FINAL REPORT

GEORGIA TECH PROJECT NO. A-833
GHD RESEARCH PROJECT NO. 6503

A STUDY OF LIGHTWEIGHT AGGREGATE CONCRETE FOR PRESTRESSED HIGHWAY BRIDGE GIRDER - PHASE III

B. B. MAZANTI

Contract with

STATE HIGHWAY DEPARTMENT OF GEORGIA

In cooperation with

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

March, 1968

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
A STUDY OF LIGHTWEIGHT AGGREGATE CONCRETE FOR
PRESTRESSED HIGHWAY BRIDGE GIRDERS - PHASE III

By

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The opinions, findings, and conclusions expressed in this publication are those of the author and not necessarily those of the State Highway Department of Georgia or the Bureau of Public Roads.
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CHAPTER I

INTRODUCTION

A. Scope of the Study

The use of lightweight aggregates in prestressed concrete for bridge construction has been increasing, since such use is often advantageous due to the lower unit weight of the concrete. One of the major detriments to the proper use of lightweight aggregates in prestressed concrete is the variability of the shrinkage and creep characteristics of a given aggregate when contrasted with aggregates from another source or plant. Published data on these two characteristics show values ranging from less-than to several-times-greater-than corresponding values for normal weight concrete.

The workability of the lightweight concrete is usually poorer than comparable normal weight concrete. This has led to the use of a "semi-lightweight" concrete made with lightweight coarse aggregate and normal weight fine aggregate. The semi-lightweight concrete is, of course, intermediate in weight between an all lightweight mix and a normal weight mix but the workability is usually much better than the lightweight mix. The problem of not knowing correct creep and shrinkage coefficients for the semi-lightweight concrete is still to be contended with.

In Georgia, a good quality, expanded shale lightweight aggregate is produced by the Georgia Lightweight Aggregate Company at its Rockmart plant. Concrete made with this aggregate has been used in both ordinary reinforced concrete and in prestressed concrete members for private construction. Creep and shrinkage data were lacking however for both lightweight and semi-lightweight concrete made with this aggregate.

Since the inception of the project, an additional source of lightweight aggregate for concrete has become readily available to the Georgia market.
Consequently, although it is not a Georgia-produced material, this aggregate was included in the present testing program.

Descriptions of both lightweight aggregates are included in Chapter III.

As originally conceived, the overall program consisted of four phases, all of which were separate and distinct with respect to the included work but dependent upon the preceding phases. This division was made so that the project could be terminated at the end of any phase and still produce a package of information having material value.

Phase I was concerned primarily with the mix design characteristics of the Georgia Lightweight Aggregate (Galite) as well as the shrinkage and creep characteristics under constant loading conditions. Equipment was designed and constructed for the creep tests. The results of Phase I were reported in "A Study of Lightweight Aggregate Concrete for Prestressed Highway Bridges", Final report - Phase I, by Billy B. Mazanti and James R. Fincher, January 1, 1959-March 1, 1962. The results of Phase I showed that the Galite was capable of producing consistent, satisfactory concrete. The shrinkage of the lightweight concrete was shown to be approximately equal to that of normal weight concrete under simulated "Field conditions", i.e., 70°F and 50 percent humidity; however, the creep strain of the lightweight concrete was significantly greater than that of the normal weight concrete under the same environmental conditions. In addition, the creep strain was shown to be a linear function of the ratio of applied stress to the strength at time of loading.

Phase II was concerned primarily with the relation between creep strains in prestressed beams and creep strains of sustained-loaded specimens. The results of this work showed that fairly good correlation exists between the creep coefficient for prestressed cylinders and for prestressed beams. Attempts
to predict the creep strain behavior of prestressed beams utilizing data from constant-loaded cylinders was unsuccessful.

Phase III was initiated to determine for semi-lightweight concrete, some of the characteristics studied for all lightweight concrete in Phases I and II. In addition, the present work was expected to provide data regarding the behavior of full sized bridge members with respect to creep, shrinkage and loss-of-prestress and the correlation between the full sized members and laboratory sized prestressed beams.

Finally, Phase IV, if initiated, would include the instrumentation and monitoring of bridges constructed of the semi-lightweight concrete. Correlation of the in-service behavior with the design criteria would follow.

B. Study Procedure

In order to accomplish the desired results, the following general procedure was established:

1. Review and check the original semi-lightweight concrete mix designs used in Phase I and Phase II.

2. Check and extend creep data for semi-lightweight concrete cylinders under conditions of constant compressive stress.

3. Study creep characteristics of semi-lightweight concrete cylinders under "prestress" conditions.

4. Study creep characteristics of laboratory sized, semi-lightweight concrete prestressed beams.

5. Instrument and study actual bridge members for analysis of their in-use performance with respect to creep, shrinkage, and loss-of-prestress.

6. Correlation of "laboratory creep, shrinkage and loss-of-prestress" with the performance of the full sized member.
C. Report Contents

The equipment, instrumentation and testing techniques used in this study are included in CHAPTER II. Of particular interest to researchers studying concrete creep will be the hydraulic pressure maintaining system and the loss-of-prestress beam test stands.

CHAPTER III deals with the materials used in the prestressed elements. Properties of the two lightweight aggregates are included as well as the mix design and batching procedures.

The test program and the results therefrom are in CHAPTER IV. The significance of the results is discussed under the various headings, e.g. Shrinkage tests, and a summary of the results and conclusions is presented in CHAPTER V. CHAPTER VI contains recommendations based on the results of this work and indicates some areas of interest for further study.
CHAPTER II

LABORATORY EQUIPMENT AND INSTRUMENTATION

Special equipment and instrumentation used in the laboratory studies is described in this chapter. Some of the equipment and instrumentation was utilized in Phases I and II and has been described in previous reports, however, more-or-less complete details are presented herein for ready reference.

