INTERACTION OF ENVIRONMENT AND SIZE ON THE DRYING SHRINKAGE AND CREEP OF CONCRETE

by

Nima Bargi

A thesis submitted to
the School of Graduate Studies and Research
in partial fulfillment of the
requirements for the degree of
Master of Engineering
in Civil Engineering*

Department of Civil Engineering
University of Ottawa
Ottawa, Ontario, Canada
May 2002

*The M.Eng. in Civil Engineering Program
is a joint program with Carleton University
administered by the Ottawa-Carleton Institute for Civil Engineering

To All Beloved, Deprived "Baha'i Institute for Higher Education" Students in Iran

ABSTRACT

This report describes the significant observations from an ongoing, long duration experimental investigation into the joint interaction of environment, specimen size, duration of moist curing on shrinkage and creep. The different environments investigated are: (a) constant temperature conditions in a laboratory, uncontrolled relative humidity, (b) in a room of 50 % relative humidity and constant temperature, (c) in water, and (d) outside exposure in the Ottawa area. The compressive strength of concrete subject to these environments was measured.

A number of 89 mm diameter, 152 mm diameter, 254 mm diameters and 610 mm diameter cylinders were cast from a single batch and moist cured in their moulds for 3 days. All specimens were exposed to the chosen environment after moist curing 3~4 days and typically loaded at 24 days. For the age of loading tests, 89 mm diameter specimens were loaded at concrete ages raging from 3 to 200 days, 152 mm diameter specimens were loaded at concrete age 24 days, 254 mm diameter specimens were loaded at concrete age 24 days (200 days for the outdoor environment specimens) and the 610 mm diameter specimens were loaded at concrete age 24 days in each of the chosen environments. The environments were inside (22°C, variable humidity), 22°C and 50 % relative humidity, outside (uncontrolled temperature and humidity) and immersed in water.

The compressive strengths of concretes stored in the laboratory and 50% RH environments had similar values but 50% RH shrinkage was slightly smaller. Although the compressive strength of specimens stored outside was slightly smaller than the identical ones stored in the lab in the first days, the ultimate compressive strength of concrete was much larger for specimens outside. The shrinkages of the specimens stored outside were 50% of the specimens stored in the 50% RH environment. The specimens stored in the 50% RH environment and the laboratory approached an ultimate limiting value ie the rate of increase in shrinkage after 1000 days was small.

Increasing the duration of moist curing from 3 days to 25 days, reduced shrinkage but increasing the duration of moist curing from 25 days to 200 days had little effect.

Storing specimens outside (specimens were cast December 1997) reduced shrinkage considerably. Whether the conclusion is valid for concrete cast in summer is not known.

Creep is reduced by increasing specimen diameter, duration of moist curing and the age of loading. The creep of the immersed and sealed specimens was less than the specimens exposed to drying. The lower the relative humidity the larger the creep. Sealing decreased creep - sealing is more effective if it is done in the first few days after casting.

Specimens stored outside had significantly smaller creeps. Lab and 50% RH had almost similar creeps but 50% RH was slightly smaller.

The creep of the immersed specimens became asymptotic with time after some 1000 days of loading. However the creep of none of the specimens exposed to drying reached an ultimate value in the observation period.

The elastic and creep Poisson's ratio of the concrete used was 0.18.

Acknowledgments

The author would like to express his deepest gratitude and understanding to his supervisor Dr. N. J. Gardner for his tireless advice, encouragement and support during his M. Eng. degree program.

The author gratefully acknowledges the financial support of Baha'i Community of Canada.

Author's gratitude goes to Sherri Yazdani for her lovely and kind support during his stay in Canada.

The author thanks all his friends in Ottawa for their help and support.

The author also thanks his parents, sister and brother for their unlimited support, understanding and love all through his life.

Finally, the author thanks his fiancée for her support, love and understanding during the period of his studies in Canada.

TABLE OF CONTENTS

List of Tables

List of Figures

CHAPTER 1

INTRODUCTION

1.1 General

As concrete ages it undergoes volume changes responding to its environment, member size and stress. While most engineers understand the immediate, time-independent volume change of concrete due to load, commonly referred to as elastic, initial or immediate deformation, many do not fully understand the concrete time-dependent deformations. In general the concrete time-dependent volume changes are several times greater than the time-independent volume changes.

The time-dependent deformations (creep and drying shrinkage) have a great influence on the structural behavior of reinforced and prestressed concrete elements. They are directly related to long-term deflection, losses in prestressing, and cracking. From a structural point of view, drying shrinkage is an adverse property of concrete. Drying shrinkage is the time-dependent volume reduction due to loss of water at constant relative humidity and temperature. If it is not accurately accounted for in structural design, severe cracking may occur, that in turn promotes increased deflection, corrosion of the reinforcement and causes a reduction in service life and structural reliability.

Concrete shrinkage is affected by several factors, one of which is specimen size and storage environment, which influence the rate of water loss. The rate of shrinkage decreases with increasing specimen size. The effect of specimen size and storage environment on ultimate shrinkage is not resolved.

The purpose of this report is to investigate the effect of specimen length, specimen size (diameter), duration of moist curing, and different environments on shrinkage of plain concrete by observing different size specimens stored in different environments. For creep in addition to these parameters, the effect of age of loading is considered.

The different environments investigated are: (a) constant temperature conditions in a laboratory, uncontrolled relative humidity, (b) in a room of 50 % relative humidity and constant temperature, (c) in water, and (d) outside exposure in the Ottawa area. The compressive strength of concrete subject to these environments is also investigated.

1.2 Shrinkage

Different kinds of shrinkage may happen in concrete:

- Plastic shrinkage occurs before the concrete sets.
- Drying shrinkage is due to moisture loss from the concrete after the concrete sets.
- Autogenous shrinkage is caused by the hydration of the cement.
- Carbonation shrinkage results as the various cement hydration products are carbonated in the presence of CO_2.

In this study, only drying shrinkage will be discussed. Shrinkage, after hardening of concrete, is the decrease of concrete volume with time. The decrease is due to changes in the moisture content of the concrete and physico-chemical changes, which occur without stress due to load. The converse of shrinkage is swelling, which is a volumetric increase due to moisture gain in hardened concrete. Shrinkage is expressed as a dimensionless strain (mm/mm) and is usually measured under steady conditions of relative humidity and temperature.

Shrinkage, which takes place while the concrete is still in the plastic state, is known as plastic shrinkage. It undergoes a volumetric contraction whose magnitude is of the order of one percent of the absolute volume of dry cement. Movement of water from hardened concrete stored in unsaturated air causes drying shrinkage. A large part of this contraction is irreversible and should be distinguished from the reversible moisture movement caused by alternating storage under wet and dry conditions.

The reaction products of the hydration reaction occupy less volume than the cement and water. This shrinkage called by the chemical reaction is called autogenous shrinkage and is usually ignored for concretes with water/cement ratios greater than 0.4.

1.3 Creep

The time-dependant increase of strain due to sustained stress, usually constant, in hardened concrete, in excess of thermal expansion, elastic strain and shrinkage, is defined as creep. It is obtained by subtracting the sum of the initial instantaneous (usually considered elastic) strain due to the sustained stress, the shrinkage, and any thermal strain in an identical load-free specimen from the total measured strain in a loaded specimen, which is subjected to the same history of relative humidity and temperature.

The above definition treats the initial instantaneous strain, the creep strain, and the shrinkage as additive, even though they affect each other. An instantaneous change in stress is most likely to produce both elastic and inelastic instantaneous changes in strain, as well as short time creep strains (10 to 100 minutes of duration), which are conventionally included in the so-called instantaneous strain. Much controversy about the best form of "practical creep equations" stems from the fact that no clear separation exists between the true instantaneous strain (elastic and inelastic strains) and early age creep strains. Also, the creep definition lumps together the basic creep and the drying creep.

- Basic creep occurs under conditions of no moisture movement to or from the environment.
- Drying creep is the additional creep exhibit by a specimen under load subjected to a drying environment.

1.4 Scope of Research

This thesis analyses the experimental results of a project initiated by Huh (1998). Huh cast a number of shrinkage and creep specimens and measured the time dependant strains for 315 days (December 1998). Shrinkage and creep strains were measured and are reported for a total duration of 1259 days (July 2001) since casting. The creep specimens were unloaded August 2000, approximately 1000 days after casting. Shrinkage and creep recovery measurements are continuing.

CHAPTER 2

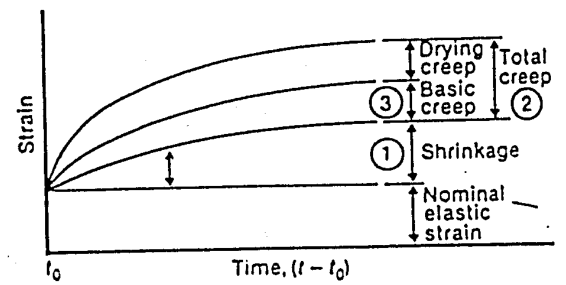
STANDARD TEST

2.1 Introduction

Concrete gains strength as a result of chemical reactions known as hydration between the cement powder and water. For a given concrete mixture, strength at any age, in normal conditions, is related to the degree of hydration. The rate of hydration and strength development of a given concrete will be, at least, a function of its temperature and humidity history. Thus, providing sufficient moisture is always present for hydration, the strength of the concrete depends on its time-temperature history.

Shrinkage, which takes place while the concrete is still in the plastic state, is known as plastic shrinkage. It undergoes a volumetric contraction whose magnitude is of the order of one percent of the absolute volume of dry cement. Withdrawal of water from hardened concrete stored in unsaturated air causes drying shrinkage. A large part of this contraction is irreversible and should be distinguished from the reversible moisture movement caused by alternating storage under wet and dry conditions.

Although creep is observed for all materials, the fundamental basis for creep of concrete must be quite different from those of metals, because significant volume changes occur at ambient temperatures and the presence of moisture in the material plays an important role. It is commonly assumed that creep and shrinkage are interrelated phenomena because there are a number of similarities in that both are affected by the same phenomena. The strain-time curves are similar, constituent materials and environmental factors affect creep in much the same way as shrinkage, the magnitudes of the strains are similar, and include a considerable amount of irreversibility.



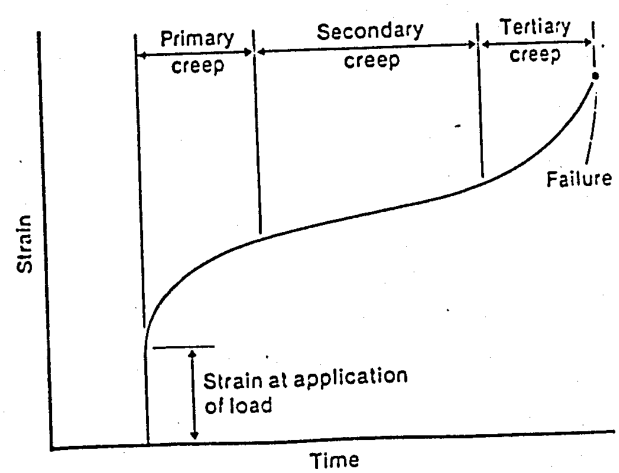


Figure 2-1: Time-dependent deformation in concrete subjected to a sustained load

The magnitude and the rate of development of shrinkage and creep are dependent upon, at least, the following parameters;

- Ambient humidity time history
- Temperature time history
- Duration of moist curing
- Duration since moist curing for shrinkage
- Duration under load for creep
- Size of concrete element
- Strength of concrete
- Strength development of concrete strength and stiffness with time
- Type of cement and any supplementary cementing materials
- Drying before loading
- Type of aggregate and stiffness of aggregate
- Water cement ratio, paste content, aggregate cement ratio

An excellent reference on creep is "Creep of Plain and Structural Concrete" by Neville, Dilger and Brooks.

2.2 Test Methods for Creep and Shrinkage

2.2.1 Test Concept

The experimental determination of creep and shrinkage of concrete is simple in concept. Deformations are measured over time on loaded and unloaded specimens in the same environment (unloaded specimens {shrinkage}, initial and total deformation).

Shrinkage is measured on the unloaded specimens, while creep is determined by subtracting the shrinkage deformation and the immediate or "elastic" deformation from the total deformation measured on the loaded specimens.

Although simple in concept, there are many experimental details that must be understood and carefully controlled to obtain meaningful test results. These include maintaining a constant load on the test specimens while ensuring the load is being transferred into the test specimens in a uniform and well controlled manner, measuring small changes in deformation over time, and maintaining the test environment within the temperature and humidity tolerances.

2.2.2 Assumptions

A test program consistent with the state-of-the-art knowledge on creep and shrinkage and the use of the test results in structural analysis, or in the development of prediction models is based on the following assumptions.

- Only creep and shrinkage strains are present.
- Creep and shrinkage do not interact.
- Separation exists between strain components from environmental and load conditions.
- Strain gradients are linear (and uniform).

2.2.3 Designing a Test Program

The more comprehensive the test program, the better the possibility of updating prediction parameters or understanding the phenomena of creep and shrinkage. The scope of a test program depends on how critical would be the effects of creep and shrinkage on the structure behavior, on the model used for prediction, on the method of structural analysis, on the time and facilities available for testing, and on the budget. Typical duration of creep and shrinkage test programs varies from months to several years.

The simplest test program may consist of determining the static modulus of elasticity, E_c, at, 1, 2, 7, 28 and 90 days in accordance with ASTM C 469. This simple program will eliminate the uncertainty in the prediction of E_c.

Various methods and techniques are used to measure creep and shrinkage. Two common standard test methods are ASTM C 512 "Standard Test Method for Creep of Concrete in Compression" and RILEM CPC-12 "Measurement of Creep in Compression". ASTM C 512 is commonly used for tests conducted in the United States and Canada. However, this method is somewhat vague and requires refinement. ACI Committee 209 "Creep and Shrinkage of Concrete" is reviewing the method and may suggest improvements. Specific areas of concern include the method of deformation measurement, the location for measuring strains, the gage length, the speed of initial loading, the schedule of deformation readings and the equation or model used to extrapolate the strains.

2.2.4 Moist Curing and Storage in ASTM C 512

For 20 to 48 hours after casting, specimens are covered in their moulds to prevent evaporation and kept at 23.0 ± 1.7 °C. All the test specimens should be cured in the moulds for the same length of time after water is added during casting.

After removal from their moulds, some specimens are moist cured until age of 7 days at 23.0 ± 1.7 °C. A moist curing condition is that in which free water is maintained on the surfaces of the specimens all time. The free water on the surface of the specimens cause some swelling. Specimens should not be exposed to running water nor stored under water.

After age of 7 days, specimens are stored at 23.0 ± 1.1 °C and a relative humidity of 50 ± 1 % until completion of test. For other than 7 day curing, drying can start at any concrete age, which may or may not be coincidental with the age of loading.

2.2.5 Basic Creep and Autogenous Shrinkage Curing in ASTM C 512

At the age of demoulding or stripping, specimens are sealed in moisture proof jackets to prevent loss of moisture by evaporation. For consistency with all other specimens in the test program they are kept in the same environment at 23 ± 1.1 °C. Basic creep is the time-dependent increase in strain of a concrete specimen under constant stress in which moisture losses or gains are prevented. Typical creep development with time is shown in Figure 2-1.

2.2.6 Standard Moist Curing and Testing Environment

ASTM C 192 and ASTM C 31 prescribe standard moist curing. Standard curing described in ASTM C 192 requires the cylinder to be demoulded at 1~2 days and stored at 23 ± 1.7 °C and a relative humidity of not less than 95 %. ASTM C 31 describes the requirement standard compression test cured under standard condition of 23 ± 1.7°C and 95 % relative humidity. However, ASTM C 512 "Creep of concrete compression" permits curing under different conditions for specific applications. The standard curing in ASTM C 512 can be used for all the specimens in the creep and shrinkage test program, including all the related tests.

2.2.7 Creep Testing

A number of different methods of maintaining constant load over time are employed to test creep in compression. Methods to maintain constant load while the specimen shortens involve weights applied through a pivoted lever system, springs in compression, and hydraulic pressure. Compression spring hydraulic systems are more commonly used than weight systems.

When designing a creep frame it is necessary to size the compression springs so that the load is maintained constant within a few percent over the range of deformations anticipated between scheduled deformation measurements and load adjustments. Stiff steel load plates are needed to limit the effects of the plate deflection on the stress distribution in the specimens.

The load must be uniformly transferred into the specimens so they are subjected to uniaxial compression only. In a typical creep frame this is accomplished by centering the specimens and by having one end of the loading system hinged. The hinged end can be comprised of a ball-seated block, a spherical seated block or a swivel seat. Whatever design is used for the hinged end the important aspect is its ability to rotate under small initial loads and become fixed as load increases.

Various shaped specimens are used to determine creep. Most common are cylindrical or prismatic specimens. In this investigation, cylindrical specimens were used. All creep specimens were subjected to sustained compressive stresses. These stresses were maintained constant by use of one or more coil springs in compression. A portable hydraulic jack applied the desired load. After loading, the nuts on the tension rods of the load-sustaining apparatus were brought up against the end plates. Upon releasing the load in the jack, the compression in the coil springs and in the specimen is maintained by the tension in the rods.

Creep is considered proportional to applied stress up to about 40% of the compressive strength and most tests are conducted with specimens stressed to between 25 to 35 % of the companion specimens' strength. Therefore, consideration should also be given to specimen size relative to the capacity of the creep test equipment and the strength of concrete. Large test specimens have a slower rate of creep and shrinkage and may require longer time drying and under load than small specimens to obtain adequate test data.

Specimen ends surfaces must be flat and plane. If cylinders are used, as is typically the case in the USA and Canada, the end condition of the cylinders should comply with requirements in ASTM C 39 for compression test specimens. That is, the loaded end surfaces shall be perpendicular to the central axis of the specimen within 0.5' and be plane within 0.050 mm. Specimens can be capped with neat cement, high-strength gypsum plaster or sulphur mortar in accordance to ASTM C 617. Grinding is the best end preparation method for creep testing. The joints between the specimens with ground ends in the creep frame should be sealed to allow radial drying only.

Various size and shape of specimens are used to determine creep. Most common are cylindrical and prismatic specimens. ASTM C 512 requires cylindrical specimens with a diameter of 150 ± 1.6 mm and a length of at least 292 mm.

2.2.8 Shrinkage Testing

Shrinkage specimens must be identical to the creep specimens, must be stored in the same controlled environment as the creep specimens and close to them, have the same surface exposed to the environment, the same gage length, and have deformations measured using the same equipment, and techniques as used on creep specimens. The end surfaces of all the shrinkage specimens should be sealed to allow radial drying only.

2.3 Prediction Methods

For structural design purposes the existing state of knowledge is summarized in the code provisions of ACI 209-93, CEB 1990 Model Code. The provisions of these two codes and the methods proposed by Bazant (B3) and Gardner GL2000 are given in the Appendix.

CHAPTER 3

EXPERIMENTAL WORK AND RESULTS*

3.1 Introduction

*This Chapter describes an ongoing research program at the University of Ottawa to investigate the effects of specimen size and environment on the long-term deformations of loaded and unloaded concrete specimens. All samples were cast from a single batch of Ready Mix Concrete on December 5th 1997. All specimens were cylindrical as shown Figure 3-1~3-2. The variables considered were specimen size (89, 152, 254 and 610 mm in diameter). The storage environments are; inside the temperature-controlled laboratory (uncontrolled humidity), outside (uncontrolled humidity and temperature), in a humidity-controlled room inside the temperature-controlled laboratory, immersed in water and sealed. All specimens were demoulded at 3

* The experimental work was performed by Huh (1998) and sections 3-1 and 3-2 are abstracted from Huh's M.Eng report.

or 4 days depending upon the test program. Some specimens were loaded at 3 or 4 days, other specimens at 25 days and a few specimens at 200 days. To investigate the effect of evaporable water on creep some specimens were allowed to dry, then sealed and loaded. Same diameter companion shrinkage specimens were available for all creep specimens. Not all specimens survived and not all measurements can be relied upon. A total of sixty-one 89 mm diameter specimens, twelve 152 mm diameter specimens, twelve 254 mm diameter specimens, two 610 mm diameter specimens and eighty standard cylinders were cast. All specimens were cast from the same batch of concrete. To avoid the problem of shrinkage being measured along a centerline and creep being measured at the surface all strain measurements were taken using 150mm cast in place vibrating wire strain gauges located on the specimen centerline.

RILEM TC 107 recommends that shrinkage specimens should have a length of two diameters outside the gauge length but ASTM only requires a total specimen length of two diameters, typically 300 mm and gauge length of 200 mm. Most reported results used specimens with length diameter ratios of typically three and gauge lengths of 200mm. To verify if it is necessary to use long specimens, replicate shrinkage and creep specimens were cast with end zones outside the gauge length of one diameter and two diameters.

3.2 Number of Test Specimens

As discussed, shrinkage is measured directly from the test specimens, however creep strains are calculated by subtracting the shrinkage strain and the initial, or elastic, strain at loading from the total strain at a given age. A test set is defined as all the specimens needed to determine shrinkage and creep, and cylinders to measure f'_c and E_c

at age of loading and at 28 days. All test specimens in a set should come from the same batch of concrete and be cured under the same conditions.

Concrete strengths were measured immediately after demoulding which was scheduled to be 3 days. Compression cylinders were stored in each environment with the shrinkage and creep specimens. Concrete strengths were measured when the creep specimens were loaded. In addition, standard 28 day compressive strengths were measured on cylinders cured under standard moist cured conditions of 23 °C and 96 ~ 99 % relative humidity.

The 89, 152 and 254 mm diameter specimens were cast in two lengths with non-instrumented end zones of D and 2D, the short specimens were 2 x D + 6″ long (because the strain gauges were 6″ (152mm) long). The long specimens were 4 x D + 6″ long (Figure 3-1~3-2). Because of specimen size, the 610 mm diameter specimens were only cast in one length 3D + 6″ (1930 mm). The specimens, which were 89 mm (3.5″) x 330 mm (2 x 3.5″ +6″) and 89 mm (3.5″) x 460 mm (4 x 3.5″+6″) cylinders, 152mm (6″) x 442 mm (2 x 6″ +6″) and 152 mm (6″) x 747 mm (4 x 6″+6″) cylinders, 254 mm (10″) x 645 mm (2 x 10″ +6″) and 254 mm (10″) x 1153 mm (4 x 10″+6″) cylinders are shown in Figure 3-1, and the 610 mm (24″) x 1930 mm (3 x 24″ +6″) cylinders are shown in Figure 3-2.

3.3 Materials

The nominal compressive strength 30 MPa and 100 mm slump Ready Mixed Concrete was supplied by CBM (local company in Ottawa). The mix properties were

760 kg fine aggregate, 1100 kg coarse aggregate, 260 kg type 10 cement, 155 kg water, 65 kg slag, 250 ml retarder and 65 ml air content admixture were used.

3.4 Testing Apparatus

Figures 3-3 to 3-6 show creep frames with a system of one to three compression springs to maintain load that was initially applied and periodically adjusted, using a hydraulic jack. The two types of creep frame used for the 89 mm specimens are shown in Figures 3-3 and 3-4. Figure 3-5 shows the 152 mm creep frame and Figure 3-6 shows the 254 mm creep frame. In the 610 mm diameter creep frame shown in Figure 3-7, the load is applied and maintained by hydraulic pressure.

In this investigation, cylindrical specimens were used. All creep specimens were subjected to sustained compressive stresses. These stresses were maintained constant by use of one or more coil springs in compression. A portable hydraulic jack were applied the desired load. After loading, the nuts on the tension rods of the load-sustaining apparatus were brought up against the end plates. Upon releasing the load in the jack, the compression in the coil spring and in the specimen was maintained by the tension in the rods. For the test program, creep specimens were subjected to compressive loads of approximately 14 to 22 % of strength at age of loading as shown in Tables 3-1 to 3-4.

All test specimen ends surfaces must be flat and plane. The ends of the 89 and 152 mm diameter creep specimens and compression cylinders were ground. However, the ends of the 254 and 610 mm diameter creep specimens were too large to be ground and were capped with cement grout.

3.5 Casting and Curing Procedure

Sixty-one 89 mm diameter specimens, twelve 152 mm diameter specimens, twelve 254 mm diameter specimens, and two 610 mm diameter specimens were cast as indicated in Tables 3-1 to 3-4. Measured slump (ASTM C143) varied from 80 mm to 55 mm during the casting period. Casting took three hours. The temperature of the fresh concrete was measured by inserting a thermometer into the concrete. The temperature of the fresh concrete was 20±1°C. Eighty standard compression test cylinders were also cast.

All 89 mm diameter concrete specimens were cast in plastic moulds and paper moulds were used for the 152, 254, and 610mm cylinders to enable rapid demoulding at very early ages without disturbing the concrete samples. All of the concrete specimens were vibrated in accordance with ASTM C 31. The 89 mm diameter specimens were vibrated on a vibration table and the 152, 254 and 610 mm diameter specimens were vibrated using a poker-vibrator.

After filling, the molds were covered by wet burlap and polyethylene sheet to minimize evaporation. The burlap was rewetted every 24 hours. The specimens were demoulded 3 days/4 days after casting. Demoulding the large number of specimens and standard cylinders took about 2 days by an average of 4 workers. After stripping, the specimens were moved to the five chosen environments, which were the lab, the 50 % RH room, the water tank, a moist-curing room, and outside the building.

3.6 Storage Environment

Creep and shrinkage are dependent on the environment, temperature and humidity to which the concrete is exposed. Controlling and monitoring the temperature and relative humidity during testing is extremely important.

Two conditions define the testing environment.

- Temperature and humidity of the testing environment, and
- The durations specimens are in a specific environment.

Testing environments are standardised. However, since the possible combinations of environments are many, minimising the number of environments in a test program must be given strong consideration during the planning stage.

To examine the significance of size and storage environment on the concrete, some specimens were moved to other environments. The various curing/storage schedules are given in Tables 3-1~3-4. In general a set of specimens consisted of one long and one short specimen of the same diameter.

3.6.1 Environment of Temperature-controlled Laboratory

- 89, 152 and 254 mm diameter specimens were stored in the structural laboratory at the University of Ottawa.
- The two 610 mm diameter specimens were stored in the structural laboratory.
- Six 89 mm diameter specimens were moist cured after demoulding for 24 days before being moved to the temperature-controlled laboratory.

