THE STRUCTURAL BEHAVIOR OF
HIGHER-STRENGTH CONCRETE

by

TAREK MOHAMED EL SAYED REFAI

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Approved by:

Stuart E Swartz
Major Professor

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Chapter 1

INTRODUCTION

Concrete has been classified as, "Normal-Strength Concrete," when it has a compressive strength in the range from 2500 to 6000 psi. "Higher-Strength Concrete," is that having a compressive strength in the range from 6000 to 12000 psi.

In recent years higher-strength concrete has been successfully produced using the present techniques of ready-mixed concrete and conventional materials, especially superplasticizers. A superplasticizer is used to produce a concrete with a plastic to fluid consistency at a low water-cement ratio.

Such higher-strength and some high-strength concrete has been used in many high-rise buildings and long-span bridges with considerable economic and design advantages. A question to ask is that "if higher-strength concrete is to be more widely accepted for general structural applications, are the provisions of the current ACI 318-83 Building Code adequate for design with this concrete?". The empirical parameters of the compressive strength concrete in the current code have been established through both experiments and experience with concrete having compressive strength considerably lower than 8000 psi. Therefore, research efforts are required to provide suitable assurance of the properties of the compressive stress block that are most important for practical purposes.

Objective

The objective of this research project on higher-strength concrete is to continue the work that has been started in the Civil Engineering Department at Kansas State University. The specific purposes of this work are:

1. To confirm the results obtained for production of higher-strength concrete and selection of the materials and their proportions for mix design. The concrete strength that had been used was about 9000 psi.
2. To reproduce the results obtained on the compressive stress block and stress-strain relations at the different stages of loading. It was desired to confirm that the stress block is generally parabolic.
3. To determine the strain at f'_c and rupture, and the effect of age of this.
4. To determine Poisson's Ratio.

Literature Survey for Compressive Stress Block

According to the American Concrete Institute Code ACI 318-83 (20) the depth of the rectangular stress block would become zero for concrete strength in excess of 21000 psi (186 MPa). In 1955 Hognestad, Hanson, and McHenry (17) reported the Concrete Stress Distribution in Ultimate Strength Design. Their investigation was conducted at the Research and Development Laboratories of Portland Cement Assn. in 1954. They evaluated previous methods and results in experimental investigations of the stress block and developed a test method leading to an improved and quantitative understanding of the stress block. An eccentrically loaded specimen and a test method were developed and the method was used to measure the properties of the stress block for five concretes with different w/c ratios at different test ages.

In 1975 a lower limit of 0.65 for the coefficient β_1 was adopted for concrete strength greater than 8000 psi.

Only a few investigations have been done recently. For example, in reinforced rectangular beams "with f'_c ranging between 9300 and 11800 psi," recommended that a triangular compressive stress block with extreme fiber stress at f'_c and zero stress at neutral axis be used. Another research that was done by Paul Zia in 1983 (26) concluded that it is suggested to revise the design values for the elastic modulus of rupture and the minimum requirement for flexural reinforcement of higher-strength concrete. In 1982 Ali Nikaeen (25) reported on research concerning the production and structural behavior of higher-strength concrete. He observed that the shape of the stress block changes from rectangular to parabolic type as the strength increases and the relation between stress and strain is almost linear up to failure.

Therefore, it is obvious that there is a very strong need to investigate the effect of these observations and recommendations on the compressive stress block.

Chapter 2

SELECTION OF MATERIALS

Introduction

Many materials have been developed to ensure good durability of concrete under a variety of conditions. The progress is so extensive and rapid that it appears to be limitless.

As the materials and their proper use in the final product (structure) are closely related, one should have at least a basic understanding of the materials and proper construction methods associated with a particular contemporary structure if maximum results at minimum costs are to be obtained.

The production of higher-strength concrete needs to optimize the use of mixing materials. Once an optimum or near optimum condition is established for a material, it should be kept fixed in the mix design as remaining variables are studied.

Cement

As proved by numerous tests and practical experience, all the significant qualities of concrete are controlled primarily by the cement characteristics, by the porosity of the paste, by strength of aggregate, and also by the strength of the bond between the paste and the aggregate particles. The rate of hydration of the cement paste is controlled (besides by the porosity) not so much by its chemical composition as by the fineness of grinding, i.e. by the increased specific surface of cement grains exposed to hydration. However, the rate of hydration depends both on the fineness and on the chemical composition of cement. The grain sizes of Portland Cement (Type I and III) may vary within a wide range - from 100μ down to 1μ - and the specific surface may vary from 200 to 20000 cm^2/gm, respectively. Therefore, the hydration and intermolecular forces are higher for fine-ground than for coarse-ground cement. The higher strength of high-early cement is especially pronounced in the early age-up to 3 days.

Cement may be classified broadly into the different kinds of Portland Cement, high alumina cement, supersulphate cement and special cements such as jasonary, Trief, expansive and oil well cements. In America, Portland Cements are divided into five types, general purpose cements requiring moderate resistance to sulphate action and moderate heat of hydration, high early strength cement, low heat cement and cement offering high resistance to sulphate action.

There are a few factors that are considered in choosing the right grade of cement; type, chemical composition, fineness and cube strength (by ASTM Standard Method of Test C-109 [22]). Compatability of cement with admixture should be checked by testing for false and flash set. In general, the selection of cement for higher-strength concrete should be based on comparative strength tests of trial mixes. It is known that the chemical composition and the fineness of cement greatly influence the strength in the cement. But there is no certain rule in the United States that classifies the cement according to strength-producing capabilities. It has been shown from tests at Cornell University that up to 22 percent difference in concrete strength is obtained using Type I cement and the same workability (3). This is also shown in Figure 2.1 (5). In Figure 2.2, Blick (6) shows the effect of different types of cement on concrete compressive strength based on mixes of the same workability. Concrete made with Type I and Type II cements, as shown in Figure 2.2, yields higher strength than Type III cement because of the increase in water requirement for the same workability. From Figure 2.2, also Type I cement gives highest compressive strength at all ages.

Type I cement was used here since it needs a lower water-cement ratio and decreases the workability. The final decision on the brand of cement is recommended to be based on strength-producing capability in concrete at ages of 52 days.

Coarse Aggregate

Since at least three-quarters of the volume of concrete is occupied by aggregate, it is not surprising that its quality is of considerable importance. Not only may the aggregate limit the strength of concrete, as weak aggregate cannot produce strong concrete, but the properties of aggregate greatly affect the durability and structural performance of concrete. It is important to consider the following properties when selecting a coarse aggregate for higher-strength concrete.

a) strength

b) maximum size and gradation

c) particle shape and texture

d) cleanliness

e) mineralogy and formation

f) bond of aggregate

g) porosity and absorption of aggregate

Strength

Clearly the compressive strength of concrete cannot exceed that of the major part of the aggregate contained therein. If we compare concrete made with different aggregates we can observe that the influence of aggregate on the strength of concrete is qualitatively the same whatever the mix proportions, and is the same regardless of whether the concrete is tested in compression or in tension. In general, the strength and elasticity of aggregate depends on its composition, texture and structure aggregate. It is reported that the minimum compressive strength of the quartzite rock which was used has a value in excess of 18000 psi (124 MPa) (24). Therefore, this property is not a major problem for production of higher-strength concrete.

Maximum Size and Gradation

The grading, the surface area and the shape of the aggregate have a very important bearing on the strength and quality of concrete. Their effect is an indirect one as they determine the amount of water necessary to obtain the required workability, and also the degree of compaction. Several researchers (7, 8, 9) have shown that in higher-strength concrete the compressive strength increases when the maximum size of aggregate decreases. A maximum size of 0.4 in. (10 mm) is recommended for most cases (10). Figures 2.3 and 2.4 show the size effect of coarse aggregate on compressive strength. From this it is concluded that the smaller the aggregate size the more efficient the use of cement we get in higher-strength concrete because of the greater bond between the cement paste and coarse aggregate. Therefore, trial batching is recommended due to the significant variation in optimum size for each aggregate and for each level of desired strength.

Particle Shape and Texture

In addition to the petrological character of aggregate, its external characteristics are of importance, in particular the particle shape and surface texture. The shape and the surface texture of aggregate influence considerably the strength of concrete. The flexural strength is more affected than the compressive strength, and the effects of shape and texture are particularly significant in the case of higher-strength concrete. Carrasquillo (3) indicated that the ideal coarse aggregate for higher-strength concrete appears to be a clean, cubical angular, 100 percent crushed stone with maximum flat size and elongated particles. He also reported that with holding all other factors constant, crushed stone coarse aggregate produces higher-strength concrete than does a rounded aggregate. Figures 2.5 and 2.6 show the comparison between some different types of coarse aggregate in the compression strength.

Cleanliness

There are three broad categories of deleterious substances that may be found in aggregates: impurities which interfere with the processes of hydration of cement; coating preventing the development of good bond between aggregate and cement paste; and certain individual particles which are weak or unsound in themselves. In production of higher-strength concrete, coarse aggregate should be free of deleterious materials. Washing the crushed stone coarse aggregate may not always be necessary, but is always recommended (11).

Mineralogy and Formation

Mineralogy and formation of the coarse aggregate increases the compressive strength of concrete as well as using crushed stone as the coarse aggregate. An experimental work was done on the effect of mineralogy on concrete strength. A strength of 17000 psi (117 MPa) was achieved on granite rock (2).

Bond of Aggregate

Bond between aggregate and cement paste is an important factor in the production of higher-strength concrete, especially the flexural strength. Bond is due, in part, to the interlocking of the aggregate and the paste owing to the roughness of the surface of the former. A rougher surface, such as that of crushed particles, results in a better bond; better bond is also usually obtained with softer, porous, and mineralogically heterogeneous particles. It has been found that the ratio of bond strength to the concrete strength increases with age (23). Alexander (12) found that the cement-aggregate bond to a 3 inch particle was almost 1/10 of that to corresponding 1/2 in. particle.

Porosity and Absorption of Aggregate

The characteristics of the internal pores that are present in the aggregate particles are very important. Its permeability and absorption influence such properties of aggregate as the bond between it and the cement paste. The pores in aggregate vary in size over a wide range. Some of the aggregate pores are wholly within the solid, others open on to the surface of the particle. However, water can enter the pores, the amount and rate of penetration depending on their size, continuity and total volume (23). For producing higher-strength concrete, one should determine the water sbsorption of aggregate which would be added to the water required for mix. This is to be determined by measuring the increase in weight of an oven-dried sample when immersed in water for 24 hours (the surface water being removed) (23).

Fine Aggregate

The fine aggregate has an important and significant role in production of higher-strength concrete. The water requirement and consequently the strength are greatly affected by fine aggregate. In sand of the same grading, a 1 percent increase in fine aggregate voids may cause a 1 gallon per cubic yard increase in water demand (13). The important role of the fine aggregate in improving the workability for higher-strength concrete mix is not so crucial because of using large amounts of cement paste as well as using superplasticizer. Fine aggregates with a fineness modulus between 2.7 and 3.2 have been most satisfactory (15). The ASTM C-33 suggested a reduction of the amount passing the No. 50 and No. 100 sieve on the lower side of the specification limit. Such reductions have been shown to increase the compressive strength by 500 to 1000 psi (3.5 to 7.0 MPa) (14).

Kaw River sand with a maximum sieve size of No. 4 was used for this investigation.

Water

The water used for producing higher-strength concrete is the same as that used for normal-strength concrete. Studies (5, 13) have shown that water meeting specification ASTM C-94 (19) has no harmful effect on higher-strength concrete. Therefore, water meeting ASTM C-94 is adequate.

Admixture

Since the production of higher-strength concrete requires the use of a low water-cement ratio, and due to the corresponding poor workability of concrete, a chemical admixture called superplasticizer was used. This admixture improves workability and slump because it reduces the angle between the water and the surface of contact. However, it is important to note that this admixture does not have a direct effect on the concrete strength at any age. It has an effect only on the fresh concrete for a short time. After adding superplasticizer to the mix it becomes more workable for a limited time and then the mix changes to its original property. Figure 2.7 shows the effect of superplasticizer on the slump versus time on a mix with water cement ratio of 0.35. Twelve fluid ounces of admixture per sack of cement were used which was recommended by the manufacturing company. Actually, the use of superplasticizer can be optimized with a trial mix using different amounts within the limit. Sikament brand of superplasticizer was chosen to be used in this investigation. It is important to take into consideration the effect of the rapid slump decrease with time when using superplasticizer as shown in Figure 2.7.

Chapter 3

MIX PRODUCTION

Introduction

Mix design can be defined as the process of selecting suitable ingredients of concrete and determining their relative quantities with the object of producing, as economically as possible, concrete of certain minimum properties, notably consistency, strength, and durability. In proportioning the higher-strength concrete for this investigation we are interested in getting optimum performance from each component so that the required higher-strength can be achieved.

Proportioning

Some different mixes were designed using the unit volume method in order to obtain the weight of the components (25). The amount of fine aggregate was a percent of total aggregate, namely 25 percent, 50 percent and 75 percent. For every water-cement ratio some different sand contents were used. The workability was the basis for comparison. The slump was kept between 2 1/2 and 3 1/2 inches for this purpose. The mix proportions obtained by Nikaeen are given in Appendix II-A, Approach I.

It should be emphasized, however, that it is possible only to obtain an approximation to the best mix and that it might still be necessary to make adjustments after the actual trial. In this investigation some adjustments have been done on the mix proportions (25) obtained. The values of the compressive strength were compared to those obtained before (25) at ages of 3, 7 and 9 days. These values are given in Table 3.1 - 3.8. The mix proportions that have been used in this investigation are given in Appendix II-A, Approach 3.

Water-Cement Ratio

In the case of higher-strength mixes the water-cement ratio significantly influences the strength more than it does in normal-strength mixes. This ratio should be kept as minimum as possible. It has been reported that the lowest possible water-cement ratio should be used together with a minimum amount of mixing water (3). The water-cement ratio is the next most important affecting the producibility of higher-strength concrete, after the selection of the optimum strength-producing materials has been made (6).

In this investigation a water-cement ratio of 0.322 was found experimentally to be the best for getting the required strength and workability. A strength of about 9600 psi and slump between 4 inches to 6 inches were obtained. The components were mixed together (sand, stones, and cement), then water and superplasticizer were mixed together and added to the mix. The time from starting of mixing action to measuring the slump was approximately the same for all mixes.

Casting and Testing

According to the standard American specifications ASTM, the cylinder samples were cast by rodding three layers for every cylinder and vibrating them for 30 seconds. After 24 hours from casting they were taken out of the mold and were put into the curing room. The cylinders were tested at different ages of 3, 7, 9 and 28 days. Eight mixes were tried to reach and ensure the required higher-strength. The first mix using Nikaeen's proportions (25) gave a lower 28-day strength because of using cement that was stored in the A/C-Room for almost a year (Table 3.1). The second mix using the same proportions (25) but other cement that was stored for almost a year outside the A/C-Room. The strength obtained at age of 3 days was less than expected by about 700 psi (Table 3.2). The third mix using the same approach with some fresh cement gave an average 3-days strength of about 300 psi less than expected (Table 3.3). The fourth mix using approach 2 and fresh cement did not give the expected higher-strength because of the poor workability (Table 3.4). The fifth mix using Nikaeen's approach gave a lower strength because of using cement that was uncovered and exposed to humidity of 50% for 24 hours (Table 3.5). The sixth mix using Nikaeen's approach with some fresh cement, gave a close strength value to Nikaeen's at the ages of 3 and 7 days (Table 3.6). The seventh mix has been done using mix approach 3 and fresh cement. The strength obtained at ages of 3-days was slightly higher than expected (Table 3.7). The eighth mix using the same proportions as that of mix No. 7 has been done, to duplicate the results obtained. The strength obtained was about the same as that of mix No. 7 (Table 3.8). The mix proportions given in Appendix II-A, Approach 3 were used in this investigation.

Chapter 4

CHOOSING THE METHOD AND THE STRUCTURAL ELEMENT

Introduction

In choosing the method and the structural element for testing higher-strength concrete, it was necessary to satisfy some conditions such as:

1. The possibility of obtaining the compressive stress block which means, the compressive stress distribution between the neutral axis and the outer fiber of the structural element.
2. Fixing the length of the stress block which means the distance between the neutral axis and the outer fiber.
3. Finding the equations which would permit stress to be expressed in terms of measured strain and other unknown parameters.
4. Taking into consideration the maximum load capacity of the available testing machine.
5. The safety during testing higher-strength concrete which explodes at failure.