A. Concrete Cylinder Molds

The cylinder molds are of heavy gage cold drawn seamless steel tubing, split longitudinally and bored to 6.00 inches inside diameter. Originally, the molds were drilled 1 inch from the top and the bottom to provide locating holes for stainless steel inserts. These holes were in pairs spaced around the mold on 120° centers and the inserts, which were cast into the fresh concrete, served to attach external gage points for measuring deformations. For the present series of tests, another method of gage point application was used (as will be later described) and, as a consequence, the drilled holes in the molds were sealed.

The mold bases are 1-1/2 inch thick steel with a 3/8 inch deep groove milled to accommodate the steel cylinder molds. Set screws hold the molds in place. The bases provide sufficient mass to allow the use of an external electric vibrator for compacting the specimens. In addition, a flat end, perpendicular to the cylinder's long axis, is assured. The molds produce standard 6 inch diameter by 12 inch long specimens.

A special "cap" is used as a means of attaching a standard electric laboratory vibrator to the cylinder mold. Figure 1 shows the essential features of the mold, base plate, and cap.
Figure 1. Cylinder Mold.
The cylinder molds were modified slightly when used for casting the hollow cylinders to prestress. To produce the hole through the specimens, a slightly-tapered steel rod with a diameter of 1-\(\frac{1}{4}\) inch was placed in a socket drilled in the mold base.

B. Static-Load Creep Test Frames

The loading frame assemblies are of steel, consisting of a table, or bench made up of three sets of three each, high strength, 1-\(\frac{1}{2}\) inch diameter steel rods spaced to accommodate the hydraulic load cells (to be described later) and supporting three individual top plates. The top plates furnish reactions for the loads applied to the cylindrical concrete specimens by the hydraulic load cells. Figure 2 shows the essential features of the loading frame assemblies as well as the pressure controller described later.

C. Hydraulic Load Cells

Three sizes of hydraulic load cells were constructed. The design of the cells are essentially that described by Best, et al.\(^{(1)}\). In order to reduce corrosion under long term exposure to high humidities, all cylinders and piston plates were cadmium plated. The piston sized and areas are as follows:

<table>
<thead>
<tr>
<th>Nominal Size (Inches)</th>
<th>Diameter (Inches)</th>
<th>Area (Square Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>9.015</td>
<td>63.83</td>
</tr>
<tr>
<td>8</td>
<td>8.015</td>
<td>50.45</td>
</tr>
<tr>
<td>6-(\frac{1}{2})</td>
<td>6.515</td>
<td>33.34</td>
</tr>
</tbody>
</table>
Figure 2. Loading Frame Assembly.
Molded rubber piston cups (Johns-Manville style 401) were used as oil seals. These cups are subject to slight leakage under hydraulic fluid pressures of 1500 psi which tends to reduce the friction between the cup and the cylinder wall and to allow the full hydraulic force to be transmitted to the specimens. Figure 3 shows the essential details of the cells.

D. Hydraulic Pressure Maintaining System

The hydraulic pressure maintaining system is similar to that described in "Loading System for Creep Studies of Concrete," by Best, Pirtz and Polinka. The system consists essentially of a hydraulic oil reservoir, fuel-injection pump operated by an electric motor, hydraulic accumulator and a pressure controller. Figure 4 shows a schematic of the hydraulic pump and control unit and a list of the parts used.

This pressure system was used for the constant-load tests on the cylindrical specimens.

E. Prestressing Elements

Both solid bars and strands were utilized as prestressing elements in the various test set-ups in the laboratory.

The solid bars were used for prestressing the hollow cylinders and consisted of "Regular Grade" Stressteel bars 1-1/8 inch in diameter. The properties of this material, based on tensile tests, are as follows:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>160,200 psi</td>
</tr>
<tr>
<td>Yield strength (0.2% offset)</td>
<td>138,500 psi</td>
</tr>
<tr>
<td>Proportional limit</td>
<td>78,450 psi</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>$27 \times 10^6$ psi</td>
</tr>
</tbody>
</table>
Figure 3. Hydraulic Load Cells.

NOMINAL DIAMETERS: 6 1/2", 8", & 9"

NOMINAL DIAMETER PLUS 0.020"
NOMINAL DIAMETER MINUS 0.020"
NOMINAL DIAMETER + 1 INCH

1" STEEL PLATE
RUBBER PISTON CUP
OIL
SAE 4140 BAR STOCK

DRILLED AND TAPPED FOR 1/4 IN. PIPE

2 3/4 IN.
1 3/4 IN.
1. RESERVOIR, VENT TO ATMOSPHERE
2. VISUAL OIL LEVEL GAGE
3. STRAINER
4. AMERICAN-BOSCH FUEL INJECTION PUMP-APE IB90P 300/3
5. VICKERS IN-LINE CHECK VALVE, 1/4 PIPE SIZE MODEL NO. DT 8PI-02-68-10
6. VICKERS REMOTE CONTROL PRESSURE RELIEF VALVE MODEL NO. C-175-F-10
7. GREER 1 GALLON, 30A-1A HYDRAULIC ACCUMULATOR, 3000 psi SERIES, NITROGEN CHARGED
8. MANIFOLD
9. PRESSURE GAGE
10. MINNEAPOLIS-HONEYWELL, ELECTROVANE PRESSURE CONTROLLER, INDICATING TYPE, 1250-2500 psi, MODEL MH 704 CIP2-23 III IV H
11. BOSTON GEAR RATIOMOTOR NO. M 115-30 EW WITH 1/3 HP, 220 V, 3φ ELECTRIC MOTOR
12. BOSTON GEAR COUPLING FC BB 15
13. MAGNETIC HOLDING COIL, 3 POLE, NORMALLY OPEN, 30 AMP SWITCH

Figure 4. Hydraulic Pressure Controller.
The Stressteel bars were threaded both ends and regular Stressteel nuts were used. Bearing plates for the cylindrical specimens were 6 inch square, 1-3/4 inch thick structural grade steel.

The strand used for laboratory prestressing was 7-wire ASTM Grade produced by Florida Wire and Cable Company, Jacksonville, Florida. These strands were utilized in the Stress Transfer studies and in the Loss of Prestress studies.