3.6.2 Outside Environment

- 89, 152 and 254 mm diameter specimens were stored outside the Engineering Building
- Three 89 mm diameter specimens were moist cured 24 days after demoulding and moved outside.

3.6.3 Immersed Environment

- Four sets of 89 mm diameter specimens were demoulded at three days, two specimens were loaded and all eight specimens were stored in the water tank. Two of the non-loaded specimens were loaded at 14 days and two were loaded at 200 days.

3.6.4 Environment of 50 % RH Room

- Sets of 89, 152 and 254 mm specimens were maintained at 50 % relative humidity.
- Four 89 mm diameter specimens were stored under standard moist curing conditions after demoulding and moved to the 50% humidity-controlled room after 24 or 25 days.
- Two 89 mm diameter specimens were stored under standard moist cured condition after demoulding and moved to the 50% humidity-controlled room after 200 days.

3.6.5 Sealed Specimens

To prevent the gain or loss of water during the storage and test period, some specimens at the time of stripping were enclosed and sealed in moisture-proof jackets to avoid loss of moisture by evaporation and remained sealed throughout the period of storage and testing. The descriptions are given in Table 3-4:

- Seven 89 mm diameter sealed specimens were stored in a controlled humidity room with 50 % relative humidity immediately after demoulding.
- Four 89 mm diameter specimens were stored in a standard moist curing room after demoulding until 25 days, sealed and then maintained in the controlled humidity room with 50 % of relative humidity.
- Four 89 mm diameter specimens were stored in a controlled humidity room with 50 % relative humidity after demoulding and sealed at 25 days and then maintained in the controlled humidity room at 50 % relative humidity.
- Three 89 mm diameter specimens were stored in a controlled humidity room with 50 % of relative humidity after demoulding, sealed at 200 days and then maintained in the 50 % relative humidity controlled humidity room.

3.7 Control Specimens and Measuring Deformations

Shrinkage specimens must be identical to the creep specimens, stored in the same environment as the creep specimens and close to them, have the same surface area exposed to the environment, the same gauge length, and have their deformations measured using the same equipment, and technique as used for the creep specimens. The end surfaces of shrinkage specimens should be sealed to allow radial drying only.

Measuring creep and shrinkage deformations is complicated by the extended time period over which the measurements are taken and by the relatively small deformation increments. Creep tests are, at a minimum, run for months and are often run for periods of years. Thus, whatever measurement system is used, there is a need for long-term stability. Furthermore, the later age deformation change between subsequent readings may be as small as approximately 0.003 mm (6×10^{-6} in.) for a specimen with a gauge length of 152 mm (6 in.). In addition to stability and precision, repeatability is needed also in the deformation measurement system.

A primary advantage of electronic transducers is that data can be collected easily. Long-term stability is the most important criterion in selecting electronic transducers since it is often not possible to calibrate or standardise these instruments after they have been attached to, or cast in the concrete. Vibrating wire strain gauges have been successfully used in many field studies and were used by this project. For gauges cast in the test specimens it is important that they are centred and aligned with the applied stress and, to the extent possible, have similar stiffness to the concrete. Temperature was measured by transducers incorporated in the vibrating wire gauges on the centre lines of the concrete specimens.

3.8 Strength Tests

A minimum of three cylinders was used to measure modulus of elasticity and compressive strength at age of every loading (typically 3, 13, 28 and 200 days) for each environment condition. The ends of 150 mm x 300 mm cylinders were grounded. The crushing strength of the concrete was taken as the average of the results in accordance with ASTM C39. In addition, the deformation of the specimen over the gauge length of 203 mm (8 in.) in the direction of loading was also measured during the compression tests using the compressometer equipped with the dial gauge essentially as described by ASTM C469.

Compressometers with mechanical (analogue) or digital dial gauges are used to measure strain on gauge points mounted on the surface of the specimen. For this project, a typical compressometer, which is equipped with a digital dial gauge reading is 203 mm

(8 in.) between gauge points on a 150 x 300 mm (6 x 12 in.) creep test specimen, was used. The compressive strength tests were carried out in a standard test machine. The average of three results of three compression tests at age of every loading is plotted in the Figure 3-8.

3.9 Measured Total Strains and Temperature

Tables 3-5 to 3-6 show the specifications of specimens according to the increase of their numbers for creep and shrinkage separately. Figures 3-9 to 3-27 present the measured strains. Figures 3-28 and 3-29 show the temperature of the outside environment at different ages. The temperature was not monitored continuously, it was only measured when strains were measured.

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)
Moist cured for 3 days	89 x 330 (Shrinkage) 89 x 330 (Creep) 89 x 460 (Shrinkage)	1 7 (24 days) 48
	89 x 460 (Creep)	56 (4 days) 31, 66 (24 days)
Moist cured for 24 days	89 x 330 (Shrinkage) 89 x 330 (Creep) 89 x 460 (Shrinkage)	17 21 (28 days) 46, 60
	89 x 460 (Creep)	26 (25 days) 37 (28 days)
Moist cured for 3 days	152 x 442 (Shrinkage) 152 x 442 (Creep) 152 x 747 (Shrinkage) 152 x 747 (Creep)	68 66 (24 days) 72 76 (24 days)
Moist cured for 3 days	254 x 645 (Shrinkage) 254 x 645 (Creep) 254 x 1153 (Shrinkage) 254 x 1153 (Creep)	79 80 (24 days) 86 88 (24 days)
Moist cured for 3 days	610 x 1930 (Shrinkage) 610 x 1930 (Creep)	111~116* 101~106* (25 days)

Table 3-1: Detail of Specimens in the Lab

* strain gauge No. detailed in Figure 3-2

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)
Moist cured for 3 days	89 x 330 (Shrinkage)	18
	89 x 330 (Creep)	12 (3 days) 20 (13 days) 64 (200 days)
	89 x 460 (Shrinkage)	28
	89 x 460 (Creep)	29 (3 days) 23 (13 days) 24 (200 days)

Table 3-2: Detail of Specimens Immersed in Water

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)
Moist cured for 3 days	89 x 330 (Creep)	19 (24 days) 14 (201 days)
	89 x 460 (Shrinkage)	39, 40
	89 x 460 (Creep)	53 (4 days) 58 (24 days) 32 (201 days)
Moist cured for 24 days	89 x 330 (Shrinkage) 89 x 460 (Shrinkage) 89 x 460 (Creep)	16 49 61 (24 days)
Moist cured for 3 days	152 x 442 (Shrinkage) 152 x 442 (Creep) 152 x 747 (Shrinkage) 152 x 747 (Creep)	71 67 (24 days) 73 75 (24 days)
Moist cured for 3 days	254 x 645 (Shrinkage) 254 x 645 (Creep) 254 x 1153 (Shrinkage) 254 x 1153 (Creep)	81 78 (201 days) 84 87 (201 days)

Table 3-3: Detail of Specimens stored Outside

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)
Moist cured for 3 days	89 x 330 (Shrinkage)	4
	89 x 330 (Creep)	65 (24 days) 11 (200 days)
	89 x 460 (Shrinkage)	47
	89 x 460 (Creep)	41 (4 days) 44 (24 days) 38 (200 days)
Moist cured for 3 days	152 x 442 (Shrinkage) 152 x 442 (Creep) 152 x 747 (Shrinkage) 152 x 747 (Creep)	70 69 (24 days) 74 77 (24 days)
Moist cured for 3 days	254 x 645 (Shrinkage) 254 x 645 (Creep) 254 x 1153 (Shrinkage) 254 x 1153 (Creep)	82 83 (24 days) 85 89 (24 days)
Moist cured for 24/25 days	89 x 330 (Shrinkage) 89 x 330 (Creep) 89 x 460 (Shrinkage) 89 x 460 (Creep)	15 2 (25 days) 13 (200 days) 27 59 (25 days)
Moist cured for 200 days	89 x 460 (Shrinkage) 89 x 460 (Creep)	55 42 (200 days)
Moist cured for 25 days & sealed	89 x 330 (Shrinkage) 89 x 460 (Shrinkage) 89 x 460 (Creep)	5 30 50 (25 days)
Moist cured for 3 days & sealed 25 days	89 x 330 (Shrinkage) 89 x 330 (Creep) 89 x 460 (Shrinkage) 89 x 460 (Creep)	6 3 (25 days) 45 35 (25 days)
Moist cured for 3 days & sealed 200 days	89 x 330 (Shrinkage) 89 x 330 (Creep) 89 x 460 (Shrinkage) 89 x 460 (Creep)	10 9 (200 days) 52 36 (200 days)
Moist cured for 3 days & sealed 3 days	89 x 330 (Shrinkage)	22, 62
	89 x 330 (Creep)	63 (28 days) 8 (200 days)
	89 x 460 (Shrinkage)	25
	89 x 460 (Creep)	33 (28 days) 54 (200 days)

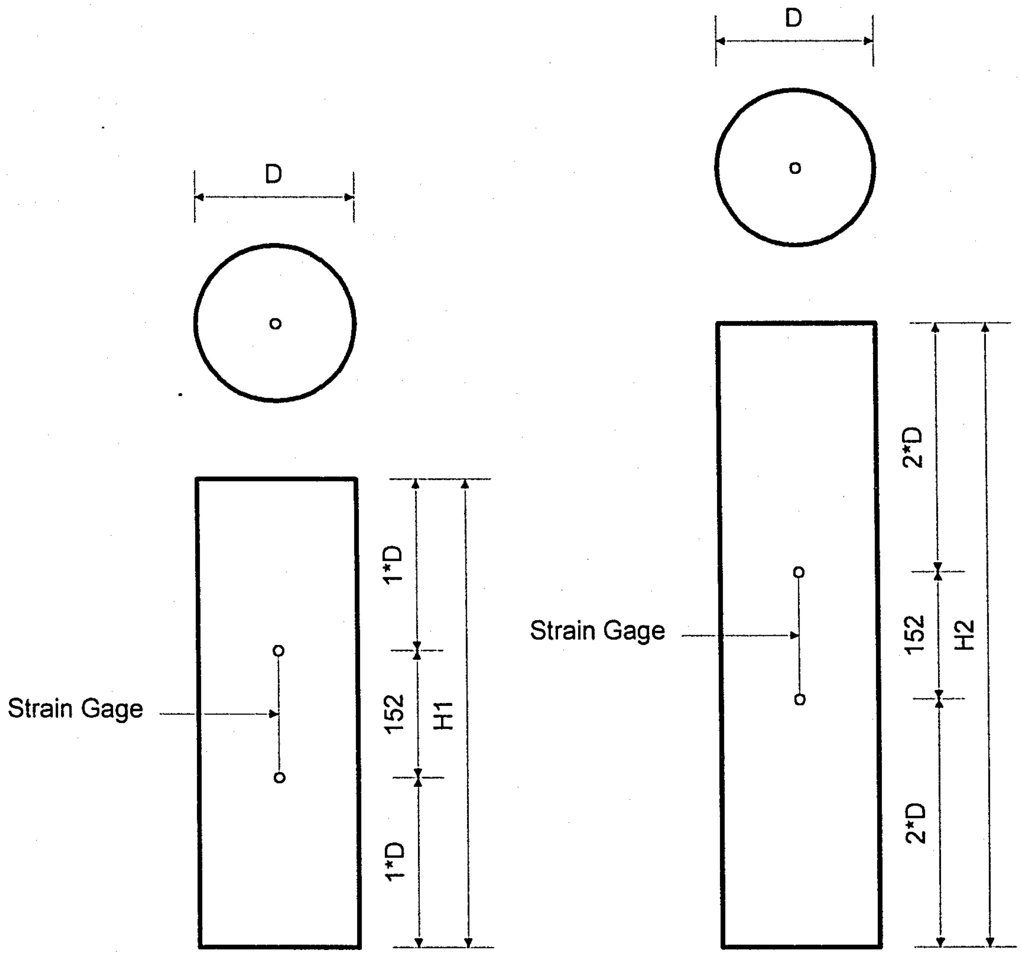
Table 3-4: Detail of Specimens in 50 % RH

Table 3-5: Specifications of Shrinkage Specimens

No of Specimen	Size of Specimen (mm)	Short or Long	Moist Cured (Days)	Sealed after (Days)	Environment
1	89*330	SHORT	3	-	LAB
4	89*330	SHORT	3	-	TENT
5	89*330	SHORT	25	S25	TENT
6	89*330	SHORT	3	S25	TENT
10	89*330	SHORT	3	S200	TENT
15	89*330	SHORT	24/25	-	TENT
16	89*330	SHORT	24	-	OUTSIDE
17	89*330	SHORT	24	-	LAB
18	89*330	SHORT	3	-	IMMERSED
22	89*330	SHORT	3	S3	TENT
25	89*460	LONG	3	S3	TENT
27	89*460	LONG	24/25	-	TENT
28	89*460	LONG	3	-	IMMERSED
30	89*460	LONG	25	S25	TENT
39	89*460	LONG	3	-	OUTSIDE
40	89*460	LONG	3	-	OUTSIDE
45	89*460	LONG	3	S25	TENT
46	89*460	LONG	24	-	LAB
47	89*460	LONG	3	-	TENT
48	89*460	LONG	3	-	LAB
49	89*460	LONG	24	-	OUTSIDE
52	89*460	LONG	3	S200	TENT
55	89*460	LONG	200	-	TENT
60	89*460	LONG	24	-	LAB
62	89*330	SHORT	3	S3	TENT
68	152*442	SHORT	3	-	LAB
70	152*442	SHORT	3	-	TENT
71	152*442	SHORT	3	-	OUTSIDE
72	152*747	LONG	3	-	LAB
73	152*747	LONG	3	-	OUTSIDE
74	152*747	LONG	3	-	TENT
79	254*645	SHORT	3	-	LAB
81	254*645	SHORT	3	-	OUTSIDE
82	254*645	SHORT	3	-	TENT
84	254*1153	LONG	3	-	OUTSIDE
85	254*1153	LONG	3	-	TENT
86	254*1153	LONG	3	-	LAB
111	610*1930	LONG	3	-	LAB
112	610*1930	LONG	3	-	LAB
113	610*1930	LONG	3	-	LAB
114	610*1930	LONG	3	-	LAB
115	610*1930	LONG	3	-	LAB
116	610*1930	LONG	3	-	LAB

Table 3-6: Specifications of Creep Specimens

No of Specimen	Size of Specimen (mm)	Short or Long	Moist Cured (Days)	Age of Loading (Days)	Sealed after (Days)	Environment
2	89*330	SHORT	24/25	L25	-	TENT
3	89*330	SHORT	3	L25	S25	TENT
7	89*330	SHORT	3	L24	-	LAB
8	89*330	SHORT	3	L200	S3	TENT
9	89*330	SHORT	3	L200	S200	TENT
11	89*330	SHORT	3	L200	-	TENT
12	89*330	SHORT	3	L3	-	IMMERSED
13	89*330	SHORT	24/25	L200	-	TENT
14	89*330	SHORT	3	L201	-	OUTSIDE
19	89*330	SHORT	3	L24	-	OUTSIDE
20	89*330	SHORT	3	L13	-	IMMERSED
21	89*330	SHORT	24	L28	-	LAB
23	89*460	LONG	3	L13	-	IMMERSED
24	89*460	LONG	3	L200	-	IMMERSED
26	89*460	LONG	24	L25	-	LAB
29	89*460	LONG	3	L3	-	IMMERSED
31	89*460	LONG	3	L24	-	LAB
32	89*460	LONG	3	L201	-	OUTSIDE
33	89*460	LONG	3	L28	S3	TENT
35	89*460	LONG	3	L25	S25	TENT
36	89*460	LONG	3	L200	S200	TENT
37	89*460	LONG	24	L28	-	LAB
38	89*460	LONG	3	L200	-	TENT
41	89*460	LONG	3	L4	-	TENT
42	89*460	LONG	200	L200	-	TENT
44	89*460	LONG	3	L24	-	TENT
50	89*460	LONG	25	L25	S25	TENT
53	89*460	LONG	3	L4	-	OUTSIDE
54	89*460	LONG	3	L200	S3	TENT
56	89*460	LONG	3	L4	-	LAB
58	89*460	LONG	3	L24	-	OUTSIDE
59	89*460	LONG	24/25	L25	-	TENT
61	89*460	LONG	24	L24	-	OUTSIDE
63	89*330	SHORT	3	L28	S3	TENT
64	89*330	SHORT	3	L200	-	IMMERSED
65	89*330	SHORT	3	L24	-	TENT
66	152*442	SHORT	3	L24	-	LAB
67	152*442	SHORT	3	L24	-	OUTSIDE
69	152*442	SHORT	3	L24	-	TENT
75	152*747	LONG	3	L24	-	OUTSIDE
76	152*747	LONG	3	L24	-	LAB
77	152*747	LONG	3	L24	-	TENT
78	254*645	SHORT	3	L201	-	OUTSIDE
80	254*645	SHORT	3	L24	-	LAB
83	254*645	SHORT	3	L24	-	TENT
87	254*1153	LONG	3	L201	-	OUTSIDE
88	254*1153	LONG	3	L24	-	LAB
89	254*1153	LONG	3	L24	-	TENT
101	610*1930	LONG	3	L25	-	LAB
102	610*1930	LONG	3	L25	-	LAB
103	610*1930	LONG	3	L25	-	LAB
104	610*1930	LONG	3	L25	-	LAB
105	610*1930	LONG	3	L25	-	LAB
106	610*1930	LONG	3	L25	-	LAB