Choosing the Method

Following the approach developed by Hognestad, Hanson and McHenry (17) and more recently Nilson and Slate (18), their equations and the C-Shape structural element were used. Hognested, Hanson and McHenry had an important role in developing the ultimate design theory and their work was considered to be one of the main bases for developing the ACI Code for ultimate strength theory. They formulated stress in concrete fibers as a function of strain in those fibers. Figure 4.1 show the fact they demonstrated, that the stress-strain relationships for concrete in concentric compression are applicable to flexure. The compressive stress block of a higher-strength concrete beam at failure is assumed to be characterized by the parameters f'_c, k_1, k_2, k_3 as shown in Figure 5.17. The stress-block shape parameter k_1 is 0.5 for a triangle (the area of a triangle = 0.5 x base x height), 0.67 for a parabola (the area of a parabola = 0.67 x base x height), and 1.0 for a rectangle (the area of a rectangle = 1.0 x base x height). The stress-block centroid parameter k_2 is 0.33 for a triangle, 0.375 for a parabola, and 0.5 for a rectangle. The developed equations that relate stress to measured strain and other parameters are (17):

$$f_c = \varepsilon_c \frac{df_o}{d\varepsilon_c} + f_o \quad \text{- -} \quad (4.1)$$

$$f_c = \varepsilon_c \frac{dm_o}{d\varepsilon_c} + 2\,m_o \quad \text{- - - - - - - - - - - - - - - - - - - -} \quad (4.2)$$

$$f_o = \frac{P_1 + P_2}{bc} \quad \text{- -} \quad (4.3)$$

$$m_o = \frac{P_1 a_1 + P_2 a_2}{bc^2} \quad \text{- -} \quad (4.4)$$

where,

f_c = concrete compressive stress in outer fiber of the beam.

ε_c = concrete strain in outer fiber of the beam.

P_1 = major thrust.

P_2 = minor thrust.

a_1 and a_2 are lever arms.

b is the width and c is the depth of the testing region.

The details and the dimensions used here are shown in Figures 4.2 and 4.5.

Structural Element

Test specimens of the "dogbone" shape similar to those used by McHenry were used. Suitable shear, bending and diagonal tension reinforcement was computed by Nidaeen (25) for the end brackets to obtain failure in the central unreinforced test region. The unreinforced test region was 16 inches long and such reinforcement ended at the beginning of the test region. The details of the reinforcement design are given by Nikaeen (25) and results shown in Figure 4.3 to 4.5. The cross-section of the test region was chosen to be 5 x 5 in. (127 x 127 mm) so that the required testing load did not exceed the limiting capacity of the testing machine. The test prism was 5 x 5 x 16 in. (127 x 127 x 406 mm).

Chapter 5

EXPERIMENTAL WORK AND RESULTS

Casting

A volume of 3 1/2 cubic feet (0.1 m^3) of higher-strength concrete mix approach 3 was used for each specimen. The specimens were cast horizontally on a level wood table which carried the mold on top. Because higher-strength concrete is more difficult to finish than normal-strength concrete, vibration was used to consolidate and finish the concrete. The reinforcing steel was tied to the mold using some pieces of wire to keep it in position while casting and vibrating. A minimum cover of 3/8 in. (9.5 mm) was used. One 6 x 12 in. (152 x 305 mm) cylinder and some 3 x 6 in. (76 x 152 mm) cylinders were cast at the same time with each mix.

Curing

After twenty-four hours the specimens as well as the cylinders were taken out of the mold and were placed in the curing room where the humidity was 100%. The specimens and the cylinders were kept in the curing room for 47 days. Then they were taken out of the curing room and were kept in a 50% humidity room for 7 days in order to attach strain gages and to otherwise prepare the specimens for the test.

Instrumentation and Apparatus

Ten longitudinal, electrical resistance strain gages (EA-06-750DT-120) were used to measure the strain in the test region. They were attached at locations shown in Figure 4.2. A relatively high-speed OPTIM data acquisition system was used to record the strain values at each loading stage.

A compression testing machine of 300,000 lb. capacity was used to produce the major P_1. The minor load P_2 was applied by a hydraulic jack through a steel frame as shown in Figure 5.1. The hydraulic jack was attached to a pressure gage system which was calibrated prior to the test. The loading lines for P_1 and P_2 the neutral axis can be made to coincide with the outside face of the specimen as shown in Figure 4.2. After each increment of the major thrust P_1, the minor thrust P_2 was adjusted so that the average strain across the neutral surface was maintained at zero. For specimen 1 which was cracked at the neutral surface before testing, small values of compressive strain were allowed at the outside face. Load and strain at each loading stage were recorded and the procedure was repeated up to failure. The inside faces of the specimens represent the extreme compressive surfaces. The load-strain data for specimen 1 at every loading stage are shown in Table 5.1. The average strain at each level is given as a function of load in Table 5.2. Two longitudinal and two transverse strain gages were mounted on a 3 x 6 in. cylinder corresponding to specimen 1 and strain was recorded as a function of load up to failure, Table 5.3. Another 3 x 6 in. cylinder with only two longitudinal strain gages was tested and the load-strain data are shown in Table 5.4. Also, 3 x 6 and 6 x 12 in. cylinders corresponding to Specimen 1 were tested on the same day that the specimen was tested in order to determine the strength of the mix. The results are given in Table 5.5. The corresponding data for Specimen 2 are given in Tables 5.6 to 5.10 and then Tables 5.11 to 5.15 for Specimen 3. Specimen 4 was broken in tension while doing the set-up, but the corresponding cylinders were tested and the recorded data are shown in Tables 5.16 to 5.19. Cylinders for Specimens 1, 2 and 3 were tested with a defective compression machine of capacity 75,000 lb. The corresponding recorded data were considered to be inaccurate. Cylinders for Specimen 4 were tested by another compression machine of capacity 300,000 lb. which gave reasonable and accurate data. The data obtained by the 300,000 lb. -

machine were considered to evaluate the compressive strength for all the specimens. Table 5.16 was used to plot the stress-strain curve which was used to evaluate the corresponding stress to the recorded strain for Specimens 1, 2 and 3.

Results and Discussion of the Results

Using the strain data and the corresponding stress values of Tables 5.3 and 5.4, the stress-strain curves are plotted by the computer in Figures 5.2 and 5.3 corresponding to Specimen 1. In the same manner, values of Tables 5.8 and 5.9 are plotted Figures 5.4 and 5.5 for Specimen 2, values of Table 5.13 and 5.14 are plotted in Figures 5.6 and 5.7 for Specimen 3, and values of Tables 5.16 to 5.18 are plotted in Figures 5.8 to 5.10. The stress values at each level of loading are determined directly for beam Specimens 1, 2 and 3 by using the strain values for the flexural tests as indicated in Tables 5.2, 5.7, 5.12 and with the cylinder stress-strain curve (Figure 5.8), one can read a stress value [17]). The shape of the stress block is shown in Figure 5.11 to 5.13 for various load increments for test Specimens 1, 2 and 3. The strain variation along the depth of each specimen can be shown for each load increment by plotting depth versus strain. The strain variations along the depth are shown in Figures 5.14 to 5.16 for Specimens 1, 2 and 3 using Tables 5.2, 5.7 and 5.12 respectively. The equilibrium concept is used to determine the ultimate strength factor, k_1, k_2 and k_3 as shown in Appendix II-C. By equilibrium of forces and moments from Figure 5.17, k_1k_3 and k_2 can be determined.

$$k_1k_3 = \frac{C}{bc\ f'_c} = \frac{P_1 + P_2}{bc\ f'_c} \text{ - - - - - - - - - - - - - - - - } (5.1)$$

$$k_2 = 1 - \frac{P_1a_1 + P_2a_2}{(P_1 + P_2)c} \text{ - - - - - - - - - - - - - - - - } (5.2)$$

From equations 5.1 and 5.2, it is clear that k_1k_3, k_2 are functions of P_1 and P_2. The values of k_1k_3, k_2 and $\frac{k_2}{k_1k_3}$ are determined at each load level from zero up to failure as given in Tables 5.20 to 5.22 for Specimens 1, 2 and 3 correspondingly. The stress factors f_o and m_o were defined as:

$$f_o = \frac{P_1 + P_2}{bc} \text{ - } (5.3)$$

$$m_o = \frac{P_1a_1 + P_1a_2}{bc^2} \text{ - } (5.4)$$

The values of f_o and m_o can be directly determined from zero up to failure as shown in Tables 5.23 to 5.25. The values of f_o and m_o are plotted against the extreme strain values at the inside surface for Specimens 1, 2 and 3 as shown in Figures 5.18 to 5.23. The outer fiber stress in the beam is also calculated using Equations (4.1) and (4.2), for all specimens. The results are given in Tables 5.23 to 5.25. The average values of the calculated stresses using Equations (4.1) and (4.2) are plotted against the corresponding strain data for Specimens 1, 2 and 3 as shown in Figures 5.24 to 5.26 correspondingly. The individual value of the coefficient k_3 is the ratio of the calculated average compreasive stresses (values from zero up to maximum only are considered in Tables 5.23 to 5.25 for Specimen 1, 2 and 3 respectively) to the corresponding average cylinder strength f'_c (17). To calculate k_1 which is the shape factor, one should evaluate k_1k_3 and k_3. The values of ultimate atrength factors are given in Tables 5.20 and 5.22 for Specimen 1, 2 and 3. The ultimate strength factor k_2 is the poaition of resultant reaction force which is produced by concrete.

Figures 5.27, 5.28 and 5.29 show the values of k_1k_3 and k_2 computed by Equations (5.1) and (5.2) as function of the strain ε_c at the compression face for Specimens 1, 2 and 3. In these figures values of 0.333 and 0.375 for k_2 are plotted and represented by dotted horizontal linea. These values of k_2 correspond to triangular and parabolic distributions respectively. k_2 has values of 0.346, 0.396 and 0.397 at the ultimate condition for Specimens 1, 2 and 3 correspondingly. As shown in Figures 5.27 to 5.29 the k_2 values at ultimate condition are much closer to the line that represents the parabolic distribution for the stress block (i.e. line of k_2 = 0.375). Figures 5.30 to 5.32 show the values of k_1 versus the inside fiber concrete strains. These graphs also prove that the stress distribution at ultimate stress condition is not rectangular (rectangular stress block corresponds to $k_1 = 1.0$). Figures 5.12 and 5.13 for Specimens 2 and 3 show the actual compresssive stress distribution for higher-strength concrete that has an ultimate strength factors k_2 larger than 0.33 and k_1 between 0.5 and 1.0.

In Tables 5.26 to 5.28, flexural stress is given using both methods of Equations 4.1, 4.2 and cylinder stress-strain curve (Figure 5.8), for comparison purposes for Specimens 1, 2 and 3. A typical shape of stress block at ultimate condition is shown in Figure 5.17.

The minor load P_2 was calibrated and found as a function of the pressure data in a general equation. This is shown in Appendix II-B.

To simplify the calculation, a computer program was used to determine f_o, m_o, k_2, k_1k_3, k_2/k_1k_3, the differential parts and the inside average concrete stresses using Equations 4.1 and 4.2. The details of the computer program are given in Appendix II-D.

Strain and Poisson's Ratio

Specimen 1, which was cracked before the test, gave a strain about .002 in/in at ultimate condition. Correspondingly, Specimens 2 and 3 gave strain values of .00269 and .00264 in/in at ultimate condition. The maximum cylinder strains at ultimate condition for Specimen 1 are .0015 and .00175, the corresponding average Poisson's ratio is 0.149. The cylinder for Specimen 2 at ultimate condition gave maximum strain values of .0022 and .002, the corresponding average Poisson's ratio is 0.198. Cylinders for Specimen 3 at ultimte condition gave maximum strain values of .0016 and 0.0023, the corresponding average Poisson's ratio is 0.158. Finally, the cylinders for Specimen 4, which was broken before the test, gave strain values of 0.00217 and 0.0020, correspondingly the average Poisson's ratio is 0.159.

From the above it is seen that the value of strain is less than .003 in/in which is proposed by the ACI Code (20). Therefore, a more conservative value of 0.0025 in/in is recommended. In reference (18) a conservative strain value of 0.0025 in/in is suggested.

Young's Modulus, E_c

The values for Young's Modulus were obtained from Figures 5.8 to 5.10 by finding the slope of the line that passes through the origion and the point of 0.45 f'_c. Values of 7.8, 7.952 and 8.52 x 10^6 psi were obtained. These values for Young's Modulus are higher than 6 x 10^6, which is given by the ACI Code (20), $E_c = 33\ W^{3/2} \sqrt{f'_c}$.

Chapter 6

SUMMARY AND CONCLUSIONS

Summary

A final mix design was reached to get a higher-strength concrete of about 9600 psi. Numerous cylinder tests were involved to determine the strength of concrete using superplasticizer in all mixes which helped in improving the workability. It was planned to test a total of four flexural specimens of the same mix design, age and strength. The first specimen was cracked at the neutral surface to about half the depth through due to malfunction of the ram. The second and third specimens were tested successfully, and gave some consistent data. The last specimen was broken without gaining any results under the axial tension of its own weight.

Conclusions

From the test results and analogy of them it is possible to conclude some points.

1. Superplasticizers are very useful to the fresh concrete in improving the workability if the right amounts are used. Too much superplasticizer decreases the strength and also segregates the mix.
2. The brittle mode of failure for higher-strength concrete is the same as any other brittle material. Only sudden failure takes place without any warning. There were no cracks observed before failure. In the case of higher-strength concrete the failure line passes through the coarse aggregate particles and gives a smooth surface of failure. Contrary to this action, the failure line for normal-strength concrete passes through interfaces of mortar and stone and gives a coarse surface of failure. This action is true

for both compressive and flexural tests. Figure 5.33 shows the type of failure.

3. The higher-strength concrete has about the same brittle mode of tension failure and coarse surface as that of normal-strength concrete. Figure 5.34 shows the surface of failure for the fourth specimen which was broken under tensile load.
4. The compressive stress-strain curve is almost linear up to a certain point, then it takes a curved shape up to failure. A slow and controlled load would give a descending part as shown in Figure 5.8 and 5.9.
5. The shape of the stress block is that given in Figure 5.12 and 5.13 for this strength. The positions of the concrete internal reaction force are $k_2 = 0.396$ and 0.397 at ultimate condition for higher-strength concrete with $f'_c = 9680$ psi (66 MPa). These values have an average of 0.3965 which is between 0.33 and 0.5, corresponding to triangular and rectangular shape respectively. This value of k_2 at ultimate condition is very close to the value of .375 for the center of gravity of a parabolic stress block. This fact is reinforced by the other ultimate strength factor k_1 which has values of 0.674 and 0.611 at ultimate condition. This factor represents the shape factor and its average value of about 0.64 lies between 0.5 and 1.0, corresponding to triangular and rectangular type respectively. Its value is very close to 0.67 which is the shape factor for a parabola.
6. Since the strain at ultimate condition is less than 0.003 in/in for higher-strength concrete, a more conservative value of 0.0025 in/in which is less than that given by ACI Code.

7. Since the formula given by ACI Code (20) underestimates the value of Young's Modulus for higher-strength concrete, it is suggested that the accurate value be obtained from the stress-strain curve.
8. The strength of higher-strength concrete increases with time. An age of 52 days is more preferable than that of 28 days.

Recommendations for Future Work

Since there is a great demand for the use of higher-strength concrete as a material that can replace normal-strength concrete, more intensive research efforts are required to bring about all theories and specifications. In this report, the compressive stress block was found to be of the parabolic type which is consistent to what Nikaeen reported and published (27). Therefore, more other experimental or theoretical work needs to be done in order to deeply investigate all properties of the parabolic compressive stress block. Research on high-strength concrete (i.e. more than 12,000 psi) may answer the question more clearly, and might be helpful to formulate a theory for higher-strength concrete.

APPENDIX I

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APPENDIX II

DETAIL OF SOME PROPORTIONS AND FORMULAS

A. Comparison between the mix proportions given by Nikaeen (25) and those used in this experiment; all weights are lb per cubic foot volume of mix, for all of the following approaches.

Approach 1, by Nikaeen (25), f'_c, 8400 psi

Water	9.390 (4250 ml.)
Cement	27.470
Sand	60.880
Quartizite	49.650
Superplasticizer	0.229 (104 ml.)

Approach 2, by experimental trials

Water	8.000 (3620 ml.)
Cement	27.470
Sand	60.880
Quartizite	49.650
Superplasticizer	0.229 (104 ml.)

Approach 3, by experimental trials, f'_c, 9600 psi

Water	8.840 (4000 ml.)
Cement	27.470
Sand	60.880
Quartizite	49.650
Superplasticizer	0.352 (160 ml.)