F. Loss-of-Prestress Beam Test Stands

The Prestress Loss Frame is basically the same as described by Hanson.\(^{(2)}\) A diagramatic sketch of this equipment is shown in Figure 5.

Eccentric prestressing is accomplished by the proper positioning of the concrete prisms so that the load is applied at the one-third point of the cross-section.

As pointed out by Hanson, the use of this arrangement eliminates or materially reduces several potential sources of error in residual load measurement in loss of prestress studies. Most important among these were:

1. Slip of the strand grips after initial loading.
2. Steel relaxation with time.

These items were essentially eliminated from consideration by pre-conditioning the frames with a 25 to 30% overload using aluminum bars as dummy
Figure 5. Prestress Loss Test Frame.
compression members. In this way, the grips were firmly anchored and the steel relaxation effects were removed due to maintaining the preload for approximately 2 hours prior to loading the test specimens.

Changes in prestress were measured by means of SR-4 strain gages mounted on each of the four prestress strands and periodically taking readings.

G. Gage Points for Deformation Measurements

External gage points were attached to all laboratory specimens for the determination of deformation under the applied loads. The gage points were cubical, made of stainless steel or hard-brass bar stock with dimensions of approximately $\frac{1}{4}$ inch. A hole was drilled in one face to a depth sufficient to accommodate a standard Whittemore gage. The gage points were cemented to the specimens with a quick-setting, non-shrink grout by drilling the concrete to a depth of one-quarter inch, filling the cavity with the grout and embedding the gage point into the grout. This procedure was utilized after considerable experimentation which indicated that more reliable results were possible by this method of attachment.

The particular arrangement and location of the gage points on the specimens was determined by the test being conducted and will be indicated in appropriate sections of this report.
CHAPTER III

MATERIALS, MIX DESIGN AND TEST SPECIMENS

A. Cement

Cement used in the project was Penn-Dixie, Type III (High Early Strength) Portland.

B. Lightweight Aggregates

The lightweight aggregate used in the tests came from two sources.

Galite Lightweight Aggregate

One aggregate is an expanded shale material which is manufactured by the Georgia Lightweight Aggregate Company, Rockmart, Georgia. The aggregate is normally supplied in three sizes: fine (No. 4 to 0), intermediate (3/8 inch to No. 8) and coarse (3/4 inch to No. 4). Since only semi-lightweight mixes were used in this work, only the coarse aggregate was lightweight material. Typical gradation of this material (as supplied) is as follows:

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>% Passing by Wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4 inch</td>
<td>100</td>
</tr>
<tr>
<td>1/2 inch</td>
<td>73.7</td>
</tr>
<tr>
<td>3/8 inch</td>
<td>44.3</td>
</tr>
<tr>
<td>No. 4</td>
<td>4.0</td>
</tr>
<tr>
<td>No. 8</td>
<td>3.2</td>
</tr>
<tr>
<td>No. 16</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The aggregate had the following characteristics:

- Unit Wt. (Dry, Rodded): 53.6pcf
- Absorption: 8.0%
- Specific Gravity
  - Apparent: 1.75
  - Bulk (S.S.D.): 1.65
  - Bulk (Dry): 1.54
Clinchlite Lightweight Aggregate

The other lightweight aggregate used in this study was furnished by the Clinchfield Coal Company, Dante, Virginia. This material, while not a locally produced aggregate, is readily available to the Georgia market and, as a consequence, was included in the project. It is an expanded shale lightweight aggregate produced by the rotary kiln process.

From the normally available sizes, fine 3/16 inch to 0), intermediate (3/8 inch to 3/16 inch) and coarse (3/4 inch to 3/16 inch), the coarse was used in this study. Typical gradation of this material (as supplied) is as follows:

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>% Passing by Wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4 inch</td>
<td>91.8</td>
</tr>
<tr>
<td>1/2 inch</td>
<td>54.5</td>
</tr>
<tr>
<td>3/8 inch</td>
<td>24.9</td>
</tr>
<tr>
<td>No. 4</td>
<td>3.6</td>
</tr>
<tr>
<td>No. 8</td>
<td>2.9</td>
</tr>
<tr>
<td>No. 16</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The aggregate had the following characteristics:

- Unit Wt. (Dry, Rodded) 57.8 pcf
- Absorption 9.4%
- Specific Gravity
  - Apparent 1.88
  - Bulk (S.S.D.) 1.75
  - Bulk (Dry) 1.60

C. Fine Aggregate

Fine aggregate used in all laboratory mixed concrete was a natural river sand as supplied by the Atlanta Sand and Supply Company. This sand
meets the current specification requirements of the State Highway Department of Georgia for gradation of fine aggregates for Portland cement concrete, size No. 10. A sieve analysis of this material is as follows:

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8 inch</td>
<td>100</td>
</tr>
<tr>
<td>No. 4</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>99</td>
</tr>
<tr>
<td>16</td>
<td>89</td>
</tr>
<tr>
<td>30</td>
<td>57</td>
</tr>
<tr>
<td>50</td>
<td>18</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
</tr>
</tbody>
</table>

The aggregate had the following characteristics:

- Unit Wt. (Dry, Rodded): 99.3 pcf
- Absorption: 0.8 %
- Specific Gravity
  - Apparent: 2.46
  - Bulk (S.S.D): 2.42
  - Bulk (Dry): 2.39

D. Mix Design, Semi-lightweight Concrete

In prior work on this project, concrete mix design had been based on accepted methods and trial mixing with re-proportioning for best work ability. It was decided that a more realistic approach would be to seek the advice of the industry with respect to mix designs which were "workable" under the conditions in which the concrete would be used. Consequently, mix designs were utilized as supplied by the respective lightweight aggregate manufacturers. The following basic mixes were used:
1. Galite Lightweight Aggregate Mix

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>677 lb.</td>
</tr>
<tr>
<td>Water</td>
<td>425 lb.</td>
</tr>
<tr>
<td>Coarse Agg. (Galite)</td>
<td>950 lb.</td>
</tr>
<tr>
<td>Fine Agg. (Sand)</td>
<td>1170 lb.</td>
</tr>
<tr>
<td>Retarder (Retardwell)</td>
<td>14 oz.</td>
</tr>
</tbody>
</table>

2. Clinchlite Lightweight Aggregate Mix

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>658 lb.</td>
</tr>
<tr>
<td>Water</td>
<td>417 lb.</td>
</tr>
<tr>
<td>Coarse Agg. (Clinchlite)</td>
<td>1188 lb.</td>
</tr>
<tr>
<td>Fine Agg. (Sand)</td>
<td>1148 lb.</td>
</tr>
<tr>
<td>Retarder (Retardwell)</td>
<td>14 oz.</td>
</tr>
</tbody>
</table>

(All weights are based on an oven dry basis and are for a cubic yard of concrete.)

