huang

Donald C. Frederickson

This work was conducted as part of the project "Prestress Losses in Pre-Tensioned Concrete Structural Members", sponsored by the Pennsylvania Department of Highways and the U. S. Bureau of Public Roads. The opinions, findings, and conclusions expressed in this report are those of the authors, and not necessarily those of the sponsors.

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July 1969

Fritz Engineering Laboratory Report No. 339.3

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PROGRESS REPORT

(6) Concrete strains in pre tensioned..

FREDERICKSON D.C. HUANG T.

Year (7) July 1969	Vol	Part (339.3) n-2	Pages	ISSN/ISBN

Edition	Source of your information

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ABSTRACT

In this report are presented the preliminary results, at the end of one year, of a long-term study of the concrete strains in pre-tensioned concrete structural members. This study is part of a comprehensive investigation, aimed at the development of a rational basis for the prediction of prestress losses in such members.

Rectangular pre-tensioned concrete specimens were fabricated at two selected prestressed concrete plants in Pennsylvania, and stored in a moderate environment. Six levels of average initial concrete stress and five stress gradients were represented by these specimens. Strain measurements indicate that the elastic and creep strains are both proportional to the ratio of initial concrete stress to concrete strength, and that the shrinkage strain is strongly affected by the amount of longitudinal steel in the member. It is also found that for the duration reported herein, the effect of stress gradient on the creep strain is insignificant, the shrinkage strain varies directly with the logarithm of time, and the creep strain varies with the square of the logarithm of time.

1. INTRODUCTION

1.1 Background

Starting with the construction of the Walnut Lane Bridge in Philadelphia in 1950, the use of prestressed concrete in highway bridges in the United States has expanded very rapidly. During the years 1957 to 1960 alone, over two thousand prestressed concrete highway bridges were authorized for construction by the U. S. Bureau of Public Roads. Various organizations have issued guide lines, recommendations and specifications for the design and analysis of prestressed concrete structural members. Designs and fabricating methods have been standardized for various purposes.

It has long been recognized that the prestress, once introduced into concrete, does not remain constant, but decreases gradually with the progress of time. It is therefore necessary for the designer to estimate the losses of prestress throughout the anticipated life of the structure, and to provide an initial prestress which is sufficiently high so that the structural integrity will not be impaired as the losses take place. The estimation of the prestress losses has become one of the most crucial steps in the design of a prestressed concrete structural member.

In a pre-tensioned member, the major components of prestress losses are those due to the elastic, creep and shrinkage deformation of concrete and that due to the relaxation of steel. Initially, the prestressing strands are stretched to the specified tensile stress, and concrete is placed and cured around these stretched strands. The strands are released from their anchors after the concrete has attained sufficient strength. Immediately upon the transfer of stress, the concrete is compressed and shortens instantaneously, allowing the strands also to shorten, and to be relieved of some of its initial stress. This decrease of prestress is usually referred to as caused by the elastic shortening of concrete.

Creep is the time-dependent deformation of concrete due to sustained compressive stresses in the fibers. Shrinkage is the shortening of the concrete due to losses of liquids, whether drying or in chemical reactions. Both of these result in loss of the prestressing force.

Relaxation is theoretically defined as the decrease of stress in the prestressing element when it is restrained to a constant length. However, in prestressed concrete, the length of the prestressing element does not remain constant, but gradually shortens because of the shrinkage and creep effects. In the following, relaxation will be defined as the losses due to the physical properties of the prestressing element, subjected to varying strain conditions.

At the present time, in the design of pre-tensioned members for the Pennsylvania Department of Highways, two methods are used for the prediction of the prestress losses. The standard highway bridge beams were designed based on a total loss of 35 ksi (20%) for box sections and 40 ksi (22.8%) for I-beams. For non-standard sections, the loss of prestress is calculated by the following equation, according to the recommendation by the U. S. Bureau of Public Roads:[28]

$$\Delta f_s = 6000 + 16\ f_{cs} + 0.04\ f_{si}$$

where Δf_s represents the loss of prestress in steel, f_{cs} represents the initial concrete stress at the level of the centroid of prestressing steel and f_{si} represents the initial tensioning stress in the prestressing element, all in psi. Of the three terms in the right hand side of the expression, the first one, 6000 psi, represents the loss due to shrinkage. The second term can be subdivided into $5\ f_{cs}$ for elastic shortening and $11\ f_{cs}$ for the creep of concrete. The remaining term represents the loss due to relaxation.

Many factors contribute to the magnitude of these losses. These include the quality of the aggregates, water-cement ratio, strength of concrete, shape of the beam, magnitude and distribution of applied stresses and the properties of the prestressing strand. The previous methods do not specifically take into account any of these factors, but rather are based on average conditions.

In order to develop a more rational means of predicting prestress losses, a research program is presently being conducted in Fritz Engineering Laboratory at Lehigh University under the sponsorship of Pennsylvania Department of Highways and the U. S. Bureau of Public Roads.

1.2 Objectives and Scope

The main purpose of this research project is to develop a method for the estimation of the loss of prestress in pre-tensioned concrete highway bridge members used in the state of Pennsylvania. The several components of the loss are separated insofar as possible. Each is examined for its dependency on time, and a method for long-term predicting is to be developed.

The primary controlled variables in this investigation are the magnitude and the lateral gradient of the initial concrete stress. Rectangular specimens are fabricated at two producing plants, each using its normal concrete mix and fabrication procedures selected to represent an upper and a lower bound of potential prestress loss as affected by the concrete characteristics. The contribution of relaxation of the steel elements is studied in a separate part of this project.

2. PREVIOUS RESEARCH

2.1 General Research

Creep and shrinkage characteristics of concrete have been studied quite widely. Several of these studies, which are pertinent to this particular research, are reviewed in this chapter. A more complete review of related research is contained in Fritz Engineering Laboratory Report Number 339.1 "Comparative Study of Several Concretes Regarding Their Potentials for Contributing to Prestress Losses".[24]

T. C. Hansen and A. H. Mattock of the Portland Cement Association Research and Development Laboratory studied the relationships between the size and shape of members and their effect on the creep and shrinkage characteristics of concrete. One series of their specimens was cylindrical in shape with the radius varying between 4 to 24 inches and the length varying from 18 to 58 inches. A second series of specimens was I-shaped, having a depth varying from 11.5 to 46 inches, and a length varying from 63 to 132 inches. They presented their initial results in 1966.[12] They found that the volume-to-surface ratio, as a measure of the relative thickness, greatly influenced the creep and shrinkage of their specimens. However, this influence on creep was found to be significant only during approximately the first three months. After this initial period the rate of creep was the same for specimens of all sizes.

Perry H. Petersen and David Watstein of the Building

Research Division Institute for Applied Technology of the National Bureau of Standards conducted a study which utilized pre-tensioned prestressed concrete specimens.[21] Three specimen shapes were used in this study: octagonal, hexagonal, and square. Along with each set of stressed specimens, unstressed specimens were also cast. The stressing elements used were wires 0.1125 inches in diameter, tensioned to an initial prestress of 125,000 psi. The results from this study, reported in 1968, confirmed those of Mr. Hansen and Mr. Mattock. Specimens with a small mass ratio, the ratio of the net cross-sectional area of concrete to the surface area of the specimen per unit length, exhibited more rapid shrinkage at an earlier age than the larger specimens. However, after approximately 500 days, the total shrinkage strain of the specimens appeared to be independent of the mass ratio. A second conclusion of this study was that the loss of prestress appeared to vary linearly with the ratio of initial concrete stress to the initial strength.

In 1965 J. R. Keeton presented his findings from an extensive study of the influence of the size of specimens and the relative humidity.[16] His conclusions with respect to the size of specimens generally agreed with the previously mentioned studies. Mr. Keeton also concluded that the relative humidity of the storage environment had an inverse influence on the volumetric changes of the specimens.

A second part of the study conducted by J. R. Keeton dealt with the influence of magnitude of the applied stress on creep. It was concluded from his study that, practically speaking, creep strain is directly proportional to the applied stress. These results confirmed results found earlier by I. Lyse.[18]

Most of the creep studies had been conducted under constant stress. Under service conditions the stress in concrete is continuously varying. It is subjected to short duration live-loads, and a constantly decreasing prestressing force. For this reason the creep of concrete under varying stress conditions is of special interest. In 1958 Professor A. D. Ross of the University of London, conducted tests to study these conditions.[26] From this study, he developed several methods of predicting the creep under varying stress from creep data under constant stress.

Ross' method of superposition is based on the assumptions that the specific creep strain, or the creep strain per unit stress, is the same for tensile and compressive stresses, and also is independent of the stress history prior to the application of any particular stress. The creep and elastic strains are computed by combining algebraically the strains due to the initial stress and those due to each and every subsequent changes of stresses. This method depends on experimental specific creep data for stresses applied at different ages of concrete.

Another method developed by Ross is named the "rate of creep method", and is based on an additional assumption that the time rate of specific creep at any time does not depend on the age of concrete when stress is applied. This method has gained considerable popularity on account of its practicality. The following procedure, recently presented by H. L. Furr of the Texas Transportation Institute,[9] serves to explain the application of the method.

1. Develop shrinkage versus time and specific creep versus time relationships from laboratory test data.
2. Compute initial concrete stress at various points of the cross-section.
3. Calculate the creep strain increment at any point in the section occurring between time t_1 and time t_2 as the product of the concrete stress at the point at time t_1 and the incremental unit creep over that time interval.

$$\epsilon_{c_{1-2}} = f_{c_1} \times \epsilon^u_{c_{1-2}}$$

$$= f_{c_1} \times (\epsilon^u_{c_2} - \epsilon^u_{c_1})$$

4. Calculate the incremental shrinkage strain over this time interval.

$$\epsilon_{s_{1-2}} = \epsilon_{s_2} - \epsilon_{s_1}$$

5. Calculate total change of steel strain over the time increment as the sum of the creep and shrinkage strain increments.

$$\epsilon_{stl_{1-2}} = (\epsilon_{c_{1-2}} + \epsilon_{s_{1-2}})_{stl}$$

6. Compute steel stress loss over the time interval.

$$\Delta f_{s_{1-2}} = E_{st} \times \epsilon_{stl_{1-2}}$$

$$\Delta F_{s_{1-2}} = A_s \times \Delta f_{s_{1-2}}$$

7. Compute steel stress at the end of time interval.

$$f_{s_2} = f_{s_1} = \Delta f_{s_{1-2}}$$

8. Compute the change of concrete stress caused by the change of steel stress, considering both the axial and the bending effects.

$$\Delta f_{c_{1-2}} = \Delta F_{s_{1-2}} \left(\frac{1}{A} + \frac{ey}{I}\right)$$

9. Compute the concrete stresses at the end of the time interval.

$$f_{c_2} = f_{c_1} \pm \Delta f_{c_{1-2}}$$

10. Calculate the total concrete strain at the end of the time interval, including the effects of elastic rebound, creep and shrinkage

$$\Delta\epsilon_{elastic_{1-2}} = \frac{\Delta f_{c_{1-2}}}{E_c}$$

$$\epsilon_2 = \epsilon_1 + (\Delta\epsilon_{elastic} + \epsilon_c + \epsilon_s)_{1-2}$$

11. Repeat steps 3 to 10 for the next time interval, using the final values from the previous interval (steps 7, 9 and 10) as initial stresses and strains.

At North Carolina State University an extensive study was conducted by P. Zia on the effects of non-uniform stress distribution on creep and camber characteristics of prestressed concrete beams.[29] In this investigation creep tests were performed on tee, triangular, and square specimens subjected to uniform and non-uniform stress distributions. Mr. Zia concluded that the specific creep under a non-uniform stress distribution may be predicted by multiplying the specific creep under uniform stress by a factor determined specifically for that particular stress gradient. This factor was always greater than one. It was also observed that the maximum specific creep occurred at the most highly stressed fiber of the specimens which had the largest gradient and the highest stress.

2.2 Preliminary Investigation

2.2.1 Purpose

At the beginning of this research undertaking, a preliminary study was made on the creep and shrinkage characteristics of the concretes regularly produced by the several producers of prestressed concrete bridge members in Pennsylvania. It was felt that in view of the constant inspection of these producers by the Department of Highways, any special control in the fabrication of specimens for this research would be unnecessary, and also unrealistic. Instead, the preliminary study would identify the two plants which produce concretes exhibiting the highest and the lowest loss characteristics, respectively. Main concrete specimens would then be fabricated at these two plants. It was reasoned that information gathered in this manner would, for practical purposes, provide an upper and a lower bound of prestress loss to be expected of bridge members fabricated in Pennsylvania.

2.2.2 Test Specimens

The preliminary study specimens are cylindrical in shape, with a diameter of 8 in., a length of 24 in., and a concentric hole of 1.5 in. diameter. Eight specimens were taken from each of the seven plants, four from each of two batches of concrete produced for bridge member at the day of sampling. Three specimens from each batch were post-tensioned to a nominal concrete stress of 2000 psi, by means of a $1\frac{3}{8}$ in. Stressteel bar. Longitudinal concrete strains were measured by means of a Whittemore mechanical strain gage with 10 in. gage length. The fourth specimen from each batch was left unstressed and provided information on shrinkage strains.

2.2.3 Extension and Conclusion of Preliminary Study

The initial preliminary study ended inconclusively when concrete from three plants showed nearly equal high loss characteristics. An extension was then carried out including these three plants as well as the one plant corresponding to the lowest potential prestress loss. The effect of transporting concrete materials from one plant to another, and the effect of the actual concrete strength at post-tensioning time, were also included in the extended portion of the preliminary study.

Through this extension, the researchers were able to identify the one plant which produces concrete with the highest characteristics affecting prestress losses. They also concluded that transportation of concrete materials greatly affect the behavior of specimens produced thereof, and that the behavior of concrete from each plant is reasonably consistent.

A more detailed description and discussion of the preliminary investigation is contained in a previous progress report of this project, Fritz Engineering Laboratory Report No. 339.1, by Rokhsar and Huang.[24]

3. DESCRIPTION OF EXPERIMENT

3.1 Purpose

The main phase of this research program dealt with the contribution of concrete to the prestress loss including creep, elastic shortening, and shrinkage. Many factors contribute to these loss characteristics. These include:

1. Type, quality, and quantity of materials
2. Quality of concrete
3. Shape and size of specimen
4. Concrete stresses
5. Lateral gradient of stresses
6. Environmental conditions

Factors 1 and 2 are varied in that two companies were selected to make the main specimens. Factor 3 was held constant, while factors 4 and 5 are the main variables in this study. Factor 6 is not controlled but recorded.

3.2 Test Specimens

3.2.1 Materials

All materials used for the main specimens were required to meet the specifications for prestressed concrete bridge members stipulated by the Pennsylvania Department of Highways. On the first dates of concreting at each plant, samples of aggregates and cement were taken by the PDH Materials Testing Laboratories, and tested for their various properties. The results of these tests are included in Appendix 1 of this report.

The minimum compressive strength requirements were 5500 psi at transfer and 6000 psi at an age of 28 days. These requirements are higher than those presently used for highway bridge members, but were selected to reflect the trend towards higher concrete strengths. From the pilot study, it was found that these strength requirements could be satisfied at both selected plants without changing the mix design normally being used. Therefore, the concrete used in the specimens is actually representative of the concrete being used presently for bridge beams, in spite of the higher required strength.

3.2.2 Treatment

The treatment of the specimens at the plants was to be essentially the same as the treatment of their bridge beams. The placement and curing of concrete were to follow procedures identical to those for bridge members.

3.2.3 Size and Shape

As previously stated, it has been found that the size and shape, more specifically the volume-to-surface ratio, has a significant effect on the magnitude of creep and shrinkage strains. An investigation of the volume-to-surface ratio of standard prestress concrete bridge beams used in Pennsylvania showed that this ratio varied between 5.6 inches and 3.1 inches with a mean of 4.0 inches. The cross-section of the specimens was selected as rectangular, 12 inches x 24 inches, with a volume-to-surface ratio of

4.0 inches, with a length of 12 feet 0 inches. This length was chosen so that complete transfer of the prestressing force would occur outside of the middle third where strain measurements would be made. Additional rectangular specimens, used for shrinkage measurements, were to have the same cross-section but a length of 3 feet 0 inches.

Two full-size specimens were also fabricated so that the results from the rectangular section could be compared and correlated to actual highway bridge members. These were a 36 inch x 36 inch box section with a closed void at one end, and a through void at the other end, and a 42 inch x 24 inch I section. Both specimens were 31 feet 0 inches in length. Three-foot shrinkage specimens were also to be fabricated along with the full-size members.

3.2.4 Prestress

It was decided to use straight prestressing strands in all the specimens. It was felt that the prestress loss in members with draped strands could be satisfactorily predicted from information obtained from straight strand specimens. Twelve different prestress distributions were used covering a range of nominal transfer stresses from zero to 3600 psi. Nominal stress is used here to designate concrete stress calculated on the basis of gross concrete section and pre-tensioning force before transfer. The various stress distributions are shown in Fig. 1. These distributions represent 6 levels of stress and 5 different gradients. The prestressing element was chosen to be 7/16 inch 270 k 7-wire uncoated stress-relieved prestressing strand. The two producers chosen for the fabrication of these main specimens both use the same strand supplier, thus eliminating one source of variation.

3.2.5 Number of Specimens

For each stress distribution, two specimens were fabricated from different batches of concrete at each plant. For example, the 1.0 series, which is comprised of three stress distributions, contains a total of twelve specimens - six from each plant. Two batches of concrete would be used at each plant. From each batch would be fabricated three of these specimens. In addition to the stressed specimens, four shrinkage specimens were also to be fabricated at each plant - two specimens from each batch. These shrinkage specimens would contain the same reinforcement and the same distribution of prestressing strands as the uniformly stressed specimens in that series, except that no force would be introduced in these strands. Table 1 lists the various specimens used in this study.

3.2.6 Non-prestressing Reinforcement

The rectangular specimens are provided with Number 3 web reinforcement at 6 inch spacing and two Number 3 longitudinal bars near the top surface. The reinforcing plan is shown in Fig. 2.

To facilitate fabrication and storage, steel end plates were used at both ends with the strand pattern drilled. These end plates also sealed off the ends to moisture movement. The two full-size beams were reinforced according to Pennsylvania Department of Highways standards with a few minor modifications (see Figs. 3, 4, and 5).

3.2.7 Instrumentation

All strain readings were measured by a 10-inch Whittemore strain indicator with a precision of 10^{-4} in., or 10 micro-inches per inch of strain. For the long rectangular specimens, strain measurements were confined within the middle third to avoid any end effect. For the full-sized specimens, strains were measured at various elevations at regular intervals along their length (Fig. 6). Each target point for strain measurements consisted of a brass insert and a stainless steel contact seat. The brass inserts were first coated with a layer of fine sand to improve their bond with concrete. These were attached to the inside of the specimen molds at their predetermined positions before the placing of concrete. At the end of curing, the forms were removed, and the stainless steel contact seats were screwed into the brass inserts. A more detailed description of this instrumentation can be found in an earlier report.[24]

3.2.8 Laboratory Arrangement

All specimens were transported to the Fritz Engineering Laboratory for storage and observation as soon as possible after transfer of prestress. The laboratory space is heated during the winter months, but has no other controls of temperature or humidity. Therefore, the specimens may be said to be exposed to a mild, but not constant environment.

The rectangular specimens were stored in vertical position, in order to avoid any longitudinal restraining effect of a support. The compressive stress caused by the weight of the specimen was approximately 10 psi at the gage points, and its effect on the measured strains was considered negligible. The variation of temperature and relative humidity over this storage area (approximately 10' x 30') was continuously recorded by a thermohygrograph.

The full-size beams were stored at a different section of the laboratory. They were supported as simple beams and were subjected to sustaining midspan loads of approximately 70,000 lbs. each. A lever mechanism with a 20 to 1 arm ratio was used to transmit the load, as shown in Fig. 7. The actual load supported by each beam was monitored by SR-4 strain gages mounted on two Stressteel loading bars.

3.2.9 Data Acquisition

Immediately prior to the transfer of prestress, a complete set of strain readings were taken. These were used as the basis of reference for all subsequent readings. Measurements were made immediately after transfer, upon arrival at the Fritz Engineering Laboratory, and thereafter at pre-selected intervals of from 3 to 100 days (see Table 2).

Most strain readings, when taken, were recorded directly on computer cards to facilitate data handling. The only exceptions were those immediately before and after transfer of prestress, taken at the producing plant. These were recorded on paper and transcribed over to punch cards at a later time.

4. FABRICATION OF SPECIMENS

4.1 Rectangular Specimens

4.1.1 Introduction and Designation

As originally planned, the two specimens of each stress distribution would be fabricated on separate dates. However, after a discussion with the producers, it was decided that both sets of the same series could be fabricated simultaneously using separate batches of concrete. By so doing, the number of fabrication dates was reduced substantially which represented considerable savings in cost and time. Also, this procedure assured that the prestress force in the two duplicating specimens was identical.

Each rectangular specimen was designated by its series name and a two-letter individual code. The series name refers to the average initial nominal concrete stress in the specimen. Of the two letters, the first identifies the concrete stress distribution, as shown in Table 1. The second letter of the two-letter code provides information on the producing plant. The specimens produced at the plant whose concrete exhibited the highest loss characteristics were designated A and B; those produced at the plant representing the lowest loss characteristics were designated C and D.

4.1.2 Fabrication of A and B Specimens

The fabrication of rectangular specimens at the plant whose concrete had the highest loss potential began on March 25, 1968 and was completed on April 25, 1968. An outdoor prestressing bed approximately 150 feet in length was used with the forms set up near the dead end.

The first step was to feed the strands through the bulkheads and through the specimens' end plates in their predetermined positions. After this had been completed, all the strands were tensioned to a low preliminary stress (approximately 1000 psi) to reduce the sag and also to insure that there were no strands tangled.

A load cell was placed on one strand near the cgs between the bulkhead and the strand chuck. This load cell served two functions. This strand would be the first to be stretched. The load cell was used to control the jacking force, and the hydraulic jacking system was adjusted accordingly so that the remaining strands would be jacked uniformly to the desired level. Strand elongation measurements were also used as a second check on the tensioning force. The load cell was left on the strand to monitor the strand stress during the fabrication period. Readings were taken after the tensioning of all strands, and again immediately prior to release so that the actual force in the strands could be determined.

In order to achieve the needed eccentricity for the non-uniform stress distributions, the bottom pallettes were elevated the required amount (Fig. 8). Once the pallettes were in position, the non-prestressing steel was tied in place. The side forms were then fastened in place. Since the brass inserts for the gauge points had been previously attached to the forms, extreme care was taken in positioning them so that the inserts would not be damaged.

The shorter shrinkage specimens were also fabricated with the same strand pattern and the same amount of mild steel per linear foot as the main specimens. However, there was no tension applied to the strands.

The maximum batching capacity at this plant was two cubic yards. As the 1.0, 1.5, and 2.0 series each contained six main specimens, requiring a total of 6 cubic yards, it became necessary to use two batches of concrete to cast each half series, plus the companion shrinkage specimens and control cylinders. Concrete for these specimens was placed in two layers of approximately equal thickness, each from one batch, and vibrated according to the same procedure as used ordinarily for bridge members. The 3.0 and 3.6 series each consists of only 2 main specimens and 2 shrinkage specimens; therefore, one batch was sufficient for each half series. One 0.0 series specimen was also cast along with each 3.0 and 3.6 half series.

In all cases fifteen standard cylinders were cast from each batch of concrete for strength and modulus determination. Information on proportion and other relevant properties of the concrete mixes are in Table 3.

The specimens and the cylinders were cured using a procedure identical to that regularly used for highway bridge members at this plant. All the rectangular members were cured by a radiant heat system. The prestressing bed was equipped with two heating pipes, one on each side of the forms. After the exposed concrete surfaces were trowel-finished and sealed to prevent moisture from escaping, tarps were draped over the beams and the heat was applied.

The standard concrete cylinders were moist-cured in a steam box at approximately the same temperature as the beams and for the same period.

The length of curing period at the plant was approximately 66 hours. This long curing period was necessitated by the high initial strength requirement. Throughout the period, temperature of the specimens and the cylinders was recorded. The concrete temperature was elevated up to approximately $140^{\circ}F$ in 8 to 12 hours. Afterwards, the temperature gradually decreased to approximately $100^{\circ}F$ at the end of the curing period.

Three cylinders from each batch of concrete were tested for compressive strength before the end of the curing process. These tests were conducted by the personnel of the producing plant, and were used to control the termination of curing. Table 4, column 3, lists the results of these tests.

Once the curing cycle was completed, the forms were removed and the stainless steel gage points were threaded into the inserts in the beams. The base strain readings were then taken, before the transfer of prestress.

At this plant, transfer of prestress was affected by cutting individual strands simultaneously at both ends of each beam.

These cuts were made by use of acetelyne torches. Immediately after the strands were released, another set of data readings was taken.

Three cylinders from each batch of concrete were immediately transported to Fritz Engineering Laboratory for strength and modulus test. This was necessary because of lack of strain-measuring capacity at the producing plant. On an average, these modulus determinations were made approximately 3 hours after transfer of prestress.

Shortly after release, the rectangular specimens were loaded on trucks and transported to the laboratory where they were placed in their upright positions.

The total time from initial tensioning to transfer of prestress varied from 72 to 76 hours.

4.1.3 Fabrication of C and D. Specimens

The fabrication of rectangular specimens at Plant C-D, the plant whose concrete exhibited the least loss characteristics, began May 20, 1968 and was completed on July 31, 1968. At this plant the prestressing and concreting facilities were indoors, and the prestressing bed used was approximately 300 feet in length.

The procedures for fabrication of the specimens were similar to those used at the other plant. In the following paragraphs, only the differences will be described.

The strands were gang-stretched to the desired stress level. Control of the initial stretching stress was by elongation primarily, and pump pressure secondarily. A load cell at the dead end was used to record the actual force in these strands from the time they were tensioned until they were released.

Plant C-D's batching equipment was large enough to enable the casting of a complete series with 2 batches. The procedure of placing the concrete used was the same as used previously, i.e., half the series from one batch, placed and vibrated in two layers, and the remaining series from the second batch. Mix proportions were recorded and standard cylinders were cast from each batch.

Control cylinders and specimens were treated together by steam-curing, for a period of approximately 31 hours. Two parallel steam pipes were positioned on either side of the specimens. These pipes had small holes drilled in them through which the steam flows in a vertical direction. The curing temperature was approximately 135^{o}F, with an initial ascending period of 4 hours, a period of constant temperature of 25 hours, and a cooling off period of 2 hours. The actual fluctuations of temperature throughout the curing period were recorded.

Just prior to release, cylinders were tested to determine the concrete strength. This information is shown in Table 4. As in stretching, the release of bulkhead anchorage was done by gang jacking, so that all strands were released simultaneously. Information pertaining to concrete mix, curing, and properties of fresh and hardened concrete is assembled in Table 3.

4.2 Full-Size Specimens

4.2.1 Fabrication of I-Beam Specimen

Both full-sized beam specimens were fabricated at the plant corresponding to the highest potential prestress loss. The fabrication of the I-beam specimen was started on June 3, 1968 and was completed on June 6, 1968. Because of economic and scheduling reasons, this specimen was not cast on one of the regular prestressing beds at this plant. Instead, two 35-foot prestressed concrete I-beams, placed approximately 5 feet apart, were used to resist the prestressing force prior to transfer. Specially reinforced steel end plates were placed across each end of these beams to serve as bulkheads. The prestressing strands were then strung in their prearranged pattern between these plates.

Each strand was initially tensioned, and then they were individually tensioned to the desired level. Because of the elastic shortening of the frame beams, tension in strands decreased as each subsequent strand was being stretched and anchored. It was necessary to re-tension each strand twice, to secure the desired stress. Two load cells were used to monitor the force in the strands.

After the completion of jacking and anchoring, the nonprestressing steel was placed and the forms for the concrete beam were assembled in position.

Three batches of concrete were used to fabricate the I-beam specimen. Each batch was placed in uniform layers, and then vibrated. As before, standard cylinders were made from each batch and pertinent mix information was recorded.

Along with the 31 foot 0 inch specimen, a shorter 3 foot 0 inch shrinkage specimen was fabricated. As in the case of the rectangular specimens, this shrinkage specimen contains untensioned strands, in the same pattern as in the prestressed specimen, and was cast from the same concrete utilizing the same placing procedures. Details of these specimens are shown in Fig. 3.

The method of curing was the same as that used for the rectangular specimens at this plant. The beams were subjected to radiant heat, and the cylinders were cured in a steam box. The temperature of curing was the same as used for the rectangular specimens.

4.2.2 Fabrication of Box Beam

The fabrication of the box beam at Plant A-B was started on June 11, 1968 and completed on June 13, 1968. The method of fabrication was similar to that used for the I-beam.

After the strands were tensioned, the lower non-prestressed reinforcement was tied in and the side forms were put in place. A uniform layer of concrete 5 inches high was then placed to form the bottom wall of the box. Plywood voids of the standard dimensions were then installed. The top reinforcement was laid in place. Then the casting of the concrete was completed.