B. Calibration for the Minor Load P_2 (Ram Load)

Pressure (psi) X	Load (lb) Y
75	500
150	1000
235	1500
315	2000
395	2500
475	3000
550	3500
625	4000

Using the Least Square Method to Find a General Equation of a Straight Line (28)

$$\begin{bmatrix} 1 & 75 \\ 1 & 150 \\ 1 & 235 \\ 1 & 315 \\ 1 & 395 \\ 1 & 475 \\ 1 & 550 \\ 1 & 625 \end{bmatrix} \begin{bmatrix} a_o \\ a_1 \end{bmatrix} = \begin{bmatrix} 500 \\ 1000 \\ 1500 \\ 2000 \\ 2500 \\ 3000 \\ 3500 \\ 4000 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 75 & 150 & 235 & 315 & 395 & 475 & 550 & 625 \end{bmatrix} \left[\begin{array}{cc|c} 1 & 75 & 500 \\ 1 & 150 & 1000 \\ 1 & 235 & 1500 \\ 1 & 315 & 2000 \\ 1 & 395 & 2500 \\ 1 & 475 & 3000 \\ 1 & 550 & 3500 \\ 1 & 625 & 4000 \end{array}\right] = \begin{bmatrix} 8 & 2{,}820 & 18{,}000 \\ 2820 & 1{,}257{,}350 & 8{,}007{,}500 \end{bmatrix}$$

$$\begin{bmatrix} a_o \\ a_1 \end{bmatrix} = \frac{1}{2{,}106{,}400} \begin{bmatrix} 1{,}257{,}350 & -2{,}820 \\ -2{,}820 & 8 \end{bmatrix} \begin{bmatrix} 18{,}000 \\ 8{,}007{,}500 \end{bmatrix} = \begin{bmatrix} 24.28 \\ 6.134 \end{bmatrix}$$

$$\boxed{Y = 24.28 + 6.134X}$$

Check

$$\begin{bmatrix} 1 & 75 \\ 1 & 150 \\ 1 & 235 \\ 1 & 315 \\ 1 & 395 \\ 1 & 475 \\ 1 & 550 \\ 1 & 625 \end{bmatrix} \begin{bmatrix} 24.28 \\ 6.134 \end{bmatrix} = \begin{bmatrix} 484 \\ 944 \\ 1466 \\ 1957 \\ 2447 \\ 2938 \\ 3400 \\ 3858 \end{bmatrix} \quad \text{compare to} \quad \begin{bmatrix} 500 \\ 1000 \\ 1500 \\ 2000 \\ 2500 \\ 3000 \\ 3500 \\ 4000 \end{bmatrix}$$

C. Derivation of Ultimate Strength Factors k_1k_3, k_2

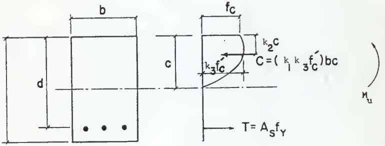

Figure a: Force Couple System

Without any assumption we obtain the equilibrium equation of force and moment:

$$\Sigma F_x = 0 \qquad T = C \rightarrow T = k_1k_3\ f_c'\ bc$$

$$k_1k_3 = \frac{T}{f_c'\ bc} \qquad \text{------------------------} \quad (I.1)$$

$$\Sigma M = 0 \qquad T(d-k_2c) = C(d-k_2c) = M_u$$

$$k_2 = \frac{d}{c} - \frac{M_u}{TC} = \frac{d}{c} - \frac{M_u}{Cc} \qquad \text{----------------} \quad (I.2)$$

Applying the same concept to the test specimen shown in Figure 4.2, we have

$$C = P_1 + P_2$$

Substitute in Equation (I.1) we obtain

$$k_1k_3 = \frac{P_1 + P_2}{bc\ f_c'} \qquad \text{--} \quad (I.3)$$

where f_c' is the cylinder compressive strength.

$$M_u = P_1a_1 + P_2a_2$$

Substitute in Equation (I.2)

$$k_2 = \frac{d}{c} - \frac{P_1a_1 + P_2a_2}{(P_1 + P_2)c}$$

d = c for test specimen

Therefore:

$$k_2 = 1 - \frac{P_1a_1 + P_2a_2}{(P_1 + P_2)c}$$

D. A Computer Program for Finding k_2, k_1k_3, and the Inside Face Stresses

```
10 'THIS PROGRAM FINDS THE AVERAGE  CONP. STRESS AT THE INNER FACE OF THE BEAN
20 INPUT"NO. OF LOADING STAGES N=?";N
30 INPUT"THE CYLINDER CONP. STRENGTH FLIST =?PSI ";F1
40 DIM P1(N),P2(N),FO(N),NO(N),K2(N),W(N),Z(N),F2(N),F3(N),F4(N),X(N),Y(N)
50 DIM B(5,3),BB(3,3),BF(3),DY(N),A(3)
60 PRINT "INPUT THE VALUES OF THE NAJOR LOAD AT THE DIFFERENT STAGES OF P1(I)=?"
70 PRINT "INPUT THE VALUES OF THE NINOR LOAD AT THE DIFFERENT STAGES OF P2(I)=?"
80 PRINT "INPUT THE AVERAGE VALUES OF THE STRAIN AT THE CONP. FACE"
90 FOR I=1 TO N
100 PRINT "LOADING STAGE NO.(";I;")"
110 INPUT "P1(I)=?Lb.";P1(I)
120 INPUT "P2(I)Lb.=?";P2(I)
130 INPUT "X(I)=?";X(I)
140 NEXT I
150 A1=2.5 : A2=27 : A3=5 : A4=5
160 REN W(I) REPRESENTS THE PRODUCT OF THE TWO COEF. K1 & K3
170 REN Z(I) REPRESENTS THE RATIO OF K2/K1*K3
180 FOR I=1 TO N
190 FO(I)=(P1(I)+P2(I))/(A3*A4)
200 MO(I)=(P1(I)*A1+P2(I)*A2)/(A3*(A4^2))
210 K2(I)=1-(NO(I)/FO(I))
220 W(I)=FO(I)/F1
230 Z(I)=K2(I)/W(I)
240 NEXT I
250 LPRINT "___________________________________________________________"
260 LPRINT "P1(I)   P2(I)   FO(I)   NO(I)    K2(I)      W(I)      Z(I)   "
270 LPRINT "___________________________________________________________"
280 FOR I=1 TO N
290 LPRINT USING"#####    ####    ####    ####";P1(I),P2(I),FO(I),NO(I);
291 LPRINT USING"   #.#####  #.#####   #.#####";K2(I),W(I),Z(I)
300 NEXT I
302 LPRINT "__________________________________________________________"
305 LPRINT
310 LPRINT " THE VALUES OF DF/DS "
315 LPRINT "____________________"
320 FOR I=1 TO N
330 Y(I)=FO(I)
340 NEXT I
350 GOSUB  570
360 FOR I=1 TO N
370 F2(I)=(X(I)*DY(I))+FO(I)
380 NEXT I
385 LPRINT
390 LPRINT " THE VALUES OF MO/DS "
395 LPRINT "____________________"
400 FOR I=1 TO N
410 Y(I)=NO(I)
420 NEXT I
430 GOSUB  570
440 FOR I=1 TO N
450 F3(I)=(X(I)*DY(I))+(2*MO(I))
460 F4(I)=(F2(I)+F3(I))/2
470 NEXT I
480 REN F4(I) STADS FOR THE AVERAGE COMP. STRESSES AT THE BEAM INNER FACE
```

```
490 LPRINT "_____________________________________"
500 LPRINT "F2(I)         F3(I)        F4(I)     "
510 LPRINT "_____________________________________"
520 FOR I=1 TO N
530 LPRINT USING"#####          #####          #####"; F2(I),F3(I),F4(I)
540 NEXT I
550 END
560 REM THIS PROGRAM FINDS THE VALUES OF DM/DS & DF/DS
570 N2=N-2
580 FOR I=3 TO N2
590 FOR J=1 TO 5
600 B(J,1)=1
610 IJ=I-3+J
620 B(J,2)=X(IJ)-X(I)
630 B(J,3)=B(J,2)^2
640 NEXT J
650 FOR J=1 TO 3
660 FOR K=1 TO 3
670 BB(J,K)=0
680 FOR L=1 TO 5
690 BB(J,K)=BB(J,K)+B(L,J)*B(L,K)
700 NEXT L,K,J
710 FOR J=1 TO 3
720 BF(J)=0
730 FOR K=1 TO 5
740 IK=I-3+K
750 BF(J)=BF(J)+B(K,J)*Y(IK)
760 NEXT K,J
770 D=BB(1,1)*(BB(2,2)*BB(3,3)-BB(2,3)*BB(3,2))-BB(1,2)*BB(2,1)*BB(3,3)
780 D=D+BB(1,2)*BB(2,3)*BB(3,1)+BB(1,3)*(BB(3,2)*BB(2,1)-BB(2,2)*BB(3,1))
790 E=BB(1,1)*(BF(2)*BB(3,3)-BB(2,3)*BF(3))-BF(1)*(BB(2,1)*BB(3,3)-BB(2,3)*BB(3,1))
800 E=E+BB(1,3)*(BB(2,1)*BF(3)-BF(2)*BB(3,1))
810 C(2)=E/D
820 E=BB(1,1)*(BB(2,2)*BF(3)-BF(2)*BB(3,2))-BB(1,2)*(BB(2,1)*BF(3)-BF(2)*BB(3,1))
830 E=E+BF(1)*(BB(2,1)*BB(3,2)-BB(2,2)*BB(3,1))
840 C(3)=E/D
850 IF I=3 THEN 890
860 IF I=N2 THEN 950
870 DY(I)=C(2)
880 GOTO 1000
890 DY(I-2)=C(2)+2*C(3)*(X(1)-X(3))
900 LPRINT"DY/DX(1)=";DY(1)
910 DY(2)=C(2)+2*C(3)*(X(2)-X(3))
920 LPRINT"DY/DX(2)=";DY(2)
930 DY(I)=C(2)
940 GOTO 1000
950 DY(I)=C(2)
960 DY(I+1)=C(2)+2*C(3)*(X(I+1)-X(I))
970 LPRINT"DY/DX(";I+1;")=";DY(I+1)
980 DY(I+2)=C(2)+2*C(3)*(X(I+2)-X(I))
990 LPRINT"DY/DX(";I+2;")=";DY(I+2)
1000 LPRINT"DY/DX(";I;")=";DY(I)
1010 NEXT I
1020 RETURN
```

APPENDIX III

TABLES AND FIGURES

Table 3.1 Cylinder Compressive Strength, Using Approach 1, Old Cement

Cylinder No.	Cylinder** Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average* Strength (psi)
1	3 x 6	28	3.5	45,000	6365	
2	3 x 6	28	3.5	47,500	6719	
3	3 x 6	28	3.5	37,000	5233	6543
4	3 x 6	28	3.5	52,000	7355	
5	3 x 6	28	3.5	53,000	7496	
6	6 x 12	28	3.5	177,000	6261	
7	6 x 12	28	3.5	180,000	6367	

*Average strength by NIKAEEN

3 - day strength = 5980 psi

7 - day strength = 6747 psi

28 - day strength = 7980 psi

**Cylinder of size 3 x 6 in. has an area = 7.07 in.^{2} (4561 mm^2)

Cylinder of size 6 x 12 in. has an area = 28.26 in.^{2} (18232 mm^2)

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.2 Cylinder Compressive Strength, Using Approach 1, Old Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	3.5	37,000	5233	
2	3 x 6	3	3.5	37,000	5233	
3	3 x 6	3	3.5	39,000	5516	5360
4	3 x 6	3	3.5	37,000	5233	
5	3 x 6	3	3.5	39,500	5587	
6	3 x 6	7	3.5	38,000	5375	
7	3 x 6	7	3.5	38,500	5445	
8	3 x 6	7	3.5	39,000	5516	5516
9	3 x 6	7	3.5	40,000	5648	
10	3 x 6	7	3.5	39,500	5587	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.3 Cylinder Compressive Strength, Using Approach 1, Fresh Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	5.0	38,000	5375	5701
2	3 x 6	3	5.0	41,000	5800	
3	3 x 6	3	5.0	41,500	5870	
4	3 x 6	3	5.0	40,000	5658	
5	3 x 6	3	5.0	40,000	5658	
6	3 x 6	3	5.0	41,200	5827	
7	3 x 6	3	5.0	40,500	5728	
8	3 x 6	3	5.0	40,250	4693	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.4 Cylinder Compressive Strength, Using Approach 2, Fresh Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	0.5	44,000	6223	
2	3 x 6	3	0.5	40,250	5963	
3	3 x 6	3	0.5	35,500	5021	
4	3 x 6	3	0.5	37,250	5268	
5	3 x 6	3	0.5	39,750	5,622	5,740
6	3 x 6	3	0.5	45,000	6365	
7	3 x 6	3	0.5	44,000	6223	
8	3 x 6	3	0.5	42,500	6011	
9	3 x 6	3	0.5	37,000	5223	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.5 Cylinder Compressive Strength, Using Approach 1, Fresh Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	2.5	36,500	5163	
2	3 x 6	3	2.5	34,000	4809	
3	3 x 6	3	2.5	36,000	5092	5064
4	3 x 6	3	2.5	35,000	4950	
5	3 x 6	3	2.5	37,500	5304	
6	3 x 6	7	2.5	42,500	6011	
7	3 x 6	7	2.5	41,000	5799	5775
8	3 x 6	7	2.5	39,000	5516	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.6 Cylinder Compressive Strength, Using Approach 1, Fresh Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	3.5	40,500	5728	
2	3 x 6	3	3.5	42,250	5976	
3	3 x 6	3	3.5	40,500	5728	5792
4	3 x 6	3	3.5	40,000	5660	
5	3 x 6	3	3.5	41,500	5870	
6	3 x 6	7	3.5	46,500	6577	
7	3 x 6	7	3.5	47,250	6683	6570
8	3 x 6	7	3.5	47,000	6648	
9	3 x 6	7	3.5	45,000	6365	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.7 Cylinder Compressive Strength, Using Approach 3, Fresh Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	5	42,300	5958	
2	3 x 6	3	5	42,300	5983	
3	3 x 6	3	5	39,800	5629	
4	3 x 6	3	5	47,000	6648	
5	3 x 6	3	5	45,000	6365	6275
6	3 x 6	3	5	45,750	6471	
7	3 x 6	3	5	46,800	6620	
8	3 x 6	3	5	47,500	6719	
9	3 x 6	3	5	42,800	6054	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 3.8 Cylinder Compressive Strength, Using Approach 3, Fresh Cement

Cylinder No.	Cylinder Size (in)	Age (days)	Slump (in)	Load (lb)	Strength (psi)	Average Strength (psi)
1	3 x 6	3	3.25	42,500	6011	
2	3 x 6	3	3.25	43,500	6153	
3	3 x 6	3	3.25	44,500	6294	6233
4	3 x 6	3	3.25	45,500	6436	
5	3 x 6	3	3.25	44,000	6233	
6	3 x 6	9	3.25	52,000	7355	
7	3 x 6	9	3.25	50,000	7072	7214
8	3 x 6	9	3.25	51,000	7214	

1 psi = 6.89 kpa

1 in = 25.4 mm

Table 5.1 Load-Strain Data for Flexural Test of Structural Specimen 1

P_1		P_2	Strain Reading in ($\mu\varepsilon$)									
Axial Load Machine Load (lb)	Ram Pressure (psi)	Eccentric Ram Load (lb)	Gage #1	Gage #2	Gage #3	Gage #4	Gage #5	Gage #6	Gage #7	Gage #8	Gage #9	Gage #10
5,000	27.5	193	0.0	0.0	- 2.8	- 0.9	- 2.8	56.9	111.9	*	5.7	7.7
22,500	110.0	699	-31	-31	19.3	24.1	- 7.7	- 58.8	- 119.7		- 275.1	-204.6
40,000	200.0	1251	-29	-29	23.1	- 0.9	-110.0	- 268.3	- 399.6		- 459.5	-323.4
59,500	320.0	1987	-29	-29	26.0	- 45.3	-258.7	- 555.1	- 793.5		- 675.7	-451.8
79,500	430.0	2662	-44	-44	27.0	-117.7	-446.9	- 871.7	-1168.1		- 892.0	-583.1
98,500	580.0	3582	-20	-20	19.3	-185.3	-701.8	-1342.8	-1717.4		-1151.7	-688.3
118,500	625.0	3858	-31	-31	- 5.7	-209.4	-926.7	-1852.6	-2054.3		-1541.7	-916.1
120,000	625.0	3858	failure									