The Compressive Strength-Age relation for these two mixes are shown in Figures 6 and 7. The gain in strength with age is very close to the same for both of the two concrete mixes. It should be noted, however, that the Galite mix has a slightly higher cement content than does the Clinchlite mix.

The static Modulus of Elasticity of the two mixes is as follows:

<table>
<thead>
<tr>
<th>Mix</th>
<th>Secant Modulus @ 50% $f'_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 day</td>
</tr>
<tr>
<td>Galite</td>
<td>3.04</td>
</tr>
<tr>
<td>Clinchlite</td>
<td>3.06</td>
</tr>
</tbody>
</table>

E. Batching Procedure

The batching procedure for the concrete consisted of the following:

1. Premix all aggregate and approximately 90 percent of the water for 20 minutes in the mixer drum.
Figure 6. Strength-age Relation, Galite Semi-lightweight Concrete.
Figure 7. Strength-age Relation, ClinchLite Semi-lightweight concrete.
2. All cement added and mixing continued for 5 minutes.

3. Slump controlled between 2 to 2-\(\frac{1}{2}\) inches by the addition of all or part of the 10 percent water withheld.

F. Test Specimens

In the laboratory testing program, the following types of specimens were utilized:

1. Strength specimens.
2. Cylindrical creep and shrinkage specimens.
3. Rectangular beams for Loss-of-Prestress and for Stress-Transfer.

Cylindrical Specimens.

All strength, cylindrical creep and shrinkage specimens were cast in the special molds previously described in this report. The casting procedure generally followed ASTM C192-57 except that external vibration was utilized by means of the special mold caps. A Mall electric concrete vibrator, Model LEV was used for all vibration purposes in the laboratory. The cylinders were vibrated, after being filled and rodded, for 5 seconds for each specimen.

Following the casting operations, heavy plastic sheet was used to cover each specimen in order to prevent excessive moisture evaporation. At an age of approximately 24 hours, the specimens were removed from the molds, and then placed in a 100 percent humidity, 70°F curing room until time for testing.

Rectangular Beams

Rectangular beams were of two types. Those for the Loss-of-Prestress studies were 6 in. x 9 in. x 36 in. They were cast in heavy-plywood forms, reinforced to minimize deformation during the casting and hardening stages.
The forms were filled with concrete in three layers, each layer being well-rodded. The concrete, after filling of the forms was complete, was vibrated in a manner which simulated that usually accomplished in the field. After completion of the casting operations, the beams were covered with heavy plastic sheet for 24 hours and then removed from the forms and placed in the curing room.

The beams for the Stress Transfer study were cast in metal forms. The forms consisted of 2 in. x 4 in. steel channels as side pieces with 1/4 in. steel plate bottoms. The forms were securely clamped to a metal vibrating table and the prestressing strand was passed through 2 inch thick steel end blocks which served to locate the strand centrally within the form. A "header" was placed approximately 1 foot from one end of the beam forms in order to leave exposed a length of strand which served as a prestress-force dynamometer. SR-4 strain gages were mounted on the prestressing strands and then calibrated prior to the use of the strands in the beams. The proper prestress force was applied to the strand by means of a Simplex prestress hydraulic ram and the prestress load was monitored by both the hydraulic pressure in the ram and the strain gages on the strand. The prestress load was maintained for a period of 24 hours prior to the pouring of the concrete. The concrete was poured in the beam forms in two layers. The form was filled to slightly above the prestressing strand, spaded and rodded, then vibrated for 10 seconds. The top layer was similarly placed. The beam was covered with heavy plastic after being struck-off level. After 24 hours, the plastic was removed, the beams were covered with burlap and the burlap kept wet until time for testing.
A. Shrinkage Tests

The shrinkage characteristics of both the Galite Semi-Lightweight concrete and the Clinchlite Semi-Lightweight concrete was determined from tests on cylindrical specimens which were not subject to loading. The specimens were each instrumented with three sets of gage points mounted at 120° intervals around the circumference of the cylinders. Nominal gage lengths of 10 inches were used. The deformation of the specimens was measured by means of a 10 inch gage length, Whittemore gage. This is a hand-held, mechanical type extensometer-compressometer allowing direct reading of deformations. Dial indicator divisions are in 0.0001 inch which allows interpolation to at least 0.00005 inch and for a nominal 10 inch gage length, strains on the order of $5 \times 10^{-6}$ inches per inch can be determined.

Since it was desired to approximate "in-practice" conditions, the shrinkage and the creep testing was accomplished in a constant-environment room where the temperature was maintained at 70°F and the relative humidity kept at 50 percent.

Shrinkage was determined for both mixes with respect to varying times of 100 percent humidity curing prior to storage at the test environment. The results of these tests are presented graphically in Figures 8 through 11 in the form of Shrinkage vs. Time curves as both arithmetic and semi-logarithmic plots.
Figure 8. Shrinkage of Galite Semi-lightweight Concrete for Various Ages of Curing, Arithmetic Plot.
Figure 9. Shrinkage of Clinchlite Semi-lightweight Concrete for Various Ages of Curing, Arithmetic Plot.
Figure 10. Shrinkage of Galite Semi-lightweight Concrete for Various Ages of Curing, Semi-log Plot.
Figure 11. Shrinkage of Clinchlite Semi-lightweight Concrete for Various Ages of Curing, Semi-log Plot.
Shrinkage of the Galite concrete was also determined by the use of a rectangular beam 6 in. x 9 in. x 36 in. This was in connection with the Loss-of-Prestress studies to be described later. The results of this test are shown in Figures 12 and 13.