This specimen was fabricated with a through-void at one end, and an end diaphragm at the other end. Correspondisgly, two shrinkage specimens were fabricated, both having the same strand pattern. One of these has the ends closed and the other has both ends open. Details of these specimens are shown on Figs. 4 and 5.

Four batches of concrete were used to cast this specimen together with the shrinkage specimens. Again, pertinent information was recorded and standard cylinders were cast from each batch.

The specimens were cured under the identical conditions as the other specimens at this plant. The method of release was also the same.

5. DATA REDUCTION

5.1 Concrete Strength and Modulus Determination

Standard concrete cylinders from each series were tested for compressive strength and modulus of elasticity characteristics at approximately 3 hours, 7 days, 28 days, and 90 days after release. These tests were conducted in compliance with the appropriate ASTM testing specifications. A 12" compressometer was used to measure the concrete strain at predetermined loads.

The secant modulus was calculated between two points on the stress-strain diagram: (1) the point corresponding to zero stress and (2) the point corresponding to the average nominal prestress in the series. The results of these tests are listed in Table 4.

5.2 Uniformly Stressed Specimen Data Reduction

For the reduction of the strain data, extensive use was made of computers. The major programs used are listed in Appendix 2.

The first step in the reduction of the data for the uniform series was to calculate the change in the readings. The initial readings which were recorded before the transfer of the prestressing force were used as the reference bases. All subsequent readings were subtracted from these original readings. The differences between these readings represent the change of gage length, and will be referred to as del values.

Next, the del values from each specimen were carefully examined; those obviously in error were discarded, and the rest averaged. For each uniformly stressed specimen, at most four of the twenty del values needed to be discarded. In most cases, no discarding was necessary. Therefore, each average del value was calculated from 16 to 20 individual readings. From these average del values, it was found that the maximum difference between the duplicate specimens of a series was less than 10%. Because of this small difference, it was decided to average the del values from the duplicated specimens. This yields an average del value representing 35 to 40 individual readings.

5.3 Non-Uniformly Stressed Specimen Data Reduction

Basically, the same approach was used for the non-uniform series strain values as was used for the uniform series. The before-release recordings were used as the reference, and subsequent readings were subtracted from these. The del values of strain from the same stress level were then averaged.

An assumption of linear strain distribution across the cross-section was then made. A least square curve fit of the strain versus distance from the high stress face was used to enforce this assumption. The maximum deviation of the experimental data from the best fit straight line was 3%. In the subsequent analysis, strain values from the straight line were used.

5.4 Shrinkage Specimen Data Reduction

The methods used for the reduction of the shrinkage data were identical to the methods used for the uniform specimens. Each average shrinkage del value was calculated from 7 to 16 measured values, representing all shrinkage specimens of one series.

5.5 Curvefitting

Regression subroutines were used to find the best-fitting functions for the data obtained from the rectangular concrete specimens. These subroutines were taken from the Bio-Medical Statistical package supplied by Control Data Corporation and modified to fit the specific requirements. In general, these subroutines make use of matrix algebra to solve the normal equations. There are 15 types of functions which may be used at one time and the data may consist of 200 observations of the independent variable. It was necessary to write short main programs to transform the original average del values into a form acceptable to these subroutines. These programs can be found in Appendix 2.

A number of different types of functions were tried in the original curvefitting so that it would be possible to choose the types of functions which showed the most consistency and accuracy for different series. The regression subroutines calculate the coefficients of the functions, the residuals, the sum of the residuals, the standard error of estimate and the correlation coefficient. With this information, the different types of functions could be readily compared and evaluated for their desirability.

6. DATA ANALYSIS AND RESULTS

6.1 Total Strains, Uniformly Stressed Specimens

Once the average del values were calculated, the next step was to find a time function which best described the variation of the volumetric changes. Initially, the total strain values were plotted against time in various scales for visual comparisons. Typical data for a series was plotted on an arithmetic scale and then transformed to a log scale in order to show the differences in the shape of the curve. This is shown in Fig. 9. Regression methods, previously described, were used to determine the various parameters and coefficients for the selected functions. The several functions were compared on the basis of the correlation coefficient and the standard error of estimate. The functions which were tried included:

1. $\epsilon = A_o + A_1\ t^b,\ b = 1/2,\ 1/3$

2. $\epsilon = \epsilon_\infty \frac{t}{N+t}$

3. $\epsilon = \epsilon_\infty \frac{t}{A+\log t}$

4. $\log \epsilon = A_o + A_1 \log t$

5. $\log \epsilon = A_o + A_1 \log t + A_2 (\log t)^2$

6. $\varepsilon = A_o + A_1 \log t$

7. $\varepsilon = A_o + A_1 \log t + A_2 (\log t)^2$

In the above equations, ε is concrete strain in microinches per inch, t is time in hours, ε_∞ is a regression constant representing the concrete strain at time infinity, and A_o, A_1, A_2 and N are other parameters also determined from regression analysis.

A few combinations of these functions were also tried. By comparing the standard error of estimate and considering the consistency for each stress level, it was found that the best fit was obtained by a second degree polynomial semi-logarithmic scale, equation 7. Figs. 10 and 11 show curves based on this equation for the various series of observed data.

The next step was to relate the regression constants to some design parameters. This necessitated the separation of total strain into its individual components, shrinkage, creep, and elastic shortening. On account of the good agreement obtained by the semi-logarithmic relationship with total strain, only this type of function was used for the individual components.

6.2 Shrinkage Strains

The average shrinkage del values were plotted on semi-log graph paper. These plots showed that the data followed an essentially linear relationship with a slight upward tendency at a late age. From these plots a curvefit was attempted utilizing the following function:

$$\epsilon_{sh} = A_1 \log t + A_2 (\log t)^2$$

where ϵ_{sh} is the concrete shrinkage strain, t is time in hours and A_1 and A_2 are constants. This expression yielded good agreement with the del values during the early age, but as t became large, it tended to predict a faster rate of growth than the test data. By statistically testing the second term, it was discovered that this term, $A_2 (\log t)^2$, had little significance in most cases. For this reason, the second term was dropped and the data was re-analyzed with the following function:

$$\epsilon_{sh} = A_1 \log t$$

Using this function, the predicted shrinkage tends to be less than the measured values at late ages. In some cases, this function does not show quite as good agreement at later ages with the data as does the previous one. It was noticed, however, that the specimens were subjected to a comparatively high humidity during the initial period from April to October (humidity during this period was approximately 55%), and that during the later period, the environment was considerably drier (relative humidity approximately 25%). This variation of humidity should have an inverse relationship on the rate of shrinkage. In Fig. 12 this effect is displayed. The observed shrinkage values are seen to be lower than the regression line during the period of high relative humidity and higher when the relative humidity is low. This general tendency of deviation is expected since the regression line represents an average humidity. At the time of this writing, most specimens have not yet experienced a complete humidity cycle. However, it is anticipated that once the humidity begins to rise, the rate of shrinkage will decrease, and the agreement between the observed data and the regression line will improve.

The result of the regression analyses for shrinkage strains are shown in Figs. 13 through 22. The shrinkage coefficient A_1 for the various series are listed in Table 5.

It is reasonable to expect that the prestressing strands in the specimens would resist the longitudinal deformation of concrete. In Fig. 23, the values of the shrinkage coefficient A_1 were plotted against the amount of longitudinal steel, and most data points fell within a narrow band. It is therefore suggested that A_1 may be expressed as

$$A_1 = B - 37.5p$$

where p is the percentage of longitudinal steel, and B is a parameter dependent upon the properties of the concrete mixture. The values of B for the various series are listed in Table 5. The two lines shown in Fig. 23 were drawn with B equated to 130 and 110, respectively.

Series 1.0 from plant AB exhibited very low shrinkage strain. The reason is unknown, but it is suspected that the shrinkage specimens behaved abnormally. Further discussion on this contention will be given in the next section.

An attempt was made to correlate the coefficients to the total amount of mixing water, but was not successful. It appears that the effect of water content is secondary and in this study was overshadowed by the steel percentage variation.

As the specimens age, it will be possible to refine these shrinkage coefficients and find a more accurate relationship to other parameters.

6.3 Elastic Shortening, Uniformly Stressed Specimens

The elastic strains were determined directly from the before-and-after release readings. For the prediction of the elastic strain, it was decided not to use the fundamental stress-strain relationship $\epsilon = \sigma/E$. This decision was made primarily because of the difficulty involved in the determination of the modulus of elasticity of concrete. Also, most prestressing plants do not have the facilities to make this determination. It is felt that a prediction formula involving the modulus of elasticity would be impractical. Instead, the initial compressive strength of concrete, which is easily determinable at any plant, was used in the suggested formulation

$$\epsilon_{el} = A_o \frac{f_c}{f'_{ci}}$$

where ϵ_{el} is the elastic shortening strain, f_c is the concrete stress calculated on the transformed section, and f'_{ci} is the actual release strength as determined by tests conducted on concrete cylinders.

It is noted that f_c was calculated on the basis of transformed section, and therefore was dependent on the modulus of elasticity of concrete. However, the effect is relatively small, and the accurate determination will not be necessary. For the concretes used in this study, an average value of 7 was used for the modulus ratio.

The values of A_o are listed in Table 5 and are plotted versus f_c/f'_{ci} in Fig. 24. It is seen that for practical purposes, A_o may be considered a constant for each concrete mix.

6.4 Creep Strain, Uniformly Stressed Specimens

The creep strain for each series was calculated by subtracting the shrinkage strain and the elastic shortening from the total strain. A semi-logarithmic plotting of the creep strain showed a distinct upward curvature, and a regression analysis was made on the basis of a second order parabolic relationship:

$$\epsilon_{cr} = A\ (\log t)^2$$

where ϵ_{cr} is the creep strain, A is a constant, and t is time in hours beginning before release. This function showed very good agreement with the actual data.

The creep constant, A, thus determined was found to be very closely related to the initial concrete stress (based on the transformed sectional area).

As a refinement to the analysis, the regression constant "A" was replaced by $A_2 f_c/f'_c$, hence

$$\varepsilon_{cr} = A_2 \frac{f_c}{f'_c} (\log t)^2$$

where ε_{cr} and t have the same meanings as before, A_2 is a constant, f_c is the initial concrete stress calculated on the transformed section, and f'_c is the 28-day concrete strength. The values of A_2 are listed for the different series in Table 5.

A plot of A_2 vs. f_c/f'_c is shown in Fig. 25. As expected, for each concrete mix, A_2 remained practically a constant independent of the level of stress.

The two 1.0 series yielded somewhat unexpected results. The 1.0 series from plant AB showed very high creep strains. It is remembered that the shrinkage strains for this series was unexpectedly low. Since the creep strains were calculated from the measured total strain values by subtracting the elastic shortening and the shrinkage strains, it is clear that an under-estimation of the shrinkage strain would result in a high creep value, and vice versa. It is suspected that the shrinkage specimens of this series sustained less shrinkage than the stressed specimens. Allowing a higher shrinkage value for the stressed specimens, the creep strains would be reduced to become more nearly consistent with the other series. The 1.0 series from plant CD yielded a low creep coefficient. From Table 4, it is seen that the concrete of this series has a relatively high modulus of elasticity, although the compressive strength is comparable to that of the other series. It is clear that the high stiffness of concrete would lead to low creep strains.

Several other parameters may be related to the creep constant A_2. The establishment of any additional relationship would require data covering longer periods, and probably more specimens reflecting other values of those parameters.

6.5 Total Strain by Summation of Components

By combining the three components, the total concrete strain is estimated by the following expression:

$$\varepsilon = A_o \frac{f_c}{f'_{ci}} + A_1 \log t + A_2 \frac{f_c}{f'_c} (\log t)^2$$

where ε is the total strain, f_c is the initial concrete stress calculated on the transformed section, t is time in hours beginning 1 hour before release, f'_{ci} and f'_c are the release strength and 28-day strength of the concrete, respectively, and A_o, A_1 and A_2 are regression coefficients.

The results of the regression analysis are plotted against actual strain values for each series in Figs. 13 through 22. As can be seen from the figures, the predicted values show a good correlation with the actual values at early ages, but at later ages in some cases there is a deviation from the regression curve. This is caused by the variation in the rate of shrinkage because of the relative humidity as previously suggested.

This total strain function can be modified to accommodate the time in days by using it in the following manner:

$$\varepsilon = A_o \frac{f_c}{f'_{ci}} + A_1 \log (24 \times t') + A_2 \frac{f_c}{f'_c} [\log (24 \times t')]^2$$

or

$$\epsilon = A_o \frac{f_c}{f'_{ci}} + A_1 (\log 24) + A_2 \frac{f_c}{f'_c} (\log 24)^2 + A_1 \log t'$$

$$+ 2 A_2 \frac{f_c}{f'_c} \log 24 \log t' + A_2 \frac{f_c}{f'_c} (\log t')^2$$

where t' is time in days and the remaining terms have the same meaning as before.

6.6 Gradient Effect

The effect of stress gradient was first studied by comparing strain measurements from the several specimens of the same series. The 1.0, 1.5 and 2.0 series each contained 2 uniformly stressed and 4 non-uniformly stressed specimens. At mid-height of the non-uniformly stressed specimens, the initial concrete stress is the same as that in the uniformly stressed specimens. Strains at these locations were compared with the results obtained from the regression analysis described earlier. Very little consistent deviation was noticed. Most of the data from the non-uniformly stressed specimens fell within 3% of the average strain values for the uniform specimens. It appears justifiable to conclude that there is no statistical evidence of any effect of the stress gradient on the total concrete strain in this comparison.

Next, comparisons were made between strains from specimens in different series, with the same initial stress level.

Comparisons of this type were made at four initial stress levels: 1.0 ksi (specimens A, F and K); 1.5 ksi (specimens E, B and K); 2.0 ksi (specimens J, F and C); and 3.0 ksi (specimens N, G and K). In Figs. 26, 27, 28 and 29, information from the non-uniformly stressed specimens was plotted against the regression curve obtained for the uniformly stressed specimens. It is seen that a definite deviation is present in most cases with the lower pre-stressed specimens showing higher total strains. Since the low-stressed specimens contain fewer strands, and were less restrained against shrinkage deformation, the noted deviation here is reasonable. Actually, the amount of deviation is comparable to the difference in shrinkage strains for the several series.

From the two types of comparisons, it is concluded that the stress gradient has an insignificant effect on the concrete strain.

7. CONCLUSIONS

In this study, the primary variables were stress level and gradient. Other factors of influence were either held constant (size, shape), given very limited variations (concrete mix, curing), or uncontrolled but measured (environment). In order to establish any relationship between concrete volumetric strain to these latter parameters, additional research must be conducted. From the studies reported, the following conclusions may be made:

1. With respect to each of the several components of concrete strain, Plant AB consistently showed higher loss potential than Plant CD.

2. Elastic strains may be estimated by the expression $\epsilon_{el} = A_o f_c / f'_{ci}$, where A_o has an average value of approximately 1400 for plant AB, and 1200 for plant CD.

3. Creep strains may be estimated by the expression $\epsilon_{cr} = A_2 (f_c / f'_c)(\log t)^2$, where A_2 has an average value of approximately 130 for plant AB, and 95 for plant CD.

4. Shrinkage strains may be estimated by the expression $\epsilon_{sh} = A_1 \log t$, where the coefficient A_1 varies in the range from 45 to 95.

5. The shrinkage coefficient A_1 is primarily controlled by the amount of longitudinal steel, and secondarily by the amount of mixing water. It may be estimated by the expression $A_1 = B - 37.5p$, where B has an average value of 120 for both

plant AB and CD.

6. The stress gradient has no significant effect on the creep strain.

7. The humidity of the storage environment has an inverse effect on the rate of shrinkage.

It should be emphasized that the foregoing conclusions were based on test results covering a period of one year only. Additional data from these same specimens in the future could conceivably modify or change any of these conclusions.

All discussions and conclusions in this report have been done with reference to the concrete strain, since that is the quantity being measured. Many other factors affect the loss of prestress, and it is not intended that the results reported herein should be directly applicable to the prediction of such losses in an actual bridge member. However, an indication of prestress loss can be obtained easily by multiplying the strain values by the modulus of elasticity of the prestressing strands, which may be taken as 28000 ksi. Thus, the indicated loss due to elastic shortening would be 39.2 f_c/f'_{ci} for plant AB, and 33.6 f_c/f'_{ci} for plant CD. The shrinkage and creep losses could be calculated in the same manner.

8. ACKNOWLEDGEMENTS

The study reported herein is a part of an investigation on the prestress losses in pre-tensioned concrete structural members, conducted at the Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University, and financially cosponsored by the Pennsylvania Department of Highways and the U. S. Bureau of Public Roads. The authors wish to express their gratitude to the following individuals for their assistance and encouragement: Professor D. A. VanHorn, Chairman of the Department of Civil Engineering and originator of the project; Professor L. S. Beedle, Director of Fritz Engineering Laboratory; Professor G. R. Jenkins, Director of the Office of Research, Lehigh University; Mr. L. D. Sandvig, Director of the Bureau of Materials, Testing and Research, Pennsylvania Department of Highways; Mr. F. C. Sankey, Research Coordinator, Pennsylvania Department of Highways; and Mr. H. P. Koretsky, Assistant Bridge Engineer, Pennsylvania Department of Highways.

Sincere thanks are due the two producers of prestressed concrete members where the concrete specimens were fabricated. They are Eastern Prestressed Concrete Corporation at Hatfield, Pennsylvania, and Schuylkill Products, Incorporated, at Cressona, Pennsylvania.

Acknowledgements are gratefully paid to personnel at the Materials Testing Laboratory, Pennsylvania Department of Highways for their analysis of the concrete materials used in this study; to Mr. K. Harpel and his crew at the Fritz Engineering Laboratory for handling the specimens; to Messrs. A. Rokhsar and E. Schultchen for their assistance in the fabrication, instrumentation and observation of the specimens; to Mr. K. Frank for his help in the statistical analysis of data; to Mr. R. Sopko, Mr. J. Gera and Mrs. S. Balogh for their assistance in preparing the figures in this report; and to Mrs. A. L. Silfies for typing the manuscript.

9. APPENDICES

1. Cement and Aggregate Properties

2. Computer Flow Charts and Programs

Appendix 1 Cement and Aggregate Properties*

Laboratory Report on Aggregates and Cements

Plant AB

Coarse Aggregate**

Average specific gravity	2.71
% Absorption	.44

**Deficient per Pennsylvania standards for #2 stone on the amount passing 3/8' and 3/4" sieve

Fine Aggregate

Fineness modulus	2.89
Average specific gravity	2.61
% Absorption	1.23

Kind of Sand	Proportions Sand/Cement	% Water	Average Strength 7 days psi	Average Strength 28 days psi	Strength Ratio 7 days %	Strength Ratio 28 days %
Ottawa	3:1 by vol.	14.5	2975	4590	100.0	100.0
Plant AB's sand	3:1 by vol.	14.0	3371	5184	113.3	112.9

Cement

Normal consistency	
% Water neat	28.0
% Water mortar	49.0
Initial set	75 mins.
Compressive strength	
1 day	2792 psi
3 days	4554 psi

*Testing and identification by Pennsylvania Department of Highways, Materials Testing Laboratory

Laboratory Report on Aggregates and Cements

Plant CD

Coarse Aggregate

Average specific gravity	2.93
% Absorption	.28

Fine Aggregate

Fineness modulus	2.98
Average specific gravity	2.61
% Absorption	.30

Kind of Sand	Proportions Sand/Cement	% Water	Average Strength 7 days psi	28 days psi	Strength Ratio 7 days %	28 days %
Ottawa	3:1 by vol.	14.5	3300	4290	100.0	100.0
Plant CD's sand		14.0	4642	6029	140.7	140.5

Cement

Normal consistency	
% Water neat	28.0
% Water mortar	49.0
Initial set	105 mins.
Compresive strength	
1 day	2779 psi
3 days	5400 psi
28 days	6642

Description of Aggregates Used by Plant AB

General Statements

This material, classified as a limestone by the producer, is actually an arenaceous dolomite or domitic limestone. Calcitic material is present but usually constitutes less than 20% of the rock. This rock, in general, is harder than limestone (4 to 5 on Mohs scale) and does not effervesce much in dilute HCI. On the basis of the petrographic study, this rock appears to be quite compact and durable.

In studying the samples provided, the individual particles were first divided according to microscopic appearance into six groups. Thin sections were then prepared from selected particles from each group and these were studied extensively under the polarizing microscope. The combined hand specimen and thin section descriptions along with the percentage by weight of each rock type in the total sample are reported on the following pages.

The terms below are defined for purposes of clarity to the reader:

Arenaceous - containing a significant amount of quartz-sand material

Micrite - calcareous mud showing no grains and appearing as a continuous mass

Blomicrite - calcareous mud containing distinct fossil material (either complete remains or fragments)

Sparite - calcitic or dolomitic material precipitated in the voids of a rock such as when micrite is washed out of a recently-formed limestone

Biosparite - a rock composed of fossil particles cemented in a sparite matrix (no micrite is present)

Petrographic Descriptions

Rock Type #1 - Arenaceous Micrite to Arenaceous Sparse Biomicrite - 2.31% of total sample

A fine-grained, medium gray dolomite containing 20% plagioclase feldspar and quartz with minor amounts of tourmaline. The grains of non-calcareous material are generally of equal size, about 0.1 mm. to 0.02 mm. in diameter (equant grains). This rock has a hardness of 3-4 on Mohs scale and effervesces little in weak hydrochloric acid.

In hand specimen this rock type can be seen to contain small amounts of dark green or black crystalline material.

Rock Type #2 - Arenaceous Sorted to Rounded Bipsparite - 6.60% of total sample

Medium gray dolomitic limestone with numerous calcite veins which range in width from 3 mm. to 0.01 mm. This rock also contains about 10%-5% quartz and feldspar in equant grains of about 0.02 mm. diameter.

Another slide from this same group contained about 40% quartz and feldspar and could almost have been called a calcareous sandstone. This particular rock type is characterized by the presence of calcite veins.

Its hardness is between 4 and 5 on Mohs scale and there is only a fair amount of effervescence in dilute HCI.

Rock Type #3 - Arenaceous Micrite with some Sparite present - 5.13% of total sample

Medium gray dolomitic limestone occurring in thin flat particles which possess no laminations. This rock type contains 40% or more quartz and mica. The quartz occurs in equant grains varying from 10 μ to 20 μ in diameter, and the mica occurs as tiny shards, about 18 μ in length. This sample contains large voids (large compared to the grains) filled with calcite. The rock effervesces little in HCI and has a hardness of between 4 and 5 on Mohs scale.

Rock Type #4 - Arenaceous Poorly Washed Biosparite - 72.03% of total sample

Medium gray, compact dolomitic limestone with a hardness of 4 to 5 on Mohs scale and possessing a fair reaction to dilute HCI. This rock type contains lenses of quartz material cemented with calcite and dolomite. Small quartz grains also appear through the calcareous mud matrix; these grains are generally about 10 μ in diameter but range from 5 μ to 30 μ and constitute about 40% to 30% of the rock.

Rock Type #5 - Shaley Dolomite - 10.45% of total sample

Rock type #5 is a medium to dark-gray rock with thin laminations (about 10 μ thick); the layer boundaries are straight. There is little effervescence when the rock is placed in dilute HCI.

This rock is shaley in appearance, both in hand specimen and thin section, but also contains a fair amount of quartz (about 20%). The quartz grains average 20 μ in diameter while the dolomite and calcite (very little present) grains range from 5 μ to 25 μ and generally appear in typical rhombohedral form. These grains are all densely dispersed throughout a clay matrix. Occasional fossil debris, mostly shell fragments, are observed in this rock type.

Rock Type #6 - Shaley Dolomite - 3.48% of total sample

Medium gray rock with somewhat weathered-looking layering; laminations are thin (about 10 μ) and layer boundaries are generally straight. The rock has a hardness of 3-3.5 and there is little reaction in dilute hydrochloric acid. It is essentially a shaley dolomite with some calcite grains present, similar to Rock Type #5; but no fossil material is present.

This rock contains about 60% dolomite, 30% clay, and 10% quartz.

Description of Aggregates Used by Plant CD

General Statements

Petrographic hand specimen and thin section analysis of this rock shows that it varies from a uniform-textured microcrystalline limestone (micritic limestone) to a micritic sparite. Little or no fossil material was observed in any of the sample particles. All but a small percentage of the sample submitted to this lab contained 60% or more $CaCO_3$. A few pieces were high in dolomite but very little quartz material was observed in any particle. The hardness of the samples ranged from 3 to 5 on Mohs scale of hardness; but, generally, the pieces were fairly soft (3-4), about the hardness which limestone usually possesses.

As in the investigation of the samples collected from Plant AB, the particles of this sample were divided into groups (12 in this case) by means of simple tests and observations through the binocular microscope. However, only seven of these groups are really significant and possessed sufficient material from which to make thin sections. Hence, these seven categories will be described first in detail; afterwards the other categories will be briefly described. The following petrographic descriptions were obtained from both thin section and microscopic analysis of the rocks; the percentage values accompanying each description are the percent by weight of each rock type in the total sample.

The terms below are defined for purposes of clarity to the reader:

<u>Micrite</u> - calcareous mud showing no grains and appearing as a continuous mass

<u>Dismicrite</u> - micrite containing a small amount of fossil material

<u>Sparite</u> - coarsely crystalline calcitic or dolomitic material precipitated in the voids of a rock such as when micrite is washed out of a recently formed limestone

<u>Petrographic Descriptions</u>

Rock Type #1 - Dismicrite - 6.79% of total sample

A light medium gray, very fine-grained, soft (3 on Mohs scale) limestone which shows much effervescence in dilute HCI. In thin section, the rock possesses a fairly homogeneous texture, composed of an interlocking mosaic of calcite crystals ranging from 5 μ to 10 μ in diameter. Calcium carbonate composes about 90% of this rock, the rest is quartz and clay. Occasional fossil material that has been replaced by coarsely crystalline calcite (sparite) is observed.

Rock Type #2 - Micrite with Sparite lenses - 11.15% of total sample

Medium dark gray, fine-grained, soft (3-3.5 on Mohs scale) limestone composed of about 90% calcite; there is much effervescence in dilute HCI. This rock contains lenses of coarser calcite in the microcrystalline matrix; these lenses appear as sugary-like crusts on the hand specimen under a low-power binocular microscope.

The matrix is similar to the texture of #1, being composed of a mosaic of calcite crystals, 5 μ to 10 μ in diameter. The lenses are composed of calcite crystals which range in size from 35 μ to 45 μ long, scattered randomly throughout the matrix. A very small amount of sparite --- replaced fossil material is present in this rock type.

Rock Type #3 - Coarse-grained micritic sparite - 32.11% of total sample

This rock is a medium gray, fairly homogeneous, medium-fine-grained, medium hard (4 on Mohs scale) limestone, which effervesces a fair amount in dilute HCI. Under the binocular microscope the rock appears somewhat grainy. The rock is composed of calcite (with some dolomite and aragonite) grains which range in diameter from 26 μ to 44 μ in diameter; these grains sometimes interlock but generally are held together by a micrite matrix composed of submicroscopic calcite grains and clay. About 60% of this rock is $CaCO_3$.

Rock Type #4 - Micrite with calcite veins - 12.12% of total sample

Medium to light gray, medium hard (4 on Mohs scale), limestone showing much effervescence in diulte HCI. The matrix is composed of generally close-fitting crystals of calcite (9 μ to 18 μ in diameter) with submicroscopic clay and carbonate material in the voids between the grains. Calcite veins ranging from 1500 μ to 10 μ in width occur throughout the matrix. This rock type is about 90% $CaCO_3$.

Rock Type #5 - Dismicrite with scattered calcite rhombs - 5.26% of total sample

Dark gray, very fine-grained, smooth-surfaced, medium soft (3-4 on Mohs scale) limestone which shows a strong reaction to dilute HCI. The ground mass or matrix of this rock is composed of interlocking grains of calcite (2 μ to 6 μ in diameter) with some mica grains (same diameter as calcite) and clay material also present. Interspersed throughout this matrix are rhombohedral calcite grains which range from 18 μ to 35 μ in length. Carbonate minerals constitute about 85% of this rock with 5%-10% mica and the rest clay and quartz.

This rock type also occurs as veins and lenses in some of the other limestone types.

Rock Type #6 - Fine-grained Sparite (or coarse-grained micrite) - 5.62% of total sample

This rock is a dark gray, medium soft (3-4 on Mohs scale) limestone which is somewhat similar to #5 in hand specimen. However, it is not as smooth-surfaced, and it appears coarser-grained than #5. This rock contains about 90% carbonate material which is found as densely-packed calcite rhombohedrons (17 μ to 40 μ in length) in a ground-mass of much finer-grained calcite and clay (1 μ or less in diameter). The calcite crystals constitute about 60% of the rock and present a uniform texture throughout the sample.

Rock Type #7 - Micritic Dolomite - 8.01% of total sample

Light gray, hard (5 on Mohs scale), dense, very fine-grained dolomitic limestone which effervesces little in dilute HCI. This rock is composed of a homogeneous microcrystalline mosaic of dolomite and calcite grains (about 4 μ in diameter) with some clay and silica present in equally small particles. Dolomite constitutes about 70% of this rock.

