CEMENT PASTE, MORTAR AND CONCRETE UNDER MONOTONIC, SUSTAINED AND CYCLIC LOADING

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ABSTRACT

The behavior of saturated specimens of cement paste and mortar under monotonic, sustained and cyclic loading, is compared to that of concrete at water - cement ratios of 0.5 and 0.7. Specimen age, at testing, ranges from 27 to 29 days. For monotonic loading, the behavior of each material is described in terms of peak stress, strain at peak stress, and initial modulus of elasticity. For sustained loading, the behavior is described in terms of creep strain as a function of stress - strength ratio and time under load. Mathematical relationships are developed on the sustained load response to estimate the cumulative static creep for a cyclic test.

Cyclic test results are examined in terms of strain at 15 seconds, the difference between the strain at 15 seconds and the peak strain for a given cycle (cyclic strain), the estimated creep strain for a cyclic test (equivalent creep, based on sustained load test results), the difference between cyclic strain and equivalent creep (cyclic action strain), and the change in secant unloading modulus (a measure of material damage). The equivalent creep during a cyclic test is used to distinguish between cyclic strain and cyclic action strain, which may include accelerated creep strain as well as strain related to microcracking. Cyclic action strain is correlated with change in modulus of elasticity to determine the extent to which these strains are the result of damage.

Monotonic test results show that for the materials used in this study, at a given water - cement ratio, cement paste has a higher strength and strain capacity than do the corresponding mortar and concrete, while mortar and concrete have a higher initial stiffness than cement paste. Similarly, mortar has a higher strength and strain capacity than the corresponding concrete, but has approximately the same initial stiffness.

The sustained load test results show that over a four hour period, creep strain increases nonlinearly with increasing stress - strength ratio. At the same stress - strength ratio, total strain and creep strain accumulate more rapidly for cement paste than for mortar and more rapidly for mortar than for concrete.

The cyclic test results show that for cyclic tests with a maximum stress - strength ratio greater than 0.6f′, cyclically loaded cement paste, mortar and concrete exhibit larger strains than similar materials exposed to a sustained load equal to the mean cyclic stress. For the load regimes studied, maximum cyclic stress appears to have a much greater impact on the cyclic action strain and change in stiffness than the mean cyclic stress or the cyclic stress range. The overall damage, as measured by the cyclic action strain and change in secant unloading modulus, in mortar in concrete is similar, suggesting that the behavior of concrete under cyclic loading is dominated by its mortar constituent.

Under monotonic, sustained and cyclic loading, the behavior of mortar more closely resembles that of concrete than it does cement paste.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Concrete is a composite material which deforms in a nonlinear, inelastic manner under load. Research indicates that the behavior of concrete depends on the behavior of its constituent materials. To predict the behavior of concrete under general load regimes requires an understanding of the stress-strain behavior and mechanisms of damage in these constituents. This understanding can only be gained through extensive testing and observation, so that the behavior can be described and theories can be developed.

Concrete is used in a variety of structural applications, many of which involve cyclic compressive loading in addition to static or sustained loading. Under sustained loading, concrete undergoes a gradual but continuous deformation known as creep. Creep is a phenomena characterized by strain accumulating over time, in addition to the "elastic" strain or the strain produced by the initial application of load. The mechanisms of creep in concrete are not fully understood, but probably involve nondestructive consolidation of the material, microcracking, and fluid movement. Research has shown (Washa and Fluck 1950, Cook and Chindaprasirt 1980) that a sustained load producing low stresses, applied prior to testing monotonically, significantly increases the initial modulus of elasticity of concrete. This implies that creep, at least at low stresses, is not a result of detrimental cracking or damage to the material.

When cyclic loading is applied, the strain measured at the maximum stress increases with each cycle. This increase in strain has also been called creep by a number of researchers (Whaley and Neville 1973, Brooks and Forsyth 1986). There is general agreement among researchers that a statically loaded specimen undergoes less strain than a specimen loaded cyclically about an equivalent mean stress. The mechanism of this additional strain is unknown and leads to some uncertainty in the definition of "creep" for a cyclically loaded specimen. Whaley and Neville (1973) suggest that the cyclic nature of the load merely accelerates the process of static creep and that there are no detrimental effects if the maximum stress is below the "fatigue limit", approximately 50 percent of the ultimate strength. Cook and Chindaprasirt (1980) found that for cyclic loading histories reaching 40 percent of ultimate, cement paste, mortar and concrete all increase in stiffness, with slight increases in strength, upon reloading to failure. Maher and Darwin (1980 and 1982) indicate that these gains in stiffness and strength occur primarily during the first cycle of loading and only for specimens cycled to a maximum stress of 56 percent of ultimate or less. Similarly, Cook and Chindaprasirt found that when specimens are cycled to 60 percent of ultimate, both stiffness and strength are reduced. For cycles to a maximum strain, Spooner, Pomeroy and Dougill (1976) found that most of the damage occurs during the first cycle and that after several cycles stability is attained.

It is apparent that at any level of stress, cyclic loads induce larger strains than static loads. The mechanism of these additional strains may or may not be the same as that of static creep. No information about the magnitude of these additional strains is available because no attempt has been made to separate them from the more familiar static creep strains. Some researchers have compared changes in cyclic strain at peak stress to static creep strain at a stress equal to the mean cyclic stress (Whaley and Neville 1973), while others (Bazant and Panula 1979) have compared changes in strain measured at the mean cyclic stress to static creep measured at the same stress.

Combining static creep strain and strain caused by cyclic loading under the general title of "creep" makes for some confusion. For the purposes of this report, the difference between the total strain at the peak stress for a cycle and the strain measured at the peak stress of the first cycle will be called cyclic strain, while the term creep will refer to static creep only.

1.2 BACKGROUND

Microcracks exist in concrete prior to loading, begin to propagate at very low strains and continue to propagate under increasing load until failure occurs (Hsu, Slate, Sturman and Winter 1963, Derucher 1978). In nonloaded concrete specimens, these cracks are primarily interfacial bond cracks between aggregate particles and the mortar matrix. Some cracks extend from the bond cracks, at right angles, into the mortar matrix (Derucher 1978). As compressive load is applied, bond cracks and mortar cracks widen and propagate. Mortar cracks eventually bridge between aggregate particles. When a sufficiently large number of these mortar cracks join each other, failure occurs. Failure of concrete results from large numbers of inclined macroscopic cracks, widely distributed throughout the material.

The nonlinear behavior of concrete is directly related to the process of damage and must be explained in terms of the behavior of its constituent materials. Comparisons of concrete, mortar and cement paste under monotonic loading indicate that damage is much more localized in cement paste, with a small number of vertical cracks causing failure, while the behavior of mortar more closely resembles that of concrete. Cement paste and mortar are not elastic-brittle materials as once thought (Shah and Winter 1966) but are nonlinear materials that are damaged continuously under load (Spooner, Pomeroy and Dougill 1976, Cook and Chindaprasirt 1980). Coarse aggregate is a linear-elastic material and usually has a higher strength and stiffness than the surrounding mortar (Hobbs 1973). Spooner et al. (1976) suggest that this difference in stiffness creates stress concentrations in the mortar matrix leading to crack initiation, and further that cement paste and mortar behavior are controlling factors in the response of concrete to load.

This research compares the behavior of cement paste, mortar and concrete under monotonic, sustained, and cyclic loading. Cyclic strains are distinguished from creep strains, and the magnitudes of each are examined. These strains are compared to changes in stiffness, a measure of internal damage, to help determine the mechanisms causing material deformation.

1.3 PREVIOUS WORK

Hsu, Slate, Sturman and Winter (1963) investigated microcrack propagation in concrete subjected to uniaxial compressive loading using a light microscope at 40x magnification. They found that interfacial bond cracks exist prior to loading. Looking at cross sections of specimens previously loaded to varying stresses and then unloaded they discovered that these cracks begin to propagate at 30 to 40 percent of the compressive strength (f'_c) of the concrete. The onset of microcracking corresponds to the beginning of nonlinear stress-strain behavior and lateral expansion of the specimen. At 70 to 90 percent of f'_c, mortar cracks begin to form and propagate at an accelerating rate until failure.

Derucher (1978) used a scanning electron microscope to examine dried concrete specimens while applying an eccentric, compressive load. He concluded that the drying process does not significantly increase microcracking. He observed cracks extending into the mortar, at right angles to the bond cracks, prior to any loading. Under increasing compression, he observed that bond cracks do not propagate, but instead widen, while the mortar cracks widen and propagate at stresses as low as 15 percent of f'_c. As the load increases, mortar cracks begin to bridge between bond cracks and, at about $0.45f'_c$, the bridging is complete. At about $0.75f'_c$, mortar cracks begin to join each other and eventually cause the specimen to fail.

To assess the importance of bond microcracking, Darwin and Slate (1970) and Perry and Gillott (1977) conducted uniaxial compressive tests of concrete made with aggregate for which the interfacial bond strength had been modified. Their results show that bond strength has a relatively small impact (maximum of 15%) on the uniaxial compressive strength of concrete.

Using a sequence of loading, unloading and reloading, Spooner and Dougill (1975) developed highly sensitive techniques to quantify damage in concrete. They measured the energy dissipated in damage, based on ideal material behavior, and compared the results with changes in modulus of elasticity based on the initial portion of the reloading curve (E_i). Their data indicates a good correlation between energy dissipated in damage and E_i. Signs of degradation appear at applied strains as low as 400 microstrain. Their work indicates that damage in cement paste and concrete is a continuous process, beginning at very low strains. The work also indicates that, for cycles to a maximum imposed strain, damage occurs primarily during the first cycle. This would seem to imply that degradation in terms of cracking, is a function of maximum strain. Spooner and Dougill also observe that an increasing aggregate concentration increases the degree of damage for a given applied load.

Karsan and Jirsa (1979), using cycles to "common points", found that stiffness reached a stable value after only a few cycles. Common points occur when the loading branch of the stress-strain curve reaches the unloading branch of the previous cycle (implying both decreased stress and strain for each successive cycle).

Whaley and Neville (1973) suggest that cyclic loads below a fatigue limit merely accelerate the process of creep. Neville and Hirst (1978) speculate that the acceleration results from limited additional bond cracking and that it is not detrimental to concrete strength or stiffness. Cook and Chindaprasirt (1980) found that cyclic loading to sixty percent of f'_c decreased both the stiffness and the strength of concrete upon reloading, indicating that cyclic loading causes damage. Specimens subjected to a sustained load, of less than sixty percent of ultimate, showed increased strength and stiffness, indicating that creep strain, per se, does not imply damage. When combined with the results of the cyclic tests, this leads to the conclusion that cyclic strain differs in nature from creep strain. Comparing concrete to mortar and paste, Cook and Chindaprasirt (1980) note that previously applied cyclic loads to forty percent of ultimate have no effect on the stiffness of cement paste or mortar, and may slightly increase the compressive strength. Cycles to forty percent of ultimate slightly decrease the strength and stiffness of concrete with a w/c ratio of 0.55, but have less effect on lower w/c ratio mixtures. For cycles to sixty percent of ultimate, they found that cement paste and mortar were slightly degraded in terms of strength and stiffness, while concrete was affected to a greater degree, with reductions in strength and stiffness being most pronounced for the highest w/c ratio. Cook and Chindaprasirt also suggest that this change in stiffness is due to limited microcracking, in agreement with Spooner and Dougill (1975), and they suggest that an increase in cement paste strength can reduce the amount of microcrack damage.

Tests of mortar (Maher and Darwin 1980, 1982) show that strengthening and stiffening due to compaction occur primarily within the first cycle of loading for stresses as high as 56 percent of ultimate, f'_m. Further cycles or higher stresses degrade the stiffness of mortar. As with concrete, damage in mortar begins at low stresses and is continuous for both monotonic and cyclic load.

Attiogbe and Darwin (1985) subjected cement paste specimens to both cyclic and monotonic loading to produce strains of up to 4000 microstrain. They observed that microcracking in the cement paste was greater, at a given total strain, for the specimens subjected to cyclic loading than for specimens subjected to either monotonic or sustained loading, indicating that damage increases as a result of the cyclic load.

The rate of loading has been shown to affect the behavior of most materials. For a single cycle, high rates of load or impact loads can yield much greater concrete strengths than slowly applied loads. A number of researchers, including Spooner (1972) and Kaplan (1980), found that increasing the rate of loading produces increases in the strength of concrete. Kaplan also found that using a slower rate of loading, up to about 30 percent of ultimate, and then increasing the load rate before loading to failure yields higher strengths in cement paste than using a constant load rate throughout the test. However, continuing the slow rate of load beyond 30 percent of ultimate results in decreased strength. Both Spooner and Kaplan indicate that curing and in particular moisture content at the time of test influence rate sensitivity. Kaplan has shown that an increasing moisture content increases the rate sensitivity, suggesting that fluid movement and pore pressure affect the response of concrete under load.

The effect of frequency of cyclic loading on concrete has been studied extensively by Brooks and Forsyth (1986). They tested concrete using frequencies ranging from 1 cycle per day (1.157×10^{-5} Hz) to 1 cycle per second (1 Hz) and loads ranging from 10 to 50 percent of ultimate for periods of up to 5 days. They note that much of the previous research performed on cyclic loading of concrete used frequencies ranging from 0.37 to 10 Hz and that information about slower and more common rates of loading is scarce. Brooks and Forsyth defined three measures of "creep", the minimum strain during a cycle minus the residual strain of the first cycle, the strain at the mean stress minus the strain at mean stress for the first cycle, and the maximum strain for a cycle minus the maximum strain for the first cycle (defined as cyclic strain in this report). They indicate that the creep measured at the mean stress is greater than the creep at the maximum stress (because of changes in the shape of the stress-strain curve with time) but that this phenomena diminishes with time to a difference of about 10 to 15 percent at 5 days. Their results also show that cyclic strain, as defined in this report, exceeds static creep measured at a stress equal to the mean cyclic stress for all loading frequencies. For saturated specimens, loaded at frequencies between 1 cycle per day and 30 cycles per hour, cyclic strain is independent of frequency. However, at higher frequencies cyclic strain increases with increasing frequency.

Using a nonlinear representation for mortar, Maher and Darwin (1977) developed a finite element model for concrete which shows that the nonlinear behavior of mortar has a significant influence on the nonlinear behavior of the composite concrete. Their work strongly suggests that the nonlinear behavior of concrete is controlled by its mortar constituent.

1.4 OBJECT AND SCOPE

This research compares the behavior of cement paste, mortar and concrete under monotonic, sustained, and cyclic loading. A model for creep strain as a function of stress is developed to estimate the creep strain occurring in a cyclically loaded specimen. This estimate is used to separate the effects of creep from the effects of the cyclic load.

Specimens of cement paste, mortar, and concrete with water-cement ratios of 0.5 and 0.7 are tested at ages of 27 to 30 days. The cement paste and mortar are representative of the constituents of the corresponding concrete. Monotonic tests are performed to determine strength, initial modulus of elasticity, and the strain at peak stress. Sustained load tests are conducted for stress levels of 20, 40, 60, 80 and 90 percent of ultimate strength (f'). Cyclic tests, designed to study the effects of mean stress level and stress range, are performed for stress ranges of 0.1-0.3f′, 0-0.4f′, 0.2-0.6f′, and 0-0.8f′, using a frequency of 0.033 Hz (2 cycles per minute). Both sustained and cyclic tests have a maximum duration of four hours.

Twenty-four batches (7 cement paste, 8 mortar, and 9 concrete) of six specimens each were tested. Some data cannot be used due to errors in measurement. The results of 17 cyclic, 62 sustained, and 40 monotonic tests are reported. The findings are compared to the results of previous research.

CHAPTER 2

EXPERIMENTAL WORK

To study the compressive behavior of concrete and its cement paste and mortar constituents, prismatic specimens were tested under monotonic, sustained, and cyclic loading using a closed-loop servo-hydraulic testing machine. Sustained and cyclic loading tests were limited to a maximum of 4 hours. The tests were designed to compare the stress-strain response and rate of degradation of concrete and its constituent materials.

2.1 MATERIALS

Materials used were:

Type I portland cement

Fine aggregate: Mainly quartz with about 25 percent feldspar. Fineness modulus = 2.8. Bulk specific gravity (saturated surface dry) = 2.58. Absorption = 1 percent. Source: Kansas River, Lawrence, Kansas.

Coarse aggregate: $^1/_2$ in. crushed limestone. Bulk specific gravity (saturated surface dry) = 2.56. Absorption = 3.5 percent. Unit weight = 95 lb/ft^3. Source: Hamm's quarry, Perry, Kansas.

The coarse aggregate was separated into size fractions, passing the $^1/_2$ in. and retained on a $^3/_8$ in. sieve, and passing the $^3/_8$ in. and retained on the No. 4 sieve. The two sizes were then combined in a ratio of 55 to 45 percent by weight, respectively.

Two concrete mixtures, along with their mortar and cement paste constituents, were used. With water-cement ratios, w/c, of 0.5 and 0.7, the concrete mixtures produced 28 day compressive strengths of 4900 and 2800 psi, respectively. Mixture proportions of the concretes and the constituent materials are given in Table 2.1.

2.2 PREPARATION

The test specimens were prepared so that the cement paste and mortar mixtures approximated the constituents of the concrete as closely as possible. Prior to batching, all aggregate was oven dried and cooled to room temperature. The mix water was then added to the aggregate and allowed to stand for a period of ten minutes. The water and aggregate weights were corrected to account for aggregate absorption obtained in a 20 minute saturation period, 0.95 percent and 2.95 percent for the fine and coarse aggregate, respectively. Following the 10 minute waiting period, the cement was added and the material was mixed for 5 minutes. After mixing, prismatic test specimens were placed vertically in steel forms, 2 x 2 x 8 in. for cement paste and mortar and 3 x 3 x 12 in. for concrete. The material was consolidated in three layers, each layer rodded 25 times with a $^3/_8$ rod. The forms were sealed at the top, and the specimens were stored in a horizontal position to reduce the effects of bleeding, and insure uniform properties throughout the height of the specimens. The importance of specimen uniformity is discussed below.

After 24 hours, the specimens were removed from the molds and stored in lime saturated water until the time of test.

Prior to testing, the specimens were shortened to obtain a length to width ratio of 3 to 1 by removing equal portions from each end with a high-speed saw lubricated with saturated calcium hydroxide solution.

Specimens were wrapped with plastic and tested in a saturated condition at ages ranging from 27 to 30 days.

2.3 TESTING

Just prior to testing, specimens were capped with a $^1/_8$ in. layer of high-strength gypsum cement. Two sheets of 4 mil thick plastic, separated by a heavy layer of grease, were placed on each end of the specimen to reduce friction with the loading platens. Specimens were placed in the test machine, separated from the loading platens by $^3/_4$ in. steel plates. The upper steel plate was then seated to the testing platen using high-strength gypsum cement (Fig. 2.1). The gypsum cement obtained a strength in excess of 7000 psi at the time of test.

A 110,000 pound capacity closed-loop, servo-hydraulic testing machine was used. The load was transmitted through flat rigid platens in order to minimize the strain gradient across the specimens.

Specimens were instrumented using either a variable length compressometer or with extensometers attached directly to the specimen. The compressometer was attached to wood strips on the test specimens, using set screws. The gage length was 1 in. shorter than the length of the specimen (5 in. for cement paste and 8 in. for concrete). A strain gage type extensometer was installed on the compressometer to monitor strain and provide closed-loop control for the testing machine. In some tests, extensometers were attached directly to the surface of the specimens with a gage length equal to two-thirds of the specimen height (4 in. for cement paste and mortar, 6 in. for concrete). Load and strain were plotted during the test and recorded using a data acquisition system.

Monotonic tests were run at a constant strain rate of 9 microstrain/sec. Readings were taken a 3 second intervals for the duration of monotonic tests. Sustained load (short-term creep) and cyclic load tests were run using load control, with the maximum load attained in 15 seconds. For sustained load tests, readings were taken at 1 second intervals for the first 135 seconds, at 2 second intervals until an elapsed time of 255 seconds, at 10 second intervals until an elapsed time of 555 seconds, at 30 second intervals until an elapsed time of 855 seconds, at 60 second intervals until an elapsed time of 3555 seconds, and at 300 second intervals until the end of the test, at an elapsed time of 14355 seconds. Cycles were applied at 2 cycles per minute for all cyclic tests. For cyclic tests readings were taken for the first 5 cycles and then for 5 cycles at 40 cycle (20 minute) intervals, specifically, cycles: 41 - 45 (1215 - 1335 sec), 81 - 85 (2415 - 2535 sec), 121 - 125 (3615 - 3735 sec), 161 - 165 (4815 - 4935), 201 - 205 (6015 - 6135), 241 - 245 (7215 - 7335), 281 - 285 (8415 - 8535), 321 - 325 (9615 - 9735), 361 - 365 (10815 - 10935), 401 - 405 (12015 - 12135), 441 - 445 (13215 - 13335), 481 - 485 (14415 - 14535). Since data was recorded with 20 minute gaps between groups of 5 cycles, the failure of most specimens was not recorded. Only cyclic specimens 2C2, 3C4 and 6C2 failed during the collection of data. Therefore, the large strains normally associated with the failure of the specimens, and measured for these three specimens, are not recorded for the remainder of the cyclic test specimens.

2.4 TEST PROGRAM

The goals of the test program were two fold: (1) to compare the behavior of concrete with its cement paste and mortar constituents, and (2) to determine what aspects of material behavior in cyclicly loaded specimens are caused by the cycles themselves and what aspects are due to creep.

Twenty-four batches (7 paste, 8 mortar, 9 concrete) of six specimens each were cast. Twenty-three of these one hundred forty-four specimens were discarded due to flaws. Specimens were subjected to three loading regimes: monotonic loading at a constant strain rate, sustained loading up to 4 hours, and cyclic loading up to 4 hours. Sustained loads were monitored at stress/strength ratios, σ/f', of 0.2, 0.4, 0.6, and 0.8 and 0.9 for each material. Cyclic loading regimes consisted of stress cycles between of stress/strength ratio 0-0.8, 0-0.4, 0.1-0.3, and 0.2-0.6 for cement paste, 0-0.8, 0-0.4, and 0.2-0.6 for mortar and 0-0.8 and 0.2-0.6 for concrete. Two specimens of cement paste with w/c = 0.5 were subjected to sustained loads equal to $0.8f'_p$ until reaching a maximum strain of 0.004 and were then unloaded to measure the secant unloading modulus. This allows a comparison of the change in modulus under a sustained load to the change in modulus under a cyclic load. These specimens will be discussed in section 3.5.

To determine possible effects of specimen size a limited number of concrete specimens with 2 in. x 2 in. cross sections and 3 in. x 3 in. cross sections were tested monotonically. The results show no significant difference and 3 in. x 3 in. specimens were used for the remainder of the test program.

CHAPTER 3

RESULTS AND EVALUATION

This chapter describes the results of the monotonic, sustained, and cyclic tests. An evaluation of the monotonic tests provides a general description of differences in material behavior for cement paste, mortar, and concrete. The results of the sustained load tests are used to estimate the contributions of static creep to total strain under cyclic load. The cyclic test data is used to better understand the mechanisms of strain and material behavior under cyclic loading.

3.1 MONOTONIC LOADING

The monotonic tests were designed to compare the stress-strain behavior of cement paste, mortar and concrete in terms of the initial modulus of elasticity, strength and strain capacity, and thereby deduce the extent to which the behavior of cement paste and mortar influences that of concrete. A summary of monotonic tests, including initial modulus of elasticity, peak stress, and strain at peak stress is presented in Table 3.1.

Typical monotonic stress-strain curves for cement paste, mortar and concrete with a w/c ratio of 0.5, including lateral strains, are shown in Fig. 3.1. Stress-strain curves for materials with a w/c ratio of 0.7 are shown in Fig. 3.2.

The figures illustrate key aspects of material behavior, some of which are not well known. For a given water-cement ratio, cement paste has a higher strength and strain capacity than do the corresponding mortar and concrete, while mortar and concrete have a higher initial stiffness than cement paste. For the current tests, the initial stiffness of the mortar and concrete are nearly the same. In general, the addition of aggregate increases the initial stiffness and decreases the strain capacity of cement paste.

The average peak stresses and corresponding strains are compared in Table 3.2 along with the initial stiffnesses for each of the materials tested.

On the average, cement paste is stronger than mortar, which is in turn stronger than concrete. This observation is at odds with earlier research by Shah and Chandra (1970) and by Cook and Chindaprasirt (1980) which found that the strength of concrete exceeded that of cement paste with the same w/c ratio. This difference in strength may be due to the difference in methods of preparation. Unlike previous research in which newly cast specimens remained vertical, the specimens in the current study were initially cured in a horizontal position. This prevented the effects of bleeding from creating a portion of weakened material at the upper end of the test specimens. The effects of bleeding are by far the greatest in cement paste, and therefore, a sizeable reduction in strength would be expected if the specimens were stored upright initially.

Although the specimens were stored in a horizontal position in the current work, some bleeding was clearly evident, especially in the cement paste specimens. The bleeding manifested itself in the form of excess bleed water on the surface of the specimen and a reduced specimen dimension in the case of w/c = 0.7 specimens (approximately 1.7 in. x 2 in.). The overall result is that the cement paste specimens had a lower effective water-cement ratio due to the loss of the bleed water (this is not especially significant for w/c = 0.5 but may be for w/c = 0.7). For mortar and concrete, this bleed water did not move to the surface on the small specimens and was instead trapped by the aggregate particles.

The rigid, non-rotating platens of the load machine forced all portions of the specimen cross section to share the load, limiting the effects of any gradient in properties caused by the bleeding.

A comparison of the monotonic stress-strain curves provides some additional information (Figs. 3.1, 3.2 and Tables 3.1, 3.2). For a w/c of 0.5, the strengths of cement paste, mortar, and concrete are closer than for a w/c of 0.7. For w/c = 0.5, paste strength averages 5916 psi, while mortar and concrete strengths average 5557 and 4931 psi, or 94 and 83 percent of the paste strength, respectively. For w/c = 0.7, paste strength averages 3865 psi, while mortar and concrete strengths average 3500 and 2779 psi, or 91 and 72 percent of the paste strength, respectively.

The strains corresponding to the peak stress decrease with increasing w/c for mortar and concrete, but increase for cement paste. For w/c's of 0.5 and 0.7 respectively, the values for cement paste are 5560 $\mu\varepsilon$ and 6403 $\mu\varepsilon$, while mortar has values of 3067 $\mu\varepsilon$ and 2516 $\mu\varepsilon$ and concrete has values of 1839 $\mu\varepsilon$ and 1489 $\mu\varepsilon$. Overall, the stress-strain curves illustrate that cement paste, mortar and concrete are highly nonlinear materials and that saturated cement paste has a higher strain capacity than either mortar or concrete. For all three materials, a decrease in water-cement ratio increases initial stiffness and strength but seems to result in a more brittle failure, as illustrated by a more rapid decrease in stress, once the peak stress is attained.

For the materials illustrated in Table 3.2, it is clear that for each water-cement ratio, cement paste is by far the most variable in terms of strength and strain at the peak stress. The relatively large standard deviations in strength (422 psi for cement paste, versus 229 psi and 380 psi for mortar and concrete at w/c = 0.5, and 275 psi for cement paste, versus 149 psi and 118 psi for mortar and concrete at w/c = 0.7) are likely due to the mode of failure of the cement paste specimens. Failure in cement paste is far more localized, with a small number of vertical cracks. Macroscopic damage in mortar and concrete is more distributed, with a large number of inclined cracks. This difference seems to indicate that the strength of cement paste is controlled by the failure of a relatively small number of local regions; whereas damage in mortar and concrete is distributed throughout a greater volume of material due to the presence of the stiffer, stronger aggregate.

The high standard deviation in the strain corresponding to the peak stress for cement paste (534 $\mu\varepsilon$ and 708 $\mu\varepsilon$ at w/c's of 0.5 and 0.7, respectively) is largely a function of the broad plateau in the stress-strain curves over which the stress varies very little. Mortar and concrete, which fail more suddenly, have lower standard deviations of the strain at peak stress (136 and 67 $\mu\varepsilon$ for mortar and 141 and 106 $\mu\varepsilon$ for concrete at w/c's of 0.5 and 0.7, respectively).

The initial modulus of elasticity, E_i, was calculated by passing a parabola through the first three recorded data points of the stress-strain curve and finding the slope of the parabola at a stress equal to 10 percent of the ultimate strength. Concrete has average E_i values of 4169 and 3303 ksi for w/c = 0.5 and 0.7, respectively. Mortar has values close to those of concrete, 4118 and 3306 ksi, which are nearly double those of cement paste, 2305 and 1681 ksi, for w/c = 0.5 and 0.7, respectively. The addition of coarse aggregate might be expected to consistently increase the initial stiffness of the mortar. This is the case for w/c = 0.7, but not for w/c = 0.5. The relatively porous coarse aggregate used in this study apparently has a stiffness greater than that of the w/c = 0.7 mortar, but not of the w/c = 0.5 mortar. Thus, for w/c = 0.5, mortar has a slightly higher initial stiffness than concrete.

Overall, the monotonic test results show that the stress-strain curves of mortar and concrete are quite similar and differ substantially from those for cement paste. This indicates that the addition of sand significantly affects the behavior of cement paste, while the addition of coarse aggregate has a measurable but less significant impact. The mortar constituent of concrete appears to strongly influence the behavior of the total composite.

3.2 SUSTAINED LOADING

The primary goal of the sustained load tests and the analysis that follows is to develop a relationship between creep strain and stress-strength ratio, σ/f', for the materials tested. This numerical description of creep strain, as a function of σ/f', is used to estimate the amount of creep strain accumulated during a cyclic test. Stress-strength ratios of 0.2, 0.4, 0.6, 0.8, and 0.9 were used for the sustained load tests. A summary of the sustained load tests, including applied stress, strain at 15 seconds, ending strain and test duration is presented in Table 3.3.

Typical sustained-load stress-strain curves for cement paste, mortar and concrete are shown in Figs. 3.3 and 3.4 for w/c's = 0.5 and 0.7, respectively.

For the purposes of this investigation, creep strain, ε_c, is defined as the total strain minus the strain at 15 seconds (when the load reaches maximum), ε_{15}. From the curves in Figs. 3.3 and 3.4, it is evident that creep strain is a nonlinear function of the stress-strength ratio, increasing to a greater degree than σ/f', as σ/f' increases.

For each material, at each stress-strength ratio, best fit curves were computed for the accumulated experimental data. Using log-time as the independent variable and total strain, ε_t, as the dependant variable, third order polynomials were fit for each of the five stress-strength ratios and for each of the six materials tested. The form of the equation is:

$$\varepsilon \quad = A + B(\log_{10} t) + C(\log_{10} t)^2 + D(\log_{10} t)^3 \tag{3.1}$$

for t between 15 sec and 4 hours (14,400 sec).

Plots of the experimental and best fit curves are shown in Figs. 3.5-3.10. The coefficients for the best fit curves are given in Table 3.4. For sustained load tests with the a stress-strength ratio of 0.8 or less, all specimens lasted the full four hours, although at a stress-strength ratio of 0.9 some specimens creeped to failure, under the constant stress, before the scheduled end of the test. These specimens resulted in highly non-linear curves, which could not be represented by Eq. 3.1. For these curves, Eq. 3.1 was applied only to the region over which a satisfactory fit could be obtained. The curves for total strain shown in Figs. 3.5 - 3.10 are converted to creep strain by subtracting the strain at 15 seconds from the total strain.

It is apparent from the data for mortar and concrete loaded at $\sigma/f' = 0.2$ (Fig. 3.6, 3.7, 3.9, 3.10) that there was slip in the strain measuring equipment, incorrectly indicating a decrease in strain for the latter portions of the tests. Where additional data at the same stress-strength ratio is available, data indicating slip in the gage is excluded from the regression analysis to minimize the impact of slip on the best fit curves. In Figs. 3.5-3.10, the experimental curves are shown as solid lines, and the actual best fit curves are shown as dotted lines. Modified best fit curves, shown as dashed lines, are used in place of the best-fit lines in cases where slip is evident (Figs. 3.7, 3.9 and 3.10). The modified best fit curves differ from the best fit curves in that strain values are not allowed to decrease. If the slope of the best fit equation becomes negative, the strain value of the modified best fit curve remains constant with respect to time until the strain value of the actual best fit curve exceeds that of the modified best fit. Where appropriate, the modified best fit curves are used in later calculations to estimate equivalent creep.

One way to estimate the total slip accumulated during a sustained load test is to sum all incremental decreases in stain throughout the test (this estimate may include random noise). Applying this method to the tests in Figs. 3.5-3.10, specimen 6A6, at $0.2f'_m$ in Fig. 3.6, accumulated 99 $\mu\varepsilon$ of slip. This is approximately 50 percent of the total strain in this test and the largest measured value of all the tests that showed slip. Specimen 2A5, at $0.6f'_m$ in Fig. 3.9, accumulated 44 $\mu\varepsilon$ of slip or approximately 10 percent of the total strain for this test. Using this measure of slip, some strains are included that are due to small but measurable fluctuations in load; many of the tests exhibited 5-10 $\mu\varepsilon$ of such "slip". The appearance of slip in some low stress tests suggests that slip may have occurred in other tests. Although the relative magnitude of the slip is less significant at higher stresses, this implies that the data may underestimate the true strains to some degree.

The effect of water-cement ratio on the stress-strain behavior of cement paste, mortar and concrete is similar. Keeping in mind that the absolute stress was higher for w/c = 0.5, the same stress-strength ratios yielded higher total strains and creep strains for w/c = 0.5 than for w/c = 0.7, except at a stress-strength ratio of 0.9 (specimens that creeped to failure). For these tests, initial total strains were also typically higher for w/c = 0.5 but were approximately equal at failure for both w/c's. Creep strains at the highest stress-strength ratio were higher for w/c = 0.7 than for w/c = 0.5.

Comparing cement paste, mortar and concrete shows that both total strain and creep strain accumulate more rapidly for cement paste than for mortar and more rapidly for mortar than for concrete at the same stress-strength ratio. This is true, except for a number of the high stress tests, where concrete or mortar specimens (5F2, 6A2, 2D5, 2D6, 8A2, 9C5, 9C6, 4A2, 2A2, 6F2, 7F2) accumulated very large strains and failed prior to the end of the test. Arbitrarily selecting a data point 954 sec into the test and using the best fit curves for cement paste, mortar and concrete at a stress-strength ratio of 0.2, average creep strains are 69, 18, and 10 microstrain, respectively, for w/c = 0.5. At the same stress-strength ratio for w/c = 0.7, the values are 46, 10, and 4 microstrain, respectively. Again at 954 sec, but at a stress-strength ratio of 0.9, creep strains for paste, mortar and concrete are 2264, 1195 and 710 microstrain, respectively, for w/c = 0.5, and are 2348, 1414 and 1119 microstrain, respectively, for w/c = 0.7.

The addition of fine and coarse aggregate to cement paste reduces both the total strain and the creep strain. At the same time, it also reduces the strain capacity and causes specimens to fail in a shorter time at a stress-strength ratio of 0.9. Although the addition of coarse aggregate results in reduced total strains and creep strains, the behavior of mortar more closely parallels that of concrete than it does the behavior of cement paste. Strains in mortar are 25 to 80 percent higher than those in concrete, and strains in cement paste are 60 to 440 percent higher than those in mortar.

A family of second order curves is used to numerically describe the relationship between stress - strength ratio and creep as a function of time. Using Eq. 3.1 at 0.2, 0.4, 0.6, and 0.8f′ for each material, the creep strain is calculated at one hundred points spaced evenly along the log-time axis. These points are plotted in the $\sigma/f' - \varepsilon_c$ domain. For each of these one hundred values of time, second order spline curves are fit exactly through the four data points, each data point representing one stress-strength ratio at the same point in time. Each spline curve is a composite of three parabolic sections. The parabolic sections are of the form:

$$\varepsilon_c = A(\sigma/f')^2 + B(\sigma/f') + C \qquad (3.2)$$

The first section is defined by the origin and the data points at 0.2 and 0.4f′. The second section is defined by the points at 0.4 and 0.6f′ and the slope of the first section at 0.4f′. Similarly, the third section is defined by the points at 0.6 and 0.8f′ and the slope of the second section at 0.6f′. Each of the three part spline curves represents one point in time during a four hour interval and can be used to estimate creep strain for intermediate values of σ/f'. This allows an estimate of creep strain for any stress-strength ratio during the four-hour loading period.

In the case of concrete, the constant time σ/f' - ε_c curves tended to be concave leftward for the range 0 - 0.2f′, falsely indicating smaller creep strains at higher stresses. To correct for this behavior, a linear relationship is used for concrete between 0 and $0.2f'_c$, and three second order curves are used from 0.2 - $0.8f'_c$. For w/c = 0.7 concrete, the slope of the second order curve between 0.2 and $0.4f'_c$ is forced to match that of the line between 0 and $0.2f'_c$, while w/c = 0.5 concrete curves are allowed to have a discontinuity in slope at $0.2f'_c$. This forces ε_c to increase monotonically with σ/f'. Figs. 3.11 - 3.16 show representative σ/f'versus ε_c curves for the six materials at t = 15, 26, 357, 9450, and 14000 sec. Data points for seven other times (t = 50, 96, 185, 688, 1324, 2549, 4908 sec) are also shown. The coefficients of equation 3.2 (A, B, and C) for each material, at all twelve time points shown in Figs. 3.11 - 3.16 are given in Appendix A.

3.3 CYCLIC LOADING

The cyclic tests were designed to compare the cyclic behavior of cement paste, mortar and concrete subjected to a variety of cyclic load regimes. The results from a total of seventeen cyclic tests are reported. The materials and σ/f' ranges for each test are given in Table 3.5.

It is clear from previous research (Whaley and Neville 1973, Cook and Chindaprasirt 1980, Brooks and Forsyth 1986), and the work presented here, that cyclically loaded concrete undergoes larger strains than concrete exposed to a sustained load equal to the mean cyclic stress. The reasons for the larger strains are at least two-fold. First, static creep is a non-linearly increasing function of stress, with greater creep occurring at stresses above the mean stress, compared to stresses below the mean stress. Thus, the "static creep" portion of the total strain accumulated in a cyclic test should be greater than static creep produced at the mean cyclic stress. Second, a portion of the total strain may result directly from the cyclic nature of the loading. The goal of the analysis that follows next is to separate the strain due to the effective sustained load (the equivalent static creep or equivalent creep) from the strain due to the cyclic action.

The resulting strains will then be used, along with changes in the material moduli, to help determine the mechanisms that cause the strain. Some strains are directly related to microcracking of the material. Microcracking and its associated strains can be correlated with permanent damage occurring in the material, and changes in the modulus of elasticity have been shown to be a useful measure of that damage (Spooner and Dougill 1975, Attiogbe and Darwin 1985). Of specific interest is whether cyclic loads result in additional microcracking or accelerated creep.

Taking a small enough time interval, a cyclic test may be thought of, mathematically, as a series of short sustained load tests. For material cycling between two fixed values of σ/f', one estimate of strain due to the mechanisms that cause static creep can be made by averaging the values of creep strain recorded for specimens at the maximum and minimum stress-strength ratios for the same point in time. However, since the relationship between creep strain and stress-strength ratio is nonlinear, a better estimate can be obtained by averaging the creep strain over the entire range of stress. This can be accomplished by integrating the σ/f' versus static creep curve, for the given material at the point in time of interest (Figs. 3.11 - 3.16), between the maximum and minimum stress-strength ratios and dividing the integral by the range of stress-strength ratio. This average strain is the equivalent creep strain, ε_{ec}.

The raw data from the cyclic tests must be modified before it can be compared with ε_{ec}, because the data collection was not synchronized with the peak stresses in each cycle. Thus, the strain at maximum stress (unloading strain, ε_u) must be estimated. This is done by passing a parabola through the last three data points on the ascending branch of the stress-strain curve. ε_u is then the strain at the point of intersection of the parabola with a straight line representing the maximum stress for the test. A typical plot of actual data and the estimated peak strain is shown in Fig. 3.17. The strain at minimum stress (residual strain, ε_r) is estimated in a similar fashion.

The portion of the strain due to the cyclic action, ε_{ca}, can be estimated by subtracting the equivalent creep, ε_{ec}, from the total cyclic strain, ε_{cy} ($\varepsilon_{cy} = \varepsilon_t - \varepsilon_{15}$, ε_t = total strain). ε_{ca} may result from damage, presumably microcracking, but may also include additional consolidation and other mechanisms of static creep aggravated by the cyclic nature of the load.

Since creep strain includes strain due to both consolidation and material damage, ε_{ec} is not strictly a measure of either. However, the microcracking studies of Attiogbe and Darwin (1985) show that sustained loading results in less damage than cyclic loading to the same strain. The tests reported in section 3.5 also support this observation. Thus, as a component of total strain, ε_{ec} should be viewed as representing less damage than ε_{ca}.

Changes in the modulus of elasticity can be used to quantify the damage occurring during a cyclic test. Two measures of the modulus of elasticity are examined. The initial modulus, E_i, is found by passing a parabola through the first three points on the ascending branch of the stress-strain curve and finding the slope at $0.1f'_c$. The secant unloading modulus, E_{su}, is defined as the slope of a line through the estimated maximum strain for a cycle and the following estimated minimum strain.

Both E_i and E_{su} provide useful gages of the structural integrity of a material, since they represent the state of the material at a particular point in time. Thus, they reflect both the positive effects of consolidation and the negative effects of microcracking. Values of E_i and E_{su} are tabulated in Appendix B as a function of number of load cycles and time. Example plots of E_i and E_{su} as functions of the number of cycles of loading (for cement paste specimen 1D2, mortar specimen 2C2, and concrete specimen 3C2, all loaded from 0 to $0.8f'$) are shown in Figs. 3.18 - 3.20.

Of the two measures of modulus, E_i exhibits more scatter than E_{su}. E_i generally exhibits less scatter in high stress range tests than in low stress range tests. This may be due to the data points lying further apart in the higher stress tests and the parabolic fit being less sensitive to minor fluctuations. E_i also exhibits less scatter for cement paste than for mortar or concrete. E_i is always greater than E_{su} for paste (as shown in Fig. 3.18) and for low stress tests of mortar and concrete. For high stress ($\sigma/f' \geq 0.6$) tests of mortar and concrete, E_i typically starts out at a higher value than E_{su} but drops below E_{su} after about 45 cycles (Figs. 3.19 and 3.20). This appears in the stress - strain curve as a change from a "clam shell" shape to a "banana" shape as the test progresses. This can be seen in Fig. 3.21, which shows cycle number 2 (leftmost cycle) and cycle number 124 (rightmost cycle), for specimen 2C2, beginning at 30 seconds and 3720 seconds, respectively. Early in the test (cycle 2), there is a significant increase in the strain, at zero stress, between the beginning and end of the cycle. Later in the test (cycle 124), the beginning and ending strain are nearly equal, indicating that larger unrecoverable strains accumulate in the initial cycles than in later cycles.

The change in the shape of the stress - strain curve (from clam shell to banana shape) is most likely due to large microcracks that open up as mortar and concrete are unloaded, thereby reducing the effective load carrying area of the specimen cross section when the load is removed. As the specimen is reloaded, the apparent stiffness of the material increases only as the cracks reclose, resulting in the lower portion of the stress-strain curve being concave leftward.

Due to the lack of aggregate and the relatively localized cracking in cement paste, the ascending branch of the stress-strain curves is typically concave rightward and more consistent from cycle to cycle.

Figs. 3.22 - 3.24 show complete stress - strain records for cement paste specimen 1D2, mortar specimen 2C2, and concrete specimen 3C2.

3.4 CYCLIC TEST RESULTS

The cyclic test results show that cycles to a maximum stress of 0.6f′ or less produce only small changes in stiffness (less than 10 percent) and similarly small cyclic action strains for all six materials. This observation is in general agreement with the work of a number of previous researchers (Whaley and Neville 1973, Cook and Chindaprasirt 1980, Maher and Darwin 1980 and 1982) who identified a value of maximum stress, about 0.5f′, below which little or no damage occurs.

Typically, both cyclic strain and equivalent creep accumulate rapidly during the first 45 cycles, and then accumulate at a slower rate throughout the balance of the test. Figs. 3.25 - 3.41 present plots of cyclic strain and equivalent creep versus time for all seventeen cyclic tests. Figs. 3.42-3.47 show cyclic action strain versus time for each test. Figs. 3.48-3.53 show the corresponding changes in E_{su} versus number of cycles.

The results from one test will be used to illustrate the information that can be obtained from the figures. Fig. 3.29 is a plot of ε_{cy} and ε_{ec} versus time for mortar specimen 2C5 (w/c = 0.5, loaded from 0.2 to $0.6f'_m$). The difference between the two curves is the cyclic action strain, ε_{ca}, shown in Fig. 3.43. Fig. 3.49 shows E_{su}

versus number of cycles for three w/c = 0.5 mortar specimens (including specimen 2C5) at stress ranges of 0-0.4f'_m, 0.2-0.6f'_m, and 0-0.8f'_m.

In tests where the maximum σ/f' is less than 0.6, the strain that accumulates after 45 cycles (1350 seconds) appears to be primarily equivalent creep (ε_{ca} tends to stabilize after 45 cycles). The change in modulus, from initial to final, generally increases with maximum stress. However, the change in modulus of specimens with $\sigma/f' \leq 0.6$ is much smaller than observed for specimens with $\sigma/f' > 0.6$.

Tests with a cyclic stress range of 0-0.8f'_m consistently exhibit a marked loss of stiffness and large cyclic action strains. The much greater changes in stiffness observed in the 0-0.8f' tests are evident in Fig. 3.49.

Comparing cement paste to mortar and concrete reveals that, in general, all measures of strain are larger for paste than for mortar and larger for mortar than for concrete. This comparison also indicates that fine and coarse aggregate reduce average creep strains and damage strains, as well as average strains on the initial load cycle, ε_{15}. The addition of aggregate increases the initial stiffness, with E_i of mortar and concrete being nearly equal for these mixes, and approximately double that of cement paste. The change in stiffness from initial loading to failure during a cyclic test is greatest for mortar and least for cement paste, with concrete falling in the middle. This may be due to the fact that the addition of fine aggregate creates numerous stress concentrations in the material, leading to crack damage in the mortar matrix (Spooner, Pomeroy and Dougill 1976).

In the descriptions that follow, specimen response will be compared at 45 cycles and at 4 hours or the time at which the test ended, prior to 4 hours. The final values of total strain, ε_t, cyclic strain, $\varepsilon_{cy} = \varepsilon_t - \varepsilon_{15}$, equivalent creep strain, ε_{ec}, and cyclic action strain, ε_{ca}, for all cyclic tests (whether the test reached the time limit of four hours or the specimen failed prior to the four hour limit) are listed in Table 3.6, in addition to the strain at the peak of the first cycle, ε_{15}.

Table 3.7 lists the values of ε_{cy} at 45 cycles and at 4 hours, or at failure, and the ratio of ε_{cy} at 45 cycles to ε_{cy} final. This table shows that, for all tests, a minimum of 16 percent and a maximum of 62 percent of the total cyclic strain occurs during the first 45 cycles. The percentage of total cyclic strain occurring during the first 45 cycles is least for 0 - 0.8f′ specimens. For these tests, an average of 26 percent of the total cyclic strain occurs during the first 45 cycles. For tests with a maximum cyclic stress of 0.6f′ or less, an average of 53 percent of the total cyclic strain occurs during the first 45 cycles.

Table 3.8 lists ε_{ec} at 45 cycles and at the end of the test, and the ratio of ε_{ec} at 45 cycles to ε_{ec} final. This table shows that a minimum of 42 percent and a maximum of 67 percent of the equivalent static creep occurs during the first 45 cycles of a test. For tests with a maximum cyclic stress of 0.8f′, an average of 60 percent of the total equivalent creep occurs during the first 45 cycles. For tests with a maximum cyclic stress of 0.6f′ or less, an average of 55 percent of total equivalent creep occurs during the first 45 cycles.

Table 3.9 lists ε_{ca} at 45 cycles, ε_{ca} final, and the change in ε_{ca} between 45 cycles and the end of the test. Change in ε_{ca} is more readily interpreted than a ratio of the value at 45 cycles to the final value. This table shows that a minimum of -7 $\mu\varepsilon$ (indicating a value close to zero) and a maximum of 2134 $\mu\varepsilon$ occurs between 45 cycles and 4 hours, or failure of the specimen. For tests with a maximum cyclic stress of 0.8f′, an average of 1413 $\mu\varepsilon$ occurs between 45 cycles (22.5 minutes) and the end of the test. For tests with a maximum cyclic stress of 0.6f′ or less, an average of 15 $\mu\varepsilon$ occurs between 45 cycles and the end of the test. The limited data presented in this table indicates that, below a stress of 0.6f′, the cyclic action of the load causes little or no additional strain due to accelerated creep or microcracking.

The absence of damage due to cycles with a maximum stress ≤ 0.6f′ is in general agreement with previous research. The fact that equivalent creep accounts for nearly all of the cyclic strain indicates that static creep is not accelerated by cyclic loading, in contrast to earlier statements by Whaley and Neville (1976). The reason for the contrasting conclusions is due to the ability of equivalent creep to take into account the nonlinear relationship of static creep and applied stress which is not taken into account when creep is based on the mean cyclic stress (Whaley and Neville 1976).

Three of the low maximum stress tests (2C3, 4C4, 5C5) had negative ending values of ε_{ca}. The cyclic action strain (a calculated, not measured, strain) actually decreases between 45 cycles and the end of the test for specimens 2C3 and 5C5. This indicates that either total cyclic strain is accumulating more slowly in the cyclically loaded specimen than is creep strain in a specimen loaded to an equivalent static load, or more likely that the total strain is due essentially to creep and that the values of ε_{ca} calculated for these tests are well within the combined accuracy of the tests and the analysis. The values of e_{ec} and ε_{ca} as a percent of total strain and cyclic strain are given in Table 3.10.

The change in modulus can be used to estimate how much of the damage is occurring early in the test. Initial E_{su}, final E_{su}, change in E_{su} and percent change in E_{su} are given in Table 3.11. For tests with a maximum cyclic stress of 0.6f′ or less, nearly all of the decrease in modulus occurs during the first 45 cycles of the test. The modulus of elasticity actually increases between 45 cycles and the end of the test for specimens 2C5 and 4C5, indicating that consolidation is taking place, with little or no additional microcracking. Specimens with a maximum cyclic stress of 0.8f′ have much greater decreases in stiffness during the first 45 cycles than lower maximum stress tests and continue to degrade in stiffness throughout the test.

3.4.1 DISCUSSION OF INDIVIDUAL TEST RESULTS

Two cyclic tests of cement paste with w/c = 0.5 were conducted, 1D2 with a cyclic stress range of 0-0.8f'_p, and 1D3 with a cyclic stress range of 0-0.4f'_p.