D (mm)	H1 (mm)	H2 (mm)
89	330	460
152	442	747
254	645	1153

Figure 3-1: Dimension of 89 mm, 152 mm and 254 mm Diameter Specimens

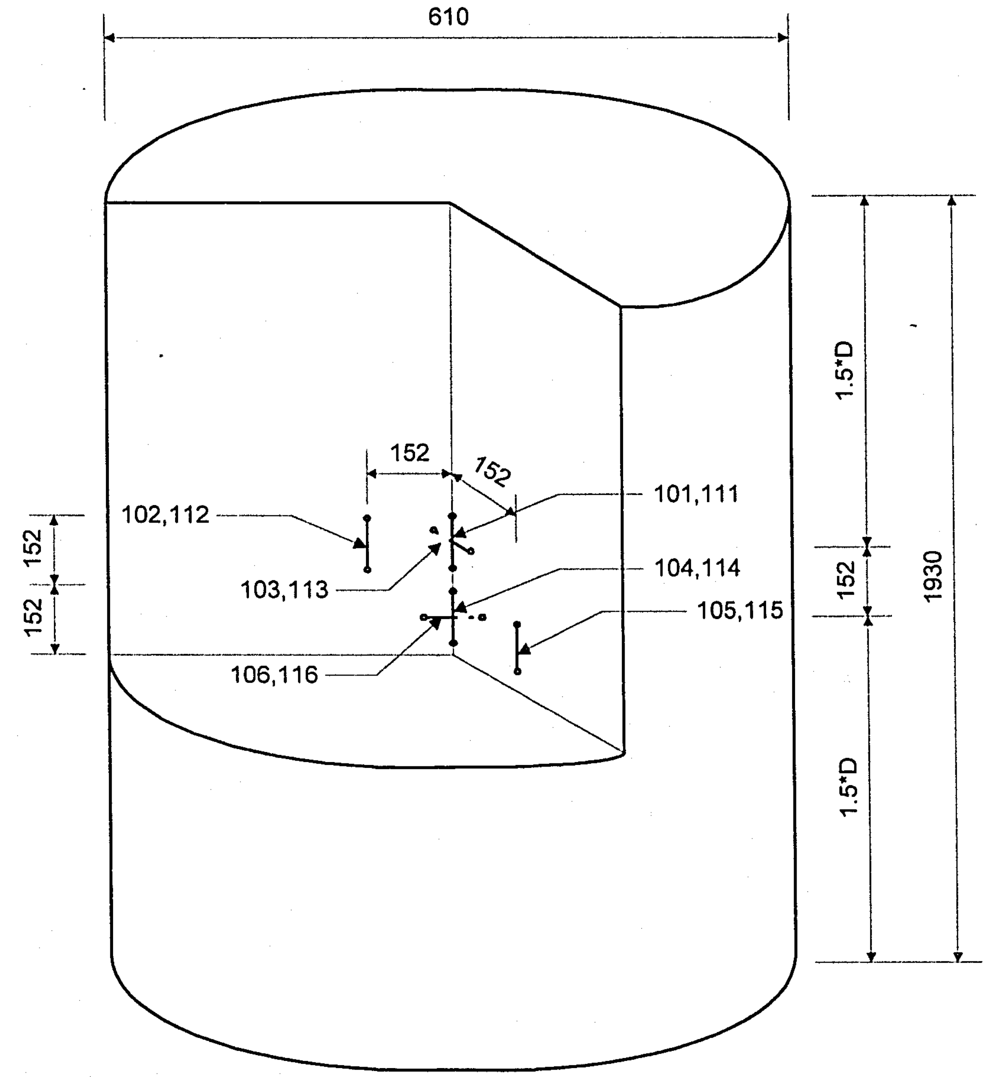


Figure 3-2: Detail of Strain Gauges Location of 610 mm Diameter Specimens

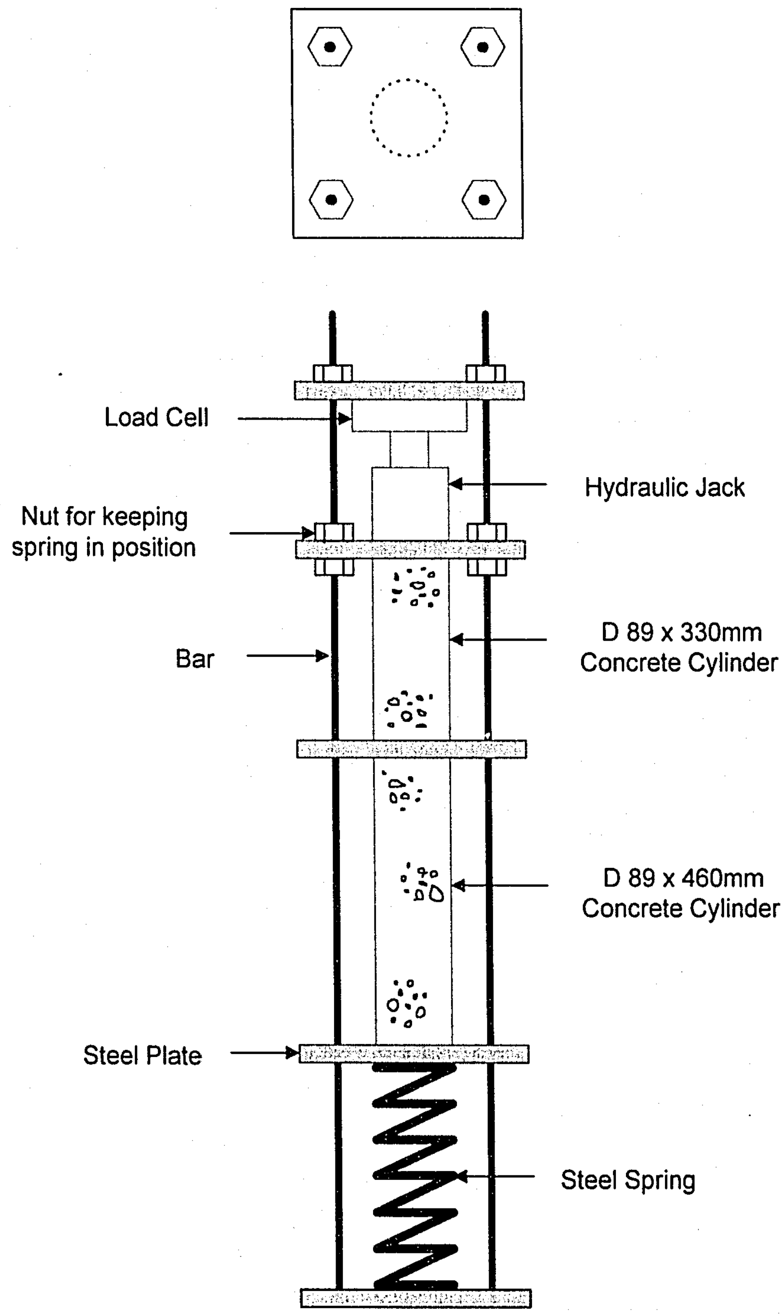


Figure 3-3: Detail of 89 mm Diameter Specimens Creep Frame Type1

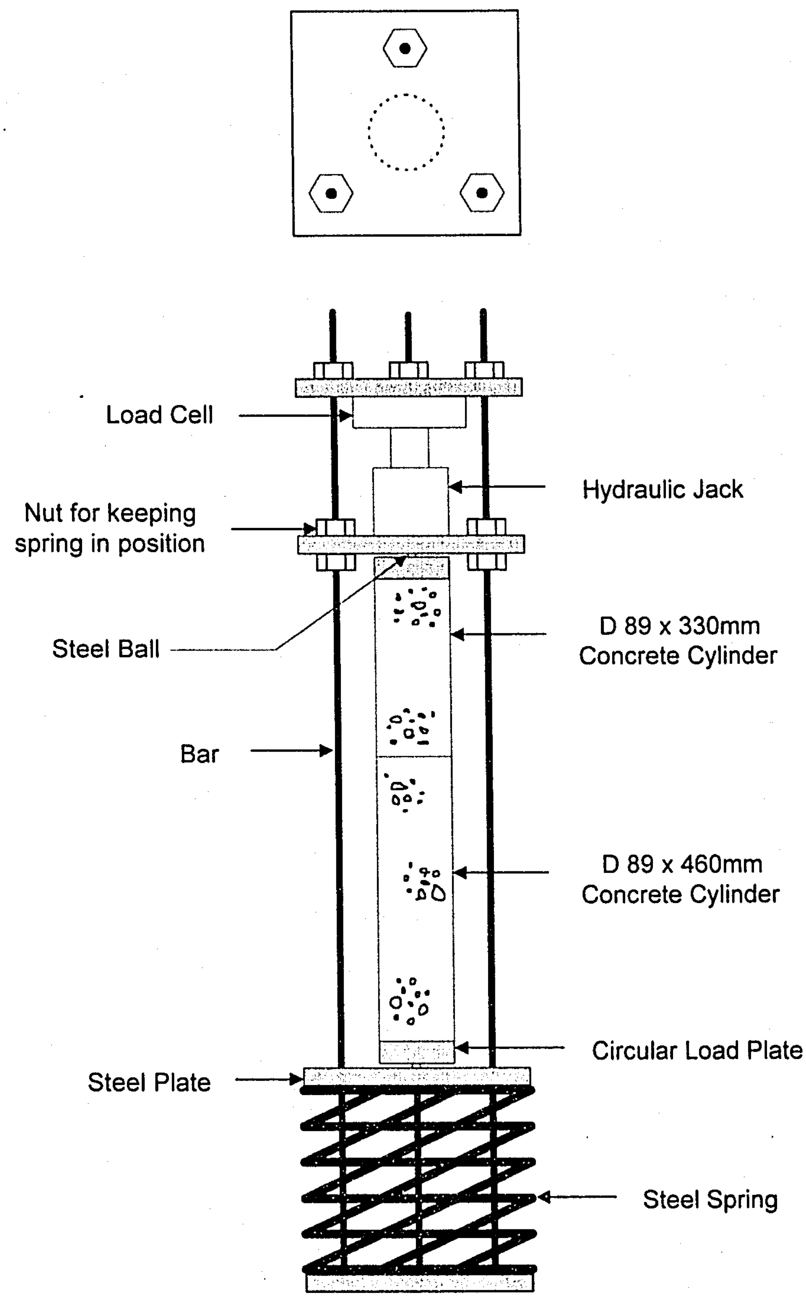


Figure 3-4: Detail of 89 mm Diameter Specimens Creep Frame Type 2

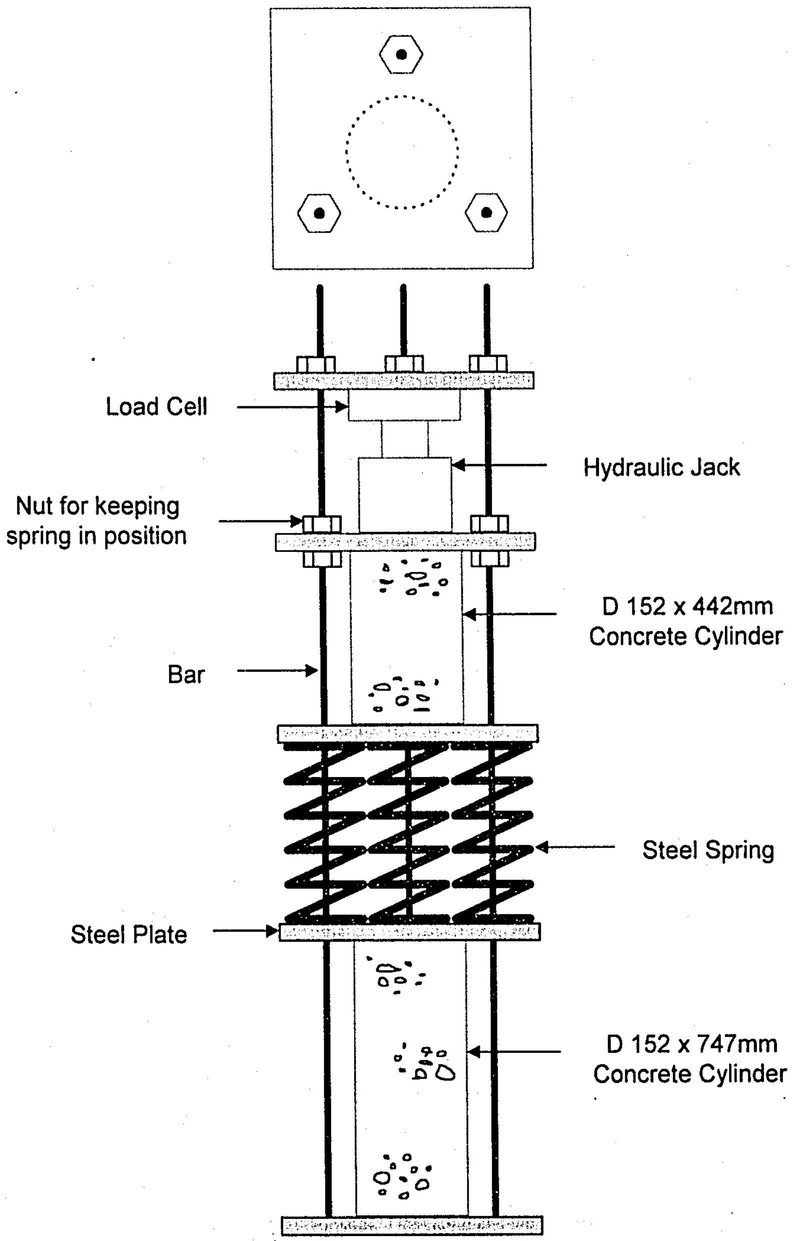


Figure 3-5: Detail of 152 mm Diameter Specimens Creep Frame

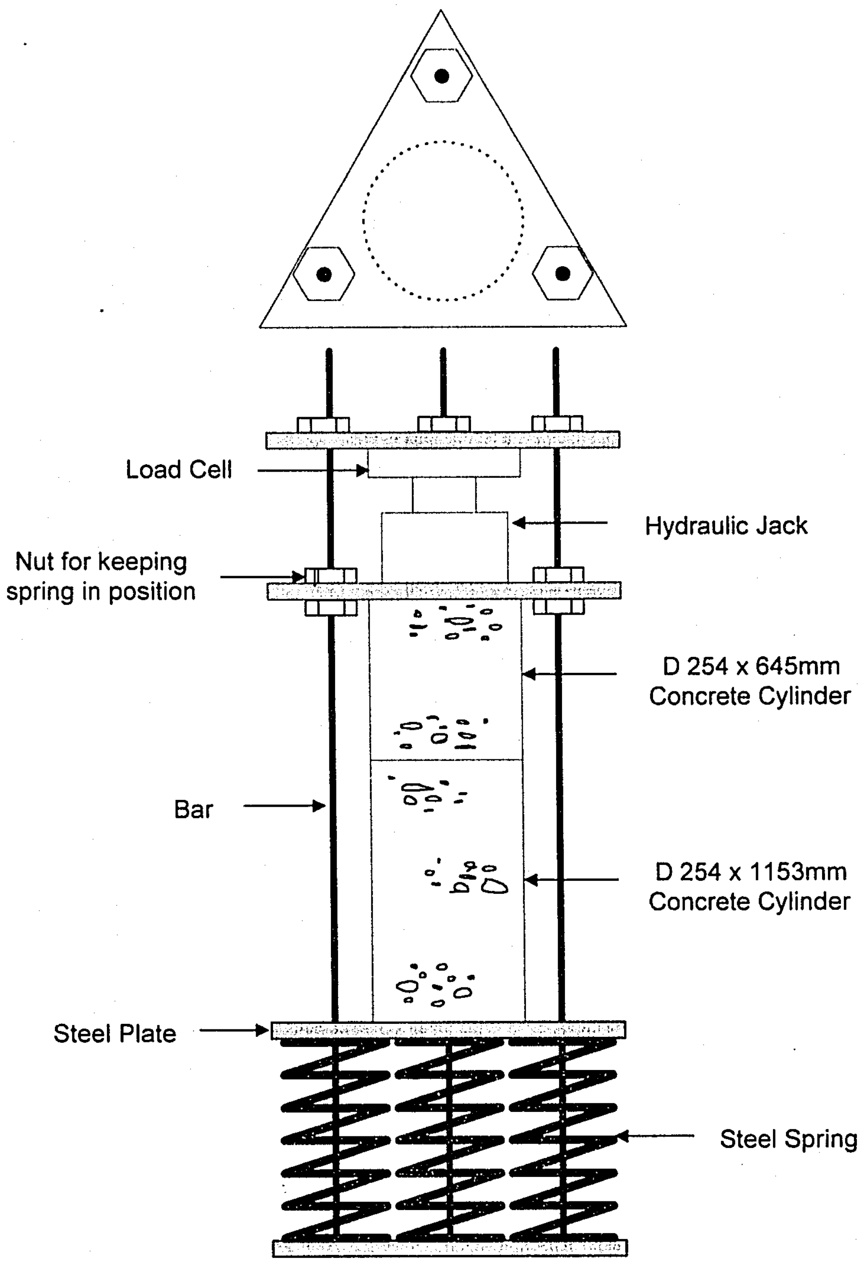


Figure 3-6: Detail of 254 mm Diameter Specimens Creep Frame

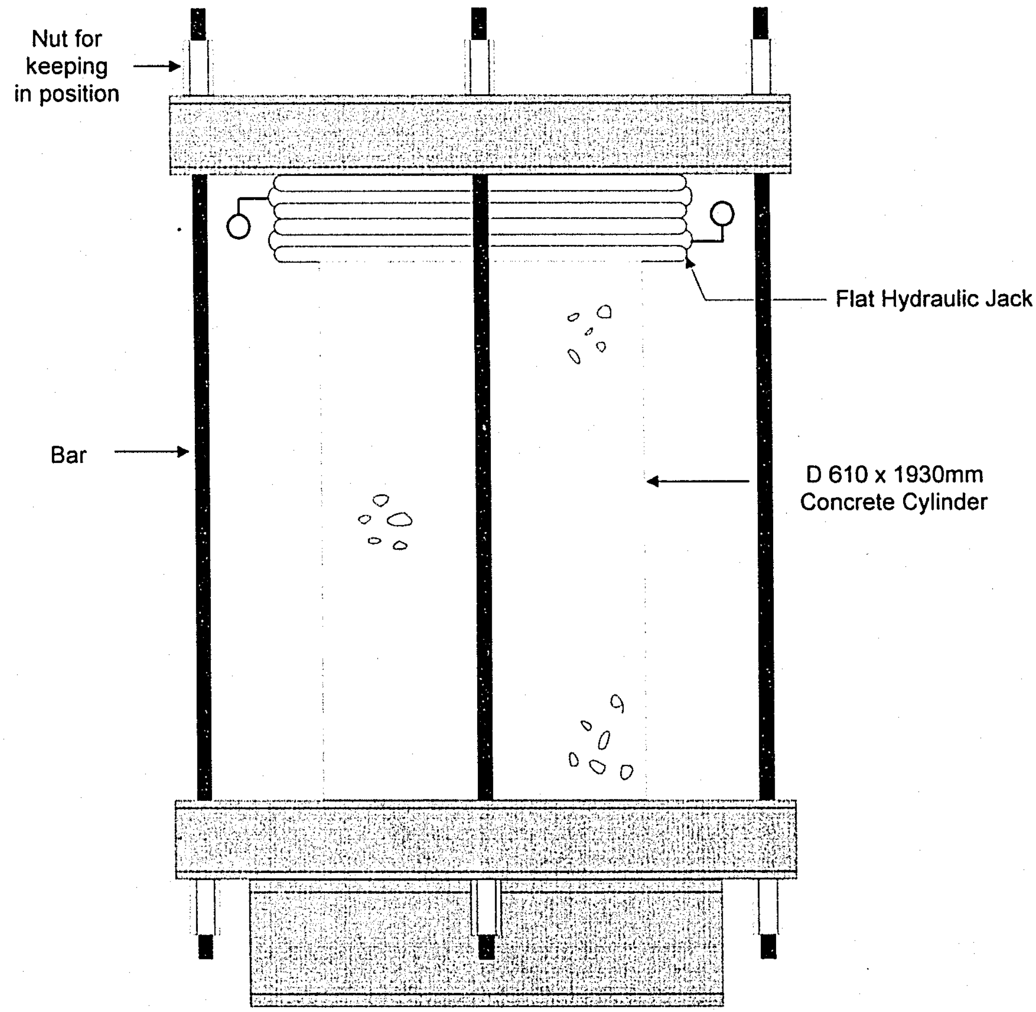


Figure 3-7: Detail of 610 mm Diameter Specimens Creep Frame

Figure 3-8: Compressive strength of at age of loading with various environment

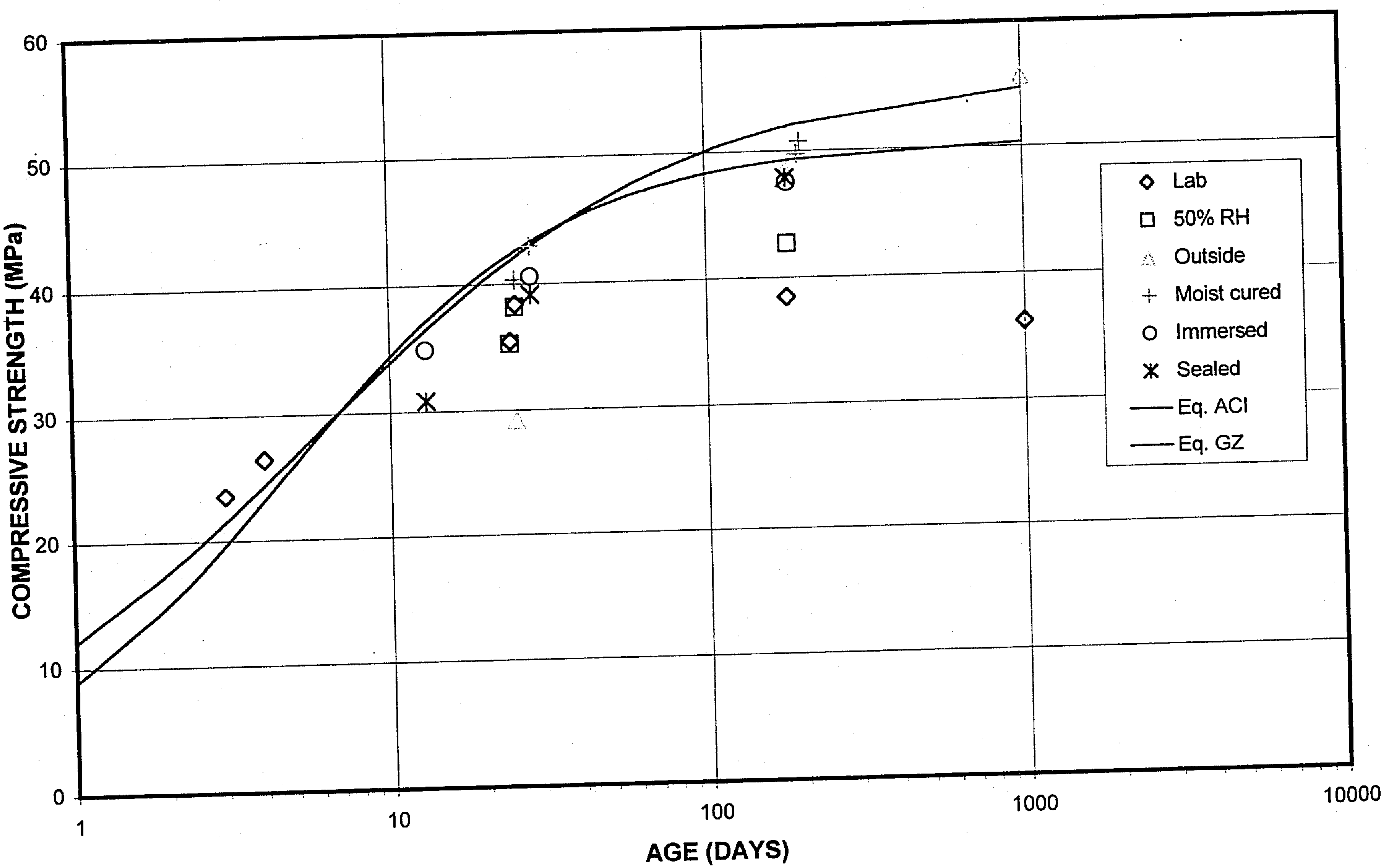


Figure 3-9: Total Strain of 89 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 56 loaded at 3 days, Specimen 7 &31 loaded at 24 days

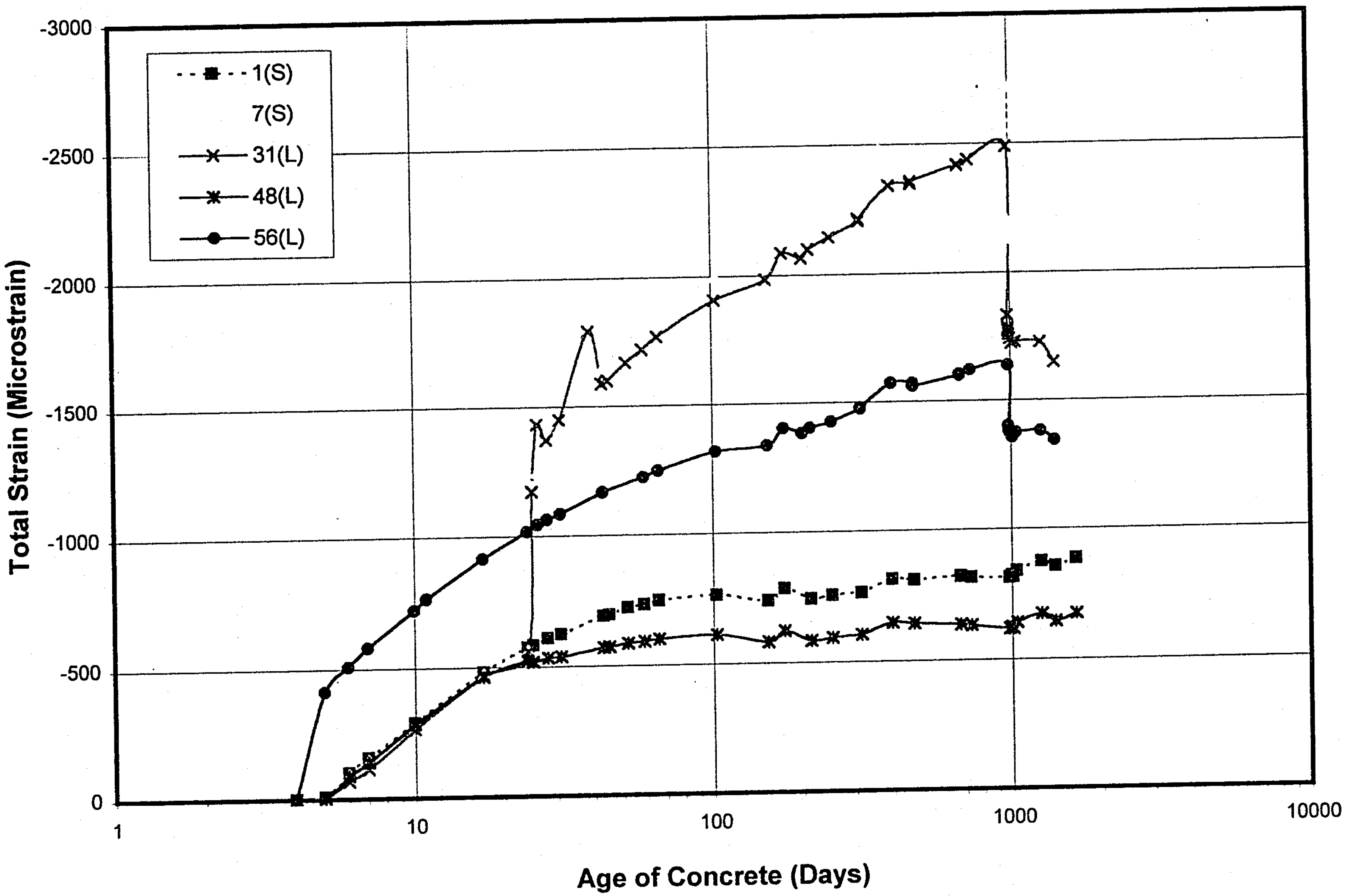


Figure 3-10: Total Strain of 89 mm Specimens in Lab Environment, Moist cured 24 days
Specimen 26 loaded at 25 days, Specimen 21 & 37 loaded at 28 days

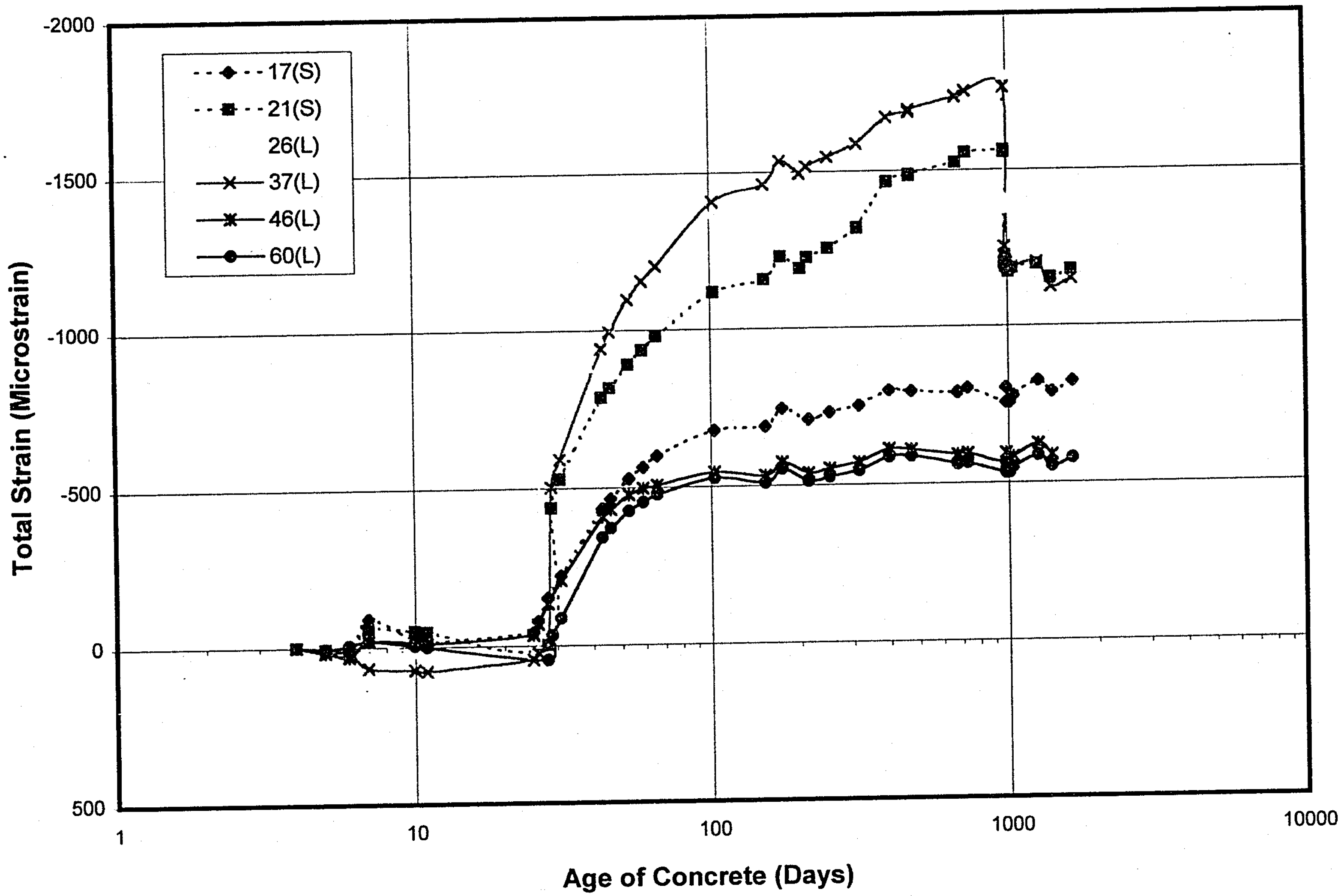


Figure 3-11: Total Strain of 152 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 66 & 76 loaded at 24 days

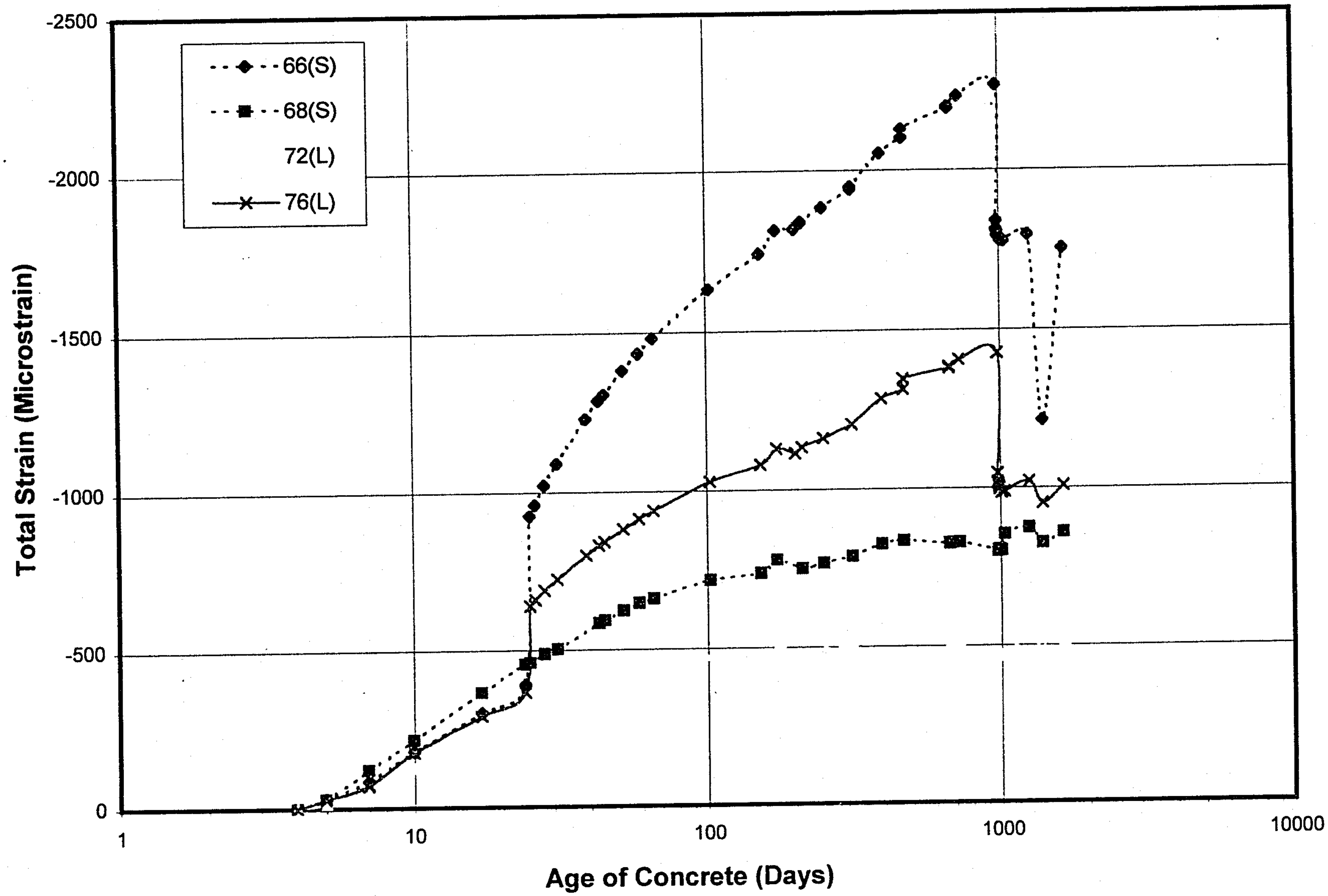


Figure 3-12: Total Strain of 254 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 80 & 88 loaded at 24 days