This completes the detailed descriptions of 90% of the material in the original sample. Following this are brief hand-specimen descriptions of the other limestone rock types present. These rock types are not identified by name, as the previous seven, because the former were not studied in thin section.

Rock Type #8 - 1.09% of total sample

Medium gray, fine-grained (a little finer than #3), soft (3-3.5 on Mohs scale) limestone which shows much effervescence in dilute HCI. Contains over 70% carbonate material.

Rock Type #9 - 2.07% of total sample

Medium hard (4 on Mohs scale), medium gray, fine-grained limestone which shows only a fair reaction to dilute HCI. This rock probably contains a large percentage of dolomite along with calcite (about 30 to 40% dolomite).

Rock Type #10 - 1.24% of total sample

Light gray, very fine-grained, soft (3 on Mohs scale), lithographic-quality limestone showing much effervescence in dilute HCI. Micro-faulting is observed in this rock; off-sets are readily evident in hand specimens.

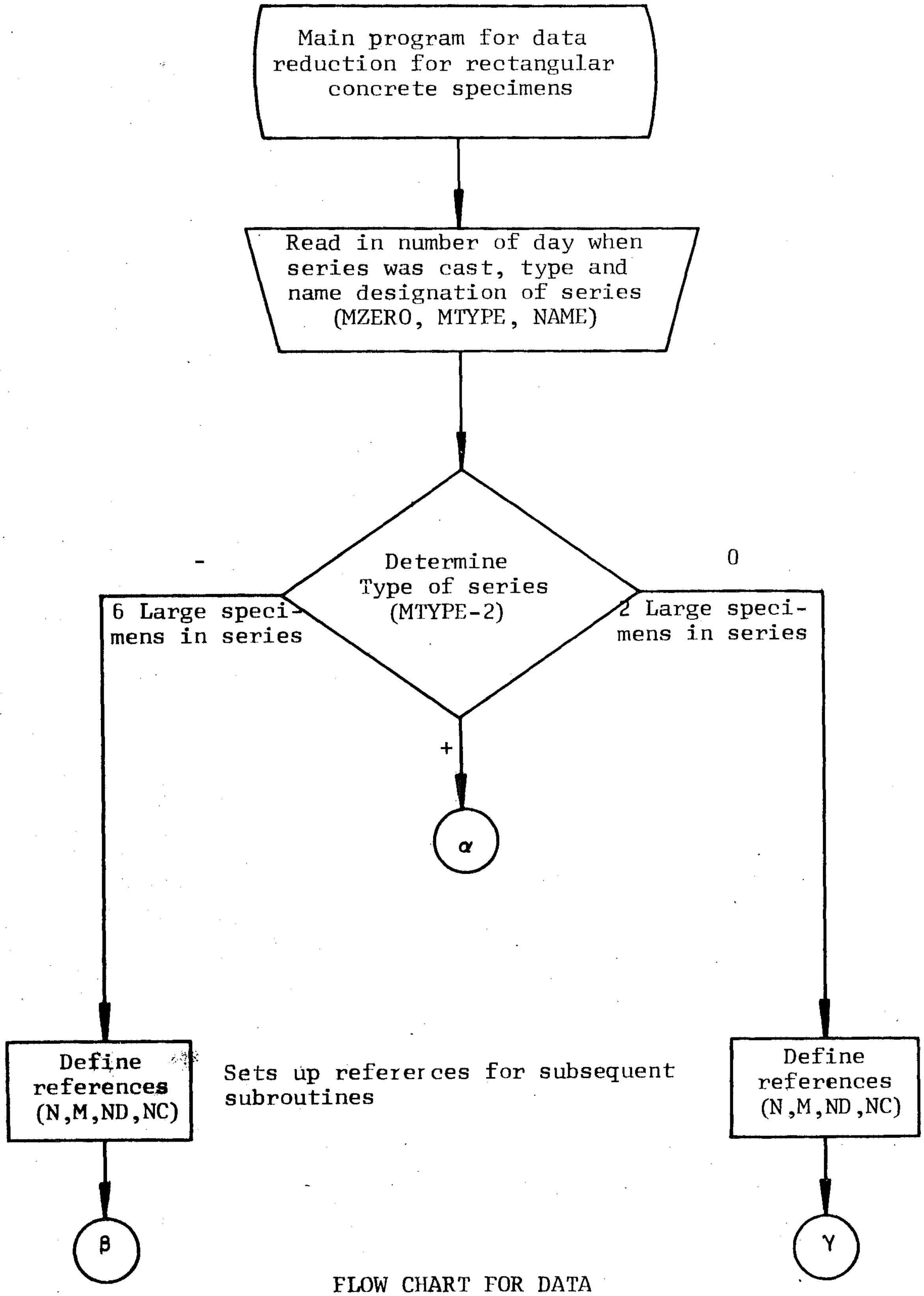
Rock Type #11 - 1.17% of total sample

Medium gray, soft (3-3.5 on Mohs scale), medium-grained, rough-textured limestone possessing thick laminations (about 50 μ in width) and a strong reaction to dilute HCI. This rock is rough to the feel and probably contains around 10% quartz which is loosely cemented by the carbonate material.

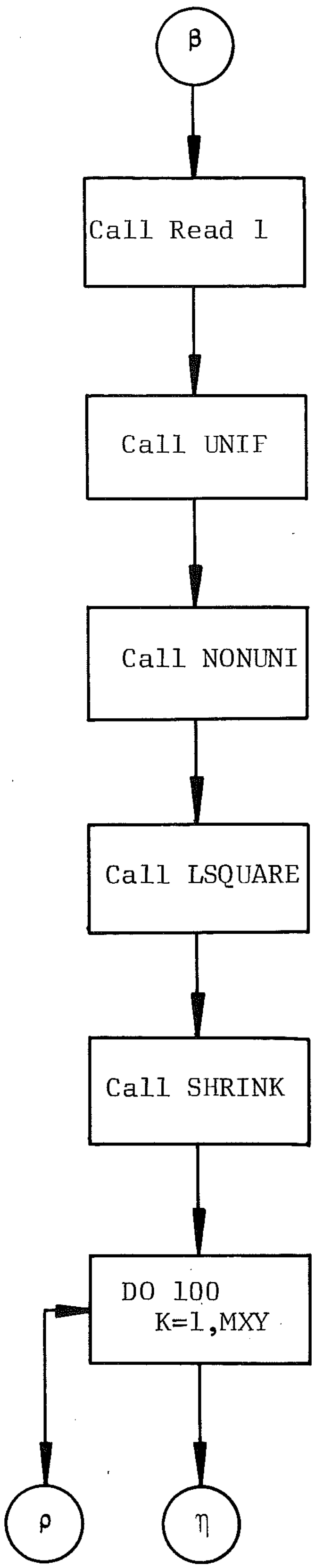
Rock Type #12 - Miscellaneous - 3.91% of total sample

This is not actually a rock type but simply a category into which were placed particles which were obviously erratic; that is, particles which were not from the same geologic formation as the great majority of rocks present in this sample. This category includes a variety of shaley limestones and dolomites as well as a few arenaceous limestones.

Appendix 2 Computer Flow Charts and Programs



FLOW CHART FOR DATA REDUCTION PROGRAM



Reads in before release and all subsequent data. Calculates age of series at time of readings, and changes in strains

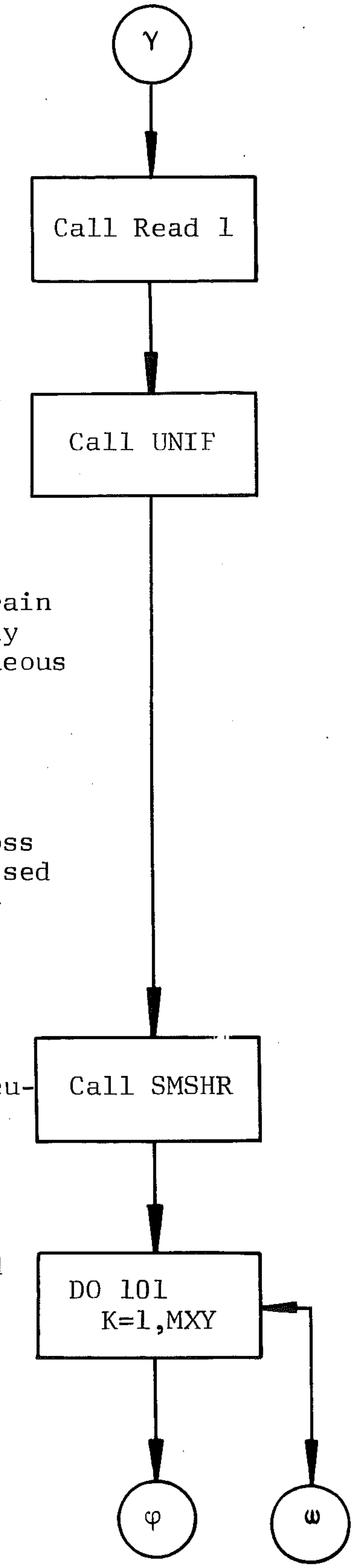
Calculates the average strain change for uniformly stressed specimens and rejects erroneous data

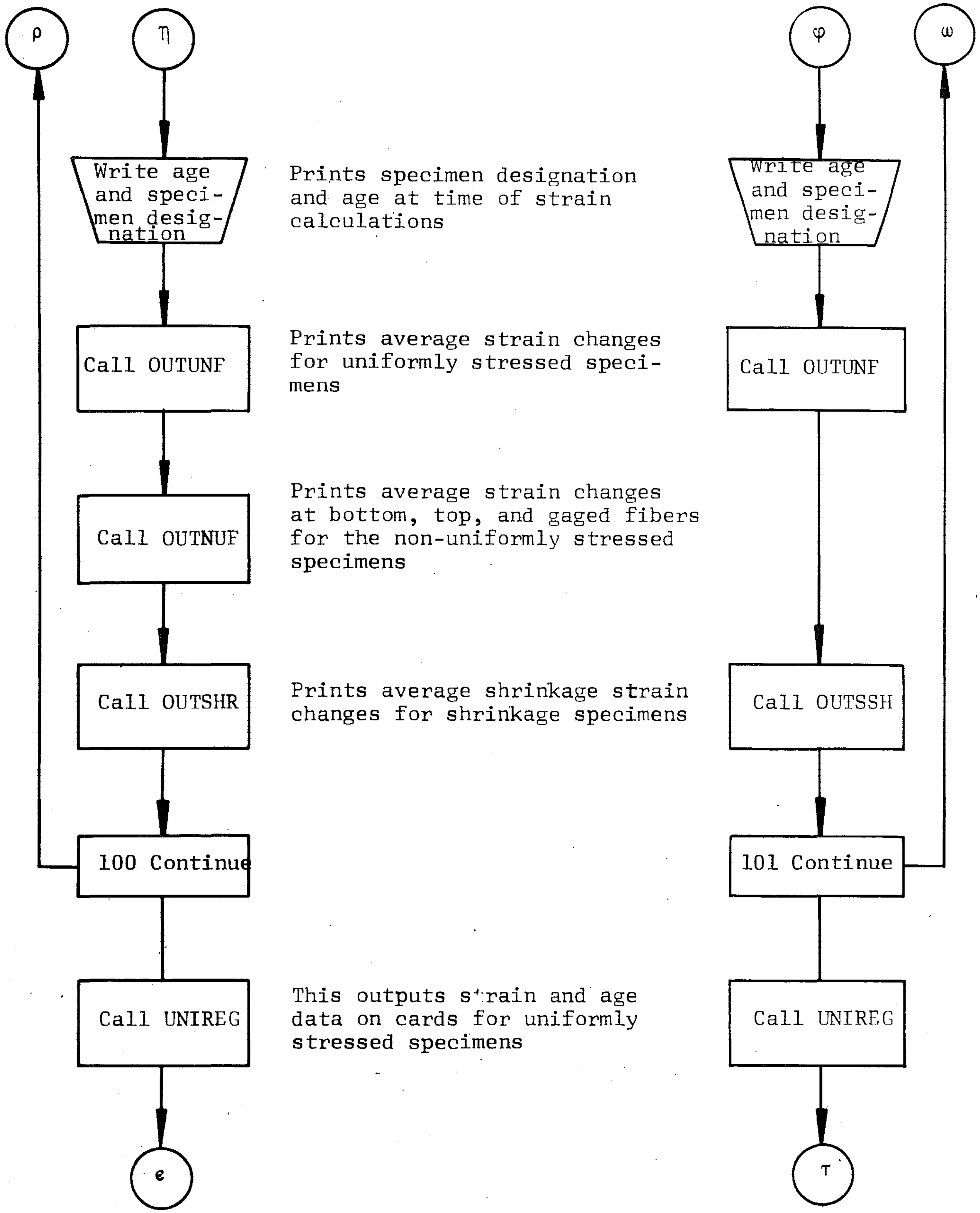
Calculates the average change in strain at gaged fibers for the non-uniformly stressed specimens and rejects erroneous data

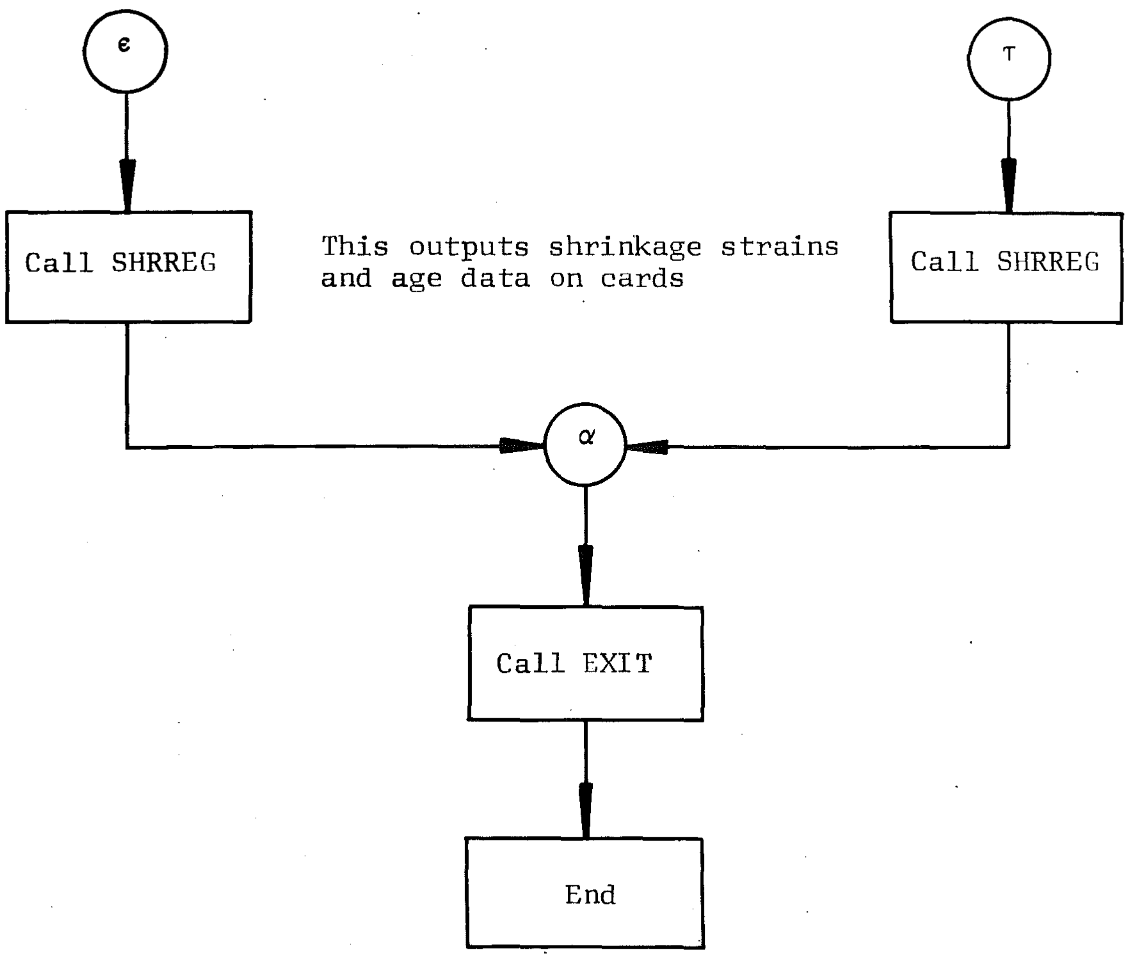
Forces linear strain assumption across cross-section of non-uniformly stressed specimens

Calculates average shrinkage strains and rejects erroneous data on particular shrinkage specimens

Sets up DO loop to output calculated information. MXY = the number of sets of strain information recorded




ρ
η
φ
ω
Write age and specimen designation
Prints specimen designation and age at time of strain calculations
Write age and specimen designation
Call OUTUNF
Prints average strain changes for uniformly stressed specimens
Call OUTUNF
Call OUTNUF
Prints average strain changes at bottom, top, and gaged fibers for the non-uniformly stressed specimens
Call OUTSHR
Prints average shrinkage strain changes for shrinkage specimens
Call OUTSSH
100 Continue
101 Continue
Call UNIREG
This outputs strain and age data on cards for uniformly stressed specimens
Call UNIREG
ε
τ


ε
T
Call SHRREG
This outputs shrinkage strains
and age data on cards
Call SHRREG
α
Call EXIT
End

```
      PROGRAM DATA (OUTPUT,TAPE6=OUTPUT,INPUT,TAPE5=INPUT,
     *PUNCH)
C
C     PROGRAM FOR THE ANALYSIS OF DATA OBTAINED FROM
C     RECTANGULAR CONCRETE SPECIMENS
C
      DIMENSION NAME(8),AGE(20),DEL(20,136),AVER(20,8),
     *AVIR(20,8,7),DEVR(20,8,7),ABZ(20,8,7),PHI(20,8),
     *SP(20,136),DIVR(20,8)
      IN=5
      IO=6
    1 CONTINUE
      READ(IN,400)MZERO,MTYPE,(NAME(N),N=1,8),N1,N2,N3,N4,N5,
     *SER
C     MZERO IS THE NUMBER OF THE DAY ON WHICH A SERIES
C     WAS CAST
C     MTYPE=1 IF SERIES CONTAINS 6 LARGE SPECIMENS OR =2
C     IF SERIES CONTAINS 2 LARGE SPECIMENS
C     NAME IS THE BEAM DESIGNATION
      IF(MZERO)200,200,201
  201 IF(MTYPE-2)202,203,204
  202 N=136
      M=128
      ND=136
      NC=129
C     SUBROUTINE READ1 INPUTS DATA, CORRECTS TO CONSTANT
C     REFERENCE VALUE, AND CALCULATES THE CHANGE IN STRAIN
      CALL READ1(MZERO,N,M,ND,NC,AGE,DEL,SP,I)
C     SUBROUTINE UNIF, REJECTS OBVIOUSLY INCORRECT DATA
C     AND AVERAGES THE DATA FOR THE UNIFORM SPECIMENS
      CALL UNIF(I,N,DEL,AVER,DIVR)
C     SUBROUTINE NONUNI PERFORMS THE SAME OPERATIONS AS UNIF
C     BUT ON THE NONUNIFORMLY STRESSED SPECIMENS
      CALL NONUNI(I,DEL,AVIR,DEVR)
C     SUBROUTINE LSQUARE CURVEFITS THE STRAIN DATA ACROSS THE
C     CROSS SECTION FOR THE NONUNIFORM SPECIMENS
      CALL LSQUARE(I,AVIR,ABZ,PHI)
C     SUBROUTINE SHRINK AVERAGES AND REJECTS SHRINKAGE DATA
      CALL SHRINK(I,DEL,SP,AVER,DIVR)
      MXY=I-1
      DO 100 K=1,MXY
C     ALL SUBROUTINES STARTING WITH OUT ARE USED TO PRINT
C     INFORMATION COMPUTED BY OTHER SUBROUTINES
      WRITE(IO,401)SER,N1,N2,N3,N4,N5,AGE(K+1)
      CALL OUTUNF(I,K,N,AVER,DIVR,NAME)
      CALL OUTNUF(I,K,N,ABZ,DEVR,NAME,PHI,AVIR)
      CALL OUTSHR(I,K,AVER,DIVR,NAME)
```

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```
  100 CONTINUE
C      SUBROUTINE UNIREG AND SHRREG OUTPUT DATA FROM UNIFORM
C      AND SHRINKAGE SPECIMENS ON CARDS
       CALL UNIREG(I,AVER,AGE)
       CALL SHRREG(I,N,AVER,AGE)
       GO TO 1
  400 FORMAT(I3,2X,I1,3X,8(A2,1X),5X,5A2,2X,F3.1)
  203 N=56
       M=44
       NC=45
       ND=48
       CALL READ1(MZERO,N,M,ND,NC,AGE,DEL,SP,I)
       CALL UNIF(I,N,DEL,AVER,DIVR)
       CALL SMSHR(I,N,DEL,SP,AVER,DIVR)
       MXY=I-1
       DO 101 K=1,MXY
       WRITE(IO,401)SER,N1,N2,N3,N4,N5,AGE(K+1)
       CALL OUTUNF(I,K,N,AVER,DIVR,NAME)
       CALL OUTSSH(I,K,N,AVER,DIVR,NAME)
  101 CONTINUE
       CALL UNIREG(I,AVER,AGE)
       CALL SHRREG(I,N,AVER,AGE)
       GO TO 1
  200 CONTINUE
  204 CONTINUE
  401 FORMAT(1H1,///,10X,F4.1,* SERIES   CAST AT *,5A2,3X,
     **AGE*,F4.0,//)
       CALL EXIT
       END
```

```
      SUBROUTINE READ1(MZERO,N,M,ND,NC,AGE,DEL,SP,I)
C     SUBROUTINE WHICH READS IN DATA, CORRECTS TO CONSTANT
C     REFERENCE, AND CALCULATES DIFFERENCES IN STRAINS
      DIMENSION IREF1(20),IREF2(20),AGE(20),IB(20,136),
     *DEL(20,136),SP(20,136)
      IN=5
      IO=6
      MC=N-15
      MD=N-25
      I=0
    1 I=I+1
      READ(IN,400) MON,MDAY,MYEAR,IREF1(I),IREF2(I)
      IF(MON)201,201,202
C     SUBROUTINE AGG CALCULATES THE AGE OF A SERIES FOR
C     PARTICULAR SET OF DATA
  202 CALL AGG(MDAY,MON,MYEAR,MAGE)
      AGE(I)=MAGE-MZERO
      DO 100 K=1,MD,10
      KK=K+9
      READ(IN,401)(IB(I,L),L=K,KK)
  100 CONTINUE
      READ(IN,402) (IB(I,L),L=MC,M)
      READ(IN,402) (IB(I,L),L=NC,ND)
      IF(N-76) 211,211,210
  211 LC=ND+1
      JC=LC+3
      LD=JC+1
      JD=LD+3
      READ(IN,404) (IB(I,L),L=LC,JC)
      READ(IN,404) (IB(I,L),L=LD,JD)
  210 CONTINUE
      READ(IN,403) IERR
      GO TO 1
  201 CONTINUE
      I=I-1
      DO 101 K=1,I
      IVREF=(IREF1(K)+IREF2(K))/2
      MCOR=760-IVREF
      DO 101 L=1,N
      IF(IB(K,L)-20.)203,203,204
C     CORRECTING READINGS TO A COMMON REFERENCE VALUE (760)
  204 SP(K,L)=IB(K,L)+MCOR
      GO TO 101
  203 SP(K,L)=0.0
  101 CONTINUE
      MXY=I-1
      DO 102 K=1,MXY
      DO 102 L=1,N
      KK=K+1
      IF(SP(KK,L)) 205,205,206
```

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```
  205 DEL(K,L)=0.0
      GO TO 102
C     CALCULATES CHANGE IN STRAIN FOR SPECFIC GAGE
C     LOCATIONS (DEL)
  206 DEL(K,L)=SP(1,L)-SP(KK,L)
  102 CONTINUE
      DO 103 L=1,N
      IF(SP(1,L)) 207,207,103
  207 DO 104 K=1,I
  104 DEL(K,L)=0.0
  103 CONTINUE
  400 FORMAT(I2,1X,I2,1X,I2,2X,I3,2X,I3)
  401 FORMAT(3X,10(I4,1X))
  402 FORMAT(3X,8(I4,1X))
  403 FORMAT(I3)
  404 FORMAT(3X,4(I4,1X))
      DO 110 K=1,MXY
      L=0
      DO 111 LB=1,12
      LC=L+1
      L=L+10
  111 CONTINUE
 110  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE AGG(MDAY,MON,MYEAR,MAGE)
C
C     COMPUTE NUMBER OF DAYS , BASED ON JANUARY 1 , 1968
C     VALID FROM MARCH 1 , 1968 TO DECEMBER 31 , 1973
C
      GO TO (1,2,3,4,5,6,7,8,9,10,11,12) MON
 1    M=0        $ GO TO 13
 2    M=31       $ GO TO 13
 3    M=59       $ GO TO 13
 4    M=90       $ GO TO 13
 5    M=120      $ GO TO 13
 6    M=151      $ GO TO 13
 7    M=181      $ GO TO 13
 8    M=212      $ GO TO 13
 9    M=243      $ GO TO 13
 10   M=273      $ GO TO 13
 11   M=304      $ GO TO 13
 12   M=334
 13   CONTINUE
      MY=MYEAR-67
      GO TO (14,15,16,17,18,19) MY
 14   N=1        $ GO TO 20
 15   N=366      $ GO TO 20
 16   N=731      $ GO TO 20
 17   N=1096     $ GO TO 20
 18   N=1461
      IF(MON.GT.2) N=N+1
      GO TO 20
 19   N=1827
 20   MAGE=M+N+MDAY
      RETURN
      END
```

```
      SUBROUTINE UNIF(I,NN,DEL,AVER,DIVR)
C     THIS SUBROUTINE AVERAGES DATA FROM THE UNIFORMLY
C     STRESSED SPECIMENS AND REJECTS ERRONEOUS DATA
      DIMENSION DEL(20,136),AVER(20,8),DIVR(20,8)
      IO=6
      IF(NN-76)206,207,206
  206 KR=21
      GO TO 1
  207 KR=41
    1 CONTINUE
      MXY=I-1
      DO 100 K=1,MXY
      NAM=0
      DO 100 N=1,KR,20
      L=N+19
      NAM=NAM+1
      DIV=0.0
      SUM=0.0
      DO 102 M=N,L
      IF(DEL(K,M)) 200,200,201
  201 DIV=DIV+1.0
  200 SUM=SUM+DEL(K,M)
  102 CONTINUE
      AVE=SUM/DIV
C     REJECTION PHASE
      TOLER=2.*(AVE**.5)
      XLOW=AVE-TOLER
      XHIGH=AVE+TOLER
      SUM=0.0
      DIVR(K,NAM)=20.0
      DO 103 M=N,L
      IF(DEL(K,M)-XLOW) 202,203,203
  203 IF(DEL(K,M)-XHIGH) 205,205,202
  202 DEL(K,M)=0.0
C     DIVR IS THE NUMBER OF INDIVIDUAL READINGS
C     MAKING UP THE AVERAGE
      DIVR(K,NAM)=DIVR(K,NAM)-1.0
C     AVER IS THE AVERAGE TOTAL STRAIN VALUES FROM THE
C     UNIFORMLY STRESSED SPECIMENS
C     AVERAGING PHASE
  205 SUM=SUM+DEL(K,M)
  103 CONTINUE
  100 AVER(K,NAM)=SUM/DIVR(K,NAM)
      RETURN
      END
```

```
      SUBROUTINE NONUNI(I,DEL,AVIR,DEVR)
C     THIS SUBROUTINE AVERAGES AND REJECTS ERRONEOUS DATA
C     FOR NON-UNIFORM SPECIMENS
      DIMENSION DEL(20,136),T(4),DEVR(20,8,7),AVIR(20,8,7)
      MXY=I-1
      DO 100 K=1,MXY
      NAM=2
      DO 101 M=41,101,20
      MM=0
      KK=M-1
      NAM=NAM+1
      DO 102 II=1,9,2
      MM=MM+1
      L=II+KK
      LL=L+1
      LM=10+L
      LLM=L+11
      T(1)=DEL(K,L)
      T(2)=DEL(K,LL)
      T(3)=DEL(K,LM)
      T(4)=DEL(K,LLM)
      DIV=4.0
      SUM=0.0
      DO 103 KLM=1,4
      IF(T(KLM)) 200,201,200
  201 DIV=DIV-1.0
  200 SUM=SUM+T(KLM)
  103 CONTINUE
      AVE=SUM/DIV
C     REJECTION PHASE
      TOLER=2.*(AVE**.5)
      XLOW=AVE-TOLER
      XHIGH=AVE+TOLER
      SUM=0.0
      DEVR(K,NAM,MM)=4.0
      DO 104 KLM=1,4
      IF(T(KLM)-XLOW) 202,203,203
  203 IF(T(KLM)-XHIGH)204,204,202
  202 T(KLM)=0.0
C     DEVR IS THE NUMBER OF INDIVIDUAL READINGS USED
C     WHICH MAKE UP AVERAGE VALUES
      DEVR(K,NAM,MM)=DEVR(K,NAM,MM)-1.0
C     AVERAGING PHASE
  204 SUM=SUM+T(KLM)
  104 CONTINUE
      IF(DEVR(K,NAM,MM))205,205,206
  205 AVIR(K,NAM,MM)=.0001
```