Results and Conclusions of Shrinkage Tests

The shrinkage of the semi-lightweight concretes follows a trend which is typical of concrete in general. The rate of shrinkage is a maximum at early ages and continuously decreases with increasing time. On semilogarithmic plots, the shrinkage curves appear to follow either straight lines or a series of straight lines.

The effect of time of moist curing prior to storage in the 50 percent relative humidity environment is not clearly defined. In the case of the Galite concrete, there was apparently an increase in the amount of drying shrinkage for the cylinders which were cured longer. This is contrary to what could be considered normal since the concrete should gain strength with increased curing times and, as a consequence, its resistance to shrinkage should decrease.

The shrinkage of the Clinchlite concrete followed a trend more in accordance with what would be expected, in that the shrinkage tended to decrease with increasing time of moist curing.

These results indicate that while there should be, and probably is, a lesser net shrinkage of the concrete with increasing curing times, the amount of the decrease is not significant when compared to the total shrinkage of concrete cured a minimum of 3 days. Variations of composition as well as variations of dimensions of actual prestressed members would probably be of
Figure 12. Shrinkage of Galite Semi-lightweight Concrete Beam, Arithmetic Plot.
Figure 13. Shrinkage of Galite Semi-lightweight Concrete Beam, Semi-log Plot.
as much importance and would preclude the practicality of allowing for a reduction in shrinkage calculations. In addition, the extra construction time of the prestressed member would probably more than offset any advantages of the reduction in shrinkage.

Final values of shrinkage (as well as for creep) of the concrete can be calculated on the basis of hyperbolic equations of the following type:

\[
\varepsilon_s = \frac{(\varepsilon_{\infty}) t}{N_s + t}
\]

where: 
\(\varepsilon_s\) = shrinkage strain at time \(t\) 
\(\varepsilon_{\infty}\) = final shrinkage strain 
\(N_s\) = constant (time at which the shrinkage strain = \(\frac{1}{2}\) final value)

For the Galite concrete, the following values may be used:
\(\varepsilon_{\infty} = 790\) millionths 
\(N_s = 62\) days

For the Clinchlite concrete, the following values may be used:
\(\varepsilon_{\infty} = 530\) millionths 
\(N_s = 36\) days

The effect of member size on shrinkage is indicated by Figure 12 and Figure 13. The shrinkage of the cylindrical specimens are contrasted with that of the 6 in. x 9 in. x 36 in. beam. It is evident that the member with the greater size has an appreciably less total shrinkage. The decrease is more than would be estimated on the basis of previous studies by Hanson and Mattock\(^3\) wherein a decrease in shrinkage of about 11 percent is indicated.
for the relative shapes and sizes used here. As a consequence, it is not recommended here that a reduction in shrinkage for prestressed members be based on this data. The comparison is made as a matter of interest only, while the beam shrinkage was intended for specific use in the Loss-of-Prestress study.

B. Static Load Creep Tests

The creep characteristics of both the Galite Semi-Lightweight concrete and the Clinchlite Semi-Lightweight concrete were determined by testing solid, cylindrical specimens under constant loads of different magnitudes. The specimens were instrumented with gage points in the same manner as the creep specimens and the total deformations of the specimens were measured at various time intervals after loading. The shrinkage of the specimens was determined from companion specimens and the creep was calculated as the difference between the total deformation and the shrinkage.

In the earlier phases of this project, three different stress levels were imposed on the concrete mixes. Such was the intention in this test program also; however, it was found impossible to load the specimens with the largest-area cell without failure of the cylinders occurring, either at the time of loading or at some later time, shortly after loading. Due to such failures, several other test series were disrupted and, in order to prevent further loss, later tests were restricted to two different stress levels. These applied stress levels were 1650 psi and 2550 psi. The results of these tests are presented graphically in the form of Creep vs. Time curves and summarized in plots of Creep vs. Ratio of Applied Stress to Strength at Time of Loading. Figures 14 through 18 show these results.
Figure 14. Creep Strain of Galite Semi-Lightweight Concrete, Arithmetic Plot.
<table>
<thead>
<tr>
<th>CURVE</th>
<th>COARSE AGGREGATE</th>
<th>APPLIED STRESS</th>
<th>F'c STRENGTH</th>
<th>f/f'c</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>GALITE</td>
<td>1650</td>
<td>6000</td>
<td>0.28</td>
</tr>
<tr>
<td>II</td>
<td>GALITE</td>
<td>2550</td>
<td>6000</td>
<td>0.43</td>
</tr>
<tr>
<td>1</td>
<td>GALITE</td>
<td>1750</td>
<td>4370</td>
<td>0.40</td>
</tr>
<tr>
<td>2</td>
<td>GALITE</td>
<td>3250</td>
<td>4370</td>
<td>0.59</td>
</tr>
</tbody>
</table>

DATA FOR CURVES 1 & 2 FROM PHASE I - FINAL REPORT

Figure 15. Creep Strain of Galite Semi-lightweight Concrete, Semi-log Plot.
Figure 16. Creep Strain of Clinchlite Semi-lightweight Concrete, Arithmetic Plot.
Figure 17. Creep Strain of Clinchlite Semi-lightweight Concrete, Semi-log Plot.
Figure 18. Predicted Terminal Creep Strain vs Stress-strength Ratio.
Results and Conclusions of Static Load Creep Tests

The behavior of concrete under constant stress produces creep curves similar to the shrinkage curves described earlier.

Figure 18 shows the predicted terminal creep strain for both the Galite and the Clinchlite in terms of Creep Strain vs. Stress-Strength ratio. The terminal values were calculated on the basis of a hyperbolic relationship between creep strain and time.