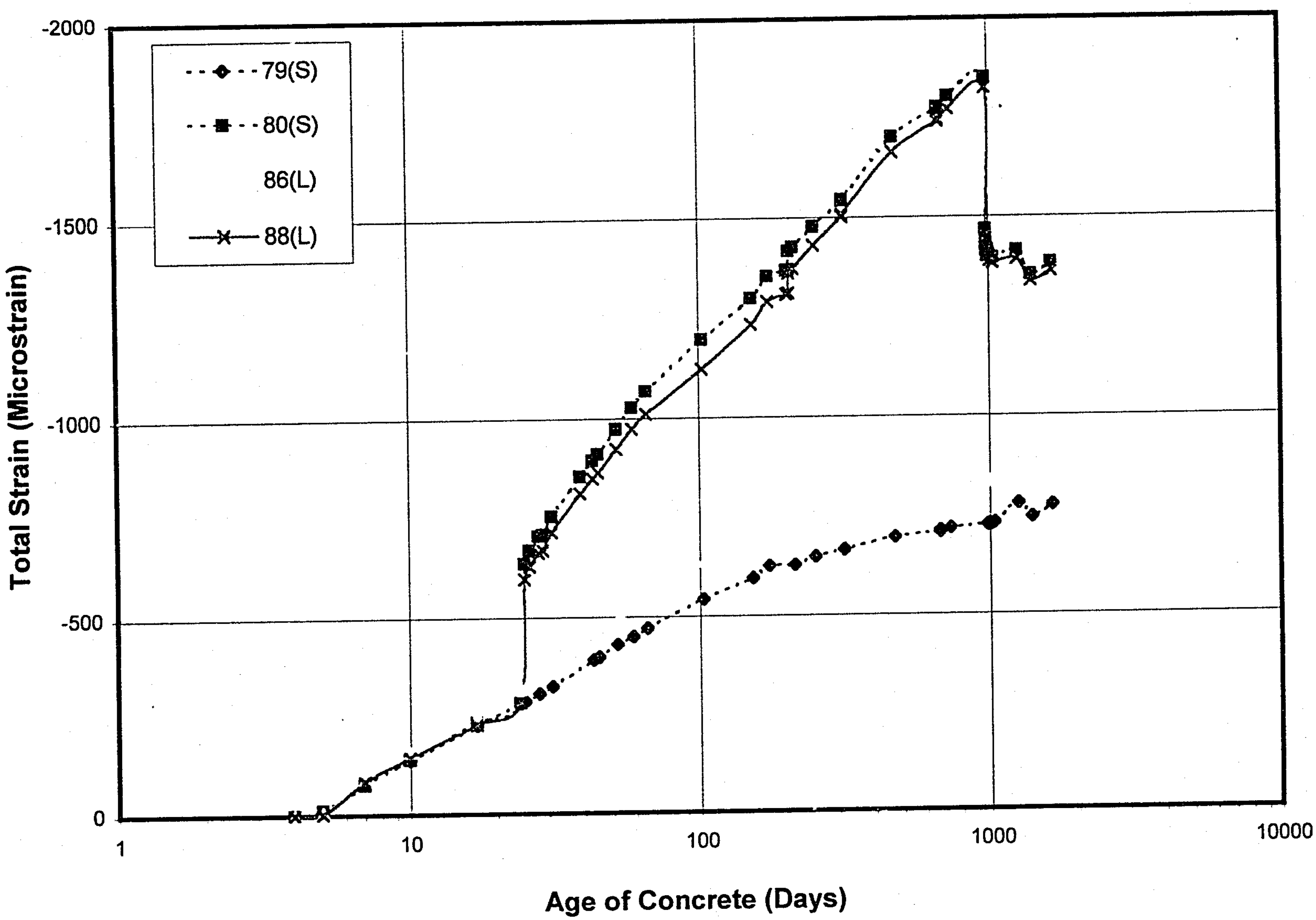


Figure 3-13: Total Strain of 610 mm Specimens in Lab Environment, Moist cured 3 days
Specimens 101~106 loaded at 25 days

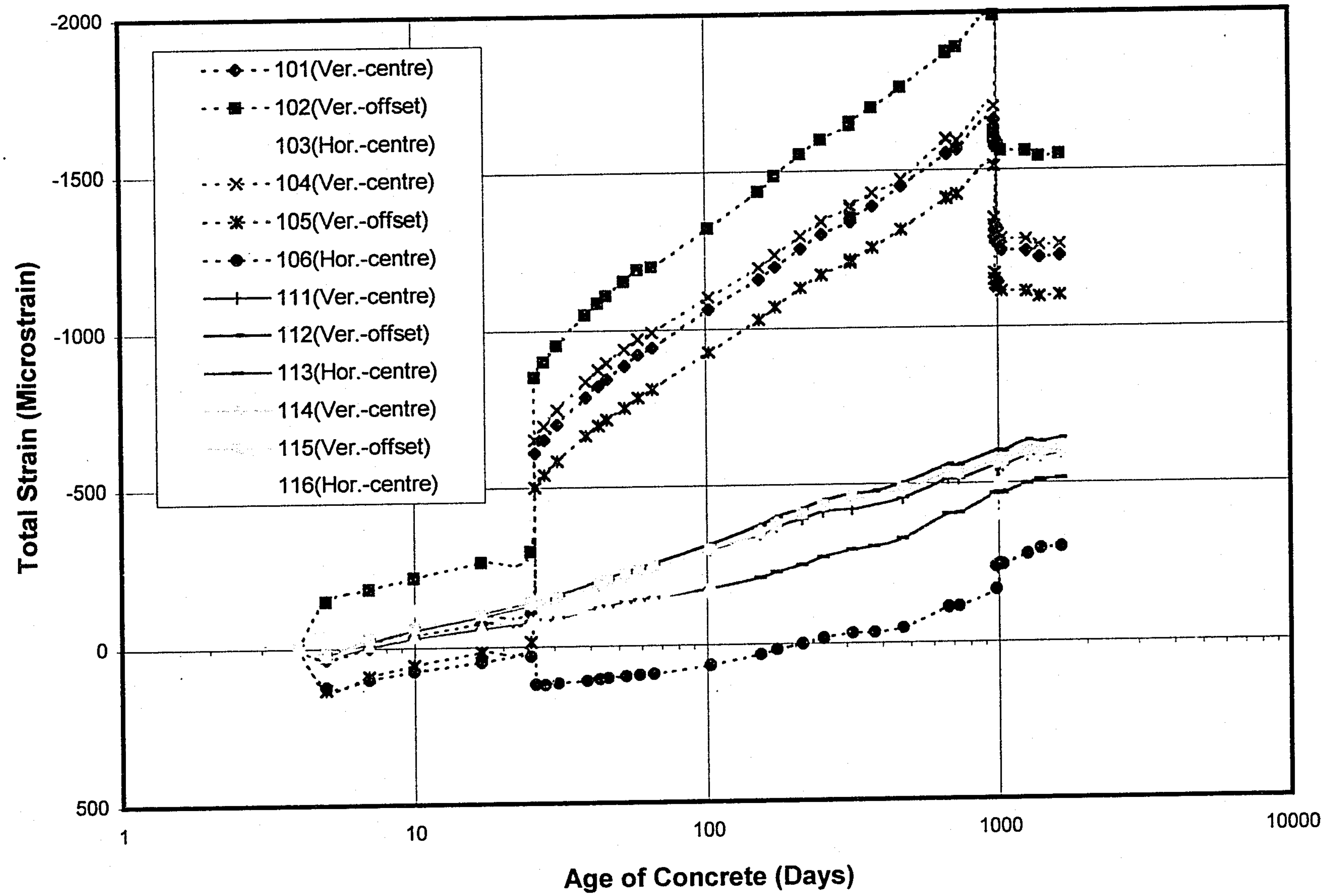


Figure 3-14: Total Strain of 89 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 53 loaded at 4 days, Specimen 19 & 58 loaded at 24 days, Specimen 14 & 32 loaded at 201 days

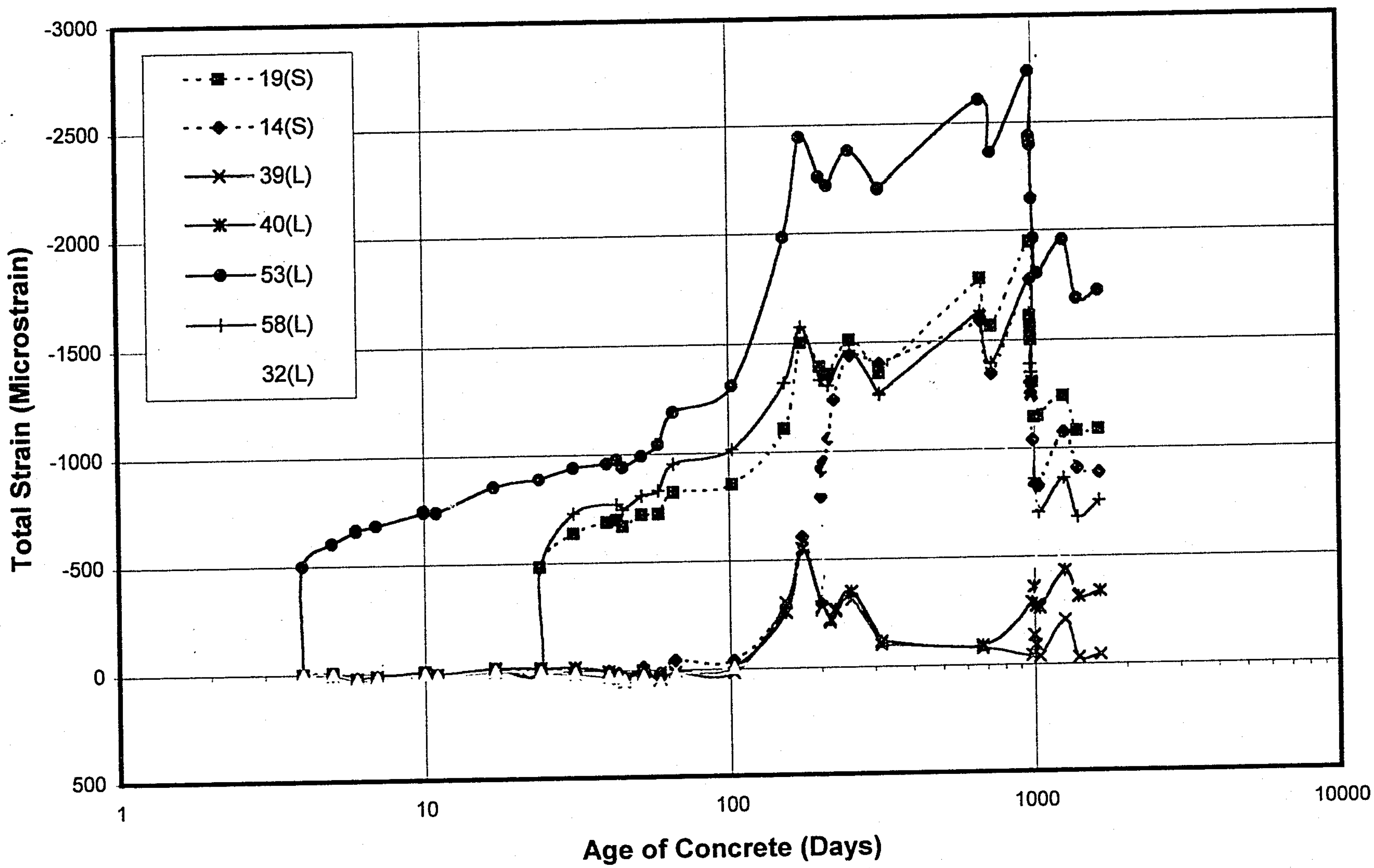


Figure 3-15: Total Strain of 89 mm Specimens Outdoor Environment, Moist cured 24 days
Specimen 61 loaded at 24 days

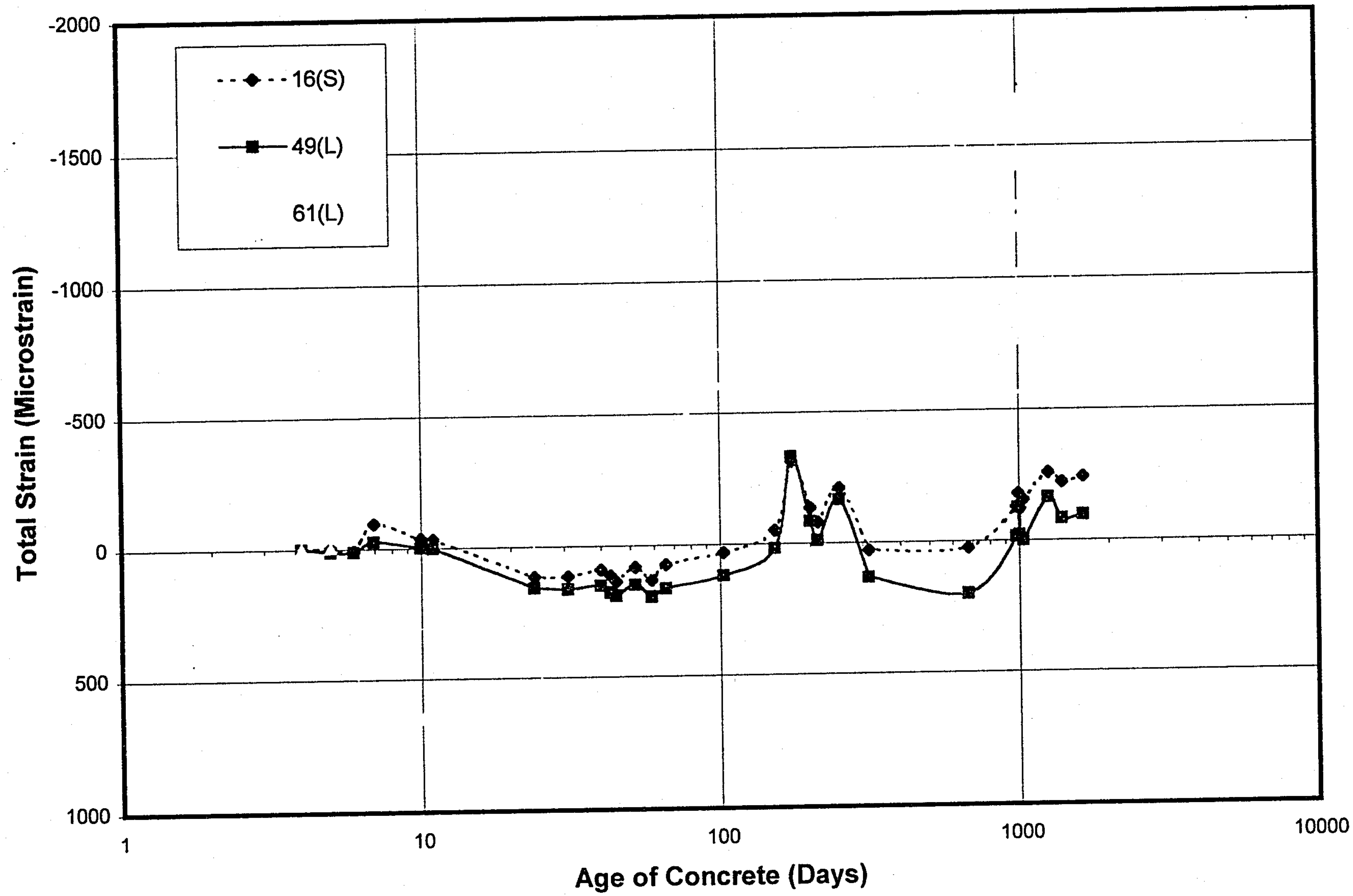


Figure 3-16: Total Strain of 152 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 67 & 75 loaded at 24 days

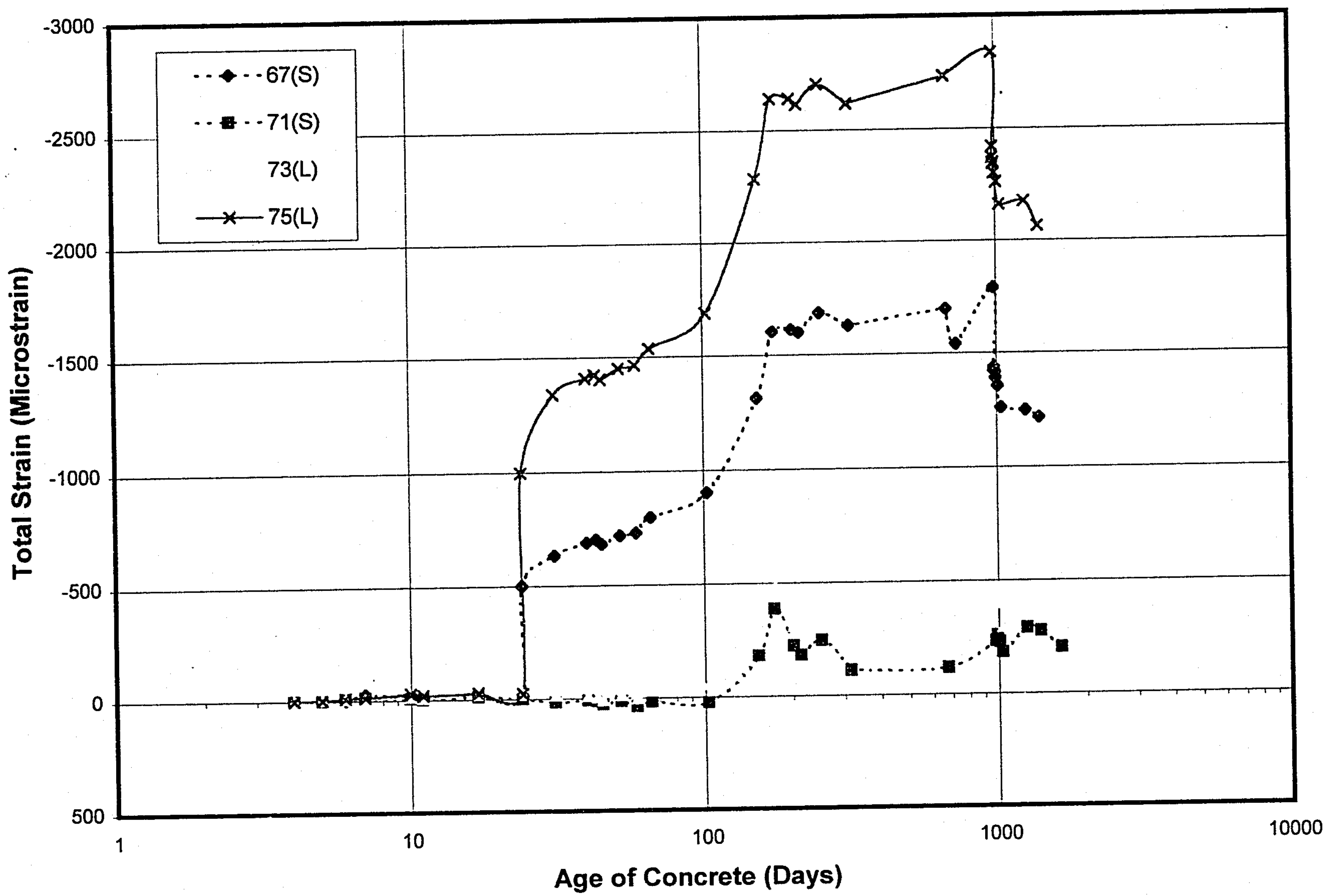


Figure 3-17: Total Strain of 254 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 78 & 87 loaded at 201 days

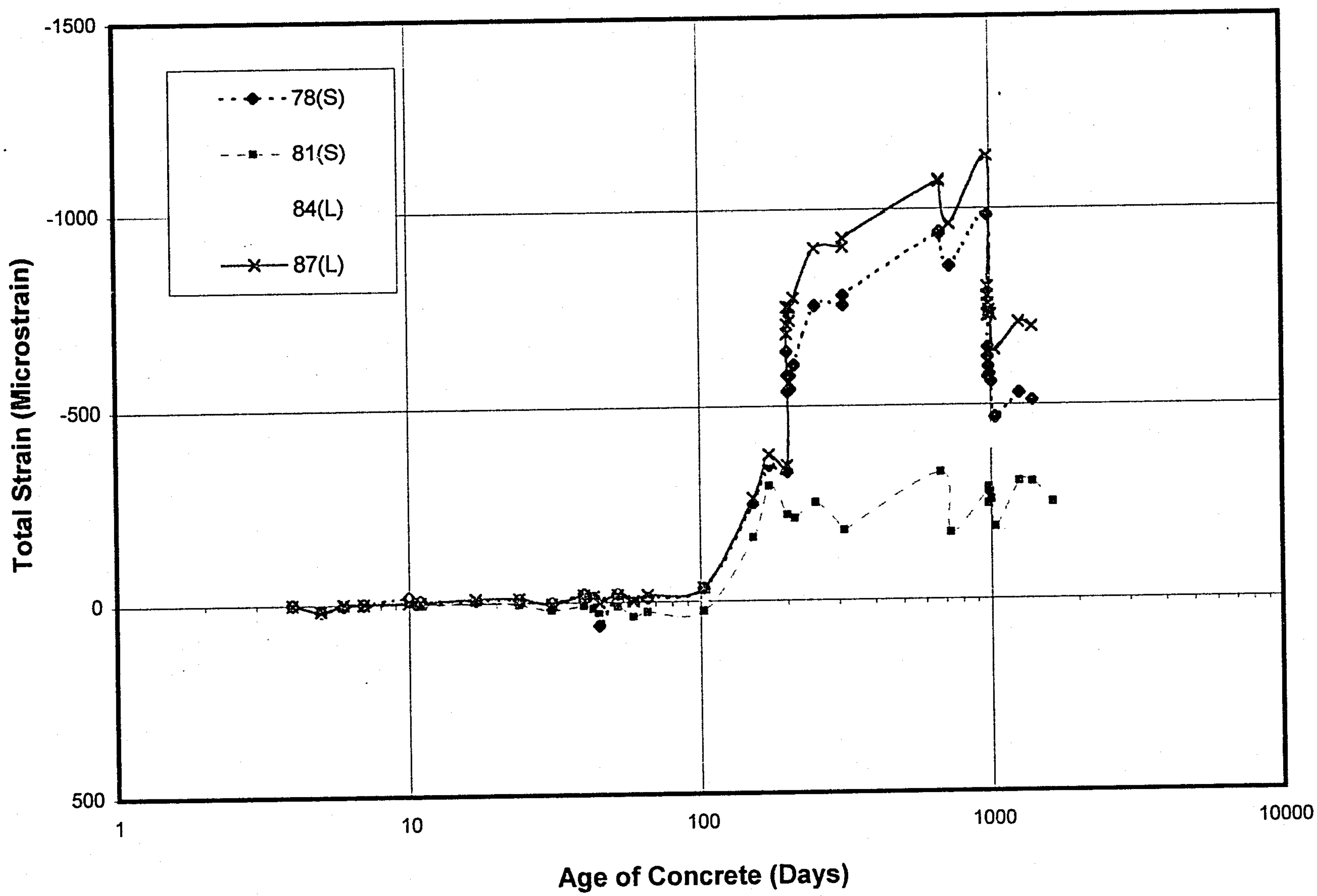


Figure 3-18: Total Strain of 89 mm Immersed Specimens, Moist cured 3 days, Specimen 12 & 29 loaded at 3 days, Specimen 20 & 23 loaded at 13 days, Specimen 64 & 24 loaded at 200 days