Note: Gage #8 was not working while testing the specimen

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.2 Load and Average Strain at Each Level, for Flexural Test of Specimen 1

P_1 Axial Load Machine Load (lb)	Ram Pressure (psi)	P_2 Eccentric Load Ram Load (lb)	Strain Reading ($\mu\varepsilon$)				
			Average Gage #1 and #2 at the Surface	Average Gage #3 and #10 at 1.25" Depth	Average Gage #4 and #9 at 2.5" Depth	Average Gage #5 and #8 at 3.75" Depth	Average Gage #6 and #7 at 5" Depth
5,000	27.5	193	0.0	2.5	2.4	- 2.8	84.4
22,500	110.0	699	-31	- 92.7	- 125.5	- 7.7	- 89.3
40,000	200.0	1251	-29	-150.2	- 230.2	- 110.0	- 334.0
59,500	320.0	1987	-29	-212.9	- 360.5	- 258.7	- 674.3
79,500	430.0	2662	-44	-278.1	- 504.9	- 446.9	-1019.9
98,500	580.0	3582	-20	-334.5	- 668.5	- 701.8	-1530.1
118,500	625.0	3858	-31	-460.9	- 875.6	- 926.7	-1953.4
120,000	625.0	3858					

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.3 Cylinder Stress-Strain Data for Specimen 1 (Cyl. No. 8)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Avg. Long. Strain (με)	Strain Reading in Gage #3 (με)	Strain Reading in Gage #4 (με)	Avg. Trans. Strain (με)	Poisson's Ratio
0	0	+ .9	+ .9	+ .9	+ 2.9	0.0	+ 1.50	0
10,000	-1414	- 472.0	- 69.0	- 270.5	+ 37.4	+ 40.3	+ 38.90	0.1436
20,000	-2829	- 759.6	- 265.1	- 512.4	+ 59.0	+ 88.5	+ 73.80	0.1439
25,000	-3536	- 899.0	- 389.0	- 644.0	+ 70.8	+117.1	+ 93.95	0.1459
30,000	-4243	-1059.6	- 532.2	- 795.9	+ 79.7	+147.6	+113.70	0.1428
35,000	-4950	-1264.8	- 726.7	- 996.0	+ 91.5	+192.9	+142.20	0.1428
40,000	-5658	-1502.8	- 946.4	-1225.0	+106.3	+250.0	+178.20	0.1454
45,000	-6365	-1842.5	-1243.5	-1543.0	+145.6	+325.8	+235.70	0.1528
50,000	-7072	-2073.8	-1422.5	-1748.0	+212.6	+398.6	+305.60	0.1748
54,000	-7640	failure						

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.4 Cylinder Stress-Strain Data for Specimen 1 (Cyl. No. 7)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Average (με)
0	0.0	+ 3.8	+ 2.9	+ 3.4
10,000	-1414.4	- 114.1	- 329.0	- 221.6
20,000	-2829.0	- 308.7	- 516.7	- 412.7
25,000	-3536.0	- 435.4	- 604.8	- 520.1
30,000	-4243.0	- 579.6	- 699.6	- 639.6
35,000	-4950.0	- 749.0	- 802.2	- 775.6
40,000	-5658.0	- 975.4	- 946.4	- 960.9
45,000	-6365.0	-1275.4	-1206.7	-1241.0
50,000	-7072.0	-1652.8	-1439.9	-1546.4
54,000	-7640.0	failure		

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.5 Cylinder Compressive Tests for Specimen 1

Cylinder Size (in)	Cylinder No.	Age (days)	Load (lb)	Comp. Stress (psi)	Average Comp. Stress (psi)
3 x 6	1	3	42,000	5,940	5,905
3 x 6	2	3	41,500	5,870	
3 x 6	3	52	56,250	7,956	7,856
3 x 6	4	52	55,500	7,850	
3 x 6	5	52	56,500	7,991	
3 x 6	6	52	57,000	8.062	
3 x 6	7	52	54,000	7,638	
3 x 6	8	52	54,000	7,638	
6 x 12	9	52	270,000	9,549	9,550

Casting Date: 6/02/84
Testing Date: 7/24/84

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.6 Load-Strain Data for Flexural Test of Structural Specimen 2

P_1 Axial Load Machine Load (lb)	Ram Pressure (psi)	P_2 Eccentric Ram Load (lb)	Strain Reading in ($\mu\varepsilon$)									
			Gage #1	Gage #2	Gage #3	Gage #4	Gage #5	Gage #6	Gage #7	Gage #8	Gage #9	Gage #10
10,000	0.0	0.0	-63	-63	- 27.0	- 46.4	- 52.2	- 66.7	- 57.0	- 72.5	- 49.3	- 62.9
10,000	22.5	162.0	0.0	0.0	- 11.6	- 47.4	- 75.4	- 117.0	- 84.1	- 83.2	- 39.6	- 28.0
20,700	90.0	576.0	0.0	0.0	- 38.7	- 119.0	- 191.6	- 273.8	- 212.9	- 183.8	- 94.8	- 62.9
30,100	140.0	883.0	0.0	0.0	- 64.8	- 179.9	- 285.4	- 397.4	- 313.5	- 261.2	- 138.3	- 89.9
41,000	200.0	1251.0	0.0	0.0	- 93.8	- 251.6	- 397.7	- 545.8	- 432.5	- 356.1	- 188.7	- 119.0
50,000	250.0	1558.0	0.0	0.0	-119.0	- 315.4	- 491.6	- 672.5	- 538.0	- 438.3	- 238.0	- 148.0
59,900	300.0	1865.0	0.0	0.0	-145.1	- 382.2	- 595.1	- 810.9	- 656.1	- 533.2	- 293.2	- 181.9
70,000	350.0	2171.0	0.0	0.0	-172.2	- 449.9	- 700.6	- 952.2	- 777.0	- 634.8	- 356.1	- 217.7
80,000	400.0	2478.0	0.0	0.0	-195.4	- 514.8	- 806.1	-1095.4	- 901.9	- 744.1	- 421.9	- 258.3
90,000	445.0	2754.0	0.0	0.0	-219.6	- 583.5	- 921.2	-1255.1	-1039.3	- 871.9	- 502.2	- 307.7
100,000	495.0	3061.0	0.0	0.0	-238.0	- 653.2	-1042.2	-1426.4	-1189.3	-1019.0	- 595.1	- 366.7
109,500	525.0	3245.0	0.0	0.0	-254.5	- 710.3	-1140.9	-1566.7	-1312.2	-1147.7	- 678.3	- 420.9
119,500	560.0	3459.0	0.0	0.0	-271.9	- 780.9	-1270.6	-1755.4	-1473.8	-1324.8	- 788.7	- 494.5
129,500	590.0	3643.0	0.0	0.0	-283.5	- 843.8	-1383.8	-1927.7	-1632.5	-1493.2	- 899.0	- 569.0
135,000	595.0	3674.0	0.0	0.0	-294.1	- 887.4	-1462.2	-2043.8	-1734.1	-1609.3	- 971.6	- 621.2
139,800	602.0	3717.0	0.0	0.0	-299.9	- 922.2	-1528.0	-2140.6	-1824.1	-1707.0	-1033.5	- 663.8
145,000	610.0	3766.0	0.0	0.0	-304.8	- 968.7	-1614.1	-2272.2	-1957.7	-1843.5	-1123.5	- 730.6
149,800	615.0	3797.0	0.0	0.0	-311.6	-1015.1	-1703.2	-2399.0	-2092.2	-1970.3	-1211.6	- 796.4
154,000	620.0	3827.0	0.0	0.0	-310.6	-1056.7	-1789.3	-2533.5	-2248.0	-2100.9	-1303.5	- 863.2
160,000	560.0	3459.0	0.0	0.0	-299.0	-1107.0	-1910.3	-2737.7	-2638.0	-2347.7	-1486.4	-1023.8
167,000	505.0	3122.0	failure									

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.7 Load and Average Strain at Each Level, for Flexural Test of Specimen 2

P_1		P_2	Strain Reading ($\mu\varepsilon$)				
Axial Load Machine Load (lb)	Ram Pressure (psi)	Eccentric Load Ram Load (lb)	Average Gage #1 and #2 at the Surface	Average Gage #3 and #10 at 1.25" Depth	Average Gage #4 and #9 at 2.5" Depth	Average Gage #5 and #8 at 3.75" Depth	Average Gage #6 and #7 at 5" Depth
10,000	22.5	162	0.0	- 19.8	- 43.5	- 79.3	- 100.6
20,700	90.0	576	0.0	- 50.8	- 106.9	- 187.7	- 243.4
30,100	140.0	883	0.0	- 77.4	- 159.1	- 273.3	- 355.5
41,000	200.0	1251	0.0	-106.4	- 220.2	- 376.9	- 498.2
50,000	250.0	1558	0.0	-133.5	- 276.7	- 465.0	- 605.3
59,900	300.0	1865	0.0	-163.5	- 337.7	- 564.2	- 733.5
70,000	350.0	2171	0.0	-195.0	- 403.0	- 667.7	- 864.6
80,000	400.0	2478	0.0	-226.9	- 468.4	- 775.1	- 998.7
90,000	445.0	2754	0.0	-263.7	- 542.9	- 896.6	-1147.2
100,000	495.0	3061	0.0	-302.4	- 624.2	-1030.6	-1307.9
109,500	525.0	3245	0.0	-337.7	- 694.3	-1144.3	-1439.5
119,500	560.0	3459	0.0	-383.2	- 784.8	-1297.7	-1614.6
129,500	590.0	3643	0.0	-426.3	- 871.4	-1438.5	-1780.1
135,000	595.0	3674	0.0	-457.7	- 929.5	-1535.8	-1889.0
139,800	602.0	3717	0.0	-481.9	- 977.9	-1617.5	-1982.4
145,000	610.0	3766	0.0	-517.7	-1046.1	-1728.8	-2115.0
149,800	615.0	3797	0.0	-554.0	-1113.4	-1836.8	-2245.6
154,000	620.0	3827	0.0	-586.9	-1180.1	-1945.1	-2390.8
160,000	560.0	3459	0.0	-661.4	-1296.7	-2129.0	-2687.9
167,000	505.0	3122	failure				

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.8 Cylinder Stress-Strain Data for Specimen 2 (Cylinder No. 11)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Avg. Long. Strain (με)	Strain Reading in Gage #3 (με)	Strain Reading in Gage #4 (με)	Avg. Trans. Strain (με)	Poisson's Ratio
0	0	3.8	4.8	4.3	1.9	3.9	2.9	0
2,100	- 297	- 72.5	- 33.8	- 53.2	4.9	21.6	13.3	0
5,000	- 707	- 150.9	- 104.5	- 127.7	5.9	48.2	27.1	0.2122
10,000	-1414	- 252.5	- 262.2	- 257.4	12.7	84.6	48.7	0.1892
15,000	-2122	- 349.3	- 432.5	- 390.9	26.5	116.1	71.3	0.1824
20,000	-2829	- 477.0	- 608.7	- 542.9	50.2	151.6	100.9	0.1859
25,000	-3536	- 624.1	- 783.8	- 704.0	79.7	185.0	132.4	0.1880
30,000	-4243	- 800.3	- 982.2	- 891.3	118.1	227.4	172.8	0.1939
35,000	-4950	- 992.9	-1190.3	-1091.6	157.5	276.6	217.1	0.1989
40,000	-5658	-1216.4	-1425.4	-1320.9	204.7	341.5	273.1	0.2068
45,000	-6365	-1486.4	-1715.8	-1601.1	261.8	413.4	337.6	0.2108
50,000	-7072	-1843.5	-2115.4	-1979.5	351.4	478.4	414.9	0.2096
52,500	-7426	-2106.7	-2344.8	-2225.8	1578.0	1159.6	1368.8	0.6150
53,500	-7567	failure						

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.9 Cylinder Stress-Strain Data for Specimen 2 (Cylinder No. 10)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Average (με)
0	0.0	0.0	0.0	0.0
2,000	- 283.0	- 46.4	- 64.8	- 55.6
5,000	- 707.0	- 130.6	- 162.5	- 146.6
10,000	-1414.4	- 266.1	- 305.8	- 286.0
15,000	-2122.0	- 412.2	- 448.0	- 430.1
20,000	-2829.0	- 562.2	- 591.2	- 576.7
25,000	-3536.0	- 734.5	- 746.1	- 740.3
30,000	-4243.0	- 904.8	- 899.9	- 902.4
35,000	-4950.0	-1092.5	-1066.4	-1079.5
40,000	-5658.0	-1301.6	-1255.1	-1278.4
45,000	-6365.0	-1555.1	-1478.7	-1517.0
50,000	-7072.0	-2027.4	-1900.6	-1964.0
54,000	-7640.0	failure		

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.10 Cylinder Compressive Tests for Specimen 2

Cylinder Size (in)	Cylinder No.	Age (days)	Load (lb)	Comp. Stress (psi)	Average Comp. Stress (psi)
3 x 6	1	3	44,000	6,223	6,223
3 x 6	2	3	44,000	6,223	
3 x 6	3	52	54,500	7,708	7,560
3 x 6	4	52	53,000	7,496	
3 x 6	5	52	55,500	7,850	
3 x 6	6	52	52,500	7,426	
3 x 6	7	52	55,000	7,779	
3 x 6	8	52	51,500	7,284	
3 x 6	9	52	51,500	7,284	
3 x 6	10	52	54,000	7,638	
3 x 6	11	52	53,500	7,567	
6 x 12	12	52	240,000	8,488	8,500

Casting Date: 6/08/84
Testing Date: 7/31/84

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.11 Load-Strain Data for Flexural Test of Structural Specimen 3

P_1 Axial Load Machine Load (lb)	Ram Preaaure (psi)	P_2 Eccentric Ram Load (lb)	Strain Reading in (με)									
			Gage #1	Gage #2	Gage #3	Gage #4	Gage #5	Gage #6	Gage #7	Gage #8	Gage #9	Gage #10
1,000	0.0	0	- 4	- 4	0.0	- 9.6	- 3.8	- 1.9	- 2.9	- 2.9	0.0	- 0.9
7,500	0.0	0	-27	-27	- 33.8	- 55.1	- 53.2	- 45.4	- 38.7	- 29.9	- 21.2	- 17.4
13,500	52.5	346	0.0	0.0	- 26.1	- 89.9	- 99.6	- 134.5	- 157.7	- 123.8	- 73.5	- 44.5
21,500	100.0	638	0.0	0.0	- 33.8	- 129.6	- 161.6	- 230.3	- 288.3	- 232.2	- 149.0	- 99.6
30,000	145.0	914	0.0	0.0	- 36.7	- 165.4	- 219.6	- 315.4	- 407.4	- 330.9	- 214.8	- 143.2
40,000	197.5	1236	0.0	0.0	- 56.1	- 225.4	- 311.6	- 435.4	- 555.4	- 447.0	- 295.1	- 191.6
50,000	230.0	1435	0.0	0.0	- 72.5	- 283.5	- 395.8	- 548.7	- 699.6	- 557.4	- 368.7	- 239.9
60,500	300.0	1865	0.0	0.0	- 98.7	- 357.0	- 499.3	- 680.3	- 862.2	- 679.3	- 450.9	- 287.4
70,000	350.0	2171	0.0	0.0	-119.9	- 423.8	- 591.2	- 798.3	-1009.3	- 794.5	- 525.4	- 331.9
80,000	392.5	2432	0.0	0.0	-145.1	- 497.4	- 694.8	- 925.1	-1162.2	- 916.4	- 608.7	- 380.3
90,000	437.5	2708	0.0	0.0	-171.2	- 574.8	- 798.3	-1049.9	-1319.9	-1040.3	- 691.9	- 429.6
100,000	485.0	2999	0.0	0.0	-203.2	- 668.7	- 927.0	-1205.8	-1508.7	-1197.0	- 794.5	- 489.6
107,000	507.5	3137	0.0	0.0	-215.8	- 718.0	- 998.7	-1288.0	-1616.1	-1286.1	- 849.0	- 516.7
114,000	535.0	3306	0.0	0.0	-231.2	- 765.4	-1064.5	-1360.6	-1711.9	-1368.3	- 900.9	- 545.8
125,700	565.0	3490	0.0	0.0	-266.1	- 868.0	-1203.8	-1514.5	-1916.1	-1549.3	-1016.1	- 612.5
130,000	590.0	3643	0.0	0.0	-283.5	- 923.2	-1275.4	-1588.0	-2015.8	-1640.3	-1074.1	- 646.4
134,600	595.0	3674	0.0	0.0	-303.8	- 986.1	-1360.6	-1680.9	-2135.8	-1752.5	-1147.7	- 689.9
140,000	605.0	3735	0.0	0.0	-323.2	-1041.2	-1435.1	-1768.0	-2226.7	-1848.3	-1207.7	- 723.8
144,000	605.0	3735	0.0	0.0	-346.4	-1112.8	-1529.0	-1887.0	-2337.0	-1963.5	-1280.3	- 765.4
150,000	615.0	3797	0.0	0.0	-373.5	-1188.3	-1631.6	-2029.3	-2444.5	-2099.0	-1368.3	- 816.7
156,000	620.0	3728	0.0	0.0	-395.8	-1266.7	-1745.8	-2182.2	-2530.6	-2249.9	-1468.0	- 876.7
159,000	555.0	3430	0.0	0.0	-420.9	-1405.1	-2052.5	-2505.4	-2771.4	-2579.9	-1713.8	-1022.9
163,000	480.0	2970	failure									