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```
      GO TO 102
C     AVIR IS THE AVERAGE STRAIN AT DIFFERENT FIBERS FOR
C     THE NON-UNIFORMLY STRESSED SPECIMENS
  206 AVIR(K,NAM,MM)=SUM/DEVR(K,NAM,MM)
  102 CONTINUE
  101 CONTINUE
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE LSQUARE(I,AVIR,ABZ,PHI)
C     THIS SUBROUTINE CURVEFITS STRAIN DATA ACROSS THE
C     CROSS SECTION OF NON-UNIFORMLY STRESSED SPECIMENS.
C     THIS FORCES LINEAR STRAIN.
      DIMENSION AVIR(20,8,7),ABZ(20,8,G), HI(20,H',Q(H',
     *O(5),Q2(8),QO(8)
      O(1)=2.0
      O(2)=6.0
      O(3)=12.0
      O(4)=18.0
      O(5)=22.0
      R=5.0
      Y=60.0
      MXY=I-1
      DO 100 K=1,MXY
      DO 101 NAM=3,6
      X=0.0
      X2=0.0
      XY=0.0
      DO 102 J=1,5
      Q(J)=AVIR(K,NAM,J)
      Q2(J)=Q(J)**2
      QO(J)=Q(J)*O(J)
      X=X+Q(J)
      XY=XY+QO(J)
      X2=X2+Q2(J)
  102 CONTINUE
      DD=R*X2-X**2
      C=X2*Y-X*XY
      E=R*XY-X*Y
      AO=C/DD
      A1=E/DD
C     ABZ IS THE STRAIN VALUES AT DIFFERENT FIBERS
      ABZ(K,NAM,1)=-AO/A1
      DO 103 J=1,5
  103 ABZ(K,NAM,J+1)=(O(J)-AO)/A1
      ABZ(K,NAM,7)=(24.-AO)/A1
C     PHI IS THE ROTATION ANGLE
      PHI(K,NAM)=(ABZ(K,NAM,7)-ABZ(K,NAM,1))/24.0
  101 CONTINUE
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SHRINK(I,DEL,SP,AVER,DIVR)
C     THIS SUBROUTINE CALCULATES AVERAGE SHRINKAGE VALUES.
C     IT ALSO REJECTS ANY ERRONEOUS DATA
      DIMENSION DEL(20,136),AVER(20,8),DIVR(20,8),S(8),
     *SP(20,136)
      MXY=I-1
      DO 100 K=1,MXY
      MMM=121
      NNN=128
      NAM=6
  212 NAM=NAM+1
      DIV=8.0
      SUM=0.0
      DO 101 IJK=MMM,NNN
      IF(DEL(K,IJK)) 200,201,200
  201 IF(SP(1,IJK)) 202,202,203
  203 IF(SP(K,IJK)) 202,202,204
  202 DIV=DIV-1.0
      GO TO 101
  204 DEL(K,IJK)=.0001
  200 SUM=SUM+DEL(K,IJK)
  101 CONTINUE
      AVE=SUM/DIV
      IF(AVE-10.) 205,206,206
  205 TOLER=5.0
      GO TO 1
  206 TOLER=2.*(AVE**.5)
    1 XLOW=AVE-TOLER
      XHIGH=AVE+TOLER
      DIV=0.0
      II=0
      DO 102  LJK=MMM,NNN
      IF(DEL(K,LJK))  207,208,207
  207 II=II+1
      S(II)=DEL(K,LJK)
      DIV=DIV+1.0
  208 CONTINUE
  102 CONTINUE
      DIVR(K,NAM)=DIV
      SUM=0.0
      DO 103  JS=1,II
      IF(S(JS)-XLOW) 209,210,210
  210 IF(S(JS)-XHIGH) 211,211,209
  209 S(JS)=0.0
      DIVR(K,NAM)=DIVR(K,NAM)-1.0
  211 SUM=SUM+S(JS)
  103 CONTINUE
```

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```
      AVER(K,NAM)=SUM/DIVR(K,NAM)
      MMM=MMM+8
      NNN=NNN+8
      IF(NNN-136) 212,212,213
  213 CONTINUE
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SMSHR(I,N,DEL,SP,AVER,DIVR)
C     THIS SUBROUTINE CALCULATES AVERAGE SHRINKAGE VALUES
C     AND REJECTS ERRONEOUS DATA
      DIMENSION DEL(20,136),AVER(20,8),DIVR(20,8),S(136),
     *SP(20,136)
      MXY=I-1
      DO 100 K=1,MXY
      NAM=2
      DO 101 L=40,52,4
      SUM=0.0
      DIV=0.0
      NAM=NAM+1
      DO 102 LM=1,4
      ML=L+LM
      IF(DEL(K,ML))200,201,200
  201 IF(SP(1,ML))202,202,203
  203 IF(SP(K,ML))202,202,200
  200 S(LM)=DEL(K,ML)+.0001
      DIV=DIV+1.0
      SUM=SUM+S(LM)
      GO TO 102
  202 S(LM)=0.0
C     REJECTION PHASE
  102 CONTINUE
      AVE=SUM/DIV
      IF(AVE-10.0)204,205,205
  204 TOLER=5.0
      GO TO 1
  205 TOLER=2.*(AVE**.5)
    1 XLOW=AVE-TOLER
      XHIGH=AVE+TOLER
      SUM=0.0
      DIVR(K,NAM)=0.0
      DO 103 MM=1,4
      IF(S(MM))211,210,211
  211 CONTINUE
      IF(S(MM)-XLOW)206,207,207
  207 IF(S(MM)-XHIGH)209,209,208
  209 DIVR(K,NAM)=DIVR(K,NAM)+1.0
C     AVERAGING PHASE
      SUM=SUM+S(MM)
  206 CONTINUE
  208 CONTINUE
  210 CONTINUE
  103 CONTINUE
  101 AVER(K,NAM)=SUM/DIVR(K,NAM)
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE OUTUNF(I,K,N,AVER,DIVR,NAME)
C     THIS SUBROUTINE PRINTS OUT AVERAGE DATA FROM THE
C     UNIFORMLY STRESSED SPECIMENS
      DIMENSION AVER(20,8),DIVR(20,8),NAME(8)
      IO=6
      IN=5
      WRITE(IO,300)
      WRITE(IO,301)
      IF(N-76)200,201,200
  201 NN=3
      GO TO 1
  200 NN=2
    1 CONTINUE
      DO 100 NAM=1,NN
C     NAME IS THE SPECIMEN DESIGNATION
C     AVER IS THE AVERAGE SHRINKAGE
C     DIVR IS THE NUMBER OF READINGS FROM WHICH THE AVERAGE
C     IS MADE UP
      WRITE(IO,302) NAME(NAM),AVER(K,NAM),DIVR(K,NAM)
  100 CONTINUE
  300 FORMAT(10X,*UNIFORM SPECIMENS*)
  301 FORMAT(///,10X,*NAME     AVE.STRAIN     NO. OF DATA*)
  302 FORMAT(/,11X,A2,8X,F5.1,10X,F5.0)
      RETURN
      END
```

```
      SUBROUTINE OUTNUF(I,K,N,ABZ,DEVR,NAME,PHI,AVIR)
C     THIS SUBROUTINE PRINTS OUT DATA FROM THE NON-UNIFORM
C     SPECIMENS
      DIMENSION ABZ(20,8,7),DEVR(20,8,7),NAME(8),PHI(20,8),
     *AVIR(20,8,7)
      IO=6
      WRITE(IO,300)
      WRITE(IO,303)
      WRITE(IO,306)
      DO 100 NAM=3,6
      WRITE(IO,304) NAME(NAM),(AVIR(K,NAM,LL),DEVR(K,NAM,LL),
     *LL=1,5)
  100 CONTINUE
      WRITE(IO,301)
      WRITE(IO,305)
      DO 101 NAM=3,6
C     NAME IS THE SPECIMEN DESIGNATION
C     ABZ IS THE STRAIN VALUES AT DIFFERENT FIBERS
      WRITE(IO,302) NAME(NAM),(ABZ(K,NAM,LL),LL=1,7),PHI(K,NAM)
C     PHI IS THE ROTATION ANGLE
  101 CONTINUE
  300 FORMAT(///,10X,*NON-UNIFORM SPECIMENS*)
  301 FORMAT(///,10X,*DATA AFTER CURVE FIT*,//)
  302 FORMAT(/,11X,A2,5X,8(F7.1,3X))
  303 FORMAT(//,10X,*AVE. OF DATA BEFORE CURVE FIT*,//)
  304 FORMAT(/,11X,A2,14X,5(F7.1,F3.0))
  305 FORMAT(10X,*NAME      LEVEL 1    LEVEL 2    LEVEL 3
     *LEVEL 4    LEVEL 6    LEVEL 7    ROTATION*)
  306 FORMAT(10X,*NAME*,15X,*LEVEL 2    LEVEL 3    LEVEL 4
     *LEVEL 5    LEVEL 6*)
      RETURN
      END
```

```
      SUBROUTINE OUTSHR(I,K,AVER,DIVR,NAME)
C     PRINTS OUT SHRINKAGE INFORMATION
      DIMENSION AVER(20,8),DIVR(20,8),NAME(8)
      IN=5
      IO=6
      WRITE(IO,300)
      WRITE(IO,301)
      DO 100 NAM=7,8
C     NAME IS THE SPECIMEN DESIGNATION
C     AVER IS THE AVERAGE SHRINKAGE
C     DIVR IS THE NUMBER OF READINGS FROM WHICH THE AVERAGE
C     IS MADE UP
      WRITE(IO,302) NAME(NAM),AVER(K,NAM),DIVR(K,NAM)
  100 CONTINUE
  300 FORMAT(///,10X,*SHRINKAGE SPECIMENS*)
  301 FORMAT(//,10X,*NAME     AVE.STRAIN     NO. OF DATA*)
  302 FORMAT(/,11X,A2,8X,F6.1,10X,F5.0)
      RETURN
      END
```

```
      SUBROUTINE OUTSSH(I,K,N,AVER,DIVR,NAME)
      DIMENSION NAME(8), AVER(20,8),DIVR(20,8)
      IO=6
      WRITE(IO,300)
      WRITE(IO,301)
  200 M=3
      MM=6
    1 CONTINUE
      DO 100 NAM=M,MM
      WRITE(IO,302) NAME(NAM),AVER(K,NAM),DIVR(K,NAM)
  100 CONTINUE
  300 FORMAT(///,10X,*SHRINKAGE*)
  301 FORMAT(//,10X,*NAME     AVE.SHR.     NO. OF DATA*)
  302 FORMAT(//,11X,A2,8X,F5.1,10X,F5.0)
      RETURN
      END
```

```
      SUBROUTINE UNIREG(I,AVER,AGE)
C     THIS SUBROUTINE OUTPUTS ON CARDA
C     THE AVERAGE OF THE TWO UNIFORM SPECIMENS
C     AND THE AGES OF READINGS
C     DATA OBTAINED FROM THIS SUBROUTINE IS USED IN
C     REGRESSION AND PLOTTING PROGRAMS
      DIMENSION AVER(20,8),AGE(20),X(20)
      MXY=I-1
      DO 100 K=1,MXY
      X(K)=(AVER(K,1)+AVER(K,2))/2.
  100 CONTINUE
      AGE(2)=.05
      PUNCH 400,MXY
      PUNCH 401,(X(K),AGE(K+1),K=1,MXY)
      NMN=000
      PUNCH 400,NMN
  400 FORMAT(I3)
  401 FORMAT(5(F8.2,F7.2))
      RETURN
      END
```

```
      SUBROUTINE SHRREG(I,N,AVER,AGE)
C     THIS SUBROUTINE OUTPUTS THE AVERAGE SHRINKAGE
C     VALUES AND AGES ON CARDS
C     DATA OBTAINED FROM THIS SUBROUTINE IS USED IN
C     REGRESSION AND PLOTTING PROGRAMS
      DIMENSION AVER(20,8),AGE(20),X(20)
      MXY=I-1
      IF(N-136)201,202,202
  201 M=3
      MM=4
      GO TO 1
  202 M=7
      MM=8
    1 CONTINUE
      DO 100 K=1,MXY
      X(K)=(AVER(K,M)+AVER(K,MM))/2.0
  100 CONTINUE
      AGE(2)=.05
      PUNCH 400,MXY
      PUNCH 401,(X(K),AGE(K+1),K=1,MXY)
      NMN=000
      PUNCH 400,NMN
  400 FORMAT(I3)
  401 FORMAT(5(F8.2,F7.2))
      RETURN
      END
```

```
      PROGRAM CURVFIT (OUTPUT,TAPE6=OUTPUT,INPUT,TAPE5=INPUT,
     *PLOT,TAPE99=PLOT)
C     THIS PROGRAM CURVEFITS THE TOTAL STRAIN DATA
C     IN THE FORM OF STRAIN=A0 + A1 LOG TIME + A2 (LOG TIME)
C     **2. AND ALSO A0 + A2 (LOG TIME) **2.
      DIMENSION STR(20),AGE(20),AX(200),AY(200),X(15,20 ),
     *BBT(2,15)
      IN=5
    1 CONTINUE
C     READS IN NUMBER OF DATA POINTS
      READ(IN,300) MXY
      IF(MXY)200,200,201
  201 CONTINUE
      READ(IN,301)(STR(K),AGE(K),K=1,MXY)
C     READS IN STRAIN AND TIME VALUES
      DO 100 K=1,MXY
      AX(K)=24.*AGE(K)
      X(1,K)=(ALOG10(AX(K)))**2.
      X(2,K)=ALOG10(AX(K))
      AY(K)=STR(K)
  100 CONTINUE
      NV=0
      IKE=MXY
      NTY=2
      NB=1
      CALL REGRES(IKE,NTY,NB,X,AY,NV,BBT)
      CALL DRAW(AGE,STR,BBT,MXY)
      GO TO 1
  200 CONTINUE
  300 FORMAT(I3)
  301 FORMAT(5(F8.2,F7.2))
      CALL EXIT
      END
```

```
      PROGRAM SHRFIT (OUTPUT,TAPE6=OUTPUT,INPUT,TAPE5=INPUT)
C     THIS PROGRAM CURVEFITS THE SHRINKAGE STRAIN DATA
C     IN THE FORM OF STRAIN=A1 LOG TIME
      DIMENSION SHR(20),AGE(20),X(15,200),BBT(2,15),AY(200)
     *AX(200)
      IN=5
    1 CONTINUE
      READ(IN,300)MXY
      IF(MXY) 200,200,201
  201 CONTINUE
C     READS IN STRAIN AND TIME VALUES
      READ(IN,301)(SHR(K),AGE(K),K=1,MXY)
      READ(IN,300)IERR
      DO 100 K=1,MXY
      AY(K)=SHR(K)
      X(1,K)=ALOG10(24.*(AGE(K)))
  100 CONTINUE
      NV=0
      IKE=MXY
      NTY=1
      NB=0
      CALL REGRES(IKE,NTY,NB,X,AY,NV,BBT)
      GO TO 1
  200 CONTINUE
  300 FORMAT(I3)
  301 FORMAT(5(F8.2,F7.2))
      CALL EXIT
      END
```

```
      PROGRAM CURVES (OUTPUT,TAPE6=OUTPUT,INPUT,TAPE5=INPUT,
     *PLOT,TAPE99=PLOT)
C     THIS PROGRAM SETS UP DATA FOR CURVEFITTING
C     OF CREEP STRAINS IN THE FORM OF
C     STRAIN=(FC/FPRC)A2(LOG TIME)**2.
      DIMENSION TOTSTR(20),SHRSTR(20),CRSTR(20),AGE(20),
     *BBT(2,15),AY(200),AX(200),X(15,200)
      IN=5
      IO=6
    1 CONTINUE
C     MXY IS THE NUMBER OF READINGS
C     FC IS THE INTIAL NOMINAL CONCRETE STRESS
C     FPRC IS THE 28 DAY CONCRETE STRENGTH
      READ(IN,302)MXY,FC,FPRC
C     FCTRAN IS THE CONCRETE STRESS CALCULATED ON THE
C     TRANSFORMED SECTION
      READ(IN,303)FCTRAN
      IF(MXY)200,200,201
  201 CONTINUE
      FACT=FC/FPRC
      FACT=FCTRAN/FPRC
C     TOTSTR IS TOTAL STRAIN, AGE IS THE AGE OF THE SPECIMEN
C     AT THE TIME OF READINGS
      READ(IN,301)(TOTSTR(K),AGE(K),K=1,MXY)
      READ(IN,300)IERR
      READ(IN,300)MXY
C     SHRSTR IS THE SHRINKAGE STRAIN
      READ(IN,301)(SHRSTR(K),AGE(K),K=1,MXY)
      READ(IN,300)IERR
      DO 100 K=1,MXY
      M=K
      AGE(K)=AGE(K)*24.
C     CREEP STRAIN=TOTAL STRAIN-SHRINKAGE STRAIN-EL.SHORTENING
      CRSTR(M)=TOTSTR(K)-SHRSTR(K)-TOTSTR(1)
      AY(M)=CRSTR(M)
      X(1,M)=FACT*(ALOG10(AGE(K))*ALOG10(AGE(K)))
  100 CONTINUE
      NV=0
      IKE=M
      NTY=1
      NB=0
      CALL REGRES(IKE,NTY,NB,X,AY,NV,BBT)
      GO TO 1
  200 CONTINUE
  300 FORMAT(I3)
  301 FORMAT(5(F8.2,F7.2))
  302 FORMAT(I3,7X,2F10.0)
  303 FORMAT(F10.0)
      CALL EXIT
      END
```

```
      SUBROUTINE REGRES(IKE,NTY,NB,AX,Y,NV,BBT)
C
C     GENERAL REGRESSION SUBROUTINE
C     ELIMINATION SCHEME USED TO DETERMINE THE SIGNIFICANCE OF
C     COMPUTATIONAL FORM---(XX)(BB)=(Q)----(BB)=(XX)-1(Q)=(CC)(Q)
C     LAST VARIABLE
C
C     IKE=NUMBER OF OBSERVATIONS
C     NTY=NUMBER OF VARIABLES
C     NB-CODED VARIABLE
C              NB=1,X(1,J)=1
C              NB=0,X(1,J)=0(NO INTERCEPT)
C     AX-INDEPENDENT VARIABLE ARRAY ,DIMENSION(15,200)
C     AY-DEPENDENT VARIABLE ARRAY,DIMENSION(200)
C     NV-VARIABLE WHICH CONFIDENCE BAND CALCULATED ON.
C              IF NV=0 THEN NO BAND CALCULATED
C     BBT-REGRESSION COEFFICENT ARRAY,DIMENSION(2,15).
C      FIRST COLUMN CONTAINS COEF. WHEN ALL VARIABLES INCLUDED
C     IN REGRESSION SECOND,  COLUMN CONTAINS COEF. WHEN LAST VAR-
C     IABLE IS NEGLECTED
C
      DIMENSION A(15,15)
      DIMENSION XX(15,15),Q(15,15),Y(200),AAY(200),R(200),
     *RPER(200),RA(2),CC(15,15),X(15,200),AX(15,200)
      DIMENSION RRBE(2),BBT(2,15)
   20 FORMAT(//17H  COEFF MATRIX XX)
   21 FORMAT(//10H  C MATRIX)
   23 FORMAT(//17H  COEFF MATRIX BB)
   25 FORMAT(1H1,18HTABLE OF RESIDUALS)
   26 FORMAT(F10.3,4X,F10.3,4X,F10.3,4X,F10.3)
   27 FORMAT(2X,8HMEASURED,4X,10HCALCULATED,6X,8HRESIDUAL,
     *7X,9HRES./EST.)
   28 FORMAT(5X,23HSUM RESIDUALS SQUARED =,F12.5)
   30 FORMAT(2X,I3,9HCONSTANTS,3X,9HRED. SSQ=,F12.3,3X,
     *10HM.S. RED.=,F12.3)
   31 FORMAT(//12H  TOTAL SSQ=,F12.4)
   32 FORMAT(21H  CORRELATION COEFF.=,F12.5)
   33 FORMAT(31H  SIGNIFICANCE OF REGRESSION F=,F12.5)
   34 FORMAT(12H  WITH D.F.=,I3,3HAND,I3)
   35 FORMAT(11H  RESIDUAL=,F12.5,3X,14HM.S. RESIDUAL=,F12.5)
   36 FORMAT(39H  F TEST FOR SIGNIFICANCE OF LAST VAR.=,F12.5)
   37 FORMAT(//10H  Q MATRIX)
   38 FORMAT(20H  WITH D.F. OF 1 AND,I3)
   39 FORMAT(1H1)
   58 FORMAT(//31H  SSQ REDUCED BY LAST VARIABLE=,F12.5)
   91 FORMAT(25H  LAST VARIABLE NEGLECTED)
   98 FORMAT(21H  REGRESSION ANALYSIS)
   99 FORMAT(25H  STD. ERROR OF ESTIMATE=,F8.5)
  151 FORMAT(I3)
      IO=6
```

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```
      IF(NB)310,310,311
  311 CONTINUE
      NTY=NTY+1
      IF(NV-1)601,600,600
  600 CONTINUE
      NV=NV+1
  601 CONTINUE
      DO 312 N=1,NTY
      M=N+1
      DO 313 J=1,IKE
      X(M,J)=AX(N,J)
  313 CONTINUE
  312 CONTINUE
      DO 314 J=1,IKE
      X(1,J)=1.
  314 CONTINUE
      GO TO 317
  310 CONTINUE
      DO 315 N=1,NTY
      DO 316 J=1,IKE
      X(N,J)=AX(N,J)
  316 CONTINUE
  315 CONTINUE
  317 CONTINUE
      DO 119 JAK=1,2
      WRITE(IO,39)
      WRITE(IO,98)
      IF(JAK-1)93,93,92
   93 CONTINUE
      DO 300 N=1,NTY
      Q(N)=0.
      DO 303 J=1,IKE
      Q(N)=Q(N)+Y(J)*X(N,J)
  303 CONTINUE
      NMV=NTY-N+1
      M=N
      DO 301 MN=1,NMV
      XX(N,M)=0.
      DO 302 J=1,IKE
      XX(N,M)=XX(N,M)+X(N,J)*X(M,J)
  302 CONTINUE
      XX(M,N)=XX(N,M)
      M=M+1
  301 CONTINUE
  300 CONTINUE
      SY=0.
      SYY=0.
```
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```
      DO 320 J=1,IKE
      SY=SY+Y(J)
      SYY=SYY+Y(J)*Y(J)
  320 CONTINUE
   92 CONTINUE
      IF(JAK-1)700,700,701
  701 CONTINUE
      WRITE(IO,91)
  700 CONTINUE
      WRITE(IO,20)
      CALL OUTP(XX,NTY,NTY,15,15)
      DO 1 N=1,NTY
      DO 2 M=1,NTY
      A(N,M)=XX(N,M)
    2 CONTINUE
    1 CONTINUE
      CALL OVER(XX,NTY,CC,15)
      WRITE(IO,21)
      CALL OUTP(CC,NTY,NTY,15,15)
      WRITE(IO,37)
      CALL OUTP(Q,NTY,1,15,1)
      CALL MULTA(CC,Q,NTY,BB,15)
      DO 500 N=1,NTY
      BBT(JAK,N)=BB(N)
  500 CONTINUE
      WRITE(IO,23)
      CALL OUTP(BB,NTY,1,15,1)
      RR=0.
      DO 70 N=1,IKE
      AAY(N)=0.
      DO 71 M=1,NTY
      AAY(N)=BB(M)*X(M,N)+AAY(N)
   71 CONTINUE
      R(N)=Y(N)-AAY(N)
      RPER(N)=R(N)*100./AAY(N)
   70 RR=RR+R(N)*R(N)
      ZNTY=NTY
      REDEC=0.
      DO 29 NOP=1,NTY
   29 REDEC=REDEC+BB(NOP)*Q(NOP)
      RESID=SYY-REDEC
      RRBE(JAK)=RESID
      Z=IKE
      ZNT=IKE-NTY
      SQR=RESID/ZNT
      SQR=SQRT(SQR)
      COR=RESID/((Z*SYY-(SY*SY))/Z)
      COR=SQRT(1.-COR)
      AMSRES=RESID/ZNT
      ZNT=NTY
```

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```
      AMSC=REDEC/ZNT
      WRITE(IO,31)SYY
      WRITE(IO,30)NTY,REDEC,AMSC
      WRITE(IO,35)RESID,AMSRES
      WRITE(IO,32)COR
      WRITE(IO,99)SQR
      FF=AMSC/AMSRES
      RA(JAK)=REDEC
      WRITE(IO,33)FF
      NNT=NTY
      NT=IKE-NNT
      WRITE(IO,34)NNT,NT
      WRITE(IO,25)
      WRITE(IO,27)
      WRITE(IO,26)(Y(N),AAY(N),R(N),RPER(N),N=1,IKE)
      WRITE(IO,28)RR
      DO 3 N=1,NTY
      DO 4 M=1,NTY
      XX(N,M)=A(N,M)
    4 CONTINUE
    3 CONTINUE
      NTY=NTY-1
      IF(NTY-1)402,403,403
  403 CONTINUE
      IF(NTY-NB)410,410,405
  405 CONTINUE
  119 CONTINUE
  410 CONTINUE
      FF=RA(1)-RA(2)
      WRITE(IO,58)FF
      FF=FF/RRBE(1)
      WRITE(IO,36)FF
      NT=IKE-NTY
      WRITE(IO,38)NT
      IF(NV-1)400,401,401
  401 CONTINUE
      CALL CONFID(IKE,X,SQR,SY,BB,NV)
  400 CONTINUE
  402 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE OUTP(A,N,M,NS,MS)
C
C     MATRIX OUTPUT SUBROUTINE
C
      DIMENSION A(NS,MS)
  811 FORMAT(/6(13X,I3))
  812 FORMAT(I5,5X,6(E12.5,4X))
  829 FORMAT(1H1)
      IO=6
      L=1
      MADD=6
      IF(M-MADD)818,818,819
  818 K=M
      GO TO 820
  819 K=MADD
  820 WRITE(IO,811)(I,I=L,K)
      DO 821 I=1,N
      WRITE(IO,812)(I,(A(I,J),J=L,K))
  821 CONTINUE
      IF(K-M)822,828,828
  822 L=L+6
      WRITE(IO,829)
      K=K+MADD
      IF(K-M)820,823,823
  823 K=M
      GO TO 820
  828 RETURN
      END
```

```
      SUBROUTINE OVER(A,I,B,NI)
C
C     MATRIX INVERSION SUBROUTINE
C
      DIMENSION A(NI,NI),B(NI,NI)
      DO 1 N=1,I
      DO 1 M=1,I
    1 B(M,N)=0.
      DO 2 MN=1,I
    2 B(MN,MN)=1.
      DO 20 K=1,I
      TI=A(K,K)
      DO 10 L=1,I
      A(K,L)=A(K,L)/TI
   10 B(K,L)=B(K,L)/TI
      DO 13 J=1,I
      SIT=A(J,K)
      IF(K-J)11,13,11
   11 DO 12 II=1,I
      A(J,II)=A(J,II)-SIT*A(K,II)
   12 B(J,II)=B(J,II)-SIT*B(K,II)
   13 CONTINUE
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MULTA(BB,CC,II,DD,NI)
C
C     MATRIX MULTIPLY SUBROUTINE
C
      DIMENSION BB(NI,NI),CC(NI),DD(NI)
      DO 10 I=1,II
      DD(I)=0
      DO 10 K=1,II
   10 DD(I)=DD(I)+BB(I,K)*CC(K)
      RETURN
      END
```

```
      SUBROUTINE CONFID(IKE,X,SQR,SY,B,NA)
C
C
C     CONFIDENCE INTERVAL OF REGRESSION
C     NOTE THAT THE VALUES OF F AND ALPHA(AL) MUST BE SET
C     FOR EACH ANALYSIS WITH THE CORRECT DEGREES OF FREEDOM
C     ANALYSIS WITH THE CORRECT DEGREES OF FREEDOM
C     INTERVAL OF THE FORM Y*=Y-SQRT(F)*CONFIDENCE INTERVAL
C
      DIMENSION YC(5),W(5),XT(5)
      DIMENSION X(15,200),B(15),X1(200)
    3 FORMAT(//37H  CONFIDENCE BAND FOR REGRESSION LINE)
    4 FORMAT(22H  CONFIDENCE INTERVAL=,F4.1,3X,2HF=,F7.4)
    5 FORMAT(6H  VAR.,I3,5X,14H   Y PREDICTED,18H
     * CONFIDENCE INT.)
    6 FORMAT(6X,F6.3,4X,F9.3,8X,F12.4)
    7 FORMAT(7H  D.F.=,I3,4H AND,I3)
    8 FORMAT(24H  GRAND TOTAL AVERAGE Y=,F12.4)
   99 FORMAT(25H  STD. ERROR OF ESTIMATE=,F8.3)
      DO 20 N=1,IKE
      X1(N)=X(NA,N)
   20 CONTINUE
      C=B(NA)
      SXX1=0.
      SX1=0.
      IO=6
      AL=0.
      F=1.
      DO 1 N=1,IKE
      SX1=SX1+X1(N)
      SXX1=SXX1+X1(N)*X1(N)
    1 CONTINUE
      Z=IKE
      X1AVG=SX1/Z
      SXX=SXX1-((SX1*SX1)/Z)
      SQX=SQRT(SXX/Z)
      N1=2
      N2=IKE-2
      SQF=SQRT(2.*F)
      YAV=SY/Z
      XA=X1AVG-2.*SQX
      DO 2 N=1,5
      XO=XA
      XT(N)=XO
      YC(N)=YAV+C*(XO-X1AVG)
      W(N)=SQRT((1./Z)+((XO-X1AVG)*(XO-X1AVG)/SXX))
      W(N)=W(N)*SQR*SQF
      XA=XA+SQX
      IF(N-3)50,51,50
   51 CONTINUE
```
CONTINUE NEXT PAGE