Fig. 3.25 shows ε_{cy} and ε_{ec} versus time for test 1D2 (0-0.8f'_p). Both ε_{cy} and ε_{ec} accumulate rapidly for the first 1350 sec (45 cycles) of the test, and then increase at a reduced, but steady, rate until failure. At failure, the cyclic strain is 2115 $\mu\varepsilon$, of which 32 percent is equivalent creep and 68 percent is cyclic action strain. Table 3.8 and Fig. 3.42 shows that the cyclic action strain at 45 cycles is 354 $\mu\varepsilon$, or 25 percent of the cyclic action strain at failure, 1439 $\mu\varepsilon$. Fig. 3.48 (dashed line) and Table 3.11 show the loss of stiffness (E_{su}) for the test. At 45 cycles, the drop in stiffness is 16 percent, slightly over half of the total change to failure. At failure, E_{su} has dropped 27 percent from its initial value. Using change in E_{su} as a measure of damage, over half of the total damage occurs during the first 45 cycles. The equivalent creep at 45 cycles is 346 $\mu\varepsilon$ or half of the 677 $\mu\varepsilon$ at failure. However, only a third of the cyclic strain occurs in the first 45 cycles. Over 67 percent of the cyclic strain and 75 percent of the cyclic action strain occur after the first 45 cycles.

Fig. 3.26 shows ε_{cy} and ε_{ec} versus time for test 1D3 (0-0.4f'_p). Again, strains accumulate more quickly for the first 45 cycles of the test and then continue to increase at a slower rate. Nearly half of the 155 $\mu\varepsilon$ total cyclic strain accumulates during the first 22 minutes of the 4 hour test. At 45 cycles, the equivalent creep is virtually equal to (actually slightly larger than) the cyclic strain resulting in a cyclic action strain of -10 $\mu\varepsilon$. This indicates that the total strain is due to creep, i.e. that the cyclic nature of the loading has no effect. After four hours, the cyclic strain is equal to the equivalent creep strain, providing the same conclusion. Fig. 3.42 shows that the cyclic action strain is negligible, while Fig. 3.48 and Table 3.11 show that E_{su}

decreases 3 percent during the first 45 cycles and decreases another 1 percent during the remainder of the test.

Three cyclic tests of mortar with w/c = 0.5 were conducted, 2C2 with a cyclic stress range of 0-0.8f'_p, 2C3 with a cyclic stress range of 0-0.4f'_p, and 2C5 with a cyclic stress range of 0.2-0.6f'_p. Specimen 2C2 failed at 296 cycles. Specimens 2C3 and 2C5 lasted the full 4 hours.

Fig. 3.27 shows ε_{cy} and ε_{ec} versus time for test 2C2 (0-0.8f'_m). As with the w/c = 0.5 paste, the rate of increase in both cyclic strain and equivalent creep is higher initially, accumulating 22 percent of the total cyclic stain and 65 percent of the total equivalent creep strain during the first 45 cycles. At 45 cycles, 25 percent of the cyclic strain is equivalent creep and 75 percent is cyclic action strain. During the first 45 cycles, 18 percent of the total cyclic action strain accumulates and 23 percent of the total change in stiffness occurs, decreasing 17 percent from its initial value. Fig. 3.49 and Table 3.11 show that the drop in E_{su} is similar to the accumulation in cyclic strain, with E_{su} dropping quickly at first, continuing to drop at a slower but steady rate, and then dropping sharply as the specimen approaches failure. Fig. 3.43 shows that the cyclic action strain accumulates very rapidly as the specimen approaches failure. At failure, the cyclic strain is 2820 $\mu\varepsilon$, of which 8 percent is equivalent creep and 92 percent is cyclic action strain. The total change in E_{su} is 56 percent. The figures show that degradation of the mortar is continuous throughout the test.

Fig. 3.28 shows ε_{cy} and ε_{ec} versus time for test 2C3 (0-0.4f'_m). At 45 cycles, 50 percent of the total cyclic strain has accumulated and is completely accounted for by equivalent creep. As the test continues, the cyclic specimen accumulates less strain than a specimen loaded with an equivalent static load. The equivalent creep at the end of the test slightly exceeds the measured cyclic strain, yielding a small negative cyclic action strain (Fig. 3.43). At 45 cycles, the decrease in E_{su} is 4 percent. Although Fig. 3.49 (dotted line) shows that E_{su} varies somewhat after 45 cycles, the decrease in E_{su} is 4 percent at the end of the test, and it appears that most of the damage to the specimen occurs during the first 45 cycles.

Fig. 3.29 shows ε_{cy} and ε_{ec} versus time for test 2C5 (0.2-0.6f'_m). Again, approximately 50 percent of the total cyclic strain and total equivalent creep occurs during the first 45 cycles. The stiffness decreases 3 percent during the first 45 cycles but recovers to a 1 percent decrease over the 4 hour test (Fig. 3.49). The increase in modulus, between 45 cycles and the end of the test, observed for this test and some of the other low stress tests indicates that beneficial consolidation may counteract the reduction in stiffness due to microcracking. At the end of the test, the total cyclic strain is 75 $\mu\varepsilon$, of which 68 percent is equivalent creep and 32 percent is cyclic action strain (Fig. 3.43). The 0.2 - 0.6f'_m test recorded 5 times as much cyclic strain and twice as much equivalent creep as the 0 - 0.4f'_m test.

Three cyclic tests of concrete with w/c = 0.5 were conducted, 3C2 and 3C4 with a cyclic stress range of 0-0.8f'_c, and 3C5 with a cyclic stress range of 0.2-0.6f'_c. Specimens 3C2 and 3C4 failed after 205 and 240 cycles, respectively, while specimen 3C5 lasted the full 4 hours.

Fig. 3.30 shows ε_{cy} and ε_{ec} versus time for test 3C2 (0-0.8f'_c). At 45 cycles, the accumulated cyclic strain is 36 percent of the final cyclic strain and the equivalent creep is 67 percent of its final value. Fig. 3.44 shows that the cyclic action strain at 45 cycles is 45 percent of its final value. At failure, the cyclic strain is 727 $\mu\varepsilon$, of which just 14 percent is equivalent creep and 86 percent is cyclic action strain. Fig. 3.50 shows that E_{su} decreases 13 percent in the first 45 cycles, with a final drop of 28 percent.

Fig. 3.31 shows ε_{cy} and ε_{ec} versus time for test 3C4 (0-0.8f'_c). This is the only duplicate cyclic test data available (same batch and load regime as 3C2). At 45 cycles, the cyclic action strain is nearly equal to that of specimen 3C2 (Fig. 3.44) and the equivalent creep is nearly identical. After 45 cycles, test 3C4 accumulates slightly higher values of cyclic action strain than specimen 3C2. Specimen 3C4 failed during one of the groups of pre-selected cycles for which data was recorded (as did cyclic specimens 2C2 and 6C2) while specimen 3C2 (and 1D2) failed at a point in time during which no data was being collected. For this reason the recorded ending strain and decrease in modulus is disproportionately small for specimen 3C2 compared to specimen 3C4. For specimen 3C4, 16 percent of the total cyclic strain and 64 percent of the equivalent creep occur during the first 45 cycles. At failure, the cyclic strain is 1818 $\mu\varepsilon$, of which 6 percent is equivalent creep and 94 percent is cyclic action strain. Fig. 3.50 (lower dashed line) shows that the percent decrease in E_{su} is 11 percent at 45 cycles and 39 percent at failure. Until the unrecorded failure of 3C2, both specimens exhibited very similar changes in E_{su} and strain.

Fig. 3.32 shows ε_{cy} and ε_{ec} versus time for test 3C5 (0.2-0.6f'_c). Over half of the total cyclic strain and equivalent creep occurs during the first 45 cycles. The final cyclic strain is 141 $\mu\varepsilon$, of which 37 percent is cyclic action strain (Fig. 3.44). As with low stress tests of cement paste and mortar, the small drop in stiffness occurs early in the test.

Four cyclic tests of cement paste with w/c = 0.7 were conducted, 4C2 with a cyclic stress range of 0-0.8f'_p, 4C3 with a cyclic stress range of 0-0.4f'_p, 4C4 with a cyclic stress range of 0.1-0.3f'_p, and 4C5 with a cyclic stress range of 0.2-0.6f'_p. None of the tests resulted in failure. Test 4C4 was terminated early at 245 cycles due to equipment problems.

Fig. 3.33 shows ε_{cy} and ε_{ec} versus time for test 4C2 (0-0.8f'_p). Again, the rate of increase in cyclic strain and equivalent creep is higher for the first 45 cycles (29 percent of the total cyclic strain and 50 percent of the total equivalent creep) than for the remainder of the test. 579 $\mu\varepsilon$ of cyclic action strain accumulates during the first 45 cycles (the highest of all tests), which is 24 percent of the final cyclic action strain value (Fig. 3.45). At 45 cycles, the equivalent creep accounts for 34 percent of the cyclic strain. Fig. 3.51 (dashed line) shows that E_{su} drops very quickly during the first 45 cycles, decreasing 23 percent, and then continues to drop at a reduced rate throughout the test, accumulating a 39 percent total loss of stiffness over the four hours. The specimen did not fail, and the cyclic strain at four hours is 3017 $\mu\varepsilon$, of which 20 percent is equivalent creep and 80 percent is cyclic action strain.

Fig. 3.34 shows ε_{cy} and ε_{ec} versus time for test 4C3 (0-0.4f'_p). During the first 45 cycles, 47 percent of the total cyclic strain and 52 percent of the total equivalent creep accumulates. At 45 cycles, all of the cyclic strain is accounted for by equivalent creep, and the cyclic action strain is 0. Fig. 3.51 (solid line) shows that all of the 3 percent total decrease in stiffness occurs during the first 45 cycles. Of the total cyclic strain (13 $\mu\varepsilon$), 90 percent is equivalent creep and 10 percent is cyclic action strain, suggesting that little, if any, damage has occurred.

Fig. 3.35 shows ε_{cy} and ε_{ec} versus time for test 4C4 (0.1-0.3f'_p). The data for this test at 45 cycles was lost and is therefore not recorded in Table 3.5. At the end of the test (245 cycles), the cyclic strain is 66 $\mu\varepsilon$ and the equivalent creep is 80 $\mu\varepsilon$, resulting in a cyclic action strain of -14 $\mu\varepsilon$ (Fig. 3.45). Fig. 3.51 (small dashed line) shows that all of the 3 percent decrease in E_{su} occurs during the first 45 cycles.

Fig. 3.36 shows ε_{cy} and ε_{ec} versus time for test 4C5 (0.2-0.6f'_p). At 45 cycles, the specimen has already accumulated 56 percent of the total cyclic strain, 53 percent of the total equivalent creep, and over 80 percent of the total cyclic action strain (43 $\mu\varepsilon$). At 45 cycles, the total cyclic strain is 219 $\mu\varepsilon$, of which 85 percent is equivalent creep. Fig. 3.51 (dotted line) shows that the decrease in E_{su} occurs almost entirely during the first 45 cycles, dropping 7 percent. E_{su} drops 9 percent by the end of the four hour test. Of the total cyclic strain (392 $\mu\varepsilon$), 89 percent is equivalent creep and 11 percent is cyclic action strain. For this test, the majority of cyclic action strain occurs, like the change in modulus, during the first 45 cycles.

Three cyclic tests of mortar with w/c = 0.7 were conducted, 5C2 with a cyclic stress range of 0-0.8f'_p, 5C3 with a cyclic stress range of 0-0.4f'_p, and 5C5 with a cyclic stress range of 0.2-0.6f'_p. None of the specimens failed during the 4 hour test.

Fig. 3.37 shows ε_{cy} and ε_{ec} versus time for test 5C2 (0-0.8f'_m). At 45 cycles, only 19 percent of the total cyclic strain has occurred. The equivalent creep is 51 percent of its final value. The cyclic action strain is 357 $\mu\varepsilon$, which is 16 percent of the final cyclic action strain of 2162 $\mu\varepsilon$ (Fig. 3.46). During the first 45 cycles, the stiffness decreases 25 percent. At four hours, the cyclic strain was 2361 $\mu\varepsilon$, of which 8 percent is equivalent creep and 92 percent is cyclic action strain. Fig. 3.52 (dashed line) shows that the change in E_{su} behaves similarly to the cyclic strain (Fig. 3.46), dropping quickly at first, continuing to drop at a slower but steady rate, and dropping quickly again near the end of the test, with a total change in E_{su} of 55 percent. The figures show that degradation of the mortar is continuous throughout the test.

Fig. 3.38 shows ε_{cy} and ε_{ec} versus time for test 5C3 (0-0.4f'_m). At 45 cycles, approximately half of the total cyclic strain, equivalent creep, and cyclic action strain have accumulated and the equivalent creep accounts for slightly less than half of the cyclic strain. Cyclic action strain versus time is plotted in Fig. 3.46. The decrease in stiffness at 45 cycles is 7 percent. At four hours, equivalent creep is 40 percent, and cyclic action strain is 60 percent of the final total cyclic strain of 59 $\mu\varepsilon$. Fig. 3.52 (dotted line) shows E_{su} drops 6 percent during the first 45 cycles and drops another 2 percent during the remainder of the four hour test.

Fig. 3.39 shows ε_{cy} and ε_{ec} versus time for test 5C5 (0.2-0.6f'_m). At 45 cycles, 62 percent of the total cyclic strain and 56 percent of the total equivalent creep have occurred, with the cyclic action strain being 5 $\mu\varepsilon$ or 10 percent of the cyclic strain. At the end of the four hour test, the cyclic action strain has decreased 6 $\mu\varepsilon$, to -1 $\mu\varepsilon$ (Fig. 3.46). Fig. 3.52 (solid line) shows that E_{su} decreases 7 percent in the first 45 cycles and only an additional 1 percent during the four hour test. Again, it appears from the change in modulus that nearly all of the damage takes place during the first 45 cycles. However, over 91 percent of the cyclic strain at 45 cycles is predicted by the equivalent creep.

Two cyclic tests of concrete with w/c = 0.7 were conducted, 6C2 with a cyclic stress range of 0-0.8f'_c and 6C5 with a cyclic stress range of 0.2-0.6f'_c. Specimen 6C2 failed at 165 cycles while specimen 6C5 lasted the full 4 hours.

Fig. 3.40 shows ε_{cy} and ε_{ec} versus time for test 6C2 (0-0.8f'_c). At 45 cycles, 73 percent of the total equivalent creep has already accumulated, while only 24 percent of the total cyclic strain has occurred. The equivalent creep only accounts for 16 percent of the 361 $\mu\varepsilon$ of cyclic stain at 45 cycles. The cyclic action strain at 45 cycles is 303 $\mu\varepsilon$ (Fig. 3.47), and the decrease in stiffness is 22 percent. At failure, the accumulated cyclic strain is 1487 $\mu\varepsilon$, of which 5 percent is equivalent creep and 95 percent is cyclic action strain. Fig. 3.53 shows that E_{su} continues to decrease, with a 47 percent drop from its initial value. Nearly half of the decrease in stiffness occurs during the first 45 cycles, but only 22 percent of the cyclic action strain has accumulated at 45 cycles. In the high stress tests of concrete, cyclic actions strains appear to increase less rapidly than stiffness decreases during the first 45 cycles. Afterward, the changes in cyclic strain and E_{su} appear to be quite similar.

Fig. 3.41 shows ε_{cy} and ε_{ec} versus time for test 6C5 (0.2-0.6f'_c). At 45 cycles, 58 percent of the total cyclic strain and 67 percent of the total equivalent creep have accumulated, and the equivalent creep accounts for half of the cyclic strain. The stiffness decreases 3 percent in the first 45 cycles and decreases to a 4 percent drop at the end of the test. Cyclic action strain versus time is plotted in Fig. 3.47. At four hours the cyclic strain is 112 $\mu\varepsilon$, of which 43 percent is equivalent creep and 57 percent is cyclic action strain. Fig. 3.53 shows that for the low stress test, a small decrease in E_{su} occurs during the first 45 cycles.

3.4.2 EFFECT OF WATER-CEMENT AND AGGREGATE-CEMENT RATIOS

The mix proportions used in this study do not allow for the direct comparison of results based on water-cement ratio alone, since concrete proportions were modified by keeping the water content constant and reducing the amount of cement to increase the water-cement ratio from 0.5 to 0.7. The volume of the concrete, thus, was maintained by replacing the cement with an equal volume of fine aggregate. The w/c = 0.7 mixes, therefore, have a higher aggregate volume than do the w/c = 0.5 mixes. Since aggregate plays a significant role in reducing strains and increasing stiffness, the increased aggregate volumes obtained with the increased water-cement ratios for mortar and concrete contribute to differences in the behavior of the mixes.

The effects of cyclic loading as a function of mix proportions can be evaluated based on strain in 15 seconds, and strain and stiffness at 45 cycles from both the low and high stress cyclic tests. In the comparison that follows, it should be kept in mind that, except for w/c = 0.5 concrete, no test is replicated. Therefore, any analysis must rely on the bulk of the data, rather than on specific comparisons.

The overall test results, as reflected in Tables 3.1-3.11, indicate that w/c = 0.5 materials generally undergo less damage than the corresponding w/c = 0.7 materials. This is particularly evident in terms of the cyclic action strain, ε_{ca}, at 45 cycles, and the relative decrease in stiffness, E_{su}, both at 45 cycles and at the conclusion of the test. In terms of material response that is less closely connected to damage than ε_{ca} and change in E_{su}, the lower water-cement ratio materials generally show greater strains at 15 seconds and in all cases exhibit higher values of equivalent creep, equivalent creep as a percentage of total strain, and, with one exception (0.2 - $0.6f'_m$), equivalent creep as a percentage of cyclic strain.

Looking at the individual comparisons in Table 3.5, w/c = 0.5 paste and mortar specimens failed prior to the conclusion of the 4 hour test, at 405 and 196 cycles, respectively. The corresponding w/c = 0.7 specimens lasted for the full 4 hour duration. For concrete, the two w/c = 0.5 specimens, at 205 and 240 cycles, respectively, lasted longer than the w/c = 0.7 specimen, which failed at 165 cycles. All of the lower stress tests lasted the full 4 hours, with the exception of the test of the w/c = 0.7 paste specimen cycled from 0.1 - $0.3f'_p$, which was terminated early. Due to the limited number of tests, it is difficult to come a conclusion about the nature of damage as a function of water-cement ratio or aggregate-cement ratio based on the duration of the high stress cyclic tests. Useful information can be obtained, however, based on the comparisons that follow.

Information in Table 3.6, on the strain at 15 seconds, cyclic strain, equivalent creep, and cyclic action strain at the conclusion of the tests is combined with more detailed information in Tables 3.7, 3.8, and 3.9 on ε_{cy}, ε_{ec}, and ε_{ca} at 45 cycles to draw some useful conclusions about the effect of the mix proportions used on the nature of the response of the individual materials. At 15 seconds, the lower water-cement ratio specimens of mortar and concrete exhibit 37 to 83 percent higher strains than the w/c = 0.7 specimens. In contrast, the values of ε_{15} for the w/c = 0.5 and 0.7 cement paste specimens do not differ by more than 5 percent for either the 0 - $0.8f'_p$ or the 0 - $0.4f'_p$ load regime. The reason for this difference is due to the fact that the specimens were loaded to fixed percentages of ultimate strength. The stiffness of the aggregate remains constant throughout the test, and the response of the aggregate to load is the same for both water-cement ratios. Since the w/c = 0.7 mortar and concrete are loaded to lower stresses than the w/c = 0.5 materials, the strains in the aggregate are lower. In addition, since there is a greater proportion of aggregate in the higher water-cement ratio materials, as stress increases, the relative contribution of aggregate to stiffness increases as the stiffness of the paste decreases. The effect of this response is illustrated in Fig. 3.54 and 3.55 where the monotonic stress-strain curves for mortar and concrete are plotted in terms of stress-strength ratio versus strain. In these cases, the higher water-cement ratio materials exhibit relatively higher stiffnesses. This type of response is not exhibited to the same extent in cement paste. As illustrated in Fig. 3.56, w/c = 0.7 paste exhibits a relative stiffness that is nearly equal to the stiffness of the w/c = 0.5 paste.

The strains, ε_t, at the end of the 0 - 0.8f′ test are lower for the w/c = 0.5 pastes and concretes and higher for the w/c = 0.5 mortar than for the corresponding w/c = 0.7 materials. For the lower stress cyclic tests, ε_t is higher for the lower water-cement ratio materials, with the exception of the 0 - 0.4 f'_p tests where the strains are nearly identical.

In making the observations that follow, unless noted, the trends observed at 45 cycles are the same as those observed at the conclusion of the tests. For the 0 - 0.8f′ tests, paste and concrete exhibit increased cyclic strains, ε_{cy}, with increasing water-cement ratio, while the opposite is true for mortar. One of the w/c = 0.5 concrete specimens, however, has a strain greater than the w/c = 0.7 specimen. Increasing ε_{cy} with increasing water-cement ratio is also observed for all three materials in the lower stress tests, except for the 0 - 0.4 f'_m tests.

Equivalent creep is greater for the 0.5 w/c specimens than for the 0.7 w/c specimens at all stages of all tests in this study. The opposite is true for cyclic action strains at 45 cycles, with the exception of the 0 - 0.8 f'_m tests. At the conclusion of the tests, ε_{ca} is lower for the lower water-cement ratio cement paste and one of the lower water-cement ratio concretes, but higher for the lower water-cement ratio mortar.

The most useful comparisons can be obtained by comparing ratios of equivalent creep, ε_{ec}, and cyclic action strain, ε_{ca}, to total strain, ε_t, and cyclic strain, ε_{cy}, and percent changes in stiffness, E_{su}, for the materials. These comparisons strongly suggest that an increase in water-cement ratio and/or aggregate-cement ratio will lead to more rapid deterioration under cyclic loading. In all cases, equivalent creep represents a greater percentage of ε_t and, in all cases but one (0.2 - 0.6 f'_m), a greater percentage of ε_{cy} for the lower water-cement material. Conversely, ε_{ca} represents a higher percentage of ε_t (except for 0.2 - 0.6 f'_m and one 0 - 0.8f'_c) and ε_{cy} (except for 0.2 - 0.6f'_m and 0 - 0.8f'_m) for the w/c = 0.7 material than for the w/c = 0.5 materials. At 45 cycles and at the conclusion of the test (with the exception of 0 - 0.8f'_m final and 0.2 - 0.6f'_c 45 cycles and final), the percentage decrease in stiffness, a principal measure of damage, is greater for the higher water-cement ratio materials.

Since the comparisons of $\varepsilon_{ca}/\varepsilon_t$, $\varepsilon_{ca}/\varepsilon_{cy}$, and change in E_{su} can be made for cement paste, mortar, and concrete, it appears that, independent of the aggregate-cement ratio, an increase in the water-cement ratio will result in an increase in the degree of cyclic damage for materials cycled to the same stress-strength ratio.

3.4.3 EFFECT OF MAXIMUM STRESS

Many previous tests of cement paste, mortar and concrete subjected to cyclic loading have been analyzed based on the mean cyclic stress and the cyclic stress range. Although the strain at 15 seconds, ε_{15}, and cyclic strain, ε_{cy}, clearly increase with increases in either mean stress or stress range, large changes in E_{su} are observed only for cycles with a maximum stress greater than 0.6f′. Figs. 3.48-3.53 show the change in E_{su} versus number of cycles for cement paste, mortar and concrete at both w/c ratios. Figs. 3.42 - 3.47 show ε_{ca} versus time for the same tests. In all tests with a maximum stress-strength ratio of 0.6 or less, changes in stiffness occur almost entirely during the first 45 cycles or 22 minutes. In two cases, the stiffness recovers slightly between 45 cycles and the end of the test. As stated earlier, this may be due to beneficial, non-destructive consolidation of the material or due simply to scatter in the data.

The strain contribution due to cycling, ε_{ca}, is no greater than 12 percent of the total strain for any test with a maximum cyclic stress of 0.6f′ or less. It is impossible to determine precisely how much of the cyclic strain is creep and how much is related to microcracking resulting form the cyclic nature of the load. However, in many cases, the equivalent creep represents nearly all of the cyclic strain in the first 45 cycles and even over predicts the cyclic strain in test 1D5 (0.5 paste, 0-0.4f'_p). This indicates that at stresses below 0.6f′, the cyclic nature of the load has little effect.

In contrast, for tests with a cyclic stress range of 0-0.8f′, ε_{ca} at failure is as high as 68 percent of the total strain (0.7 w/c mortar). The corresponding 55 percent decrease in E_{su} confirms that considerable damage is taking place during cycling. The equivalent creep at failure is highest for 0-0.8f′ cycles, but equivalent creep as a percentage of total strain is generally lower for the high stress range tests than for low stress range tests (Table 3.10). Equivalent creep, as a percentage of total strain, is largest in tests with a cyclic stress range of 0.2 - 0.6f′, reaching 21 percent of the total strain and 89 percent of the cyclic strain for 0.7 w/c paste.

3.4.4 EFFECT OF MEAN STRESS

Previous research has separated the effect of stress range from that of mean cyclic stress. Stress ranges of 0 - 0.4f′ and 0.2 - 0.6f′ were tested for cement paste with w/c = 0.7 and mortar with w/c = 0.5 and 0.7 for the purpose of examining the effect of mean stress.

For w/c = 0.7 cement paste, holding the variation in stress constant while increasing the mean stress from 0.2 to $0.4f'_p$ increases the total strain by 70 percent and the cyclic strain, equivalent creep and cyclic action strains by 200 percent. For the 0 - $0.4f'_p$ test, the total cyclic action strain is only 1 percent of the final total strain and for the 0.2 - $0.6f'_p$, the total cyclic action strain is 3 percent of the final total strain. For w/c = 0.5 mortar, increasing the mean stress from 0.2 to $0.4f'_m$, increases the total strain by 100 percent, the cyclic strain by 400 percent and the equivalent creep and cyclic action strains by 200 percent. $\varepsilon_{cy}/\varepsilon_t$ increases from 0 for the 0 - $0.4f'_m$ test to 7 percent for the 0.2 - $0.6f'_m$ test. For w/c = 0.7 mortar, the total strain and cyclic strain increase by 30 percent and the equivalent creep increases by 200 percent, while the cyclic action strain actually decreases. However, in this case, $\varepsilon_{cy}/\varepsilon_t$ decreases from 9 percent for the 0-$0.4f'_m$ test to 0 percent for the 0.2-$0.6f'_m$ test.

With the limited amount of data available, it is difficult to make quantitative assessments of the relationship between mean stress and the various measures of strain and stiffness. However, it should be noted that equivalent creep, as a percent of total strain, is greatest for the 0.2 - 0.6f′ tests (a mean stress level of 0.4f′), because the cyclic strain values remain relatively small as long as the stress remains below 0.6f′. Consideration of the mean stress value alone fails to account for the large increases in all measures of strain that occur when the maximum stress is greater than or equal to 0.8f′.

3.4.5 EFFECT OF CYCLIC STRESS RANGE

Holding the mean cyclic stress constant and increasing the range of stress over which the specimen is loaded produces increases in both consolidation and cracking. A comparison of the stress ranges 0.2-0.6f′ and 0-0.8f′ was intended to provide some insight into the effect of stress range. It is obvious that, for all materials tested, the 0-0.8f′ stress range produces considerably larger strains and changes in stiffness. It is not clear whether this is a result of increased range of stress or increased maximum stress. Similarly, maintaining an average cyclic stress of $0.2f'_p$ and increasing the cyclic stress range from $0.1\text{-}0.3f'_p$ to $0\text{-}0.4f'_p$ (w/c= 0.7) results in a small increase in cyclic action and total strains, but with a 3 percent decrease in modulus occurring for both tests. Again, it is difficult to distinguish between the effects of stress range and the effects of maximum stress. Comparing results for the 0.2-0.6f′ range tests to results for the 0-0.4f′ tests, there is clearly a small increase in accumulated cyclic strains. This lends some support to the idea that maximum stress is the primary factor. Other research has indicated that there is an effect of stress range. However, based on research by Maher and Darwin (1980, 1982) and others (Whaley and Neville 1973), these results are probably influenced to a larger degree by the level of maximum stress.

3.4.6 PASTE COMPARED TO MORTAR

At a w/c = 0.5 and a stress range of 0-0.8f′, cement paste exhibits about 50 percent more strain at 15 seconds and 200 percent more equivalent creep at failure than mortar. However, at failure, mortar exhibits 30 percent more cyclic strain than paste; the total strains at failure are approximately equal. The cyclic action strain in mortar is nearly 100 percent greater than that of cement paste, and the change in stiffness of mortar is about 200 percent greater than that of cement paste. This is in agreement with the earlier observation of Spooner, Pomeroy and Dougill (1976) that the introduction of aggregate makes the mortar more susceptible to microcracking damage than cement paste. Fig. 3.57 shows that w/c = 0.5 mortar degrades faster than cement paste. After 45 cycles, the rate of degradation of both materials tends to slow and the loss of stiffness continues at a much reduced rate. Near failure, the stiffness of the mortar drops precipitously, in contrast to cement paste which appears to loose stiffness at nearly a constant rate until failure. This is related to the fact that mortar fails more gradually than cement paste, with a large volume of material sustaining damage, while damage in cement paste is relatively localized.

The 0-0.4f′ test results show that paste has 100 percent more strain at 15 seconds and at the end of the test, and 200 percent more cyclic strain, equivalent creep, and cyclic action strain than mortar. The change in modulus is negligible in either case. Very little damage occurs at the lower stress range, and the stiffer mortar accumulates less strain than the cement paste. At the higher stresses, strains that result from damage dominate the behavior, and mortar suffers more damage than paste due to its nonhomogeneous nature.

For the w/c = 0.7 materials at 0 - 0.8f′, the strain at 15 seconds, cyclic strain, and equivalent creep are all at least 50 percent higher for cement paste than for mortar, while the cyclic action strains are nearly equal. The decrease in stiffness at the end of the test is 55 percent for mortar compared to 39 percent for cement paste. Fig. 3.58 shows that mortar degrades in stiffness more rapidly than cement paste throughout the test. The w/c = 0.7 mortar does not exhibit the accelerated loss of stiffness that the 0.5 w/c mortar does near failure, but the w/c = 0.7 mortar did not fail (note only a single test of each was conducted). At 485 cycles, cement paste exhibits a decreased stiffness, although the curve appears to be concave upward, indicating possible stability at some greater number of cycles.

For tests at 0 - 0.4f′ and 0.2 - 0.6f′, as with the higher stress tests, the strains in cement paste are somewhat larger than in the corresponding mortar. For the 0 - 0.4f′ stress range, mortar drops 7 percent in stiffness while cement paste drops only 3 percent. For the 0.2-0.6f′ stress range, paste drops 9 percent in stiffness while the mortar drops 8 percent.

These comparisons indicate some trends, but it should be kept in mind that these results represent only individual tests of each material and load regime combination. In general, the primary differences between mortar and cement paste are in stiffness and susceptibility to damage. The aggregate particles in mortar give the material a higher initial stiffness than cement paste and therefore the strains, at stresses below 0.6f′, are smaller for mortar. The aggregate, being stiffer than the surrounding paste, also creates stress concentrations in the paste. When the stresses are high enough, the stress concentrations cause microcracks to form and propagate through the paste. The result is a greater drop in stiffness for mortar than for cement paste (note that this is so, even though the maximum stresses are less for mortar than for cement paste loaded over the same σ/f' range). Thus, it can be concluded that, for loads above 0.6f′, mortar sustains more crack damage than does the more homogeneous cement paste.

3.4.7 MORTAR COMPARED TO CONCRETE

The behavior of mortar more closely resembles that of concrete than it does cement paste. The composite nature of these materials dominates their behavior. Looking at tests with a cyclic stress range of 0-0.8f′ for mortar and concrete at w/c = 0.5, mortar sustains 30 to 300 percent more strain, for each measure of strain, than does concrete. The lower strain in the concrete is undoubtedly due to the higher total aggregate content which limits average strains in the material. ε_{ca} is higher for mortar than for concrete as is the decrease in modulus (73 percent for mortar versus 27 and 63 percent for the two concrete specimens). Fig. 3.57 shows that the stiffness of mortar degrades more rapidly than the stiffness of concrete throughout the test. For both materials, stiffness decreases rapidly at the beginning of the test, continues to decrease at a reduced rate as the test continues, and decreases rapidly once again as failure is approached. $\varepsilon_{ca}/\varepsilon_{cy}$ are about equal for both materials. The mortar specimen lasted 196 cycles, while the two concrete specimens lasted 205 cycles and 240 cycles. It is important to note that, although the concrete sustains substantial damage and fails in less than the four hour test period, as did the mortar, the presence of the coarse aggregate limits both total strain and reduction in stiffness. Tests at lower stress ranges for the same w/c yield similar comparisons. In general, mortar undergoes larger strains and a greater decrease in stiffness than concrete at this w/c.

For w/c = 0.7, the mortar accumulates larger strains than does concrete. For both high and low stress tests, $\varepsilon_{ca}/\varepsilon_{cy}$ is about equal for the two materials. Fig. 3.57 shows that mortar initially looses stiffness more rapidly than concrete, but that after the first 45 cycles, concrete looses stiffness more rapidly than mortar and fails after just 165 cycles. In contrast, mortar maintains a steady decrease in stiffness and does not fail within the 485 cycle test. The change in stiffness (initial to final) for the 0-0.8f′ tests is 55 percent for mortar and 46 percent for concrete. For the 0.2-0.6f′ stress range, mortar accumulates more total strain and cyclic strain but less cyclic action strain than concrete. The mortar drops 8 percent in stiffness while the concrete drops 3 percent.

In spite of the differences in material response, the overall nature of damage appears to be quite similar in mortar and concrete, which suggests that the behavior of concrete under cyclic loading is dominated by its mortar constituent.

3.4.8 PASTE COMPARED TO CONCRETE

For w/c = 0.5, over the course of the tests, cement paste cycled from 0 to 0.8f′ accumulates 100 to 200 percent higher strain than concrete, for each measure of strain, with the exception of equivalent creep, which is 500 to 600 percent higher for paste than for concrete. Cyclic action strain as a percent of cyclic strain is 68 percent for the paste and 86 percent for the concrete, while the decrease in modulus is 27 percent for both.

For w/c = 0.7 paste and concrete cycled from 0 to 0.8f′, paste also accumulates much higher strain than does concrete. However, the cyclic action strain as a percent of cyclic strain is 80 percent for paste compared to 95 percent for concrete, and the decrease in modulus is 39 percent for paste compared to 46 percent for concrete. Although the strain is larger in cement paste than in concrete, a greater percentage of the strain in concrete, than in cement paste, is damage related. Figs. 3.57 and 3.58 show that the moduli of elasticity of the concrete specimens drop more rapidly than the moduli of the cement paste specimens at both w/c's. The greater loss of stiffness seen in concrete shows that cement paste is damaged less by cyclic loading than is concrete.

For the lower stress range tests, only 0.7 w/c cement paste and concrete loaded from 0.2 - 0.6f′ can be compared, as no other matching data is available. The concrete accumulates 64 $\mu\varepsilon$ while the cement paste accumulates 43 $\mu\varepsilon$ over the course of the test. $\varepsilon_{ca}/\varepsilon_{cy}$ is 57 percent for concrete and 11 percent for cement paste.

However, the drop in stiffness is 3 percent for concrete compared to 9 percent for cement paste. This comparison provides no clear conclusions.

For w/c = 0.5, the 0-0.8f′ test of cement paste lasted 405 cycles, while the tests of concrete lasted 205 cycles and 240 cycles. The lower stress range tests lasted the full four hours for both materials. For w/c = 0.7, only the 0-0.8f'_c test (specimen 6C2) failed prior to the end of the 4 hour test.

In general, it appears that for high stress tests, both cement paste and concrete initially undergo large decreases in stiffness. After 45 cycles, the decrease in stiffness of cement paste is more gradual while that of concrete continues to be higher and accelerates near failure. The behavior of concrete appears to be dominated by its non-homogeneous nature. However, both cement paste and concrete sustain little damage for stresses below 0.6f′ and significant damage for stresses above 0.6f′, indicating that cement paste is clearly the critical material in controlling the strength of concrete.

3.5 SUSTAINED LOADING COMPARED TO CYCLIC LOADING

For the purpose of determining how much damage is caused by sustained loading compared to that caused by cyclic loading, the total change in modulus for a sustained load test can be compared to the total change in modulus for cyclic tests of the same material at the same mean stress-strength ratio and/or at the same maximum stress-strength ratio. A measure of the change in modulus for sustained load tests can be obtained only if the specimen does not fail and is unloaded at the end of the four hour test.

The measure of change in modulus used here is the difference between the secant loading modulus, E_{s1}, for the initial loading branch of the test and the secant unloading modulus, E_{su}, of the unloading branch at four hours (or at some other point in a cyclic test). The secant loading modulus is obtained by calculating the slope of a straight line passing through the origin and the first point on the stress-strain curve where the load has reached its maximum stress-strength ratio. Examination of cyclic test results reveals, for later cycles, that for a given cycle the secant loading modulus differs from the secant unloading modulus by less than a percent.

To make valid comparisons, it is desirable to compare sustained load tests to cyclic tests at equal strains. Some additional information can be gained by comparing decreases in modulus over the entire 4 hour test. In the following paragraphs, cyclic tests are compared to sustained load tests of the same material at stresses equal to the maximum and/or mean stress - strength ratios for which data is available, at equivalent values of strain if possible, or at the end of the test if the total strain in the cyclic specimen never matches the ending strain of the sustained load specimen. The comparisons are summarized in Table 3.12.

For w/c = 0.5 cement paste, at 0 - $0.8f'_p$, cyclic specimen 1D2 can be compared to sustained load specimens 8C5 and 8C6 at 4000 $\mu\varepsilon$. The sustained load specimens exhibit decreases in modulus of 374 ksi and 435 ksi, representing decreases of 17 and 21 percent, while cyclic specimen 1D2 exhibits a decrease in modulus of 538 ksi or 24 percent. For 0 - $0.4f'_p$, cyclic specimen 1D3 ($\varepsilon_t = 1030\ \mu\varepsilon$) can be compared at 4 hours to sustained load tests at $0.2f'_p$ (5A5, $\varepsilon_t = 1548\ \mu\varepsilon$) and at $0.4f'_p$ (5A6, $\varepsilon_t = 648\ \mu\varepsilon$). In this case, the cyclic specimen exhibits a drop of 3 percent in stiffness, while the sustained load test at the same mean stress exhibits a 7 percent drop and the sustained load test at the same maximum stress exhibits a 3 percent drop in stiffness.

Although this data is limited, some observations can be made. First, for 0 - $0.8f'_p$, while both types of loading result in material damage, cyclic loading causes more damage than sustained loading to the same strain. This is so even though the mean stress for the cyclic load is only one-half of the sustained load stress. These observations agree with the measurements of submicroscopic cracking by Attiogbe and Darwin (1985) for cement paste specimens subjected to similar stress histories. Secondly, at 0 - $0.4f'_p$, the cyclically loaded specimen exhibits a smaller decrease in stiffness than the sustained load specimens at either the same maximum stress or the same mean stress. This illustrates the point, made by a number of previous researchers (Whaley and Neville 1973, Cook and Chindaprasirt 1980, Maher and Darwin 1980 and 1982), that at low stresses, the cyclic nature of the loading may be beneficial.

For 0.5 w/c mortar, at a stress range of $0\text{-}0.8f'_m$, cyclic specimen 2C2 can be compared to sustained load specimens 6A3 and 5F3, both of which were loaded to the same maximum stress-strength ratio. At the conclusion of the test, at a maximum strain of 2921 $\mu\varepsilon$, sustained load specimen 6A3 exhibits a 17 percent drop in stiffness. At the same strain, cyclic specimen 2C2 exhibits a 34 percent drop in stiffness. At a maximum strain of 2613 $\mu\varepsilon$, sustained load specimen 5F3 exhibits a 18 percent drop in stiffness. At the same strain, cyclic specimen 2C2 exhibits a 28 percent drop in stiffness. This demonstrates the fact that, at high stress-strength ratios, a cyclic load is more damaging than a sustained load equivalent to the maximum cyclic stress and therefore much more damaging than a sustained load equivalent to the mean cyclic stress.

For the $0\text{-}0.4f'_m$ stress range, specimen 2C3, a comparison can be made to sustained load specimens 5F5 and 6A5, both loaded to the same maximum stress - strength ratio. The modulus of specimen 5F5 decreases 4 percent during the 4 hour test and specimen 6A5 suffers no loss of stiffness, while cyclic specimen 2C3 shows a 3 percent decrease in stiffness.

Specimen 2C5, 0.2 - $0.6f'_m$, experiences a 10 percent increase in stiffness over the 4 hour test. Sustained load specimen 6A4, loaded at the same maximum stress range exhibited a 9 percent drop in stiffness. For low stress range tests, cyclic loads appear to cause little if any increased loss of stiffness over a sustained load test to the same maximum stress - strength ratio and may result in increased stiffness due to consolidation.

For w/c = 0.5 concrete at a stress range of 0-0.8f'_c, specimens 3C2 and 3C4 can be compared at a strain of 1558 $\mu\varepsilon$ to sustained load specimen 8A3, which was loaded to the same maximum stress. Cyclic specimens 3C2 and 3C4 exhibit 21 and 15 percent drops in stiffness, respectively, while sustained load specimen 8A3 exhibits a 5 percent drop in stiffness. At 0.2-0.6f'_c, cyclic specimen 3C5 (ε_t = 780 $\mu\varepsilon$) exhibits a 6 percent increase in stiffness at 4 hours, and sustained load specimen 8A5 (ε_t = 513 $\mu\varepsilon$) exhibits a 1 percent drop in stiffness. For concrete, as for mortar and cement paste, cyclic loads appear to be more damaging than sustained loads at high stress-strength ratios and less detrimental at low stress-strength ratios.

For w/c = 0.7 cement paste at a stress range of 0-0.8f'_p, cyclic specimen 4C2 (ε_t = 4850 $\mu\varepsilon$) exhibits a 35 percent drop in stiffness at 4 hours. Sustained load specimen 3A3 (ε_t = 5678 $\mu\varepsilon$), loaded to the same maximum stress-strength ratio, exhibits a 26 percent drop in stiffness at 4 hours, and sustained load specimen 3A5 (ε_t = 1240 $\mu\varepsilon$), loaded to the mean stress-strength ratio exhibits a 7 percent drop in stiffness. Specimen 4C3, 0-0.4f'_p, exhibited a 3 percent increase in stiffness at 4 hours (ε_t = 1009 $\mu\varepsilon$). At 0.2-0.6f'_p, cyclic specimen 4C5 (ε_t = 1703 $\mu\varepsilon$) exhibits only a 2 percent drop in stiffness, while sustained loads to the same maximum (3A4, ε_t = 2264 $\mu\varepsilon$) and mean (3A5, ε_t = 1240 $\mu\varepsilon$) stress-strength ratio produced 15 and 7 percent drops, respectively.

For w/c = 0.7 mortar at a stress range of 0-0.8f'_m, cyclic test specimen 5C2 exhibits a 33 percent drop in stiffness at 1949 $\mu\varepsilon$, while sustained load specimen 4A3 (loaded to the same maximum stress-strength ratio) exhibits a 19 percent drop in stiffness at the same strain. At 2560 $\mu\varepsilon$, specimen 5C2 exhibits a 42 percent drop in stiffness, and at the same strain, sustained load specimen 2A3 (loaded to the same maximum stress-strength ratio) exhibits a 25 percent drop in stiffness. After 4 hours, specimen 5C2 suffers a 52 percent drop in stiffness. The drop in stiffness for 4A3 and 2A3 at 4 hours are the same as given above. These results agree with the other 0-0.8f′ tests in the sense that, at high stress-strength ratios, cyclic loads cause more damage than sustained loads equivalent to either the mean stress or the maximum stress. Cyclic test specimen 5C5 ($0.2 - 0.6f'_m$, $\varepsilon_t = 640\ \mu\varepsilon$) cannot be compared at any equivalent strains but can be compared at 4 hours to sustained load specimens 2A4 ($\varepsilon_t = 843\ \mu\varepsilon$) and 4A4 ($\varepsilon_t = 760\ \mu\varepsilon$) at the equivalent maximum stress, and 2A5 ($\varepsilon_t = 476\ \mu\varepsilon$) and 4A5 ($\varepsilon_t = 428\ \mu\varepsilon$), at the same mean stress. At 4 hours, cyclic specimen 5C5 exhibits a 3 percent drop in stiffness. Specimen 4A4 exhibits a 9 percent drop, 2A4 exhibits a 10 percent drop, 4A5 exhibits a 6 percent drop, and 2A5 exhibits an 5 percent loss. These observations also agree with previous results, in that cyclic tests with a maximum stress-strength ratio of 0.6 or less accumulate less damage than sustained load tests with an stress-strength ratio equal to either the maximum or mean stress-strength ratio.

For 0.7 w/c concrete, cyclic specimen 6C2 ($0 - 0.8f'_c$) exhibits a 20 percent drop in stiffness at 1098 $\mu\varepsilon$, while sustained load specimen 7F3 exhibits a 11 percent drop in stiffness at the same strain. At 1176 $\mu\varepsilon$, 6C2 exhibits a 23 percent drop in stiffness, while sustained load specimen 6F3 exhibits 11 percent drop in stiffness at the same strain. At 4 hours, 6C2 ($\varepsilon_t = 2157\ \mu\varepsilon$) exhibits a 44 percent drop as compared to 11 percent for both 7F3 and 6F3. Sustained load specimen 6F5 (loaded to the mean cyclic stress-strength ratio) exhibits a 3 percent drop in stiffness at four hours. Again, the cyclic load is much more detrimental than the sustained load, even at the maximum cyclic stress-strength ratio.

At 4 hours specimen 6C5 (0 - 0.4f′$_c$, ε_t = 553 με) exhibits a decrease in modulus of 4 percent, while specimens 6F4 (ε_t = 652 με) and 7F4 (ε_t = 637 με) with the same maximum stress - strength ratio exhibit 5 and 6 percent decreases, respectively. As for the other tests of w/c = 0.7 concrete with a maximum stress of 0.6f′ or less, the cyclically loaded specimens exhibit smaller decreases in stiffness than sustained load specimens loaded to the same maximum stress - strength ratio.

In general, it appears that cyclic loading is less damaging, or at least shows a lower drop in stiffness, than sustained loading (at either the mean or maximum stress-strength ratio) for stress-strength ratios not exceeding 0.6f′. This behavior may be due to consolidation that occurs under cyclic loading, but not sustained loading. However, if the stress-strength ratio exceeds 0.6f′, cyclic loading results in a greater loss of stiffness than sustained loading at either the mean or maximum cyclic stress-strength ratio.

3.6 CORRELATION OF CHANGE IN MODULUS TO CYCLIC ACTION STRAIN

The cyclic action strain, ε_{ca}, and the change in the secant unloading modulus, E_{su}, are the principal measures of damage used in the current study. The question arises as to how closely these responses mirror one another. A check of the data indicates that the high stress tests provide the clearest comparisons. Before making those comparisons, however, it is important to note that neither E_{su} or ε_{ca} represents damage alone. Changes in E_{su} provide a measure of both damage, which causes E_{su} to decrease, and consolidation, which causes E_{su} to increase. Likewise, ε_{ca} serves as a measure of strain due to both accumulated damage and accelerated consolidation, if any, that occurs as the result of cyclic loading. Both damage and consolidation will increase ε_{ca}.

A comparison of the cyclic action strain, ε_{ca}, plots, Figs. 3.42-3.47, with the corresponding plots for changes in E_{su}, Figs. 3.48-3.53, indicates that, for the 0-0.8 f'_c tests, both measures of damage increase most rapidly during the early cycles and increase more slowly afterward. For cement paste, ε_{ca} exhibits relatively more change than E_{su} after 45 cycles. For mortar, the changes in ε_{ca} and E_{su} are closely matched throughout the tests. For concrete, ε_{ca} changes more rapidly than E_{su} during in the first 45 cycles; afterward the changes are similar. Alternatively, it could be observed that the two quantities match for the first 45 cycles, but that ε_{ca} exhibits relatively less change after 45 cycles.

For cement paste, the changes in E_{su} are almost identical for the 0.5 and 0.7 w/c materials. For mortar, the changes in E_{su} are very close for the two water-cement ratios over the first 100 cycles (with the w/c = 0.5 mortar showing somewhat less deterioration). The drop in E_{su} for w/c = 0.5 exceeds that for w/c = 0.7 above 100 cycles. The w/c = 0.5 mortar deteriorates rapidly after approximately 170 cycles, while the w/c = 0.7 mortar exhibits a nearly constant rate of decrease in E_{su}. For concrete, the w/c = 0.5 material exhibits a slower drop in E_{su} than w/c = 0.7 concrete throughout the duration of the test. These general trends are mirrored by ε_{ca}, which accumulates more rapidly for the high water-cement ratio paste and concrete and more slowly for the high water-cement ratio mortar.

Overall, the current tests suggest that trends observed in changes in E_{su} and ε_{ca} are similar, but the details of the changes are different, and the two measures of damage appear to represent different aspects of material response. The subject of measures of damage is worthy of additional study.

CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1 SUMMARY

The purpose of this investigation is to study the behavior of cement paste, mortar and concrete under monotonic, sustained and cyclic loading. The behavior of cement paste and mortar under the various load regimes is compared to that of concrete to determine the contribution each constituent makes to the overall behavior of the composite material. For monotonic loading, the behavior of each material is described in terms of peak stress, strain at peak stress, and initial modulus of elasticity. For sustained loading, the behavior is described in terms of creep strain as a function of stress-strength ratio and time under load. Mathematical relationships are developed on the sustained load response to estimate the cumulative static creep for a cyclic test.

Saturated cement paste, mortar and concrete specimens with water-cement ratios of 0.5 and 0.7 are used. Specimens are tested at ages ranging from 27 to 29 days. Specimens are loaded in compression using a closed-loop servo-hydraulic testing machine.

Cyclic test results are examined in terms of strain at 15 seconds, the difference between the strain at 15 seconds and the peak strain for a given cycle (cyclic strain), the estimated creep strain for a cyclic test (equivalent creep, based on sustained load test results), the difference between cyclic strain and equivalent creep (cyclic action strain), and the change in secant unloading modulus (a measure of material damage). The equivalent creep during a cyclic test is used to distinguish between cyclic strain and cyclic action strain. The cyclic action strain may include accelerated creep strain as well as strain related to microcracking. Creep strain may include consolidation of the material as well as some microcracking. The cyclic action strains are correlated with changes in modulus of elasticity to determine the extent to which these strains are the result of damage.

4.2 CONCLUSIONS

The following conclusions are based on the findings of this study:

1. For the materials used in this study, at a given water - cement ratio, cement paste has a higher strength and strain capacity than do the corresponding mortar and concrete, while mortar and concrete have a higher initial stiffness than cement paste.
2. For the materials used in this study, at a given water - cement ratio, mortar has a higher strength and strain capacity than does the corresponding concrete but has approximately the same initial stiffness as concrete.
3. At a water - cement ratio of 0.5, the strengths of cement paste, mortar, and concrete are closer than for a water-cement ratio of 0.7.
4. The strains corresponding to the peak stress decrease with increasing water-cement ratio for mortar and concrete, but increase for cement paste.
5. Under monotonic loading, the stress - strain curves of mortar and concrete are quite similar but differ substantially from the stress - strain curves of cement paste. The addition of aggregate increases the initial stiffness of the mortar and concrete, and reduces total strain, but also reduces the ultimate strength of the material.
6. Over a four hour period, creep strain is a nonlinear function of the stress - strength ratio, increasing to a greater degree than stress - strength ratio as the stress - strength ratio increases.

7. For the sustained load tests at a given stress - strength ratio ($\sigma \leq 0.8f'$), specimens of cement paste, mortar and concrete with a water - cement ratio of 0.5 exhibit higher total strains than specimens with a water - cement ratio of 0.7.