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.12 Load and Average Strain at Each Level, for Flexural Test of Specimen 3

P_1		P_2	Strain Reading (με)				
Axial Load Machine Load (lb)	Ram Pressure (psi)	Eccentric Load Ram Load (lb)	Average Gage #1 and #2 at the Surface	Average Gage #3 and #10 at 1.25" Depth	Average Gage #4 and #9 at 2.5" Depth	Average Gage #5 and #8 at 3.75" Depth	Average Gage #6 and #7 at 5" Oepth
1,100	0.0	0	- 4	- 0.5	- 4.8	- 3.40	- 2.4
7,500	0.0	0	-27	- 25.6	- 38.2	- 41.55	- 40.1
13,500	52.5	346	0.0	- 35.3	- 81.1	- 111.70	- 146.1
21,500	100.0	638	0.0	- 66.7	- 139.3	- 196.90	- 259.3
30,000	145.0	914	0.0	- 90.0	- 190.1	- 275.30	- 361.4
40,000	197.5	1236	0.0	-123.9	- 260.3	- 379.30	- 495.4
50,000	230.0	1435	0.0	-156.2	- 326.1	- 476.60	- 624.2
60,500	300.0	1865	0.0	-193.1	- 404.0	- 589.30	- 771.3
70,000	350.0	2171	0.0	-225.9	- 474.6	- 692.20	- 903.8
80,000	392.5	2432	0.0	-262.7	- 553.1	- 805.60	-1043.7
90,000	437.5	2708	0.0	-300.4	- 633.4	- 919.30	-1184.9
100,000	485.0	2999	0.0	-346.4	- 731.6	-1062.00	-1357.3
107,000	507.5	3137	0.0	-366.3	- 783.8	-1142.40	-1452.1
114,000	535.0	3306	0.0	-388.5	- 833.2	-1216.40	-1536.3
125,700	565.0	3490	0.0	-439.3	- 920.1	-1376.60	-1715.3
130,000	590.0	3643	0.0	-465.0	- 998.7	-1457.90	-1801.9
134,600	595.0	3674	0.0	-496.9	-1066.9	-1556.60	-1908.4
140,000	605.0	3735	0.0	-523.5	-1124.5	-1641.70	-1997.4
144,000	605.0	3735	0.0	-555.9	-1196.6	-1746.30	-2112.0
150,000	615.0	3797	0.0	-595.1	-1278.3	-1865.30	-2236.9
156,000	620.0	3827	0.0	-636.3	-1367.4	-1997.90	-2356.4
159,000	555.0	3430	0.0	-721.9	-1559.5	-2316.20	-2638.4
163,000	480.0	2970		failure			

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.13 Cylinder Stress-Strain Data for Specimen 3 (Cyl. No. 8)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Avg. Long. Strain (με)	Strain Reading in Gage #3 (με)	Strain Reading in Gage #4 (με)	Avg. Trans. Strain (με)	Poisson's Ratio
0	0.0	0.9	1.9	1.4	0.9	22.6	11.80	0
2,000	- 283.0	- 65.8	- 31.9	- 48.9	13.7	- 6.8	3.45	0
5,000	- 707.0	- 222.5	- 68.7	- 145.6	18.7	19.6	19.20	0.1320
10,000	-1414.0	- 407.4	- 161.6	- 284.5	30.5	61.0	45.80	0.1608
15,000	-2122.0	- 574.8	- 282.5	- 428.7	44.2	94.5	69.35	0.1618
20,000	-2829.0	- 745.1	- 419.9	- 582.5	60.0	126.0	93.00	0.1600
22,000	-3111.7	- 890.3	- 548.7	- 719.5	73.8	153.5	113.70	0.1580
25,000	-3536.0	- 943.5	- 595.1	- 769.3	79.7	166.3	123.00	0.1600
30,000	-4243.0	-1138.0	- 780.9	- 959.5	101.3	203.7	152.50	0.1589
35,000	-4950.0	-1373.2	- 991.9	-1182.6	126.0	248.0	187.00	0.1581
40,000	-5658.0	-1692.5	-1261.9	-1477.2	155.5	301.2	228.40	0.1546
43,000	-6082.0	-2048.7	-1523.2	-1786.0	184.0	364.2	274.10	0.1535
46,000	-6506.0	-2619.6	-1915.1	-2267.4	245.1	307.1	276.10	0.1218
46,500	-6577.0	failure						

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.14 Cylinder Stress-Strain Data for Specimen 3 (Cylinder No. 7)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Average (με)
0	0.0	- 1.9	0.9	0.0
2,000	- 283.0	- 58.0	- 47.4	- 52.7
5,000	- 707.0	- 153.8	- 134.5	- 144.2
10,000	-1414.4	- 273.8	- 252.5	- 263.2
15,000	-2122.0	- 416.1	- 391.9	- 404.0
20,000	-2829.0	- 581.6	- 558.3	- 570.0
25,000	-3536.0	- 738.3	- 712.2	- 725.3
30,000	-4243.0	- 927.0	- 890.3	- 908.7
35,000	-4950.0	-1141.9	-1089.6	-1115.8
40,000	-5658.0	-1417.7	-1351.9	-1384.8
43,000	-6082.0	-1644.1	-1573.5	-1608.8
46,000	-6506.0	failure		

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.15 Cylinder Compressive Tests for Specimen 3

Cylinder Size (in)	Cylinder No.	Age (days)	Load (lb)	Comp. Stress (psi)	Average Comp. Stress (psi)
3 x 6	1	3	45,800	6,478	6,372
3 x 6	2	3	44,300	6,266	
3 x 6	3	52	52,000	7,355	6,648
3 x 6	4	52	51,000	7,214	
3 x 6	5	52	49,000	6,931	
3 x 6	6	52	46,000	6,506	
3 x 6	7	52	46,000	6,506	
3 x 6	8	52	46,500	6,577	
6 x 12	9	52	265,000	9,377	9,400

Casting Date: 6/16/84
Testing Date: 7/08/84

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.16 Cylinder Stress-Strain Data for Specimen 4 (Cyl. No. 11)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Avg. Long. Strain (με)	Strain Reading in Gage #3 (με)	Strain Reading in Gage #4 (με)	Avg. Trans. Strain (με)	Poisson's Ratio
0	0	2.9	1.9	0.0	2.9	0.0	0.0	0
5,000	- 707	- 55.1	- 89.0	- 72.1	33.4	11.8	22.6	0.31350
10,000	- 1,414	- 151.9	- 209.0	- 180.5	52.1	23.6	37.9	0.20990
15,000	- 2,122	- 242.9	- 315.4	- 279.2	67.9	36.4	52.2	0.18680
20,000	- 2,829	- 329.0	- 406.4	- 368.2	80.7	46.2	63.5	0.17230
25,000	- 3,536	- 430.6	- 506.1	- 468.4	94.5	59.0	76.8	0.16390
30,000	- 4,243	- 528.3	- 607.7	- 568.0	108.2	73.8	91.0	0.16020
35,000	- 4,950	- 626.1	- 705.4	- 665.8	126.0	87.6	106.8	0.16040
39,000	- 5,516	- 715.4	- 795.4	- 755.3	138.8	99.4	119.1	0.15769
43,000	- 6,082	- 805.1	- 881.6	- 843.4	153.5	107.3	130.4	0.15460
47,000	- 6,648	- 899.9	- 972.5	- 936.2	171.2	119.1	145.2	0.15500
51,000	- 7,214	-1008.3	-1073.2	-1040.8	190.9	130.9	160.9	0.15460
55,000	- 7,779	-1116.7	-1174.8	-1145.8	216.5	141.7	179.1	0.15630
59,000	- 8,345	-1233.8	-1286.1	-1260.0	243.1	158.4	200.8	0.15930
62,000	- 8,769	-1337.4	-1386.7	-1362.1	271.7	167.0	219.4	0.16100
65,000	- 9,194	-1438.0	-1486.4	-1462.2	305.1	181.1	243.1	0.16630
68,000	- 9,618	-1561.9	-1610.3	-1586.1	349.4	194.9	272.2	0.17160
70,000	- 9,901	-1677.0	-1721.6	-1699.3	392.7	210.6	301.7	0.17750
72,000	-10,184	-1804.8	-1850.3	-1827.6	463.6	232.3	348.0	0.19040
73,500	-10,396	-1983.8	-2015.8	-1999.8	640.8	268.7	454.8	0.24880

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.17 Cylinder Stress-Strain Data for Specimen 4 (Cyl. No. 12)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Average (με)
0	0.0	0.0	0.9	
2,000	- 283.0	- 54.1	- 32.9	- 43.5
5,000	- 707.0	- 89.9	- 98.7	- 94.3
10,000	-1414.7	- 131.6	- 239.0	- 185.3
15,000	-2122.0	- 179.0	- 359.9	- 269.5
20,000	-2829.0	- 257.4	- 460.6	- 359.0
25,000	-3536.0	- 345.4	- 554.5	- 450.0
30,000	-4243.0	- 431.6	- 648.3	- 540.0
35,000	-4950.0	- 518.7	- 746.1	- 632.4
40,000	-5658.0	- 619.3	- 857.4	- 738.4
43,000	-6082.0	- 688.0	- 931.9	- 810.0
46,000	-6577.0	- 741.2	- 995.8	- 868.5
51,000	-7214.0	- 841.9	-1112.8	- 977.4
55,000	-7779.0	- 933.8	-1221.2	-1077.5
59,000	-8345.0	-1030.6	-1341.2	-1185.9
62,000	-8769.0	-1111.9	-1443.8	-1277.9
65,000	-9194.0	-1199.9	-1571.6	-1385.8
68,000	-9618.0	-1306.4	-1742.8	-1524.6
70,000	-9901.0	-1785.4	-2557.7	-2171.6
	failure			

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.18 Cylinder Stress-Strain Data for Specimen 4 (Cyl. No. 13)

Load (lb)	Stress (psi)	Strain Reading in Gage #1 (με)	Strain Reading in Gage #2 (με)	Average (με)
0	0	0.9	0.9	0.90
2,000		- 10.6	- 2.9	- 6.75
10,000	- 354	- 56.1	- 28.0	- 42.05
20,000	- 708	- 98.7	- 68.7	- 83.70
30,000	-1062	- 143.2	-102.5	- 122.85
40,000	-1415	- 194.5	-128.7	- 161.60
50,000	-1769	- 247.7	-153.8	- 200.75
60,000	-2123	- 299.9	-180.9	- 240.40
70,000	-2477	- 353.2	-209.0	- 281.10
80,000	-2831	- 408.3	-241.9	- 325.10
90,000	-3185	- 464.5	-273.8	- 369.15
100,000	-3539	- 524.5	-308.7	- 416.60
110,000	-3892	- 580.6	-340.6	- 460.60
120,000	-4246	- 636.7	-373.5	- 505.10
130,000	-4600	- 691.9	-403.5	- 547.70
140,000	-4954	- 746.1	-430.6	- 588.35
150,000	-5308	- 811.9	-469.3	- 640.60
160,000	-5662	- 872.9	-502.2	- 687.55
170,000	-6016	- 935.8	-537.0	- 736.40
180,000	-6369	- 998.7	-572.9	- 785.80
190,000	-6723	-1056.7	-607.7	- 832.20
200,000	-7077	-1120.6	-645.4	- 883.00
210,000	-7431	-1184.5	-688.0	- 936.25
220,000	-7785	-1338.3	-725.8	-1032.05
230,000	-8139	failure		

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.19 Cylinder Compressive Tests for Specimen 4

Cylinder Size (in)	Cylinder No.	Age (days)	Load (lb)	Comp. Stress (psi)	Average Comp. Stress (psi)
3 x 6	1	3	45,000	6,365	6,418.0
3 x 6	2	3	45,750	6,471	
3 x 6	3	52	61,000	8,628	
3 x 6	4	52	72,000	10,184	
3 x 6	5	52	72,800	10,297	
3 x 6	6	52	71,800	10,155	
3 x 6	7	52	74,400	10,523	9,678.6
3 x 6	8	52	62,000	8,769	9,680.0
3 x 6	9	52	62,000	8,769	
3 x 6	10	52	64,800	9,165	
3 x 6	11	52	73,500	10,396	
3 x 6	12	52	70,000	9,900	
6 x 12	13	52	230,000	8,139	8,140.0*

Casting Date: 8/23/84
Testing Date: 8/14/84

1 psi = 6.89 kpa, 1 lb. = 4.45 N

* Cylinder was damaged.

Table 5.20 Load and Ultimate Strength Factors for Specimen 1

P_1 Axial Load (machine load) (lb)	P_2 Minor Thrust (lb)	ε_c at Comp. Face (ε_c)	k_2	k_3*	k_1k_3	$k_1 = \frac{k_1k_3}{k_3}$	$\frac{k_2}{k_1k_3}$	f_c** (psi)	$\beta_1 = \frac{k_1k_3}{0.85}$
0	0	0.0	0.000	0.0000	0.0000	0.0000	0.000	0	0.0000
5,000	193	84.4	0.318	0.0072	0.0210	2.9000	14.814	+ 665	0.0247
22,500	699	- 89.3	0.352	0.1400	0.0959	0.6846	3.676	- 725	0.1128
40,000	1251	- 334.0	0.351	0.2794	0.1705	0.6101	2.062	- 2550	0.2006
59,500	1987	- 674.3	0.342	0.4314	0.2541	0.5890	1.345	- 5000	0.2989
79,500	2662	-1020.0	0.341	0.5737	0.3395	0.5918	1.005	- 7175	0.3994
98,500	3582	-1530.1	0.328	0.7196	0.4128	0.5736	0.778	- 9000	0.4856
118,500	3858	-1953.4	0.346	0.8236	0.5056	0.6139	0.683	-10325	0.5948
120,000	3858	failure							

$$^{*}k_3 = \frac{\text{Average } f_c \text{ (Table 5.23)}}{f_c'} \frac{7972}{9680} = 0.824$$ 1 psi = 6.89 kpa, 1 lb. = 4.45 N

**f_c values are based on cylinder stress-strain curve (Figure 5.9)

Table 5.21 Load and Ultimate Strength Factors for Specimen 2

P_1 Axial Load (machine load) (lb)	P_2 Minor Thrust (lb)	ε_c at Comp. Face (ε_c)	k_2	k_3*	k_1k_3	$k_1 = \frac{k_1k_3}{k_3}$	$\frac{k_2}{k_1k_3}$	f_c** (psi)	$\beta_1 = \frac{k_1k_3}{0.85}$
0	0	0.0	0.000	0.00000	0.000	0.00000	0.000	0	0.0000
10,000	162	- 100.6	0.422	0.07530	0.042	0.58290	10.047	- 850	0.0494
20,700	576	- 243.4	0.367	0.16940	0.088	0.54290	4.178	- 1900	0.1035
30,100	883	- 355.5	0.360	0.24618	0.128	0.54350	2.815	- 2725	0.1500
41,000	1251	- 498.2	0.355	0.34050	0.175	0.53720	2.033	- 3750	0.2050
50,000	1558	- 605.3	0.352	0.41270	0.213	0.53940	1.652	- 4475	0.2506
59,900	1865	- 733.5	0.352	0.48900	0.255	0.54490	1.379	- 5400	0.3000
70,000	2171	- 864.6	0.353	0.56730	0.298	0.54910	1.182	- 6200	0.3506
80,000	2478	- 998.7	0.353	0.63760	0.341	0.55900	1.035	- 7000	0.4012
90,000	2754	-1147.2	0.355	0.70880	0.383	0.56480	0.925	- 7800	0.4506
100,000	3061	-1307.9	0.354	0.77100	0.426	0.57760	0.832	- 8600	0.5012
109,000	3245	-1439.5	0.359	0.83960	0.466	0.58020	0.771	- 9150	0.5482
119,500	3459	-1614.6	0.362	0.89810	0.508	0.59120	0.713	- 9750	0.5976
129,500	3643	-1780.1	0.366	0.94310	0.550	0.60910	0.665	-10125	0.6471
135,000	3676	-1889.0	0.370	0.95220	0.573	0.62900	0.646	-10250	0.6741
139,800	3717	-1982.4	0.373	0.95440	0.593	0.64940	0.629	-10400	0.6976
145,000	3766	-2115.0	0.376	0.95420	0.615	0.67360	0.612	-10515	0.7235
149,800	3797	-2245.6	0.379		0.635		0.597	-10575	0.7471
154,000	3827	-2390.8	0.381		0.652		0.584	-10600	0.7671
160,000	3459	-2687.9	0.396		0.675		0.587	-10350	0.7941
167,000	3122	failure							

$$^{*}k_3 = \frac{\text{Average } f_c \text{ (Table 5.24)}}{f'_c} = \frac{9261}{9680} = 0.9567 \qquad 1 \text{ psi} = 6.89, \quad 1 \text{ lb.} = 4.45 \text{ N}$$