```
      XA=XA+0.001
   50 CONTINUE
    2 CONTINUE
      WRITE(IO,3)
      WRITE(IO,4)AL,F
      WRITE(IO,7)N1,N2
      WRITE(IO,5)NA
      WRITE(IO,6)(XT(N),YC(N),W(N),N=1,5)
      WRITE(IO,8)YAV
      WRITE(IO,99)SQR
      RETURN
      END
```

```
      SUBROUTINE DRAW(AGE,STR,BBT,MXY)
C     THIS SUBROUTINE PLOTS CURVEFIT INFORMATION
C     AND ORIGINAL DATA
      DIMENSION COGT(20),AGE(20),STR(20),BAGE(200),
     *BSTR(200),BBT(2,15),BLOGT(200)
      IO=6
      DO 100 N=1,MXY
      COGT(N)=ALOG10(24.*AGE(N))
  100 CONTINUE
      BAGE(1)=1.2
      BLOGT(1)=ALOG10(BAGE(1))
      DO 103 J=2,5
      BAGE(J)=BAGE(J-1)+25.
      BLOGT(J)=ALOG10(BAGE(J))
  103 CONTINUE
      DO 104 J=6,100
      BAGE(J)=BAGE(J-1)+100.
      BLOGT(J)=ALOG10(BAGE(J))
  104 CONTINUE
      DO 105 J=101,200
      BAGE(J)=BAGE(J-1)+781.
      BLOGT(J)=ALOG10(BAGE(J))
  105 CONTINUE
      DO 102 N=1,200
      BSTR(N)=BBT(1,1)+BBT(1,3)*BLOGT(N)+BBT(1,2)*BLOGT(N)**2.
  102 CONTINUE
      NUM=-MXY
      N=199
      CALL NAMPLT
      CALL QIKSET(8.0,0.0,0.70,5.0,0.0,070.0)
      CALL QIKPLT(COGT,STR,NUM,18H*LOG TIME IN HRS.*,8H*STRAIN*,
     *23H*TOTAL STRAIN VS. TIME*)
      CALL PLOT(-9.0,1.0,-3)
      CALL QLINE(BLOGT,BSTR,N)
      CALL PLOT(10.0,0.0,3)
      CALL ENDPLT
      RETURN
      END
```

10. TABLES

Table 1 Designation and Number of Rectangular Concrete Specimens

Series	Designation First Letter	Number of Specimens From Each Plant	Fiber Nominal Stress Top (f_t)	Bottom (f_b)	Center	Differential Stress (f_b-f_t)
			ksi	ksi	ksi	ksi
1.0	A	2	1.0	1.0	1.0	0.0
	B	2	0.5	1.5	1.0	1.0
	C	2	0.0	2.0	1.0	2.0
	D	4	Shrinkage (14 strands)			
1.5	E	2	1.5	1.5	1.5	0.0
	F	2	1.0	2.0	1.5	1.0
	G	2	0.0	3.0	1.5	3.0
	H	4	Shrinkage (20 strands)			
2.0	J	2	2.0	2.0	2.0	0.0
	K	2	1.0	3.0	2.0	2.0
	L	2	0.4	3.6	2.0	3.2
	M	4	Shrinkage (28 strands)			
3.0	N	2	3.0	3.0	3.0	0.0
	O	2	Shrinkage (40 strands)			
3.6	P	2	3.6	3.6	3.6	0.0
	Q	2	Shrinkage (48 strands)			
0.0	R	2	Shrinkage (no strand)			
	S	2				
	TOTAL from each plant	42				

Table 2 Typical Reading Schedule for Concrete Specimens

Number of Reading	Age of Specimen at Time of Reading
1	0 (before release)
2	Approx. 1 hr. (after release)
	DAYS
3	1