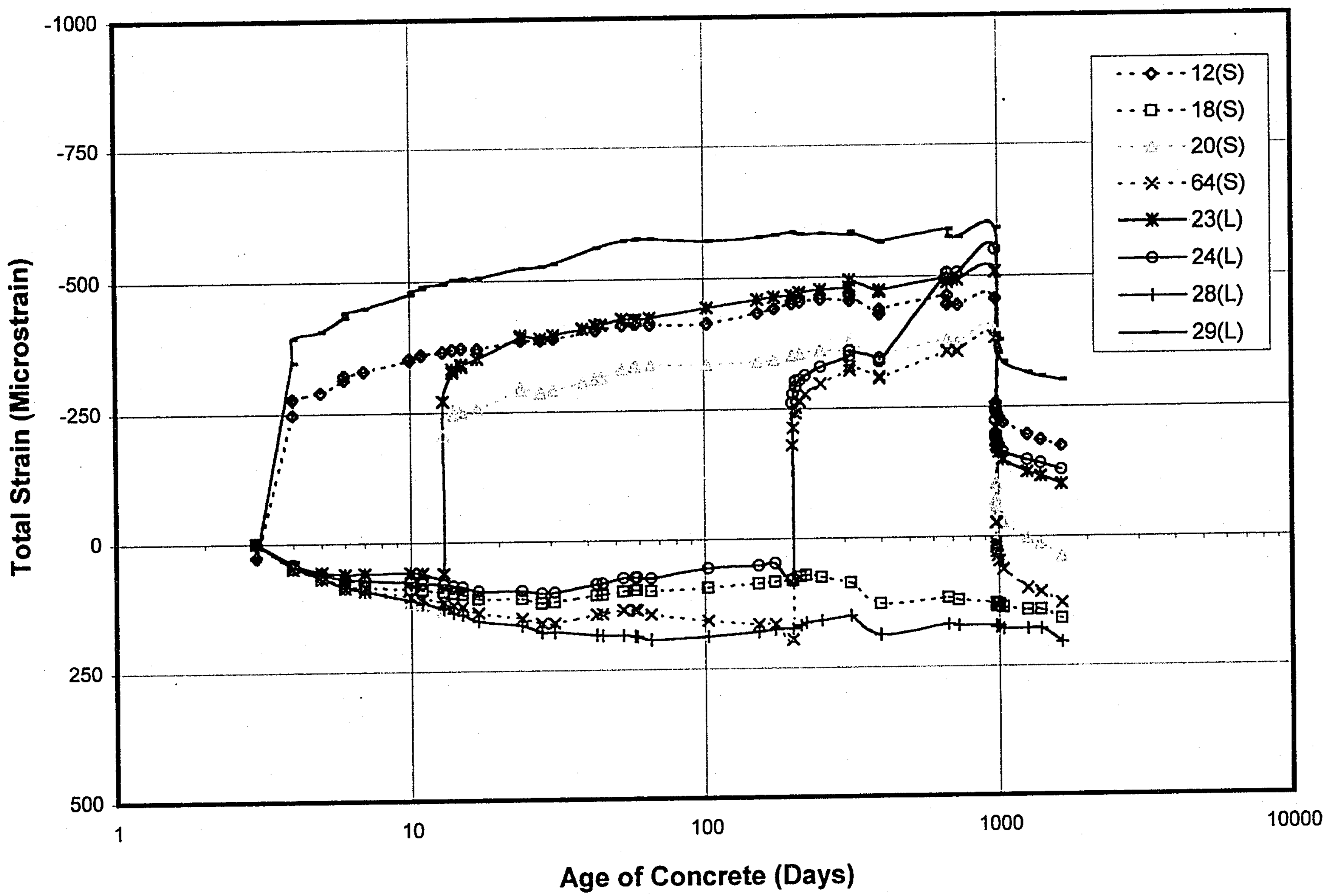


Figure 3-19: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 41 loaded at 4 days, Specimen 65 & 44 loaded at 24 days, Specimen 11 & 38 loaded at 200 days

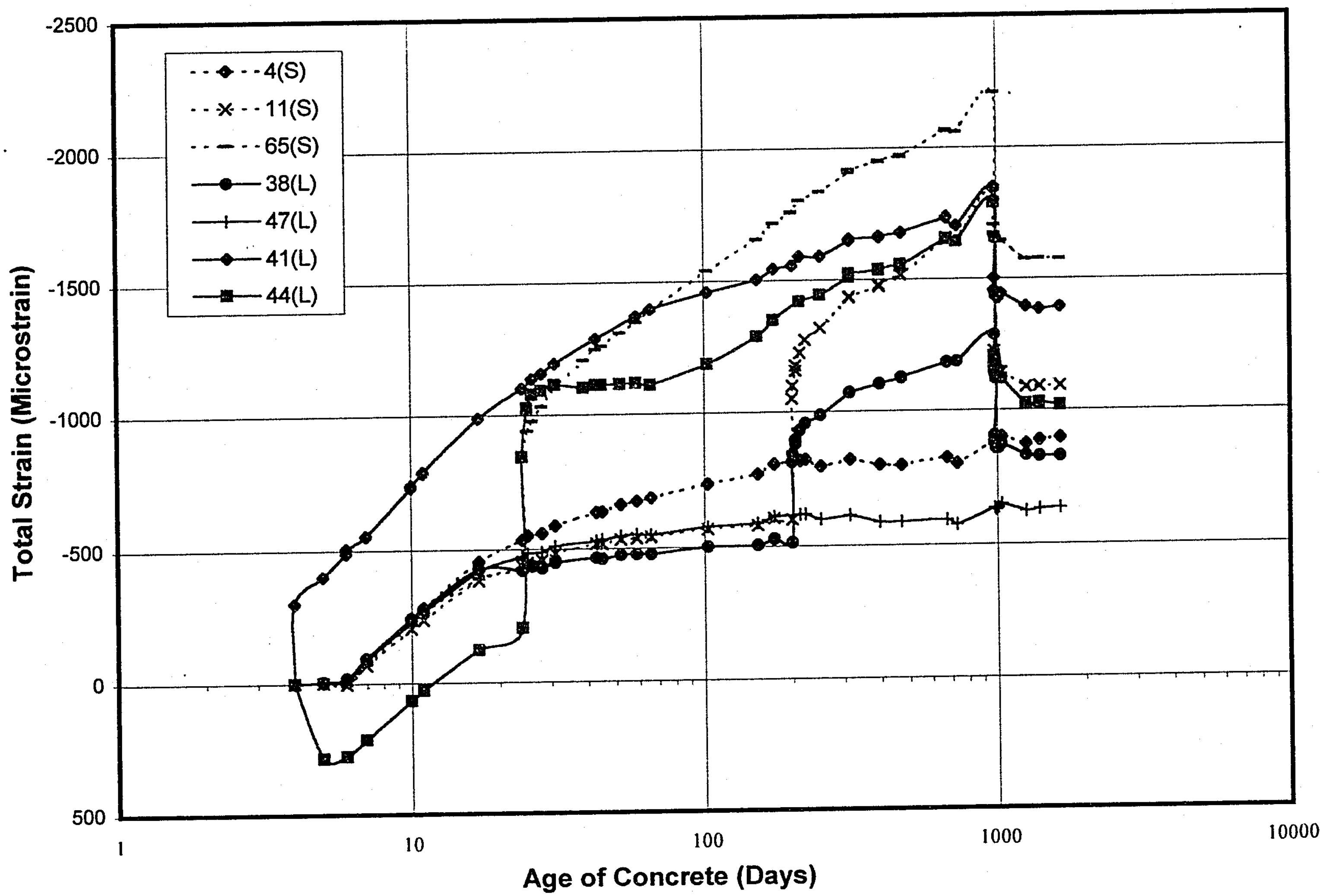


Figure 3-20: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 24/25 days Specimen 2 & 59 loaded at 25 days, Specimen 13 loaded at 200 days

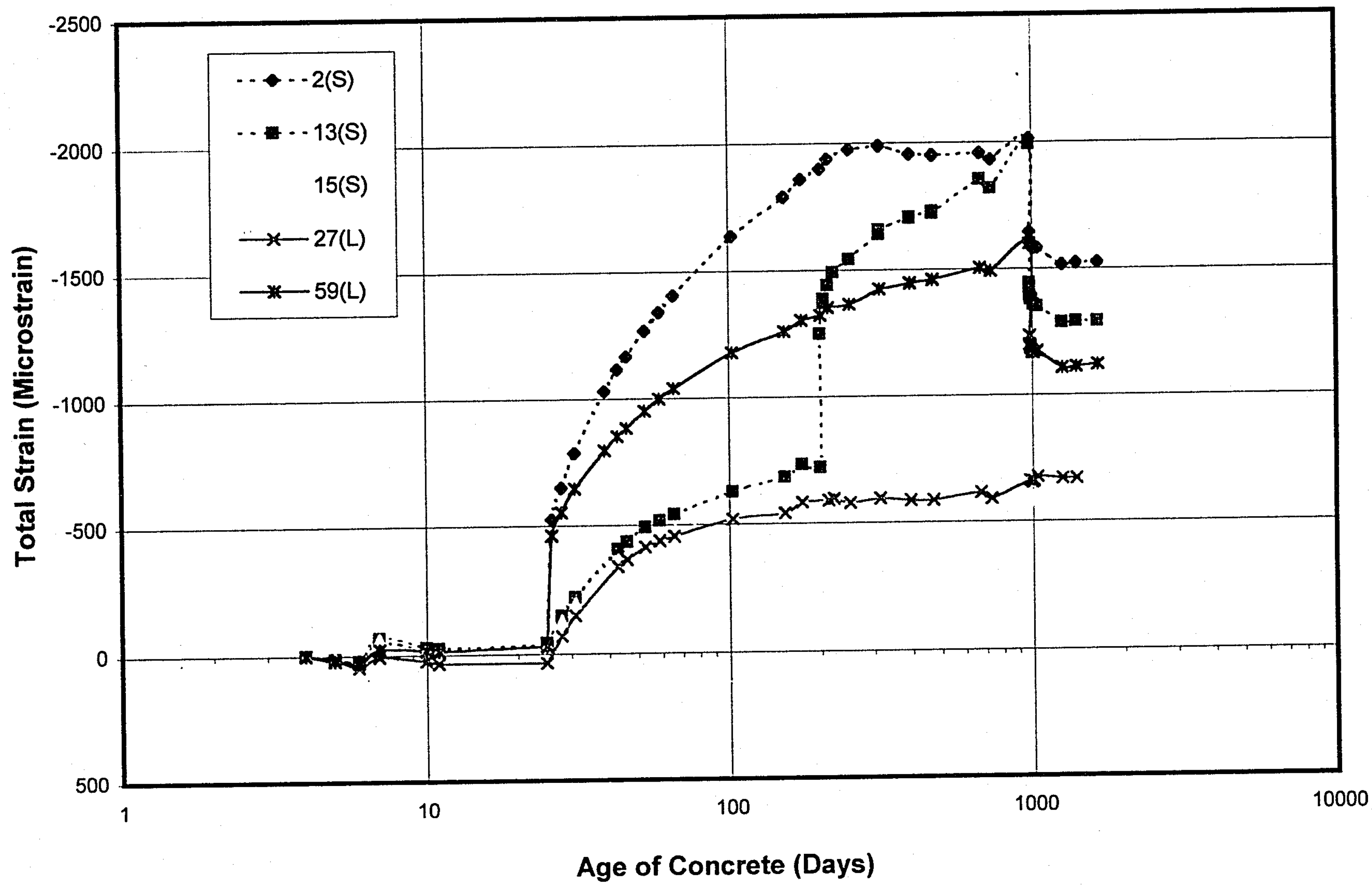


Figure 3-21: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 200 days
Specimen 42 loaded at 200 days

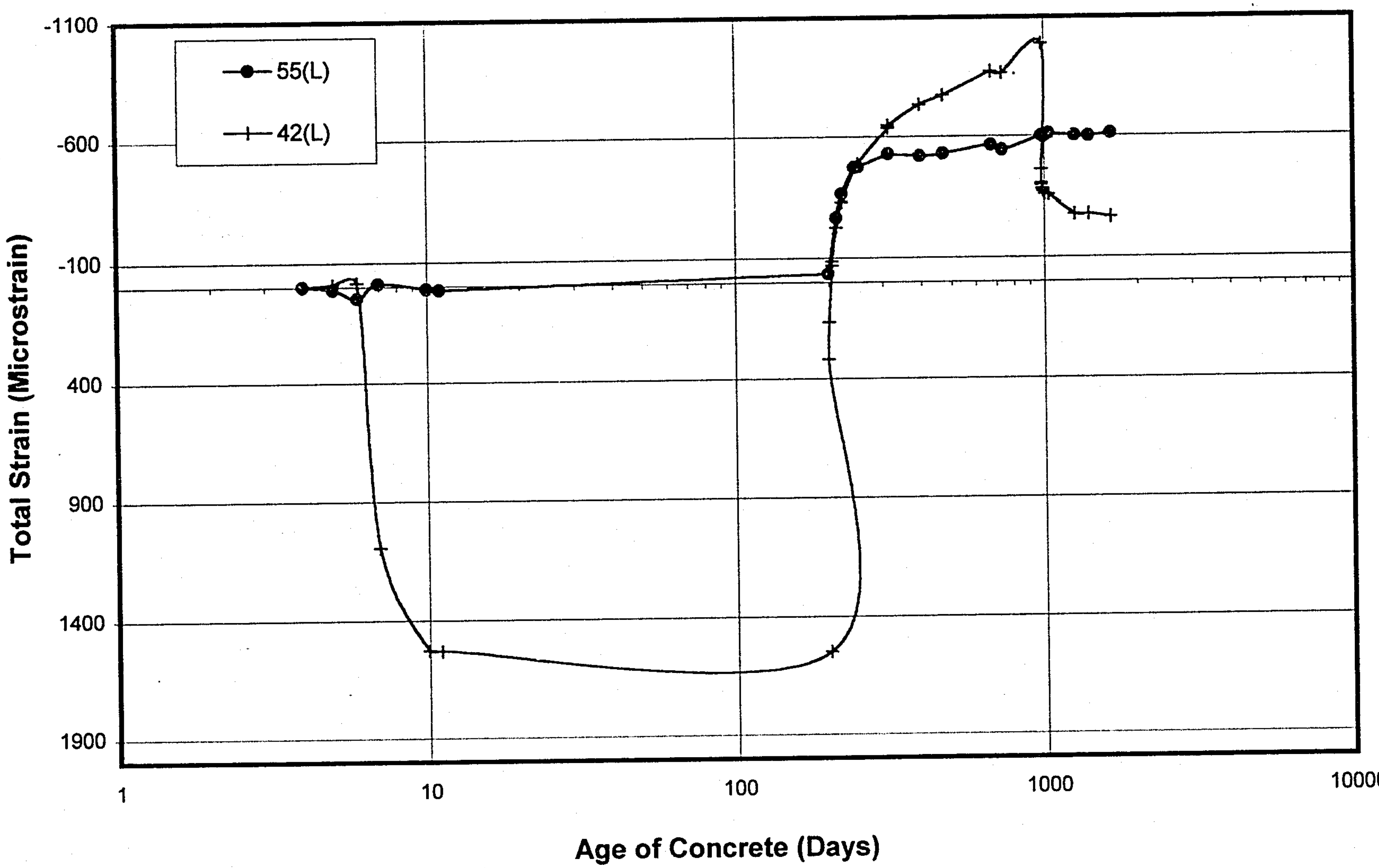


Figure 3-22: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 3 days, Specimen 63 & 33 loaded at 28 days, Specimen 8 & 54 loaded at 200 days

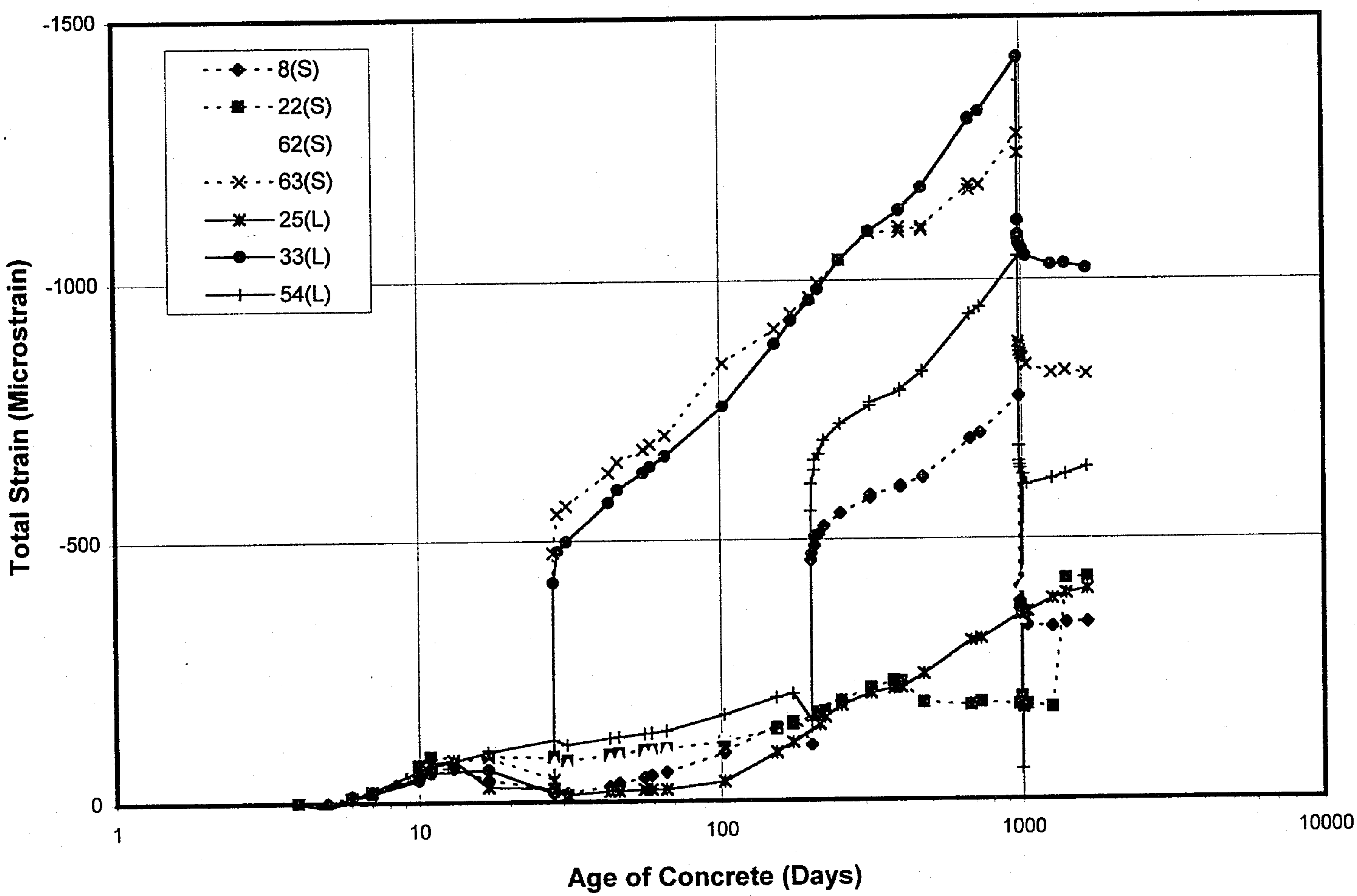


Figure 3-23: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 25 days and Sealed after 25 days, Specimen 50 loaded at 25 days

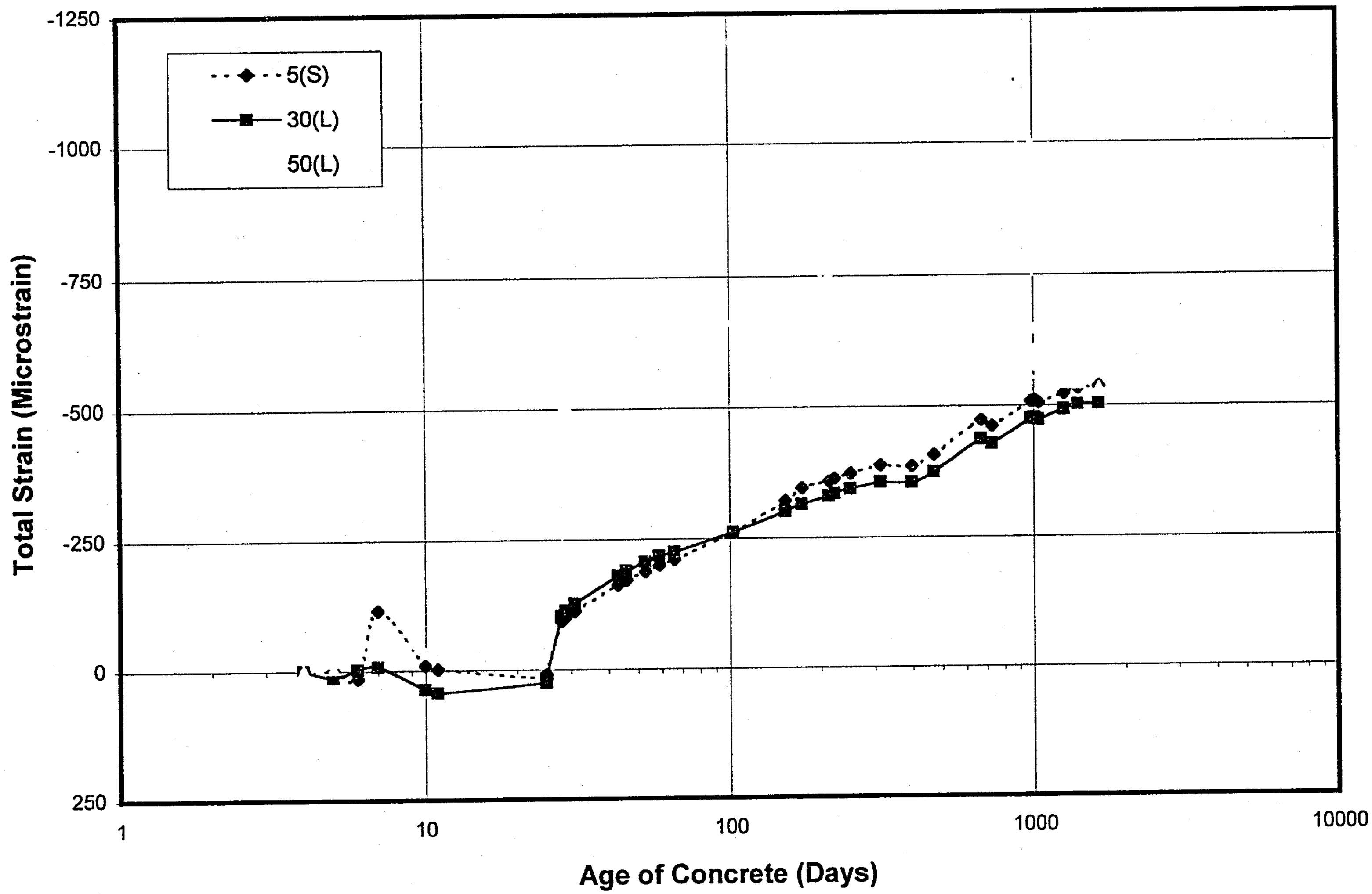


Figure 3-24: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 25 days, Specimen 3 & 35 loaded at 25 days

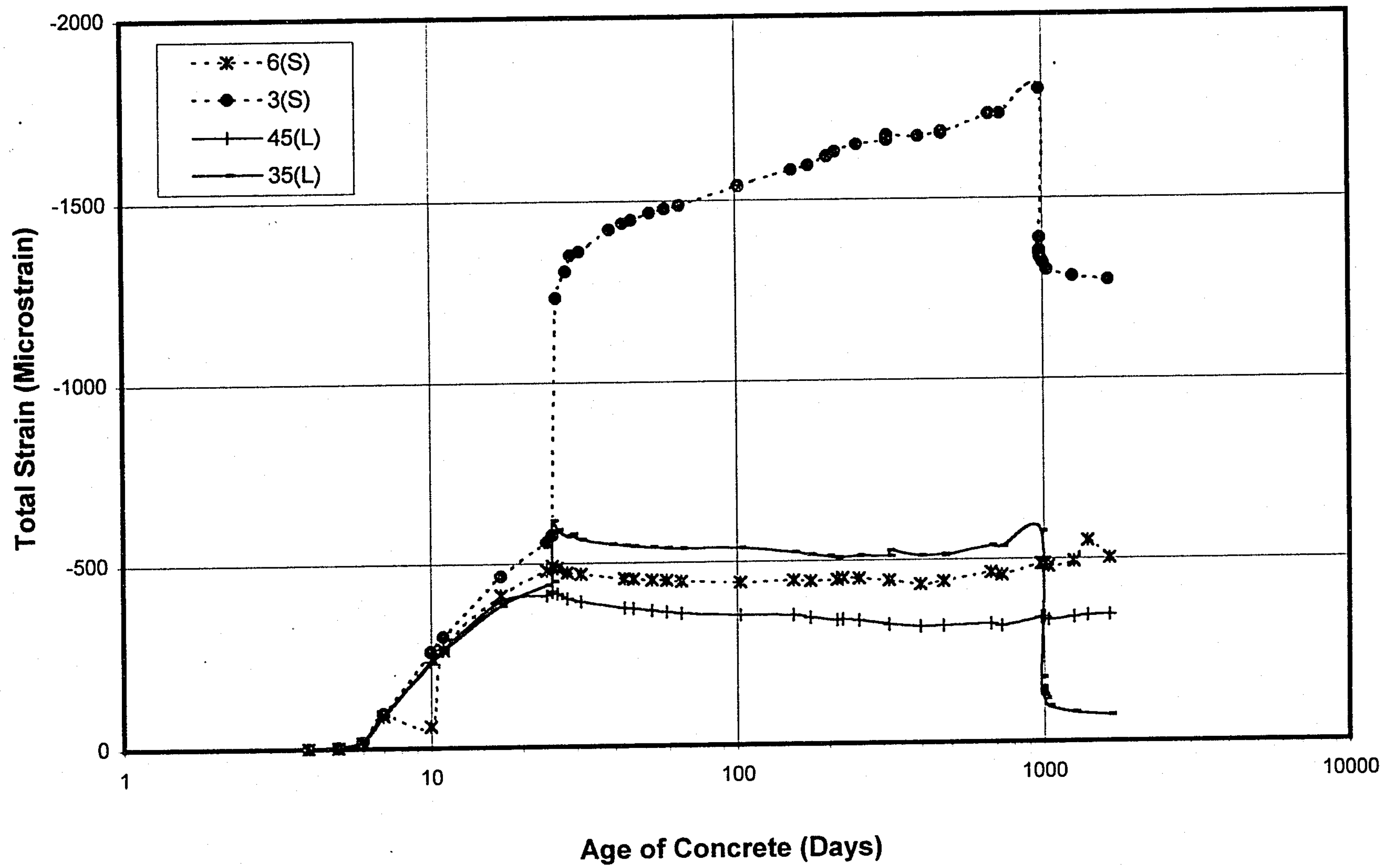


Figure 3-25: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 200 days, Specimen 9 & 36 loaded at 200 days