For a given concrete strength, \( f'_{ci} \), Figure 16 can be used to determine a creep coefficient in terms of strain per psi of applied stress. This is illustrated in Figure 19 for \( f'_{ci} = 4000 \) psi. From this graph creep coefficients have been determined as follows:

\[
\begin{align*}
\text{Creep Coefficient} & \\
\text{Galite Semi-Lightweight Concrete} & \quad 0.67 \times 10^{-6} \text{ in/in/psi} \\
\text{Clinchlite Semi-Lightweight Concrete} & \quad 0.77 \times 10^{-6} \text{ in/in/psi}
\end{align*}
\]

Note: These values are based on \( f'_{ci} = 4000 \) psi

In practice, the prestressed beam will be subject to variable flexural stresses ranging from some maximum value, e.g., \( f/f'_{ci} = 0.4 \), down to a value of zero. Under such conditions, it would be assumed that the "effective" beam prestress would be \( 2/3 \) of the maximum \( f/f'_{ci} \). Then the terminal creep strain for the beam as a whole could be based on the "effective" prestress value rather than on the maximum prestress value when calculating loss-of-prestress.

The above assumption is substantiated somewhat by the results of the Loss-of-Prestress study reported later, wherein the measured creep strains for a given \( f/f'_{ci} \) were lower than under static load conditions.
Figure 19. Predicted Terminal Creep Strain vs Applied Stress for Assigned Strength of 4000 psi at Time of Loading.
C. Concrete Creep Under "Prestressing-Type" Loads

In this study cylindrical specimens were subjected to prestress loads which were allowed to vary (diminish) with time as the concrete specimens shortened due to creep and shrinkage. Such conditions are probably more representative of the behavior of a full-sized prestressed member; however, there are other considerations which cannot be accounted for and this type of test also does not correctly represent the field conditions. The value of this test is to determine a lower bound for the creep strain of a prestressed member due to the lowering of the prestress force.

The Galite Semi-Lightweight concrete was tested at 4 days age under two prestress values. Each cylinder load was applied by means of a Stressteel bar passed through an axially located hole cast into the cylinder. The deformation of the specimens were measured by the use of a Whittemore Gage as previously described.

In order to obtain a measure of the effect of age (strength) on the creep of the concrete the Clinchlite Semi-Lightweight concrete was loaded to the same initial value of prestress load at ages of 5, 12 and 19 days.

The results of these tests are shown in Figures 20 through 22.

Results and Conclusions of "Prestressed Cylinder" Study

The strain-time relation of the concrete under this type of diminishing load has a characteristic strain-time curve similar to that of constant-loaded concrete. The creep strain rate is high at early ages and decreases with increasing time. The Creep vs. Time results are shown to arithmetic scales in Figures 20 and 21. It is of interest that there is a considerable decrease in creep strain with increasing age of concrete prior to loading. In terms
I. INITIAL PRESTRESS = 3020 psi

II. INITIAL PRESTRESS = 1610 psi

$\frac{f_{ci}}{f} = 5200 \text{ psi}$

Figure 20. Creep Strain of Prestressed Galite Cylinders under Various Prestress Loads.
I. LOADED AT 5 DAYS, $f'_{ci} = 5200$ psi
II. LOADED AT 12 DAYS, $f'_{ci} = 6300$ psi
III. LOADED AT 19 DAYS, $f'_{ci} = 6700$ psi

INITIAL PRESTRESS WAS 1610 psi
IN ALL CASES

Figure 21. Creep Strain of Prestressed Clinchlite Cylinders Loaded at Various Ages.
1 CLINCHLITE SEMI-LIGHTWEIGHT CONCRETE @ 60 DAYS, PRESTRESS LOAD
2 GALITE SEMI-LIGHTWEIGHT CONCRETE @ 60 DAYS, PRESTRESS LOAD
I CLINCHLITE SEMI-LIGHTWEIGHT CONCRETE @ 60 DAYS, CONSTANT LOAD
II GALITE SEMI-LIGHTWEIGHT CONCRETE @ 60 DAYS, CONSTANT LOAD

Figure 22. Contrast of Creep Strain for Prestress and Constant Loading.
of construction time, however, there is not sufficient difference to offset the additional time delay. Prior tests for lightweight concrete indicated about the same behavior. Figure 22 shows the results in terms of the Creep Strain versus Stress-Strength ratio and contrasts these results with those of the Constant Load Tests. It is readily apparent that a considerable reduction in creep strain occurs under the prestress-type loading.

D. Loss-of-Prestress Study

The purpose of this test series was to determine the behavior of the concrete under load conditions which approximate those in practice. Prestressed concrete beams and girders are subjected to load conditions which produce flexural stresses in the member. The stresses vary through the depth of the member from approximately zero to the maximum allowable prestress value. These conditions are essentially reproduced in the laboratory-sized beams used in this study.

Beams, 6 in. x 9 in. x 36 in., of both Galite and Clinchlite Semi-Lightweight concrete were eccentrically prestressed in the special loading frames described in Chapter II. The prestressing loads are caused to act at the 1/3 point of the beam ends with respect to the 9 inch dimension. This induces compressive stresses in the beam which vary linearly from a maximum at one side to zero at the other. As the concrete shortens, (due to creep and shrinkage), there is a loss of the initial prestressing force. By monitoring the prestress force, the loss of prestress with time can be assessed.

Deformation of the specimens was determined by the use of mechanical gage points attached to the exterior faces of the beams. Two sets of gages
were utilized on the face where the prestress was a maximum and on the minimum prestress face. Gage points were attached at 1/3 and at 2/3 of the distance between the minimum and the maximum stress faces. Gage points were attached to both sides of these faces in order to obtain average deformations in the event of a slight eccentricity of the load.

The measured deformations of the beams at the gage points were corrected for shrinkage and the deformations due to creep were determined.

Two values of initial prestress load were utilized. For the Galite, the initial load was 60.72 Kips which produced a maximum compressive stress in the concrete of approximately 2250 psi. For the Clinchlite, the initial load was 50.8 Kips which produced a maximum compressive stress of approximately 1880 psi.