8. For sustained loading at the highest stress-strength ratios ($0.9f'$), the 0.7 water-cement ratio specimens exhibit higher values of creep strain than 0.5 water-cement ratio specimens.

9. Under sustained loading, at the same stress-strength ratio, total strain and creep strain accumulate more rapidly for cement paste than for mortar and more rapidly for mortar than for concrete.

10. Under sustained loading, the addition of fine aggregate to cement paste reduces the total strain, creep strain and strain capacity of the material.

11. Under sustained loading, strains in mortar are 25 to 80 percent higher than those in concrete, and strains in cement paste are 60 to 440 percent higher than those in mortar.

12. For cyclic tests with a maximum stress-strength ratio greater than $0.6f'$, cyclically loaded cement paste, mortar and concrete exhibit larger strains than similar materials exposed to a sustained load equal to the mean cyclic stress.

13. For cyclic loading, the initial modulus of elasticity exhibits more scatter than the secant unloading modulus.

14. For cyclic loading the initial modulus of elasticity is always greater than the secant unloading modulus for tests of cement paste and for tests of mortar and concrete with a maximum stress of $0.6f'$ or less. However, for mortar and concrete with a maximum stress of $0.8f'$, the initial modulus typically starts out higher and then drops below the secant un-

loading modulus.

15. For materials under cyclic load, the relative change in the secant unloading modulus over the duration of the test is greatest for mortar and least for cement paste with concrete falling in the middle.

16. In many of the tests with a maximum stress of 0.6f′ or less, equivalent creep predicts all of the measured cyclic strain, and, in some cases, even over predicts the cyclic strain, during the first 45 cycles. This indicates that no additional damage occurs due to the cyclic nature of the load.

17. For the load regimes studied, maximum cyclic stress appears to have a much greater impact on the cyclic action strain and change in stiffness than the mean cyclic stress or the cyclic stress range.

18. For maximum stresses above 0.6f′, cyclic loads produce larger changes in stiffness, at the same total strain, than sustained load tests at either the mean cyclic stress or the maximum cyclic stress.

19. For cyclic loads, at stresses of 0.6f′ and below, mortar accumulates smaller strains and smaller changes in modulus than cement paste. However at high stresses, damage related strains dominate the behavior, and mortar suffers more damage than cement paste due to its non-homogeneous nature.

20. For the cyclic load ranges used in these tests, mortar sustains larger strains and (with the exception of one test, $0.2\text{-}0.6f'_m$ at $w/c = 0.5$) larger changes in stiffness than does concrete at the same water-cement ratio.

21. Under monotonic, sustained and cyclic loading, the behavior of mortar more closely resembles that of concrete than it does cement paste.

22. The overall nature of damage, as measured by cyclic action strain and decrease in secant unloading modulus, in mortar and concrete is quite similar, which suggests that the behavior of concrete under cyclic loading is dominated by its mortar constituent.

4.3 FUTURE WORK

Although this study provides significant insight into the behavior of concrete and its dependance on the behavior of its cement paste and mortar constituents, a number of important questions cannot be answered with the available data. One limitation of the current study is due to the number of cyclic test specimens and the lack of duplicate tests. Additional tests need to be conducted to provide a statistically valid foundation for the observations made here.

Another aspect of the current study that needs further examination is the relative influence of the water - cement ratio and the aggregate - cement ratio. In the current study these ratios are varied simultaneously. Additional tests need to be conducted to determine the individual effects of these parameters.

Of particular interest is the possible existence of a "endurance limit" or a stress - strength ratio below which concrete would suffer no damage due to the cyclic nature of the load. From the current study, and from the existing body of evidence, it would appear that such a stress - strength ratio exists and that it is between 0.5f′ and 0.8f′. Further tests within this stress range are needed to verify the existence of a limit and to accurately determine its value.

The test results analyzed in this study are for load durations of only 4 hours. Although it appears that the majority of strains and changes in modulus occur during the first 45 cycles (with the exception of stress ranges above 0.6f′), longer duration tests are required to obtain a complete understanding of material behavior in real structures.

Finally, further tests of the materials, combined with morphological studies, are needed to develop a complete understanding of the microscopic and macroscopic behavior of concrete. Only through a full understanding of the response of concrete to general types of load can the behavior of this important construction material be understood.

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Table 2.1 Mix Proportions

	Water Cement Ratio			
	0.5		0.7	
	Concrete Mix Proportions			
Materials	lb/cu yd	kg/cu m	lb/cu yd	kg/cu m
Cement	610	303.7	436	845.6
Water	305	591.5	305	591.5
Fine Aggregate	1401	2717.2	1542	2990.6
Coarse Aggregate	1539	2984.8	1539	2984.8
Slump, in(mm)	3 (75)		3 (75)	
	Relative Proportions by Weight, C:FA:CA			
Concrete	1 : 2.30 : 2.52		1 : 3.54 : 3.53	
Mortar	1 : 2.30 : 0.0		1 : 3.54 : 0.0	
Cement Paste	1 : 0.0 : 0.0		1 : 0.0 : 0.0	

Table 3.1
Summary of Monotonic Tests

Batch	#	Mat	w/c	E init (ksi)	f' (ksi)	ε @ f' με
1C	1	P	0.5	2296753	5558	4922
1D	1	P	0.5	2307599	5385	5322
1F	1	P	0.7	1744532	4192	6950
1G	1	P	0.5	2234338	6189	5838
2A	1	M	0.7	3662848	3582	2515
2C	1	M	0.5	4376234	5555	3064
2D	1	M	0.5	4095601	5166	2867
3A	1	P	0.7	1643500	4098	7050
3D	2	C	0.5	4118857	5262	2041
	4	C	0.5	4056727	5262	1836
	5	C	0.5	4275068	5438	2051
	6	C	0.5	3996124	5258	1864
3E	1	P	0.7	1574545	3862	6570
4A	1	M	0.7	3103349	3342	2491
4B	1	C	0.7	3107442	2795	1300
	2	C	0.7	3352756	2670	1450
	3	C	0.7	3254668	2660	1430
	4	C	0.7	3334237	2935	1520
	5	C	0.7	3316589	2935	1560
4C	1	P	0.7	1784342	3543	5700
4E	1	P	0.5	2315634	5757	5180
5A	1	P	0.5	2234063	6499	6199
5C	1	M	0.7	3255734	3411	2450
5F	1	M	0.5	4126789	5627	3159
6A	1	M	0.5	4198864	5705	3025
6B	4	C	0.5	3953671	4839	1730
	5	C	0.5	4392319	4859	1811
	6	C	0.5	4314171	5108	1810
6F	1	C	0.7	3202144	2768	2768
7A	2	P	0.7	1564349	3541	3541
7B	1	P	0.5	2247532	6331	6331
7C	1	M	0.5	3791776	5733	5733
7F	1	C	0.7	3555249	2688	2688
8A	1	C	0.5	4015752	4834	4834
8C	1	P	0.5	2496418	5695	5695
8E	1	P	0.7	1776473	3952	3952
9A	1	C	0.5	3996233	4258	4258
	2	C	0.5	4414651	4357	4357
9C	1	C	0.5	4325634	4765	4765
9E	1	M	0.7	3203457	3664	3664

Table 3.2
Material Properties Under Monotonic Loading

	Water/Cement Ratio					
	0.5			0.7		
	Paste	Mortar	Concrete	Paste	Mortar	Concrete
No. of Specimens	7	5	11	6	4	7
Avg. Compr. Strength (f′) ksi	5916	5557	4931	3865	3500	2779
Std. Dev. (f′) ksi	422	229	380	275	149	118
Avg. Strain @ Pk. Strs. (ε (f′))	5560	3067	1839	6403	2516	1489
Std. Dev. (ε(f′))	534	136	141	708	67	106
Avg. Initial Modulus (Ei) ksi	2305	4118	4169	1681	3306	3303
Std. Dev. (Ei) ksi	91	212	177	100	246	140

Table 3.3
Summary of Sustained Load Specimens

Specimen	Material	w / c	σ / f'	σ (psi)	ε_{15} $\mu\varepsilon$	ε_t $\mu\varepsilon$	$\varepsilon_t - \varepsilon_{15}$ $\mu\varepsilon$	$T_{failure}$
1C6 *	P	0.5	0.6	3347	1353	2228	875	14355
1D6	P	0.5	0.6	3231	1386	2216	830	14355
1G2	P	0.5	0.9	5556	2764	8639	5875	10455
1G4	P	0.5	0.8	4892	2254	5243	2989	14355
1G5	P	0.5	0.4	2484	1029	1413	384	11955
1G6	P	0.5	0.6	3701	1588	2673	1085	14355
2A2	M	0.7	0.9	3240	1139	3456	2317	1395
2A3	M	0.7	0.8	2822	945	2560	1615	14355
2A4	M	0.7	0.6	2144	598	852	254	14055
2A5	M	0.7	0.4	1431	378	476	98	14355
2A6	M	0.7	0.2	721	174	174	0	12855
2C6	M	0.5	0.6	3322	759	1095	336	14355
2D5	M	0.5	0.9	4640	1359	2513	1154	1275
2D6	M	0.5	0.9	4643	1417	2501	1084	923
3A2	P	0.7	0.9	3654	2565	10617	8052	8184
3A3	P	0.7	0.8	3279	2226	5706	3480	14055
3A4	P	0.7	0.6	2458	1405	2264	859	14355
3A5	P	0.7	0.4	1634	901	1240	339	14355
3A6	P	0.7	0.2	828	444	542	98	14055
3C6	C	0.5	0.6	2855	659	844	185	14355
4A2	M	0.7	0.9	3030	1109	3979	2870	2245
4A3	M	0.7	0.8	2696	874	1949	1075	14355
4A4	M	0.7	0.6	2004	545	760	215	14355
4A5	M	0.7	0.4	1363	353	428	75	14355
4A6	M	0.7	0.2	670	160	1888	1728	14355
4C6	P	0.7	0.6	2127	1233	1890	657	14355
5A2	P	0.5	0.9	5841	2796	8707	5911	6901
5A3	P	0.5	0.8	5196	2399	6119	3720	14355
5A4	P	0.5	0.6	3897	1658	2844	1186	13755
5A5	P	0.5	0.4	2609	1073	1548	475	14355
5A6 **	P	0.5	0.2	1312	524	648	124	14355

* Corresponding monotonic specimens, summarized in Table 3.1, can be identified by matching the first two characters of the specimen ID#.

** Continued on following page.

Table 3.3
Summary of Sustained Load Specimens (Cont.)

Specimen	Material	w/c	σ / f'	σ (psi)	ε_{15} $\mu\varepsilon$	ε_t $\mu\varepsilon$	$\varepsilon_t - \varepsilon_{15}$ $\mu\varepsilon$	$T_{failure}$
6C6	C	0.7	0.6	1696	429	466	37	14355
6F2	C	0.7	0.9	2494	896	2958	2062	1245
6F3	C	0.7	0.8	2215	680	1176	496	14355
6F4	C	0.7	0.6	1656	481	652	171	14355
6F5	C	0.7	0.4	1109	289	323	34	14355
6F6	C	0.7	0.2	557	143	130	-13	13455
7C6	M	0.5	0.6	3433	826	1279	453	14355
7F2	C	0.7	0.9	2420	825	1980	1155	855
7F3	C	0.7	0.8	2145	637	1098	461	14355
7F4	C	0.7	0.6	1616	468	642	174	14055
7F6	C	0.7	0.2	540	130	141	11	14355
8A2	C	0.5	0.9	4350	1183	2779	1596	1203
8A3	C	0.5	0.8	3868	925	1564	639	14055
8A4	C	0.5	0.6	2899	660	847	187	8655
8A5	C	0.5	0.4	1939	426	514	88	14055
8A6	C	0.5	0.2	966	195	205	10	14355
8C5	P	0.5	0.8	4550	2154	3985	1831	3555
8C6	P	0.5	0.8	4548	2117	4002	1885	3075
9C5	C	0.5	0.9	4282	1122	1503	381	265
9C6	C	0.5	0.9	4278	1107	1499	392	545
5F2	M	0.5	0.9	5070	1503	4518	3015	3555
5F3	M	0.5	0.8	4508	1200	2609	1409	13755
5F4	M	0.5	0.6	3403	831	1288	457	14355
5F5	M	0.5	0.4	2268	509	658	149	14355
5F6	M	0.5	0.2	1144	239	294	55	14055
6A2	M	0.5	0.9	5133	1498	4998	3500	3040
6A3	M	0.5	0.8	4601	1271	2919	1648	14055
6A4	M	0.5	0.6	3442	813	1160	347	14055
6A5	M	0.5	0.4	2290	535	661	126	14355
6A6	M	0.5	0.2	1153	243	208	-35	4755

Table 3.4
Coefficients of Creep Strain vs. Log-Time Best-Fit Curves

Material	σ / f'	A	B	C	D
0.5 Paste	0.2	-3.423	0.1829	-0.06212	0.007618
	0.4	-3.123	0.1809	-0.05744	0.007488
	0.6	-2.928	0.1165	-0.02811	0.004494
	0.8	-2.817	0.1951	-0.04712	0.007920
	0.9	-2.865	0.3850	-0.1238	0.01974
0.5 Mortar	0.2	-3.791	0.2361	-0.09450	0.01268
	0.4	-3.349	0.08777	-0.02798	0.003980
	0.6	-3.202	0.1374	-0.03659	0.004872
	0.8	-3.021	0.1340	-0.02736	0.005324
	0.9	-3.310	0.6621	-0.2704	0.04394
0.5 Concrete	0.2	-3.843	0.1767	-0.06635	0.007831
	0.4	-3.468	0.1286	-0.04481	0.005843
	0.6	-3.243	0.07740	-0.02093	0.002954
	0.8	-3.140	0.1570	-0.04675	0.006803
	0.9	-3.427	0.7249	-0.3319	0.05600
0.7 Paste	0.2	-3.496	0.1937	-0.07055	0.008973
	0.4	-3.146	0.1328	-0.04177	0.005713
	0.6	-3.010	0.1617	-0.04658	0.006398
	0.8	-2.812	0.1838	-0.03768	0.006435
	0.9	-3.035	0.5898	-0.2206	0.03508
0.7 Mortar	0.2	-3.960	0.2553	-0.1015	0.01272
	0.4	-3.545	0.1442	-0.04927	0.006285
	0.6	-3.364	0.1551	-0.04720	0.006125
	0.8	-3.159	0.1334	-0.02288	0.004914
	0.9	-3.482	0.7617	-0.3251	0.05693
0.7 Concrete	0.2	-3.942	0.1071	-0.03881	0.004054
	0.4	-3.655	0.1440	-0.04707	0.005171
	0.6	-3.401	0.09307	-0.02338	0.003210
	0.8	-3.274	0.1054	-0.01963	0.003248
	0.9	-3.764	1.0470	-0.4892	0.08625

Table 3.5
Cyclic Test Stress Ranges

Material	Test #	σ/f'	# Cycles
0.5 Paste	1D2 *	0-0.8	405
	1D3	0-0.4	485
0.5 Mortar	2C2	0-0.8	196
	2C3	0-0.4	485
	2C5	0.2-0.6	485
0.5 Concrete	3C2	0-0.8	205
	3C4	0-0.8	240
	3C5	0.2-0.6	485
0.7 Paste	4C2	0-0.8	485
	4C3	0-0.4	485
	4C4	0.1-0.3	245 **
	4C5	0.2-0.6	485
0.7 Mortar	5C2	0-0.8	485
	5C3	0-0.4	485
	5C5	0.2-0.6	485
0.7 Concrete	6C2	0-0.8	165
	6C5	0-0.4	485

* Corresponding monotonic tests, summarized in Table 3.1, can be identified by matching the first two characters of the specimen ID#.

** Test 4C4 was terminated early due to equipment problems.

Table 3.6
Final Elastic, Total, Cyclic, Equivalent Creep, and Cyclic Action Strains

Material	Test	σ / f'	ε_{15} $\mu\varepsilon$	ε_t $\mu\varepsilon$	ε_{cy} $\mu\varepsilon$	ε_{ec} $\mu\varepsilon$	ε_{ca} $\mu\varepsilon$
0.5 Paste	1D2	0-0.8	0.001938	0.004054	0.002115	0.000677	0.001439
	1D3	0-0.4	0.000875	0.001030	0.000155	0.000153	0.000002
0.5 Mortar	2C2	0-0.8	0.001247	0.004067	0.002820	0.000226	0.002594
	2C3	0-0.4	0.000486	0.000537	0.000051	0.000057	-0.000006
	2C5	0.2-0.6	0.000808	0.001042	0.000234	0.000159	0.000075
0.5 Concrete	3C2	0-0.8	0.000918	0.001644	0.000727	0.000102	0.000625
	3C4	0-0.8	0.000947	0.002765	0.001818	0.000106	0.001712
	3C5	0.2-0.6	0.000639	0.000780	0.000141	0.000089	0.000052
0.7 Paste	4C2	0-0.8	0.001833	0.004850	0.003017	0.000609	0.002409
	4C3	0-0.4	0.000880	0.001009	0.000129	0.000116	0.000013
	4C4	0.1-0.3	0.000586	0.000652	0.000066	0.000080	-0.000014
	4C5	0.2-0.6	0.001311	0.001703	0.000392	0.000349	0.000043
0.7 Mortar	5C2	0-0.8	0.000839	0.003200	0.002361	0.000199	0.002162
	5C3	0-0.4	0.000355	0.000414	0.000059	0.000024	0.000036
	5C5	0.2-0.6	0.000548	0.000640	0.000092	0.000093	-0.000001
0.7 Concrete	6C2	0-0.8	0.000670	0.002157	0.001487	0.000079	0.001408
	6C5	0.2-0.6	0.000441	0.000553	0.000112	0.000049	0.000064

Table 3.7
Cyclic Strain at 45 Cycles and end of Test

Material	Test	σ / f'	$\varepsilon_{cy}^{@\,45}$ $\mu\varepsilon$	ε_{cy}^{final} $\mu\varepsilon$	$\varepsilon_{cy}^{@\,45} / \varepsilon_{cy}^{final}$
0.5 Paste	1D2	0-0.8	0.000699	0.002115	33%
	1D3	0-0.4	0.000075	0.000155	48%
0.5 Mortar	2C2	0-0.8	0.000607	0.002820	22%
	2C3	0-0.4	0.000025	0.000051	50%
	2C5	0.2-0.6	0.000115	0.000234	49%
0.5 Concrete	3C2	0-0.8	0.000263	0.000727	36%
	3C4	0-0.8	0.000282	0.001818	16%
	3C5	0.2-0.6	0.000081	0.000141	57%
0.7 Paste	4C2	0-0.8	0.000883	0.003017	29%
	4C3	0-0.4	0.000061	0.000129	47%
	4C4	0.1-0.3	–	0.000066	–
	4C5	0.2-0.6	0.000219	0.000392	56%
0.7 Mortar	5C2	0-0.8	0.000457	0.002361	19%
	5C3	0-0.4	0.000032	0.000059	54%
	5C5	0.2-0.6	0.000057	0.000092	62%
0.7 Concrete	6C2	0-0.8	0.000361	0.001487	24%
	6C5	0.2-0.6	0.000065	0.000112	58%

avg =0.8	26%
avg≤0.6	53%
avg all	41%

Table 3.8
Equivalent Creep at 45 Cycles and end of Test

Material	Test	σ / f'	$\varepsilon_{ec}^{@45}$ $\mu\varepsilon$	ε_{ec}^{final} $\mu\varepsilon$	$\varepsilon_{ec}^{@45} / \varepsilon_{ec}^{final}$
0.5 Paste	1D2	0-0.8	0.000346	0.000677	51%
	1D3	0-0.4	0.000085	0.000153	55%
0.5 Mortar	2C2	0-0.8	0.000147	0.000226	65%
	2C3	0-0.4	0.000024	0.000057	42%
	2C5	0.2-0.6	0.000084	0.000159	53%
0.5 Concrete	3C2	0-0.8	0.000068	0.000102	67%
	3C4	0-0.8	0.000068	0.000106	64%
	3C5	0.2-0.6	0.000048	0.000089	55%
0.7 Paste	4C2	0-0.8	0.000304	0.000609	50%
	4C3	0-0.4	0.000061	0.000116	52%
	4C4	0.1-0.3	0.000052	0.000080	65%
	4C5	0.2-0.6	0.000185	0.000349	53%
0.7 Mortar	5C2	0-0.8	0.000101	0.000199	51%
	5C3	0-0.4	0.000014	0.000024	60%
	5C5	0.2-0.6	0.000052	0.000093	56%
0.7 Concrete	6C2	0-0.8	0.000057	0.000079	73%
	6C5	0.2-0.6	0.000033	0.000049	67%

avg =0.8	60%
avg≤0.6	56%
avg all	58%

Table 3.9
Cyclic Action Strain at 45 Cycles and end of Test

Material	Test	σ / f'	$\varepsilon_{ca}^{@45}$ $\mu\varepsilon$	ε_{ca}^{final} $\mu\varepsilon$	$\varepsilon_{ca}^{final} - \varepsilon_{ca}^{@45}$
0.5 Paste	1D2	0-0.8	0.000354	0.001439	0.001085
	1D3	0-0.4	-0.000010	0.000002	0.000012
0.5 Mortar	2C2	0-0.8	0.000460	0.002594	0.002134
	2C3	0-0.4	0.000001	-0.000006	-0.000007
	2C5	0.2-0.6	0.000031	0.000075	0.000044
0.5 Concrete	3C2	0-0.8	0.000195	0.000625	0.000431
	3C4	0-0.8	0.000214	0.001712	0.001498
	3C5	0.2-0.6	0.000033	0.000052	0.000020
0.7 Paste	4C2	0-0.8	0.000578	0.002409	0.001830
	4C3	0-0.4	0.000000	0.000013	0.000013
	4C4	0.1-0.3		-0.000014	
	4C5	0.2-0.6	0.000035	0.000043	0.000008
0.7 Mortar	5C2	0-0.8	0.000357	0.002162	0.001806
	5C3	0-0.4	0.000018	0.000036	0.000018
	5C5	0.2-0.6	0.000005	-0.000001	-0.000006
0.7 Concrete	6C2	0-0.8	0.000303	0.001408	0.001105
	6C5	0.2-0.6	0.000032	0.000064	0.000032

avg =0.8	0.001413
avg≤0.6	0.000015
avg all	0.000626

Table 3.10

Ratios of Equivalent Creep and Cyclic Action Strain to Total Strain and Cyclic Strain At Conclusion of Test

Material	Test	σ / f′	$\varepsilon_{ec} / \varepsilon_t$	$\varepsilon_{ec} / \varepsilon_{cy}$	$\varepsilon_{ca} / \varepsilon_t$	$\varepsilon_{ca} / \varepsilon_{cy}$
0.5 Paste	1D2	0-0.8	17%	32%	35%	68%
	1D3	0-0.4	15%	99%	0%	1%
0.5 Mortar	2C2	0-0.8	6%	8%	64%	92%
	2C3	0-0.4	11%	112%	-1%	-12%
	2C5	0.2-0.6	15%	68%	7%	32%
0.5 Concrete	3C2	0-0.8	6%	14%	38%	86%
	3C4	0-0.8	4%	6%	62%	94%
	3C5	0.2-0.6	11%	63%	7%	37%
0.7 Paste	4C2	0-0.8	13%	20%	50%	80%
	4C3	0-0.4	12%	90%	1%	10%
	4C4	0.1-0.3	12%	121%	-2%	-21%
	4C5	0.2-0.6	21%	89%	3%	11%
0.7 Mortar	5C2	0-0.8	6%	8%	68%	92%
	5C3	0-0.4	6%	40%	9%	60%
	5C5	0.2-0.6	15%	101%	0%	-1%
0.7 Concrete	6C2	0-0.8	4%	5%	65%	95%
	6C5	0.2-0.6	9%	43%	12%	57%

Table 3.11

Initial and Final Secant Unloading Modulus, Change in Modulus and Percent Change in Modulus

Material	Test	σ / f′	Esu initial	Esu@50	Esu final	delta Esu@45	delta Esu	delta Esu@45/init	delta Esu/init
			(psi)	(psi)	(psi)	(psi)	(psi)		
0.5 Paste	1D2	0-0.8	2320542	1956846	1691402	-363696	-629140	-16%	-27%
	1D3	0-0.4	2500493	2433581	2395023	-66912	-105470	-3%	-4%
0.5 Mortar	2C2	0-0.8	3788582	3148270	1673047	-640312	-2115535	-17%	-56%
	2C3	0-0.4	4635852	4436713	4433829	-199139	-202023	-4%	-4%
	2C5	0.2-0.6	4551164	4427214	4514931	-123950	-36233	-3%	-1%
0.5 Concrete	3C2	0-0.8	4364818	3799242	3159698	-565576	-1205120	-13%	-28%
	3C4	0-0.8	4290319	3800486	2599701	-489833	-1690618	-11%	-39%
	3C5	0.2-0.6	4916879	4704835	4713052	-212044	-203827	-4%	-4%
0.7 Paste	4C2	0-0.8	1627207	1257123	995152	-370084	-632055	-23%	-39%
	4C3	0-0.4	1709926	1660093	1659502	-49833	-50424	-3%	-3%
	4C4	0.1-0.3	1917399	- -	1863602	- -	-53797	- -	-3%
	4C5	0.2-0.6	1741545	1613251	1583081	-128294	-158464	-7%	-9%
0.7 Mortar	5C2	0-0.8	3504828	2632193	1564721	-872635	-1940107	-25%	-55%
	5C3	0-0.4	3937729	3716264	3609745	-221465	-327984	-6%	-8%
	5C5	0.2-0.6	4094860	3825293	3757695	-269567	-337165	-7%	-8%
0.7 Concrete	6C2	0-0.8	3546139	2766080	1878530	-780059	-1667609	-22%	-47%
	6C5	0.2-0.6	4133549	4001190	3978566	-132359	-154983	-3%	-4%

Table 3.12

Initial Secant Loading Modulus, Final Secant Unloading Modulus, Change in Modulus and Percent Change in Modulus

Specimen	Material	w/c	σ / f' *	Time (sec)	ε_t $\mu\varepsilon$	Es1 (psi)	Esu (psi)	Esu-Es1 (psi)	(Esu-Es1)/Es1
1D2	P	0.5	0-0.8	11858	4000	2229071	1691402	-537669	-24%
8C5	P	0.5	0.8	5672	4000	2147725	1773617	-374108	-17%
8C6	P	0.5	0.8	3075	4000	2112388	1677809	-434579	-21%
1D3	P	0.5	0-0.4	14550	1030	2458200	2392108	-66092	-3%
5A5	P	0.5	0.4	14355	1548	2432687	2262634	-170053	-7%
5A6	P	0.5	0.2	14355	648	2502823	2436147	-66676	-3%
2C2	M	0.5	0-0.8	4874	2921	3553896	2362093	-1191803	-34%
6A3	M	0.5	0.8	14355	2921	3621189	2988257	-632932	-17%
2C2	M	0.5	0-0.8	3993	2613	3553896	2569945	-983951	-28%
5F3	M	0.5	0.8	14355	2613	3756253	3069304	-686949	-18%
2C3	M	0.5	0-0.4	14550	537	4563367	4446284	-117083	-3%
5F5	M	0.5	0.4	14355	126	4453006	4256461	-196545	-4%
6A5	M	0.5	0.4	14355	661	4280099	4293337	13238	0%
2C5	M	0.5	0.2-0.6	14550	1042	4102112	4522208	420096	10%
6A4	M	0.5	0.6	14355	1156	4235809	3861598	-374211	-9%
3C2	C	0.5	0-0.8	5509	1558	4119507	3267082	-852425	-21%
8A3	C	0.5	0.8	14355	1558	4003446	3783560	-219886	-5%
3C4	C	0.5	0-0.8	4296	1558	4006768	3386282	-620486	-15%
3C5	C	0.5	0.2-0.6	14550	780	4461106	4708502	247396	6%
8A5	C	0.5	0.4	14355	513	4549792	4484766	-65026	-1%
4C2	P	0.7	0-0.8	14550	4850	1532290	997210	-535080	-35%
3A3	P	0.7	0.8	14355	5678	1473157	1082920	-390237	-26%
3A5	P	0.7	0.4	14355	1240	1814222	1683744	-130478	-7%
4C3	P	0.7	0-0.4	14550	1009	1612462	1655061	42599	3%
4C5	P	0.7	0.2-0.6	14550	1703	1610703	1578755	-31948	-2%
3A4 **	P	0.7	0.6	14355	2264	1749782	1488526	-261256	-15%

* Loads such as 0-0.8 are cyclic and loads such as 0.8 are sustained.

** Continued on following page.

Table 3.12
Initial Secant Loading Modulus, Final Secant Unloading Modulus, Change in Modulus and Percent Change in Modulus

Specimen	Material	w/c	σ / f' *	Time (sec)	ε_t $\mu\varepsilon$	Es1 (psi)	Esu (psi)	Esu-Es1 (psi)	(Esu-Es1)/Es1
5C2	M	0.7	0-0.8	6015	1949	3250516	2181912	-1068604	-33%
4A3	M	0.7	0.8	14355	1949	3083248	2504724	-578524	-19%
5C2	M	0.7	0-0.8	10308	2560	3250516	1888142	-1362374	-42%
2A3	M	0.7	0.8	14355	2560	2985744	2243724	-742020	-25%
5C2	M	0.7	0-0.8	14550	3200	3250516	1558115	-1692401	-52%
5C3	M	0.7	0-0.4	14550	414	3867582	3609745	-257837	-7%
4A5	M	0.7	0.4	14355	428	3866667	3637321	-229346	-6%
2A5	M	0.7	0.4	14355	476	3790853	3591919	-198934	-5%
5C5	M	0.7	0.2-0.6	14550	640	3800416	3701506	-98910	-3%
4A4	M	0.7	0.6	14355	760	3676941	3360337	-316604	-9%
2A4	M	0.7	0.6	14355	843	3585189	3214142	-371047	-10%
6C2	C	0.7	0-0.8	1709	1098	3373378	2689487	-683891	-20%
7F3	C	0.7	0.8	14355	1098	3366681	2986983	-379698	-11%
6C2	C	0.7	0-0.8	1884	1176	3373378	2600649	-772729	-23%
6F3	C	0.7	0.8	14355	1176	3255420	2900461	-354959	-11%
6C2	C	0.7	0-0.8	14550	2157	3373378	1878530	-1494848	-44%
6F5	C	0.7	0.4	14355	0	3839418	3716127	-123291	-3%
6C5	C	0.7	0.2-0.6	14550	553	3978566	3835213	-143353	-4%
6F4	C	0.7	0.6	14355	652	3444121	3270087	-174034	-5%
7F4	C	0.7	0.6	14355	637	3453687	3259637	-194050	-6%

* Loads such as 0-0.8 are cyclic and loads such as 0.8 are sustained.

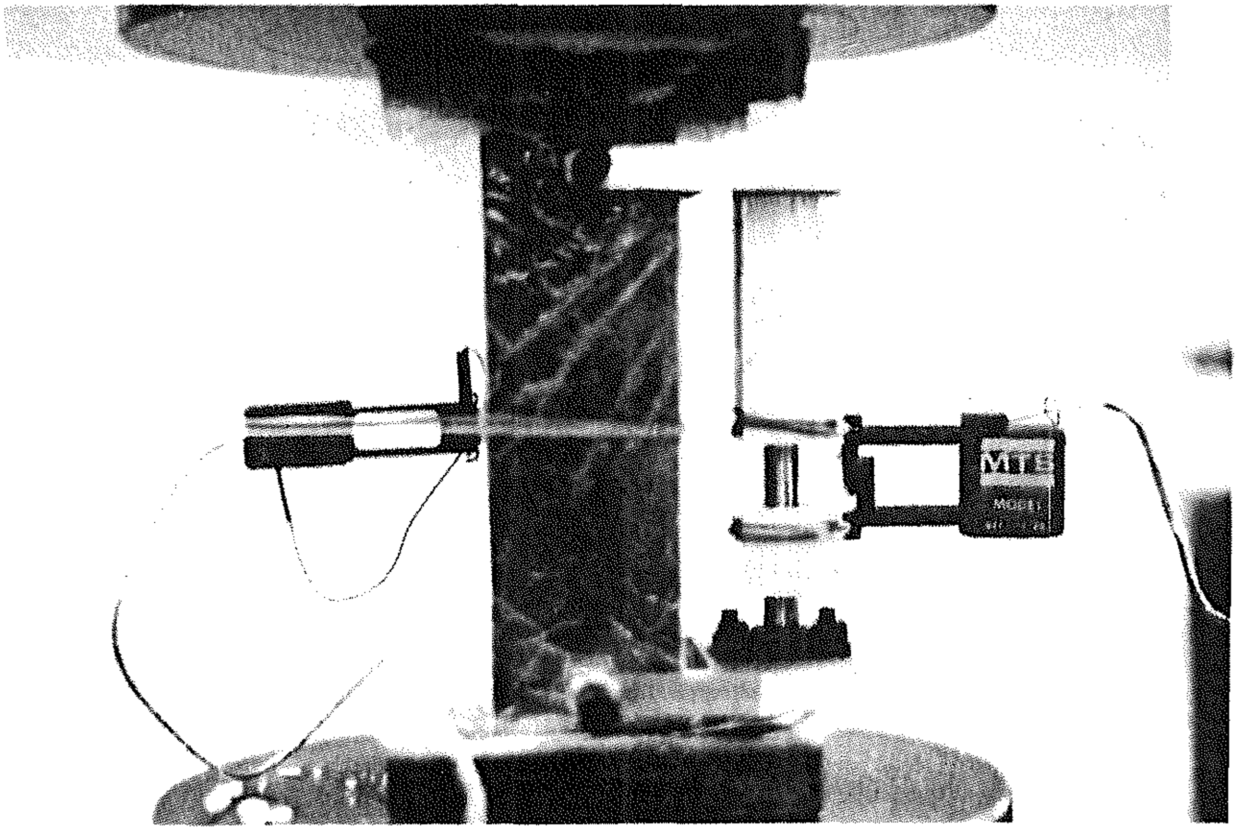

Fig. 2.1 Test setup

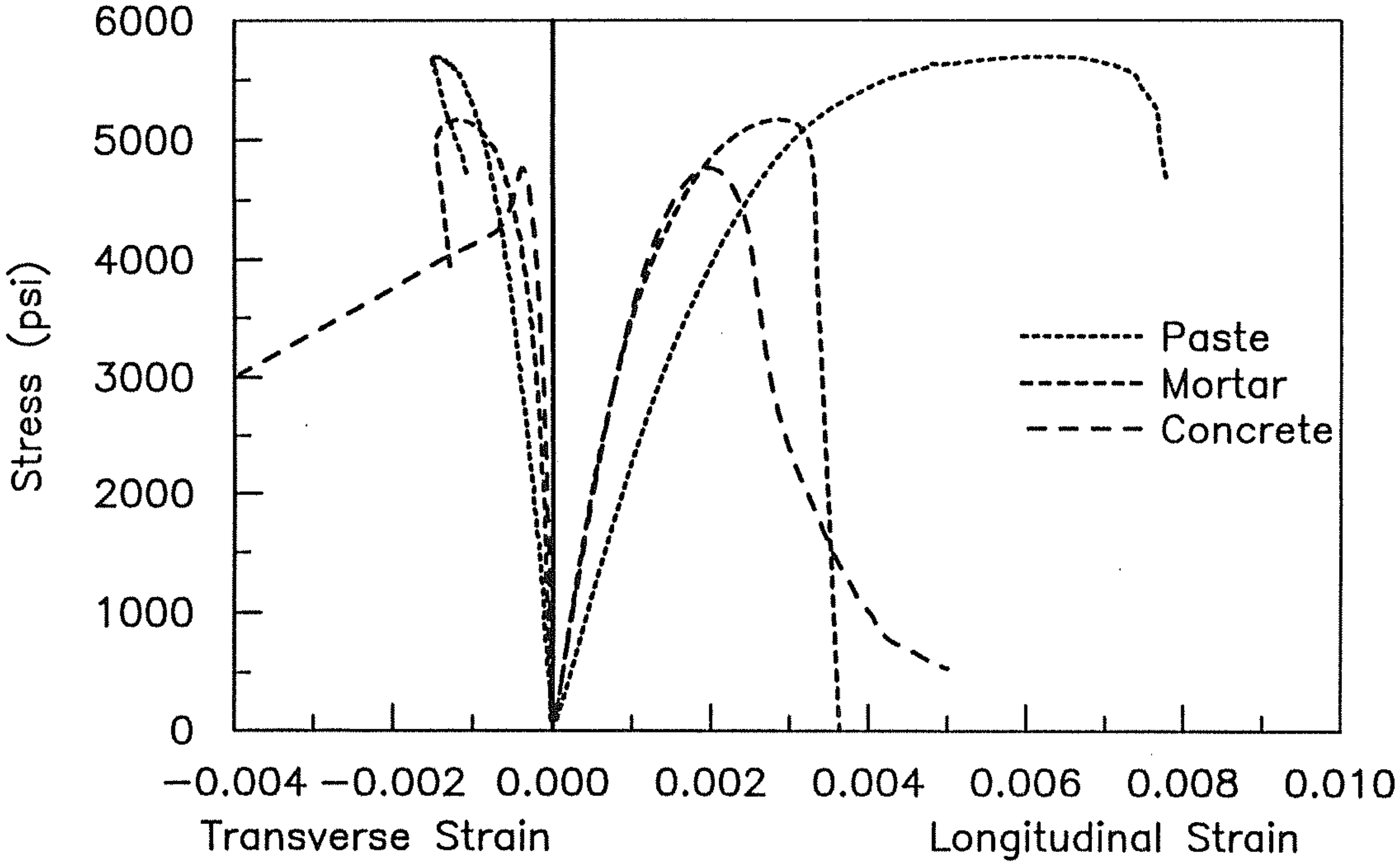

Fig. 3.1 Monotonic stress versus longitudinal and transverse strain for w/c = 0.5 cement paste, mortar, and concrete under monotonic loading.

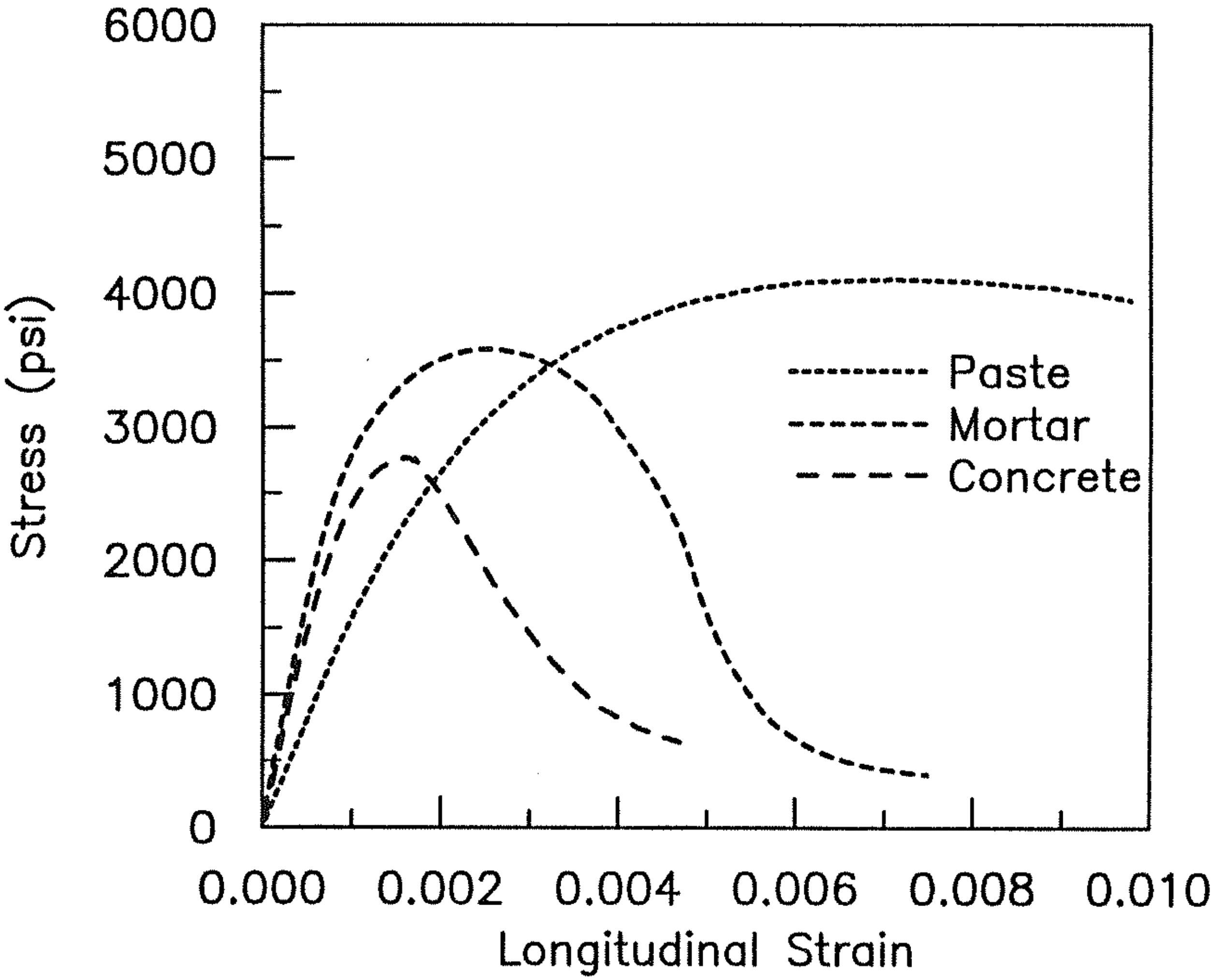

Fig. 3.2 Stress versus longitudinal strain for w/c = 0.7 cement paste, mortar, and concrete under monotonic loading.

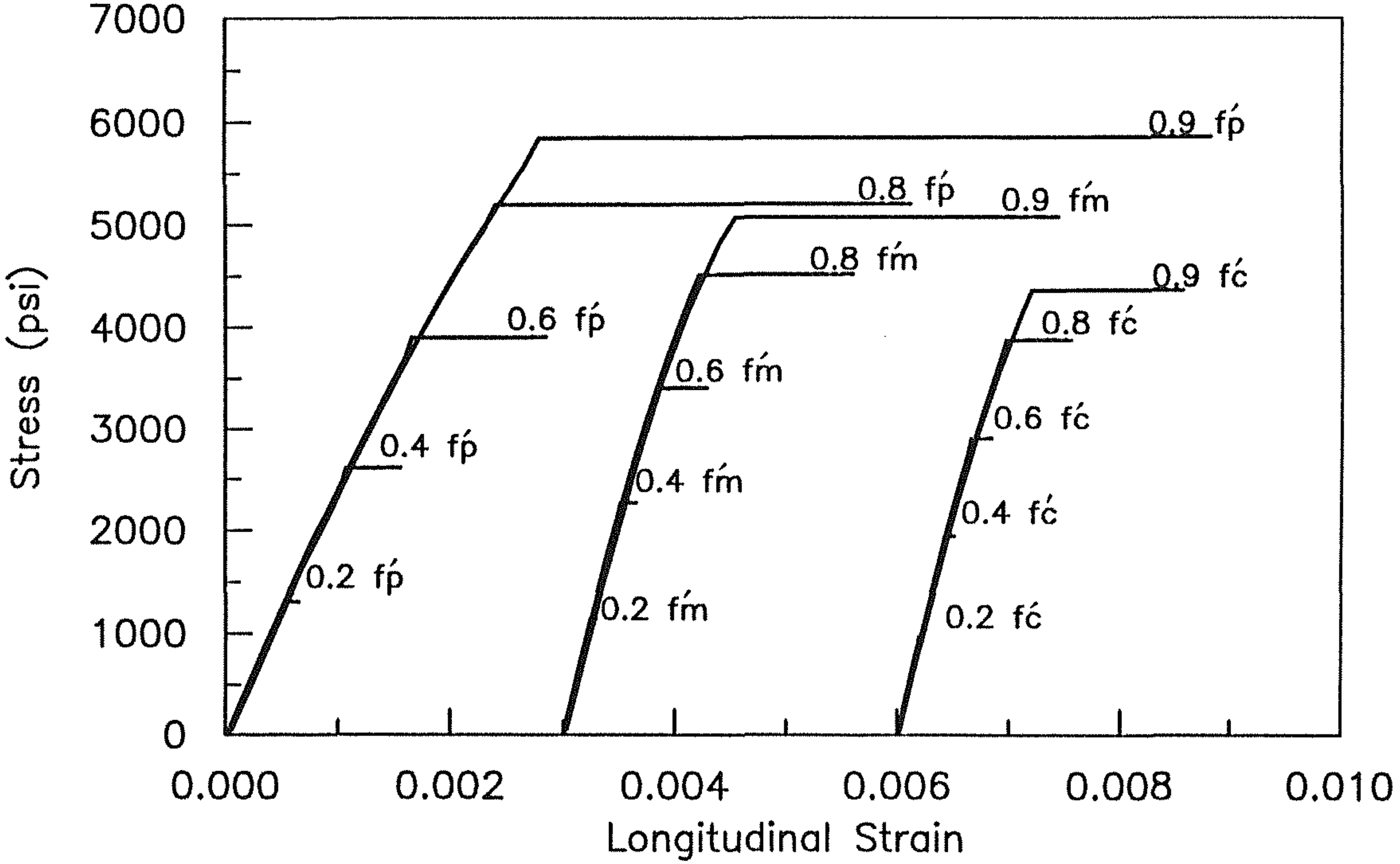

Fig. 3.3 Stress versus longitudinal strain for w/c = 0.5 cement paste, mortar, and concrete at stress - strength ratios of 0.2, 0.4, 0.6, 0.8, and 0.9f′ under sustained loading.

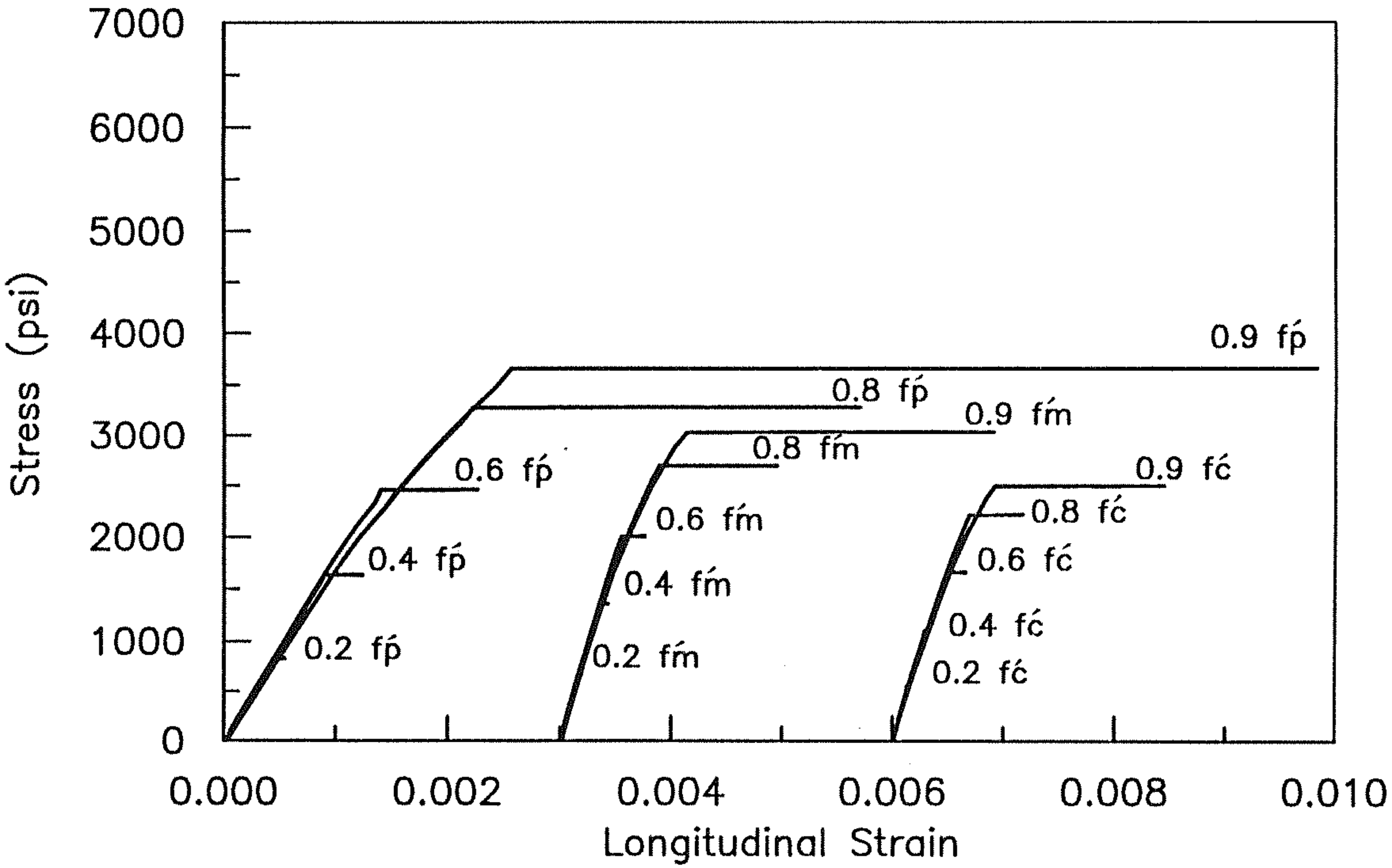

Fig. 3.4 Stress versus longitudinal strain for w/c = 0.7 cement paste, mortar, and concrete at stress - strength ratios of 0.2, 0.4, 0.6, 0.8, and 0.9f′ under sustained loading.