4	4
5	7
6	14
7	21
8	28
9	42
10	56
11	77
12	98
13	126
14	154
15	182
16	210
17	266
18	300
19	350
Subsequent readings	every 100 days

Table 3 Concrete Mix Information and Fabrication Schedule

Series	Plant	Design Proportions	Cement Bags/cu. yd.	Actual Total Water Gals./cu. yd.	Slump In.	Air Entrainment %	Time of Curing Hrs.
1.0	AB	1:1.51:2.78	7.5	32.75	2	3.6	67
1.5	AB	"	"	31.9	2 1/2	3.4	73
2.0	AB	"	"	32.1	2 3/8	3.2	72
3.0	AB	"	"	31.5	2 1/2	2.9	68
3.6	AB	"	"	30.8	2 1/2	3.0	71
1.0	CD	1:1.15:2.41	8.5	33.5	1 1/4	4.4	35
1.5	CD	"	"	35.2	1 3/8	4.1	34
2.0	CD	"	"	36.7	1 7/8	4.3	33
3.0	CD	"	"	39.1	1 7/8	4.7	31
3.6	CD	"	"	38.5	1 3/4	4.8	32

Table 4 Concrete Strength and Modulus Used in Rectangular Specimens

Series	Plant	Plant Release f'ci ksi	Lehigh Release f'ci ksi	Lehigh Release Eci ksi	7-Day f'c ksi	7-Day Ec ksi	29-Day f'c ksi	29-Day Ec ksi	90-Day f'c ksi	90-Day Ec ksi
1.0	AB	5.41	5.86	4.23	6.23	4.17	6.81	4.04	6.73	3.99
1.5	AB	5.48	5.24	3.52	6.56	3.79	7.11	3.87	6.88	3.92
2.0	AB		6.03	3.73	6.15	3.77	6.78	3.70	7.07	3.77
3.0	AB	5.49	5.66	3.86	5.47	3.96	6.67	4.13	6.89	4.27
3.6	AB	5.48	5.74	4.02	6.47	3.93	6.75*		7.14	4.07
1.0	CD	6.50	6.75	4.94	7.21	5.10	7.64	5.15	7.79	5.17
1.5	CD	6.51	6.80*		7.31	5.04	7.85	5.02	7.76	5.03
2.0	CD	6.17	5.84	4.48	6.18	4.59	7.02	4.78	7.18	4.98
3.0	CD	5.70	5.50	4.23	6.28	4.44	6.59	4.51	6.79	4.54
3.6	CD	5.54	5.75	4.29	6.52	4.24	6.60*		6.86	4.43

*assumed values

Table 5 Coefficients of Strain Equations

Series	Plant	A_o	A_1	A_2	B
1.0	AB	1365.2	73.8	216.7	95
1.5	AB	1263.3	94.1	115.3	125
2.0	AB	1566.2	88.3	129.0	131
3.0	AB	1389.0	53.7	134.3	115
3.6	AB	1380.3	47.6	137.8	121
1.0	CD	1117.8	88.9	55.5	110
1.5	CD	1384.6	79.0	99.3	110
2.0	CD	1185.6	80.1	92.2	123
3.0	CD	1176.4	66.9	89.5	128
3.6	CD	1296.5	48.2	94.2	121

11. FIGURES

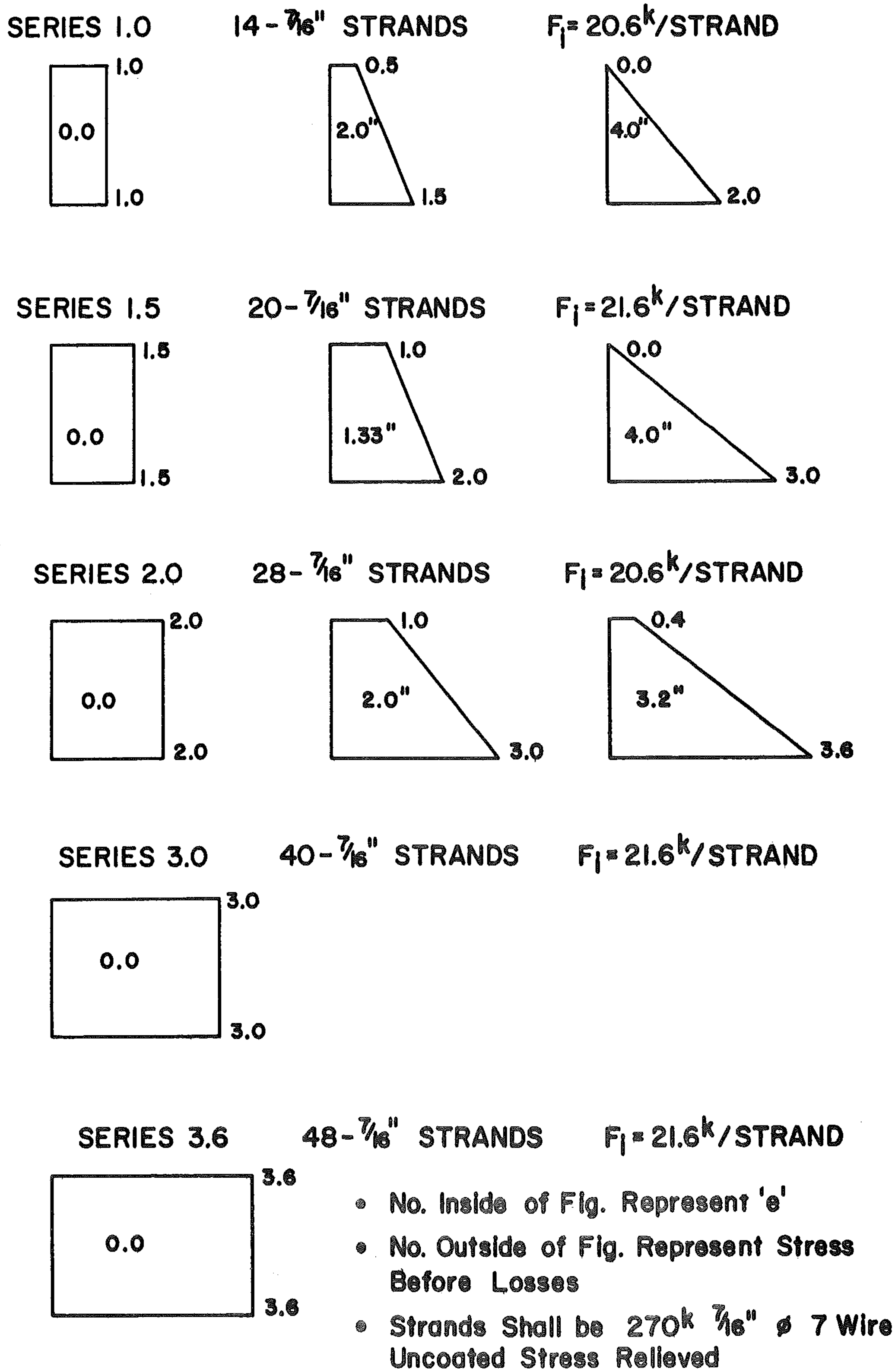
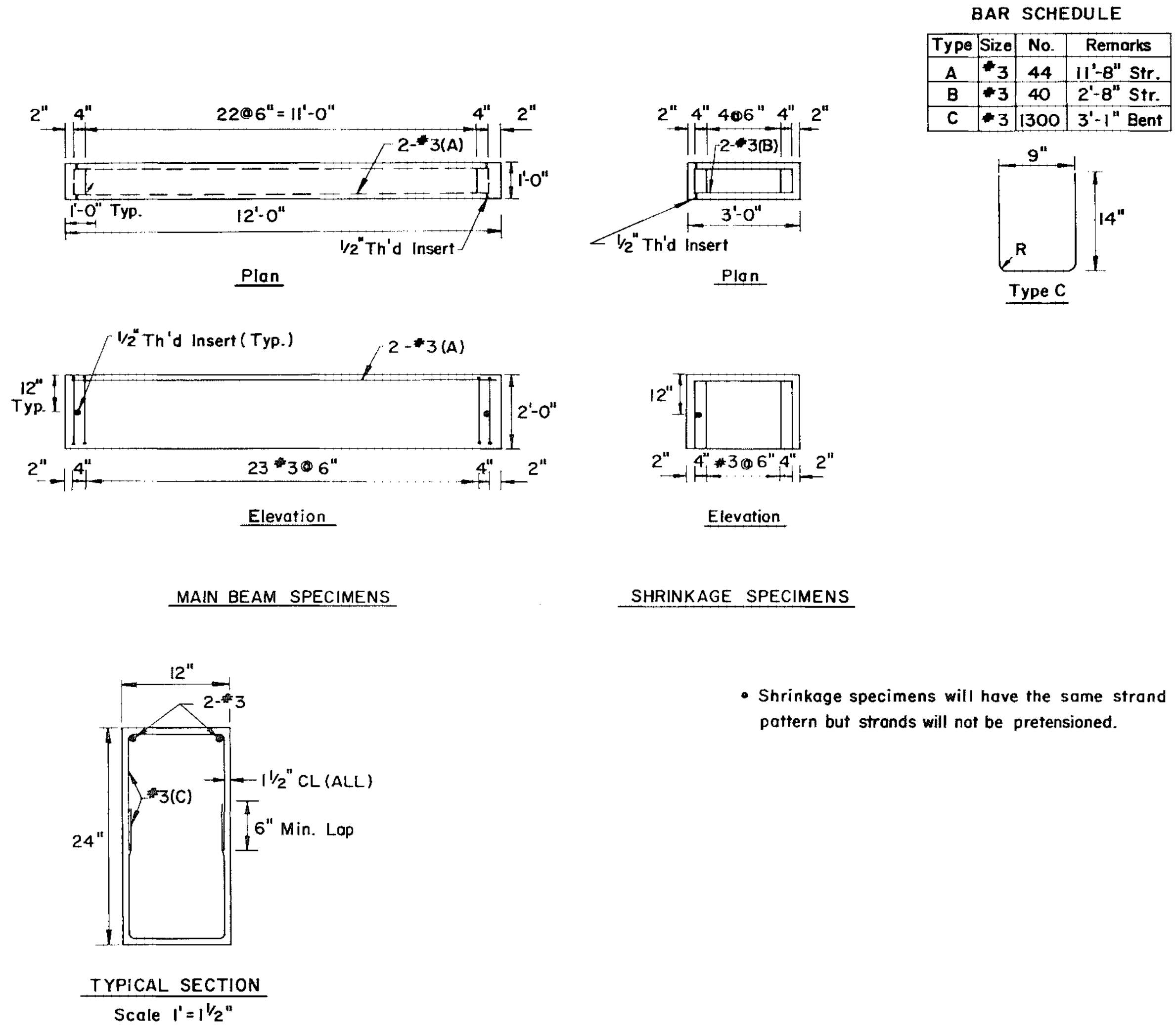
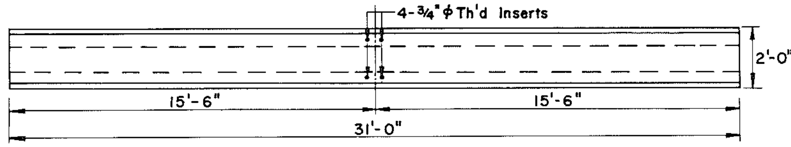


Fig. 1 Stress Distributions for Rectangular Specimens



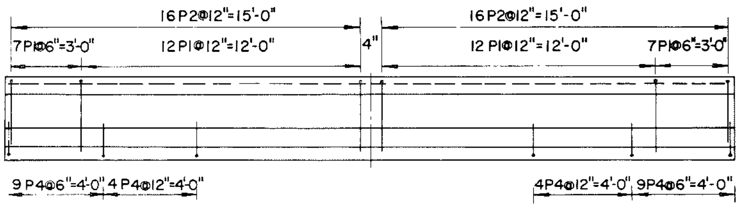
Type	Size	No.	Remarks
A	#3	44	11'-8" Str.
B	#3	40	2'-8" Str.
C	#3	1300	3'-1" Bent

Fig. 2 Reinforcement of Rectangular Specimens

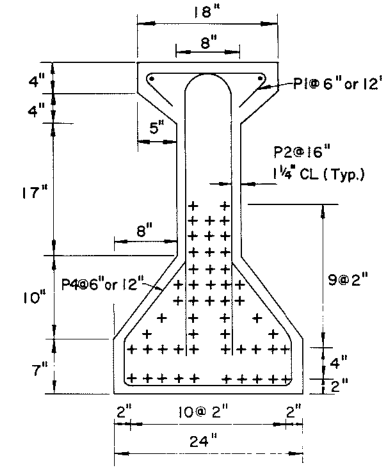


PLAN

Scale=⅜"=1'-0"