**f_c values are based on cylinder stress-strain curve (Figure 5.9)

Table 5.22 Load and Ultimate Strength Factors for Specimen 3

P_1 Axial Load (machine load) (lb)	P_2 Minor Thrust (lb)	ε_c at Comp. Face (ε_c)	k_2	k_3*	k_1k_3	$k_1 = \frac{k_1k_3}{k_3}$	$\frac{k_2}{k_1k_3}$	f_c** (psi)	$\beta_1 = \frac{k_1k_3}{0.85}$
0	0	0.0	0.000	0.0000	0.000	0.0000	0.000	0	0.0000
13,500	346	- 146.1	0.378	0.1069	0.057	0.5331	6.600	- 940	0.0671
21,500	638	- 259.3	0.359	0.1771	0.091	0.5139	3.920	- 2100	0.1071
30,000	914	- 361.4	0.355	0.2435	0.128	0.5257	2.780	- 2750	0.1506
40,000	1236	- 495.4	0.353	0.3279	0.170	0.5185	2.070	- 3735	0.2000
50,000	1435	- 624.2	0.363	0.4037	0.213	0.5276	1.710	- 4510	0.2506
60,500	1865	- 771.3	0.353	0.4923	0.258	0.5241	1.370	- 5900	0.3035
70,000	2171	- 903.8	0.353	0.5689	0.298	0.5238	1.180	- 6460	0.3506
80,000	2432	-1043.7	0.355	0.6387	0.340	0.5323	1.040	- 7050	0.4000
90,000	2708	-1184.9	0.357	0.7098	0.383	0.5396	0.932	- 8000	0.4506
100,000	2999	-1357.3	0.357	0.8099	0.426	0.5259	0.840	- 8775	0.5012
107,000	3137	-1452.1	0.360	0.8555	0.455	0.5319	0.792	- 9160	0.5353
114,000	3306	-1536.3	0.362	0.9277	0.485	0.5256	0.747	- 9475	0.5706
125,700	3490	-1715.3	0.368	0.9284	0.534	0.5752	0.689	- 9985	0.6282
130,000	3643	-1801.9	0.366	0.9452	0.552	0.6178	0.664	-10120	0.6494
134,600	3674	-1908.4	0.370	0.9395	0.571	0.6078	0.647	-10270	0.6718
140,000	3735	-1997.4	0.373	0.9650	0.594	0.6155	0.627	-10425	0.6990
144,000	3735	-2112.0	0.376	0.9986	0.610	0.6109	0.616	-10510	0.7176
150,000	3797	-2236.9	0.379		0.636		0.596	-10540	0.7482
156,000	3827	-2356.4	0.383		0.660		0.579	-10580	0.7765
159,000	3430	-2638.4	0.397		0.671		0.591	-10440	0.7894
163,000	2970	failure							

$$^{*}k_3 = \frac{\text{Average } f_c \text{ (Table 5.25)}}{f'_c} = \frac{9433}{9680} = 0.9745$$

1 psi = 6.89, 1 lb. = 4.45 N

**f_c values are based on cylinder stress-strain curve (Figure 5.9)

Table 5.23 Load-Stress Data for Flexural Test of Specimen 1, Using Equations (4.1) and (4.2)

Major Thrust P_1 (lb)	Minor Thrust P_2 (lb)	Strain at Comp. Face ($\mu\varepsilon$)	$^*f_o$ (psi)	$^{**}m_o$ (psi)	$\frac{df_o}{d\varepsilon_c}$	$\frac{dm_o}{d\varepsilon_c}$	$f_c = \varepsilon_c \frac{df_o}{d\varepsilon_c} + f_o$ Eq. (4.1) (psi)	$f_c = \varepsilon_c \frac{dm_o}{d\varepsilon_c} + 2m_o$ Eq. (4.2) (psi)	f_c Average of Eq. (4.1) and Eq. (4.2) (psi)
0	0	0.0	0	0	4.28	2.73	0	0	0
5,000	193	84.4	208	142	4.58	2.91	+ 179	- 38	+ 70
22,500	699	- 89.3	928	601	3.97	2.55	-1282	-1430	-1356
40,000	1251	- 334.0	1650	1070	2.93	1.92	-2629	-2782	-2705
59,500	1987	- 674.3	2459	1619	2.35	1.58	-4047	-4305	-4176
79,500	2662	-1020.0	3286	2165	2.05	1.37	-5373	-5732	-5553
98,500	3582	-1530.1	4083	2744	1.49	1.11	-6746	-7185	-6966
118,500	3858	-1953.4	4894	3203	1.74	0.89	-7798	-8145	-7972
120,000	3858	failure							

$^*f_o = \frac{P_1 + P_2}{bc}$ $\quad$ $^{**}m_o = \frac{P_1a_1 + P_2a_2}{bc^2}$ $\quad$ $bc = 25$ in^2, $a_1 = 2.5$ in., $a_2 = 27$ in., $c = 5$ in.,

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.24 Load-Stress Data for Flexural Test of Specimen 2, Using Equations ((4.1) and (4.2)

Major Thrust P_1 (lb)	Minor Thrust P_2 (lb)	Strain at Comp. Face ($\mu\varepsilon$)	$^*f_o$ (psi)	$^{**}m_o$ (psi)	$\frac{df_o}{d\varepsilon_c}$	$\frac{dm_o}{d\varepsilon_c}$	$f_c = \varepsilon_c \frac{df_o}{d\varepsilon_c} + f_o$ Eq. (4.1) (psi)	$f_c = \varepsilon_c \frac{dm_o}{d\varepsilon_c} + 2m_o$ Eq. (4.2) (psi)	f_c Average of Eq. (4.1) and Eq. (4.2) (psi)
0	0	0.0	0	0	3.67	2.280	0	0	0
10,000	162	- 100.6	406	235	3.54	2.240	- 763	- 695	- 729
20,700	576	- 243.4	851	538	3.36	2.190	-1670	-1609	-1640
30,100	883	- 355.5	1239	793	3.28	2.180	-2406	-2360	-2383
41,000	1251	- 498.2	1690	1090	3.30	2.170	-3333	-3259	-3296
50,000	1558	- 605.3	2062	1337	3.25	2.120	-4030	-3959	-3995
59,900	1865	- 733.5	2471	1601	3.22	2.090	-4831	-4734	-4782
70,000	2171	- 864.6	2887	1869	3.07	1.970	-5539	-5443	-5491
80,000	2478	- 998.7	3299	2135	2.91	1.870	-6208	-6136	-6172
90,000	2754	-1147.2	3710	2395	2.79	1.760	-6910	-6813	-6861
100,000	3061	-1307.9	4122	2661	2.64	1.640	-7582	-7463	-7522
109,500	3245	-1439.5	4510	2891	2.58	1.570	-8217	-8037	-8127
119,500	3459	-1614.6	4918	3137	2.42	1.420	-8824	-8563	-8694
129,500	3643	-1780.1	5326	3377	2.22	1.250	-9281	-8978	-9129
135,000	3674	-1889.0	5547	3494	2.01	1.110	-9347	-9086	-9217
139,000	3717	-1982.4	5741	3599	1.82	0.980	-9343	-9136	-9239
145,000	3766	-2115.0	5951	3713	1.57	0.840	-9262	-9213	-9237
149,800	3797	-2245.6	6144	3816	1.30	0.650	-9058	-9090	-9074
154,000	3827	-2390.8	6313	3907	1.04	0.410	-8789	-8804	-8796
160,000	3459	-2687.9	6538	3947	0.50	0.066	-7879	-7718	-7799
167,000	failure								

$^*f_o = \frac{P_1 + P_2}{bc}$ $^{**}m_o = \frac{P_1 a_1 + P_2 a_2}{bc^2}$ $bc = 25\ \text{in}^2$, $a_1 = 2.5$ in., $a_2 = 27$ in., $c = 5$ in.,

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.25 Load-Stress Data for Flexural Test of Specimen 3, Using Equations (4.1) and (4.2)

Major Thrust P_1 (lb)	Minor Thrust P_2 (lb)	Strain at Comp. Face ($\mu\varepsilon$)	$^*f_o$ (psi)	$^{**}m_o$ (psi)	$\frac{df_o}{d\varepsilon_c}$	$\frac{dm_o}{d\varepsilon_c}$	$f_c = \varepsilon_c \frac{df_o}{d\varepsilon_c} + f_o$ Eq. (4.1) (psi)	$f_c = \varepsilon_c \frac{dm_o}{d\varepsilon_c} + 2m_o$ Eq. (4.2) (psi)	f_c Average of Eq. (4.1) and Eq. (4.2) (psi)
0	0	0.0	0	0	3.650	2.310	0	0	0
13,500	346	- 146.1	554	345	3.450	2.210	-1057	-1013	-1035
21,500	638	- 259.3	886	568	3.290	2.140	-1738	-1690	-1714
30,000	914	- 361.4	1237	797	3.160	2.050	-2378	-2335	-2357
40,000	1236	- 495.4	1649	1067	3.150	2.030	-3210	-3139	-3174
50,000	1436	- 624.2	2057	1310	3.050	1.980	-3962	-3854	-3908
60,500	1865	- 771.3	2495	1613	2.995	1.940	-4805	-4725	-4765
70,000	2171	- 903.8	2887	1869	2.950	1.910	-5549	-5465	-5507
80,000	2432	-1043.7	3297	2125	2.820	1.790	-6244	-6123	-6183
90,000	2708	-1184.9	3708	2385	2.730	1.710	-6943	-6798	-6871
100,000	2999	-1357.0	4120	2648	2.850	1.760	-7994	-7686	-7840
107,000	3137	-1452.1	4405	2818	2.800	1.690	-8469	-8093	-8281
114,000	3306	-1536.3	4692	2994	2.930	1.750	-9189	-8674	-8932
125,700	3490	-1715.3	5168	3268	2.300	1.360	-9105	-8868	-8987
130,000	3643	-1801.5	5346	3387	2.170	1.260	-9261	-9038	-9150
134,600	3674	-1908.4	5531	3486	1.910	1.070	-9172	-9015	-9094
140,000	3735	-1997.4	5749	3607	1.860	1.000	-9474	-9211	-9342
144,000	3735	-2112.0	5909	3687	1.880	0.997	-9853	-9480	-9666
150,000	3797	-2236.9	6152	3820	1.520	0.750	-9558	-9321	-9439
156,000	3827	-2356.4	6393	3947	1.110	0.440	-9000	-8931	-8965
159,000	3430	-2638.4	6497	3921	0.124	0.294	-6825	-7067	-6946
163,000	2970	failure							

$^*f_o = \frac{P_1 + P_2}{bc}$ $\quad$ $^{**}m_o = \frac{P_1 a_1 + P_2 a_2}{bc^2}$ $\quad$ $bc = 25$ in^2, $a_1 = 2.5$ in., $a_2 = 27$ in., $c = 5$ in.,

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.26 Load and Stress Data for Flexural Test of Specimen 1, Using Eq. 4.1 and 4.2 and Cylinder Stress-Strain Curve

Major Thrust P_1 (lb)	Minor Thrust P_2 (lb)	Strain at Compression Face ε_c (με)	f_c Average of Eq. (4.1) and Eq. (4.2) (psi)	f_c Reading Using Cylinder Stress-Strain Curve (psi)
0	0	0.0	0	0
5,000	193	84.4	70	665
22,500	699	- 89.3	-1356	- 725
40,000	1251	- 334.0	-2705	- 2550
59,500	1987	- 674.3	-4176	- 5000
79,500	2662	-1020.0	-5553	- 7175
98,500	3582	-1530.1	-6966	- 9000
118,500	3858	-1953.4	-7972	-10325
120,000	3858	failure		

1 psi = 6.89 kpa, 1 lb. = 4.45 N

Table 5.27 Load and Stress Data for Flexural Test of Specimen 2, Using Eqs. 4.1 and 4.2 and Cylinder Stress-Strain Curve

Major Thrust P_1 (lb)	Minor Thrust P_2 (lb)	Strain at Compression Face ε_c ($\mu\varepsilon$)	f_c Average of Eq. (4.1) and Eq. (4.2) (psi)	f_c Reading Using Cylinder Stress-Strain Curve (psi)
0	0	0.0	0	0
10,000	162	- 100.6	- 729	- 850
20,700	576	- 243.4	-1640	- 1900
30,100	883	- 355.5	-2383	- 2725
41,000	1251	- 498.2	-3296	- 3750
50,000	1558	- 605.3	-3995	- 4475
59,900	1865	- 733.5	-4782	- 5400
70,000	2172	- 864.6	-5491	- 6200
80,000	2478	- 998.7	-6172	- 7000
90,000	2754	-1147.2	-6861	- 7800
100,000	3061	-1307.9	-7522	- 8600
109,500	3245	-1439.5	-8127	- 9150
119,500	3459	-1614.6	-8694	- 9750
129,500	3643	-1780.1	-9129	-10125
135,000	3674	-1889.0	-9217	-10250
139,800	3717	-1982.4	-9239	-10400
145,000	3766	-2115.0	-9237	-10515 *
149,800	3797	-2245.6	-9074	-10575 *
154,000	3827	-2390.8	-8796	-10600 *
160,000	3459	-2687.9	-7799	-10350 *
167,000	failure			

1 psi = 6.89 kpa, 1 lb. = 4.45 N

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[*] These stress values were obtained by extending the curve in Fig. 5.8.

Table 5.28 Load and Stress Data for Flexural Test of Specimen 3, Using Eqs. 4.1 and 4.2 and Cylinder Stress-Strain Curve

Major Thrust P_1 (lb)	Minor Thrust P_2 (lb)	Strain at Compression Face ε_c ($\mu\varepsilon$)	f_c Average of Eq. (4.1) and Eq. (4.2) (psi)	f_c Reading Using Cylinder Stress-Strain Curve (psi)
0	0	0.0	0	0
13,500	346	− 146.1	−1035	− 940
21,500	638	− 259.3	−1714	− 2100
30,000	914	− 361.4	−2537	− 2750
40,000	1236	− 495.4	−3174	− 3735
50,000	1436	− 624.2	−3908	− 4510
60,500	1865	− 771.3	−4765	− 5900
70,000	2171	− 903.8	−5507	− 6460
80,000	2432	−1043.7	−6183	− 7050
90,000	2708	−1184.9	−6871	− 8000
100,000	2999	−1357.3	−7840	− 8775
107,000	3137	−1452.1	−8281	− 9160
114,000	3306	−1536.3	−8932	− 9475
125,700	3490	−1715.3	−8987	− 9985
130,000	3643	−1801.5	−9150	−10120
134,600	3674	−1908.4	−9094	−10270
140,000	3735	−1997.4	−9342	−10425
144,000	3735	−2112.0	−9666	−10510*
150,000	3797	−2236.9	−9439	−10540*
156,000	3827	−2356.4	−8965	−10580*
159,000	3430	−2429.5	−6946	−10440*
163,000	2970	failure		

1 psi = 6.89 kpa, 1 lb. 4.45 N

*These stress values were obtained by extending the curve in Fig. 5.8.