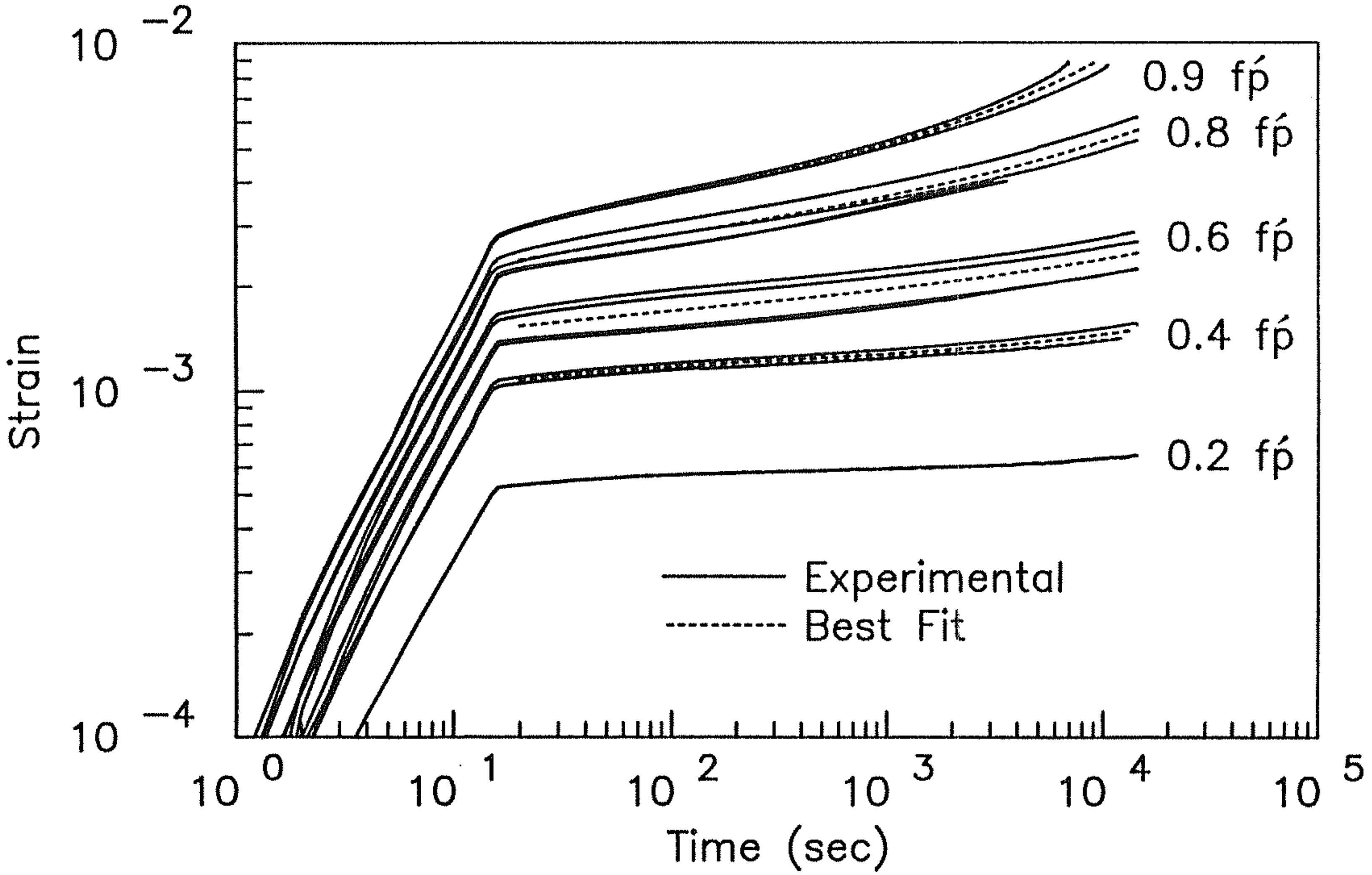

Fig. 3.5 Experimental and best fit strain versus time curves for sustained load tests of w/c = 0.5 cement paste.

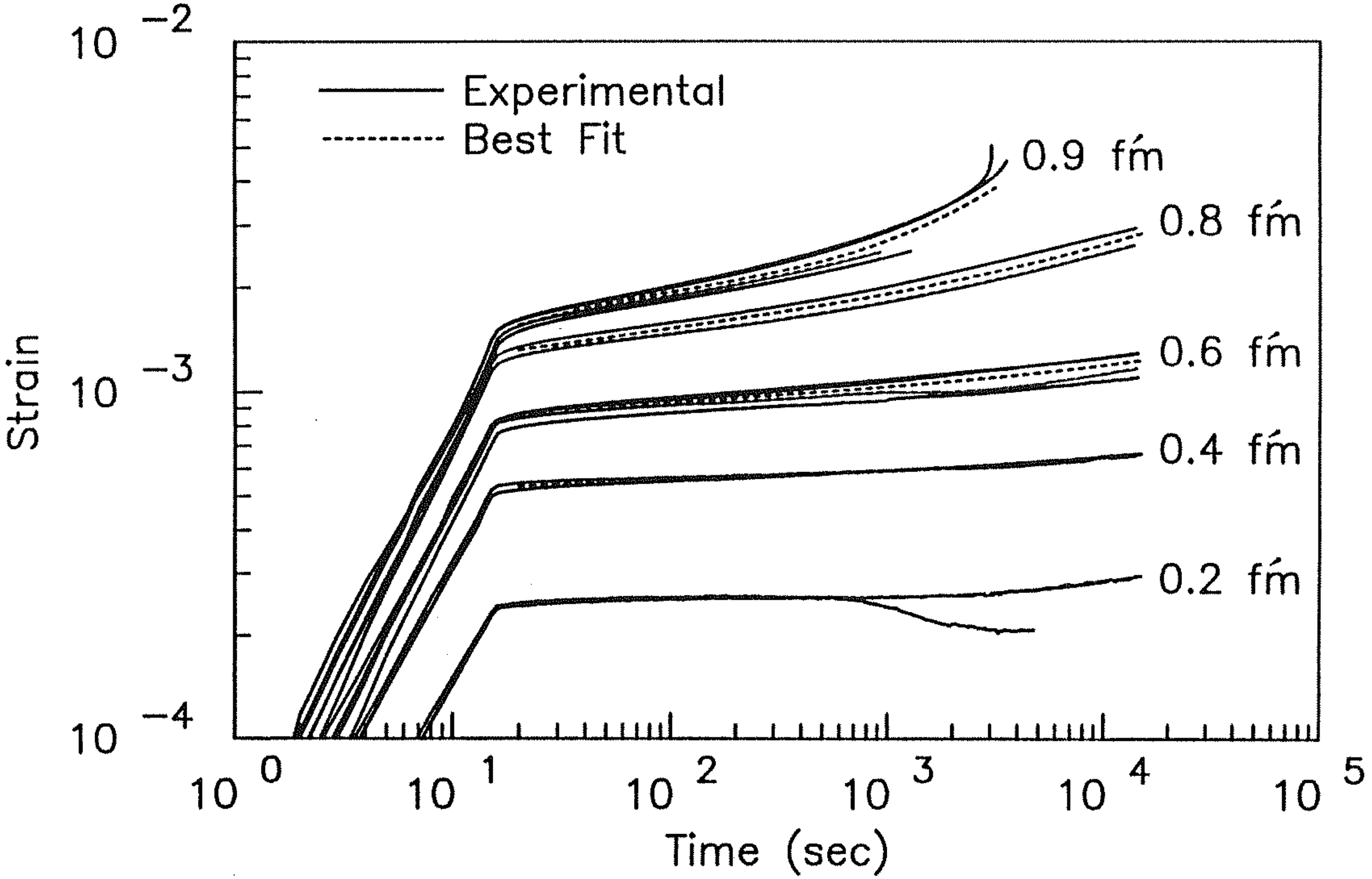

Fig. 3.6 Experimental and best fit strain versus time curves for sustained load tests of w/c = 0.5 mortar.

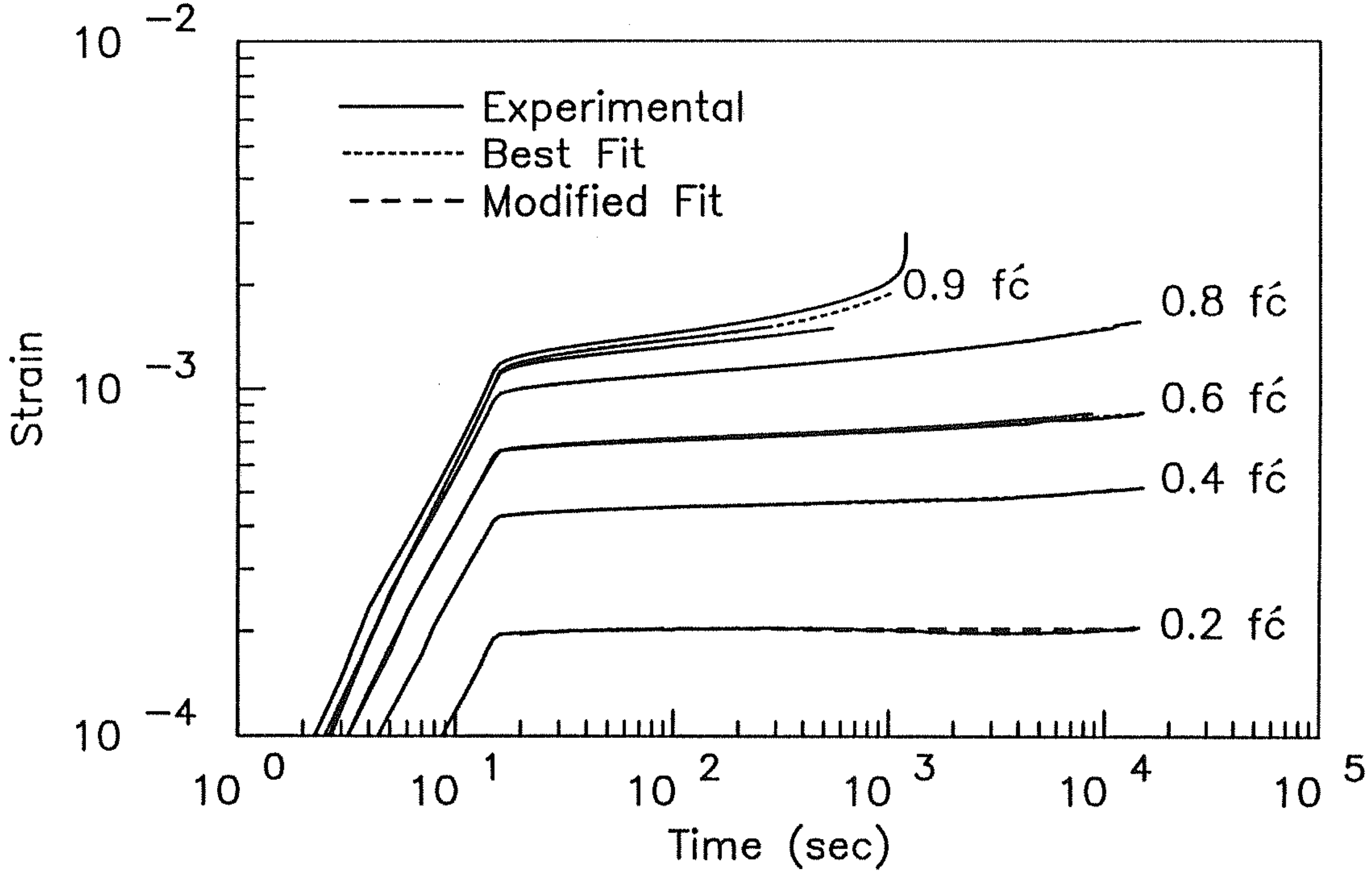

Fig. 3.7 Experimental and best fit strain versus time curves for sustained load tests of w/c = 0.5 concrete.

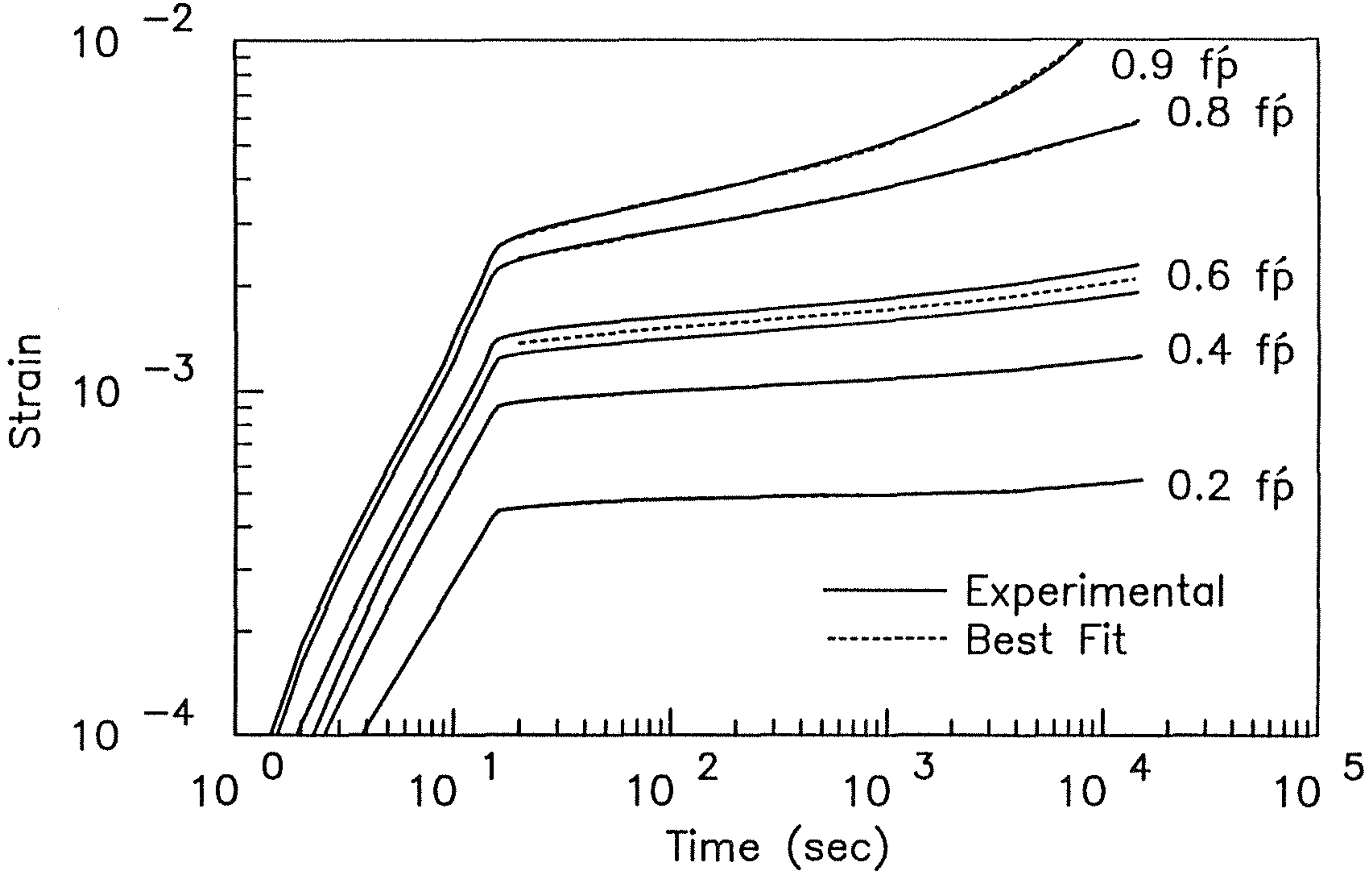

Fig. 3.8 Experimental and best fit strain versus time curves for sustained load tests of w/c = 0.7 cement paste.

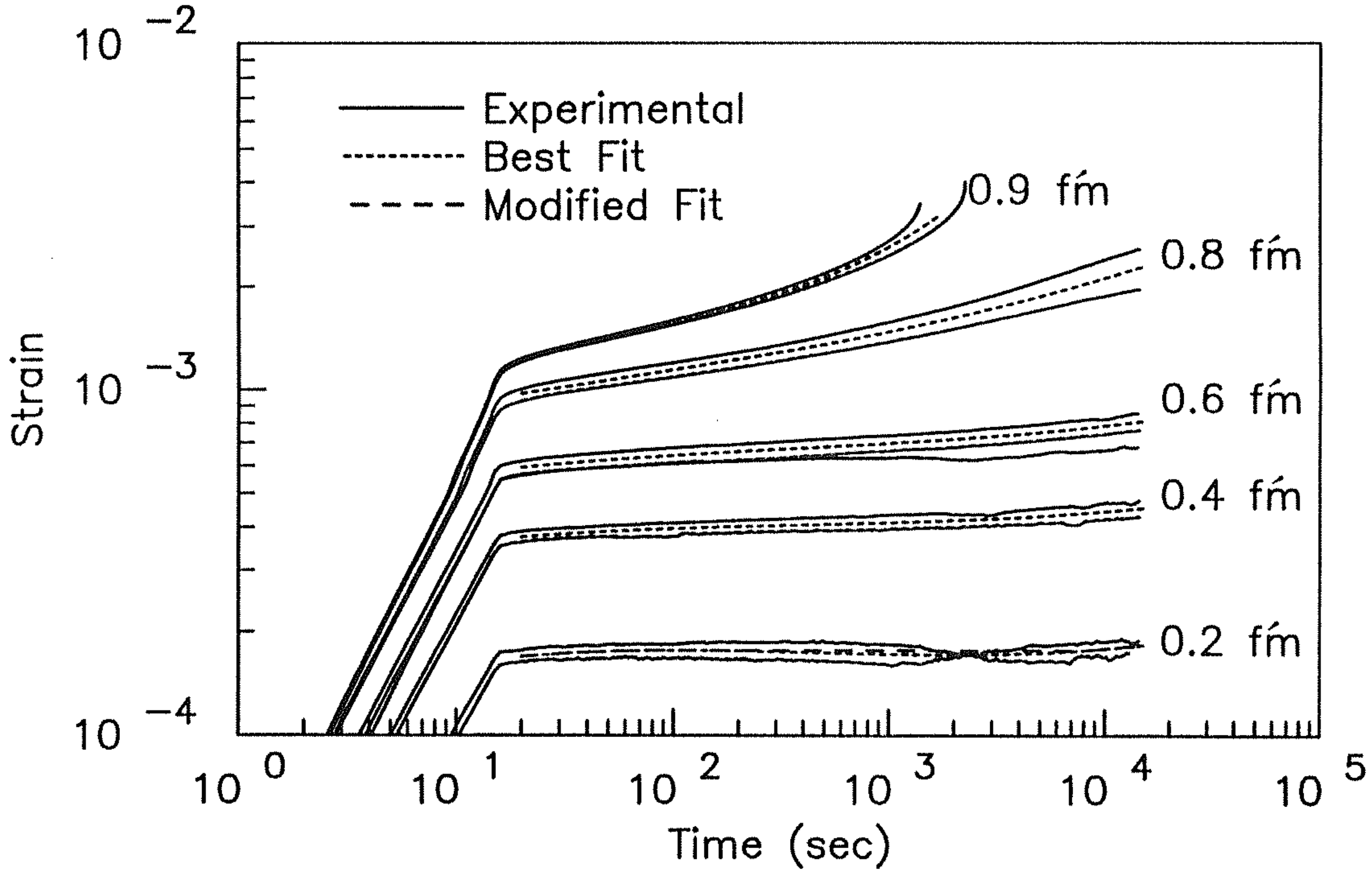

Fig. 3.9 Experimental, best fit, and modified fit strain versus time curves for sustained load tests of w/c = 0.7 mortar.

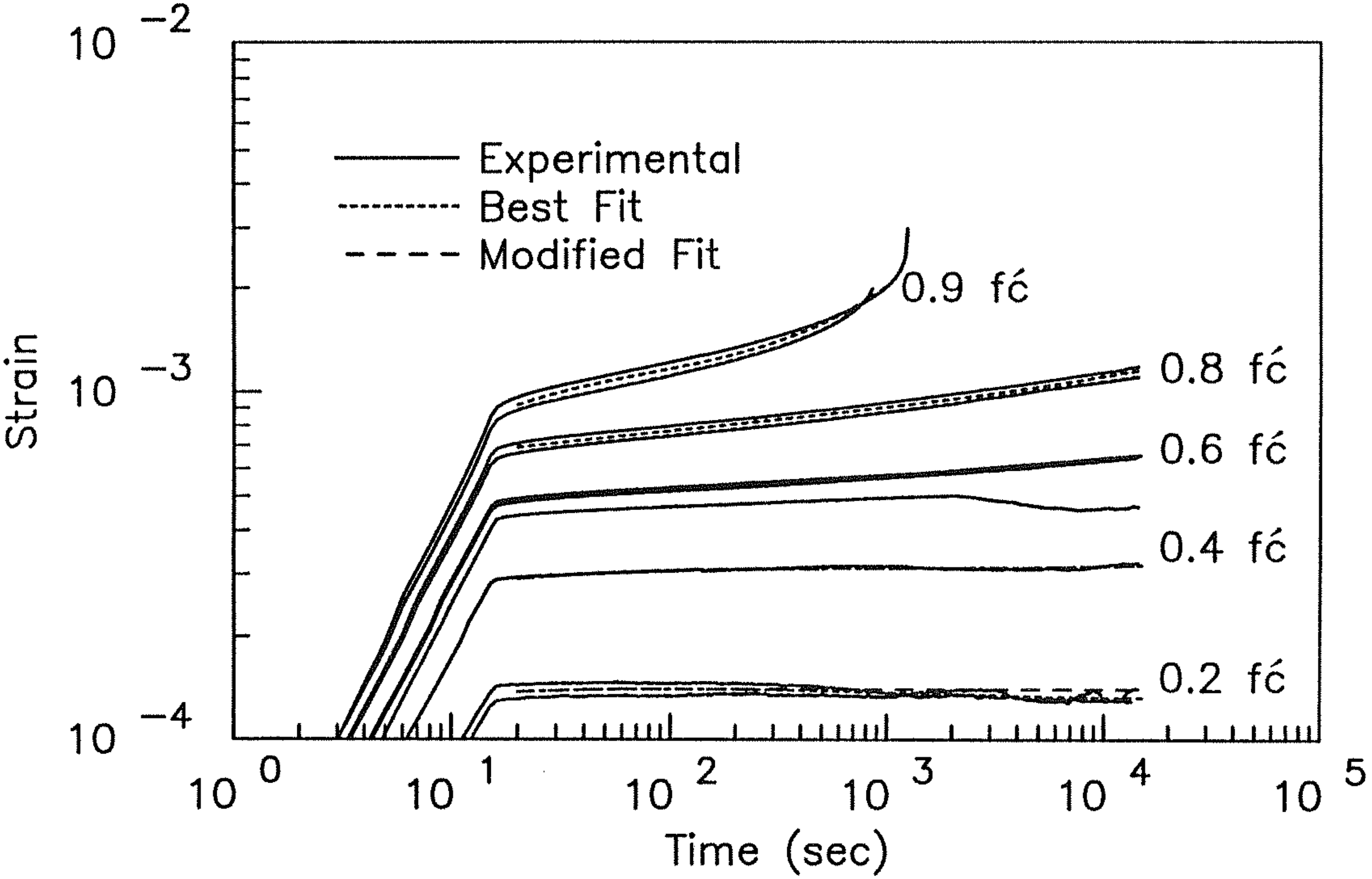

Fig. 3.10 Experimental, best fit, and modified fit strain versus time curves for sustained load tests of w/c = 0.7 concrete.

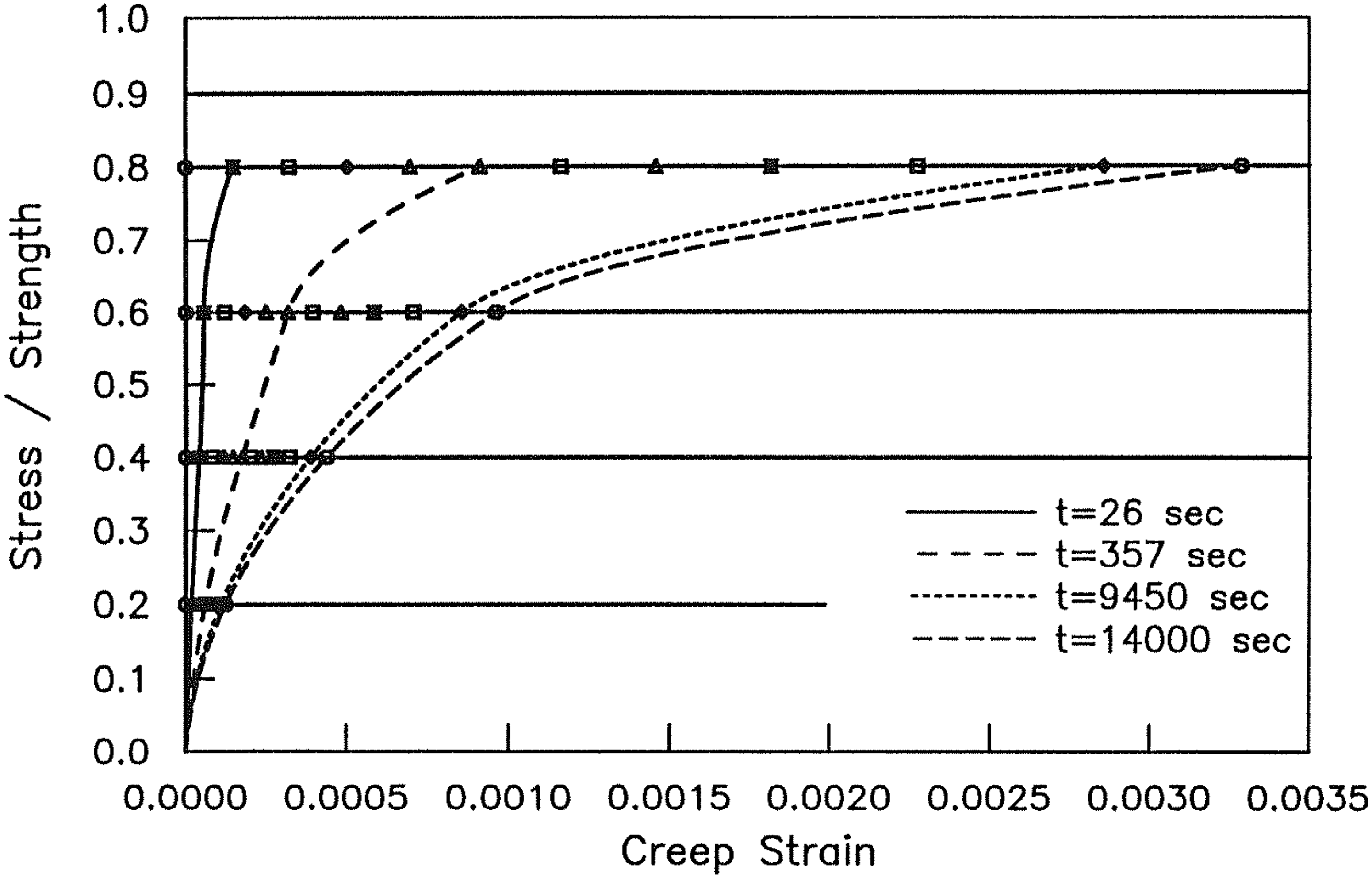

Fig. 3.11 Family of second order spline curves representing creep strain as a function of stress - strength ratio, at several points in time, for w/c = 0.5 cement paste.

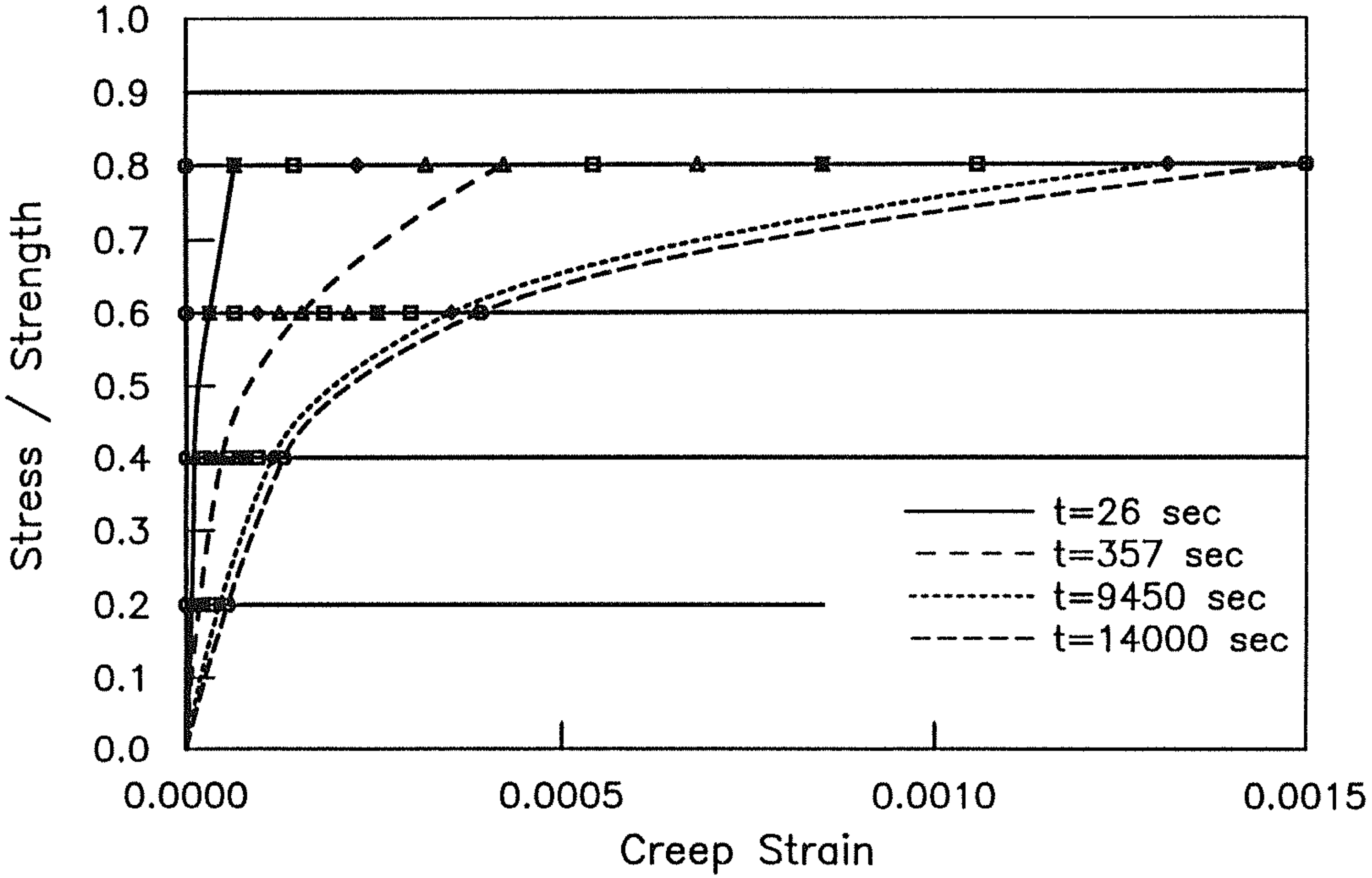

Fig. 3.12 Family of second order spline curves representing creep strain as a function of stress - strength ratio, at several points in time, for w/c = 0.5 mortar.

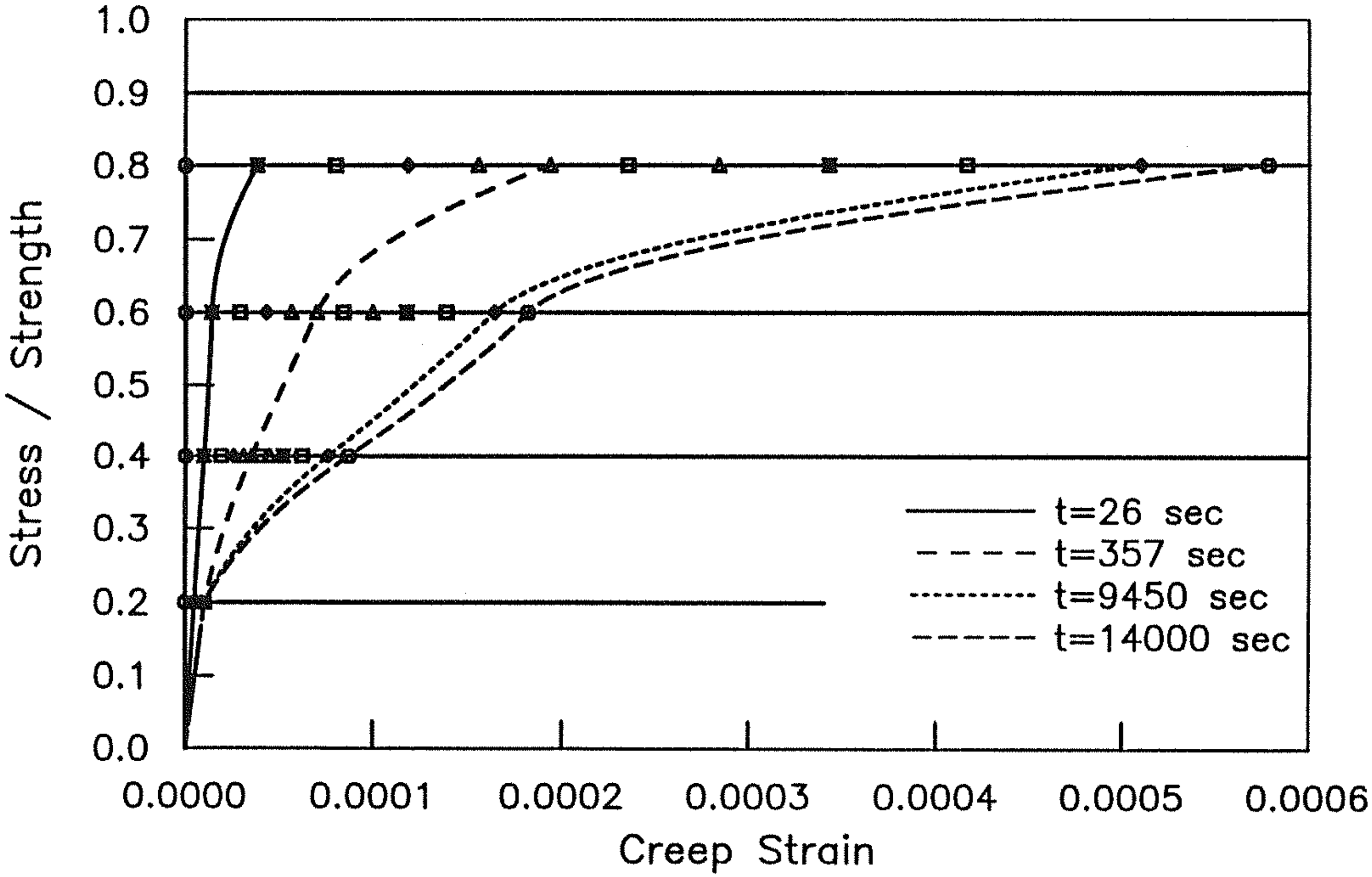

Fig. 3.13 Family of second order spline curves representing creep strain as a function of stress - strength ratio, at several points in time, for w/c = 0.5 concrete.

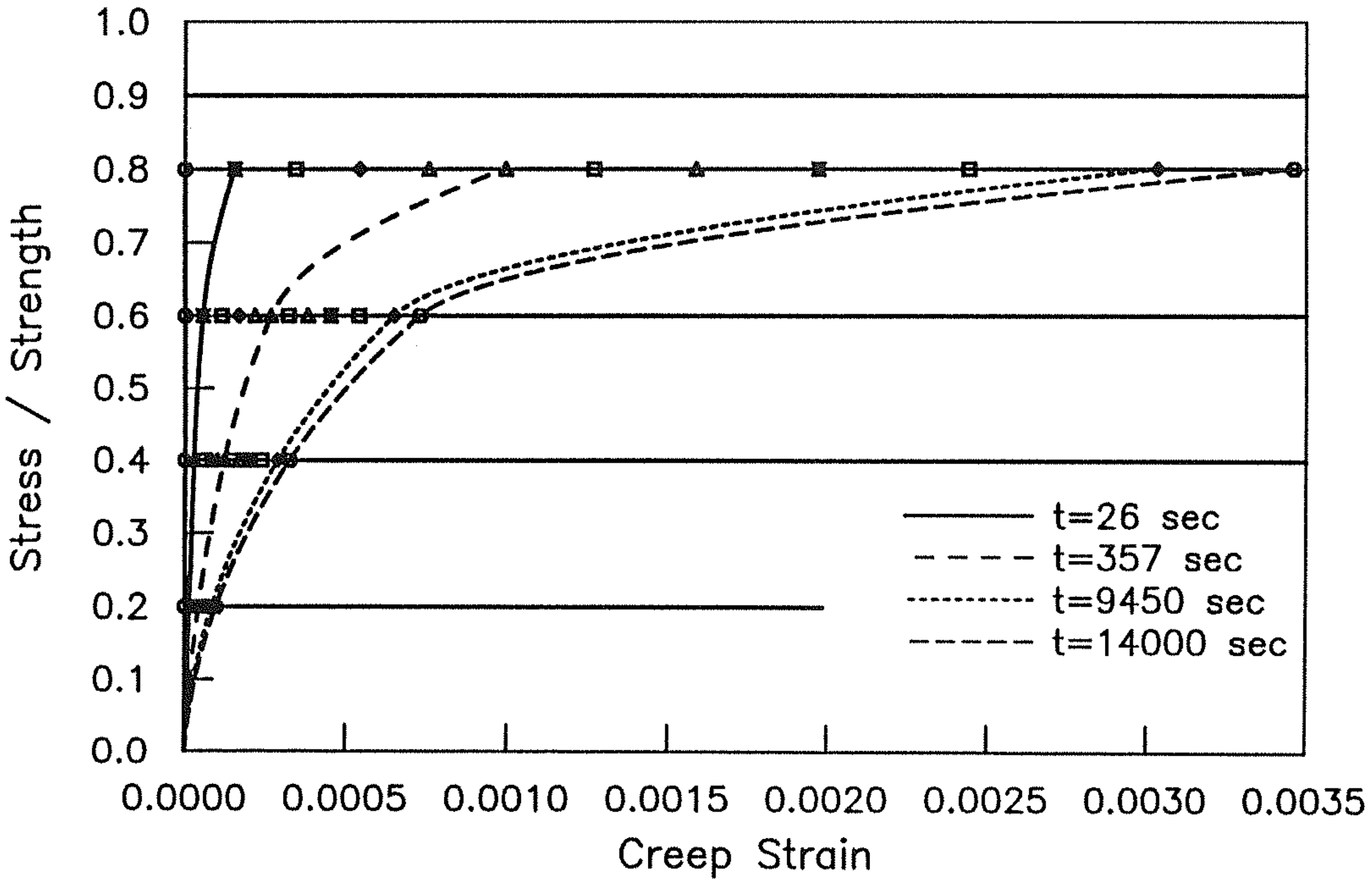

Fig. 3.14 Family of second order spline curves representing creep strain as a function of stress - strength ratio, at several points in time, for w/c = 0.7 cement paste.

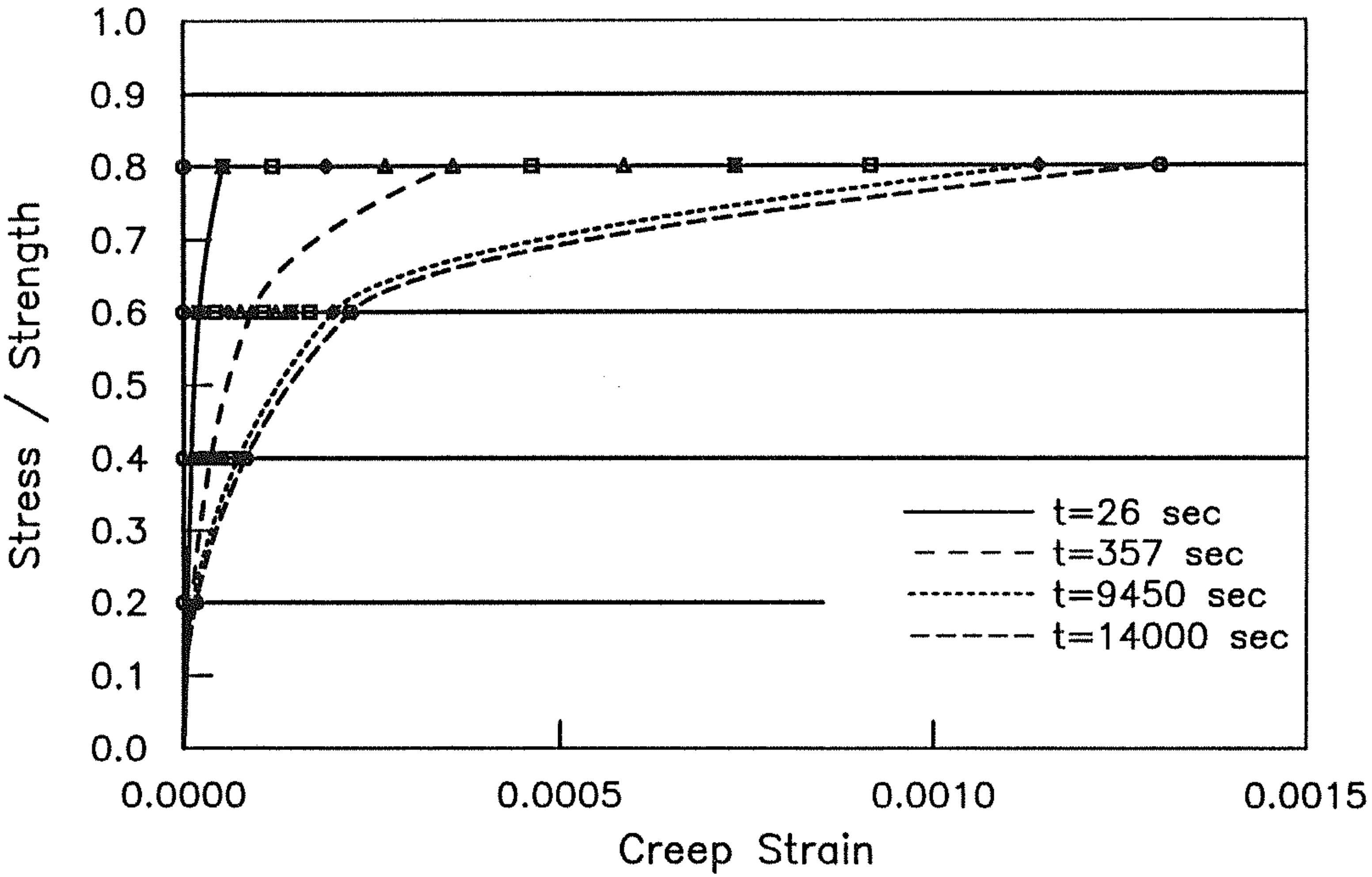

Fig. 3.15 Family of second order spline curves representing creep strain as a function of stress - strength ratio, at several points in time, for w/c = 0.7 mortar.

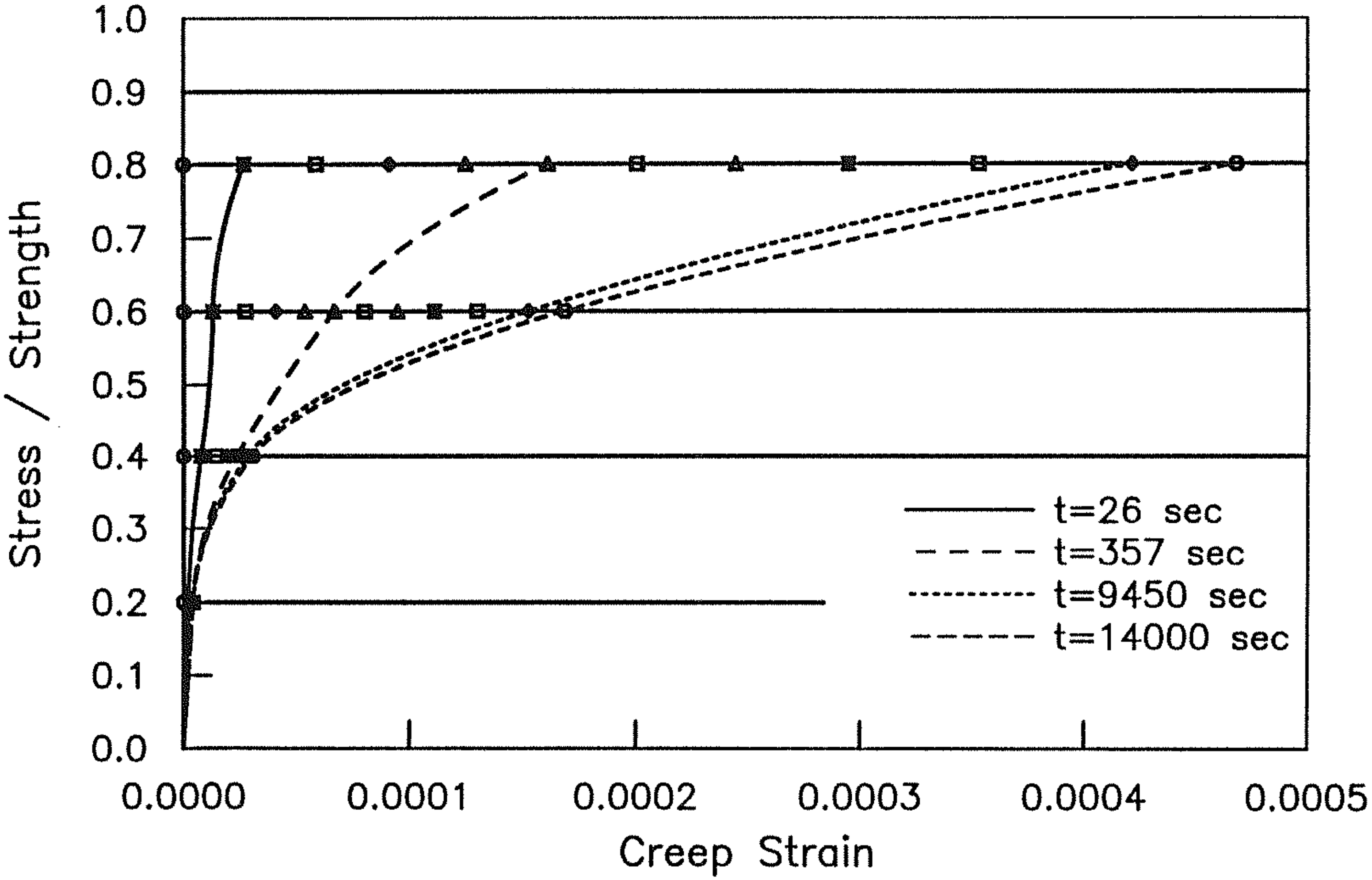

Fig. 3.16 Family of second order spline curves representing creep strain as a function of stress - strength ratio, at several points in time, for w/c = 0.7 concrete.

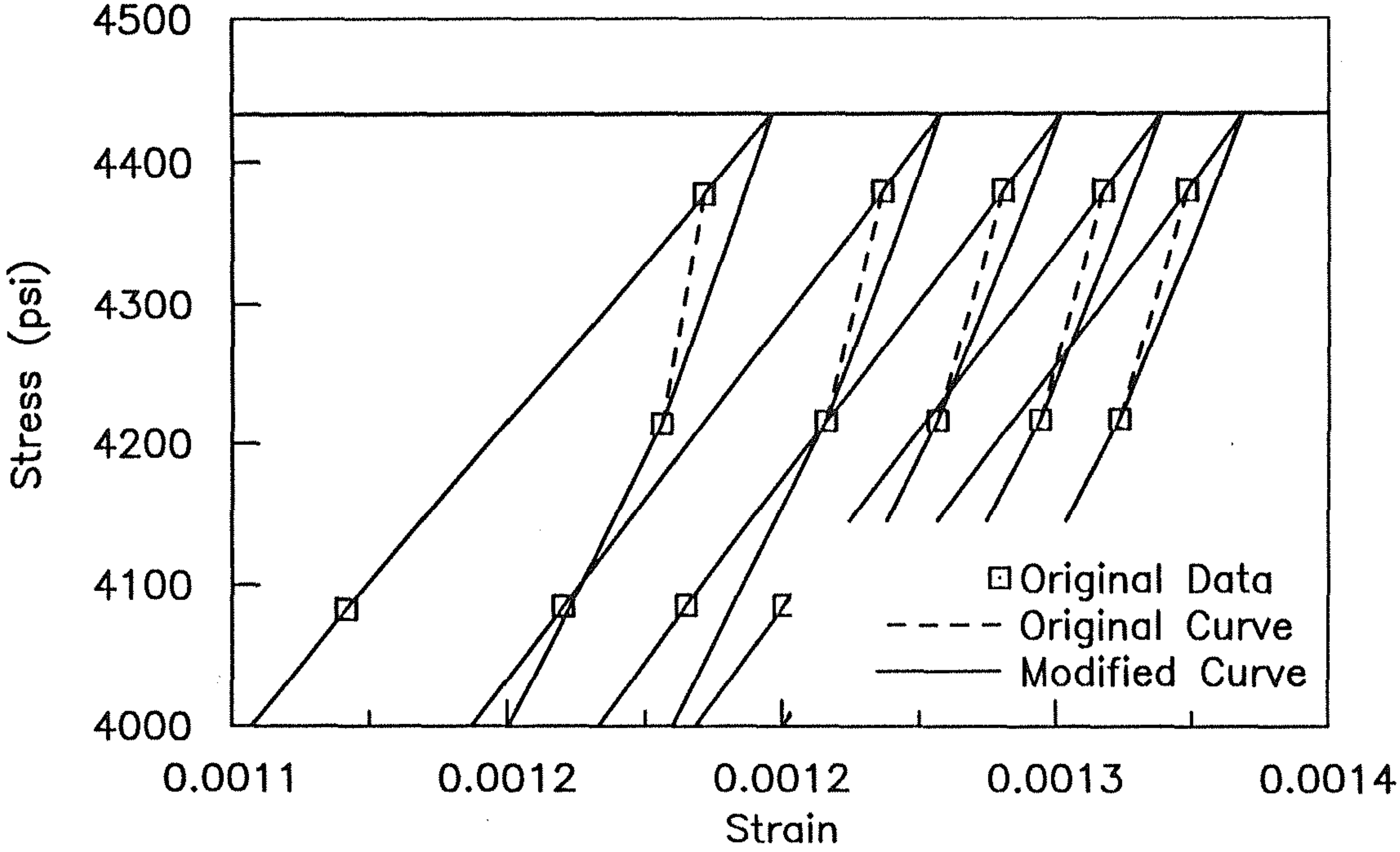

Fig. 3.17 Cyclic stress versus longitudinal strain for cyclic test 2C2 (w/c = 0.5 mortar) showing the original recorded data and the calculated peak at the maximum stress.