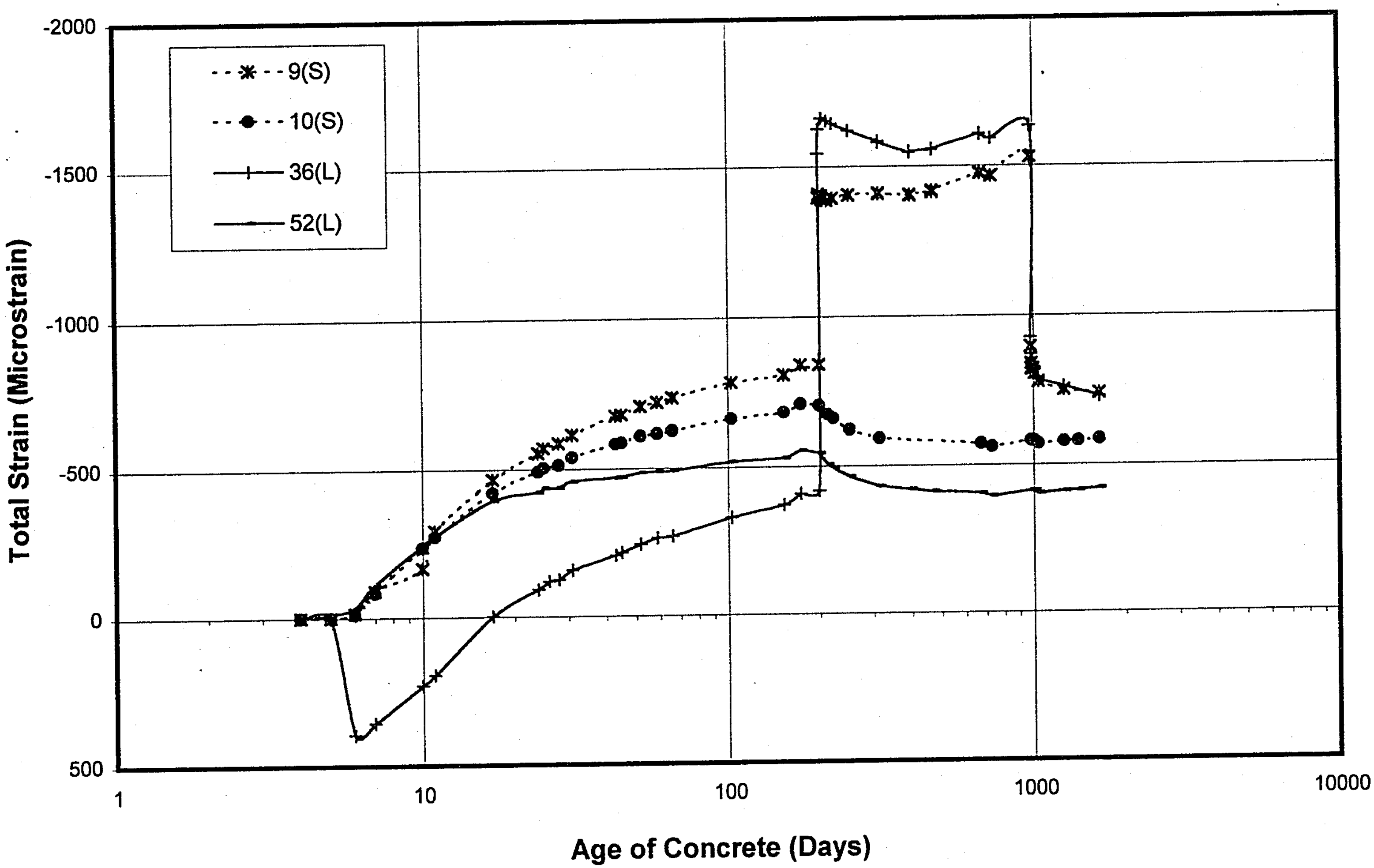


Figure 3-26: Total Strain of 152 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 69 & 77 loaded at 24 days

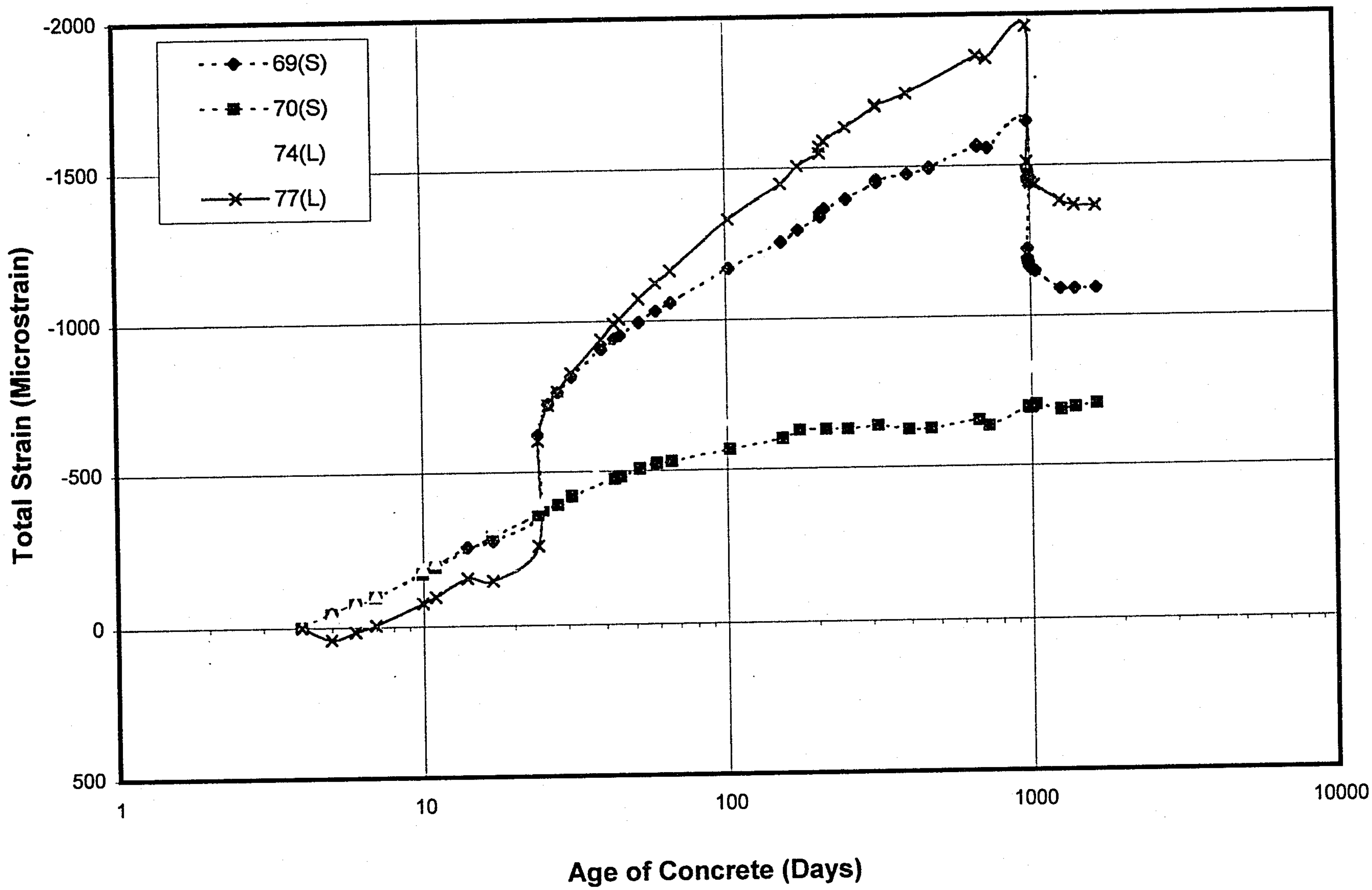


Figure 3-27: Total Strain of 254 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 83 & 89 loaded at 24 days

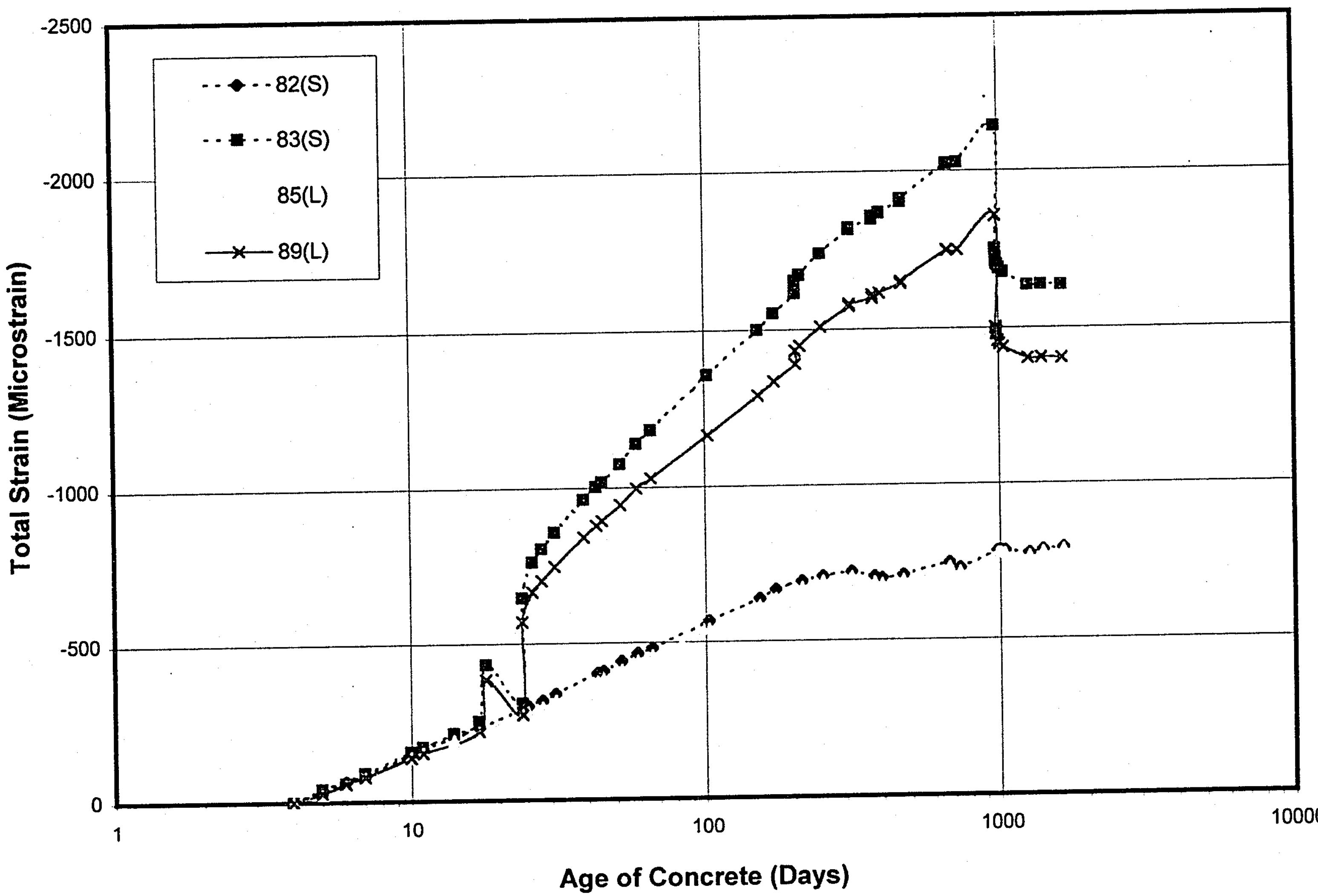


Figure 3-28: Average Temperature Outside during the test period (log scale)
Day 1 was 1997/12/06

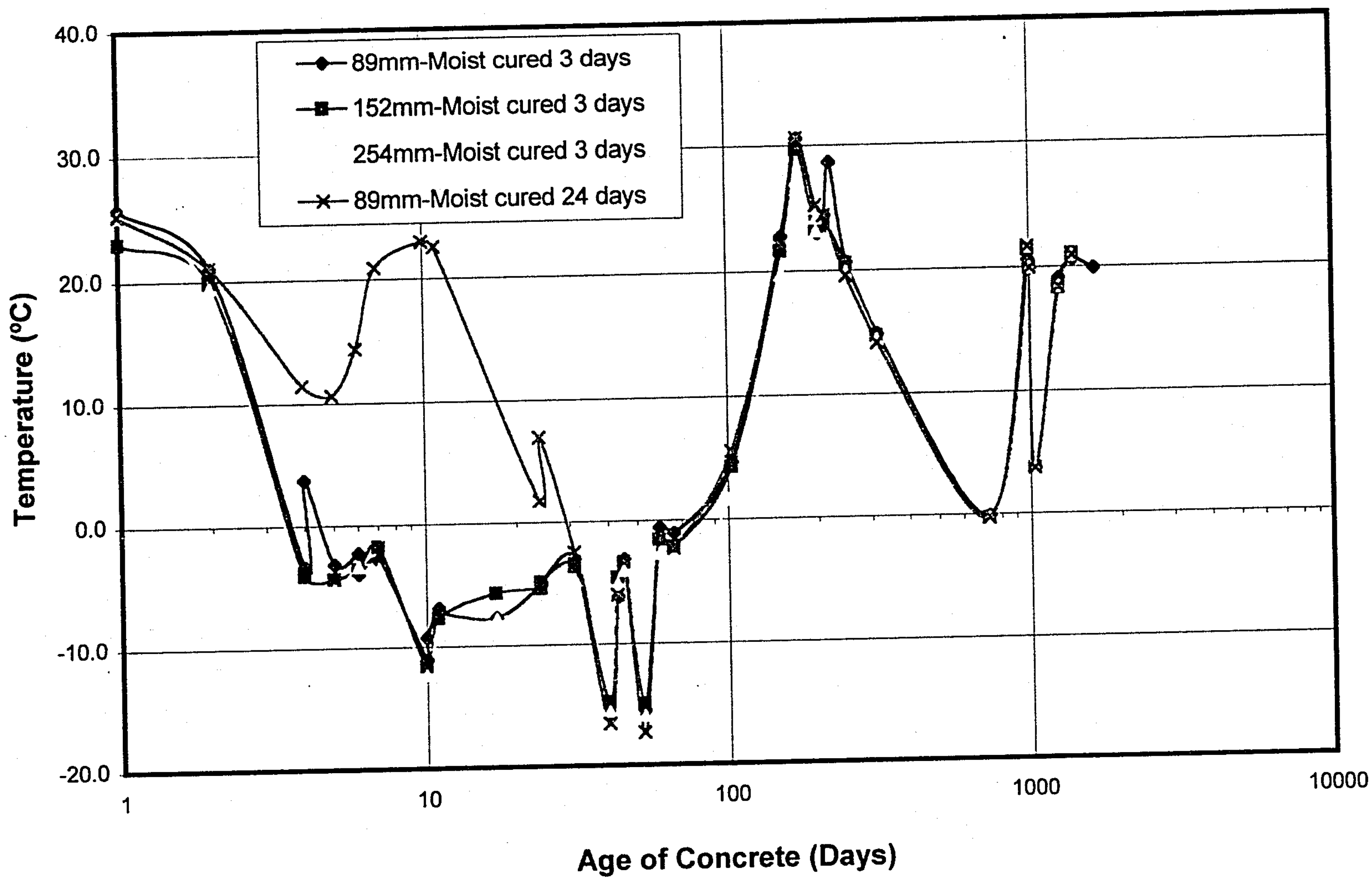
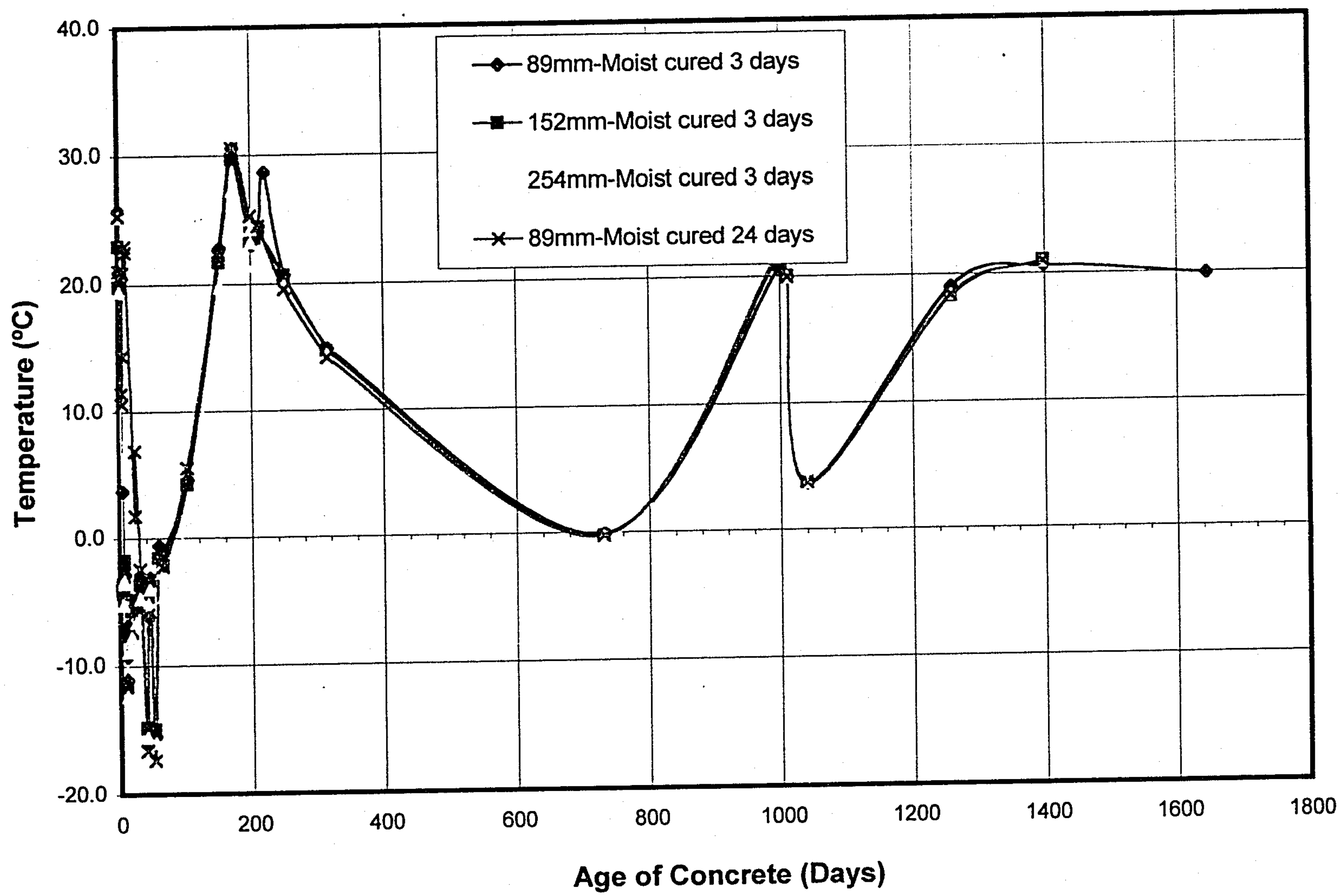


Figure 3-29: Average Temperature Outside during the test period (normal scale)
Day zero was 1997/12/05



CHAPTER 4

SHRINKAGE

This chapter discusses the results from the shrinkage specimens.

Four important parameters were changed in this study on shrinkage:

- Specimen size (diameter= 89 mm, 152mm, 254mm and 610mm)
- Environment (50% RH, lab, immersed in water, outside and sealed)
- Moist curing duration (3 days, 24 or 25 days and 200 days)
- Length of specimens (short or long)

In addition some of the specimens were sealed after 3, 25 or 200 days.

The best way to consider the effect of one of these parameters is keeping three of them constant and studying the effect of the changed parameter.

4.1 Effect of Specimen Length on Shrinkage

To investigate the specimen length effect, the other three parameters are kept constant, and each pair of specimens has been investigated. For example specimens 1 and

48, which are 89 mm in diameter, kept in a lab environment and moist cured for 3 days. Specimen 1 is short and 48 is long.

Because only one length (1930 mm) was available for the 610 mm specimen diameter, gauges 111, 112, 113, 114, 115 and 116 are not considered.

The effect of shrinkage is investigated for 1259 days, so creep specimens that were loaded at different concrete ages (at most 200 days) seem not to be useful as the drying duration was too short. Therefore none of the creep specimens measurements before loading were considered in the shrinkage investigation.

In the next paragraphs, each pair of long and short samples is examined separately for the effect of length of specimen on shrinkage during the period of study (1259 days). Compressive strain is negative and tension strain is positive.

4.1.1 Comparing Lab Observations

1 and 48: Lab, moist cured for 3 days, d=89 mm, *Fig.4-1*

a) Strain of short specimen is always more than the longer specimen.
b) In all the points the pattern of strain development seems to be the same.
c) Up to 17 days (3 to 17 days) the values of shrinkage strains are very close but a significant difference starts after 17 days.
d) Between 103 days and 1012 days there seems to be some decreases in the shrinkage strains, which may be because of changes in relative humidity.
e) Short specimen strains are always greater and in the range of 800 microstrain.
f) The ratio of measured shrinkage strain S/L is 1.30 at 1259 days and as mentioned before, seems to be nearly constant at all ages.
g) Average shrinkage of long and short specimens is -773.4 microstrain.

17, 46 and 60: Lab, moist cured for 24 days d=89mm, specimen No. 17 is short and 46 and 60 are long. Fig. *4-2*

A) Comparing **46 and 60** (long ones)

a) In the first few days (3- 11) there seems to be a smooth swelling effect in specimen No.46 but totally the values are reasonable.

b) Up to 25 days the strains are effectively zero, which was expected because of the 25 days moist curing period.

c) The pattern of strain development is similar to *Fig. 4-1.*

d) Practically there is no difference observed between these two specimens.

B) Comparing **17 and 46** short and long

a) The differences between long and short specimen strains start at 43 days, 17 days after moist curing, which is the same as the first example.

b) In general the behavior is similar to that previously discussed.

c) The ratio of measured shrinkage strain S/L is 1.36 and the pattern conforms nearly everywhere.

d) Average strain of the two specimens is -676.2 microstrain.

68 and 72: Lab, moist cured for 3 days, d=152 mm, *Fig.4-3*

a) These two specimens seem to behave exactly like the previous ones in their pattern of behavior.

b) The ratio of measured shrinkage strain S/L is 1.68, which is near the previous values.

c) Average shrinkage of long and short specimens is -697 microstrain.

79 and 86 Lab, moist cured for 3 days, d= 254 mm, *Fig. 4-4*

a) Both graphs have the same pattern of behavior.

b) However the ratio of measured shrinkage strain S/L is 0.88, which is different from the last three pairs.

c) In addition the average shrinkage strains of long and short specimens is -830.7 microstrain, which is larger than the 152 and 89 mm specimens.

111-116 Lab. moist cured for 3 days, d=610 mm, *Fig. 4-5*

There are three pairs of gauges in these specimens:

Gauges No. 111 and 114 are located vertically on the centerline at mid-height.

Gauges No. 112 and 115 are located vertically but offset by 150 mm.

Gauges No. 113 and 116 are located horizontally at mid-height of the specimen.

The ratio of vertical center shrinkage to vertical offset shrinkage is 0.95, which is reasonable and shows the same behavior of concrete in shrinkage in both positions.

The ratio of vertical center shrinkage to horizontal center shrinkage is 1.15. This can be explained because of the different sizes of the specimens in height and width, (1930 versus 610, nearly a ratio of 3) and hence the different of evaporation in each direction. But more shrinkage in the longer dimension, height, (vertical shrinkage) is contrary with our expectation and no explanation can be suggested.

The following results are the averages calculated for the 610 mm specimen:

Gauges 111 and 114, vertical center: -589.7 microstrain

Gauges 112 and 115, vertical offset: -618.4 microstrain

Gauges 113 and 116, horizontal center: -512.1 microstrain

The average shrinkage for all lab specimens is -717.5 microstrain, regardless of their size.

4.1.2 Outside Specimens

39 and 40 Outside, moist cured for 3 days, d=89 mm, *Fig. 4-6*

a) Both specimens are long.

b) The expectation is to have exactly the same results.

c) Up to 984 days the results are nearly the same.

d) At 984 days S_{39}=-41.8 while S_{40}=-285.7 which seems to be wrong. After this age the pattern is the same but a drop is observed.

e) Up to 103 days the strains are approximately zero. This is strange and is ascribed to the specimens freezing.

f) Sudden changes are completely obvious which should be the consequence of temperature changes and/or humidity.

g) From 100 days to 174 days there is a sudden change of shrinkage=0 to shrinkage=-587.0 microstrain, which seems to be because the specimens thawed.

h) The length effect of these two specimens cannot be considered because both specimens are long.

16 and 49 Outside, moist cured for 24 days, d=89 mm, *Fig. 4-7*

a) The rate of change seems to be similar to specimens 39 and 40 stored outside.

b) Both specimens seem to have the same pattern of changes of strain.

c) Range of being positive is longer because of the 25 days moist curing period.

d) The ratio of measured shrinkage strain S/L is 1.60.

e) Average shrinkage of long and short specimens is-208.9 microstrain.

71 and 73, Outside, moist cured for 3 days, d=152 mm, *Fig. 4-8*

a) The pattern of strain seems to be the same as the previously described specimens.

b) The long specimen shrinkage is longer with a ratio of short to long strain of 0.68.

c) Again the shrinkage strain is almost zero for the first 100 days, which may be because of freezing.

d) Average shrinkage of long and short specimens is –357.7 microstrain.

81 and 84, Outside, moist cured for 3 days, d=254 mm, *Fig. 4-9*

a) The ratio of measured shrinkage strain S/L is 0.66 and the pattern of change is similar.

b) The same pattern is seen in these pair of specimens as those in *Fig.4-8.*

c) Average shrinkage of long and short specimens is -379.4 microstrain.

An average of –316.4 microstrain is calculated for outside specimens regardless of their size.

4.1.3 Immersed Specimens

18 and 28 Immersed, moist cured for 3 days, d=89 mm, *Fig 4-10*

Looking at measurements for the immersed specimens shows:

a) None of them has drying shrinkage. Both specimens have positive strains, which is expected. In fact swelling occurred in these samples at all ages.

b) The longer specimen shows more strain changes.

c) The pattern of strain is the same for both specimens.

d) The ratio of measured shrinkage strain S/L is 0.79.

e) Average shrinkage (swelling) of long and short specimens is +160 microstrain.

An average of +160.0 microstrain is calculated for the immersed specimens.

4.1.4 50% RH

4 and 47, 50% RH, moist cured for 3 days, d=89 mm, *Fig.4-11*

a) The strains are nearly the same as the analogous lab specimens.

b) The ratio of measured shrinkage strain S/L is 1.40.

c) The strain gauge values are comparable with the lab specimens gauges.

d) An average final strain of –747.0 microstrain was observed.