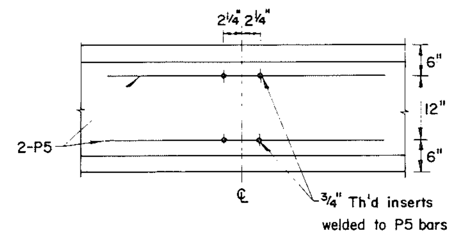


ELEVATION



TYPICAL SECTION

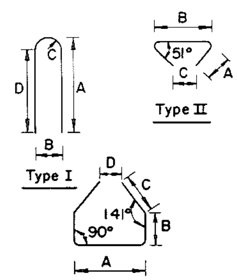
Scale 1 ½" = 1'-0"



Detail A

BAR SCHEDULE

Call	Type	Size	No.	Length	A	B	C	D	Remarks
P1	II	#4	38	28"	6"	15½"	5¼"		
P2	I	#4	32	83¼"	36"	5¼"	2⅝"	33⅝"	
P4	III	#4	26	57"	21½"	5¾"	12"	7½"	
P5	STR.	#4	2	48"					



- The strand pattern is the same in the shrinkage beams and the 31'-0" beam, but the strands are not tensioned.
- F_o 21.6^K per strand in large beam.
- $\frac{7}{16}$" φ 270^K 7 wire stress relieved prestressing strand is to be used.
- f'ci = 5000 psi f'c = 6000 psi
- All materials must meet P.D.H. Specs.

Fig. 3 Reinforcement of I-Beams

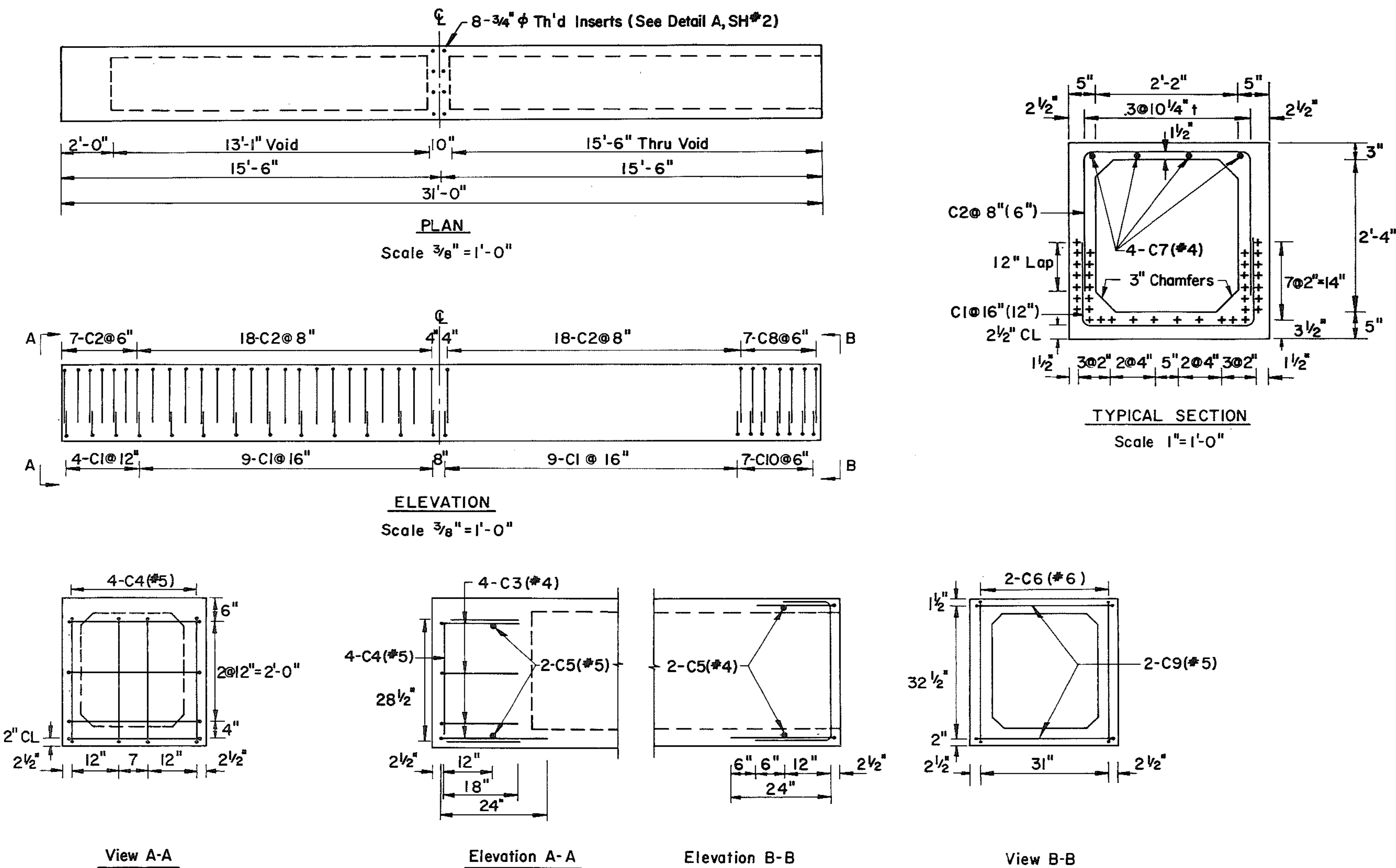
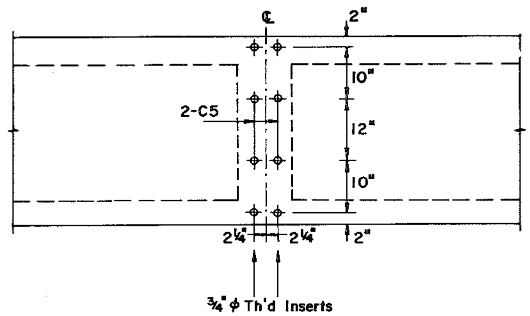


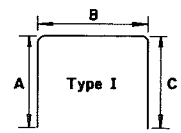
Fig. 4 Reinforcement of Box Beam

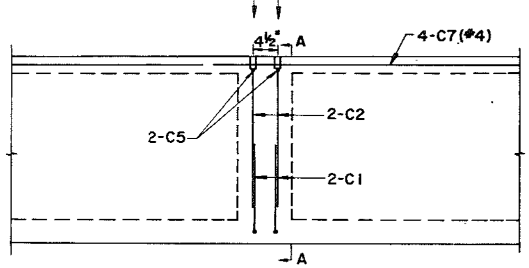


- Inserts to be welded to C5 bars
- Positioning of inserts is critical
- C5 bar positioned under C7 bars

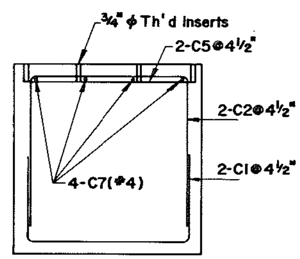
BAR SCHEDULE

Mark	Size	No.	Length	Type	A	B	C	D	Remarks
C1	#4	28	5'-9"	I	19"	31"	19"		
C2	#4	53	7'-1"	I	27"	31"	27"		
C3	#4	4	5'-10"	I	18"	31"	18"		
C4	#5	4	6'-0"	I	24"	28"	18"		
C5	#4	14	2'-8½"	STR					
C6	#6	2	5'-9"	I	18"	32½"	18"		
C7	#4	4	30'-8"	STR					
C8	#5	7	7'-2"	I	27"	31"	27"		
C9	#5	2	6'-5"	I	18"	31"	27"		
C10	#5	7	5'-10"	I	19"	31"	19"		

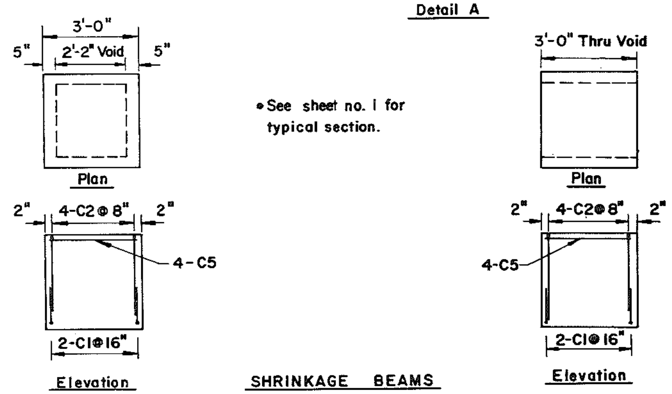




ELEVATION



Detail A



SHRINKAGE BEAMS

- The strand pattern is the same in the shrinkage beams and the 31'-0" beam, but the strands are not tensional.
- F_0 = 21.6^K per strand in large beam
- $\frac{7}{16}$" ϕ 270^K 7 wire stress relieved prestressing strand is to be used.
- f'ci = 5000 psi f'c = 6000 psi
- All materials must meet P.D.H. specs.

Fig. 5 Reinforcement of Box Beam

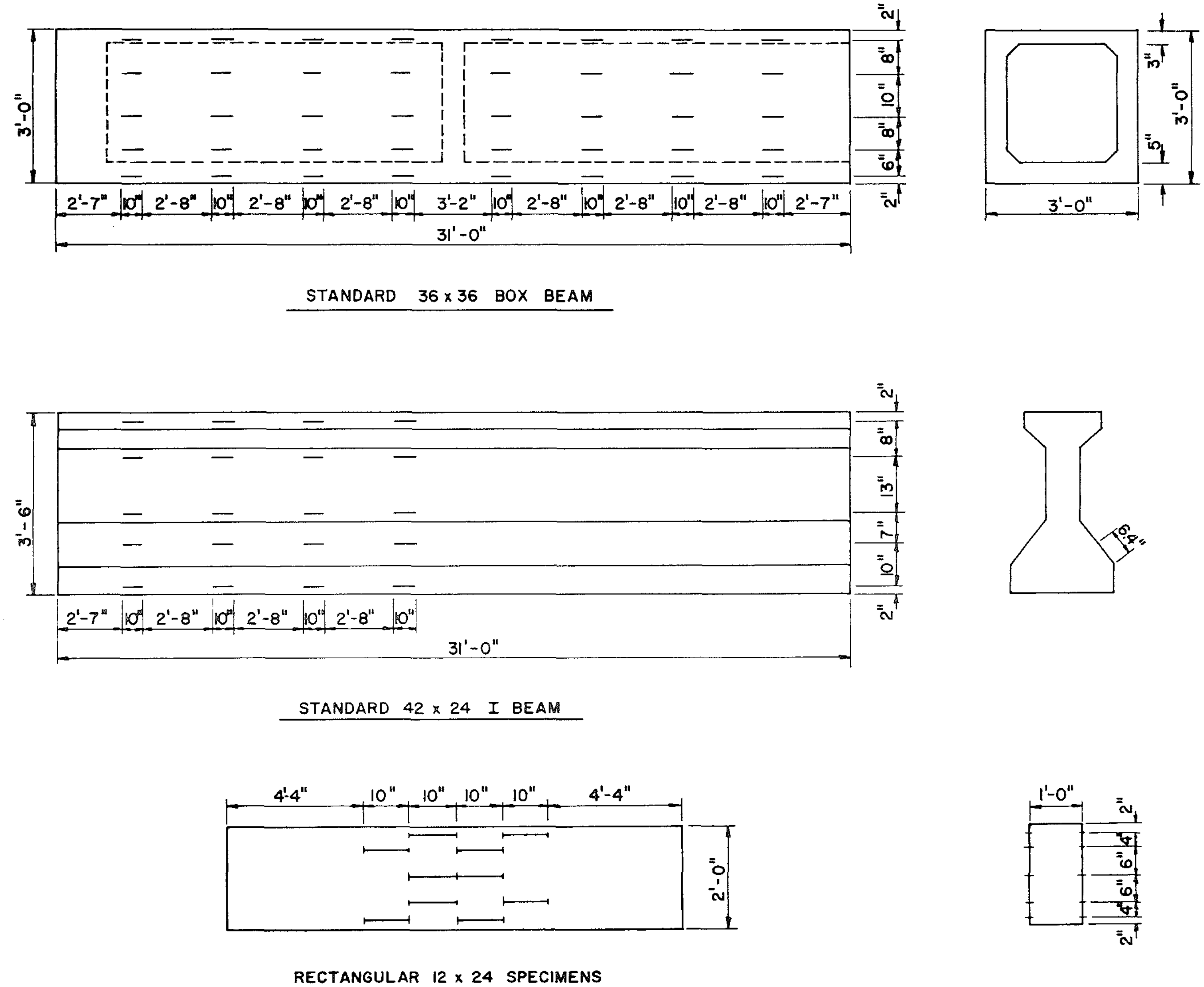


Fig. 6 **Gage Locations**

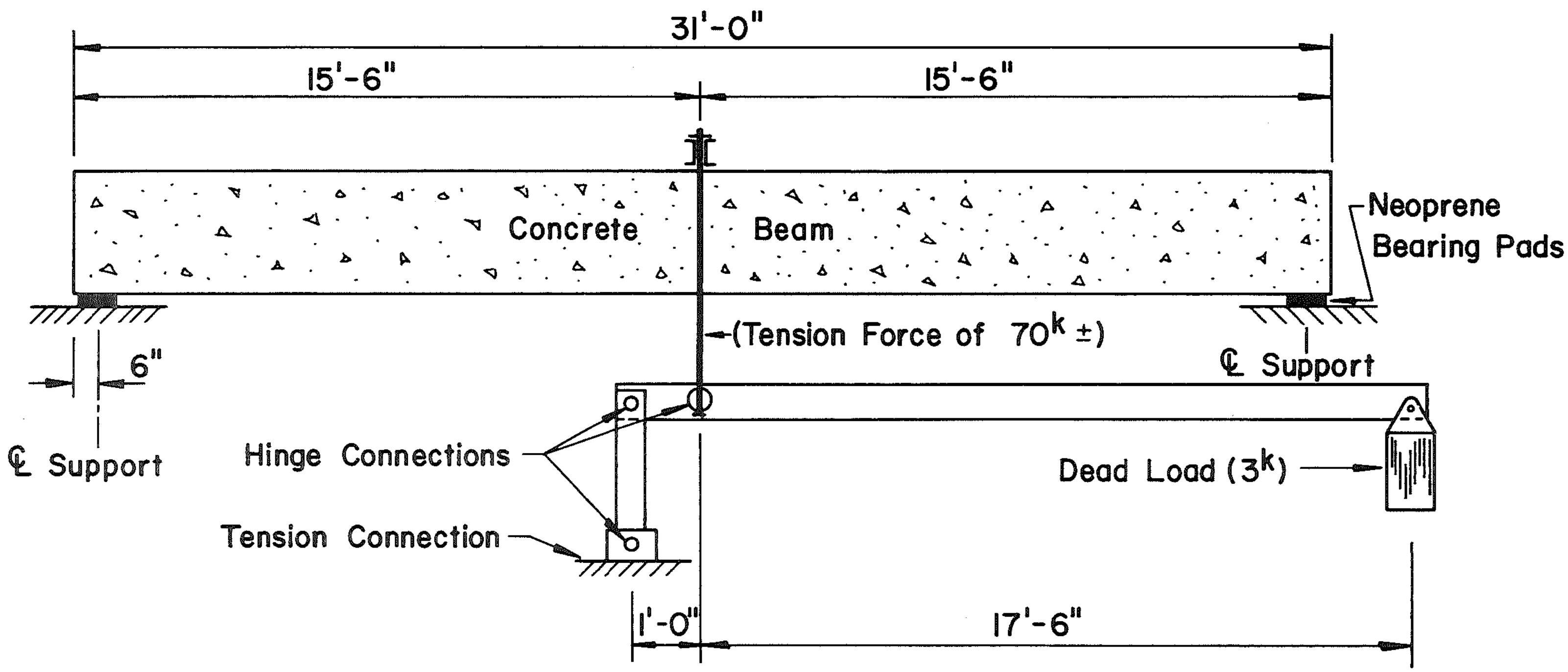
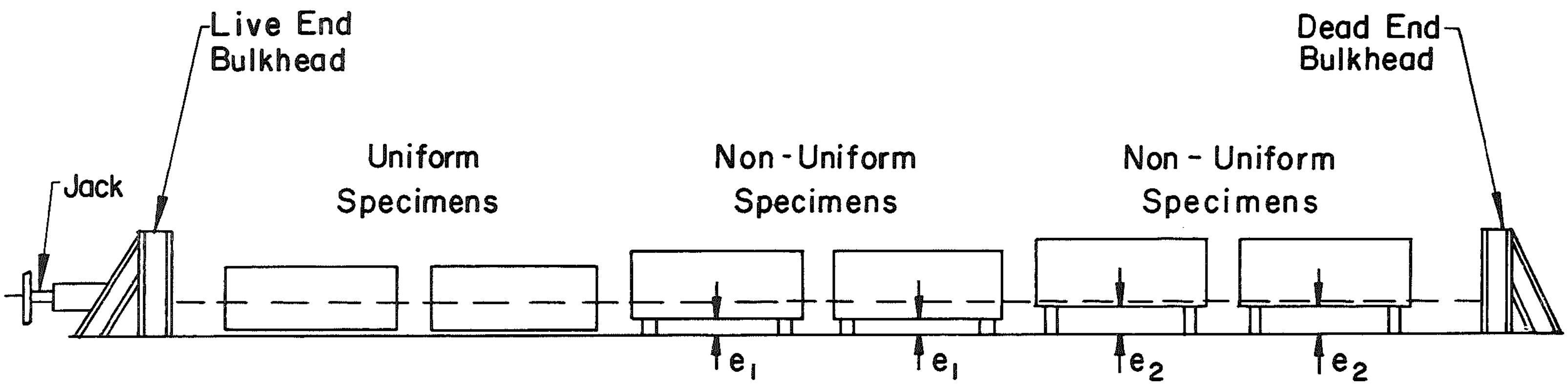


Fig. 7 Loading Frame for Full-Size Members

TYPICAL FORM LAYOUT
FOR RECTANGULAR 1'x 2'x 12' LONG
CONCRETE SPECIMENS



SERIES	SPECIMENS	SPECIMENS	e_1	SPECIMENS	e_2
1.0	1.0-0.0	1.0-0.5	2.0"	1.0-1.0	4.0"
1.5	1.5-0.0	1.5-0.5	1.33"	1.5-1.5	4.0"