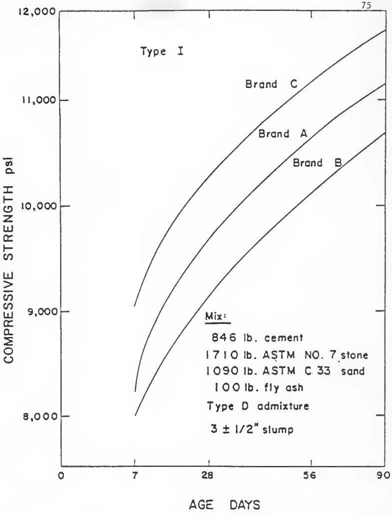


Figure 2.1: Effect of Various Brands of Type I Cement on Concrete Compressive Strength (5)

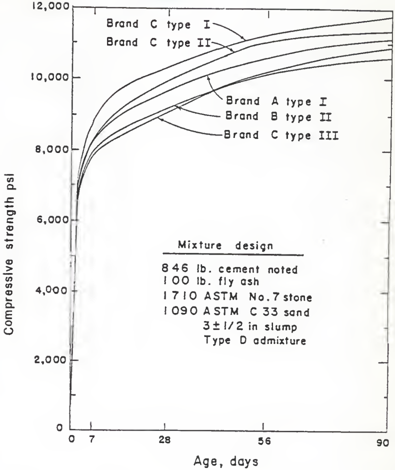


Figure 2.2: Effect of Various Cements on Concrete Compressive Strength (6)

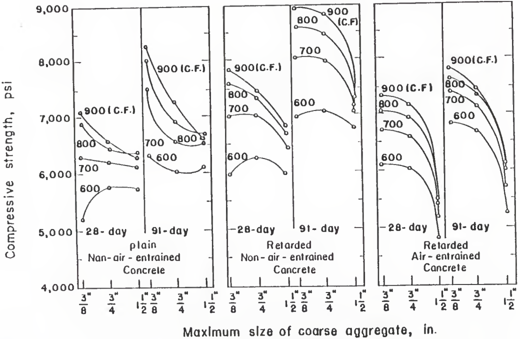


Figure 2.3: Effect of Size of Coarse Aggregate on Compressive Strength in Different Types of Concrete (adapted from Ref. 3)

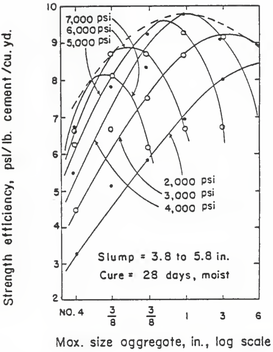


Figure 2.4: Maximum Size Aggregate for Strength Efficiency Envelope (14)

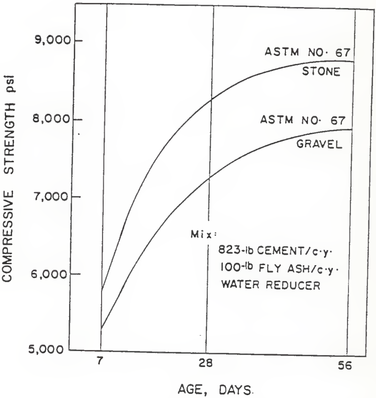


Figure 2.5: Compressive Strength of Concrete Using Two Sizes and Types of Coarse Aggregate for 7,500 psi Concrete (12)

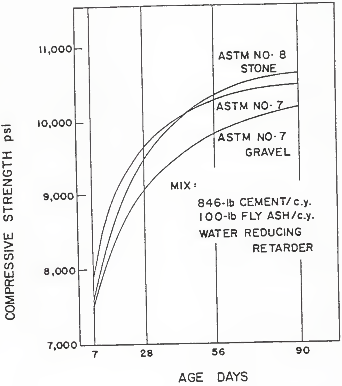


Figure 2.6: Compressive Strength of High-Strength Concrete Using Three Sizes and Types of Coarse Aggregate

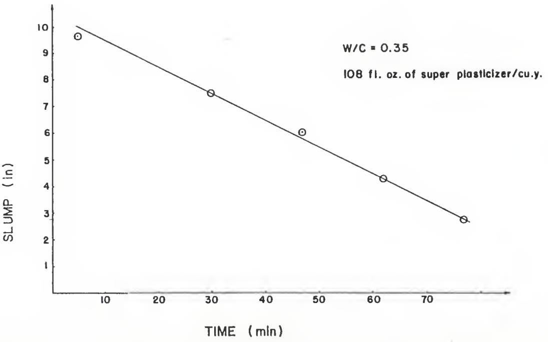


Figure 2.7 : Slump vs. Time When Using Superplasticizer (25)

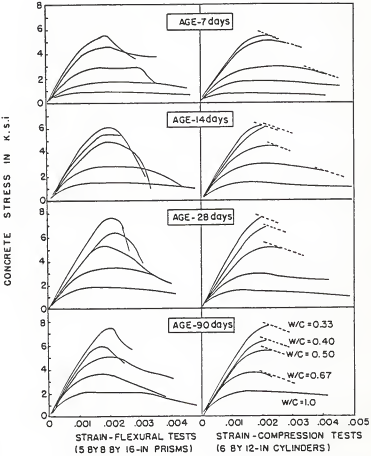


Figure 4.1: Concrete Stress-Strain Relations (17)

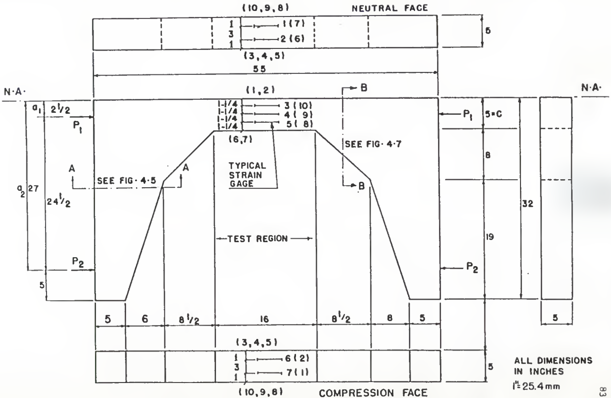


Figure 4.2 C-Shape Structural Element for Flexural Tests (25)

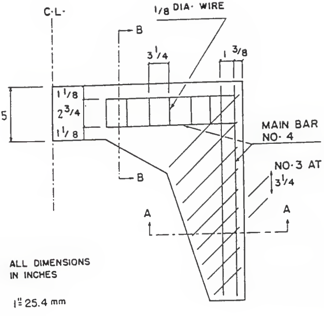
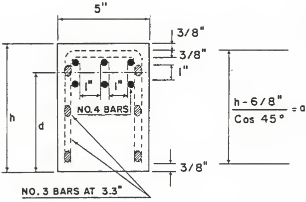


Figure 4.3: Reinforcement Layout for Specimens (25)



SECTION A - A (SEE FIG. 4.2, 4.3, 4.4)
1" = 25.4 mm

a = the leg size of stirrup

Figure 4.4: An Arbitrary Section A-A With Rebar Arrangement at Each Leg (25)

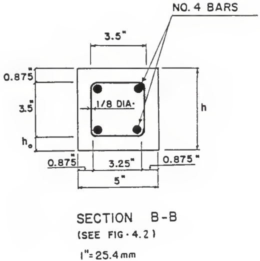


Figure 4.5: An Arbitrary Section of Column Part (25)

Figure 5.1 The Set-up of the Structural Element in Testing Machine

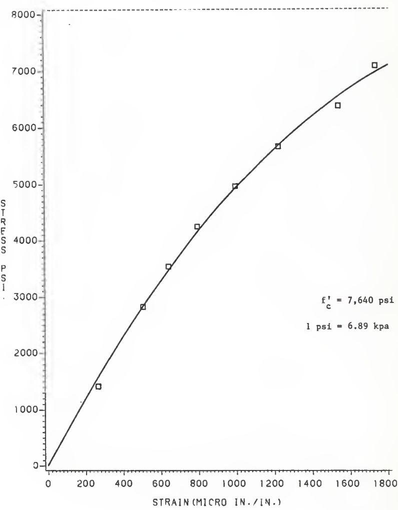


Figure 5.2 Compressive Stress-Strain Curve-Cylinder Test (No. 8) for Specimen 1

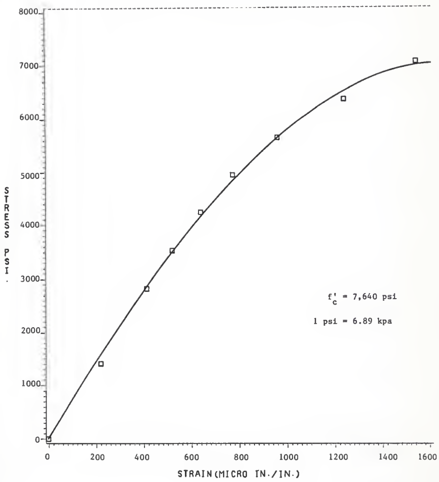


Figure 5.3 Compressive Stress-Strain Curve-Cylinder Test (No. 7) for Specimen 1

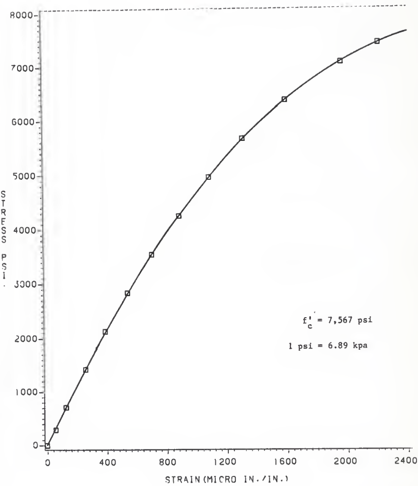


Figure 5.4 Compressive Stress-Strain Curve-Cylinder Test (No. 11) for Specimen 2

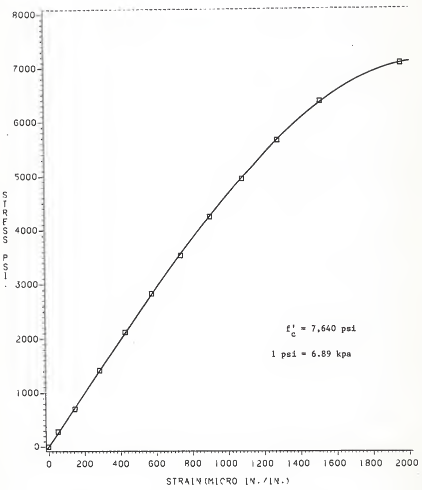


Figure 5.5 Compressive Stress-Strain Curve-Cylinder Test (No. 10) for Specimen 2

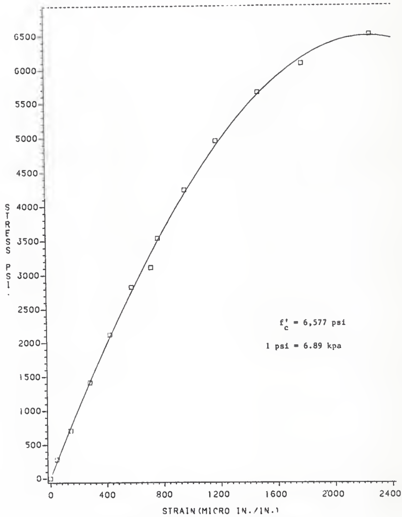


Figure 5.6 Compressive Stress-Strain Curve-Cylinder Test (No. 8) for Specimen 3

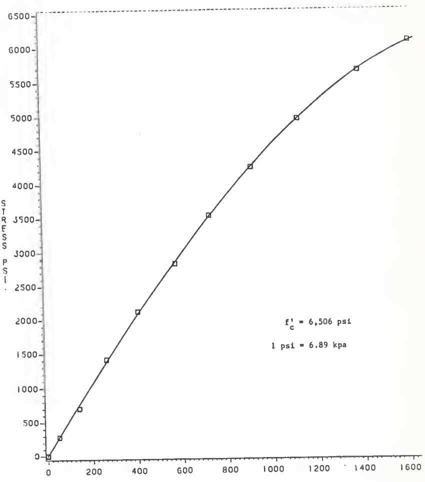


Figure 5.7 Compressive Stress-Strain Curve-Cylinder Test (No. 7) for Specimen 3

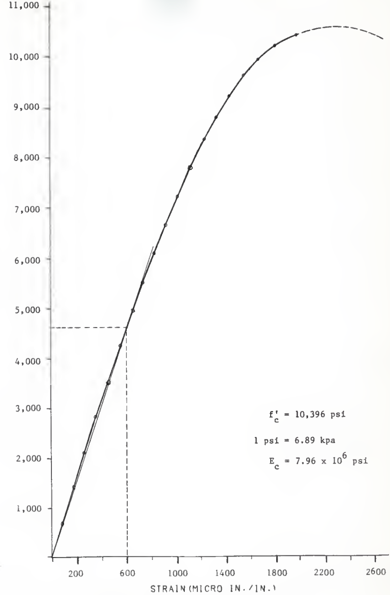


Figure 5.8 Compressive Stress-Strain Curve-Cylinder Test (No. 11) for Specimen 4

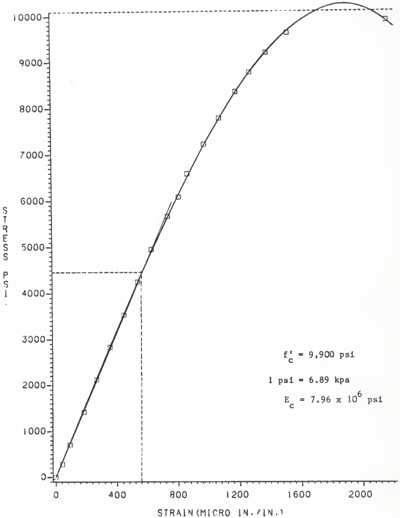


Figure 5.9 Compressive Stress-Strain Curve-Cylinder Test (No. 12) for Specimen 4

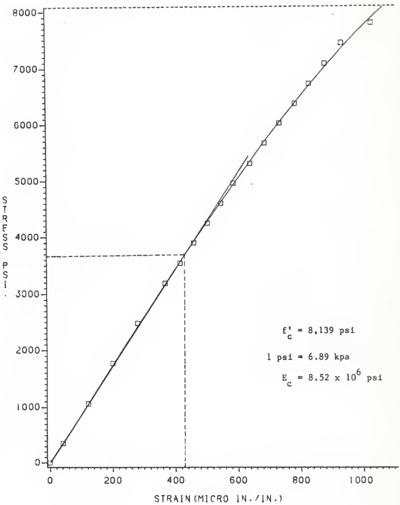


Figure 5.10 Compressive Stress-Strain Curve-Cylinder Test (No. 13) for Specimen 4

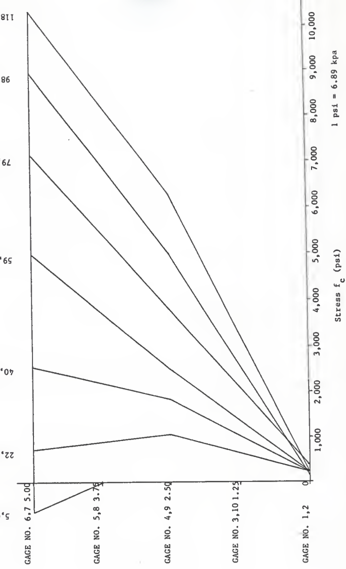


Figure 5.11 Stress Block of Specimen 1

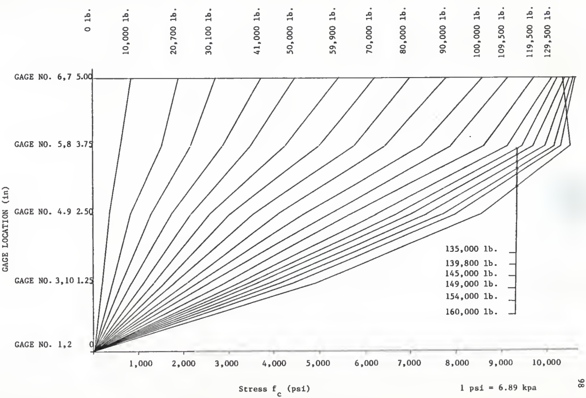
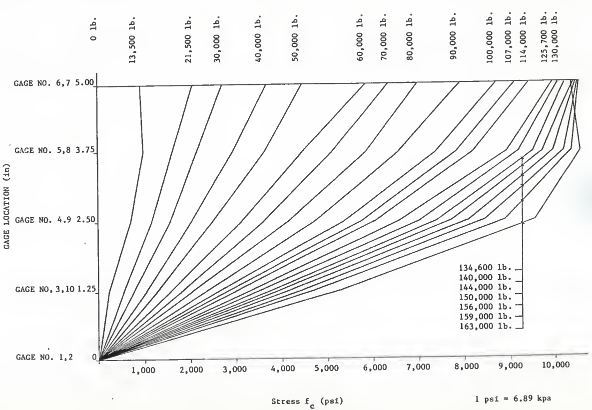