15 and 27, 50% RH, moist cured for 24 days, d=89 mm, *Fig. 4-12*

a) Due to the 25-day moist curing period, the strain before 25 days is effectively zero.

b) After 25 days difference in strains start but long and short specimens are similar.

c) The ratio of measured shrinkage strain S/L is 0.87.

d) Average final shrinkage of long and short specimens is -623.4 microstrain.

55 and 42, 50% RH, moist cured for 200 days, d=89 mm, *Fig. 4-13*

a) Shrinkage of specimen 55 in 200 first days is almost zero, which is expected and starts to have different shrinkage strains afterwards.

b) Average strain is –598.6 microstrain.

c) Observing the absolute shrinkage strain values of the last three pairs of specimens (4 &47, 15 & 27 and 55 & 42) with different moist curing period, shows decrease in 1259 days of shrinkage for 15% and 20% with increase in moist curing duration from 3 days to 25 days and 3 days to 200 days respectively.

22, 62 and 25, 50% RH, moist cured for 3 days, and sealed after 3 days, d= 89 mm, *Fig. 4-14*

a) Specimens 22 and 62 are short and 25 is long.

b) The patterns are not the same in these samples despite the fact that they are all in the exact same situation, especially No. 22 and 62, which are both long.

c) A sudden change was observed in gauge No. 25 around day 13.

d) At day 398 there is a sudden increase in specimen 22.

e) It was expected that the two short ones be very close, which is completely wrong.

f) It seems that sealing was not done effectively; otherwise we should have had less shrinkage.

g) The average shrinkage of long and short specimens is -344.1 which is considerably less than the analogous specimens in 50% RH. This should be the effect of sealing, albeit not perfect.

h) The ratio of measured shrinkage strain S/L is 0.80

<u>**5 and 30**, 50% RH, moist cured for 25 days and sealed after 25 days, d=89 mm, *Fig. 4-15*</u>

a) Moist curing duration 25 days resulted in near zero strain during first 25 days.

b) Short specimen No.5 has a sudden change in the day 7, which is strange. This may be the result of a wrong reading for that single observation.

c) The ratio of measured shrinkage strain S/L is 1.06.

d) Average shrinkage of long and short specimens is -507.8 microstrain, which is 20% less than the similar specimen but not sealed. Hence this decrease should be the effect of sealing.

<u>**6 and 45**, 50% RH, moist cured for 3 days and sealed after 25 days, d= 89 mm, *Fig. 4-16*</u>

a) Up to 3 days the strain is nearly zero.

b) For short specimen (No.6) there seems to be a drop at the 10^{th} day, which may be a bad observation reading.

c) The ratio of measured shrinkage strain S/L is 1.46.

d) After 25 days there is a drop in both specimens because of sealing. In these two specimens good sealing seems to have been achieved.

e) Average shrinkage of long and short specimens is -414.8 microstrain, which is almost 50% less than the analogous specimen not sealed.

10 and 52, 50% RH, moist cured for 3 days and sealed after 200 days, d=89 mm, *Fig. .4-17*

a) The pattern of shrinkage changes is typical..

b) There is a drop for both specimens after 200 days, which is because of sealing after 200 days and is completely reasonable.

c) The ratio of measured shrinkage strain S/L is 1.41.

d) Average shrinkage of long and short specimens is -493.5 microstrain.

70 and 74, 50% RH, moist cured for 3 days, d= 152 mm, *Fig. 4-18*

a) Both the pattern and the values are very nearly the same for both specimens.

b) The ratio of measured shrinkage strains S/L is 0.84.

c) Average shrinkage of long and short specimens is -750.7 microstrain.

82 and 85, 50% RH, moist cured for 3 days, d= 254 mm, *Fig. 4-19*

a) Only there are smooth changes after 315 days.

b) The ratio of measured shrinkage strain S/L is 1.01, which is really good.

c) Average shrinkage of long and short specimens is -770.3 microstrain, which is the same as the last pair discussed.

Overall an average of –698.0 microstrain was obtained for the unsealed 50% RH specimens, regardless of the size, which can be compared with –717.5 microstrain of the lab environment.

An average of -422.2 is calculated for the 50% RH ones sealed, regardless of the size, which is what is expected by sealing of specimens.

4.1.5 Conclusion on Length Effect

After looking at each pair of specimens for the effect of length on shrinkage, the average and the standard deviation of the ratio of short specimens value to long specimens value are given in Table. 4-1.

Looking in the results of this table (Average=1.11 and Standard Deviation= 0.34) and noticing at results which are half more and half less than average, leads us to the point that the specimen length doesn't have a considerable effect on the last measured shrinkage (1259 days).

Considering each pair of specimens, which have almost always the same pattern in shrinkage of the long and the short specimens, it can be concluded that specimen length does not have a major effect at any time during the consideration of shrinkage values.

In conclusion it can be said that at any point of time the average of the short and long specimens is a good representative of any specimens with the same diameter, moist curing duration and the same environment.

In other words all the specimens whatever the length, with the same size (diameter), moist curing period and same environment, have similar behavior for shrinkage or the length doesn't have a significant effect on shrinkage.

4.2 Effect of Environment on Shrinkage

To consider the effect of environment on shrinkage the specimen size and moist curing duration will be kept constant. The following groups will be discussed:

4.2.1 Specimens with d= 89 mm and Moist Curing Duration of 3 Days

The results of this group are shown in Table 4-8 and Fig.4-20. The specimens are:

Lab specimens: 1 and 48

Outside specimens: 39 and 40

Immersed specimens: 18 and 28

50% RH specimens: 4 and 47

Looking at results it can be said that lab and 50% RH specimens have almost the same shrinkage and lab is larger by 3%. On the other hand the lab shrinkage is larger than outside by a ratio of 2.4. Again it means that shrinkage in real life is much less than what is experienced in the special conditions of labs. As expected swelling happened in the immersed specimens.

4.2.2 Specimens with d= 89 mm and Moist Curing Duration of 24/25 Days

The specimens are:

Lab specimens: 17 and 46

Outside specimens: 16 and 49

50% RH specimens: 15 and 27

As shown in Table 4-9, again the ultimate shrinkages of lab and 50% RH specimens are similar but lab values are larger by 15 percent. The ultimate shrinkage of outside specimens is less than lab specimens with a ratio of 3.5, which is considerable.

4.2.3 Specimens with d=152 mm and Moist Curing Duration of 3 Days

The results are gathered in Table 4-10 and Fig. 4-22. The specimens are:

Lab specimens: 68 and 72

Outside specimens: 71 and 73

50% RH specimens: 70 and 75

The table shows that again the ultimate shrinkage of lab and 50% RH samples are similar. This time the 50% RH shrinkage is larger by 7 percent. The ratio of lab to outside specimens is 1.95.

4.2.4 Specimens with d=254 mm and Moist Curing Duration of 3 Days

The specimens are:

Lab specimens: 79 and 86.

Outside specimens: 81 and 84

50% RH specimens: 82 and 85

Table 4-11 and Fig. 4-23 show the results. Again lab ultimate shrinkage is more by a percentage of 7%. The ratio of lab to outside shrinkage is 2.19.

4.2.5 Conclusion on Environment Effect

In conclusion lab and 50% RH ultimate shrinkages are almost the same but the lab shrinkage is usually a little larger than 50% RH shrinkages. The average for lab ultimate shrinkage is –755.9 microstrain and for 50% RH is –722.9 microstrain. On the other hand outside ultimate shrinkage with an average of –316.3 microstrain is less than lab by a ratio of 2.4. This means that if the concrete is cast outside and in winter, the amount of shrinkage in a long period is much less than what it is in experimental environment. The swelling of the immersed specimens with an average of +160.0 microstrain shows the importance of evaporation of water in shrinkage of specimens.

4.3 Effect of Size of Specimen on Shrinkage

As stated before, to understand the effect of size of specimen on shrinkage we should try to keep the other three variables constant. So we consider specimens with the same environment and moist curing period. As concluded before, the values of the long and short specimens will be averaged. *Figures 4-25 to 4-27* show the effect of size on shrinkage for each of the storage environments.

4.3.1 Lab Specimens

Fig. 4-25 shows the behavior of different samples in lab environment. The moist curing period of 3 days is common for all samples. As discussed before, the average value graphs can be used for the following specimens:

d= 89 mm Specimens 1 and 48

d= 152 mm Specimens 68 and 72

d= 254 mm Specimens 79 and 86

d= 610 mm Specimens 111 and 114

Figure 4-25 indicates that as expected the smaller specimens lose moisture more rapidly and hence shrink more at early age. It is surprising that the horizontally measured shrinkage on the 610 mm diameter specimens is less than the vertically measured shrinkage.

Observing the average graphs shows that the pattern of graphs are completely different and are in no way comparable, but as expected the smaller specimens lose moisture quicker and shrink more at any given early age. On the other hand the ultimate values can be compared. The results of this comparison are gathered in Table 4-2.

4.3.2 Outside Specimens

Fig. 4-26 and Table 4-3 show the same study for the outdoor samples. Again all specimens were placed outside at 3 or 4 days, after a moist curing period of 3 days. The average graphs can be used for following specimens:

d= 89 mm Specimens 39 and 40

d= 152 mm Specimens 71 and 73

d= 254 mm Specimens 81 and 84

Shrinkage of the specimens stored outside, Figure 4-26, is dominated by the fact that the temperatures were below freezing for the first 100 days and no shrinkage was measured.

4.3.3 50% RH Specimens

The same study has been performed for the *Fig. 4-27a and 4-27(b2)* for 50% RH specimens. The average graphs are used for:

d= 89 mm Specimens 4 and 47

d= 152 mm Specimens 70 and 74

d= 254 mm Specimens 82 and 85

The results are shown in Table 4-4a.

4.3.4 Conclusion on Size Effect

Looking at the results as a group shows that, in general, for last measured shrinkage, with increasing diameter, in the same environment and moist curing period, shrinkage will become slightly bigger. This is in contrary with what is expected.

4.4 Effect of Sealing on Shrinkage

A separate study can be performed of the effect of sealing on shrinkage of specimens in 50% RH, of the same size of d=89 mm and moist cured for 3 days but sealed after 3, 24/25 and 200 days. The results are shown in Table 4-4a.

The following specimens are considered:

50% RH, d= 89 mm, moist cured for 3 days, sealed after 3 days, Specimens 22 and 25

50% RH, d= 89 mm, moist cured for 3 days, sealed after 25 days, Specimens 6 and 45

50% RH, d= 89 mm, moist cured for 3 days, sealed after 200 days, Specimens 10 and 52

Looking in the results of Table 4-4a it can be observed that the shrinkage of samples sealed at 3 days is less than the ones sealed at 25 days and the ones sealed at 25 days are less than those sealed at 200 days. This conforms to what was expected. Another deduction is that the decrease for the specimens sealed after 3 days to those sealed after 25 days is much more than the ratio of decrease for specimens sealed after 25 days to the ones sealed after 200 days.

4.5 Effect of Moist Curing Duration on Shrinkage

To determine the effect of moist curing duration on shrinkage of concrete, the size and environment are kept constant and the average of long and short specimen results are used for comparison of different samples.

4.5.1 Lab Specimens

The following specimens are used for lab:

d=89 mm, moist cured for 3 days, specimens 1 and 48

d=89 mm, moist cured for 24 days, specimens 46 and 60

The results are collected in Table 4-5. Increasing the duration of moist curing from 3 to 25 days causes a decrease of about 13% in shrinkage.

4.5.2 Outside Specimens

The specimens used for outdoor are as follows:

d=89 mm, moist cured for 3 days, Specimens 39 and 40

d=89 mm, moist cured for 24 days, Specimens 16 and 49

The results are given in Table 4-6. As expected increasing the period of moist curing from 3 days to 24 days causes a decrease of 40% in shrinkage, which is really noticeable, and is three times as much as the lab specimens. However the effect of temperature, (probably the specimens froze) contributed to this decrease.

4.5.3 50% RH Specimens

Table 4-7 and Figure 4-27(b1) show the effect of moist curing duration on the specimens stored in 50% RH. In 50% RH there are three different groups of specimens:

d=89 mm, moist cured for 3 days, specimens 4 and 47

d=89 mm, moist cured for 24 days, specimens 15 and 27

d=89 mm, moist cured for 200 days, specimen No.55

A decrease of 22% is observed by increasing the moist curing period from 3 days to 24 days, whereas increasing the moist curing duration from 24 to 200 days only decreases the shrinkage by 4%.

4.5.4 Conclusion on Moist Curing Duration Effect

In conclusion, increasing the duration of moist curing from 3 days to 25 days reduces shrinkage but increasing the duration of moist curing from 24 days to 200 days has little effect on decrease of shrinkage.

The most significant effect was for the samples stored outside, which means that in real life we have less problem with shrinkage if the moist curing period is increased. However the outside specimens were exposed to very low (below freezing) temperatures for most of their first 100 days.

Table 4-1: Effect of length on shrinkage

No of Specimen	Size of Specimen (mm)	Short or Long	Moist Cured (Days)	Environment	Strain at 1259 days (microstrain)	Average of Pairs (microstrain)	Average of Environments (microstrain)	Short/Long Ratio
1	89*330	SHORT	3	LAB	-873.4	*-773.4*	*-676.3*	**1.30**
48	89*460	LONG	3	LAB	-673.3			
17	89*330	SHORT	24	LAB	-822.7	*-712.9*		**1.36**
46	89*460	LONG	24	LAB	-622.0			
60	89*460	LONG	24	LAB	-584.0			
68	152*442	SHORT	3	LAB	-873.1	*-697.0*		**1.68**
72	152*747	LONG	3	LAB	-520.8			
79	254*645	SHORT	3	LAB	-777.5	*-830.7*		**0.88**
86	254*1153	LONG	3	LAB	-883.9			
111	610*1930	LONG	3	LAB	-587.0	*-589.7*		
112	610*1930	LONG	3	LAB	-635.5	*-618.35*		
113	610*1930	LONG	3	LAB	-496.1	*-512.1*		
114	610*1930	LONG	3	LAB	-592.4			
115	610*1930	LONG	3	LAB	-601.2			
116	610*1930	LONG	3	LAB	-528.0			
18	89*330	SHORT	3	IMMERSED	141.3	*160.0*	*160.0*	**0.79**
28	89*460	LONG	3	IMMERSED	178.7			
39	89*460	LONG	3	OUTSIDE	-206.2	*-319.3*	*-316.3*	
40	89*460	LONG	3	OUTSIDE	-432.4			
16	89*330	SHORT	24	OUTSIDE	-256.8	*-208.9*		**1.60**
49	89*460	LONG	24	OUTSIDE	-160.9			
71	152*442	SHORT	3	OUTSIDE	-290.3	*-357.7*		**0.68**
73	152*747	LONG	3	OUTSIDE	-425.0			
81	254*645	SHORT	3	OUTSIDE	-301.5	*-379.4*		**0.66**
84	254*1153	LONG	3	OUTSIDE	-457.2			
4	89*330	SHORT	3	50%	-872.7	*-747.0*	*-698.0*	**1.40**
47	89*460	LONG	3	50%	-621.3			
15	89*330	SHORT	24	50%	-580.8	*-623.4*		**0.87**
27	89*460	LONG	24	50%	-666.0			
55	89*460	LONG	200	50%	-598.6	*-598.6*		
22	89*330	SHORT	3 & Sealed 3	50%	-174.3	*-344.1*		**0.80**
62	89*330	SHORT	3 & Sealed 3	50%	-436.7			
25	89*460	LONG	3 & Sealed 3	50%	-382.6			
5	89*330	SHORT	25 & Sealed 25	50%	-523.0	*-507.8*		**1.06**
30	89*460	LONG	25 & Sealed 25	50%	-492.6			
6	89*330	SHORT	3 & sealed 25	50%	-491.7	*-414.8*		**1.46**
45	89*460	LONG	3 & sealed 25	50%	-337.9			
10	89*330	SHORT	3 & Sealed 200	50%	-577.0	*-493.5*		**1.41**
52	89*460	LONG	3 & Sealed 200	50%	-410.0			
70	152*442	SHORT	3	50%	-685.9	*-750.7*		**0.84**
74	152*747	LONG	3	50%	-815.4			
82	254*645	SHORT	3	50%	-774.6	*-770.3*		**1.01**
85	254*1153	LONG	3	50%	-766.0			
							Mean=	***1.11***
							S.D=	***0.34***

Table 4-2: Effect of size for specimens stored in lab, moist cured 3 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
1	89	S	Lab	3	-873.4	
48	89	L	Lab	3	-673.3	*-773.4*
68	152	S	Lab	3	-873.1	
72	152	L	Lab	3	-520.8	*-697.0*
79	254	S	Lab	3	-777.5	
86	254	L	Lab	3	-883.9	*-830.7*
111	610	–	Lab	3	-587.0	
114	610	–	Lab	3	-592.4	*-589.7*
Ave.						*-722.7*
Coefficient of Variation						*14.4* %

Table 4-3: Effect of size for specimens stored outside, moist cured 3 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
39	89	L	Outside	3	-206.2	
40	89	L	Outside	3	-432.4	*-319.3*
71	152	S	Outside	3	-290.3	
73	152	L	Outside	3	-425.0	*-357.7*
81	254	S	Outside	3	-301.5	
84	254	L	Outside	3	-457.2	*-379.4*
Ave.						*-352.1*
Coefficient of Variation						*8.6* %

Table 4-4: Effect of size for specimens stored in 50% RH, moist cured 3 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
4	89	S	50% RH	3	-872.7	
47	89	L	50% RH	3	-621.3	*-747.0*
70	152	S	50% RH	3	-685.9	
74	152	L	50% RH	3	-815.4	*-750.7*
82	254	S	50% RH	3	-774.6	
85	254	L	50% RH	3	-766.0	*-770.3*
Ave.						*-756.0*
Coefficient of Variation						*1.7* %

Table 4-4a: Effect of sealing on specimens stored in 50% RH, moist cured 3 days, d=89 mm

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Sealed after (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
22	89	S	50% RH	3	S3	-174.3	
25	89	L	50% RH	3	S3	-382.6	
62	89	S	50% RH	3	S3	-436.7	*-331.2*
6	89	S	50% RH	3	S25	-491.7	
45	89	L	50% RH	3	S25	-337.9	*-414.8*
10	89	S	50% RH	3	S200	-577.0	
52	89	L	50% RH	3	S200	-410.0	*-493.5*
Ave.							*-413.2*
Coefficient of Variation							*19.6 %*

Table 4-5: Effect of moist curing period for specimens stored in lab, d=89mm

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
1	89	S	Lab	3	-873.4	
48	89	L	Lab	3	-673.3	*-773.4*
46	89	L	Lab	24	-622.0	
60	89	L	Lab	24	-584.0	*-603.0*
Ave.						*-688.2*
Coeff. of Variation						*17.5 %*

Table 4-6: Effect of moist curing period for specimens stored outside, d=89mm

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
39	89	L	Outside	3	-206.2	
40	89	L	Outside	3	-432.4	*-319.3*
16	89	S	Outside	24	-256.8	
49	89	L	Outside	24	-160.9	*-208.9*
Ave.						*-264.1*
Coeff. of Variation						*29.6 %*

Table 4-7: Effect of moist curing period for specimens stored in 50% RH, d=89mm

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
4	89	S	50% RH	3	-872.7	
47	89	L	50% RH	3	-621.3	*-747.0*
15	89	S	50% RH	24	-580.8	
27	89	L	50% RH	24	-666.0	*-623.4*
55	89	L	50% RH	200	-598.6	*-598.6*
Ave.						*-656.3*
Coeff. of Variation						*12.1 %*

Table 4-8: Effect of environment for specimens moist cured 3 days, d=89 mm

No.	Diameter (mm)	Short or Long	Environment	Moist curing period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
1	89	S	Lab	3	-873.4	
48	89	L	Lab	3	-673.3	***-773.4***
39	89	L	Outside	3	-206.2	
40	89	L	Outside	3	-432.4	***-319.3***
18	89	L	Immersed	3	141.3	
28	89	L	Immersed	3	178.7	***160.0***
4	89	S	Tent	3	-872.7	
47	89	L	Tent	3	-621.3	***-747.0***

Table 4-9: Effect of environment for specimens moist cured 24/25 days, d=89 mm

No.	Diameter (mm)	Short or Long	Environment	Moist curing period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
17	89	S	Lab	24	-822.7	
46	89	L	Lab	24	-622.0	***-722.4***
16	89	S	Outside	24	-256.8	
49	89	L	Outside	24	-160.9	***-208.9***
15	89	S	Tent	24/25	-580.8	
27	89	L	Tent	24/25	-666.0	***-623.4***

Table 4-10: Effect of environment for specimens moist cured 3 days, d=152 mm

No.	Diameter (mm)	Short or Long	Environment	Moist curing period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
68	152	S	Lab	3	-873.1	
72	152	L	Lab	3	-520.8	***-697.0***
71	152	S	Outside	3	-290.3	
73	152	L	Outside	3	-425.0	***-357.7***
70	152	S	Tent	3	-685.9	
74	152	L	Tent	3	-815.4	***-750.7***

Table 4-11: Effect of environment for specimens moist cured 3 days, d=254 mm

No.	Diameter (mm)	Short or Long	Environment	Moist curing period (days)	Strain at 1259 days (microstrain)	Ave. (microstrain)
79	254	S	Lab	3	-777.5	
86	254	L	Lab	3	-883.9	***-830.7***
81	254	S	Outside	3	-301.5	
84	254	L	Outside	3	-457.2	***-379.4***
82	254	S	Tent	3	-774.6	
85	254	L	Tent	3	-766.0	***-770.3***