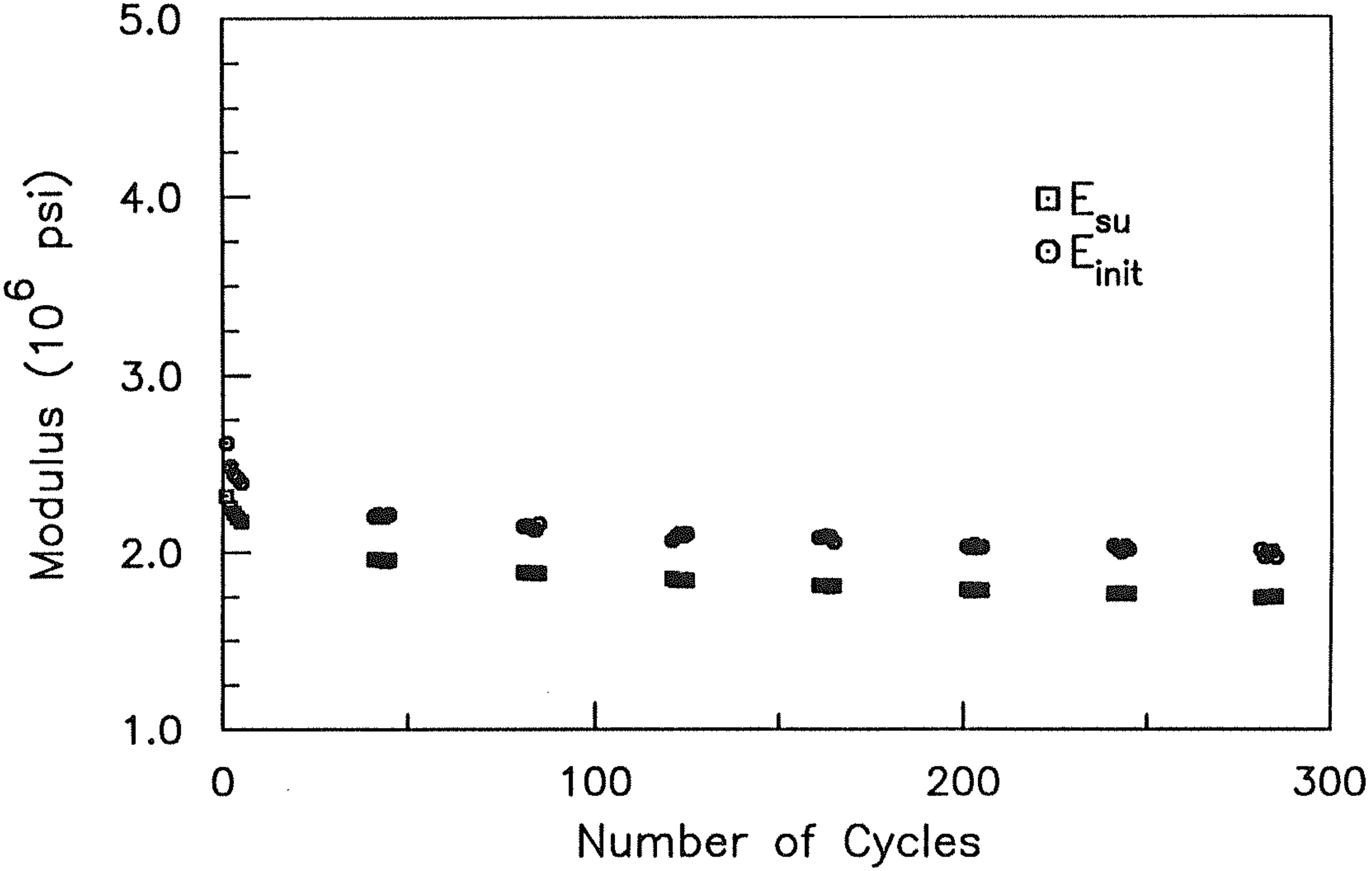

Fig. 3.18 Secant unloading modulus and initial modulus versus number of cycles for cyclic test 1D2 (w/c = 0.5 cement paste).

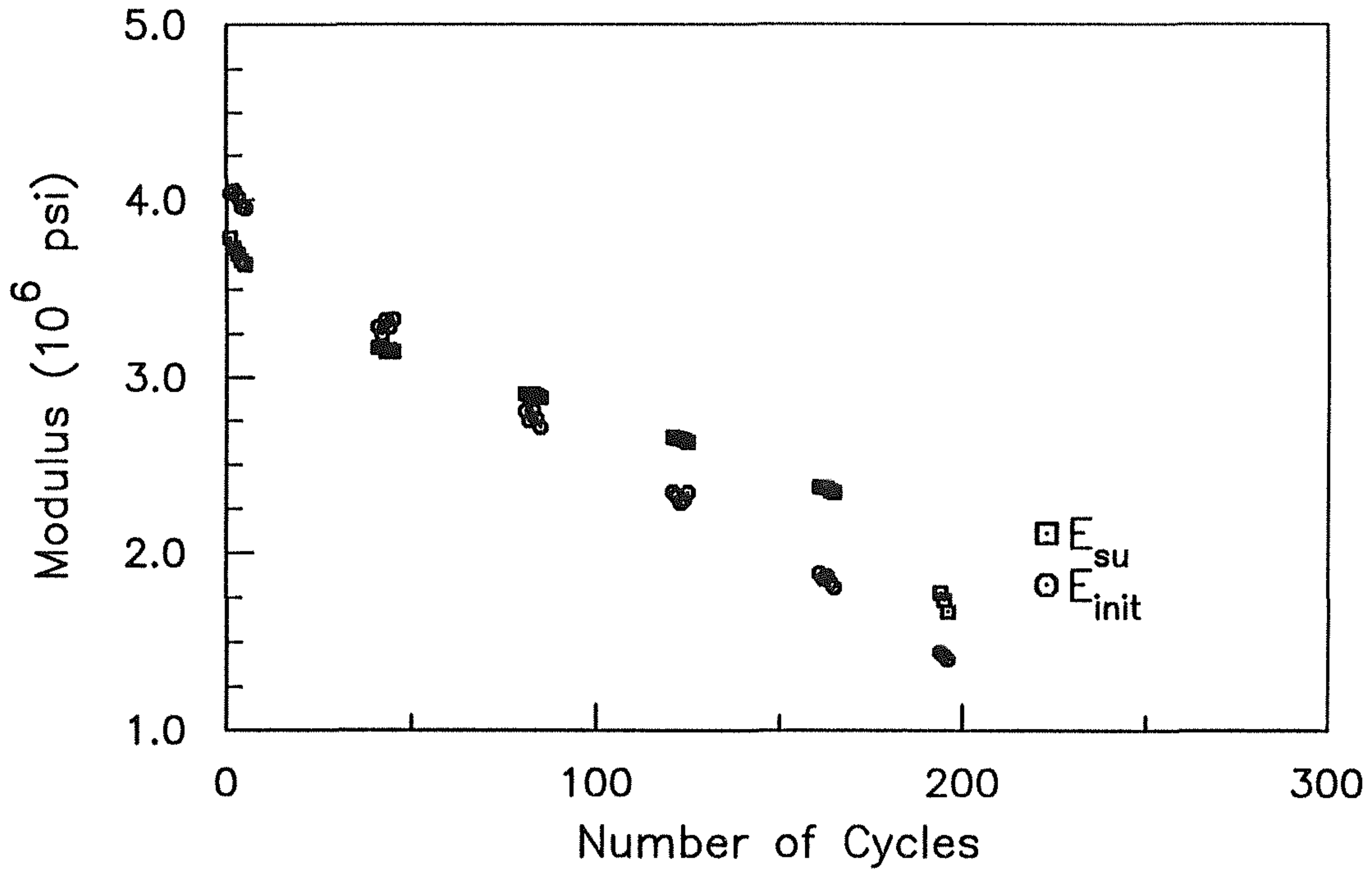

Fig. 3.19 Secant unloading modulus and initial modulus versus number of cycles for cyclic test 2C2 (w/c = 0.5 mortar).

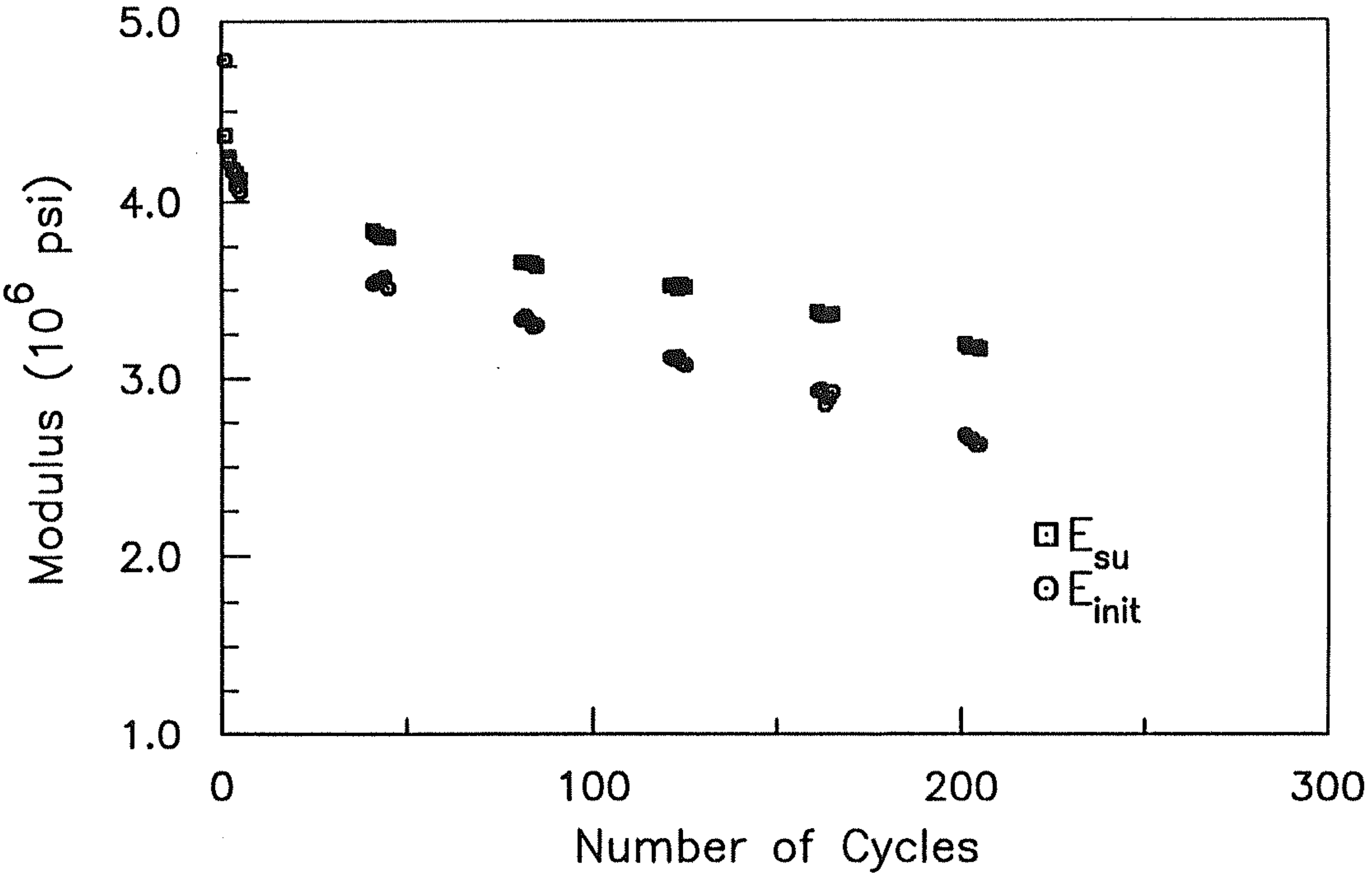

Fig. 3.20 Secant unloading modulus and initial modulus versus number of cycles for cyclic test 3C2 (w/c = 0.5 concrete).

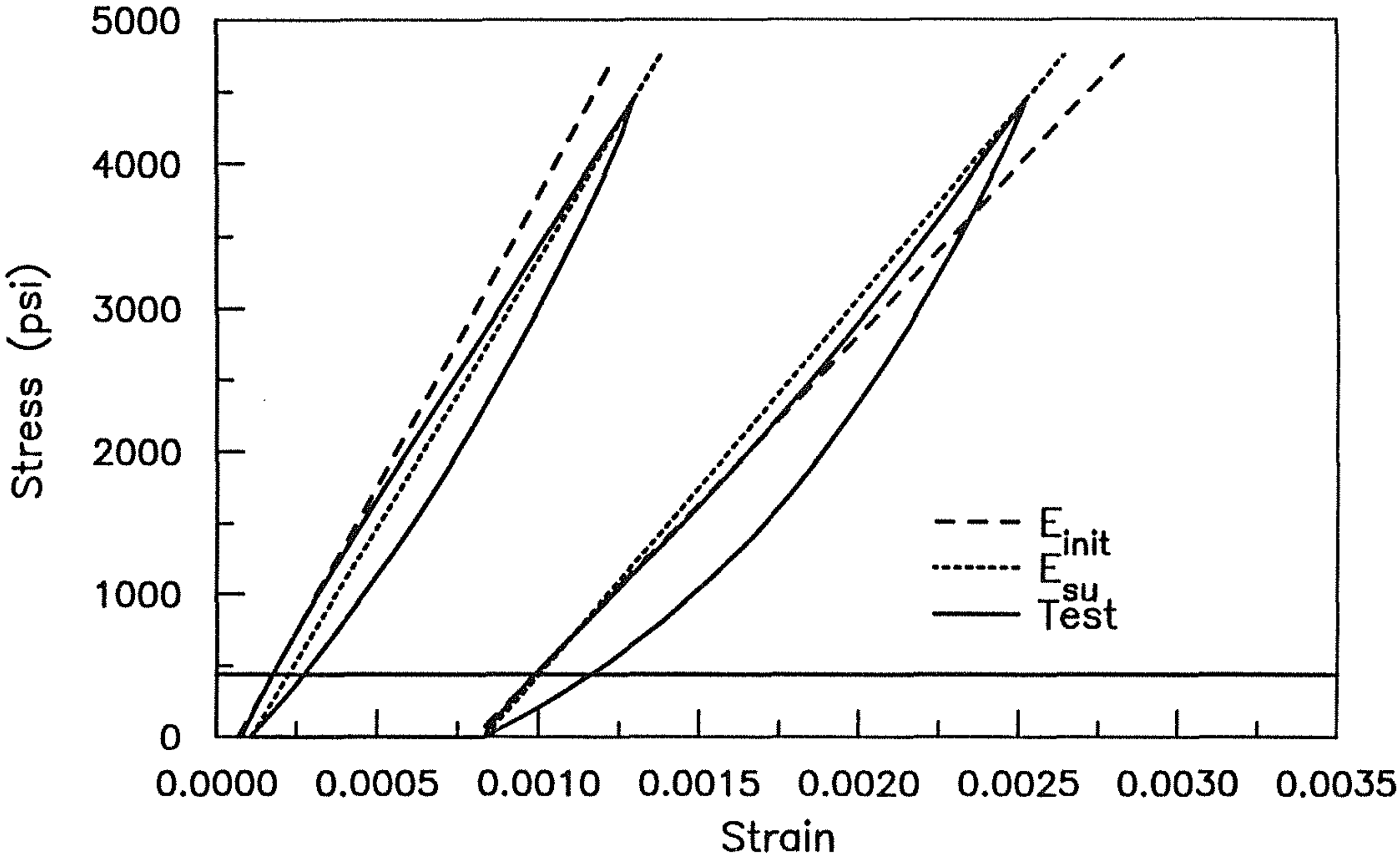

Fig. 3.21 Cyclic stress versus strain for cycles at different times, showing how the changing shape of the stress - strain curve affects the initial modulus and secant unloading modulus.

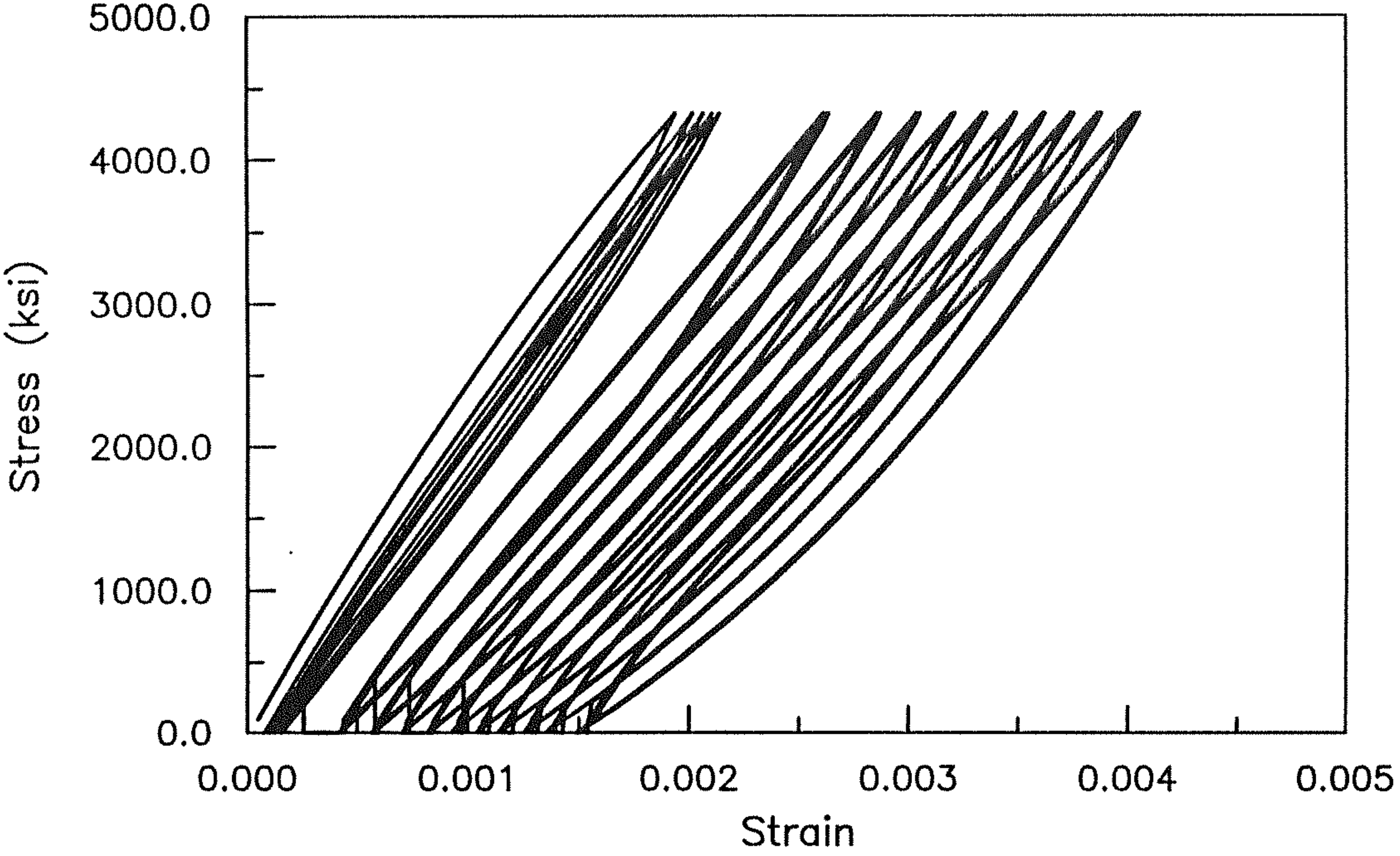

Fig. 3.22 Cyclic stress - strain record for test 1D2 (w/c = 0.5 cement paste).

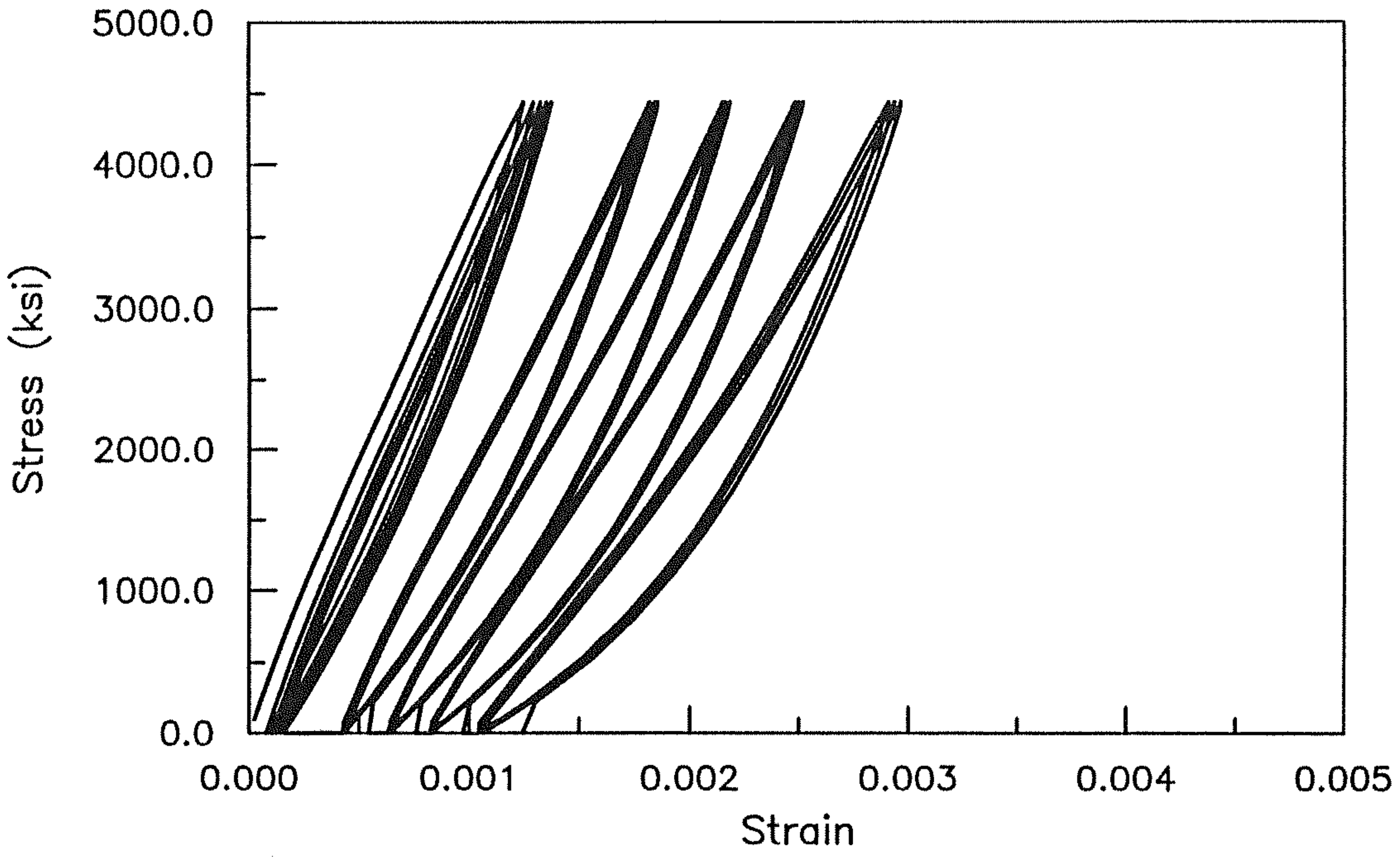

Fig. 3.23 Cyclic stress - strain record for test 2C2 (w/c = 0.5 mortar).

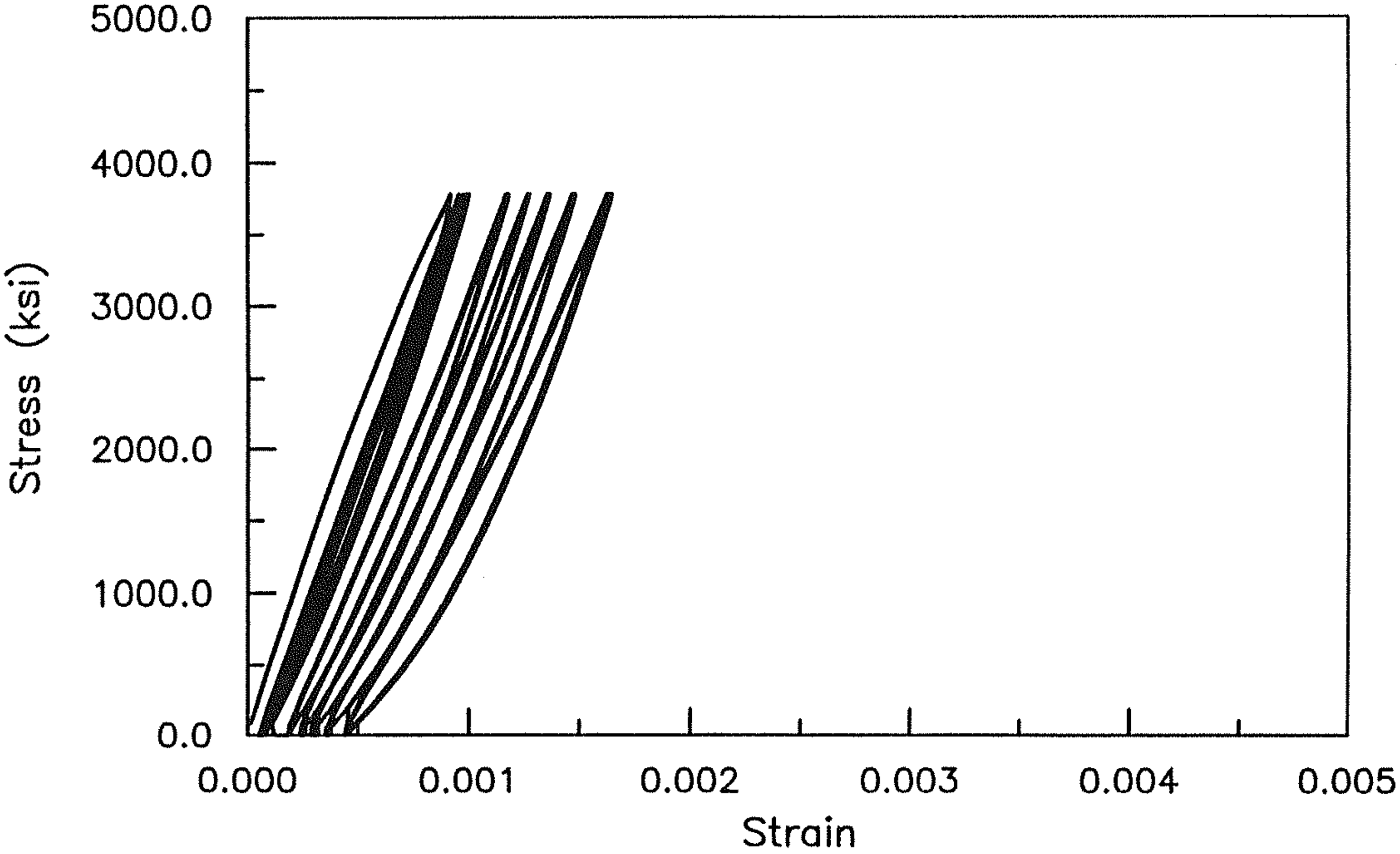

Fig. 3.24 Cyclic stress - strain record for test 3C2 (w/c = 0.5 concrete).

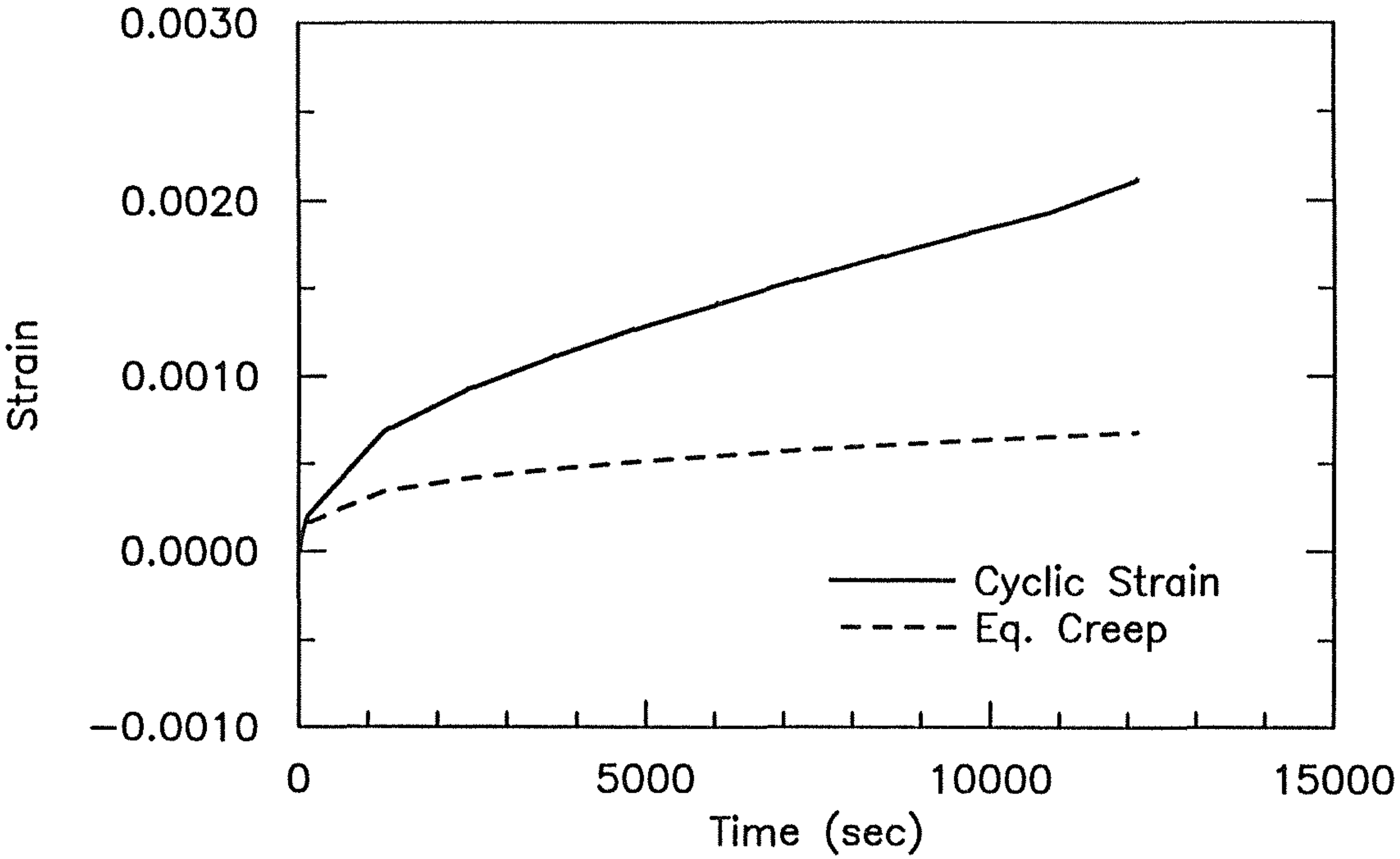

Fig. 3.25 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 1D2, (w/c = 0.5 cement paste) loaded from 0 to 0.8 f'_p.

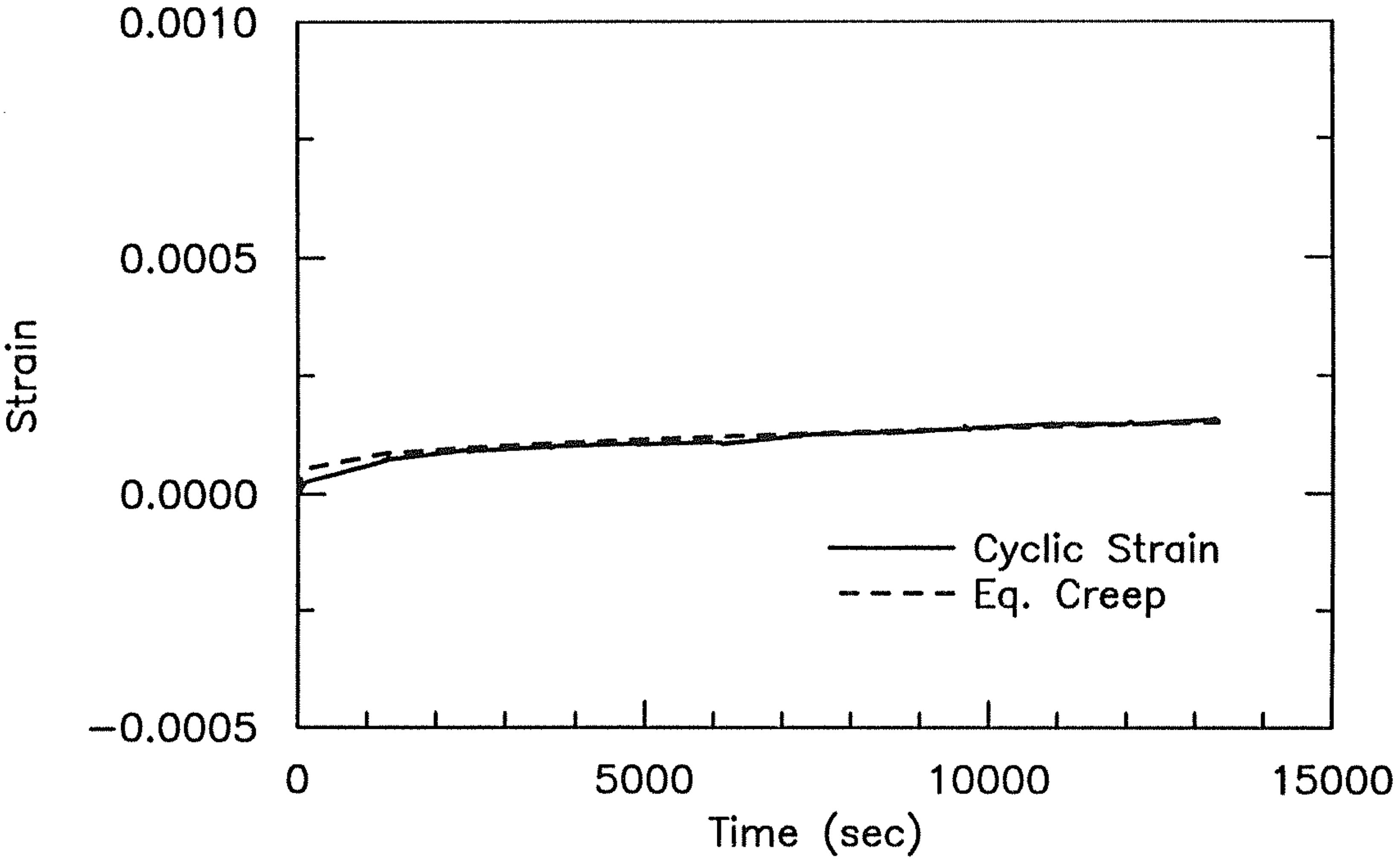

Fig. 3.26 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 1D3, (w/c = 0.5 cement paste) loaded from 0 to 0.4 f'_p.

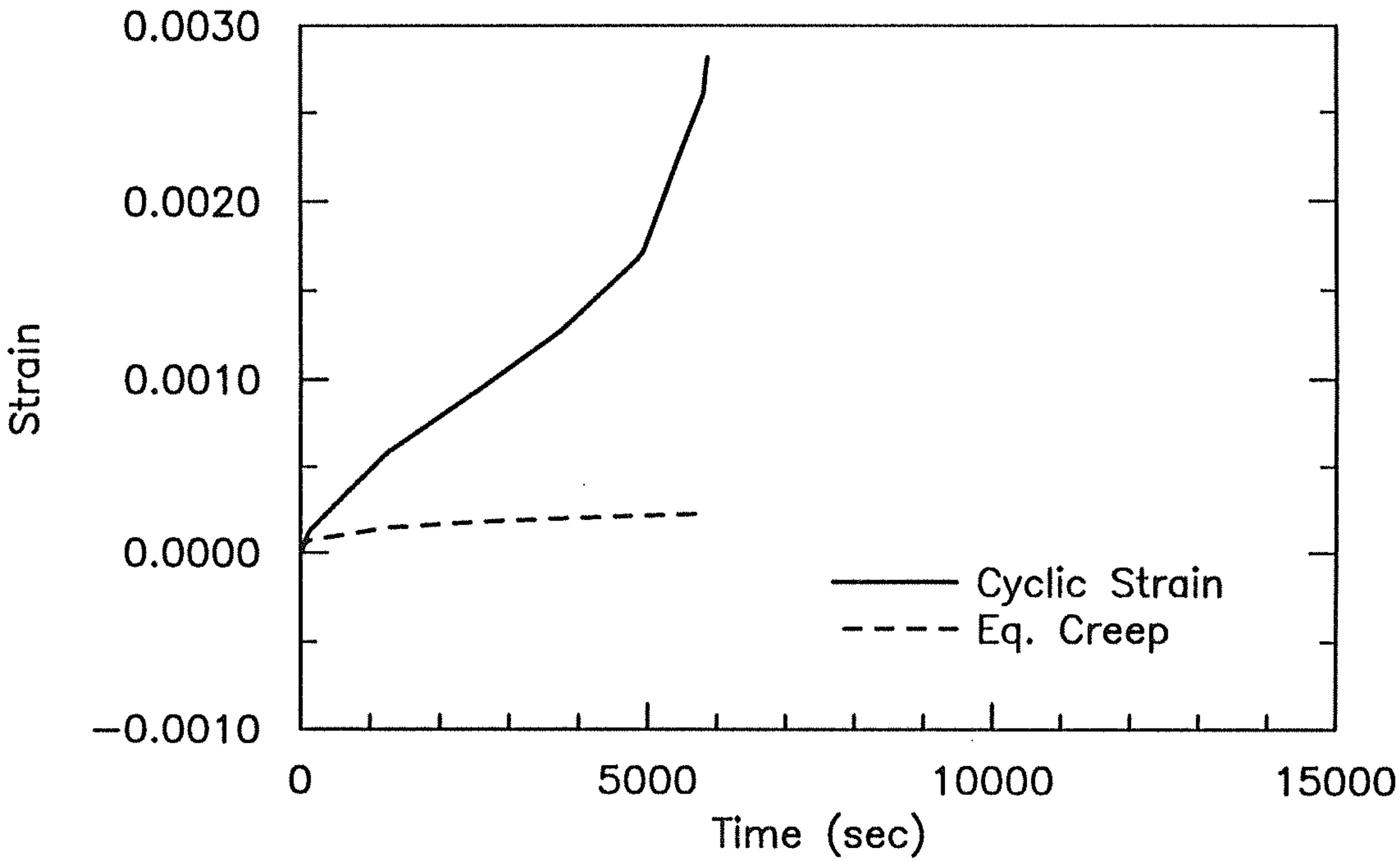

Fig. 3.27 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 2C2, (w/c = 0.5 mortar) loaded from 0 to 0.8 f'_m.

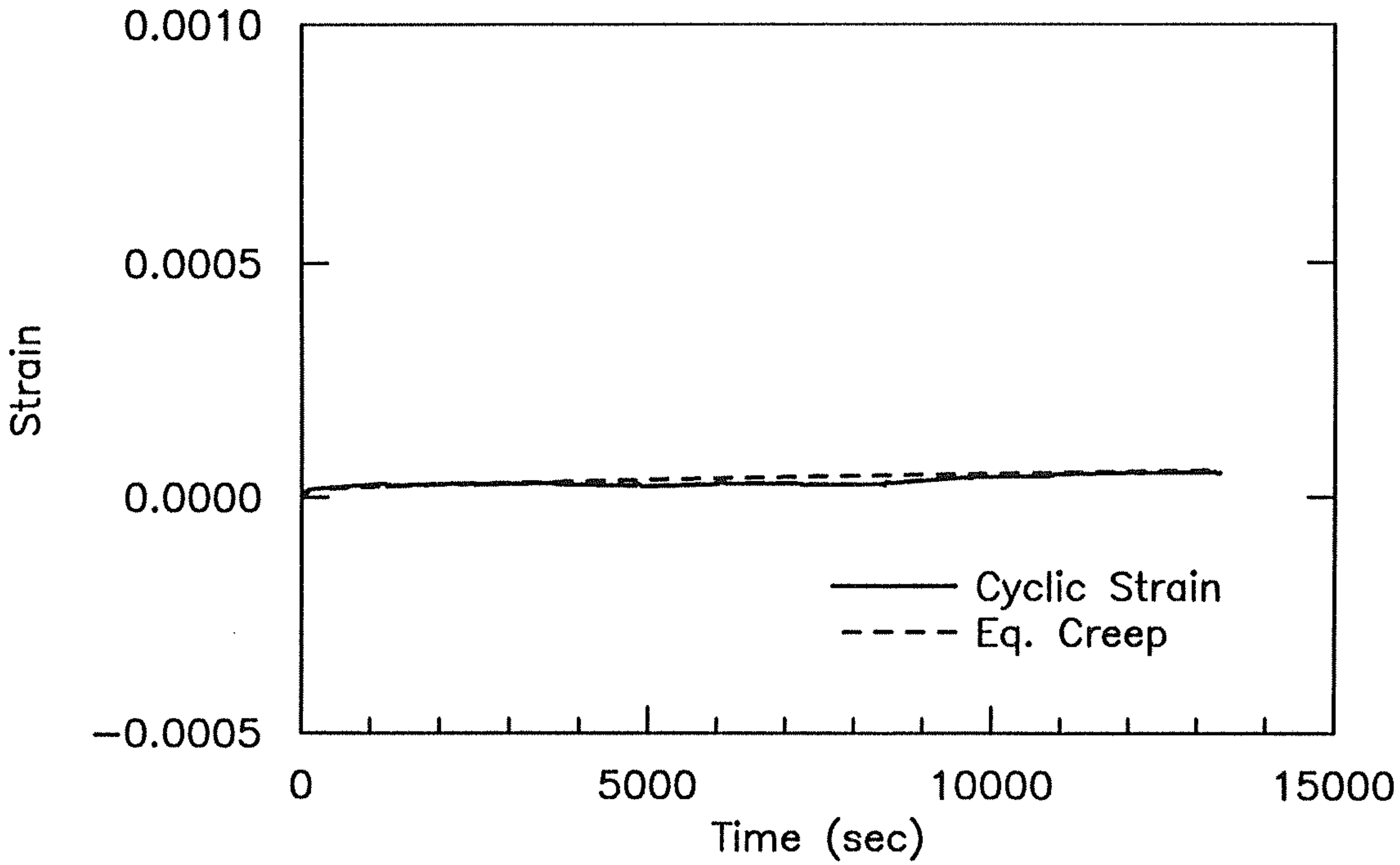

Fig. 3.28 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 2C3, (w/c = 0.5 mortar) loaded from 0 to 0.4 f'_m.

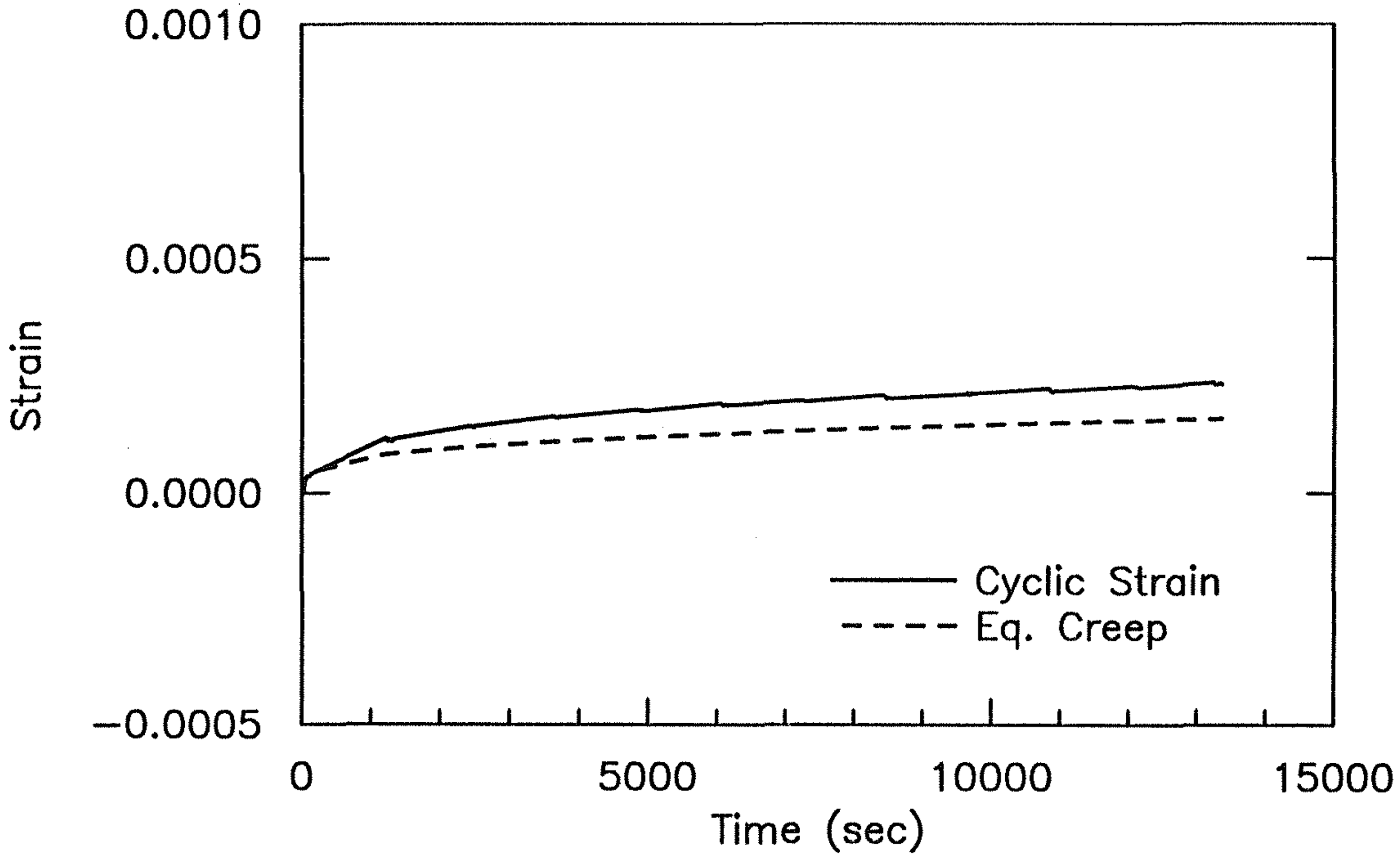

Fig. 3.29 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 2C5, (w/c = 0.5 mortar) loaded from 0.2 to 0.6 f'_m.

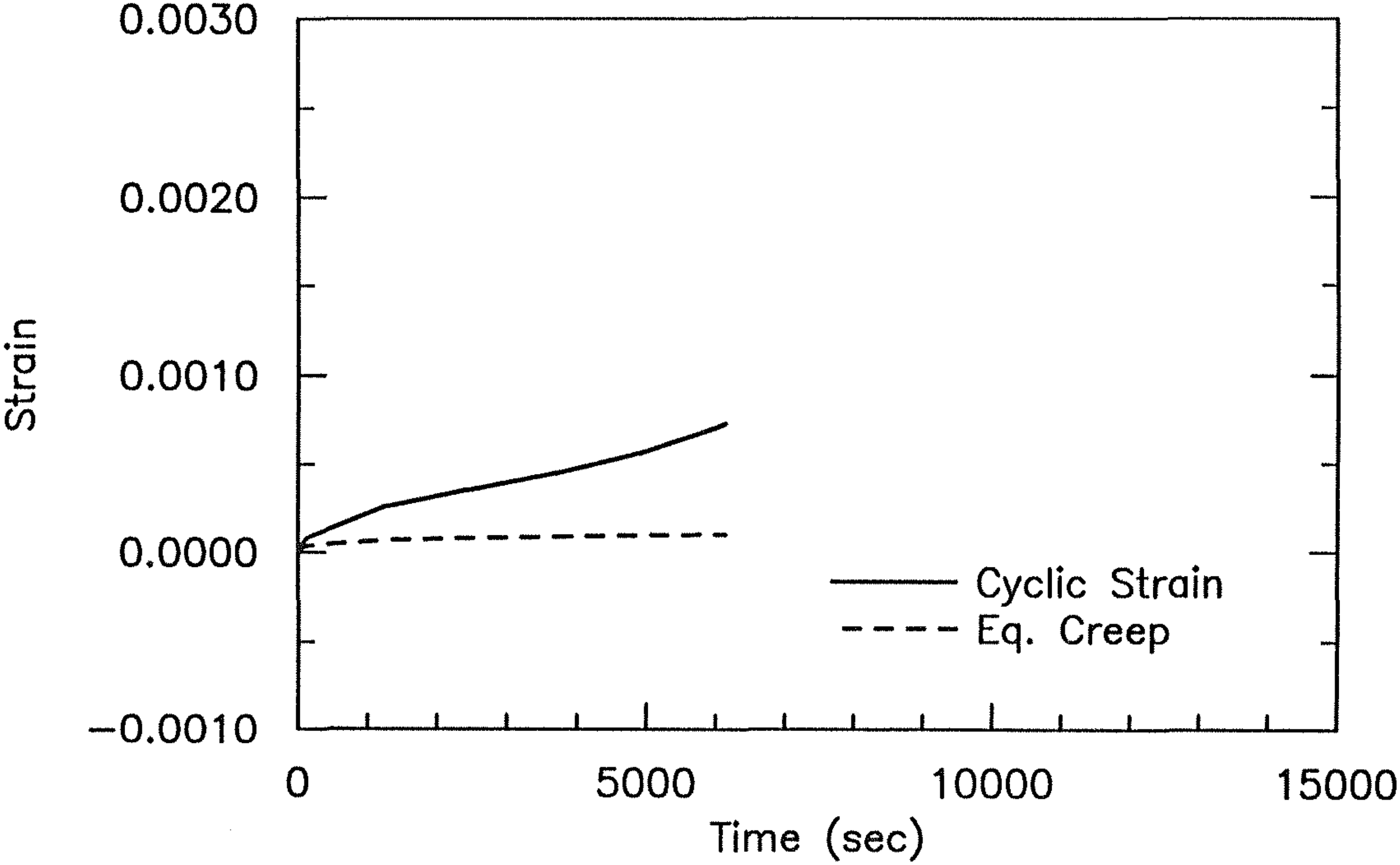

Fig. 3.30 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 3C2, (w/c = 0.5 concrete) loaded from 0 to 0.8 f'_c.

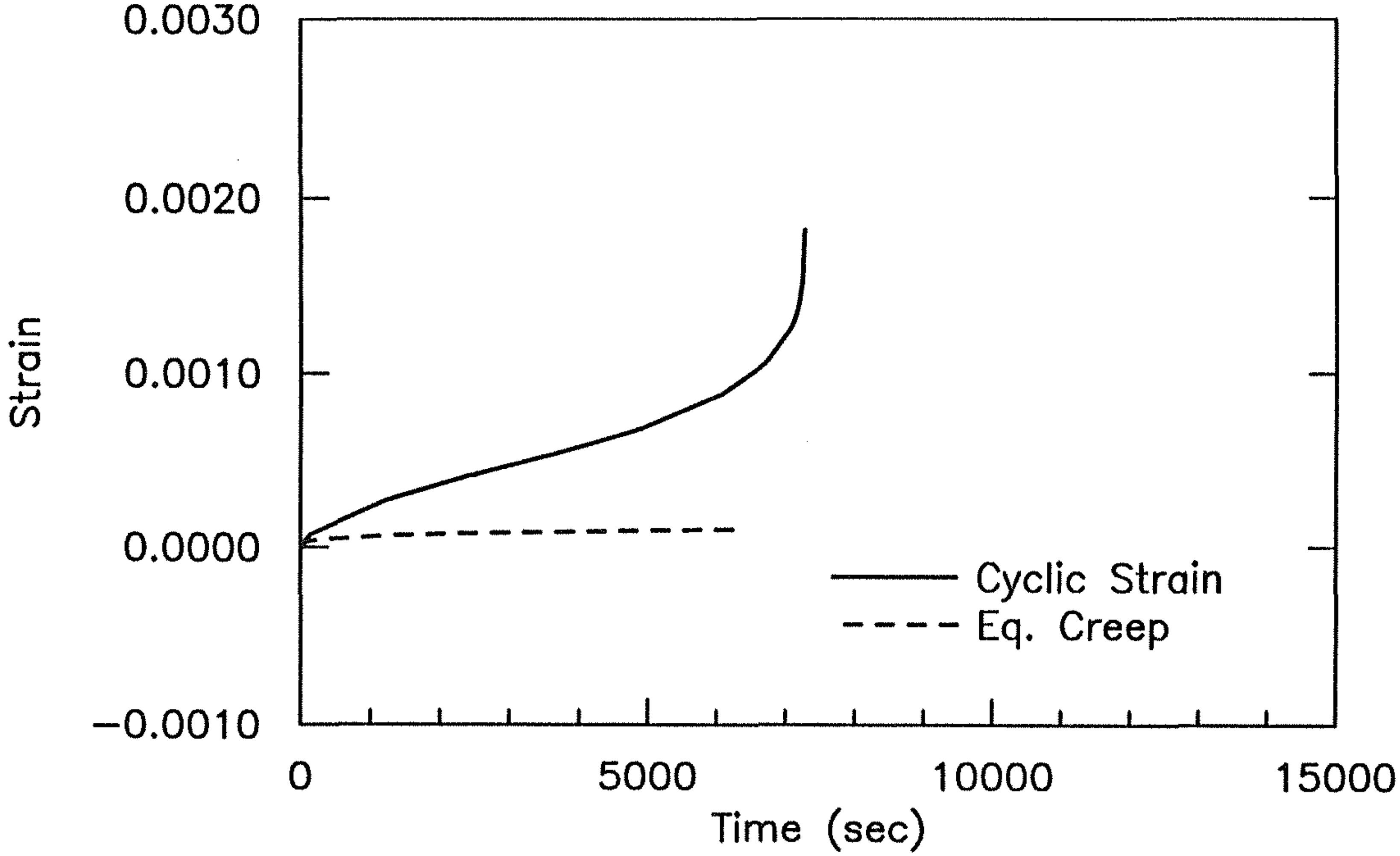

Fig. 3.31 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 3C4, (w/c = 0.5 concrete) loaded from 0 to 0.8 f'_c.