The results of this series are shown graphically in Figures 23 through 32.

Results and Conclusions of Loss-of-Prestress Study

The strain vs. time behavior of concrete subjected to stresses which diminish with time due to creep and shrinkage is similar to that of concrete under constant stress with respect to the general shape of the strain-time curves.

Galite. Creep strain vs. time curves for the Galite concrete are shown in Figures 23 and 24.

It is evident that the minimum-stress face of the concrete was under a very slight initial compression. This changed with time, due probably to small geometry changes as creep and shrinkage progressed, until an apparent slight tension was effective as evidenced by negative values of creep strain. These strains are quite small, however, and indicate that the desired stressing action was being closely maintained.
Figure 23. Creep Strain vs Time, Galite Prestressed Beam, Arithmetic Plot.
Figure 24. Creep strain vs Time, Galite Prestressed Beam, Semi-log Plot.
Figure 25. Creep Strain vs Distance through Beam Depth, Galite Prestressed Beam.
Figure 26. Creep Strain vs Stress-strength Ratio, Galite Prestressed Beam.
Figure 27. Loss of Prestress, Galite Prestressed Beam.
Figure 28. Creep Strain vs Time, Clinchlite Prestressed Beam, Arithmetic Plot.
Figure 29. Creep Strain vs Time, Clinchlite Prestressed Beam, Semi-log Plot.
Figure 30. Creep Strain vs Distance through Beam Depth, Clinchlite Prestressed Beam.
Figure 31. Creep Strain vs Stress-strength Ratio, Clinchlite Prestressed Beam.
Figure 32. Loss of Prestress, Clinchlite Prestressed Beam.
The magnitude of the initial maximum stress in the concrete with respect to the strength of the concrete at the time of loading was within the range wherein the creep is linear. The creep strain through the depth of the beam should therefore be linear. The variation within the Galite beam is shown in Figure 25 for several ages after loading. The curves are reasonably linear.

Figure 26 shows the relation between creep strain and the stress to strength ratio. The linear relation between the creep and applied stress is also evident in this plot. The magnitude of creep strain is somewhat less for a given value of stress-strength ratio for the beam than is the case for cylindrical specimens. This corresponds with the shrinkage behavior of the two types of members and suggests the possibility of utilizing a reduced creep and shrinkage coefficient for prestressed beams as opposed to values obtained from tests on cylindrical specimens. Due to the limit amount of such data available, however, it is not recommended that any such reduction be made.

The loss-of-prestress for the Galite beam was calculated and the results are shown graphically in Figure 27. This plot shows that the major part of the prestress loss occurs rather quickly and that the final prestress loss will be on the order of 18 percent. While the Prestress Loss is given in terms of percent, it should be recognized that these values were computed from the measured losses and the initial prestress value actually applied. For other initial prestress values, the percent loss due to shrinkage would be in proportion to the ratio of this test load to the actual load.

Clinchlite. The Clinchlite concrete beam behaved quite similar to the Galite beam. Creep strain curves are shown in Figures 28, 29, 30 and 31. The loss of prestress is shown in Figure 32.
It is apparent that both the Galite and the Clinchlite concrete can be expected to behave similarly under flexural stresses to their behavior under direct compression. There will be a somewhat lower total creep strain in a prestressed member than is indicated by direct comparison with constant-loaded cylinders due to the stress-relieving action.

For both the Galite and the Clinchlite, however, it is recommended that the constant-stress creep values be utilized until much more data are available with respect to creep under flexural stresses.

E. Stress Transfer Study

The purpose of this study was to determine the stress transfer-length characteristics of semi-lightweight concrete made from the two lightweight aggregates when prestressed.

The concrete was cast in metal forms to produce prisms 3-1/2 inches in width, 4 inches in height and 8 feet in length. The members were each prestressed with a single 7/16 inch diameter, conventional pretensioned strand which passed through the center of the concrete. The strands were in "field condition" in that no cleaning of the strands was done; however, the strands were not rusted and would be representative of strands utilized by a commercial prestressing plant which exercised reasonable care in their operations. Each strand was pretensioned to a load of 18.9 kips. This produced a maximum pre-stress in the concrete of 1575 psi.

Mechanical gage points were attached to both of the 3-1/2 inch faces of the specimens at the level of the prestressing strand. The gages were located at intervals of 2 inches along the beams beginning 4 inches from an end and extending about 36 inches. A Whittemore mechanical gage was used to measure deformations between the gage points immediately prior to and after the detensioning.
The stress transferred at any position along the beam was assumed to be proportional to the deformation which occurred at that position. The prestress transferred to that which occurred in the section where the deformation became constant.

The results are shown in Figure 33 as graphs of Percent of Steel Stress Transferred versus Distance From End of Member.

For both semi-lightweight concretes tested, the full prestress force was transferred at a distance of approximately 25 inches from the "cut end" of the members.

F. Full-Sized Bridge Girder Study

Three full-sized prestressed bridge girders were instrumented and constructed. These girders were 40 feet in length with standard dimensions according to Georgia State Highway Department specifications without end blocks. Each of the girders was made with different concrete. One was of normal weight concrete, one was of Galite semi-lightweight concrete and one was of Clinchlite semi-lightweight concrete. These were cast in the production facilities of the Macon Prestressed Concrete Company, Macon, Georgia. They were cast in line on the same bed, utilizing the same prestress strands.

It was originally planned to monitor both the prestress force in the strands as well as the concrete strains by means of SR-4 resistance gages cemented to the strands prior to the casting and to the outer surface of the concrete subsequent to stripping of the forms. Additionally, mechanical gage points were to be applied to the exterior of the concrete for deformation measurements.
Figure 33. Stress Transfer-length Relation for Semi-light Concrete.
Laboratory checks were made on the gage application techniques as well as a field check under actual prestressing construction operations. Results from the lab work as well as from the field check indicated that the intended techniques would be satisfactory.