Figure 5.12 Stress Block of Specimen 2



1 psi = 6.89 kpa

Figure 5.13 Stress Block of Specimen 3

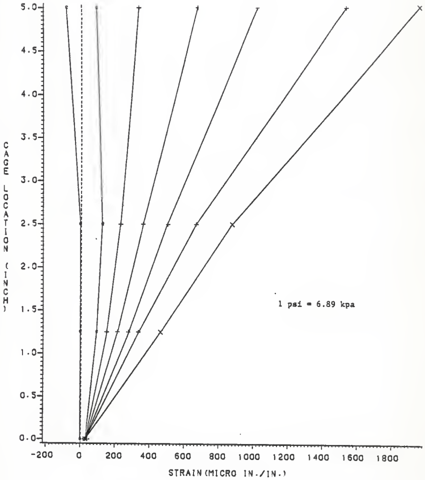


Figure 5.14 Strain Gage Location vs. Strain for Specimen 1

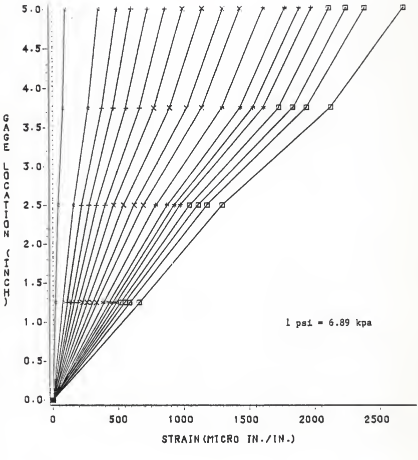


Figure 5.15 Strain Gage Location vs. Strain for Specimen 2

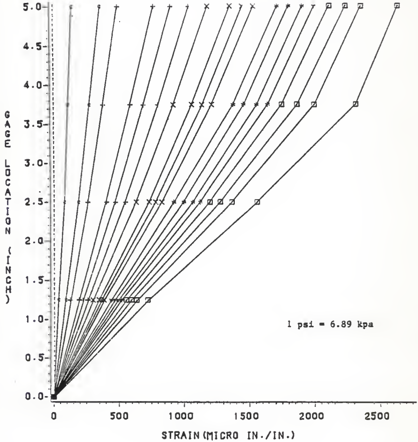


Figure 5.16 Strain Gage Location vs. Strain for Specimen 3

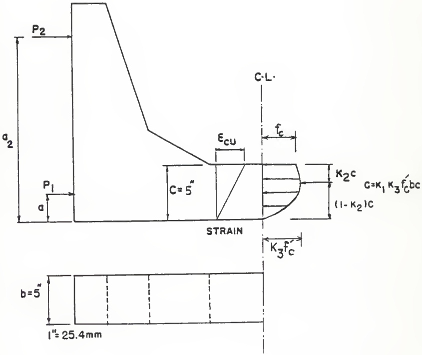


Figure 5.17 Condition at Ultimate Load in Test Specimen

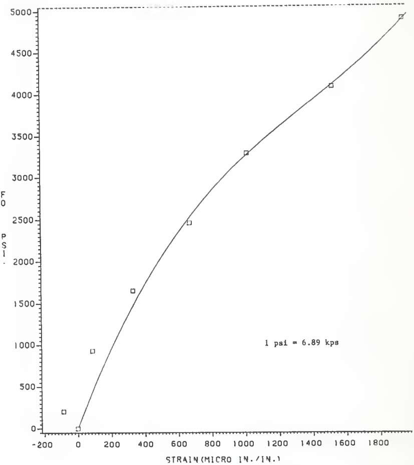


Figure 5.18 Stress Coefficient f_o vs. Strain for Specimen 1

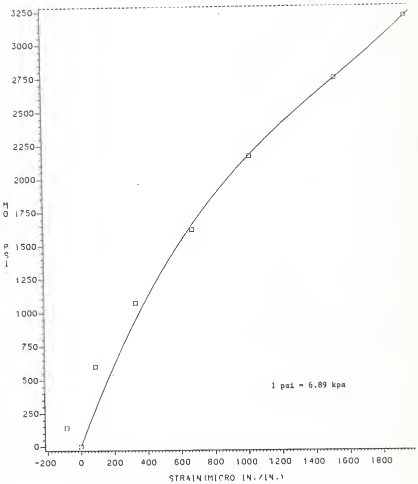


Figure 5.19 Stress Coefficient m_o vs. Strain for Specimen 1

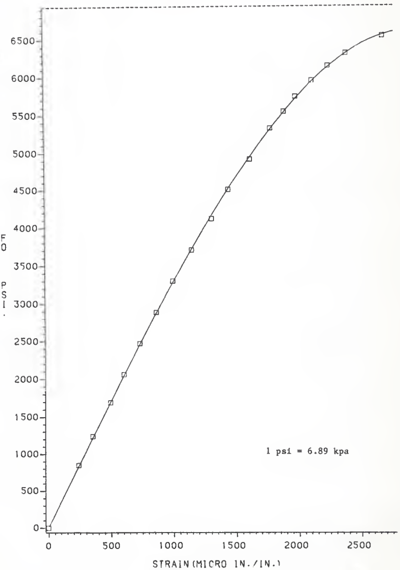


Figure 5.20 Stress Coefficient f_o vs. Strain for Specimen 2

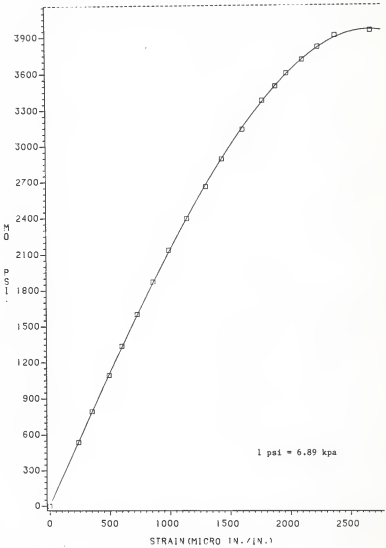


Figure 5.21 Stress Coefficient m_o vs. Strain for Specimen 2

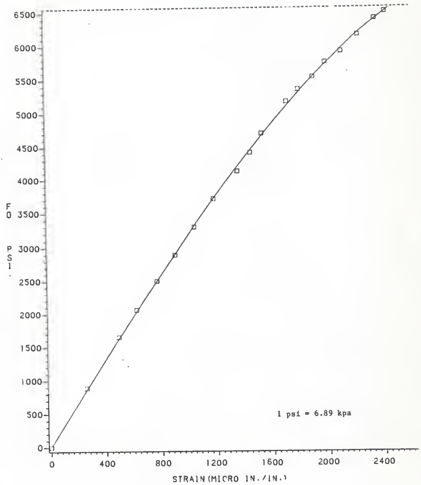


Figure 5.22 Stress Coefficient f_o vs. Strain for Specimen 3

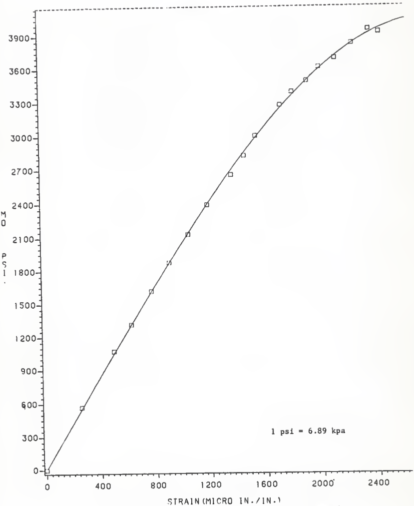


Figure 5.23 Stress Coefficient m_o vs. Strain for Specimen 3

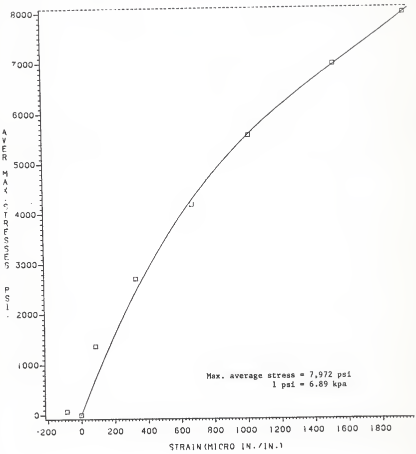
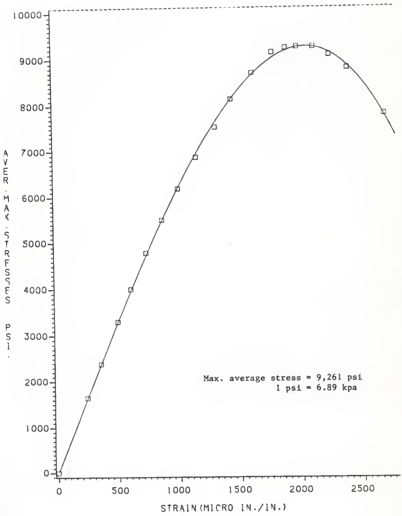


Figure 5.24 Average of the Inside Fiber Stress vs. Strain
for Specimen 1



Max. average stress = 9,261 psi
1 psi = 6.89 kpa

Figure 5.25 Average of the Inside Fiber Stress vs. Strain for Specimen 2

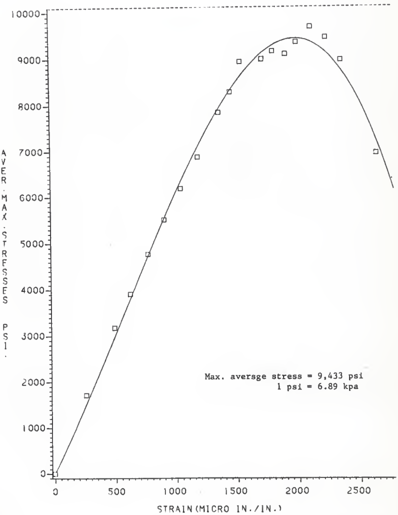


Figure 5.26 Average of the Inside Fiber Stress vs. Strsin for Specimen 3

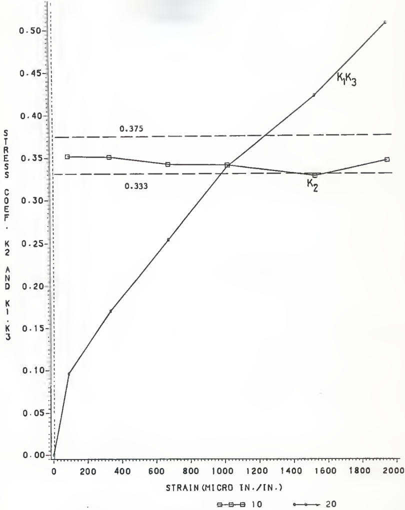


Figure 5.27 Stress Factors k_2 and k_1k_3 vs. Strain for Specimen 1

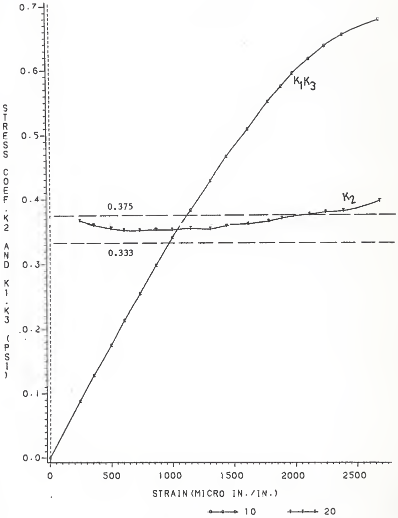


Figure 5.28 Stress Factors k_2 and k_1k_3 vs. Strain for Specimen 2

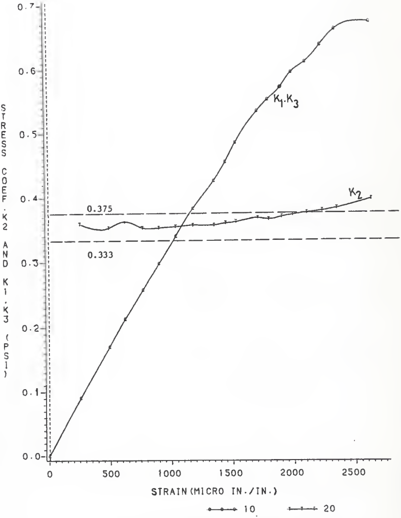


Figure 2.29 Stress Factors k_2 and $k_1 k_3$ vs. Strain for Specimen 3

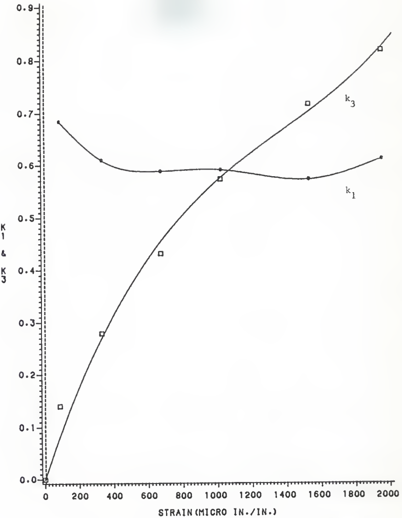


Figure 5.30 Stress Factors k_1 & k_3 vs. Strain for Specimen 1

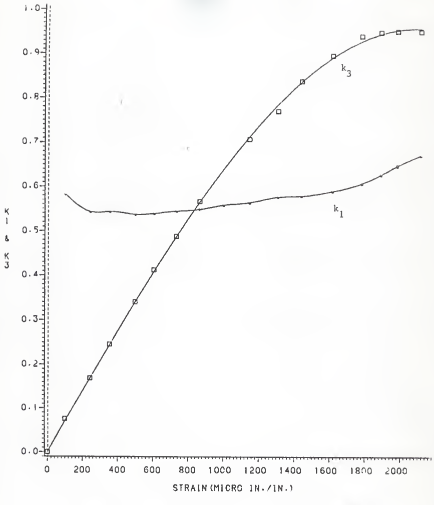


Figure 5.31 Stress Factors k_1 & k_3 vs. Strain for Specimen 2

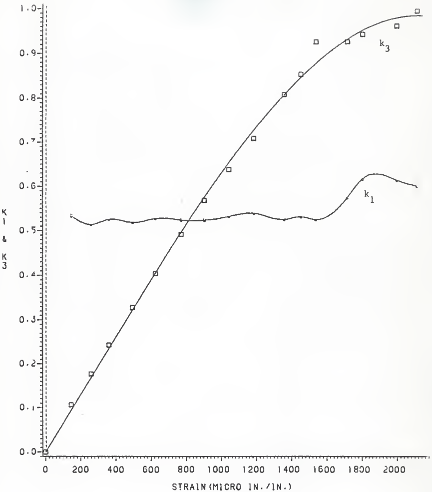


Figure 5.32 Stress Factors k_1 & k_3 vs. Strain for Specimen 3

Figure 5.33 The Failure Mode for Specimens 1, 2 and 3

Figure 5.34 The Surface of Failure for Specimen 4

APPENDIX IV

NOTATION

a = lever arm

b = width of beam

C = concrete internal force

c = depth of beam

d = distance for outermost fiber to center of gravity of steel

f_c = stress in concrete at different levels of loading

f'_c = concrete cylinder strength

f_o, m_o = cross-section stress parameters

h = height of beam

k_1, k_2, k_3 = ultimate strength factors (k_1,k_3 are shape factors and k_2 is the position of concrete internal force from outermost compression fiber)

M = moment

M_u = ultimate moment

P_1 = axial load applied by testing machine (i.e., major thrust)

P_2 = eccentric load applied by hydraulic ram system (i.e., minor thrust)

T = force carried by reinforcement

w/c = water-cement ratio

ε = strain

ε_c = strain at compression face

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THE STRUCTURAL BEHAVIOR OF HIGHER-STRENGTH CONCRETE

by

TAREK MOHAMED EL SAYED REFAI

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Kansas State University
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ABSTRACT

Higher-strength concrete has been defined as that which has a compressive strength in the range from 6000 psi (41 MPa) to 12000 psi (83 MPa). The purpose of this report is to confirm the results obtained for production of higher-strength concrete and also to present results of some experimental trials for adjusting the mix proportions.

In addition, the compressive and flexural behavior of higher-strength concrete made with Kansas aggregates was studied in order to verify assumptions for certain stress-strain relations and to confirm the parabolic shape of the compressive stress block in bending. Also, the strain at rupture and the values of Poisson's Ratio were determined.