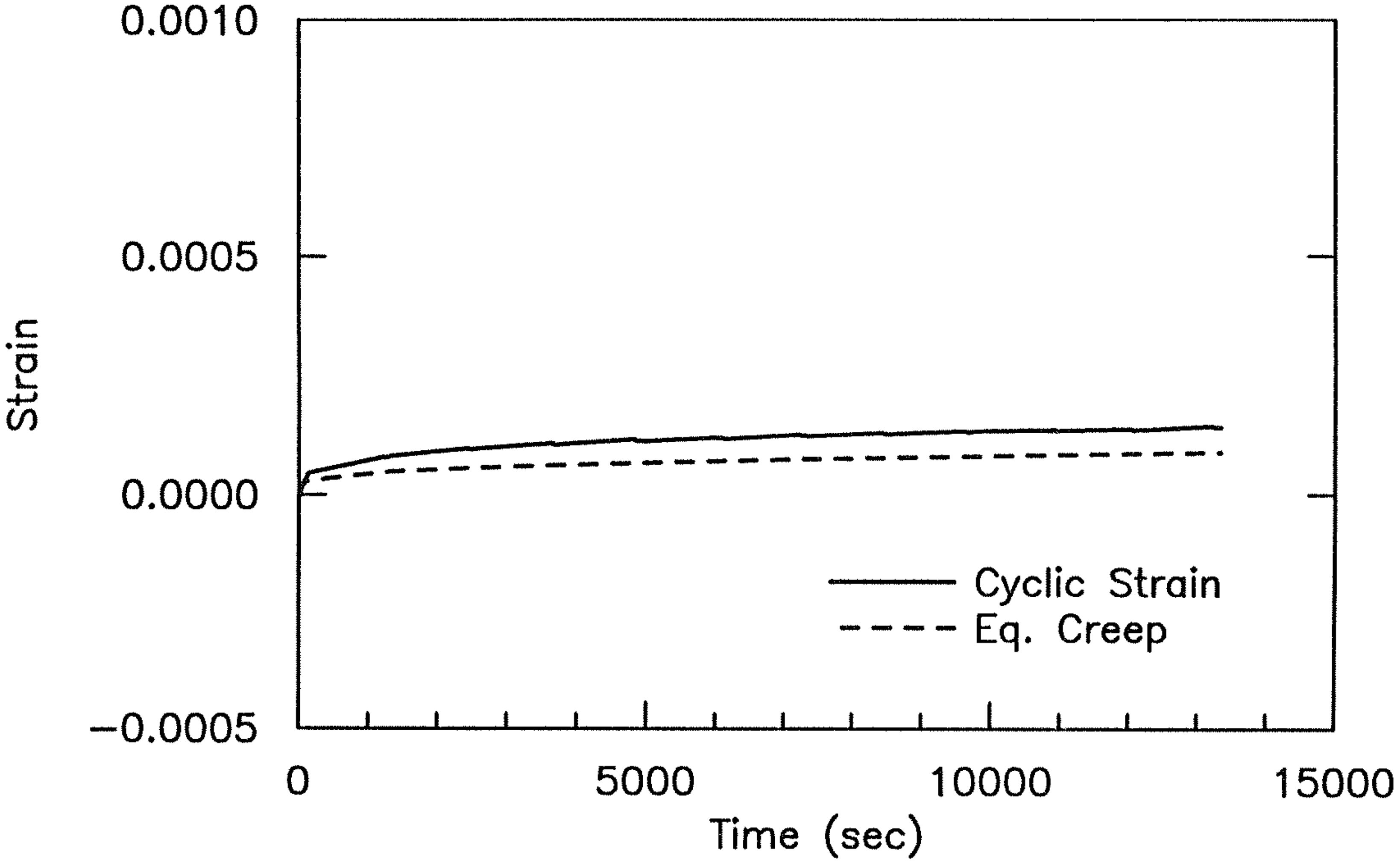

Fig. 3.32 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 3C5, (w/c = 0.5 concrete) loaded from 0.2 to 0.6 f'_c.

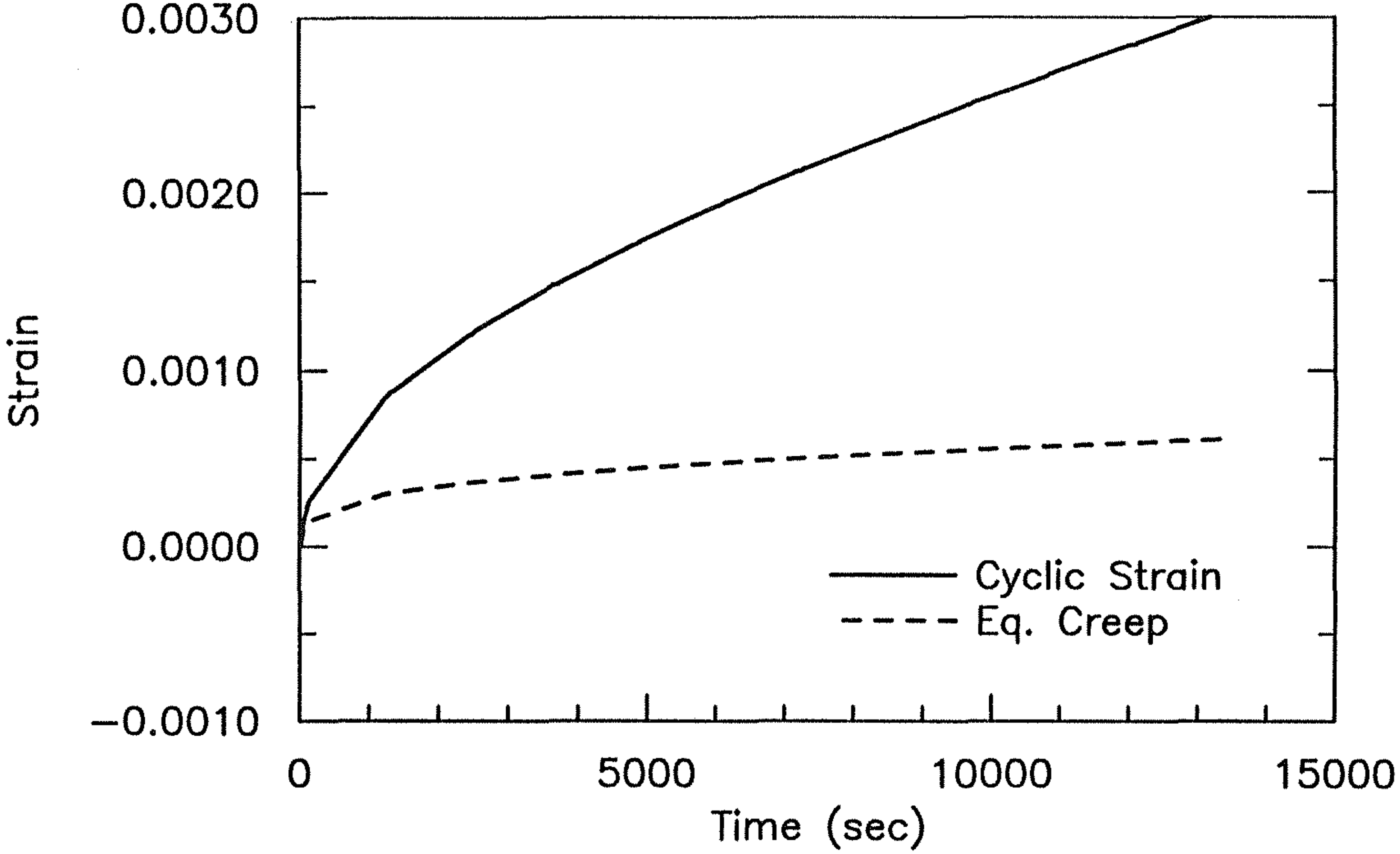

Fig. 3.33 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 4C2, (w/c = 0.7 cement paste) loaded from 0 to 0.8 f'_p.

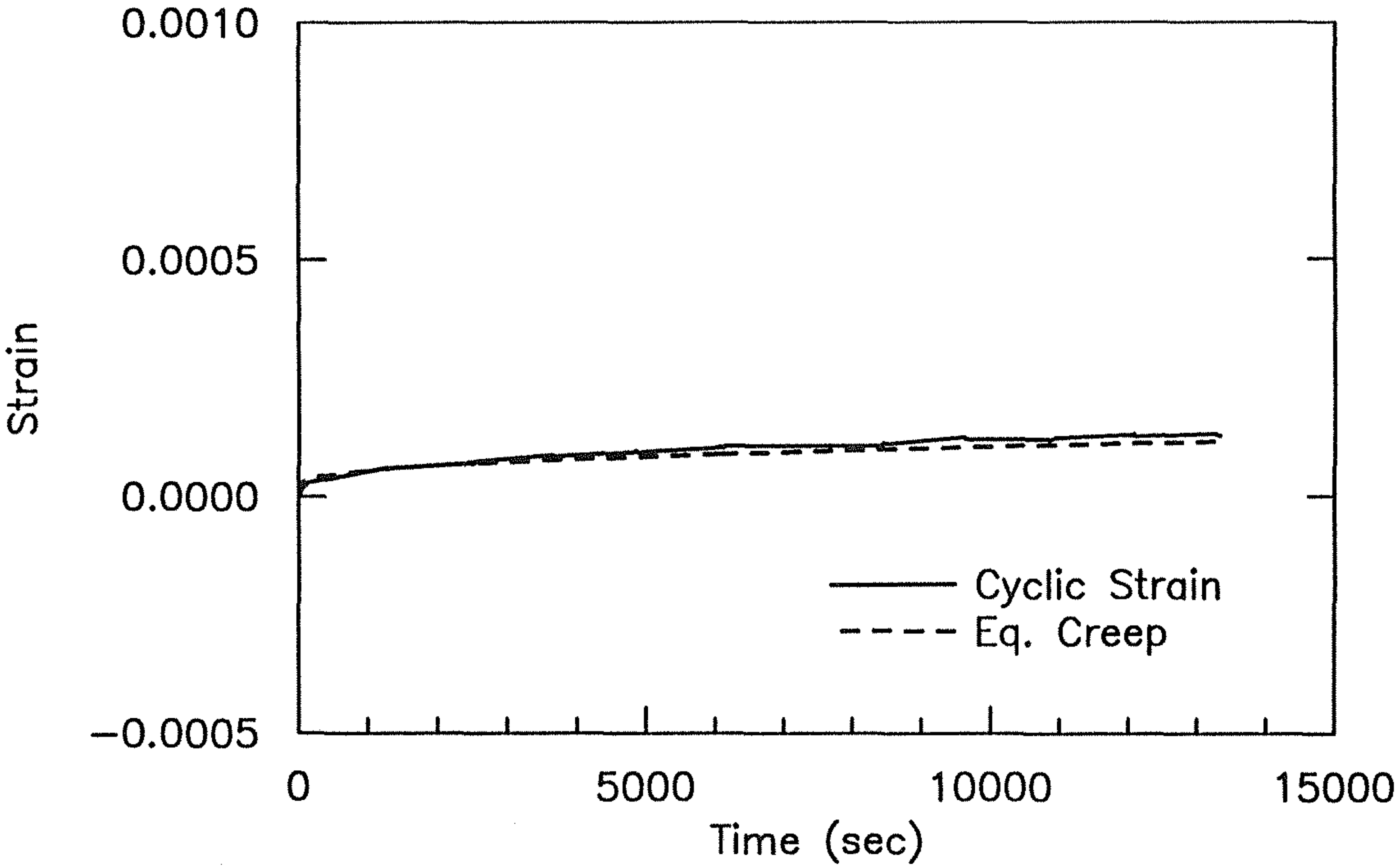

Fig. 3.34 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 4C3, (w/c = 0.7 cement paste) loaded from 0 to 0.4 f'_p.

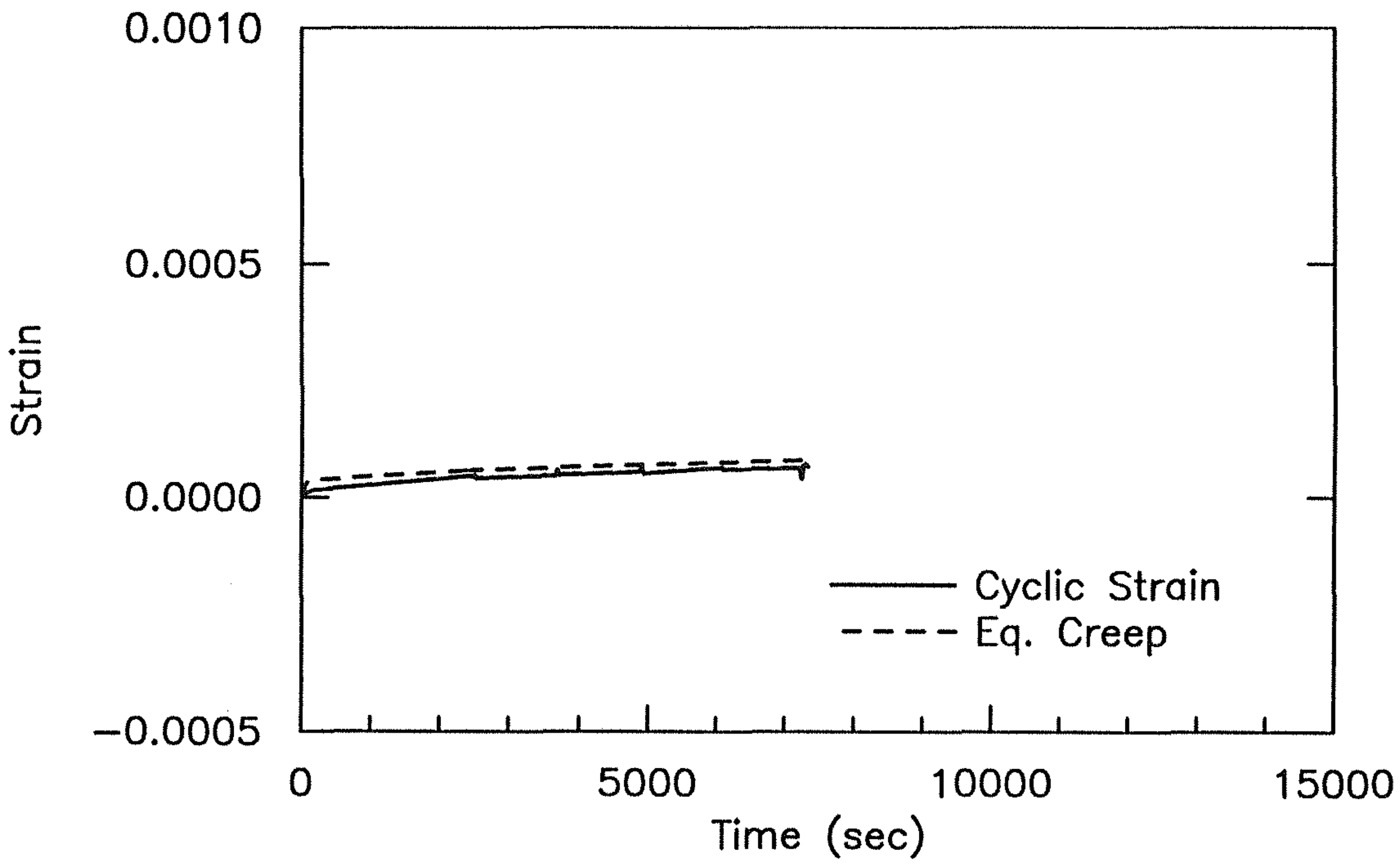

Fig. 3.35 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 4C4, (w/c = 0.7 cement paste) loaded from 0.1 to 0.3 f'_p.

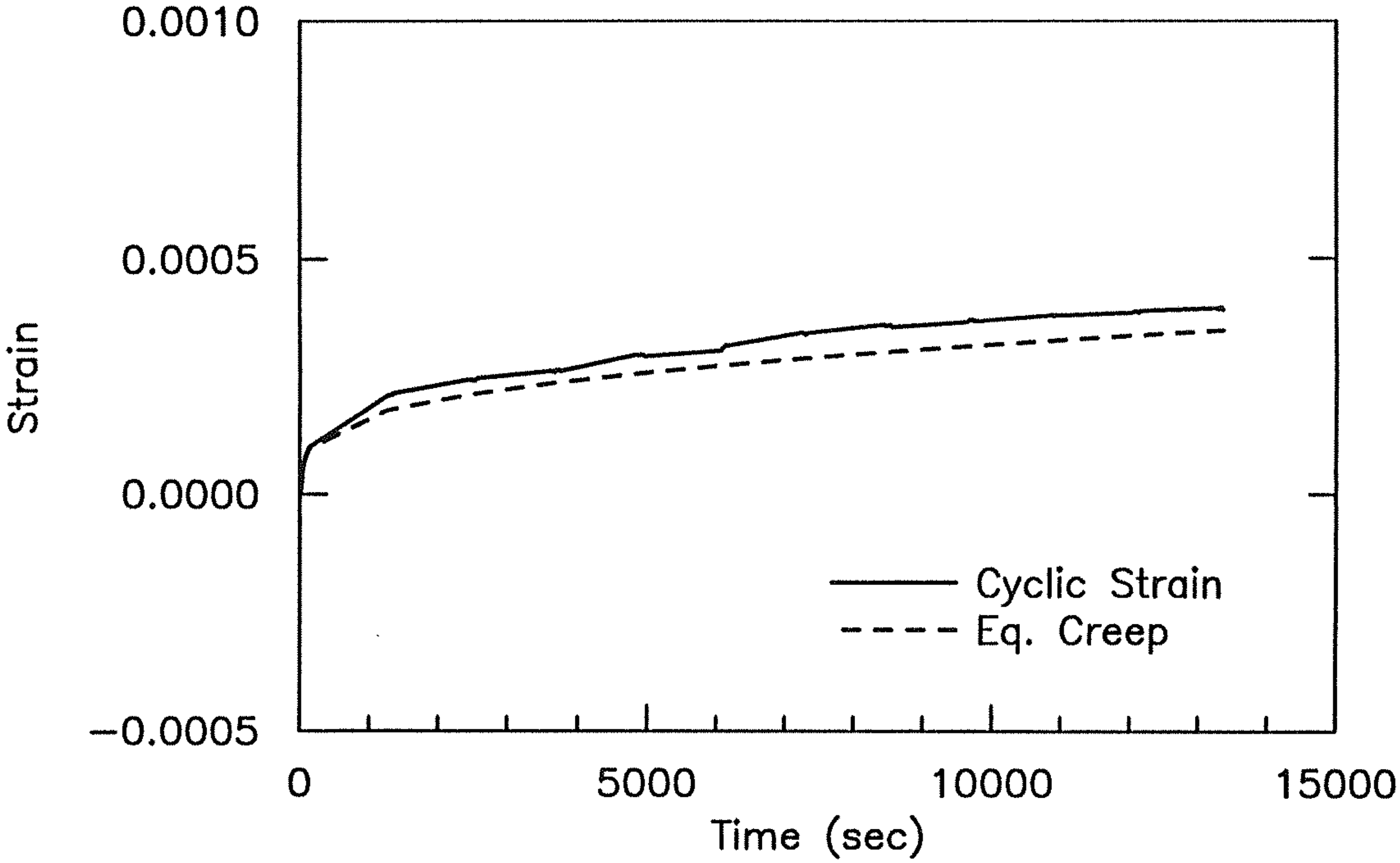

Fig. 3.36 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 4C5, (w/c = 0.7 cement paste) loaded from 0.2 to 0.6 f'_p.

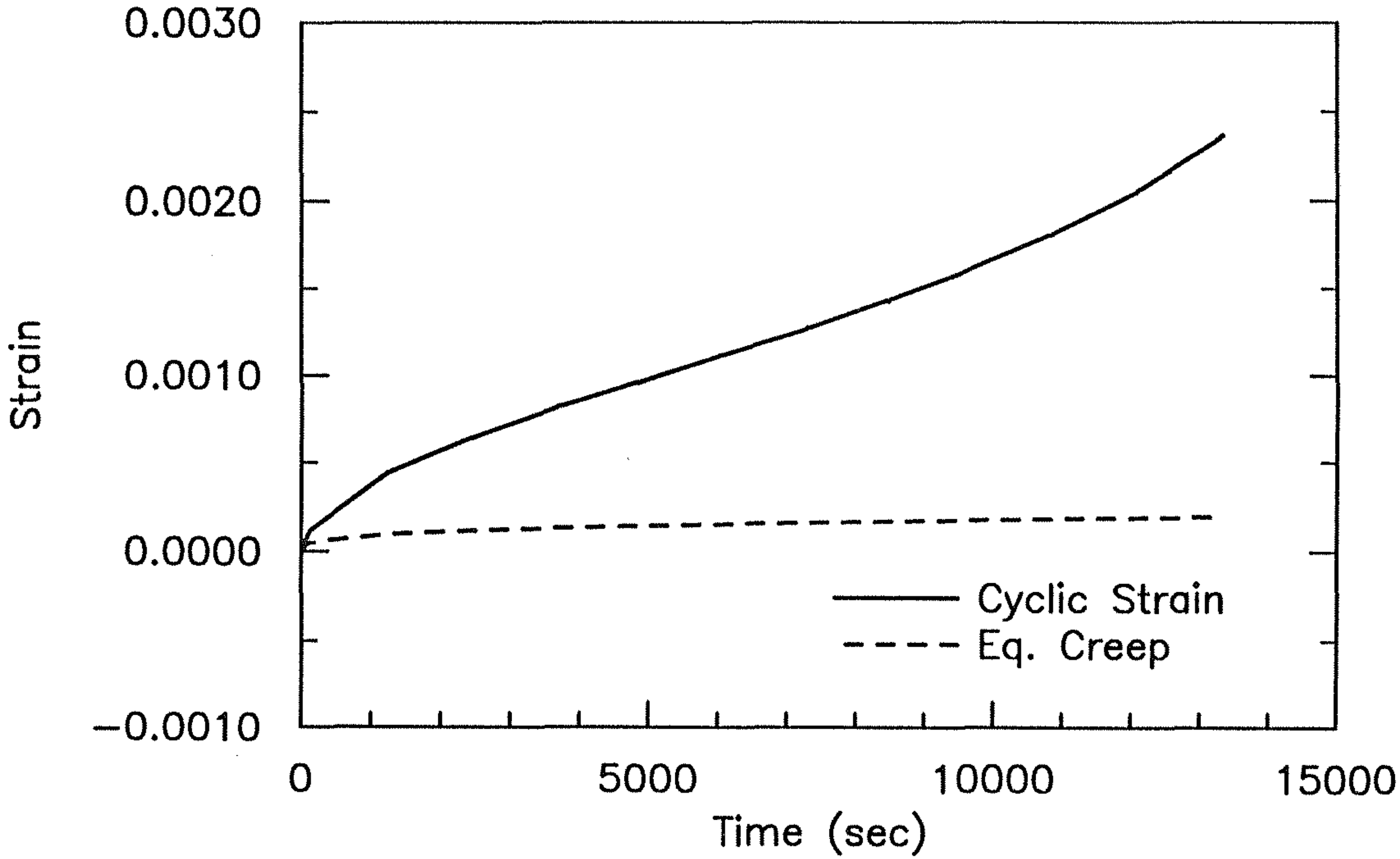

Fig. 3.37 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 5C2, (w/c = 0.7 mortar) loaded from 0 to 0.8 f'_m.

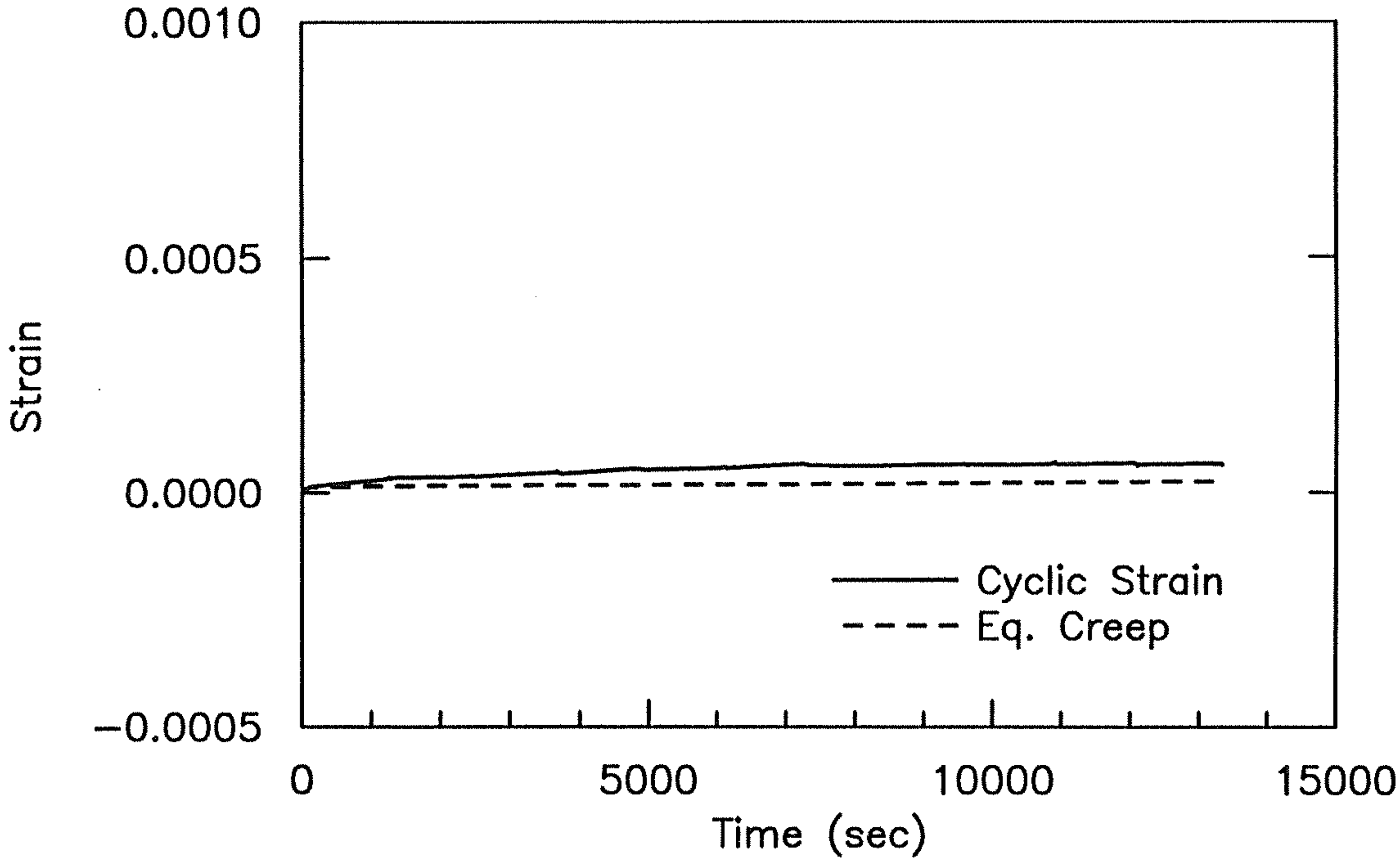

Fig. 3.38 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 5C3, (w/c = 0.7 mortar) loaded from 0 to 0.4 f'_m.

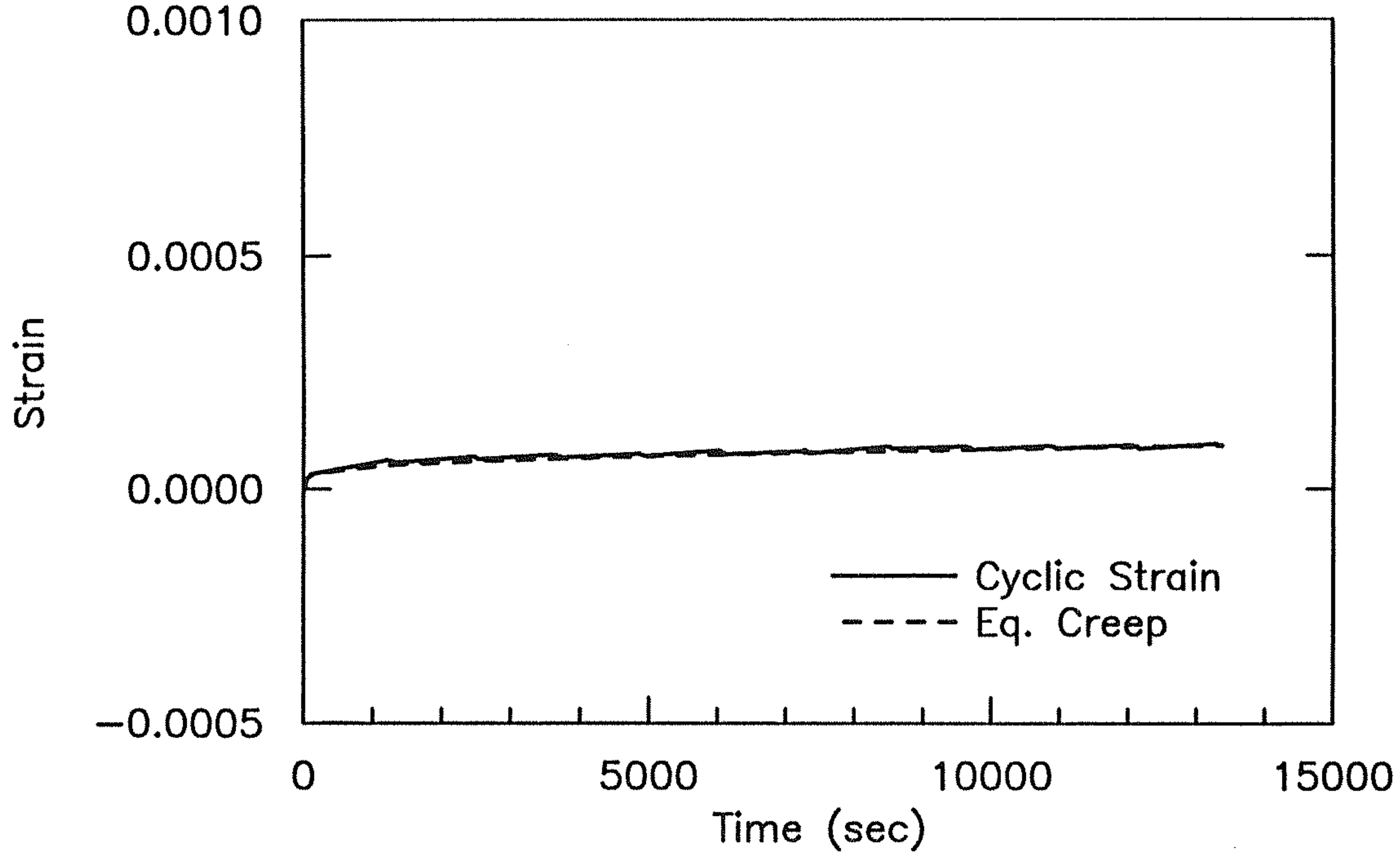

Fig. 3.39 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 5C5, (w/c = 0.7 mortar) loaded from 0.2 to 0.6 f'_m.

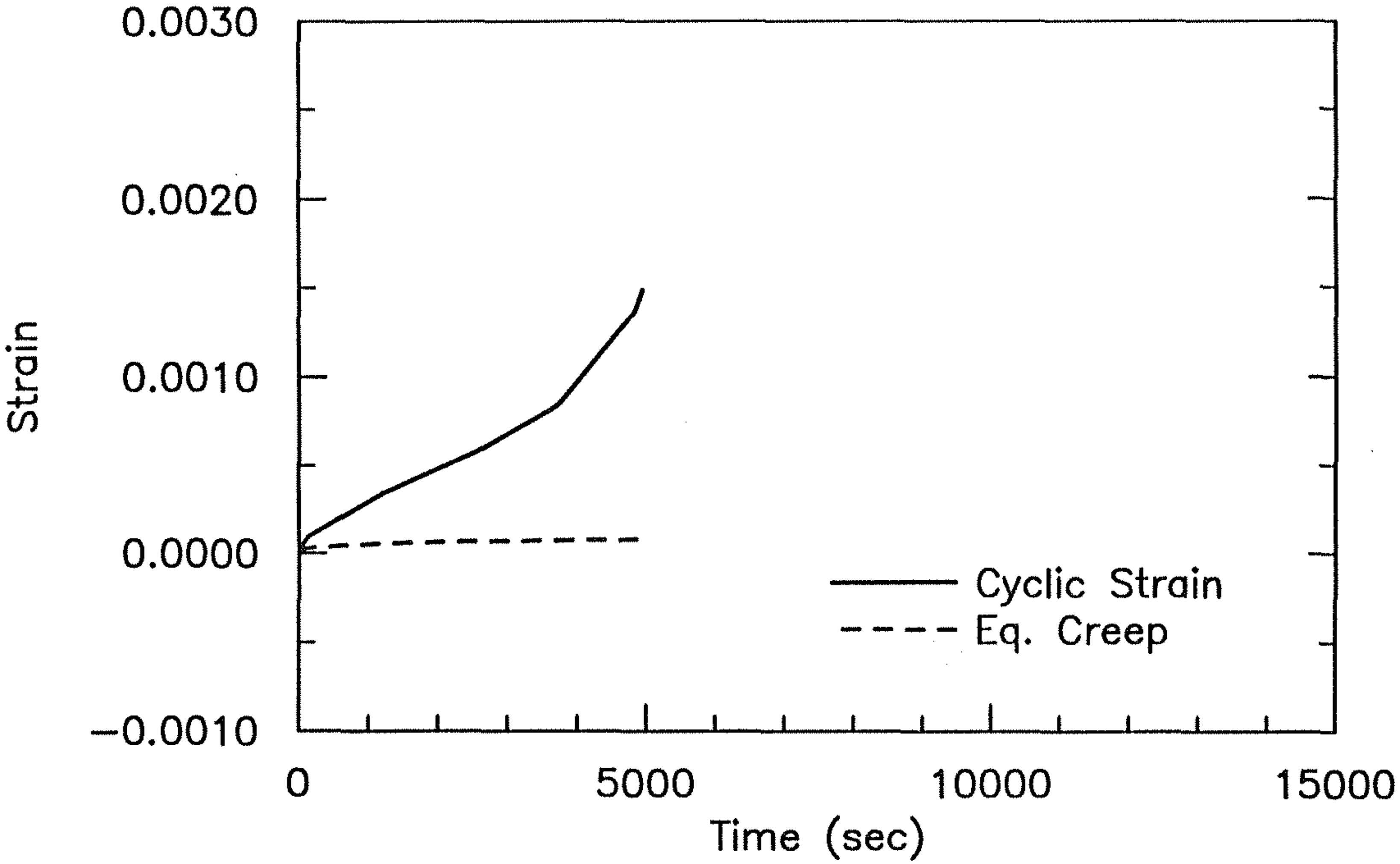

Fig. 3.40 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 6C2, (w/c = 0.7 concrete) loaded from 0 to 0.8 f'_c.

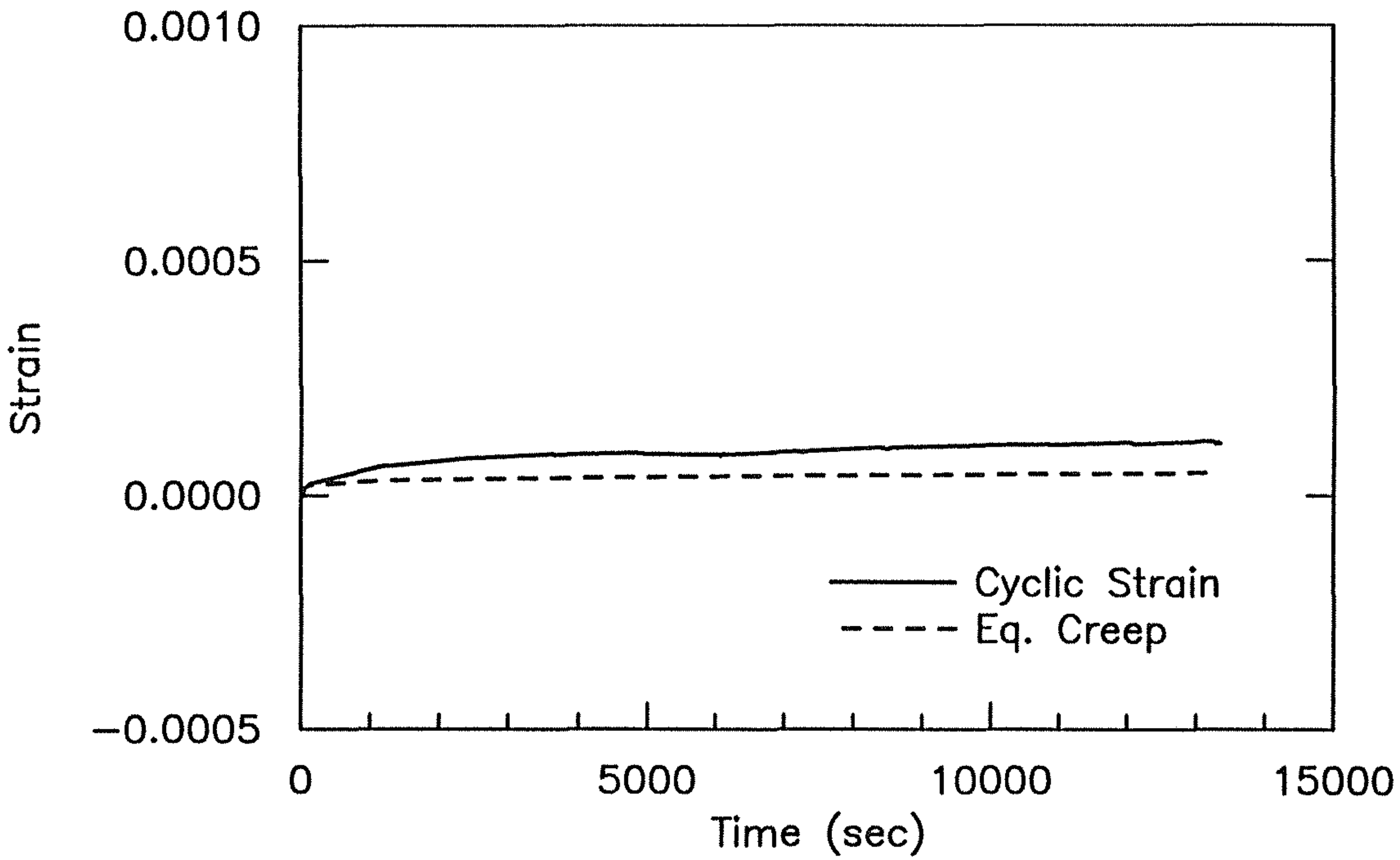

Fig. 3.41 Cyclic strain, ε_{cy}, and equivalent creep strain, ε_{ec}, versus time for cyclic test 6C5, (w/c = 0.7 concrete) loaded from 0.2 to 0.6 f'_c.

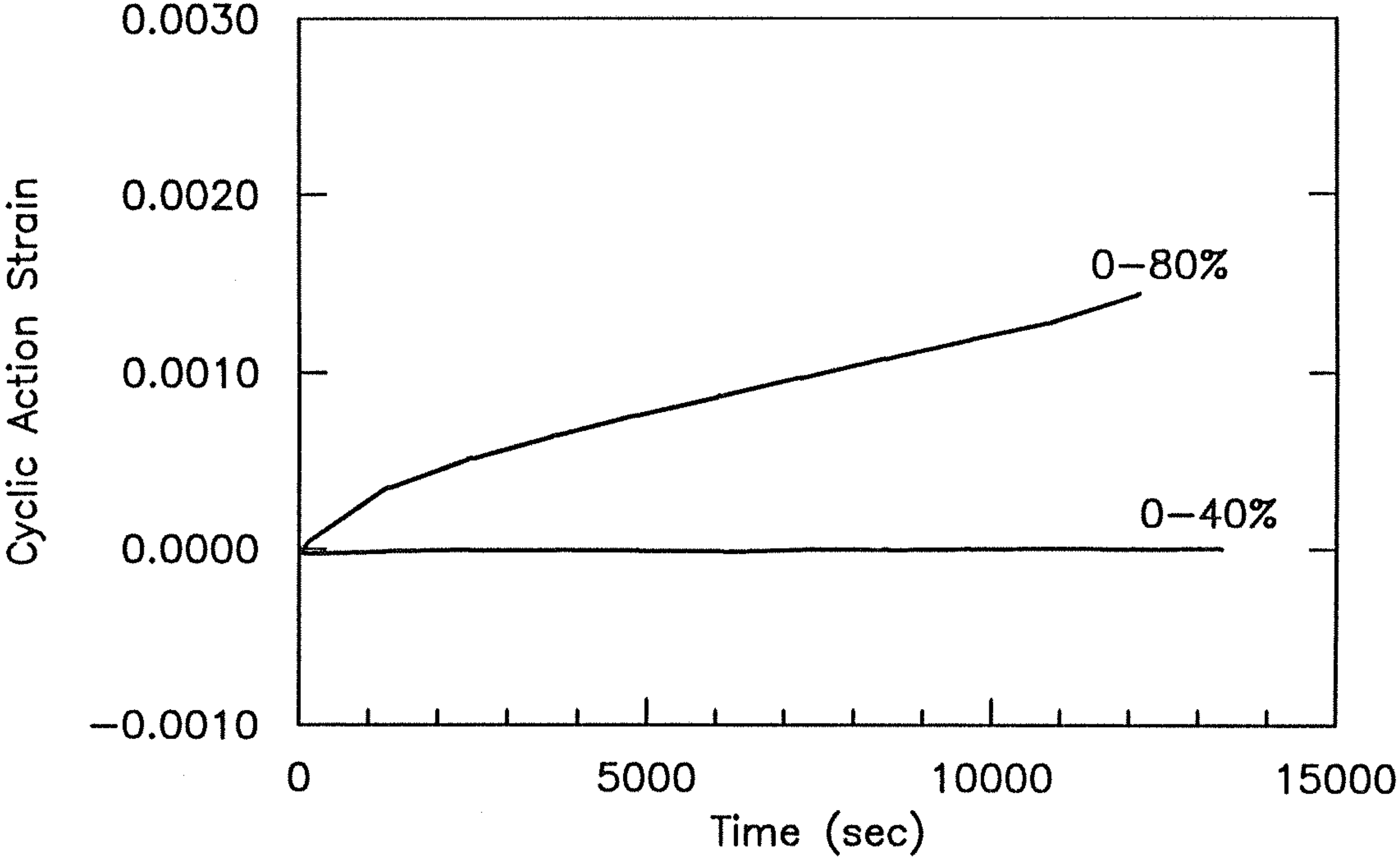

Fig. 3.42 Cyclic action strain, ε_{ca}, versus time for w/c = 0.5 cement paste, loaded from 0 to $0.8f'_p$ (1D2) and from 0 to $0.4f'_p$ (1D3).

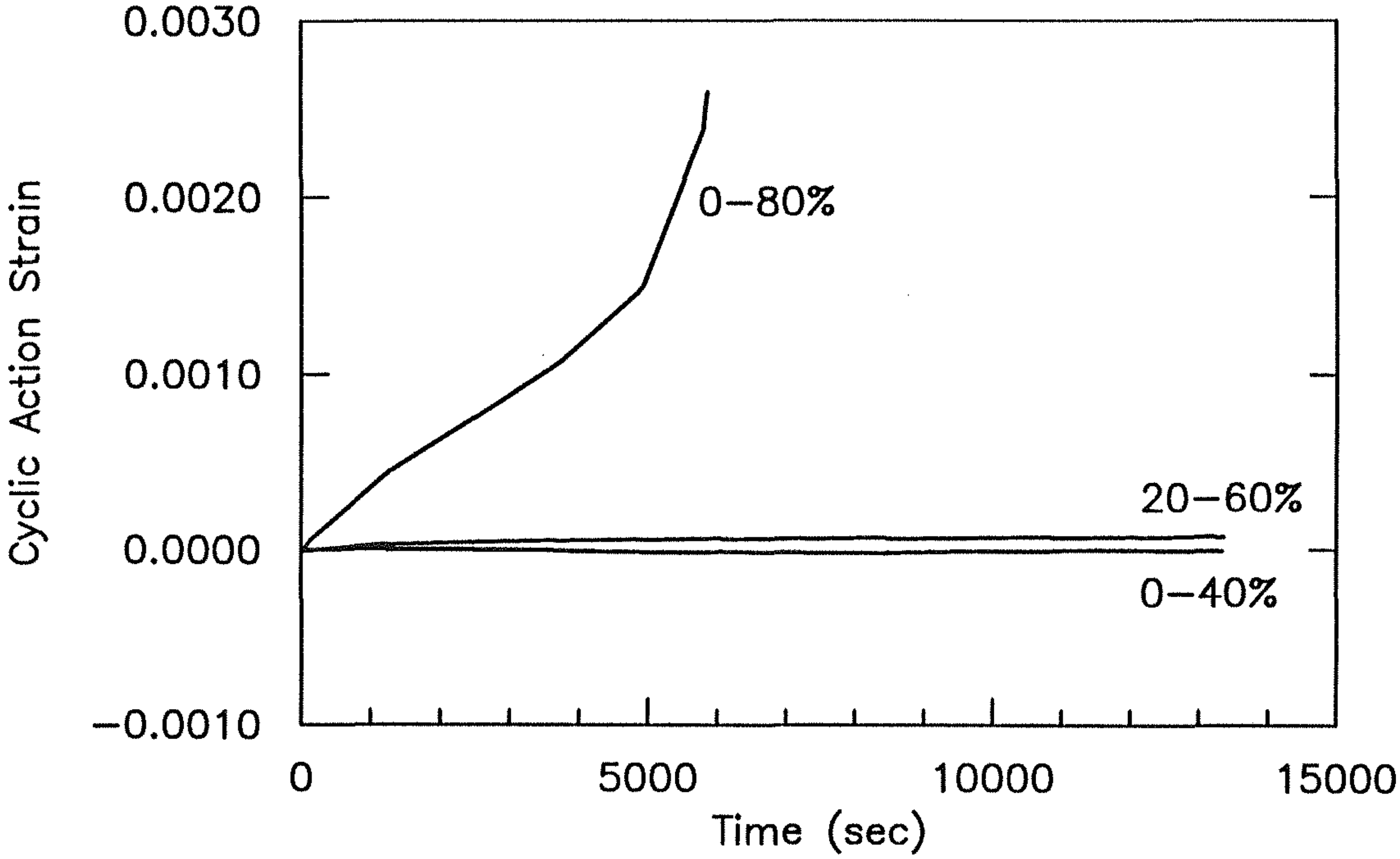

Fig. 3.43 Cyclic action strain, ε_{ca}, versus time for w/c = 0.5 mortar, loaded from 0 to 0.8f'_m (2C2), from 0 to 0.4f'_m (2C3) and from 0.2 to 0.6f'_m (2C5).

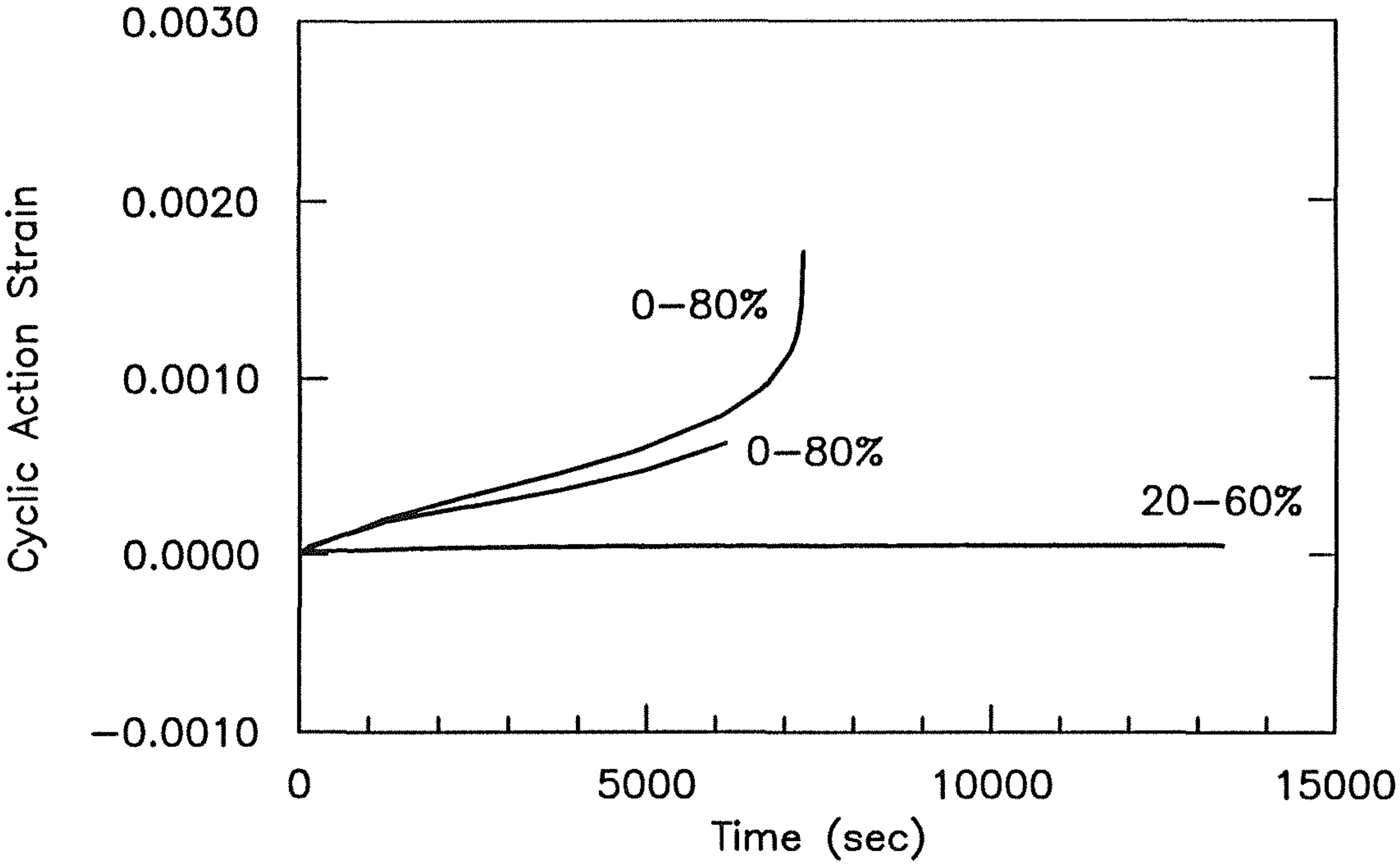

Fig. 3.44 Cyclic action strain, ε_{ca}, versus time for w/c = 0.5 concrete, loaded from to 0.8f′$_c$ (3C2 and 3C4) and from 0.2 to 0.6f′$_c$ (3C5).