The prestressing strands were placed in position and tensioned with a "pre-load" force of 1000 pounds, as is standard operating procedure with the company. This is to take-out most of the slack in the prestressing system and to have a base-length from which to measure elongation of the strands. After the "pre-loading", epoxy cement "patches" were applied to the strands at certain locations and the strain gages were cemented to the epoxy. The lead wires were brought-out from the girder forms, the gage installations were waterproofed and the strands were stressed to their full prestress level. The stressing of the strands was monitored with the strain gage installations and a very good correlation was found between the prestress loads as measured by the gages and the prestress loads as determined by the elongation of the strands.

The girders were cast one at a time in order to utilize the one set of forms available. After the removal of the forms the exterior resistance gages were applied and the girders were prestressed by cutting the strands in a pattern as would be done in practice.

It was found that many of the strain gages had been either shortened by moisture or damaged during the concreting operations. It appeared at first that a sufficient quantity were in good working order and that the data being taken would be of satisfactory quality. Close examination of the reduced data, however, shows that there is no meaningful correlation even between deformation and time for a given gage. For instance, many of the
gages on the strands indicate prestress losses greater than the original pre-
stress force by factors of two or three. There are many concrete deformations
indicated which would necessitate compressive failure of the concrete.

It is concluded that this portion of the testing program has not produced
meaningful data with respect to the creep and loss-of-prestress behavior of the
concretes. The erratic behavior of the strain gages is, of course, the source
of the poor data. Attempts to understand the gage performance lead to the
following conclusions:

1. The immediate shorting of gages was probably due to poor waterproofing.

2. Later shorting of gages could be due to either poor waterproofing, or
   a migration of moisture through the epoxy "patches" on which the gages were
cemented.

3. Lost gages were attributable to damage during the concreting
   operations or to damage at the time of the strand cutting.

At the time of the instrumenting of the strands as well as of the beam
exterior, the humidity was extremely high. It is possible that much of the
poor performance of the gages can be attributed to the effect of the humidity
on the porosity of the epoxy.
CHAPTER V

SUMMARY OF RESULTS AND CONCLUSIONS

Results of the testing program and conclusions derived therefrom are summarized as follows:

A. Use of Galite and Clinchlite Aggregate in semi-lightweight concrete for prestressed bridge girders is quite practical. Prestressed members of good quality have been produced from semi-lightweight concrete made from each of the aggregates.

B. Each of the two aggregates is capable of producing semi-lightweight concrete having strengths which meet the requirements of the Georgia State Highway Department specifications for prestressed concrete bridge girders.

C. The static secant modulus of elasticity for both the Galite concrete and the Clinchlite concrete is approximately $3.05 \times 10^6$ psi at 3 days of age using Type III Portland Cement and moist curing techniques.

D. Shrinkage of the two semi-lightweight concretes is calculated to be as follows:

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Terminal Shrinkage-millionths*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galite</td>
<td>790</td>
</tr>
<tr>
<td>Clinchlite</td>
<td>530</td>
</tr>
</tbody>
</table>

E. Creep of both the galite and the Clinchlite semi-lightweight concrete is approximately proportional to the Stress-Strength Ratio** for values of applied stresses up to and greater than those ordinarily used in prestressed work.

*One millionth = $1 \times 10^{-6}$ strain units (inches per inch).

**The Stress-Strength Ratio is the ratio of the applied compressive stress to the compressive strength at prestress age, $f/f'_{cl}$.
F. Creep coefficients for $f'_c = 4000$ psi compressive strength are as follows for constant loading conditions:

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Creep Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galite Semi-Lightweight Concrete</td>
<td>$0.67 \times 10^{-6}$ in/in/psi</td>
</tr>
<tr>
<td>Clinchlite Semi-Lightweight Concrete</td>
<td>$0.77 \times 10^{-6}$ in/in/psi</td>
</tr>
</tbody>
</table>

G. Prestress-type loading of beams and cylinders indicate that lesser creep will occur in prestressed members due to the unloading effect of creep and shrinkage (as well as relaxation), however, no value can be assigned to such reductions from presently available data.

H. Loss of Prestress for both the Galite and the Clinchlite semi-lightweight concretes is approximately 18 percent* due to the combined effect of creep and shrinkage.

I. The stress-transfer characteristics of both concretes are satisfactory and the full prestress force will be transmitted to the concrete within 30 inches for a 7/16 inch conventional pretensioned strand.

*This value is dependent upon the initial prestress force among other things and should be used with caution.
CHAPTER VI

RECOMMENDATIONS

The results of this investigation have indicated the difficulty of making a rational analysis of the loss of prestress in prestressed concrete members regardless of the aggregate used in the construction. It has been well established that factors such as aggregate type, concrete composition, specimen shape and size, and character of loading as well as others all influence the loss of prestress in a prestressed member. Efforts to interrelate the effects of some of these variables have been relatively unsuccessful. Although some generalizations can be made, it appears that an assigned value for total prestress loss is still the only practical solution at the present time.

These results indicate that the combined total loss due to creep and shrinkage should not be greater than 20% for concrete made with either of the two aggregates tested.

It has been considered good practice to delay the beam-stressing operation (i.e. cutting of strands in pretensioned work) for as long as economically possible in order to reduce the prestress losses due to shrinkage of the concrete. The present test results indicate no great benefits from such delays since the creep and shrinkage losses are interrelated and a reduction in shrinkage losses tends to be offset by greater creep losses. Therefore, from a prestress loss point-of-view, the benefits of delayed stressing will be derived primarily from elastic shortening and camber considerations.

Further attempts to define the behavior of prestressed concrete on a rational basis by the use of material properties are necessary in order to advance the art of prestressed work. Among the more promising areas for
research would appear the following:

A. Laboratory-sized beams prestressed by external means similar to that used in this study. Variables should include initial prestress level, concrete proportions, and environmental conditions (temperature and humidity).

B. Instrumentation of full sized members, in an "unloaded" condition as well as "in service" situations in order to observe the behavior of the members with time and under service loads. The "unloaded" members could be subjected to static load tests to failure.

C. Investigation of the effects of repetitive loading on creep of prestressed members.
CHAPTER VII

BIBLIOGRAPHY