2.0	2.0-0.0	2.0-1.0	2.0"	2.0-1.6	3.2"
3.0	3.0-0.0				
3.6	3.6-0.0				

Fig. 8 Pallette Elevations

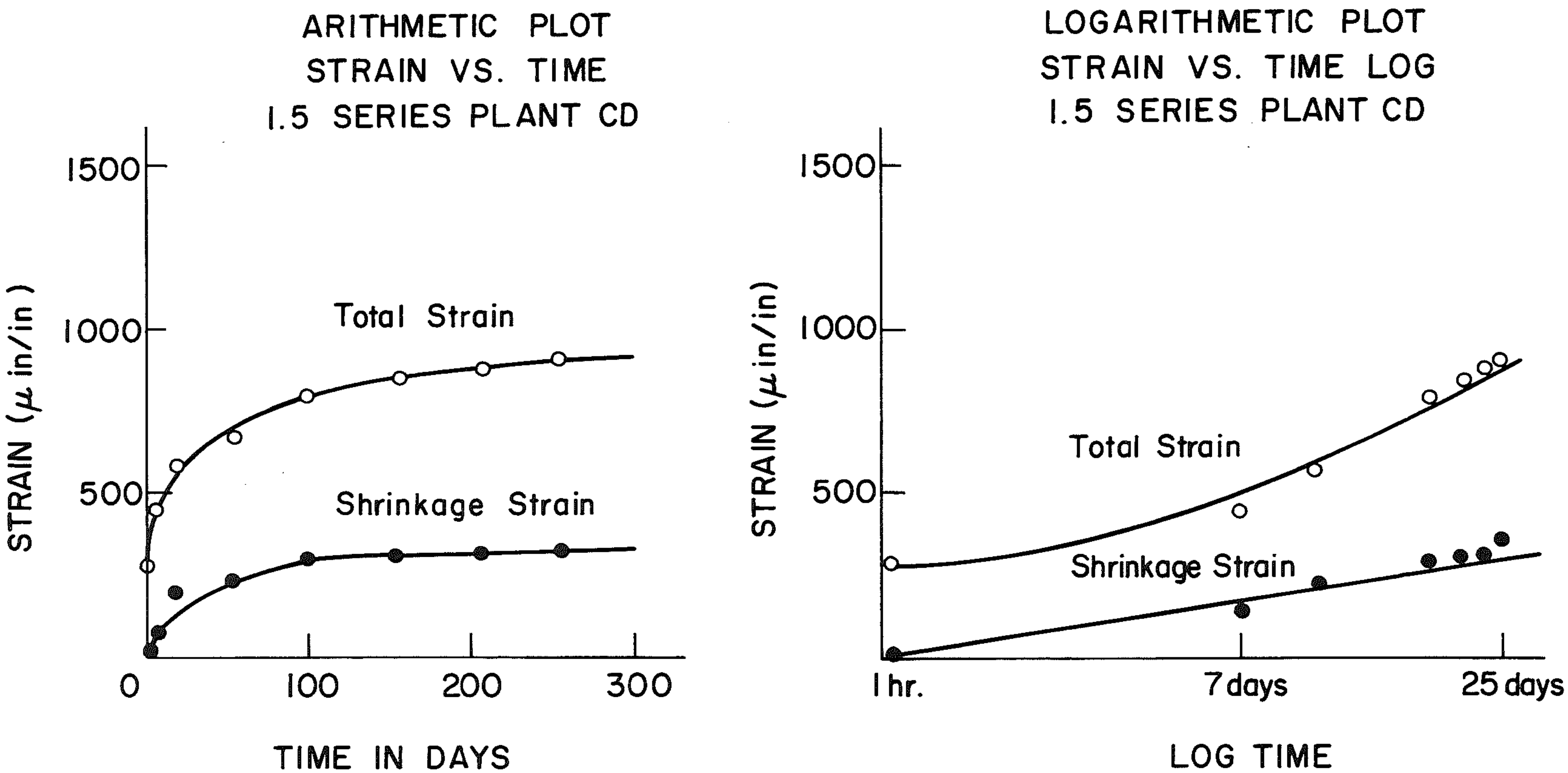


Fig. 9 Comparison Curves

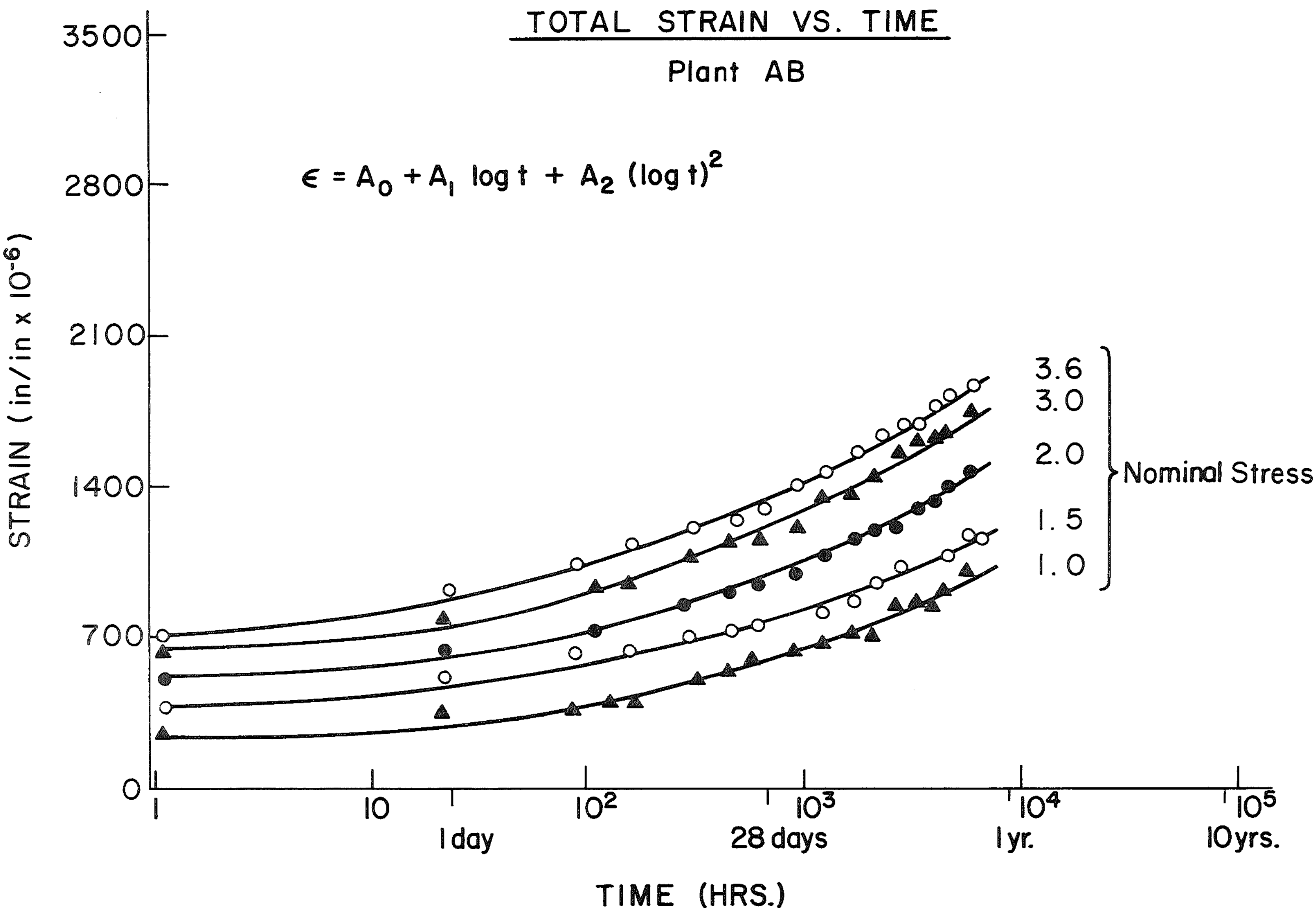


Fig. 10 Total Strains vs. Time - Plant AB

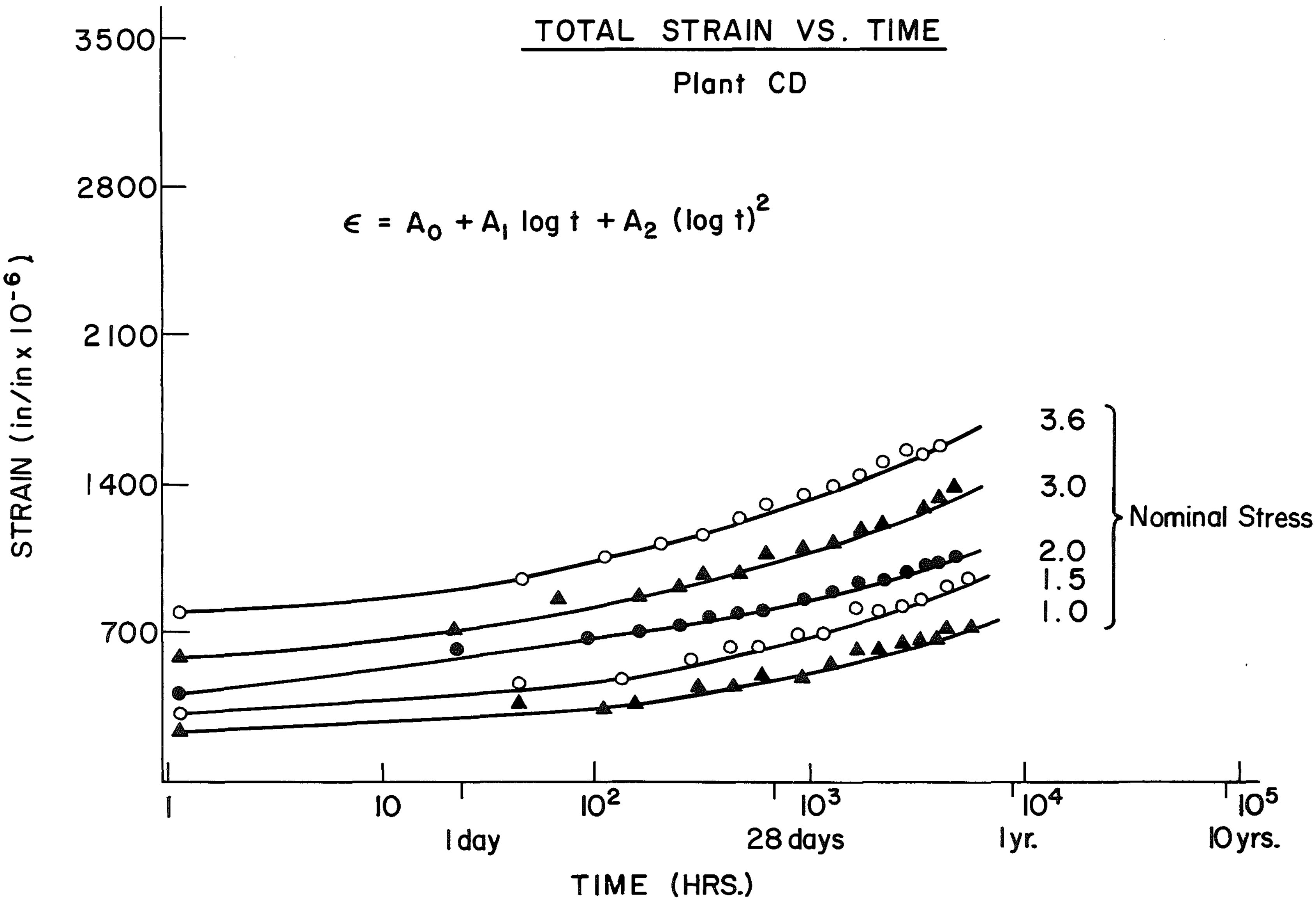


Fig. 11 Total Strains vs. Time - Plant CD

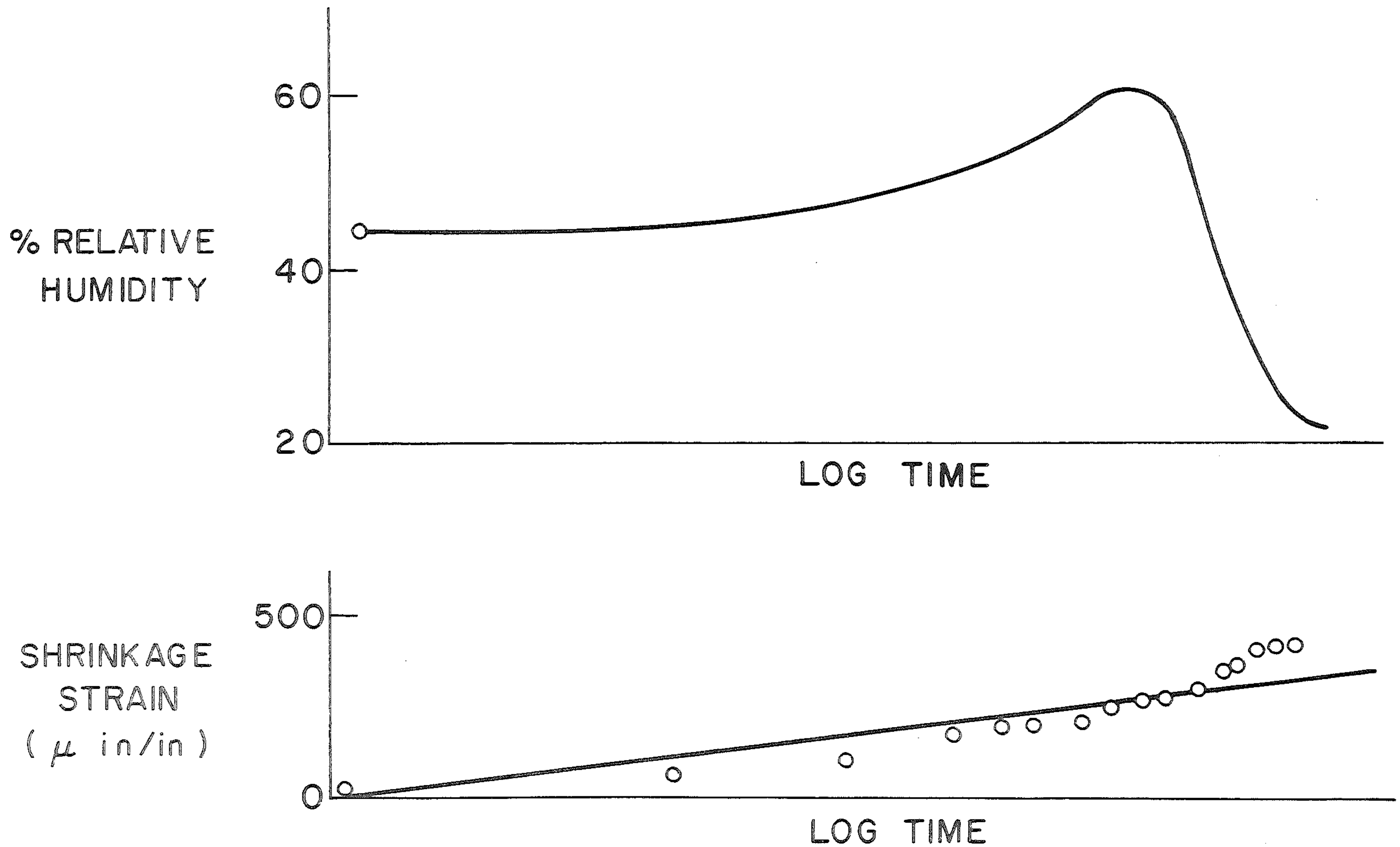


Fig. 12 Effect of Relative Humidity on Shrinkage

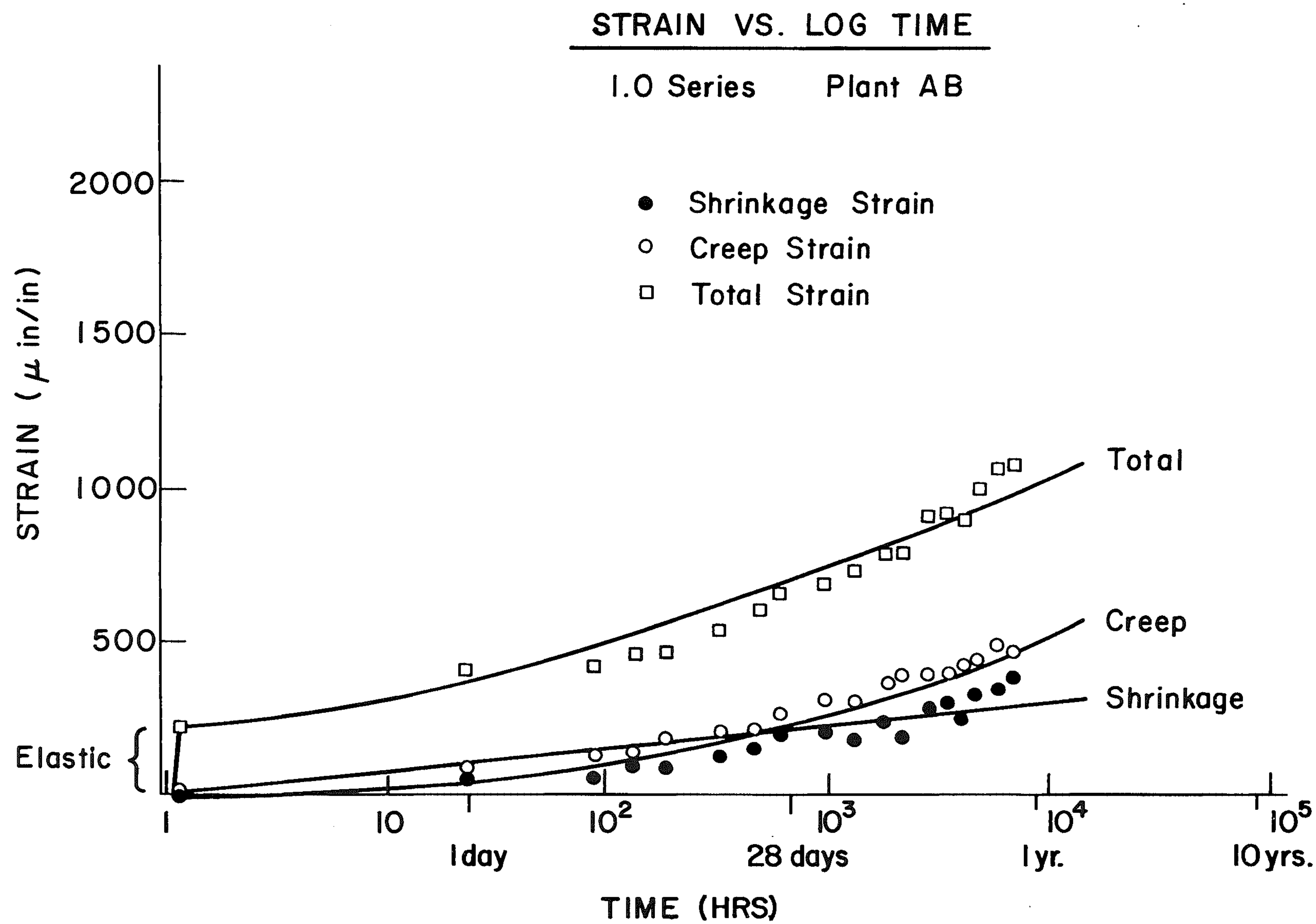


Fig. 13 Strain vs. Time - 1.0 Series - Plant AB

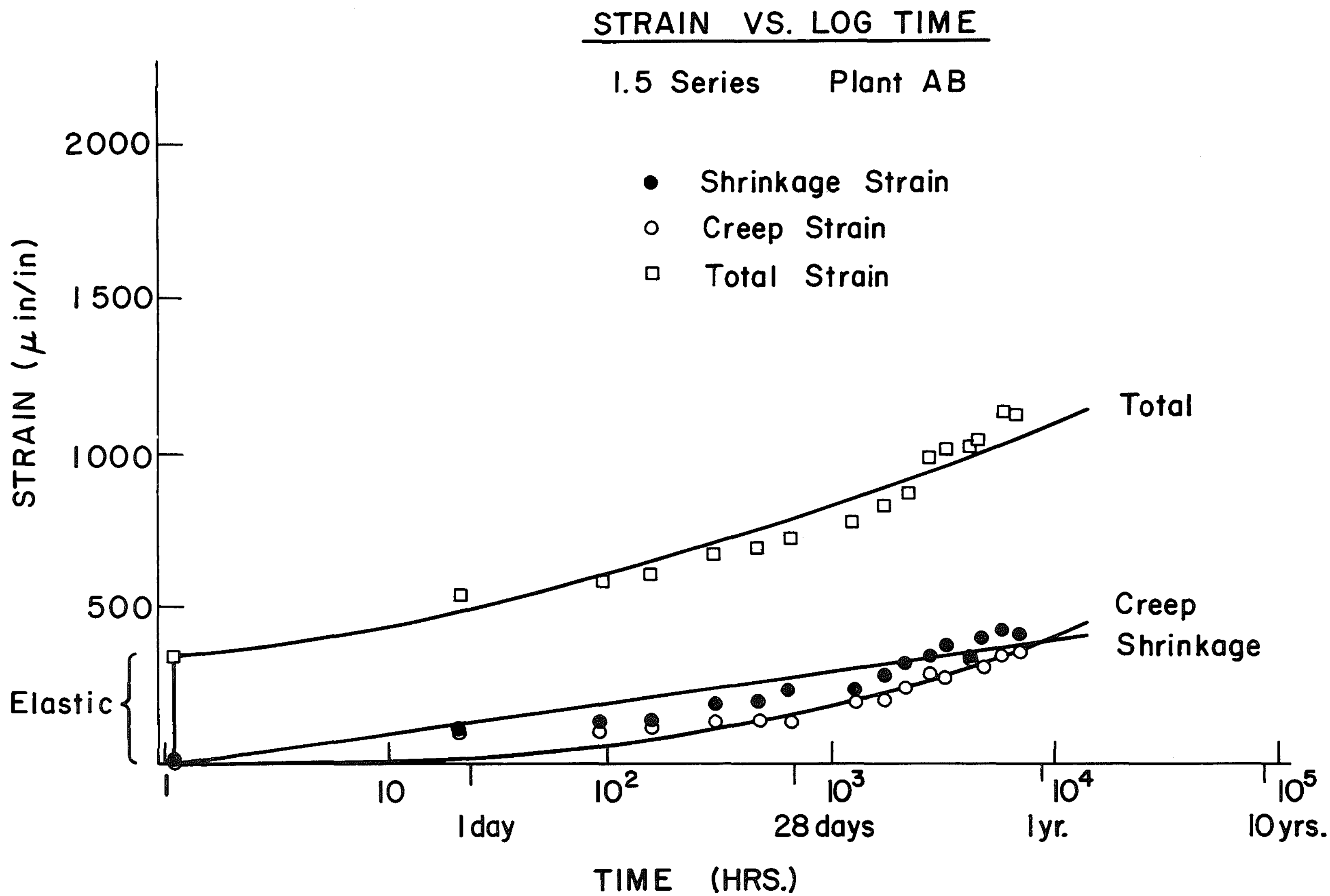


Fig. 14 Strain vs. Time - 1.5 Series - Plant AB

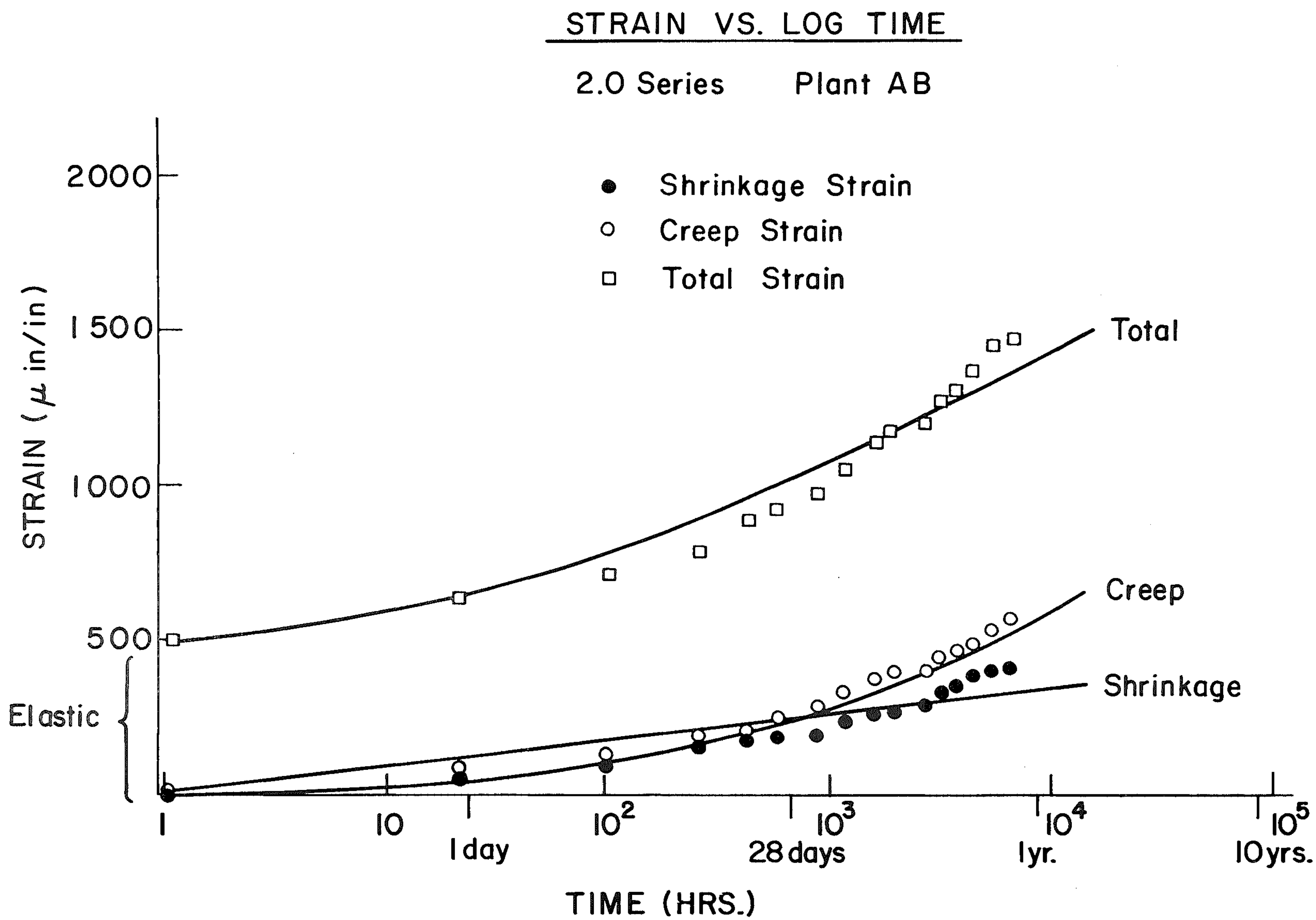


Fig. 15 Strain vs. Time - 2.0 Series - Plant AB

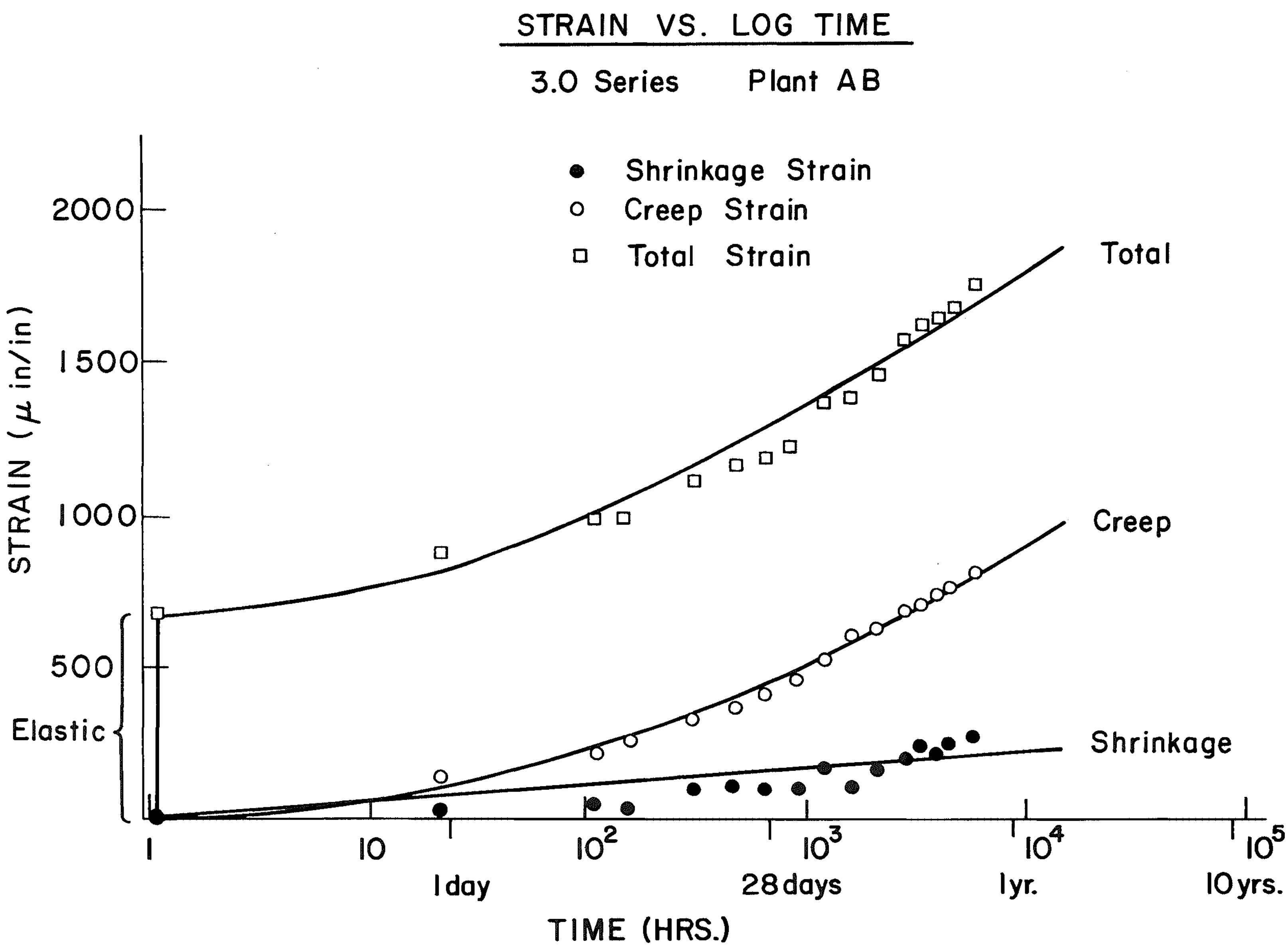


Fig. 16 Strain vs. Time - 3.0 Series - Plant AB

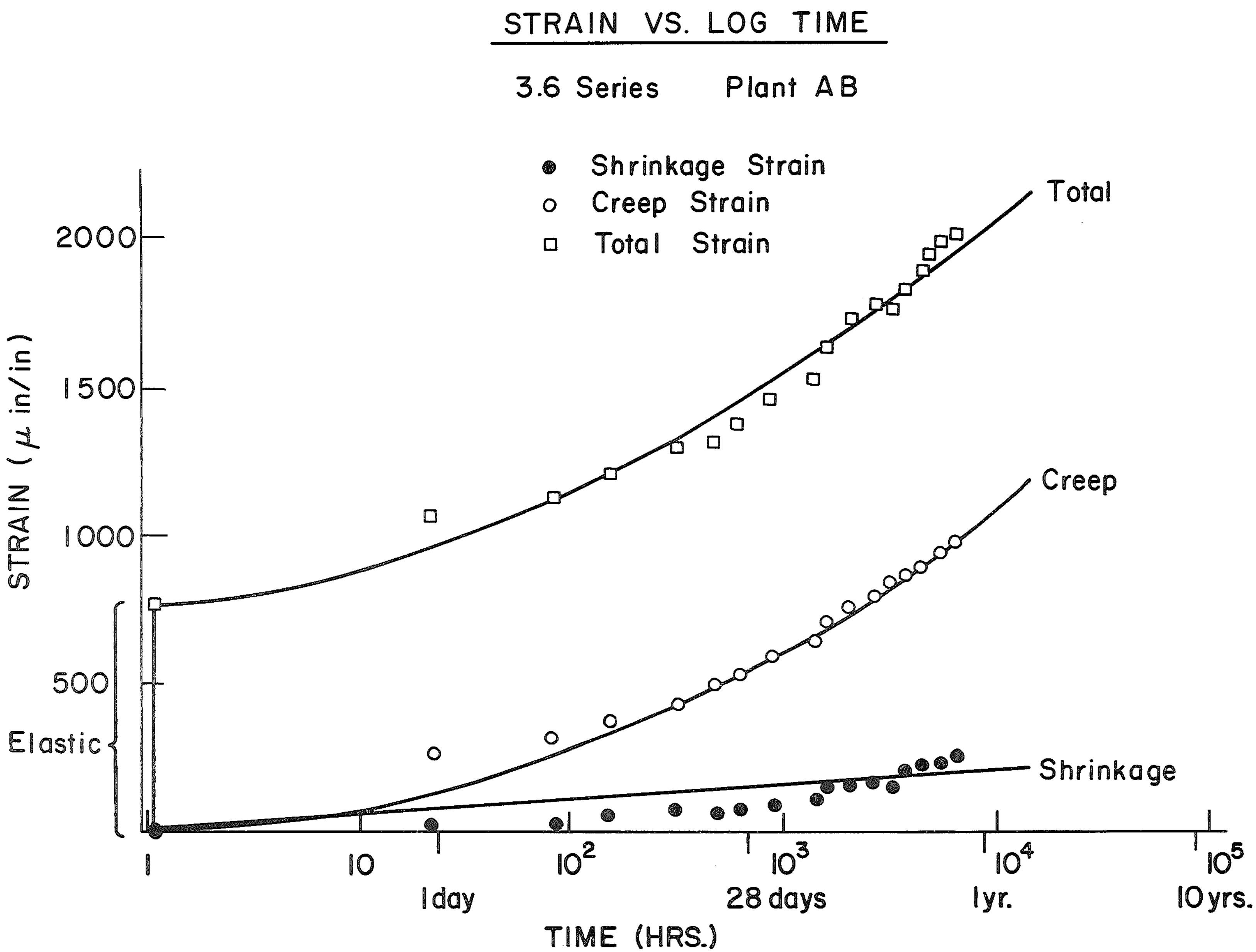


Fig. 17 Strain vs. Time - 3.6 Series - Plant AB

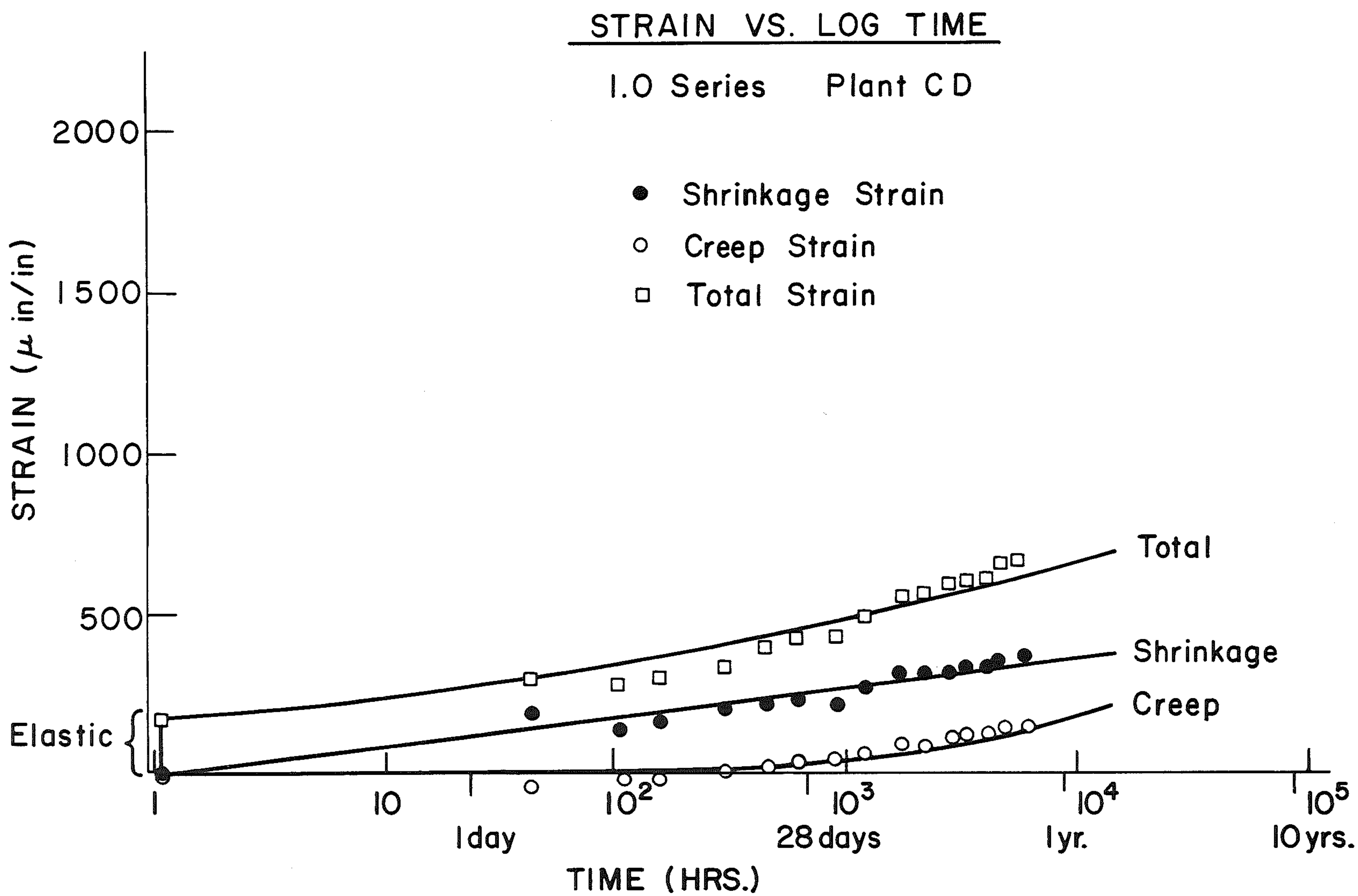


Fig. 18 Strain vs. Time - 1.0 Series - Plant CD

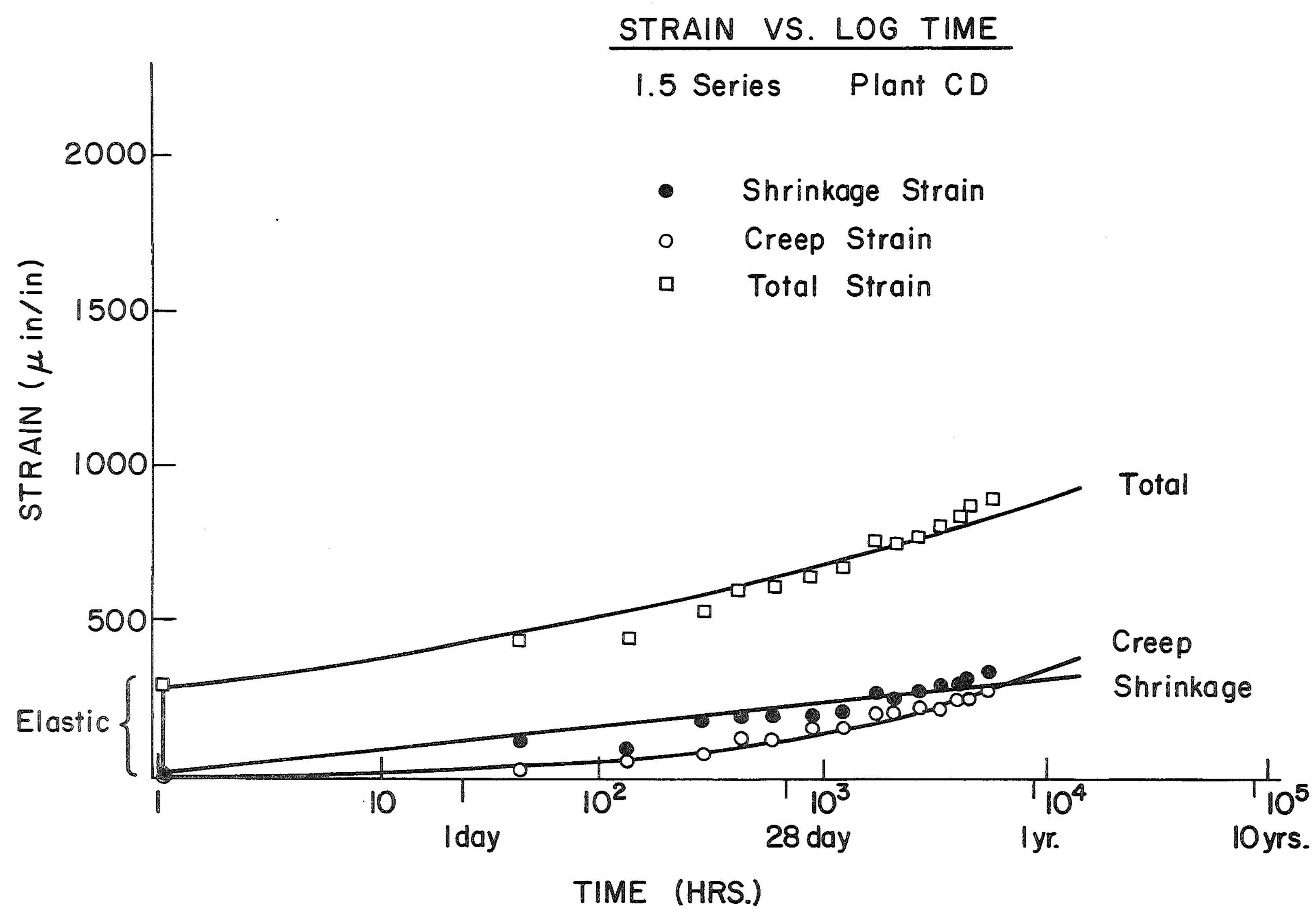


Fig. 19 Strain vs. Time - 1.5 Series - Plant CD

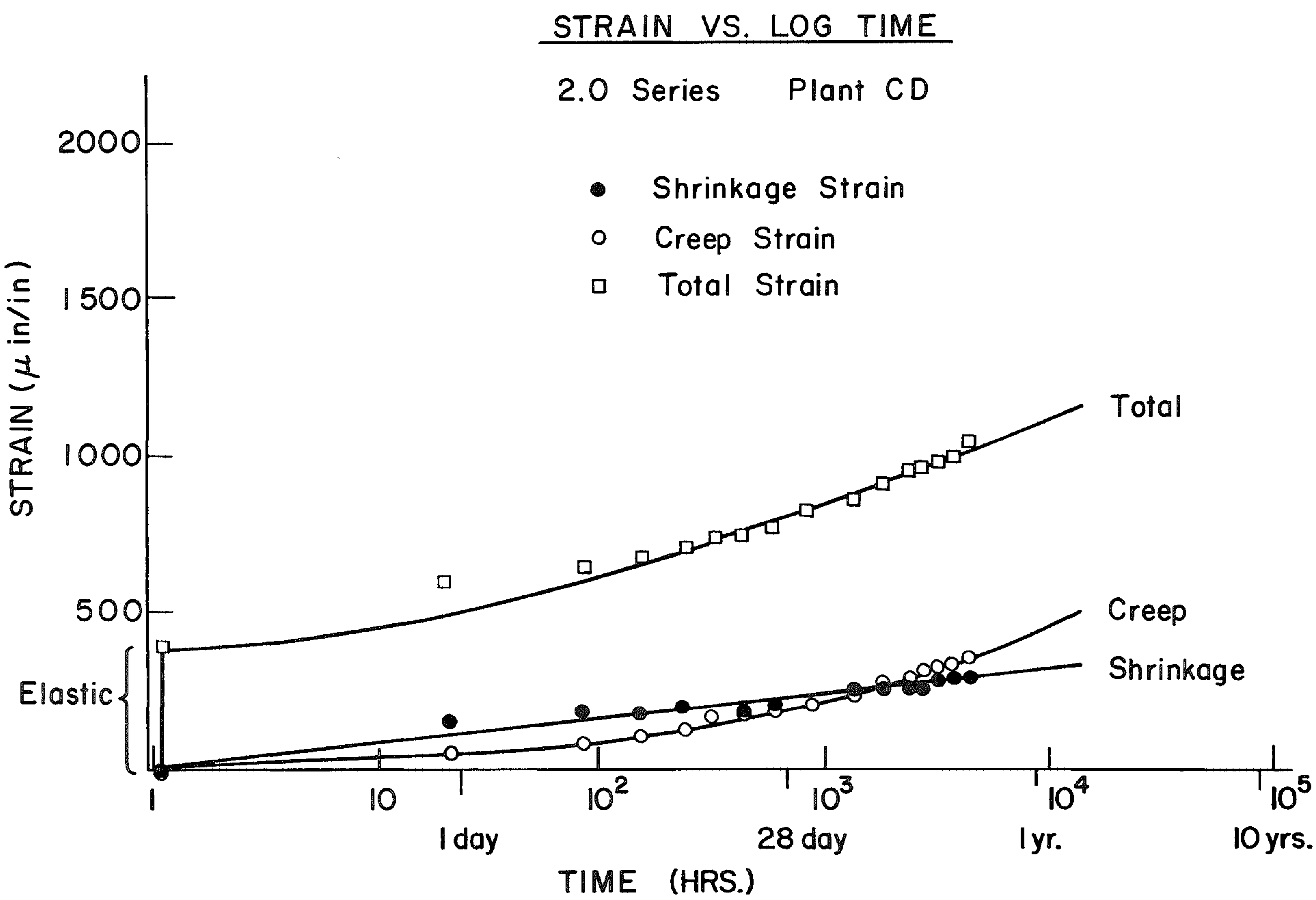


Fig. 20 Strain vs. Time - 2.0 Series - Plant CD

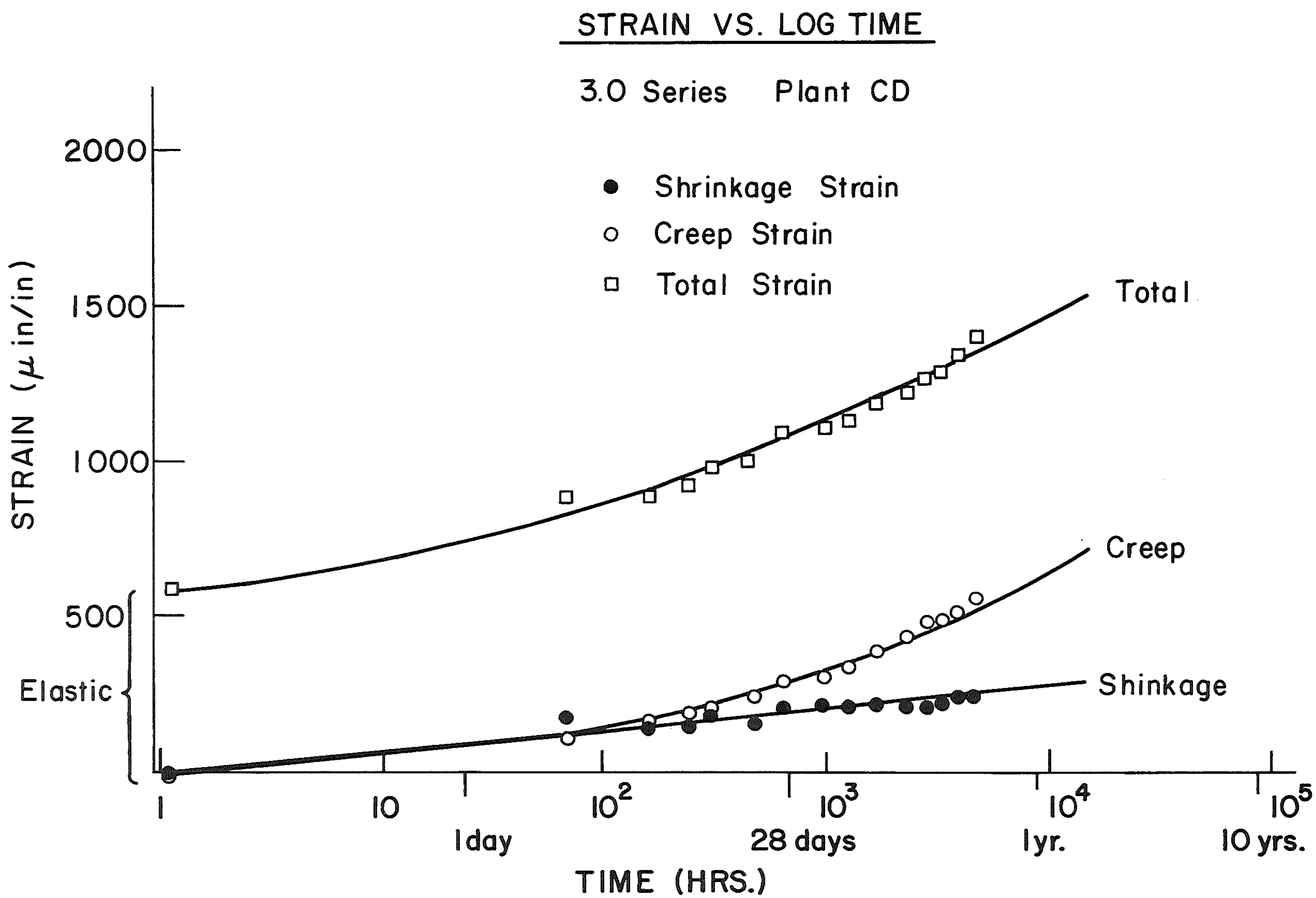


Fig. 21 Strain vs. Time - 3.0 Series - Plant CD

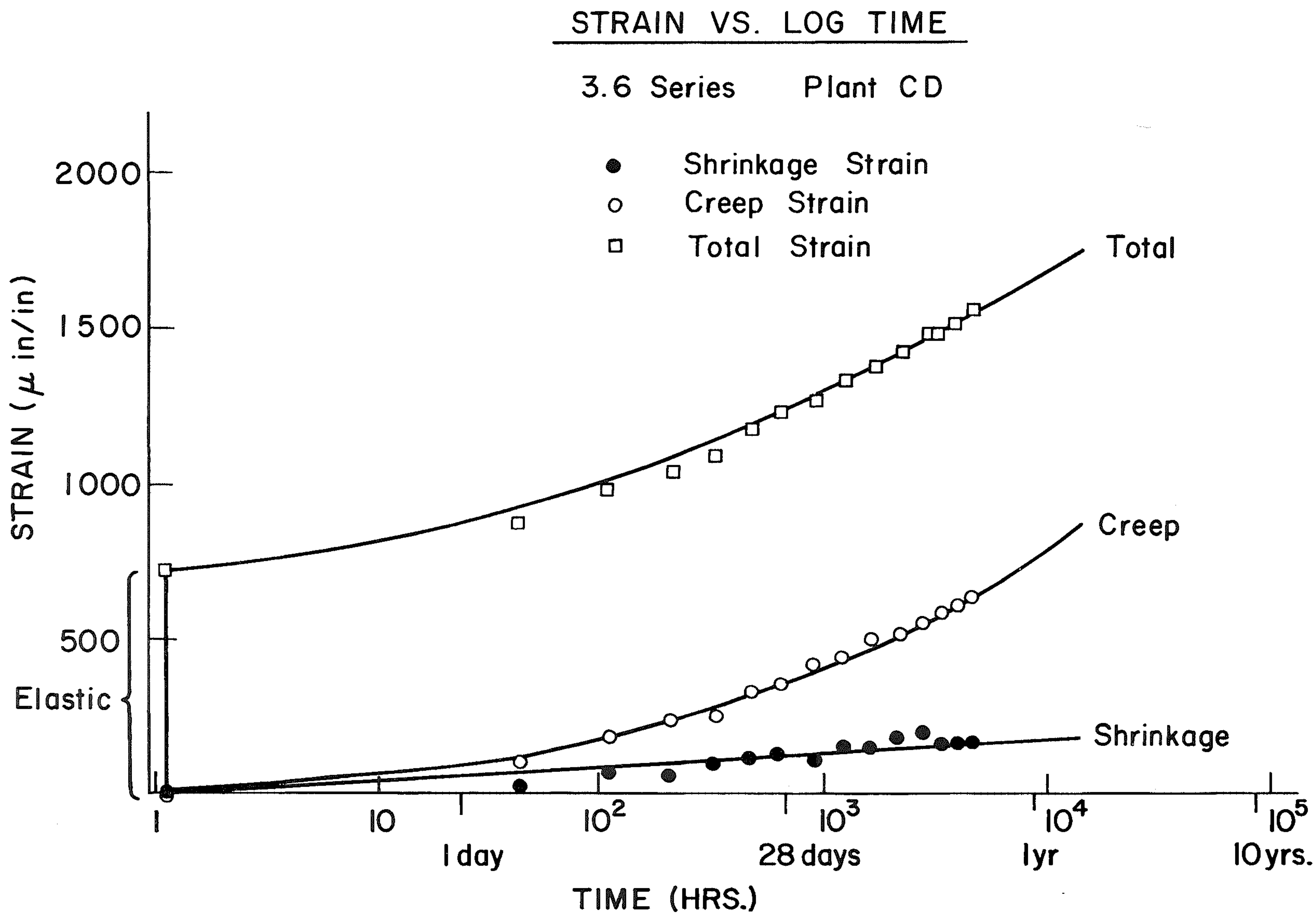


Fig. 22 Strain vs. Time - 3.6 Series - Plant CD

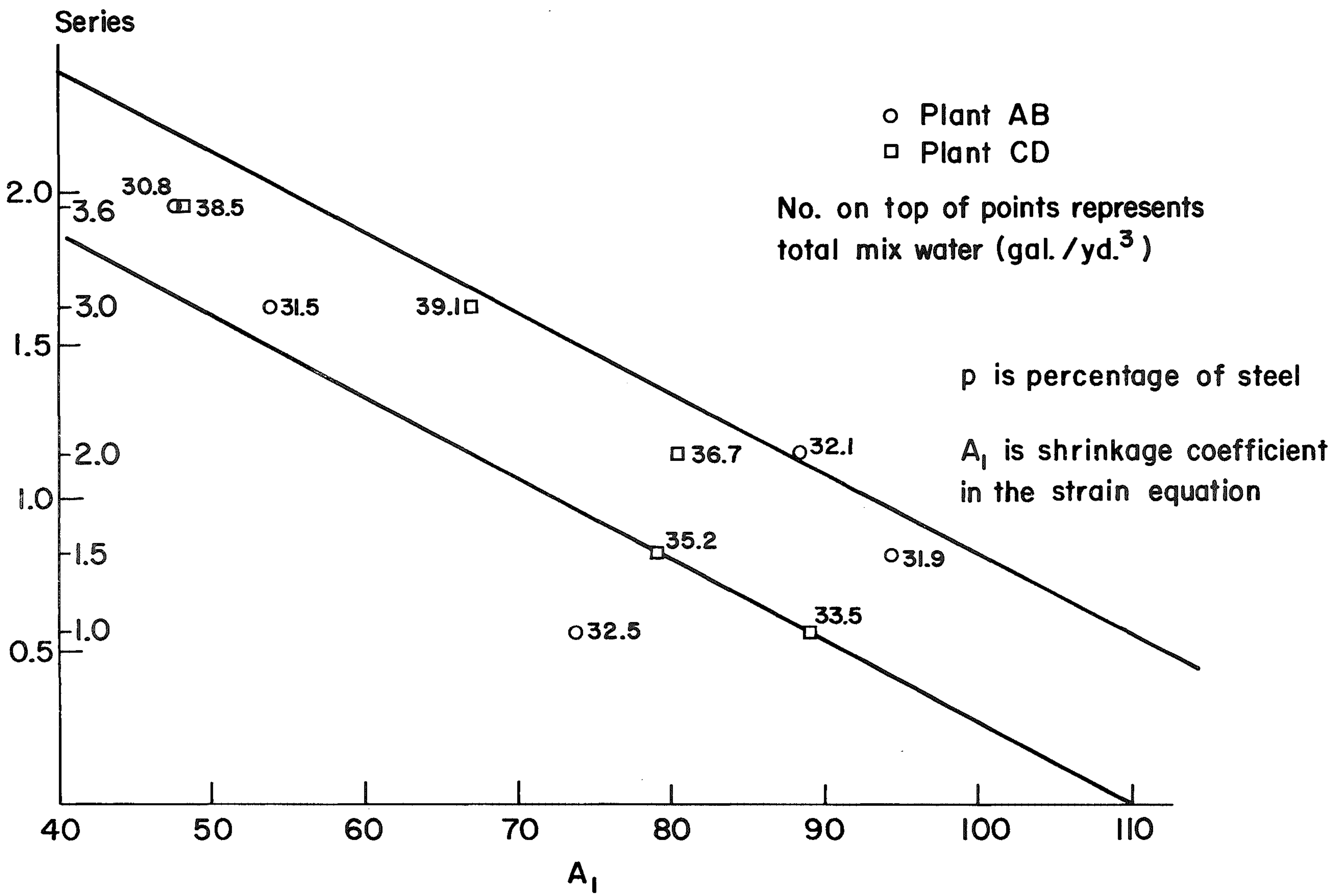


Fig. 23 Shrinkage Coefficient

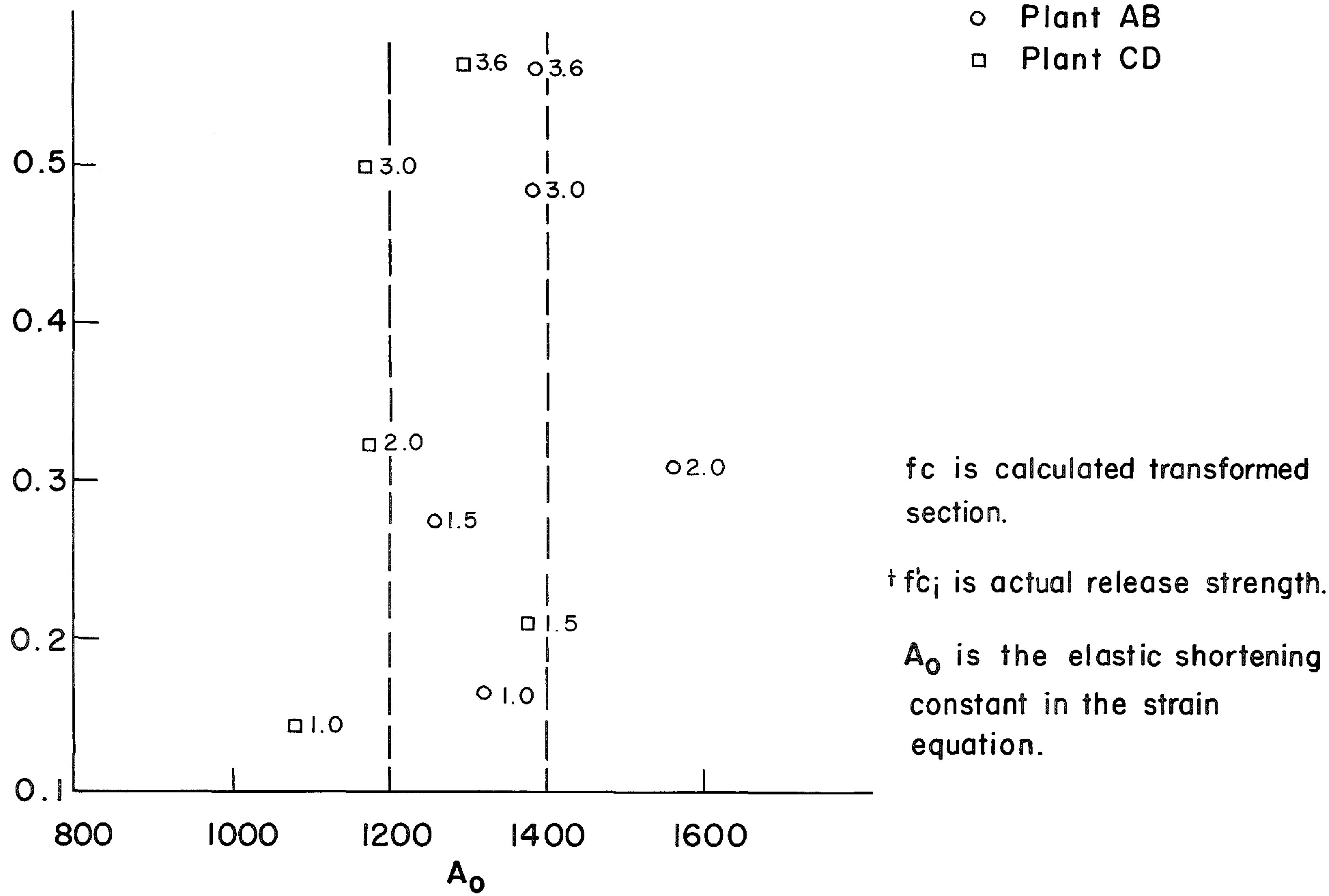
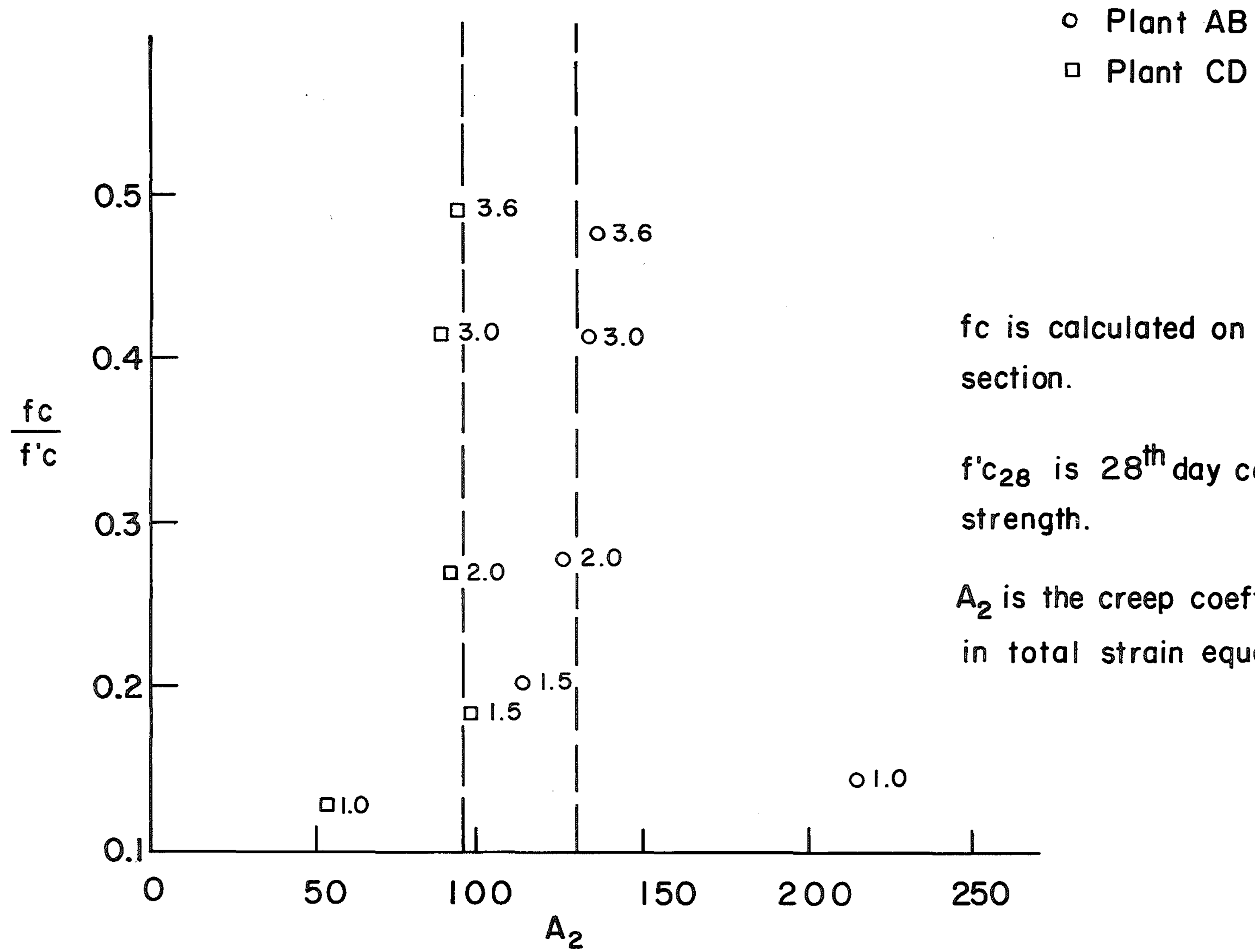


Fig. 24 Elastic Shortening Coefficient



fc is calculated on transformed section.

$f'c_{28}$ is 28^{th} day concrete strength.

A_2 is the creep coefficient in total strain equation.

Fig. 25 Creep Coefficient

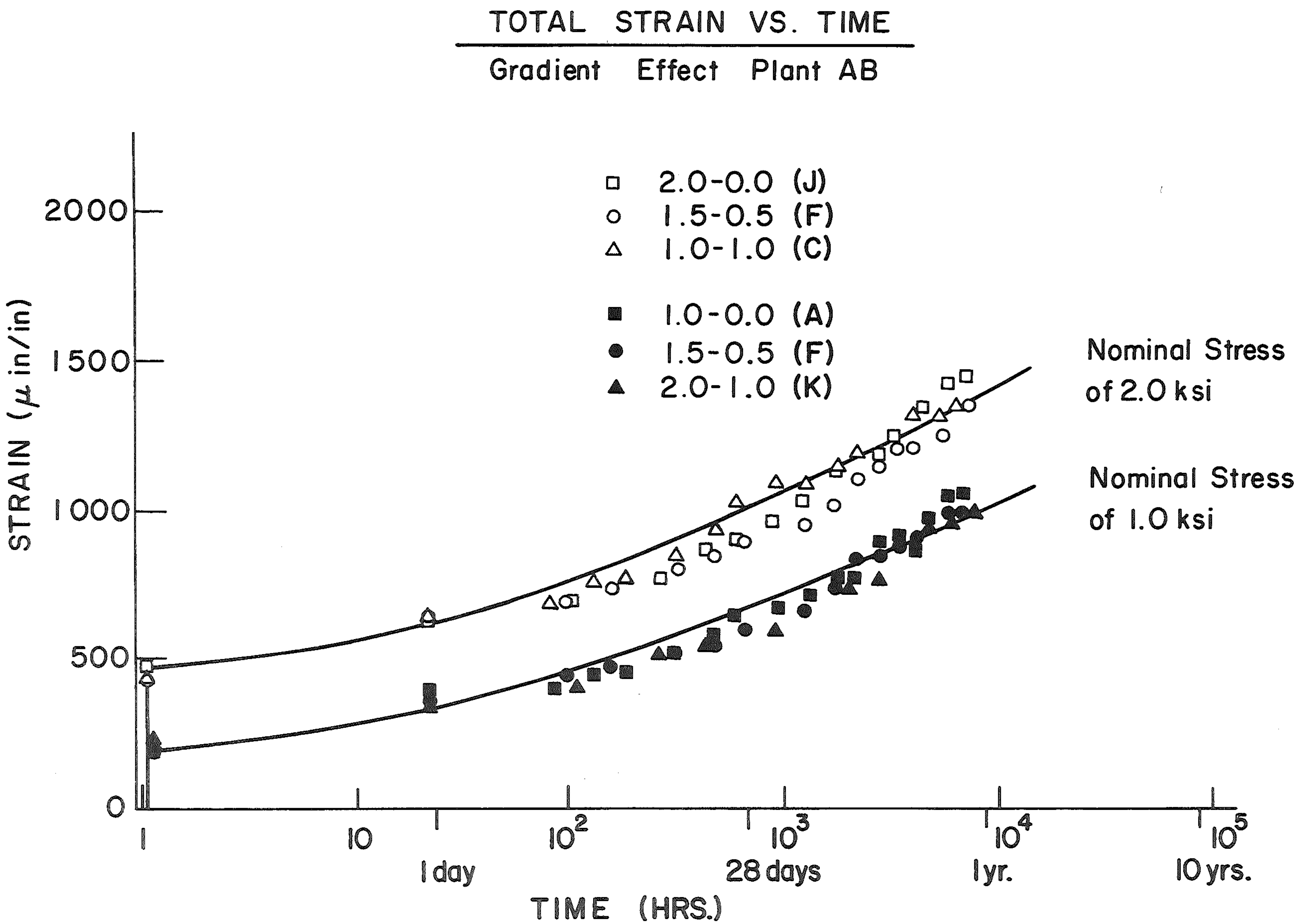


Fig. 26 Gradient Effect - 1.0 and 2.0 Series - Plant AB

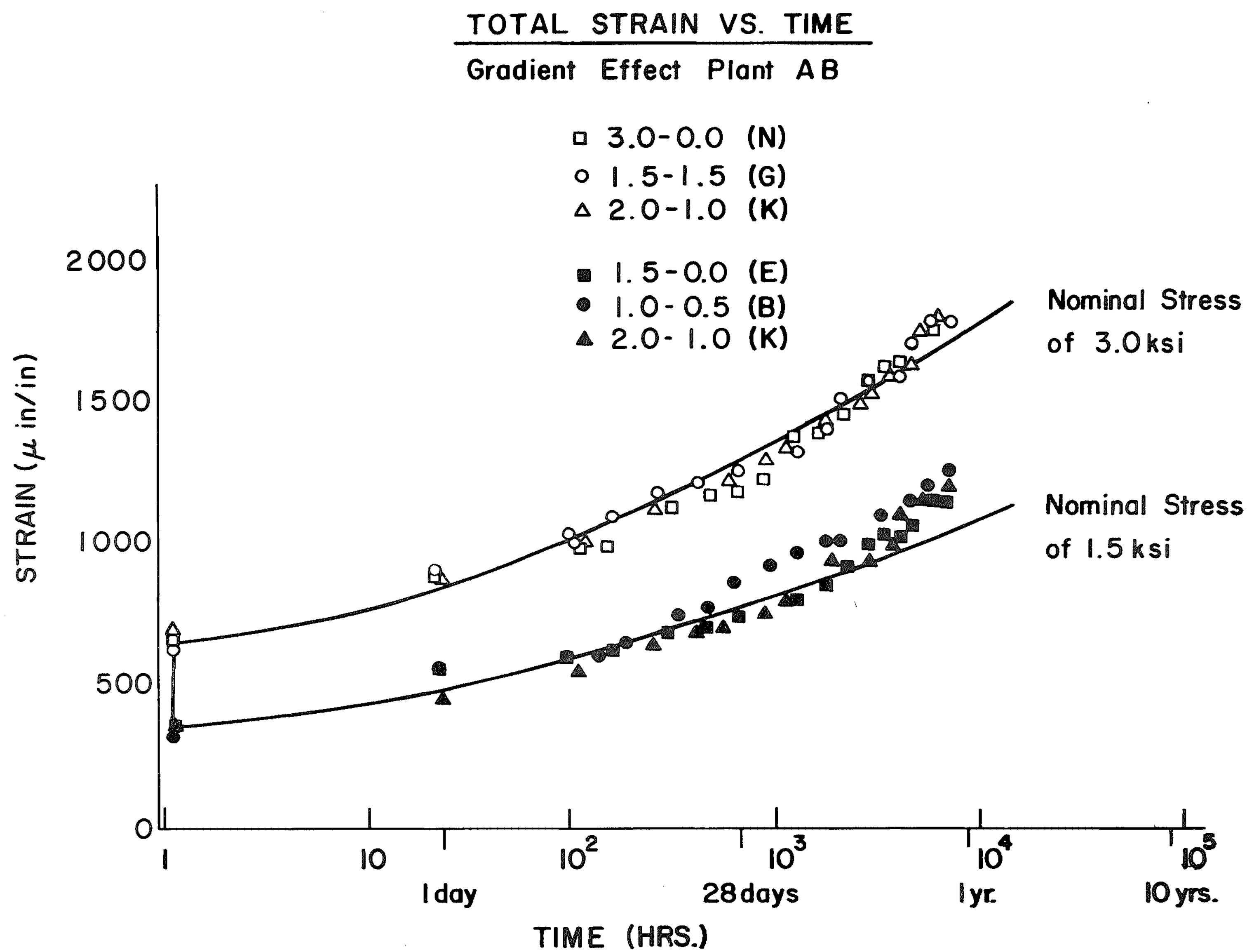


Fig. 27 Gradient Effect - 1.5 and 3.0 Series - Plant AB

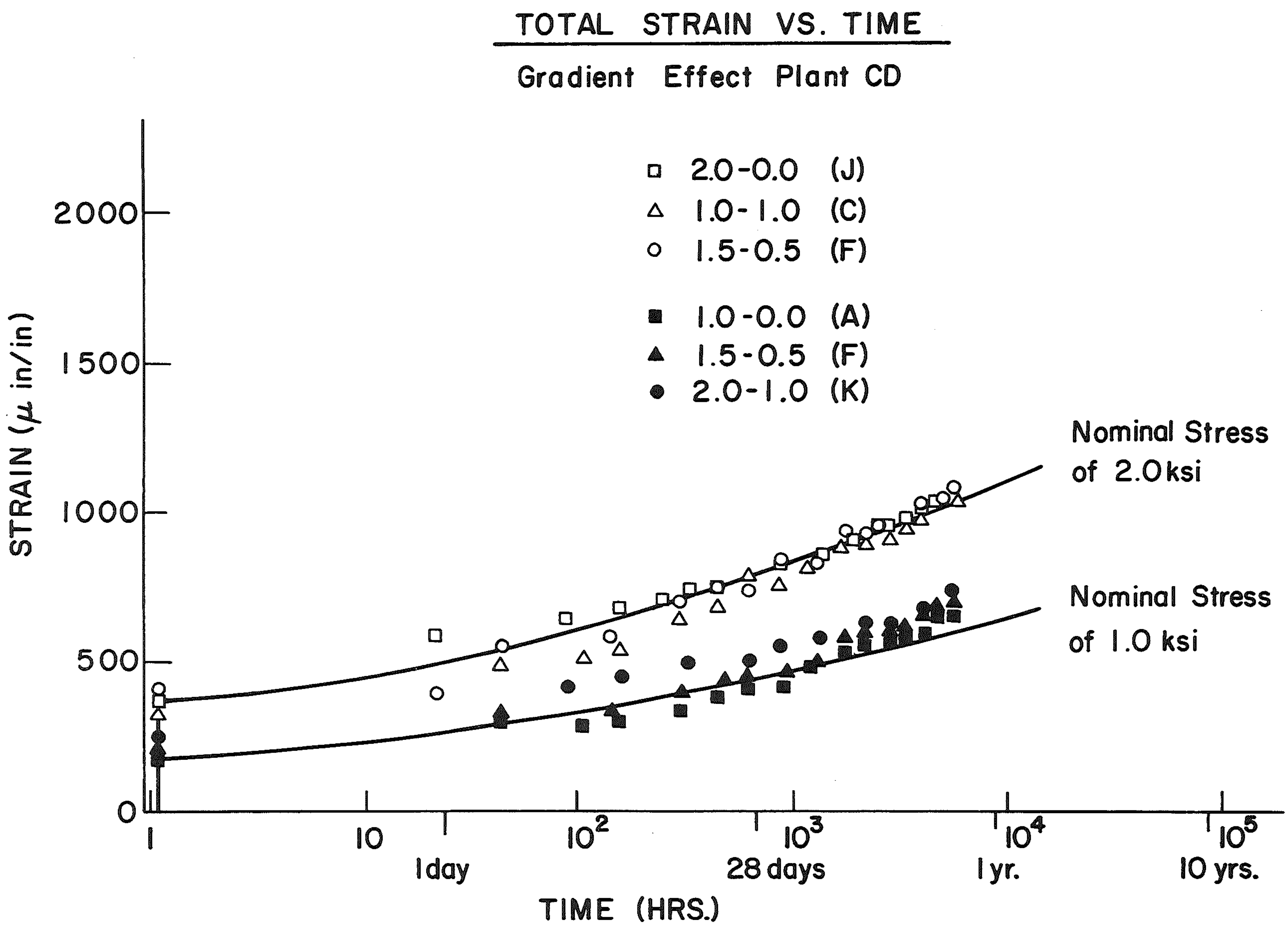


Fig. 28 Gradient Effect - 1.0 and 2.0 Series - Plant CD

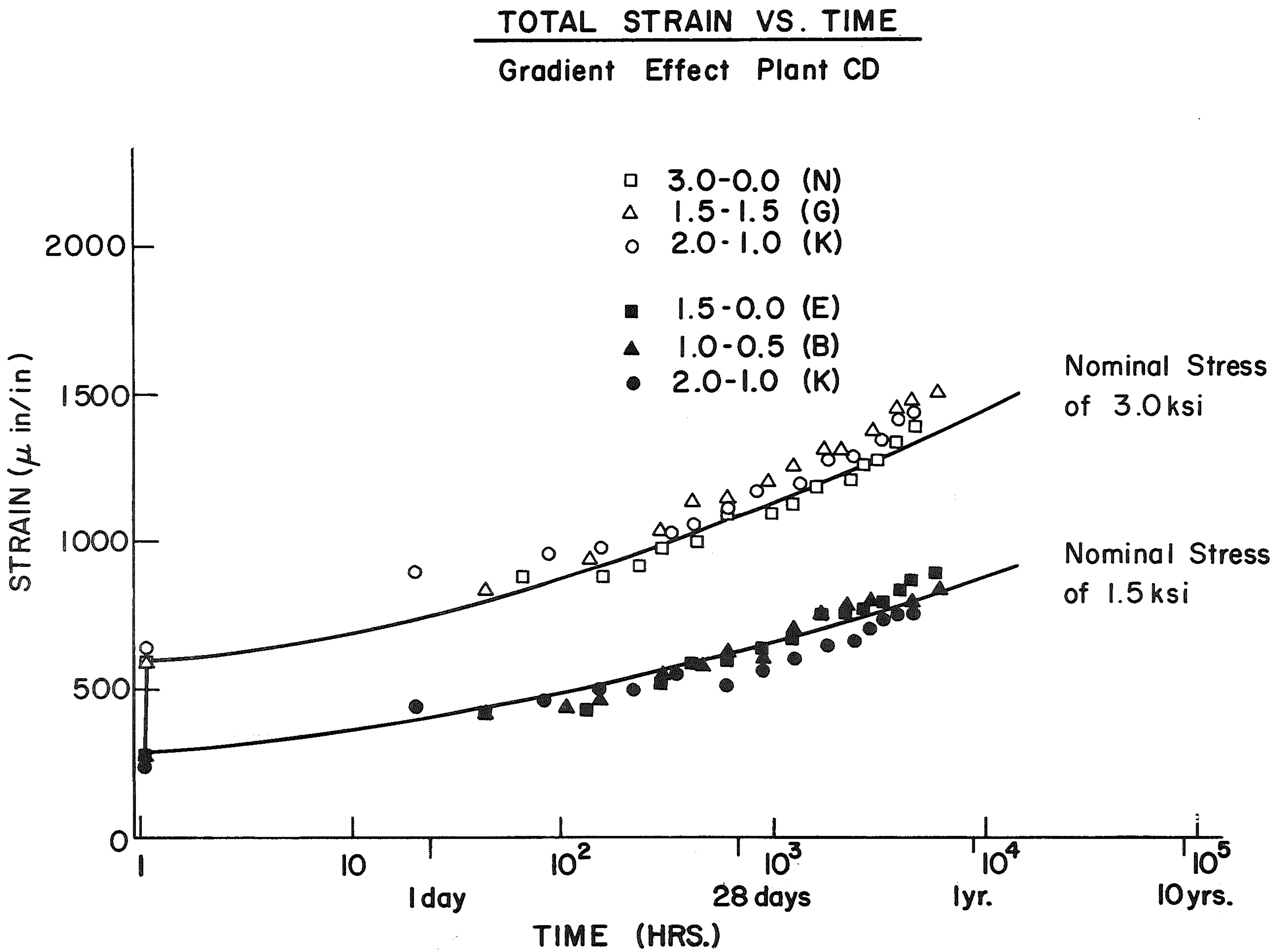


Fig. 29 Gradient Effect - 1.5 and 3.0 Series - Plant CD

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