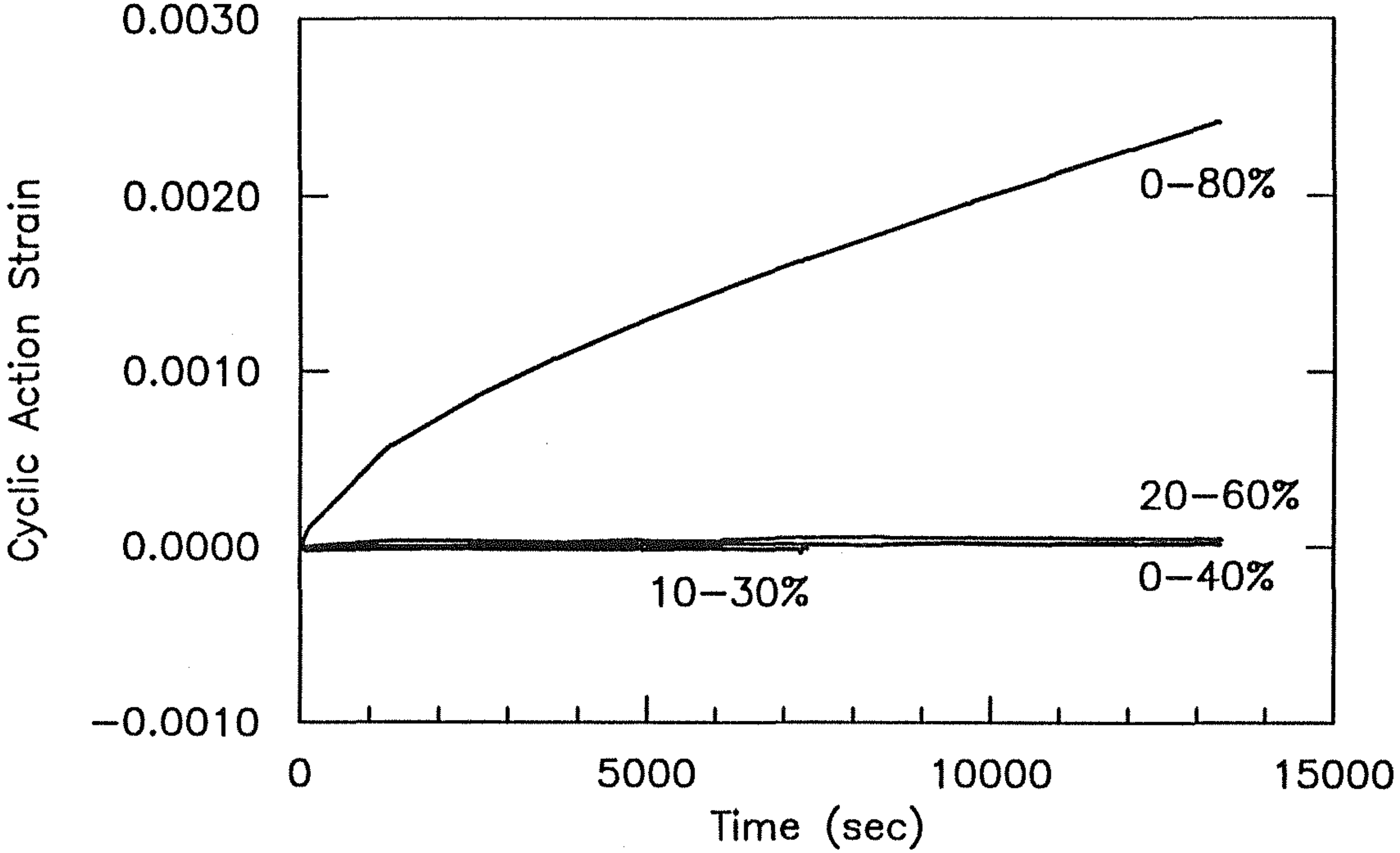

Fig. 3.45 Cyclic action strain, ε_{ca}, versus time for w/c = 0.7 cement paste, loaded from 0 to 0.8f′$_p$ (4C2), from 0 to 0.4f′$_p$ (4C3) and from 0.1 to 0.3f′$_p$ (4C4) and from 0.2 to 0.6f′$_p$ (4C5).

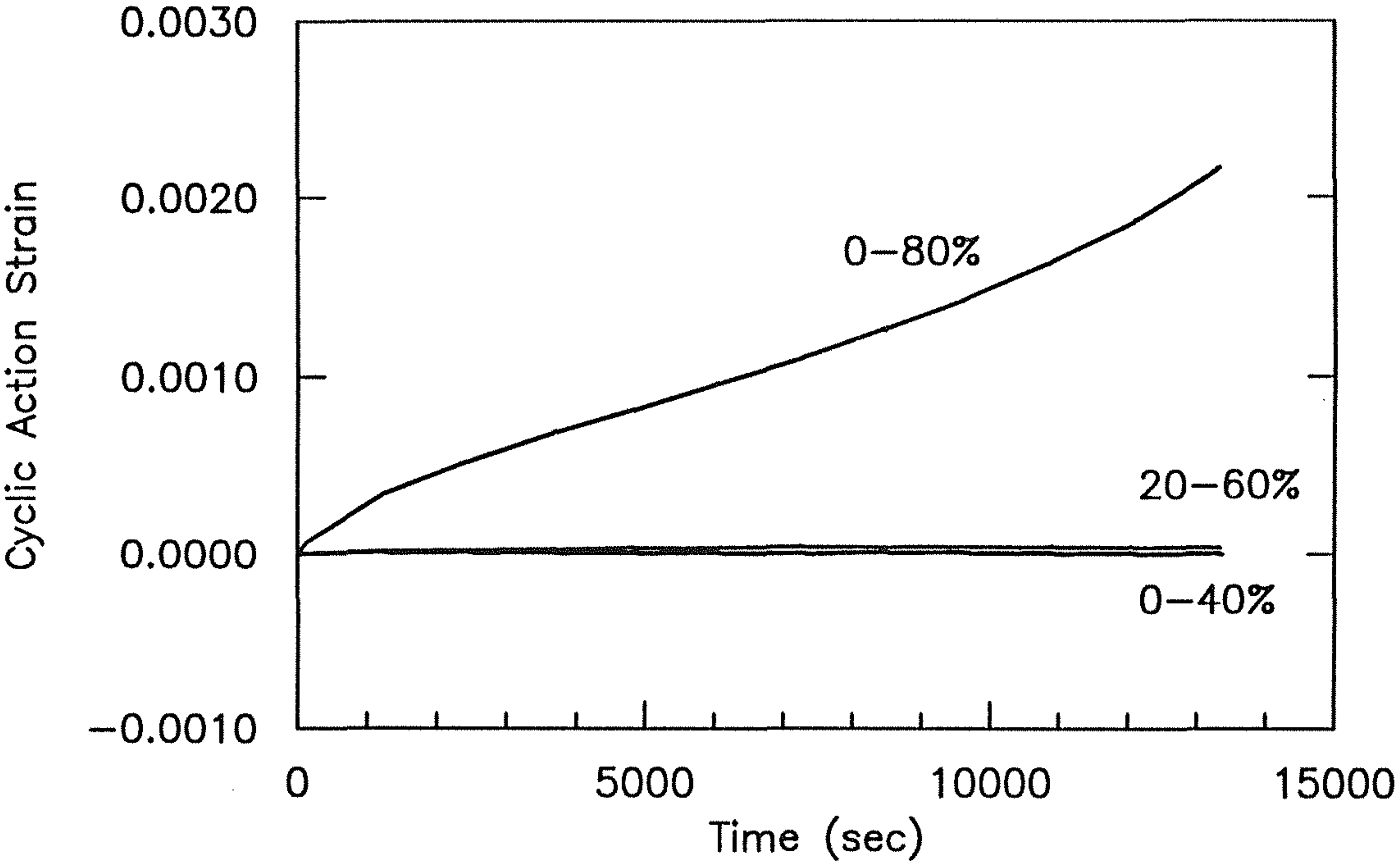

Fig. 3.46 Cyclic action strain, ε_{ca}, versus time for w/c = 0.7 mortar, loaded from 0 to $0.8f'_m$ (5C2), from 0 to $0.4f'_m$ (5C3) and from 0.2 to $0.6f'_m$ (5C5).

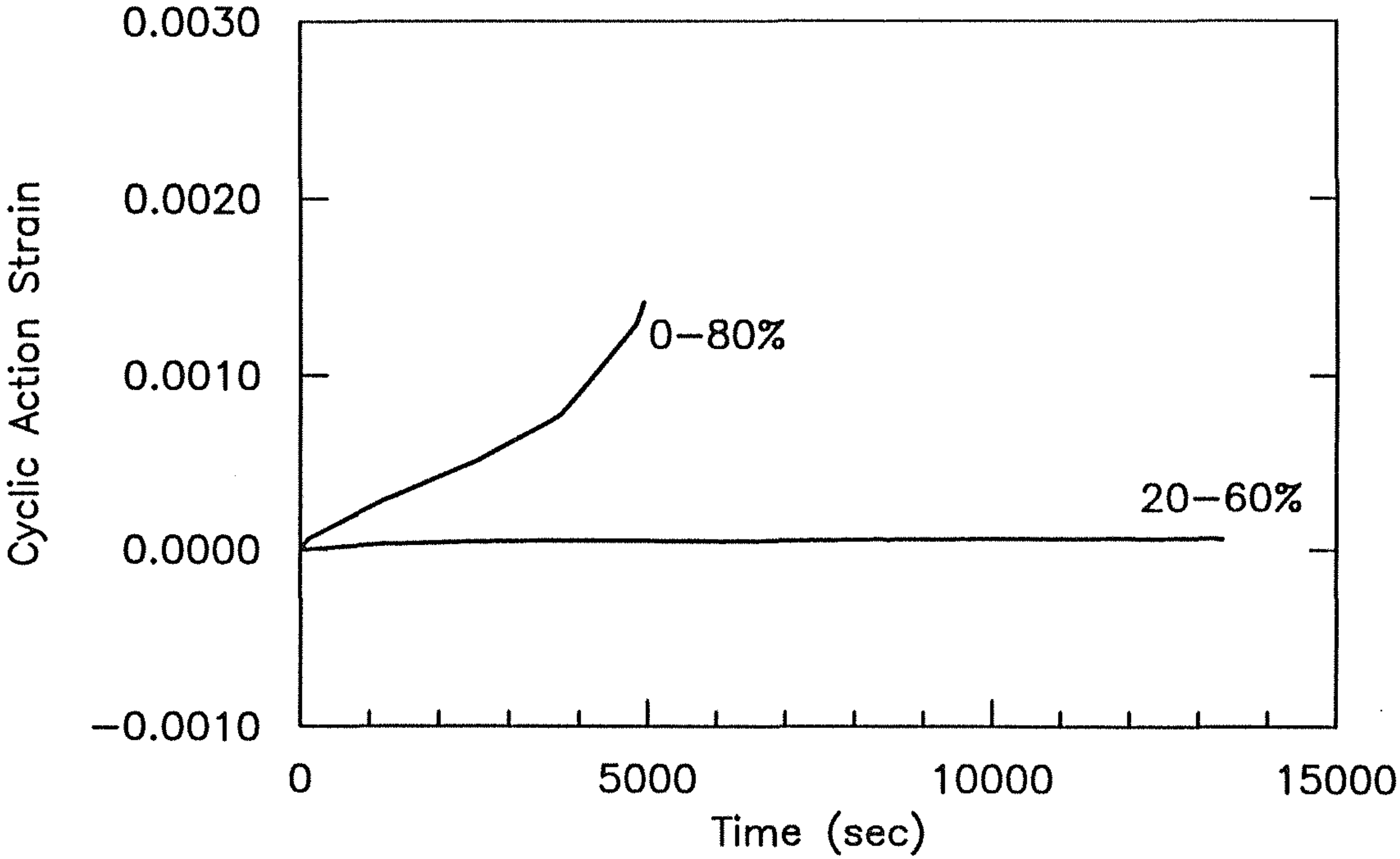

Fig. 3.47 Cyclic action strain, ε_{ca}, versus time for w/c = 0.7 concrete, loaded from 0 to 0.8f´$_c$ (6C2), and from 0.2 to 0.6f´$_c$ (6C5).

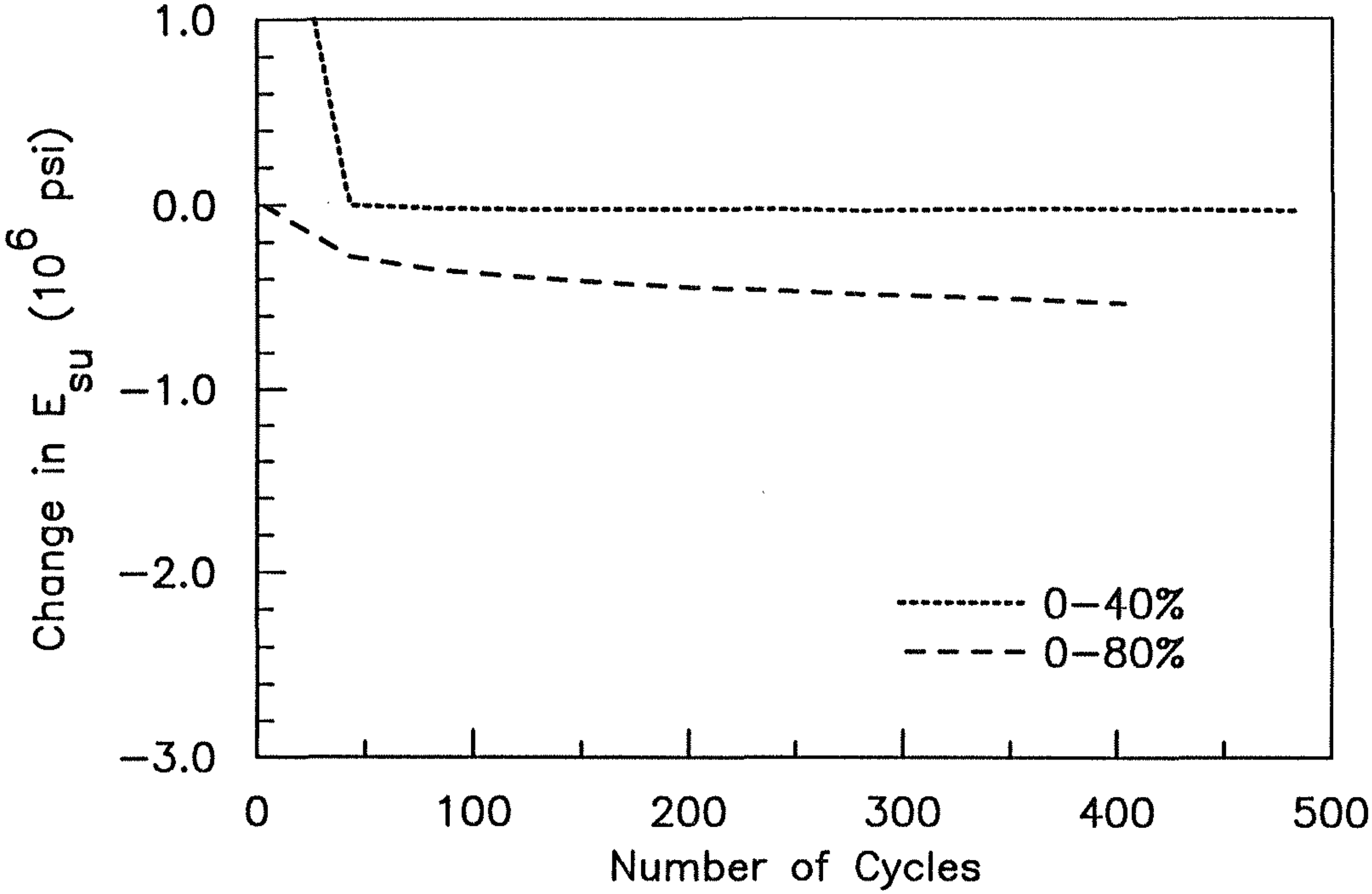

Fig. 3.48 Change in secant unloading modulus of elasticity, E_{su}, versus time for w/c = 0.5 cement paste, loaded from 0 to $0.8f'_p$ (1D2) and from 0 to $0.4f'_p$ (1D3).

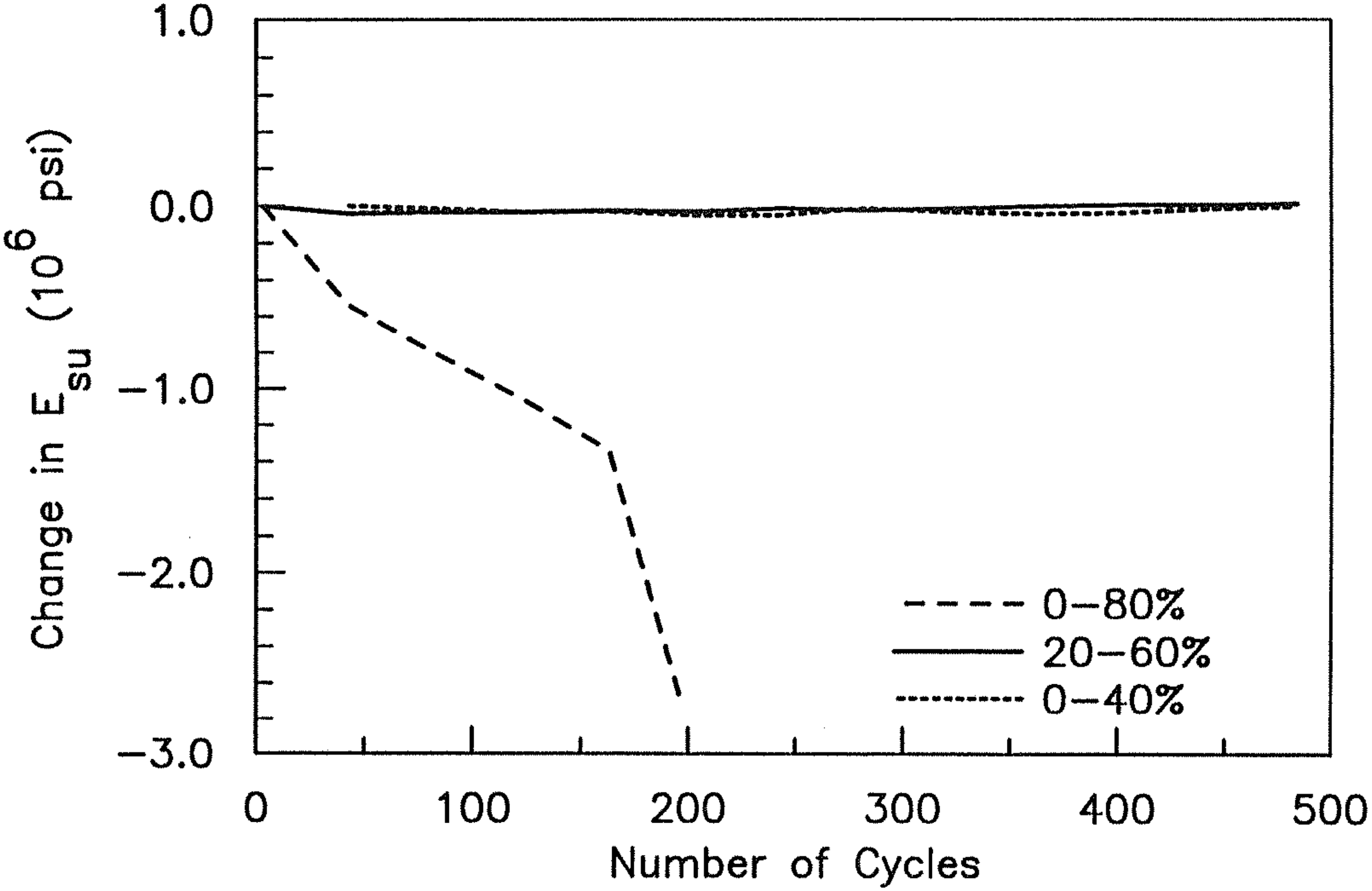

Fig. 3.49 Change in secant unloading modulus of elasticity, E_{su}, versus time for w/c = 0.5 mortar, loaded from 0 to $0.8f'_m$ (2C2), from 0 to $0.4f'_m$ (2C3) and from 0.2 to $0.6f'_m$ (2C5).

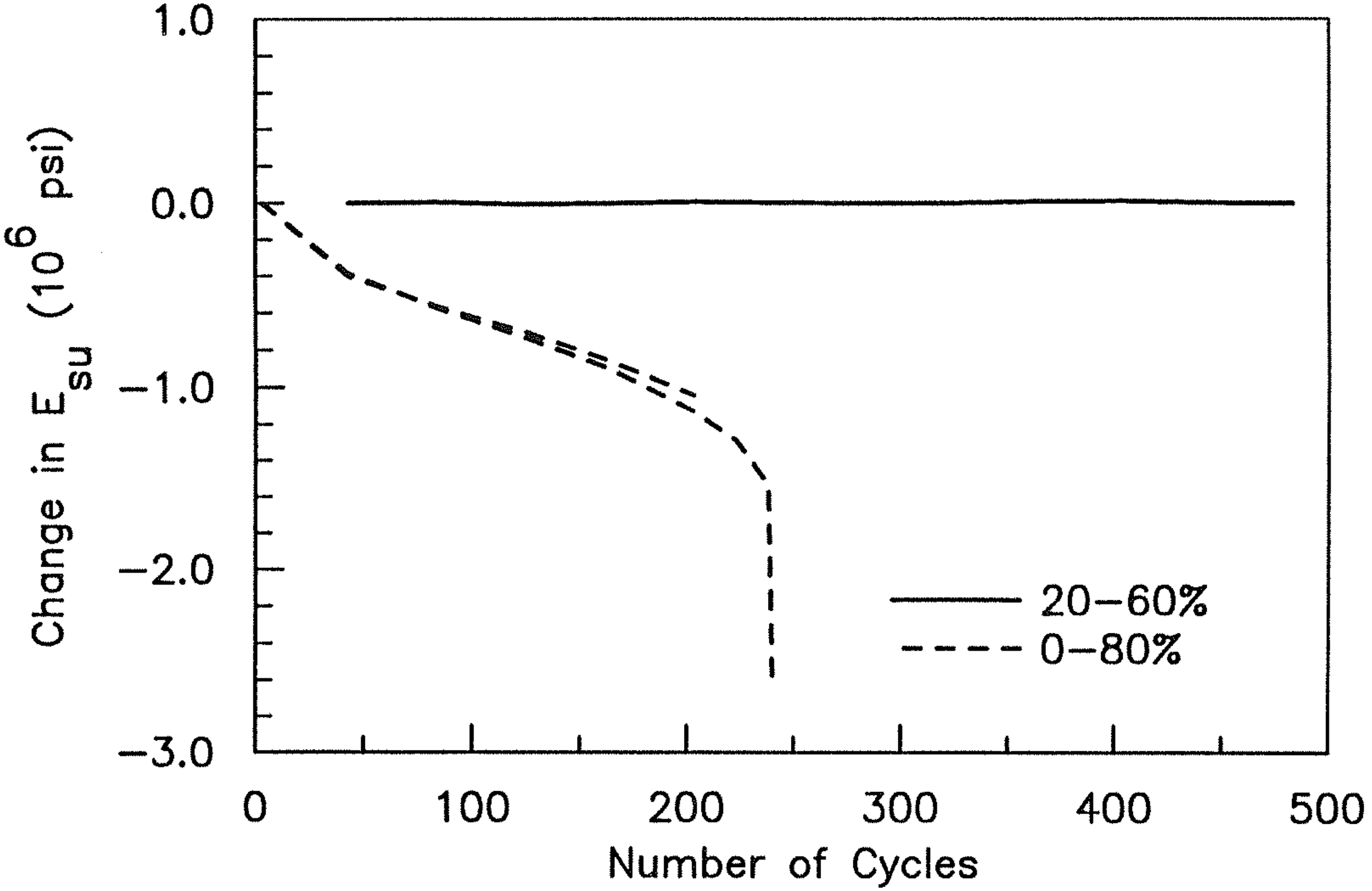

Fig. 3.50 Change in secant unloading modulus of elasticity, E_{su}, versus time for w/c = 0.5 concrete, loaded from 0 to 0.8f′$_c$ (3C2 and 3C4) and from 0.2 to 0.6f′$_c$ (3C5).

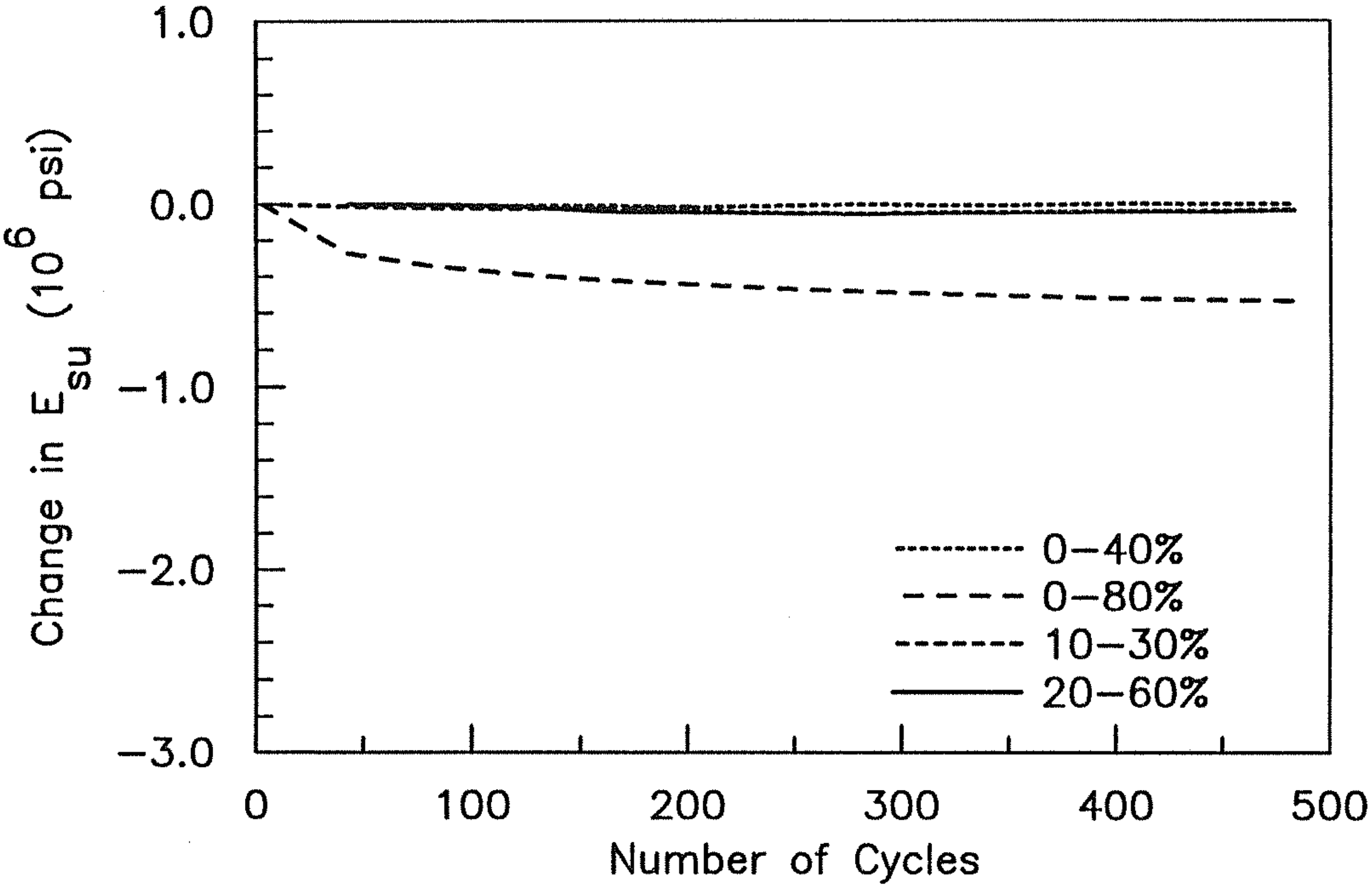

Fig. 3.51 Change in secant unloading modulus of elasticity, E_{su}, versus time for w/c = 0.7 cement paste, loaded from 0 to $0.8f'_p$ (4C2), from 0 to $0.4f'_p$ (4C3) and from 0.1 to $0.3f'_p$ (4C4) and from 0.2 to $0.6f'_p$ (4C5).

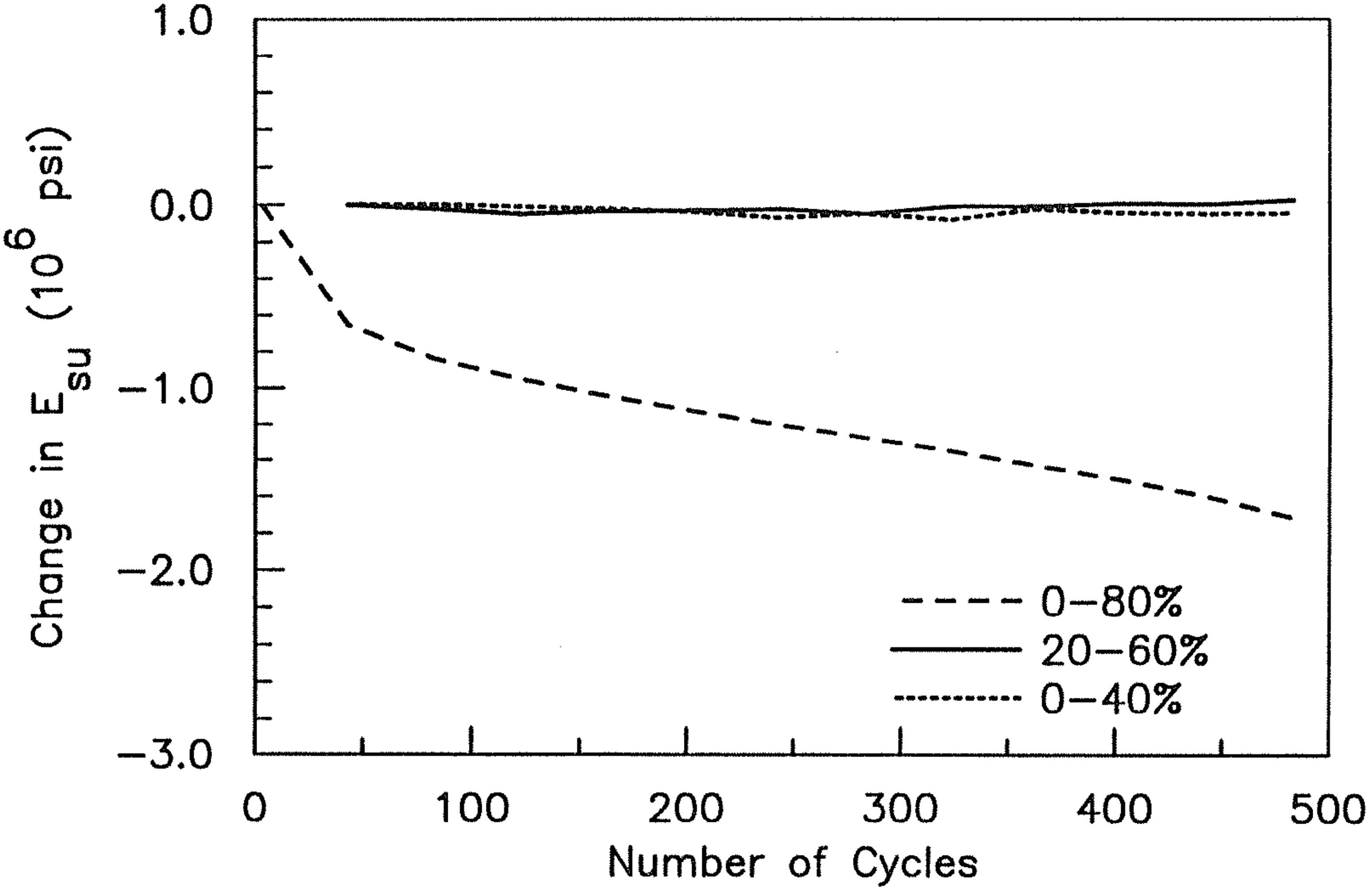

Fig. 3.52 Change in secant unloading modulus of elasticity, E_{su}, versus time for w/c = 0.7 mortar, loaded from 0 to 0.8f'_m (5C2), from 0 to 0.4f'_m (5C3) and from 0.2 to 0.6f'_m (5C5).

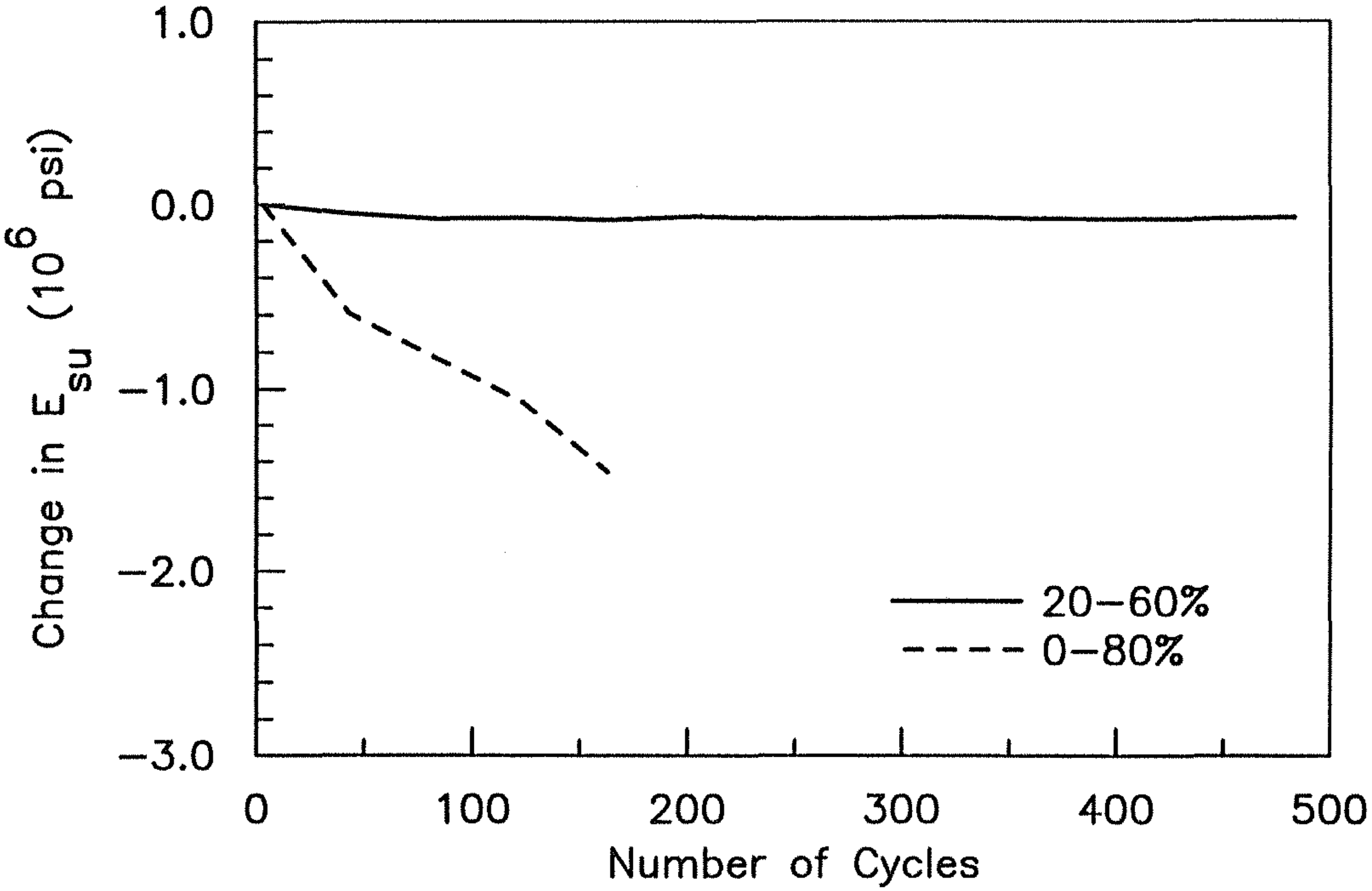

Fig. 3.53 Change in secant unloading modulus of elasticity, E_{su}, versus time for w/c = 0.7 concrete, loaded from 0 to 0.8f′$_c$ (6C2), and from 0.2 to 0.6f′$_c$ (6C5).

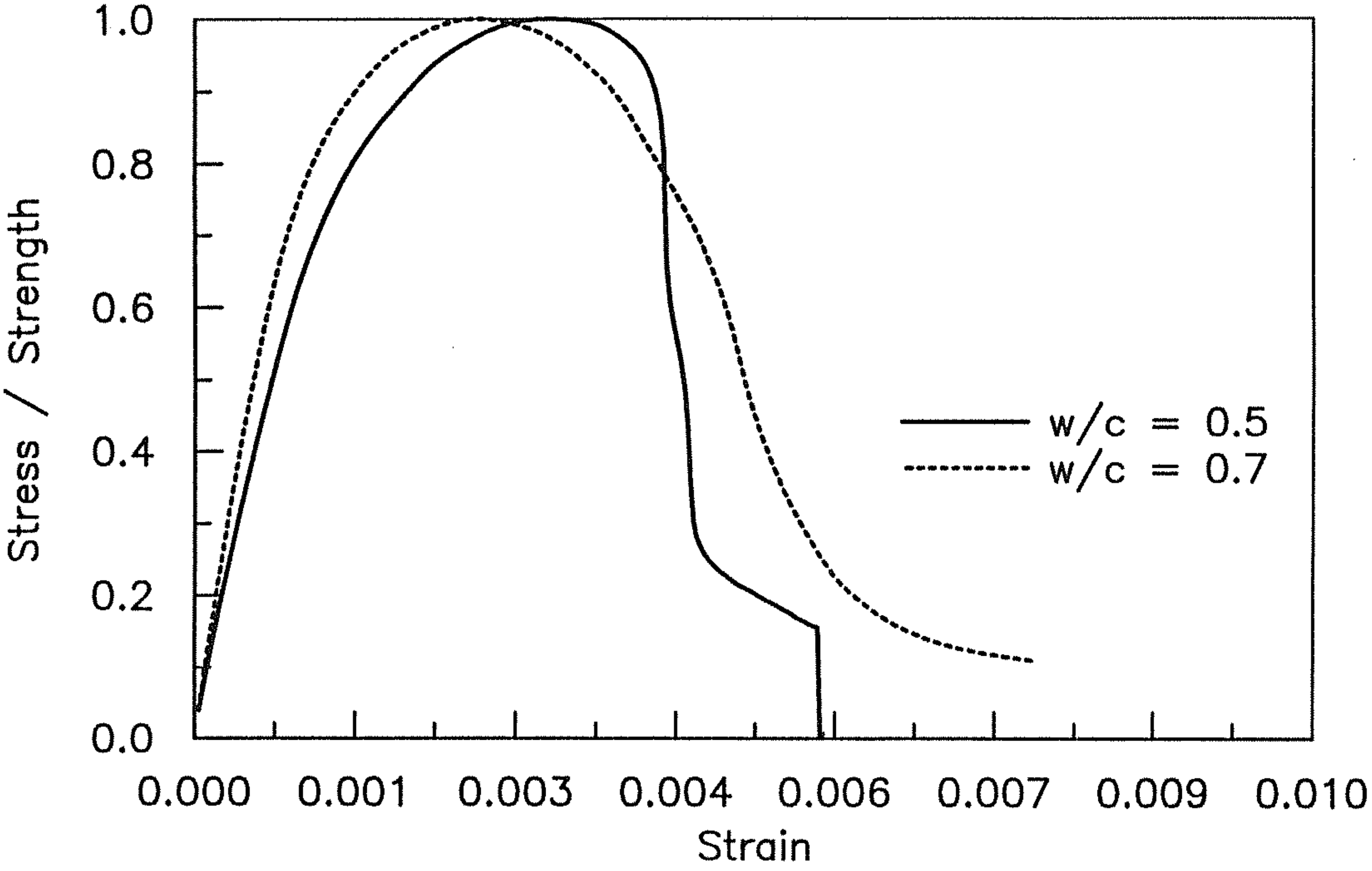

Fig. 3.54 Stress - strength ratio versus strain for w/c = 0.5 and 0.7 mortar (tests 2A1 and 5F1) under monotonic load.

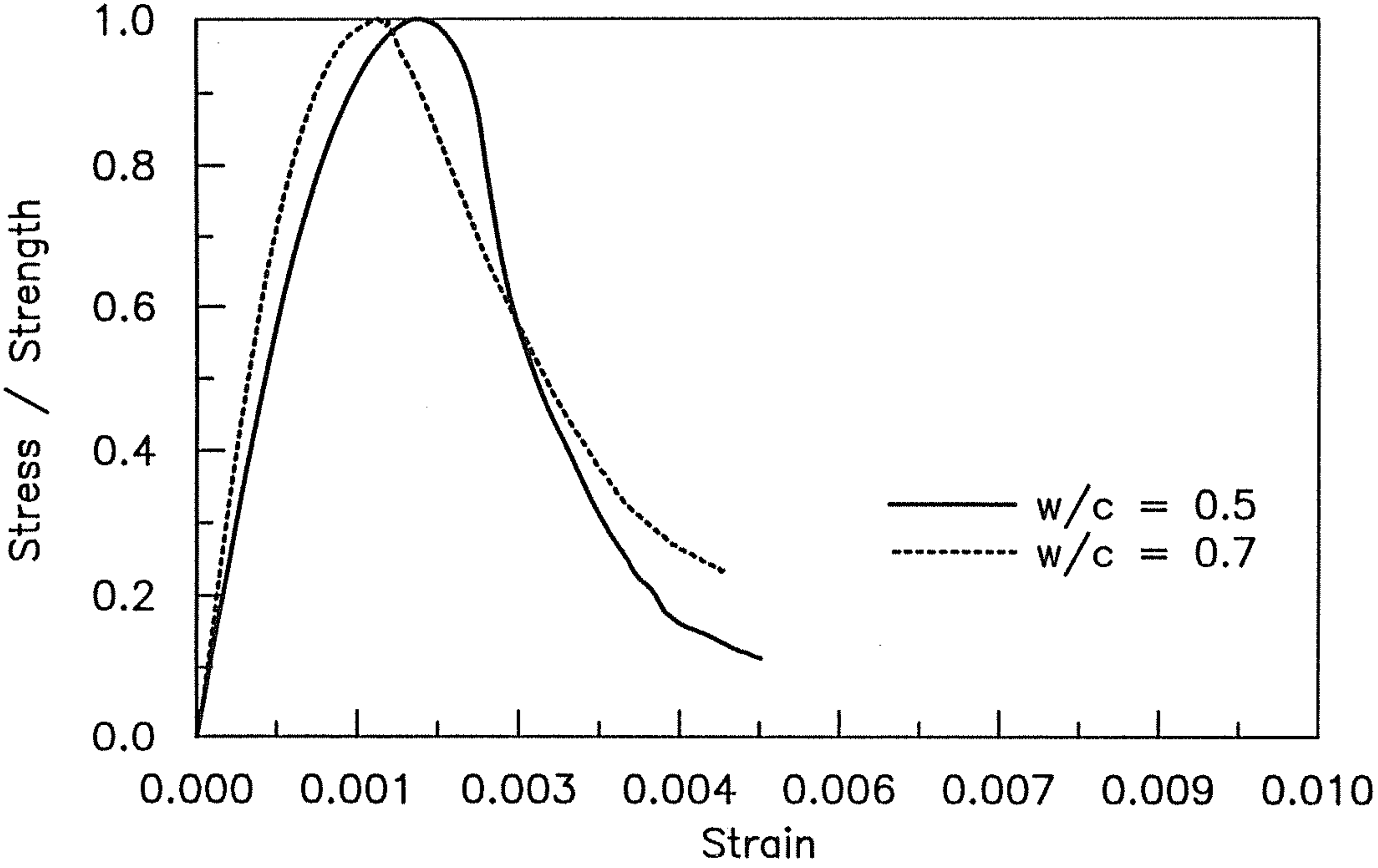

Fig. 3.55 Stress - strength ratio versus strain for w/c = 0.5 and 0.7 concrete (tests 9C1 and 6F1) under monotonic load.

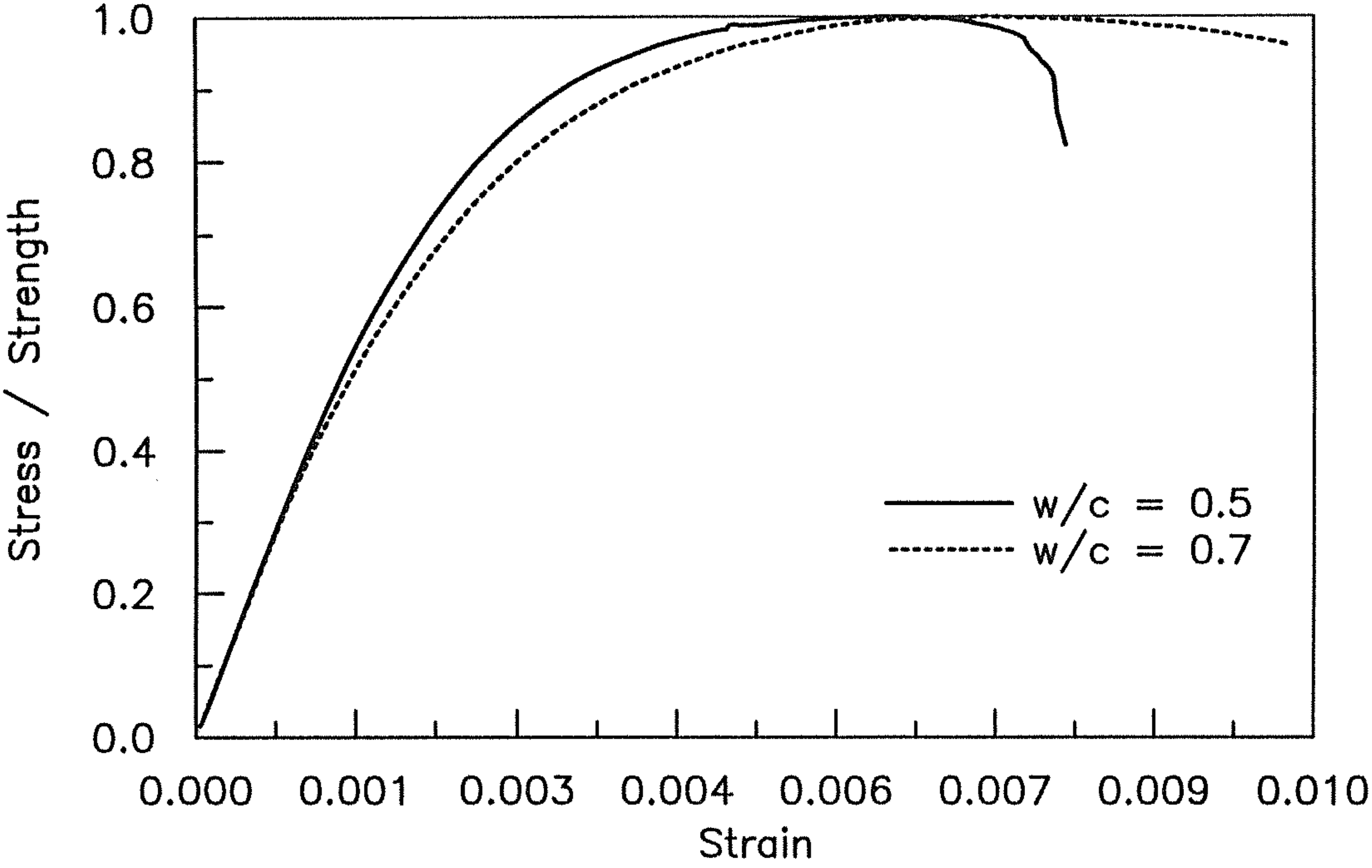

Fig. 3.56 Stress - strength ratio versus strain for w/c = 0.5 and 0.7 cement paste (tests 3A1 and 8C1) under monotonic load.

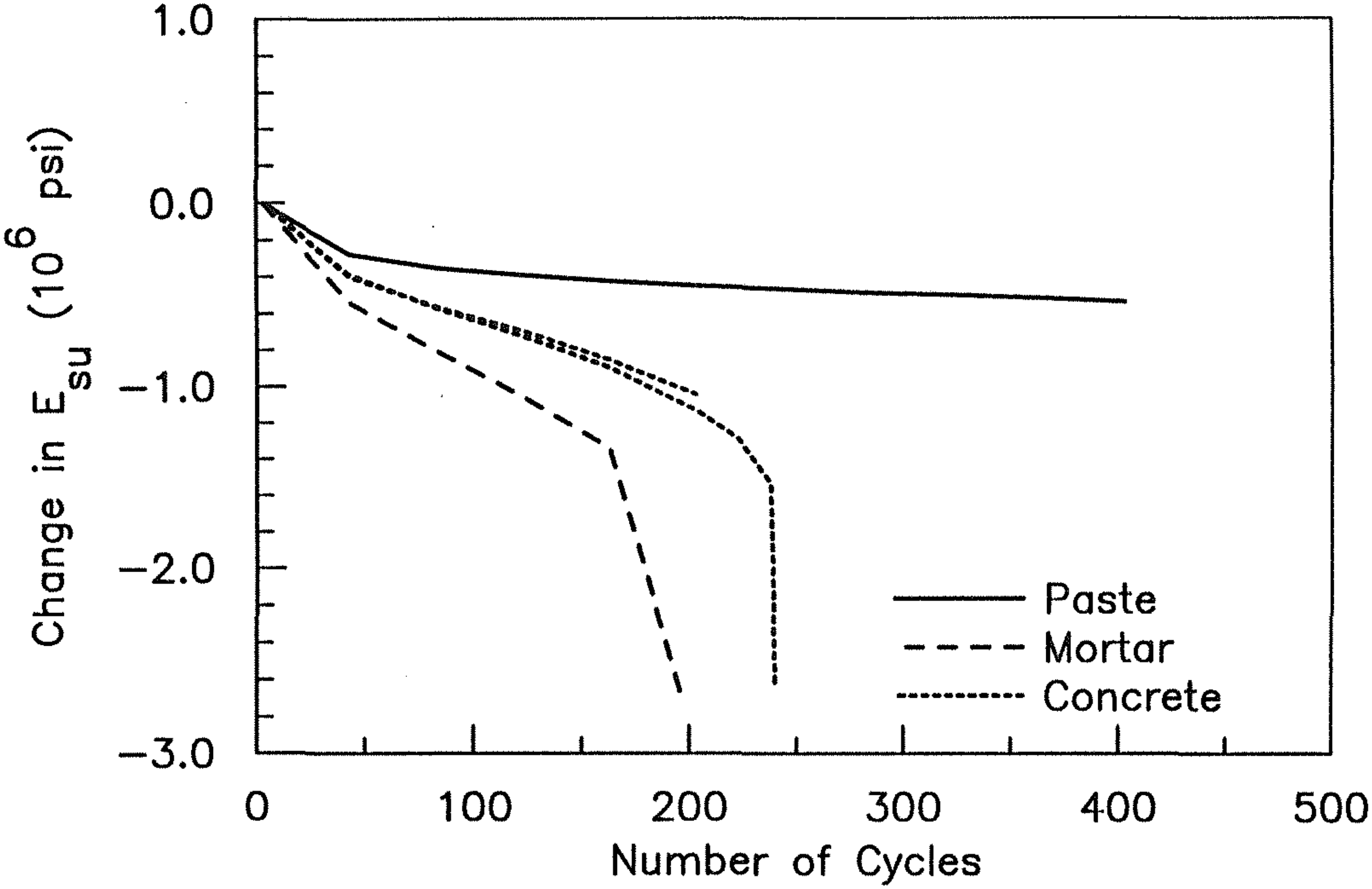

Fig. 3.57 E_{su} versus number of cycles for cement paste, mortar, and concrete with w/c = 0.5.

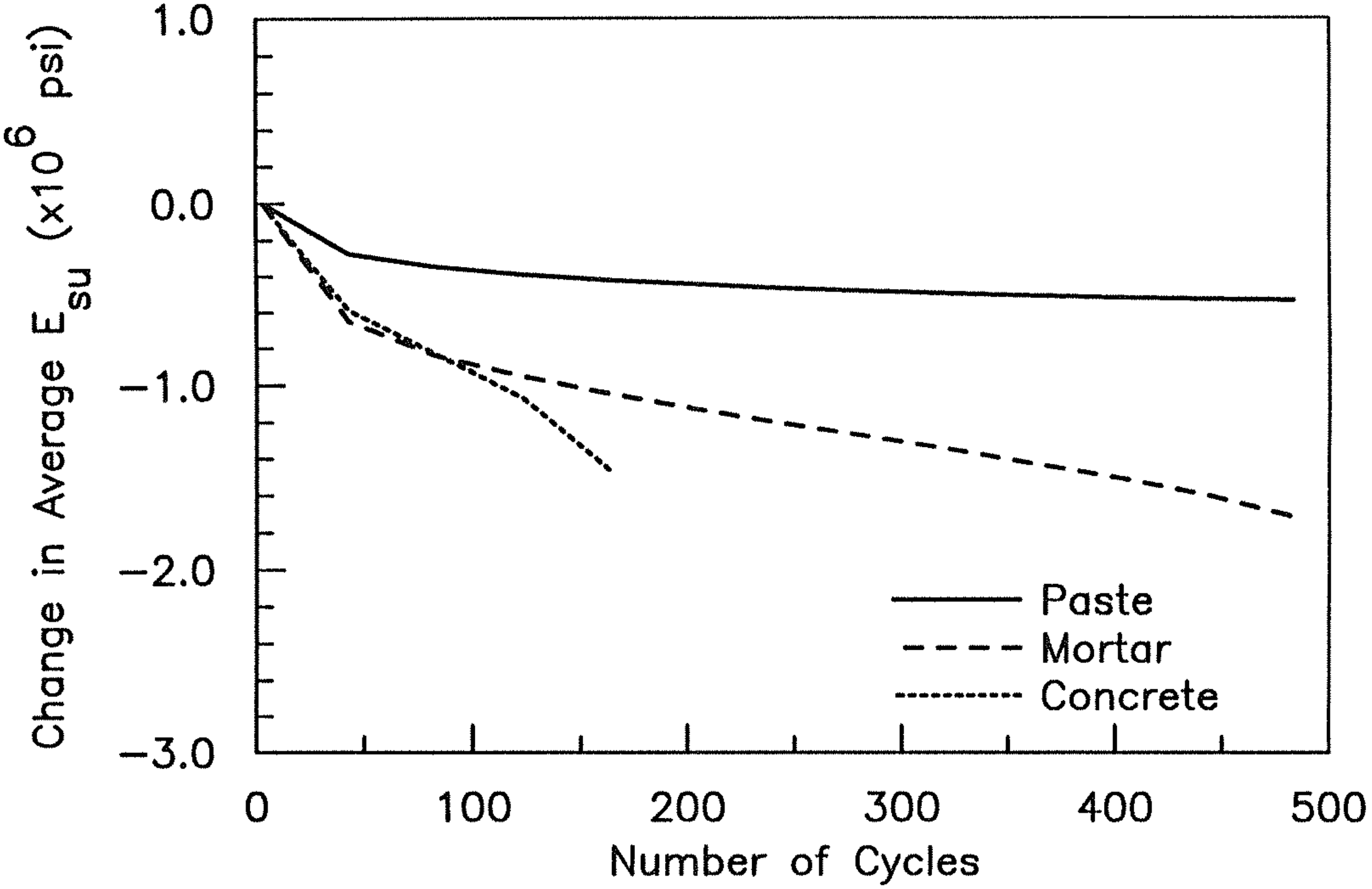

Fig. 3.58 E_{su} versus number of cycles for cement paste, mortar, and concrete with w/c = 0.7.

APPENDIX A

Coefficients A, B and C of equation 3.2 for w/c = 0.5 cement paste.

Stress	Time	A	B	C
0-0.4f′	15	0.0000000	0.0000000	0.0000000
	26	7.3833510E-05	7.3622500E-05	0.0000000
	50	1.8619760E-04	1.3214270E-04	0.0000000
	96	3.2447420E-04	1.6311710E-04	0.0000000
	185	4.8803000E-04	1.7215980E-04	0.0000000
	357	6.7683880E-04	1.6556700E-04	0.0000000
	688	8.9207220E-04	1.4987590E-04	0.0000000
	1324	1.1367490E-03	1.3156900E-04	0.0000000
	2549	1.4163910E-03	1.1694310E-04	0.0000000
	4908	1.7398800E-03	1.1209850E-04	0.0000000
	9450	2.1206320E-03	1.2309000E-04	0.0000000
	14000	2.3843850E-03	1.3988360E-04	0.0000000
0.4-0.6f′	15	0.0000000	0.0000000	0.0000000
	26	-2.9777730E-04	3.7091120E-04	-5.9457730E-05
	50	-4.6462710E-04	6.5280240E-04	-1.0413200E-04
	96	-4.4109720E-04	7.7557420E-04	-1.2249150E-04
	185	-2.5057420E-04	7.6304310E-04	-1.1817670E-04
	357	7.7679750E-05	6.4489390E-04	-9.5865460E-05
	688	5.1161930E-04	4.5423820E-04	-6.0872640E-05
	1324	1.0176170E-03	2.2687530E-04	-1.9061150E-05
	2549	1.5611410E-03	1.1431980E-06	2.3159780E-05
	4908	2.1052130E-03	-1.8016810E-04	5.8453060E-05
	9450	2.6072440E-03	-2.6619810E-04	7.7857640E-05
	14000	2.8664740E-03	-2.4578910E-04	7.7134460E-05
0.6-0.8f′	15	0.0000000	0.0000000	0.0000000
	26	2.2098800E-03	-2.6382770E-03	8.4329860E-04
	50	4.5847320E-03	-5.4064290E-03	1.7136380E-03
	96	6.7686830E-03	-7.8761610E-03	2.4730290E-03
	185	8.9017290E-03	-1.0219720E-02	3.1766530E-03
	357	1.1169810E-02	-1.2665660E-02	3.8973010E-03
	688	1.3808640E-02	-1.5502180E-02	4.7260530E-03
	1324	1.7118320E-02	-1.9093970E-02	5.7771920E-03
	2549	2.1488270E-02	-2.3911410E-02	7.1969280E-03
	4908	2.7441830E-02	-3.0584110E-02	9.1796360E-03
	9450	3.5708300E-02	-3.9987460E-02	1.1994240E-02
	14000	4.2198150E-02	-4.7443790E-02	1.4236540E-02

Coefficients A, B and C of equation 3.2 for w/c = 0.5 mortar.

Stress	Time	A	B	C
0-0.4f′	15	0.0000000	0.0000000	0.0000000
	26	-5.4162270E-05	4.7568190E-05	0.0000000
	50	-6.1591130E-05	7.6932670E-05	0.0000000
	96	-1.8513730E-05	8.2608190E-05	0.0000000
	185	5.9761860E-05	7.2317040E-05	0.0000000
	357	1.5675320E-04	5.4376000E-05	0.0000000
	688	2.5591570E-04	3.7230810E-05	0.0000000
	1324	3.4104380E-04	2.9314540E-05	0.0000000
	2549	3.9559180E-04	3.9343110E-05	0.0000000
	4908	4.0115480E-04	7.6996790E-05	0.0000000
	9450	3.3463920E-04	1.5414100E-04	0.0000000
	14000	2.4730560E-04	2.2577000E-04	0.0000000
0.4-0.6f′	15	0.0000000	0.0000000	0.0000000
	26	4.9604870E-04	-3.9260060E-04	8.8033750E-05
	50	9.5829550E-04	-7.3897680E-04	1.6318190E-04
	96	1.3038600E-03	-9.7529050E-04	2.1157980E-04
	185	1.5669270E-03	-1.1334150E-03	2.4114640E-04
	357	1.7870390E-03	-1.2498530E-03	2.6084580E-04
	688	2.0068250E-03	-1.3634960E-03	2.8014540E-04
	1324	2.2711840E-03	-1.5147970E-03	3.0882240E-04
	2549	2.6288890E-03	-1.7472950E-03	3.5732760E-04
	4908	3.1363850E-03	-2.1111870E-03	4.3763680E-04
	9450	3.8644230E-03	-2.6696860E-03	5.6476530E-04
	14000	4.4455170E-03	-3.1328000E-03	6.7171390E-04
0.6-0.8f′	15	0.0000000	0.0000000	0.0000000
	26	0.0000000	1.6980780E-04	-7.0833760E-05
	50	0.0000000	3.9909120E-04	-1.7467250E-04
	96	3.7762710E-04	1.3618870E-04	-1.2186410E-04
	185	1.1478960E-03	-6.3057800E-04	9.0295330E-05
	357	2.2554120E-03	-1.8118990E-03	4.2945980E-04
	688	3.7145750E-03	-3.4127970E-03	8.9493530E-04
	1324	5.5577190E-03	-5.4586360E-03	1.4919740E-03
	2549	7.8427700E-03	-8.0039500E-03	2.2343250E-03
	4908	1.0661850E-02	-1.1141750E-02	3.1468040E-03
	9450	1.4153790E-02	-1.5016920E-02	4.2689360E-03
	14000	1.6652600E-02	-1.7781300E-02	5.0662650E-03

Coefficients A, B and C of equation 3.2 for w/c = 0.5 concrete.

Stress	Time	A	B	C
0-0.2f′	15	0.0000000	0.0000000	0.0000000
	26	0.0000000	2.3863830E-05	0.0000000
	50	0.0000000	4.1694950E-05	0.0000000
	96	0.0000000	4.9788580E-05	0.0000000
	185	0.0000000	5.0914250E-05	0.0000000
	357	0.0000000	5.0914250E-05	0.0000000
	688	0.0000000	5.0914250E-05	0.0000000
	1324	0.0000000	5.0914250E-05	0.0000000
	2549	0.0000000	5.0914250E-05	0.0000000
	4908	0.0000000	5.0914250E-05	0.0000000
	9450	0.0000000	5.0914250E-05	0.0000000
	14000	0.0000000	5.0914250E-05	0.0000000
0.2-0.4f′	15	0.0000000	0.0000000	0.0000000
	26	5.1492100E-06	2.2833990E-05	0.0000000
	50	3.0260750E-05	3.5642800E-05	0.0000000
	96	7.4667330E-05	3.4855110E-05	0.0000000
	185	1.3374620E-04	2.4165000E-05	0.0000000
	357	1.8830420E-04	1.3253400E-05	0.0000000
	688	2.4325130E-04	2.2639940E-06	0.0000000
	1324	3.0953890E-04	-1.0993530E-05	0.0000000
	2549	3.9867030E-04	-2.8819820E-05	0.0000000
	4908	5.2301250E-04	-5.3688260E-05	0.0000000
	9450	6.9636800E-04	-8.8359360E-05	0.0000000
	14000	8.3048860E-04	-1.1518350E-04	0.0000000
0.4-0.6f′	15	0.0000000	0.0000000	0.0000000
	26	-3.1439470E-05	5.2104940E-05	-5.8541920E-06
	50	-4.4219490E-05	9.5226980E-05	-1.1916840E-05
	96	-3.7793880E-05	1.2482410E-04	-1.7993810E-05
	185	-1.5743310E-05	1.4375660E-04	-2.3918330E-05
	357	4.6419790E-05	1.2676100E-04	-2.2701510E-05
	688	1.2465450E-04	9.7141430E-05	-1.8975490E-05
	1324	1.8301730E-04	9.0223620E-05	-2.0243430E-05
	2549	1.8438200E-04	1.4261090E-04	-3.4286170E-05
	4908	8.9471000E-05	2.9314470E-04	-6.9366620E-05
	9450	-1.4545370E-04	5.8509830E-04	-1.3469150E-04
	14000	-3.7456440E-04	8.4885900E-04	-1.9280850E-04

Coefficients A, B and C of equation 3.2 for w/c = 0.5 concrete.

Stress	Time	A	B	C
0.6-0.8f′	15	0.0000000	0.0000000	0.0000000
	26	5.4148710E-04	-6.3540700E-04	2.0039940E-04
	50	1.0627540E-03	-1.2331410E-03	3.8659360E-04
	96	1.4854290E-03	-1.7030430E-03	5.3036630E-04
	185	1.8515750E-03	-2.0970250E-03	6.4831620E-04
	357	2.1824490E-03	-2.4364740E-03	7.4626900E-04
	688	2.5547090E-03	-2.8189240E-03	8.5584400E-04
	1324	3.0645000E-03	-3.3675560E-03	1.0170900E-03
	2549	3.8197810E-03	-4.2198680E-03	1.2744570E-03
	4908	4.9461780E-03	-5.5349030E-03	1.6790480E-03
	9450	6.5973430E-03	-7.5062570E-03	2.2927150E-03
	14000	7.9195690E-03	-9.1041030E-03	2.7930800E-03

Coefficients A, B and C of equation 3.2 for w/c = 0.7 cement paste.

Stress	Time	A	B	C
0-0.4f′	15	0.0000000	0.0000000	0.0000000
	26	-8.1767500E-06	7.1438850E-05	0.0000000
	50	3.9242850E-05	1.2197820E-04	0.0000000
	96	1.4160750E-04	1.4085210E-04	0.0000000
	185	2.8886230E-04	1.3588810E-04	0.0000000
	357	4.6989800E-04	1.1578760E-04	0.0000000
	688	6.7394450E-04	8.9519720E-05	0.0000000
	1324	8.9128930E-04	6.6037230E-05	0.0000000
	2549	1.1135150E-03	5.4293430E-05	0.0000000
	4908	1.3332850E-03	6.3537740E-05	0.0000000
	9450	1.5434640E-03	1.0400950E-04	0.0000000
	14000	1.6616600E-03	1.4825610E-04	0.0000000
0.4-0.6f′	15	0.0000000	0.0000000	0.0000000
	26	3.6711300E-04	-2.2879300E-04	6.0046370E-05
	50	7.0158110E-04	-4.0789240E-04	1.0597410E-04
	96	9.3755130E-04	-4.9590270E-04	1.2735100E-04
	185	1.0979810E-03	-5.1140650E-04	1.2945890E-04
	357	1.2122630E-03	-4.7810380E-04	1.1877830E-04
	688	1.3132930E-03	-4.2195940E-04	1.0229570E-04
	1324	1.4369440E-03	-3.7048660E-04	8.7304740E-05
	2549	1.6225380E-03	-3.5292380E-04	8.1443460E-05
	4908	1.9153250E-03	-4.0209430E-04	9.3126320E-05
	9450	2.3709930E-03	-5.5801310E-04	1.3240440E-04
	14000	2.7521480E-03	-7.2413310E-04	1.7447780E-04
0.6-0.8f′	15	0.0000000	0.0000000	0.0000000
	26	1.4498450E-03	-1.5280720E-03	4.4982990E-04
	50	3.6066650E-03	-3.8939940E-03	1.1518040E-03
	96	6.2689800E-03	-6.8936190E-03	2.0466650E-03
	185	9.4875970E-03	-1.0578950E-02	3.1497210E-03
	357	1.3334540E-02	-1.5024830E-02	4.4827960E-03
	688	1.7918040E-02	-2.0347650E-02	6.0800050E-03
	1324	2.3398680E-02	-2.6724570E-02	7.9935280E-03
	2549	3.0011460E-02	-3.4419630E-02	1.0301450E-02
	4908	3.8095680E-02	-4.3818510E-02	1.3118050E-02
	9450	4.8140610E-02	-5.5481550E-02	1.6609470E-02
	14000	5.5390210E-02	-6.3889810E-02	1.9124180E-02

Coefficients A, B and C of equation 3.2 for w/c = 0.7 mortar.

Stress	Time	A	B	C
0-0.4f′	15	0.0000000	0.0000000	0.0000000
	26	-7.1013350E-06	2.7643980E-05	0.0000000
	50	1.7179230E-05	4.0926100E-05	0.0000000
	96	7.1200750E-05	3.6514950E-05	0.0000000
	185	1.3580700E-04	2.3746210E-05	0.0000000
	357	1.8978880E-04	1.2949850E-05	0.0000000
	688	2.4220190E-04	2.4672340E-06	0.0000000
	1324	3.0329840E-04	-9.7520750E-06	0.0000000
	2549	3.8385380E-04	-2.5863140E-05	0.0000000
	4908	4.9546190E-04	-4.8184770E-05	0.0000000
	9450	6.1402500E-04	-6.4491060E-05	0.0000000
	14000	6.2780890E-04	-4.5878680E-05	0.0000000
0.4-0.6f′	15	0.0000000	0.0000000	0.0000000
	26	1.5869450E-04	-1.0499270E-04	2.6527320E-05
	50	2.9303630E-04	-1.7975960E-04	4.4137140E-05
	96	3.7788770E-04	-2.0883470E-04	4.9069910E-05
	185	4.5069920E-04	-2.2816760E-04	5.0382730E-05
	357	5.5430450E-04	-2.7866280E-04	5.8322500E-05
	688	6.7238420E-04	-3.4167870E-04	6.8829160E-05
	1324	7.8793650E-04	-3.9746260E-04	7.7542090E-05
	2549	8.8479220E-04	-4.2661400E-04	8.0150090E-05
	4908	9.4747400E-04	-4.0979450E-04	7.2321910E-05
	9450	1.0346780E-03	-4.0101380E-04	6.7304470E-05
	14000	1.2259170E-03	-5.2436530E-04	9.5697290E-05
0.6-0.8f′	15	0.0000000	0.0000000	0.0000000
	26	3.4595640E-05	-3.0824620E-05	8.6190010E-06
	50	1.0671660E-03	-1.1087150E-03	3.2282360E-04
	96	2.0370690E-03	-2.1998520E-03	6.4637510E-04
	185	3.2749650E-03	-3.6172860E-03	1.0671180E-03
	357	4.7741920E-03	-5.3425270E-03	1.5774820E-03
	688	6.6011430E-03	-7.4561900E-03	2.2031820E-03
	1324	6.6011430E-03	-7.4561900E-03	2.2031820E-03
	2549	1.1614860E-02	-1.3302700E-02	3.9429750E-03
	4908	1.5071300E-02	-1.7358390E-02	5.1569010E-03
	9450	1.9350280E-02	-2.2379740E-02	6.6609230E-03
	14000	2.2296590E-02	-2.5809180E-02	7.6811400E-03

Coefficients A, B and C of equation 3.2 for w/c = 0.7 concrete.

Stress	Time	A	B	C
0-0.2f′	15	0.0000000	0.0000000	0.0000000
	26	0.0000000	1.0238800E-05	0.0000000
	50	0.0000000	1.7464410E-05	0.0000000
	96	0.0000000	1.9980360E-05	0.0000000
	185	0.0000000	2.0005170E-05	0.0000000
	357	0.0000000	2.0005170E-05	0.0000000
	688	0.0000000	2.0005170E-05	0.0000000
	1324	0.0000000	2.0005170E-05	0.0000000
	2549	0.0000000	2.0005170E-05	0.0000000
	4908	0.0000000	2.0005170E-05	0.0000000
	9450	0.0000000	2.0005170E-05	0.0000000
	14000	0.0000000	2.0005170E-05	0.0000000
0.2-0.4f′	15	0.0000000	0.0000000	0.0000000
	26	9.0021790E-05	-2.5769910E-05	3.6008710E-06
	50	1.8929140E-04	-5.8252160E-05	7.5716570E-06
	96	2.8038040E-04	-9.2171810E-05	1.1215220E-05
	185	3.5114650E-04	-1.2045340E-04	1.4045860E-05
	357	3.8838920E-04	-1.3535050E-04	1.5535570E-05
	688	4.0415550E-04	-1.4165700E-04	1.6166220E-05
	1324	4.1110250E-04	-1.4443580E-04	1.6444100E-05
	2549	4.2201570E-04	-1.4880110E-04	1.6880630E-05
	4908	4.4977120E-04	-1.5990330E-04	1.7990850E-05
	9450	5.0749160E-04	-1.8299140E-04	2.0299660E-05
	14000	5.6220070E-04	-2.0487510E-04	2.2488030E-05
0.4-0.6f′	15	0.0000000	0.0000000	0.0000000
	26	-9.7651110E-05	1.2436840E-04	-2.6426790E-05
	50	-1.4562540E-04	2.0968130E-04	-4.6015040E-05
	96	-1.2210490E-04	2.2981650E-04	-5.3182430E-05
	185	-1.2693520E-05	1.7061850E-04	-4.4168560E-05
	357	1.9784340E-04	1.7086220E-05	-1.4951800E-05
	688	4.8690060E-04	-2.0785320E-04	2.9405430E-05
	1324	8.3187160E-04	-4.8105110E-04	8.3767150E-05
	2549	1.2113330E-03	-7.8025470E-04	1.4317140E-04
	4908	1.6056720E-03	-1.0846230E-03	2.0293490E-04
	9450	1.9972150E-03	-1.3747700E-03	2.5865540E-04
	14000	2.2240700E-03	-1.5343700E-03	2.8838710E-04

Coefficients A, B and C of equation 3.2 for w/c = 0.7 concrete.

Stress	Time	A	B	C
0.6-0.8f′	15	0.0000000	0.0000000	0.0000000
	26	3.0847370E-04	-3.6298130E-04	1.1977810E-04
	50	6.0958650E-04	-6.9657290E-04	2.2586120E-04
	96	8.4579900E-04	-9.3166810E-04	2.9526300E-04
	185	8.4579900E-04	-9.3166810E-04	2.9526300E-04
	357	1.0949250E-03	-1.0594110E-03	3.0799730E-04
	688	1.1356200E-03	-9.8631620E-04	2.6294440E-04
	1324	1.1678640E-03	-8.8424260E-04	2.0472440E-04
	2549	1.2295880E-03	-8.0215980E-04	1.4974280E-04
	4908	1.3605240E-03	-7.9044650E-04	1.1468170E-04
	9450	1.6033740E-03	-9.0216100E-04	1.1687240E-04
	14000	1.8224660E-03	-1.0524450E-03	1.4380970E-04

APPENDIX B

CYCLIC TEST 1D2 (0 - 0.8f′$_p$)

Time (sec)	Stress (psi)	Strain (με)	Ei (10^6 psi)	E$_{su}$ (10^6 psi)
74.81438,	4320.13000,	0.0020668780,		
89.89345,	0.00000,	0.0001243510,	2.223974,	2.198466
1274.85300,	4320.13000,	0.0026283230,		
1289.87500,	0.00000,	0.0004204672,	1.956708,	1.955047
2474.89000,	4320.13000,	0.0028705230,		
2489.91000,	0.00000,	0.0005750622,	1.882032,	1.878139
3674.92500,	4320.13000,	0.0030524580,		
3689.94800,	0.00000,	0.0007042772,	1.839778,	1.835583
4874.96300,	4320.13000,	0.0032050150,		
4889.98600,	0.00000,	0.0008209384,	1.812077,	1.808744
6075.00400,	4320.13000,	0.0033512210,		
6090.02400,	0.00000,	0.0009294359,	1.783862,	1.781239
7275.04300,	4320.13000,	0.0034875040,		
7290.08300,	0.00000,	0.0010434550,	1.767612,	1.765115
8475.08300,	4320.13000,	0.0036164400,		
8490.12100,	0.00000,	0.0011423390,	1.746141,	1.748381
9675.12300,	4320.13000,	0.0037465610,		
9690.14000,	0.00000,	0.0012610560,	1.738130,	1.736206
10875.11000,	4320.13000,	0.0038718950,		
10890.13000,	0.00000,	0.0013526230,	1.714833,	1.714399
12075.21000,	4320.13000,	0.0040388850,		
12090.21000,	0.00000,	0.0015004400,	1.701880,	1.696524

CYCLIC TEST 1D3 (0 - 0.4f'_p)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	**E$_{su}$** (10^6 psi)
74.79221,	2151.13000,	0.0008922413,		
89.89400,	0.00000,	0.0000286512,	2.490915,	2.462799
1274.86900,	2151.13000,	0.0009476815,		
1289.88000,	0.00000,	0.0000697910,	2.450340,	2.440882
2474.89800,	2151.13000,	0.0009653385,		
2489.91800,	0.00000,	0.0000770304,	2.421603,	2.428052
3674.94000,	2151.13000,	0.0009740305,		
3689.95700,	0.00000,	0.0000880664,	2.428010,	2.419352
4874.98900,	2151.13000,	0.0009813198,		
4889.98900,	0.00000,	0.0000917859,	2.418266,	2.416777
6075.01000,	2151.13000,	0.0009845399,		
6090.03000,	0.00000,	0.0000892250,	2.402652,	2.421318
7275.05100,	2151.13000,	0.0009999106,		
7290.06400,	0.00000,	0.0001082856,	2.412595,	2.417484
8475.08500,	2151.13000,	0.0010056300,		
8490.10600,	0.00000,	0.0001141151,	2.412892,	2.408566
9675.12800,	2151.13000,	0.0010167940,		
9690.14400,	0.00000,	0.0001218655,	2.403689,	2.402896
10875.12000,	2151.13000,	0.0010227220,		
10890.16000,	0.00000,	0.0001332899,	2.418544,	2.414935
12075.18000,	2151.13000,	0.0010264470,		
12090.20000,	0.00000,	0.0001354290,	2.414239,	2.416678
13275.21000,	2151.13000,	0.0010361630,		
13290.21000,	0.00000,	0.0001400048,	2.400391,	2.393482
14475.29000,	2151.13000,	0.0010407010,		
14490.30000,	0.00000,	0.0001492283,	2.413006,	2.407770

CYCLIC TEST 2C2 (0 - $0.8f'_m$)

Time (sec)	**Stress** (psi)	**Strain** ($\mu\varepsilon$)	**Ei** (10^6 psi)	**E_{su}** (10^6 psi)
74.76691,	4433.19000,	0.0013265870,		
89.85569,	0.00000,	0.0001270665,	3.695801,	3.632705
1274.84900,	4433.19000,	0.0018413700,		
1289.87800,	0.00000,	0.0004331449,	3.148068,	3.141637
2474.88400,	4433.19000,	0.0021675940,		
2489.91600,	0.00000,	0.0006413986,	2.904732,	2.887601
3674.91700,	4433.19000,	0.0025030350,		
3689.95400,	0.00000,	0.0008280538,	2.646711,	2.637765
4874.96300,	4433.19000,	0.0029364690,		
4889.98400,	0.00000,	0.0010657720,	2.369807,	2.351480
5864.30300,	4433.19000,	0.0040674990,		
5799.73600,	0.00000,	0.0014177280,	2.369807,	2.351480

CYCLIC TEST 2C3 (0 - $0.4f'_m$)

Time (sec)	**Stress** (psi)	**Strain** ($\mu\varepsilon$)	**Ei** (10^6 psi)	**E$_{su}$** (10^6 psi)
74.80930,	2218.67000,	0.0004938991,		
89.89262,	0.00000,	0.0000084774,	4.570602,	4.586191
1274.86100,	2218.67000,	0.0005126289,		
1289.91200,	0.00000,	0.0000163753,	4.470839,	4.446107
2474.90400,	2218.67000,	0.0005168803,		
2489.94900,	0.00000,	0.0000148582,	4.419467,	4.428293
3674.94100,	2218.67000,	0.0005144562,		
3689.98900,	0.00000,	0.0000134267,	4.428223,	4.419119
4874.97700,	2218.67000,	0.0005136039,		
4890.02600,	0.00000,	0.0000102458,	4.407738,	4.399371
6075.02000,	2218.67000,	0.0005171598,		
6090.06100,	0.00000,	0.0000149674,	4.417968,	4.387840
7275.05600,	2218.67000,	0.0005126094,		
7290.09700,	0.00000,	0.0000076008,	4.393331,	4.415849
8475.08700,	2218.67000,	0.0005180554,		
8490.13700,	0.00000,	0.0000134958,	4.397241,	4.416957
9675.12300,	2218.67000,	0.0005262978,		
9690.17800,	0.00000,	0.0000230972,	4.409116,	4.427630
10875.19000,	2218.67000,	0.0005317339,		
10890.24000,	0.00000,	0.0000278856,	4.403449,	4.424983
12075.19000,	2218.67000,	0.0005385844,		
12090.24000,	0.00000,	0.0000360358,	4.414836,	4.416133
13275.28000,	2218.67000,	0.0005372268,		
13290.33000,	0.00000,	0.0000382315,	4.446274,	4.437724
14475.30000,	2218.67000,	0.0005428488,		
14490.34000,	0.00000,	0.0000399902,	4.412115,	4.435139

CYCLIC TEST 2C5 (0.2 - $0.6f'_m$)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	E_{su} (10^6 psi)
74.64081,	3313.53000,	0.0008439466,		
89.65060,	1112.94000,	0.0003497206,	4.452599,	4.346592
1279.05300,	3313.53000,	0.0009213540,		
1293.92600,	1112.94000,	0.0004292413,	4.471719,	4.472440
2483.52200,	3313.53000,	0.0009466847,		
2498.52200,	1112.94000,	0.0004610155,	4.531047,	4.491145
3688.07400,	3313.53000,	0.0009677686,		
3703.07400,	1112.94000,	0.0004824332,	4.534163,	4.498813
4892.64800,	3313.53000,	0.0009837630,		
4907.67700,	1112.94000,	0.0004953355,	4.505459,	4.520187
6097.35500,	3313.53000,	0.0009943752,		
6112.36900,	1112.94000,	0.0005089070,	4.532923,	4.520195
7301.97400,	3313.53000,	0.0010027000,		
7317.04000,	1112.94000,	0.0005153524,	4.515441,	4.545153
8476.78200,	3313.53000,	0.0010104650,		
8491.80100,	1112.94000,	0.0005243559,	4.526946,	4.549834
9681.61900,	3313.53000,	0.0010176880,		
9696.64600,	1112.94000,	0.0005328765,	4.539064,	4.547716
10886.50000,	3313.53000,	0.0010242060,		
10901.53000,	1112.94000,	0.0005397173,	4.542086,	4.547642
12091.40000,	3313.53000,	0.0010355250,		
12106.48000,	1112.94000,	0.0005465253,	4.500188,	4.552601
13296.60000,	3313.53000,	0.0010404040,		
13311.70000,	1112.94000,	0.0005550593,	4.534079,	4.563177
14501.90000,	3313.53000,	0.0010475320,		
14516.99000,	1112.94000,	0.0005620002,	4.532333,	4.569517

CYCLIC TEST 3C2 (0 - $0.8f'_c$)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	E_{su} (10^6 psi)
74.73652,	3780.30000,	0.0009752683,		
89.86593,	0.00000,	0.0000703932,	4.177703,	4.149374
1274.89500,	3780.30000,	0.0011766890,		
1289.89200,	0.00000,	0.0001820055,	3.800505,	3.820114
2474.92200,	3780.30000,	0.0012699450,		
2489.92500,	0.00000,	0.0002351127,	3.653055,	3.651536
3674.96500,	3780.30000,	0.0013655360,		
3689.95900,	0.00000,	0.0002864572,	3.503265,	3.509640
4874.99800,	3780.30000,	0.0014774010,		
4889.99400,	0.00000,	0.0003484030,	3.348369,	3.350217
6075.03500,	3780.30000,	0.0016338990,		
6090.02800,	0.00000,	0.0004411705,	3.169455,	3.164515

CYCLIC TEST 3C4 (0 - 0.8f′$_c$)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	**E$_{su}$** (10^6 psi)
74.74200,	3795.49000,	0.0009936226,		
89.88303,	0.00000,	0.0000861975,	4.182703,	4.133769
1274.90200,	3795.49000,	0.0012215440,		
1289.88100,	0.00000,	0.0002255570,	3.810781,	3.804849
2474.93900,	3795.49000,	0.0013590220,		
2489.91700,	0.00000,	0.0003115006,	3.623307,	3.630921
3674.98600,	3795.49000,	0.0014864510,		
3689.95300,	0.00000,	0.0003947776,	3.476765,	3.456666
4875.01900,	3795.49000,	0.0016291610,		
4889.98800,	0.00000,	0.0004765014,	3.292810,	3.299791
6075.04100,	3795.49000,	0.0018294800,		
6090.02500,	0.00000,	0.0005957290,	3.076384,	3.061183
6675.07200,	3795.49000,	0.0019958520,		
6690.04200,	0.00000,	0.0006928185,	2.912812,	2.887635
7125.07600,	3795.49000,	0.0022474080,		
7140.05600,	0.00000,	0.0008214813,	2.661771,	2.634119

CYCLIC TEST 3C5 (0.2 - $0.6f'_c$)

Time (sec)	Stress (psi)	Strain (με)	Ei (10^6 psi)	E_{su} (10^6 psi)
75.01709,	2851.67000,	0.0006684504,		
90.14597,	957.94000,	0.0002731834,	4.791014,	4.710273
1280.40300,	2851.67000,	0.0007177773,		
1295.52100,	957.94000,	0.0003161249,	4.714848	4.755039
2486.01300,	2851.67000,	0.0007338184,		
2501.11600,	957.94000,	0.0003323795,	4.717355,	4.764292
3691.74900,	2851.67000,	0.0007428579,		
3706.83600,	957.94000,	0.0003421615,	4.726097,	4.747661
4897.50200,	2851.67000,	0.0007510165,		
4912.60600,	957.94000,	0.0003483415,	4.702874,	4.753535
6103.19800,	2851.67000,	0.0007583466,		
6118.34500,	957.94000,	0.0003555399,	4.701337,	4.737368
7278.80600,	2851.67000,	0.0007620479,		
7293.89900,	957.94000,	0.0003611680,	4.723933,	4.751259
8484.64300,	2851.67000,	0.0007653610,		
8499.75200,	957.94000,	0.0003635355,	4.712817,	4.760038
9690.50600,	2851.67000,	0.0007701438,		
9705.62900,	957.94000,	0.0003685626,	4.715684,	4.759778
10896.30000,	2851.67000,	0.0007754468,		
10911.46000,	957.94000,	0.0003724957,	4.699652,	4.724977
12102.20000,	2851.67000,	0.0007750635,		
12117.37000,	957.94000,	0.0003749010,	4.732403,	4.749571
13277.90000,	2851.67000,	0.0007799857,		
13293.06000,	957.94000,	0.0003777683,	4.708224,	4.749741
14483.80000,	2851.67000,	0.0007845041,		
14498.95000,	957.94000,	0.0003822181,	4.707422,	4.734073

CYCLIC TEST 4C2 (0 - $0.8f'_p$)

Time (sec)	Stress (psi)	Strain (με)	Ei (10^6 psi)	E_{su} (10^6 psi)
74.74000,	2809.63000,	0.0020049010,		
89.89783,	0.00000,	0.0001562548,	1.519831,	1.501688
1274.90300,	2809.63000,	0.0026994870,		
1289.90100,	0.00000,	0.0004693674,	1.259856,	1.256576
2474.93800,	2809.63000,	0.0030350840,		
2489.94000,	0.00000,	0.0006744859,	1.190220,	1.189066
3674.98700,	2809.63000,	0.0033132180,		
3689.97600,	0.00000,	0.0008568688,	1.143824,	1.141613
4875.01700,	2809.63000,	0.0035470090,		
4890.01400,	0.00000,	0.0010189500,	1.111378,	1.109843
6075.04900,	2809.63000,	0.0037625690,		
6090.04400,	0.00000,	0.0011827920,	1.089098,	1.085819
7275.08800,	2809.63000,	0.0039611770,		
7290.08500,	0.00000,	0.0013290080,	1.067420,	1.066423
8475.12900,	2809.63000,	0.0041539410,		
8490.11900,	0.00000,	0.0014772020,	1.049647,	1.047497
9675.15900,	2809.63000,	0.0043333910,		
9690.16200,	0.00000,	0.0016229880,	1.036610,	1.036713
10875.17000,	2809.63000,	0.0045157730,		
10890.15000,	0.00000,	0.0017670630,	1.022163,	1.019233
12075.24000,	2809.63000,	0.0046776160,		
12090.24000,	0.00000,	0.0018990620,	1.011184,	1.011947
13275.31000,	2809.63000,	0.0048515560,		
13290.30000,	0.00000,	0.0020462390,	1.001537,	0.9992914
14475.33000,	2809.63000,	0.0049978090,		
14490.31000,	0.00000,	0.0021805720,	0.9972997,	0.9941835

CYCLIC TEST 4C3 (0 - 0.4f'_p)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	**E_{su}** (10^6 psi)
74.79456,	1418.89000,	0.0009012103,		
89.87791,	0.00000,	0.0000607258,	1.688181,	1.684406
1274.82700,	1418.89000,	0.0009388378,		
1289.88100,	0.00000,	0.0000878642,	1.667372,	1.655111
2474.86800,	1418.89000,	0.0009516324,		
2489.91000,	0.00000,	0.0000950439,	1.656443,	1.654685
3674.90400,	1418.89000,	0.0009655718,		
3689.94300,	0.00000,	0.0001029008,	1.644764,	1.658249
4874.94100,	1418.89000,	0.0009738611,		
4889.97900,	0.00000,	0.0001140233,	1.650183,	1.649991
6074.98200,	1418.89000,	0.0009853563,		
6090.02700,	0.00000,	0.0001178073,	1.635516,	1.643631
6074.98200,	1418.89000,	0.0009853563,		
6090.02700,	0.00000,	0.0001178073,	1.635516,	1.643631
8475.06400,	1418.89000,	0.0009917595,		
8490.09700,	0.00000,	0.0001382464,	1.662411,	1.657909
9675.08800,	1418.89000,	0.0010013480,		
9690.13500,	0.00000,	0.0001371941,	1.641940,	1.659112
10875.14000,	1418.89000,	0.0010001460,		
10890.19000,	0.00000,	0.0001445050,	1.658278,	1.655644
12075.14000,	1418.89000,	0.0010124780,		
12090.19000,	0.00000,	0.0001564245,	1.657479,	1.650104
13275.17000,	1418.89000,	0.0010120440,		
13290.20000,	0.00000,	0.0001610985,	1.667428,	1.652922
14475.25000,	1418.89000,	0.0010199400,		
14490.29000,	0.00000,	0.0001597728,	1.649551,	1.650867

CYCLIC TEST 4C4 (0.1 - $0.3f'_p$)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	E_{su} (10^6 psi)
75.64088,	1070.80000,	0.0005957757,		
90.50249,	359.40000,	0.0002186744,	1.886496,	1.856667
2505.57200,	1070.80000,	0.0006333736,		
2520.41200,	359.40000,	0.0002437550,	1.825888,	1.835074
2505.57200,	1070.80000,	0.0006333736,		
2520.41200,	359.40000,	0.0002437550,	1.825888,	1.835074
3689.70700,	1070.80000,	0.0006448599,		
3704.57500,	359.40000,	0.0002480561,	1.792826,	1.804202
4903.99800,	1070.80000,	0.0006512101,		
4918.82800,	359.40000,	0.0002572170,	1.792826,	1.804202
6088.23600,	1070.80000,	0.0006493339,		
6103.09100,	359.40000,	0.0002619179,	1.805616,	1.795160
7271.89100,	1070.80000,	0.0006536755,		
7287.19100,	359.40000,	0.0002674776,	1.836269,	1.843278

CYCLIC TEST 4C5 (0.2 - $0.6f'_p$)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	E_{su} (10^6 psi)
74.64352,	2111.53000,	0.0013901180,		
89.75251,	709.81000,	0.0005487949,	1.666090,	1.638243
1303.93900,	2111.53000,	0.0015245100,		
1318.85800,	709.81000,	0.0006582385,	1.618107,	1.621386
2502.84400,	2111.53000,	0.0015562550,		
2517.76400,	709.81000,	0.0006869642,	1.612487,	1.622187
3701.88300,	2111.53000,	0.0015780360,		
3716.82100,	709.81000,	0.0007009668,	1.598186,	1.604288
4901.12300,	2111.53000,	0.0016098200,		
4916.04800,	709.81000,	0.0007151620,	1.566767,	1.569385
6099.95600,	2111.53000,	0.0016256740,		
6114.90500,	709.81000,	0.0007338434,	1.571733,	1.569818
7299.00900,	2111.53000,	0.0016517390,		
7313.91300,	709.81000,	0.0007569033,	1.566455,	1.564998
8498.30100,	2111.53000,	0.0016707200,		
8513.20000,	709.81000,	0.0007708920,	1.557765,	1.561883
9697.72400,	2111.53000,	0.0016808200,		
9712.64600,	709.81000,	0.0007862807,	1.566973,	1.570263
10897.01000,	2111.53000,	0.0016899410,		
10911.93000,	709.81000,	0.0007981716,	1.571841,	1.572453
12096.45000,	2111.53000,	0.0016997830,		
12111.36000,	709.81000,	0.0008080953,	1.571985,	1.573558
13295.90000,	2111.53000,	0.0017040490,		
13310.85000,	709.81000,	0.0008106799,	1.569026,	1.574946
14465.34000,	2111.53000,	0.0017157610,		
14480.26000,	709.81000,	0.0008262205,	1.575781,	1.570774

CYCLIC TEST 5C2 (0 - 0.8f′$_m$)

Time (sec)	Stress (psi)	Strain (με)	Ei (10^6 psi)	E_{su} (10^6 psi)
74.74100,	2730.73000,	0.0009156662,		
89.88618,	0.00000,	0.0000772439,	3.256986,	3.235381
1274.89600,	2730.73000,	0.0012836450,		
1289.88300,	0.00000,	0.0002537639,	2.651501,	2.640837
2474.92100,	2730.73000,	0.0014835870,		
2489.92200,	0.00000,	0.0003670299,	2.445669,	2.449184
3674.97600,	2730.73000,	0.0016596010,		
3689.95200,	0.00000,	0.0004950145,	2.344807,	2.321284
4874.99200,	2730.73000,	0.0018015120,		
4889.98900,	0.00000,	0.0005830084,	2.241052,	2.244510
6075.03400,	2730.73000,	0.0019578970,		
6090.02400,	0.00000,	0.0006967033,	2.165195,	2.150862
7275.07600,	2730.73000,	0.0021043440,		
7290.05700,	0.00000,	0.0007973941,	2.089391,	2.088247
8475.10800,	2730.73000,	0.0022674320,		
8490.09300,	0.00000,	0.0009134212,	2.016771,	2.015489
9675.14700,	2730.73000,	0.0024515330,		
9690.13300,	0.00000,	0.0010438810,	1.939918,	1.936317
10875.17000,	2730.73000,	0.0026533230,		
10890.15000,	0.00000,	0.0011850410,	1.859814,	1.861086
12075.25000,	2730.73000,	0.0028860660,		
12090.24000,	0.00000,	0.0013586940,	1.787863,	1.775247
13275.25000,	2730.73000,	0.0031803290,		
13290.24000,	0.00000,	0.0015629520,	1.688370,	1.682364
14475.29000,	2730.73000,	0.0036181580,		
14490.27000,	0.00000,	0.0018881410,	1.578441,	1.570891

CYCLIC TEST 5C3 (0 - $0.4f'_m$)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	**E_{su}** (10^6 psi)
74.79322,	1372.03000,	0.0003631167,		
89.91969,	0.00000,	0.0000056958,	3.838695,	3.838937
1275.31800,	1372.03000,	0.0003852185,		
1290.32200,	0.00000,	0.0000144886,	3.700888,	3.702926
2474.90300,	1372.03000,	0.0003905860,		
2489.92500,	0.00000,	0.0000194706,	3.697044,	3.716015
3674.93700,	1372.03000,	0.0003998394,		
3689.95800,	0.00000,	0.0000236737,	3.647409,	3.678216
4874.96500,	1372.03000,	0.0004050093,		
4889.99000,	0.00000,	0.0000325538,	3.683742,	3.706196
6075.00500,	1372.03000,	0.0004079813,		
6090.03400,	0.00000,	0.0000322300,	3.651431,	3.677027
7275.04000,	1372.03000,	0.0004149443,		
7290.05900,	0.00000,	0.0000387710,	3.647336,	3.651318
8475.08600,	1372.03000,	0.0004127954,		
8490.08800,	0.00000,	0.0000359525,	3.640854,	3.646525
9675.56400,	1372.03000,	0.0004148393,		
9690.56400,	0.00000,	0.0000372410,	3.633570,	3.602215
10875.11000,	1372.03000,	0.0004177176,		
10860.13000,	0.00000,	0.0000429951,	3.626001,	3.661456
12075.13000,	1372.03000,	0.0004165519,		
12090.16000,	0.00000,	0.0000388297,	3.632379,	3.682763
13275.18000,	1372.03000,	0.0004158983,		
13290.20000,	0.00000,	0.0000398442,	3.648491,	3.651035
14475.27000,	1372.03000,	0.0004180816,		
14490.29000,	0.00000,	0.0000410407,	3.638943,	3.654289

CYCLIC TEST 5C5 (0.2 - 0.6f'_m)

Time (sec)	**Stress** (psi)	**Strain** (με)	**Ei** (10^6 psi)	E_{su} (10^6 psi)
74.84593,	2054.60000,	0.0005731414,		
89.90622,	693.43000,	0.0002270737,	3.933249,	3.881403
1277.51200,	2054.60000,	0.0006079125,		
1292.53800,	693.43000,	0.0002458363,	3.759347,	3.749016
2480.08300,	2054.60000,	0.0006172906,		
2495.11800,	693.43000,	0.0002526947,	3.733367,	3.730416
3682.79000,	2054.60000,	0.0006185042,		
3697.80400,	693.43000,	0.0002513403,	3.707254,	3.718802
4885.31400,	2054.60000,	0.0006217058,		
4900.33700,	693.43000,	0.0002572366,	3.734665,	3.713563
6088.14800,	2054.60000,	0.0006257525,		
6103.18300,	693.43000,	0.0002602486,	3.724092,	3.744624
7290.82400,	2054.60000,	0.0006304911,		
7305.84700,	693.43000,	0.0002649690,	3.723907,	3.707510
8493.32500,	2054.60000,	0.0006392162,		
8508.36000,	693.43000,	0.0002719838,	3.706564,	3.702535
9695.85000,	2054.60000,	0.0006368654,		
9710.86600,	693.43000,	0.0002739905,	3.751073,	3.733525
10898.54000,	2054.60000,	0.0006390252,		
10913.55000,	693.43000,	0.0002758026,	3.747482,	3.731047
12101.11000,	2054.60000,	0.0006389936,		
12116.14000,	693.43000,	0.0002775168,	3.765580,	3.753724
13303.64000,	2054.60000,	0.0006438351,		
13318.68000,	693.43000,	0.0002796306,	3.737378,	3.756179
14475.60000,	2054.60000,	0.0006434527,		
14490.60000,	693.43000,	0.0002878985,	3.828305,	3.806071

CYCLIC TEST 6C2 (0 - $0.8f'_c$)

Time (sec)	**Stress** (psi)	**Strain** ($\mu\varepsilon$)	**Ei** (10^6 psi)	**E_{su}** (10^6 psi)
74.74000,	2262.08000,	0.0007329574,		
89.89893,	0.00000,	0.0000543999,	3.333660,	3.305062
1274.89000,	2262.08000,	0.0010214050,		
1289.87100,	0.00000,	0.0002040204,	2.767462,	2.766981
2474.92400,	2262.08000,	0.0012350540,		
2489.90500,	0.00000,	0.0003450312,	2.541600,	2.522637
3674.95800,	2262.08000,	0.0015026280,		
3689.94600,	0.00000,	0.0005208724,	2.304118,	2.287387
4874.99000,	2262.08000,	0.0020898330,		
4889.97900,	0.00000,	0.0009024698,	1.905128,	1.871861

CYCLIC TEST 6C5 (0.2 - 0.6f′$_c$)

Time (sec)	Stress (psi)	Strain (με)	Ei (10^6 psi)	E_{su} (10^6 psi)
75.08006,	1691.78000,	0.0004598558,		
90.15495,	566.89000,	0.0001838946,	4.076262,	3.933892
1280.89300,	1691.78000,	0.0005055098,		
1296.03300,	566.89000,	0.0002253331,	4.014931,	4.056714
2486.93700,	1691.78000,	0.0005208298,		
2502.06700,	566.89000,	0.0002393679,	3.996597,	4.024671
3692.89700,	1691.78000,	0.0005293136,		
3708.03300,	566.89000,	0.0002463215,	3.974988,	4.014087
4898.88700,	1691.78000,	0.0005317281,		
4914.00900,	566.89000,	0.0002482643,	3.968372,	4.018147
6104.96100,	1691.78000,	0.0005301477,		
6120.11100,	566.89000,	0.0002473344,	3.977500,	4.001044
7280.78600,	1691.78000,	0.0005360527,		
7295.90800,	566.89000,	0.0002533896,	3.979613,	4.009365
8486.61900,	1691.78000,	0.0005404724,		
8501.74100,	566.89000,	0.0002597356,	4.006920,	4.037667
9692.38300,	1691.78000,	0.0005486957,		
9707.51600,	566.89000,	0.0002672937,	3.997449,	4.004279
10898.00000,	1691.78000,	0.0005494636,		
10913.14000,	566.89000,	0.0002685067,	4.003782,	4.020519
12103.80000,	1691.78000,	0.0005516688,		
12118.91000,	566.89000,	0.0002692835,	3.983529,	4.055128
13279.30000,	1691.78000,	0.0005531632,		
13294.42000,	566.89000,	0.0002722835,	4.004881,	4.047411
14484.80000,	1691.78000,	0.0005554134,		
14499.90000,	566.89000,	0.0002743244,	4.001899,	4.043025