Figure 4-1: Shrinkage of 89 mm Specimens in Lab Environment, Moist cured 3 days

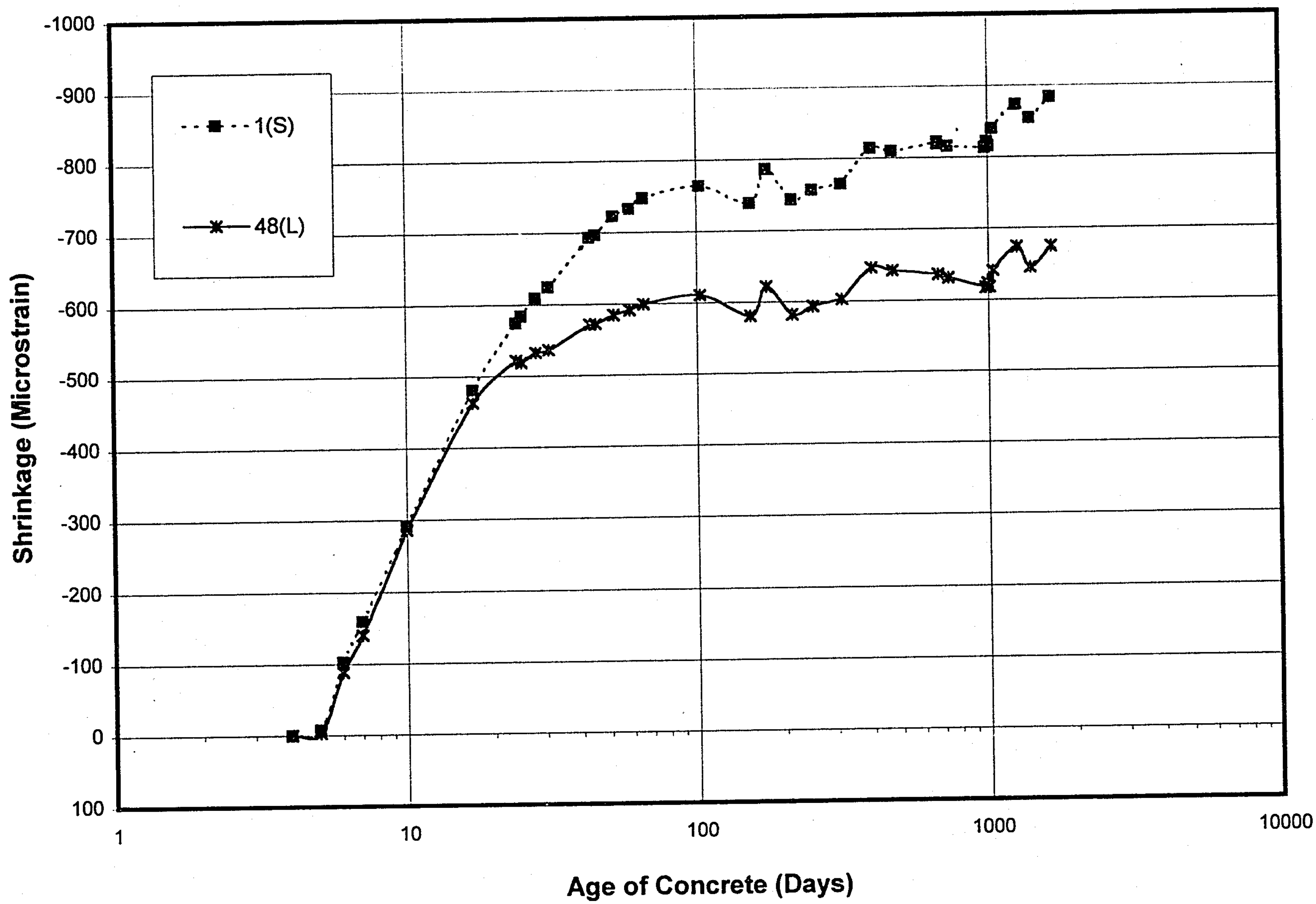


Figure 4-2: Shrinkage of 89 mm Specimens in Lab Environment, Moist cured 24 days

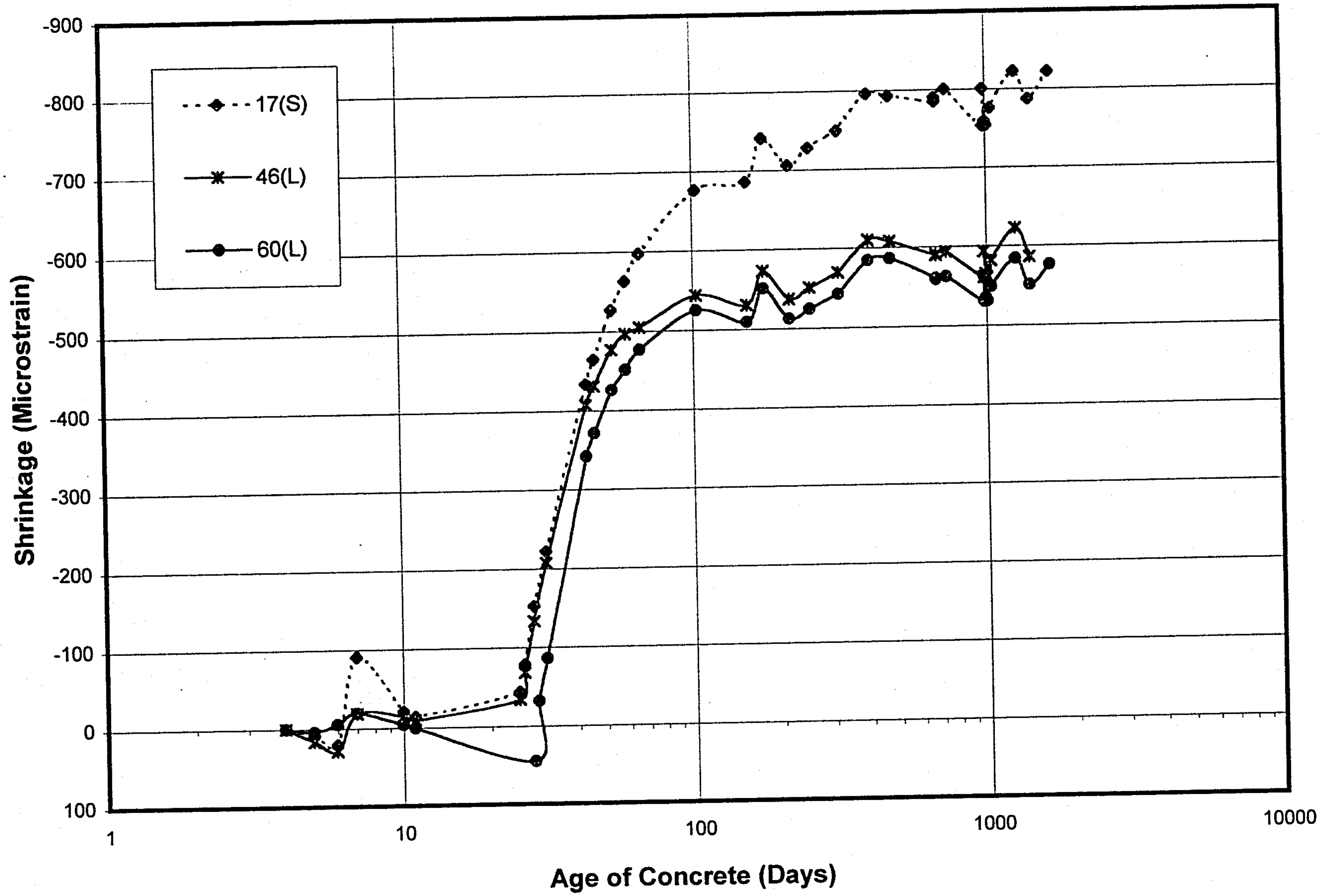


Figure 4-3: Shrinkage of 152 mm Specimens in Lab Environment, Moist cured 3 days

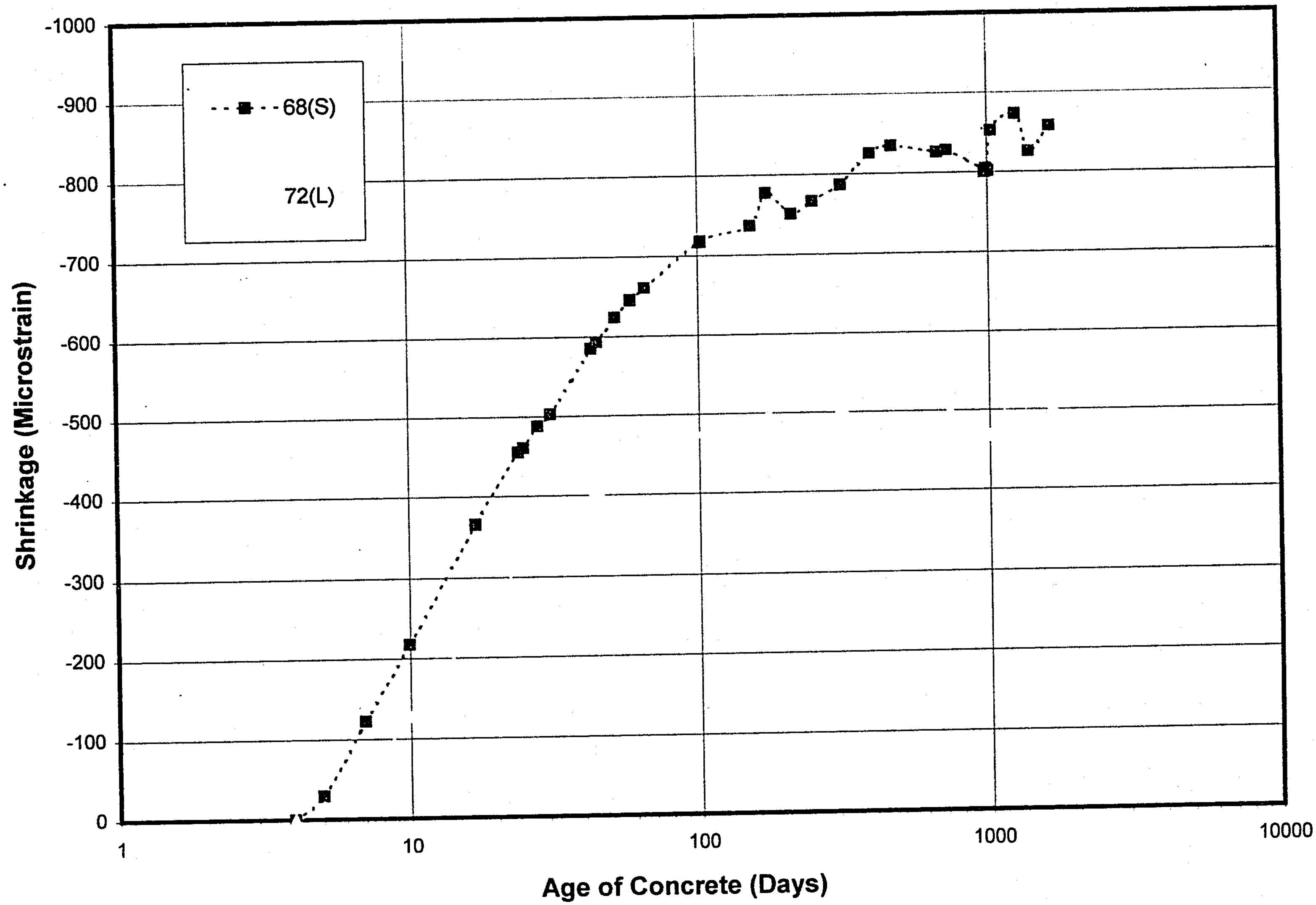


Figure 4-4: Shrinkage of 254 mm Specimens in Lab Environment, Moist cured 3 days

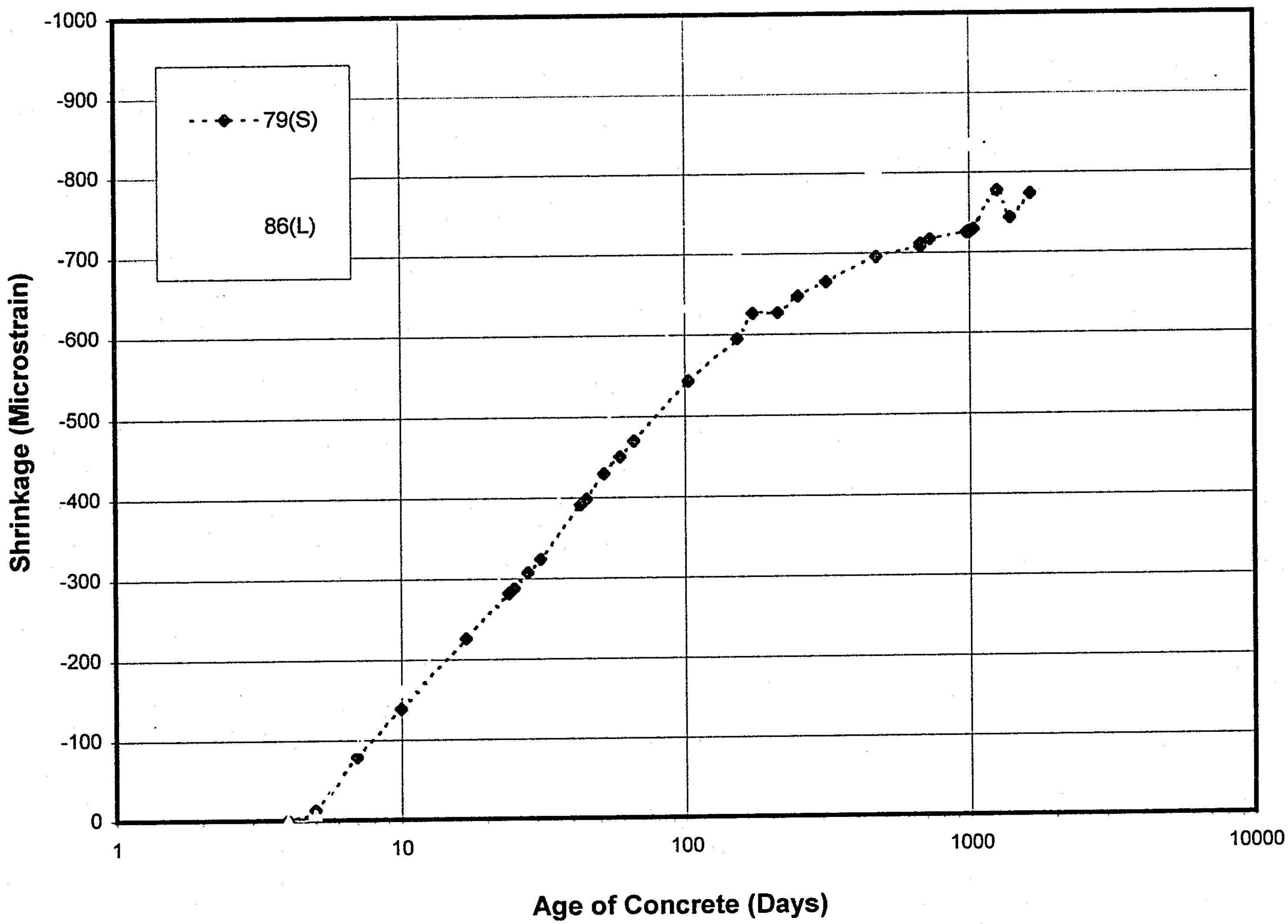


Figure 4-5: Shrinkage of 610 mm Specimens in Lab Environment, Moist cured 3 days

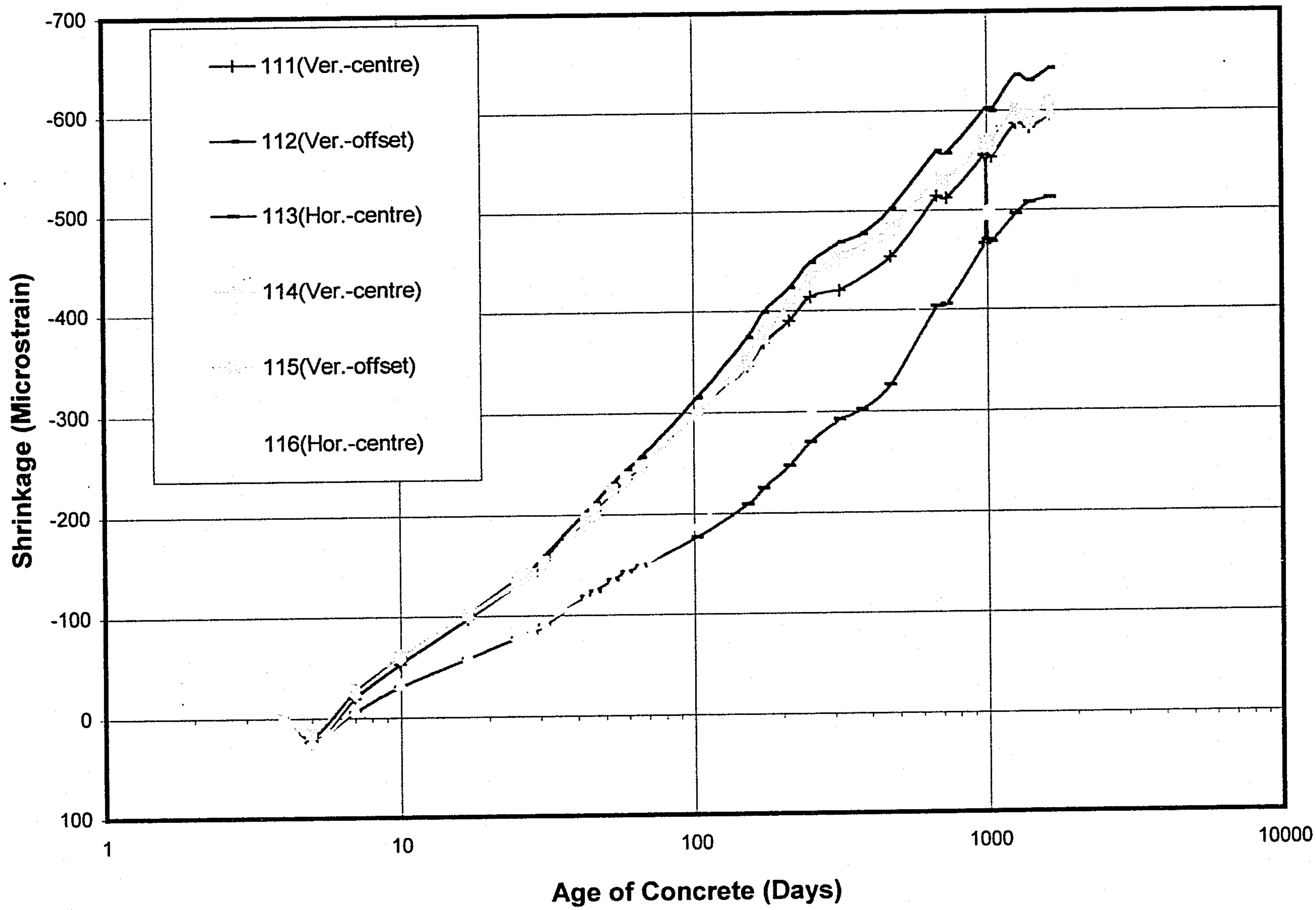


Figure 4-6: Shrinkage of 89 mm Specimens Outdoor Environment, Moist cured 3 days

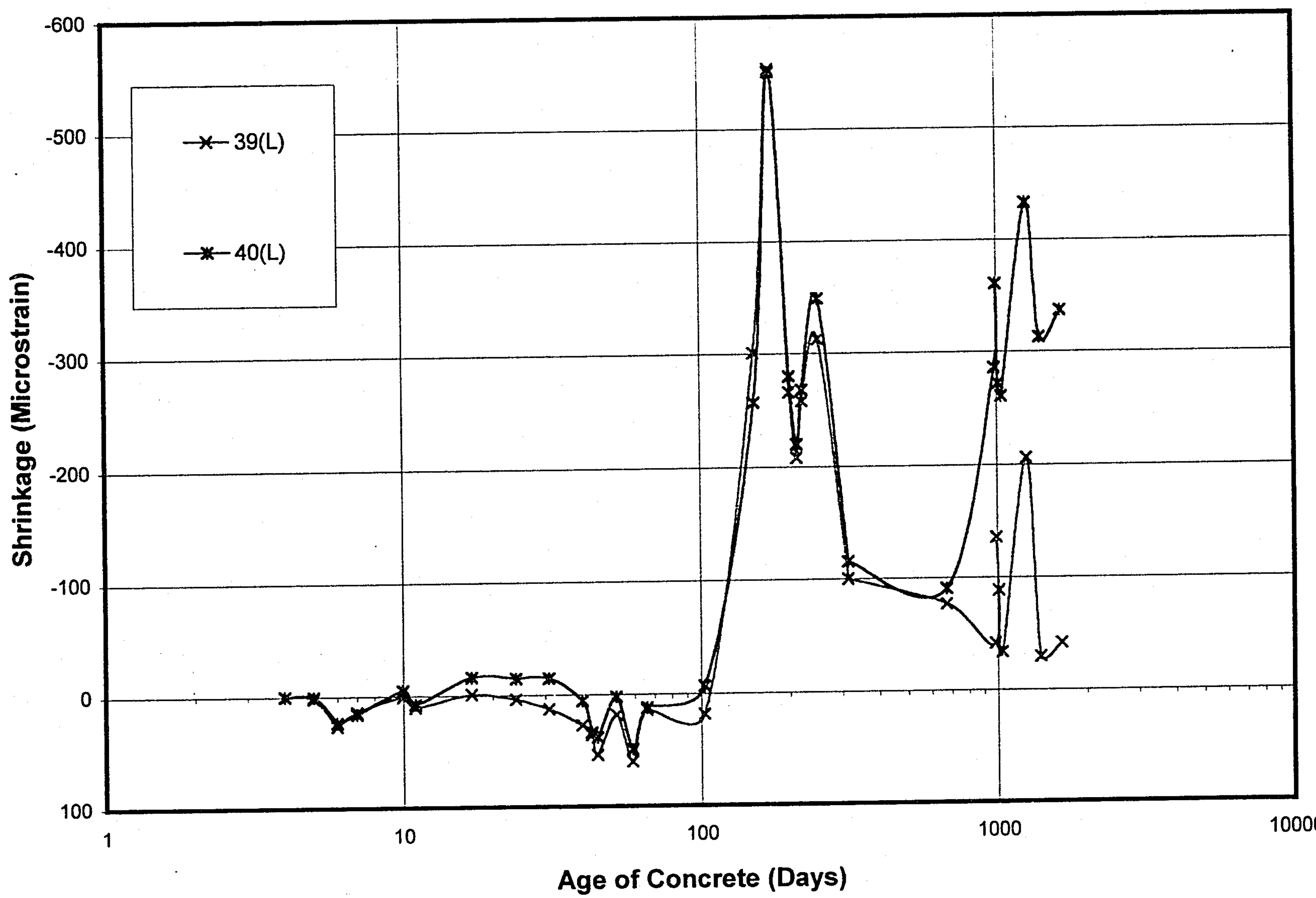


Figure 4-7: Shrinkage of 89 mm Specimens Outdoor Environment, Moist cured 24 days

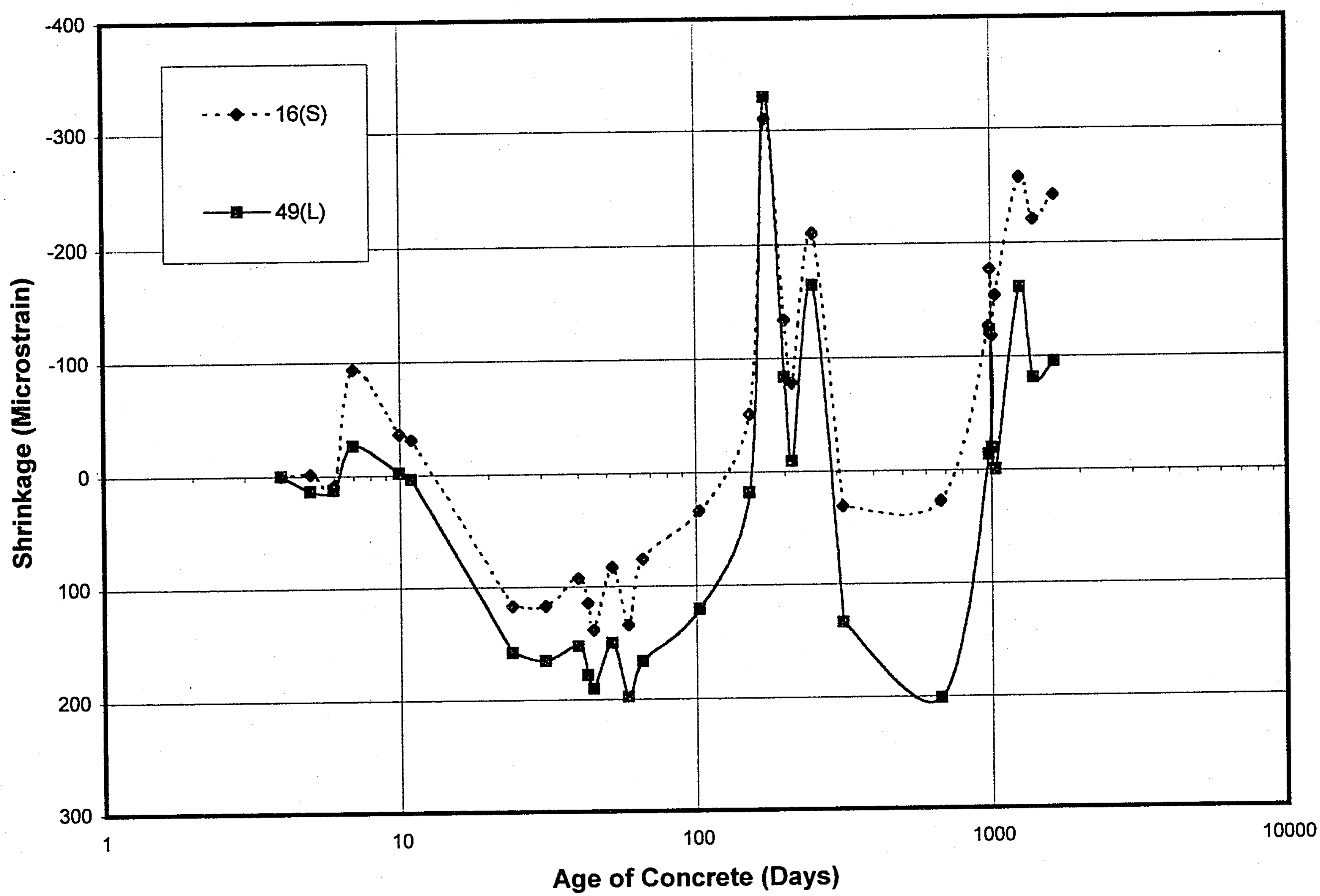


Figure 4-8: Shrinkage of 152 mm Specimens Outdoor Environment, Moist cured 3 days

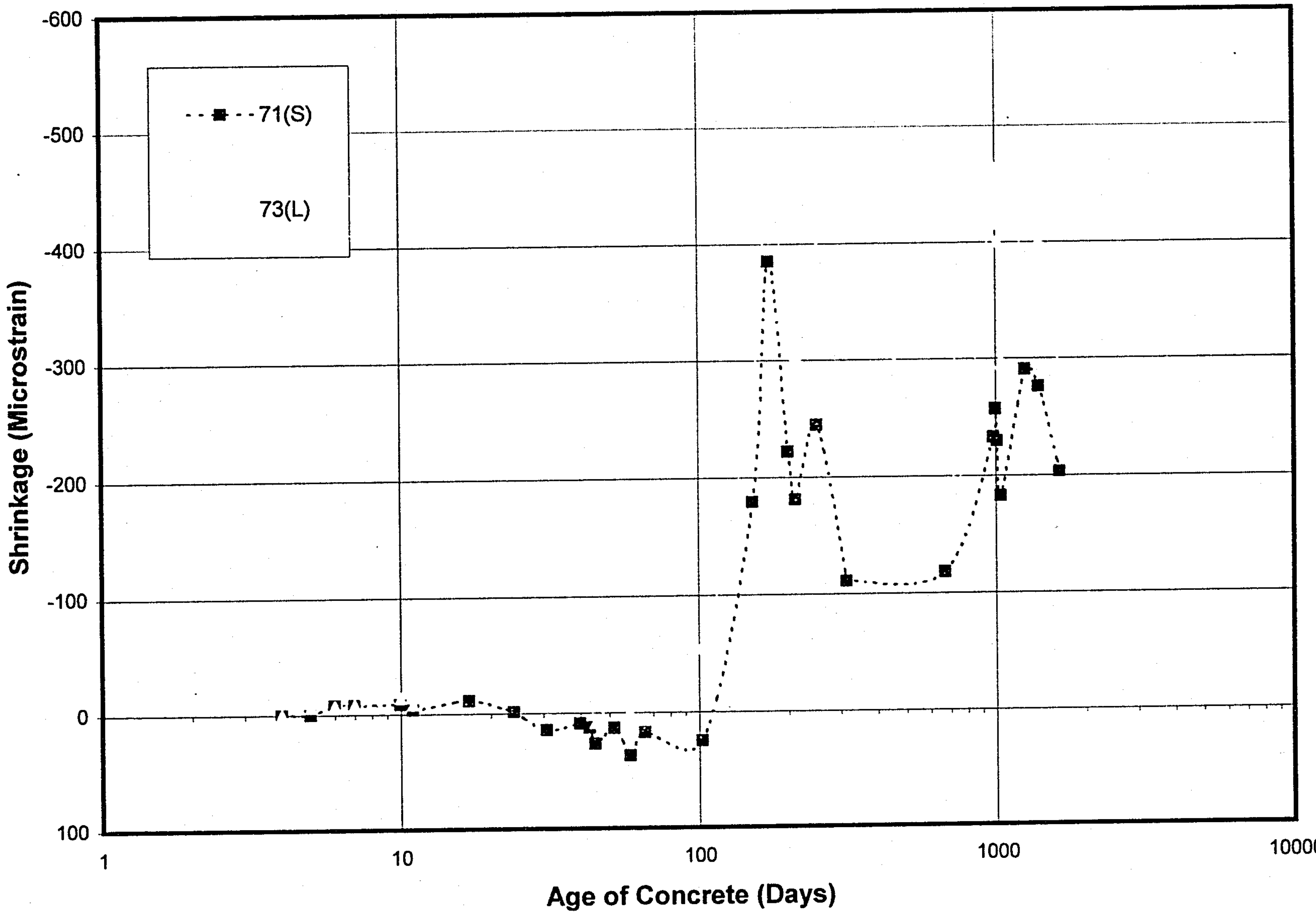


Figure 4-9: Shrinkage of 254 mm Specimens Outdoor Environment, Moist cured 3 days

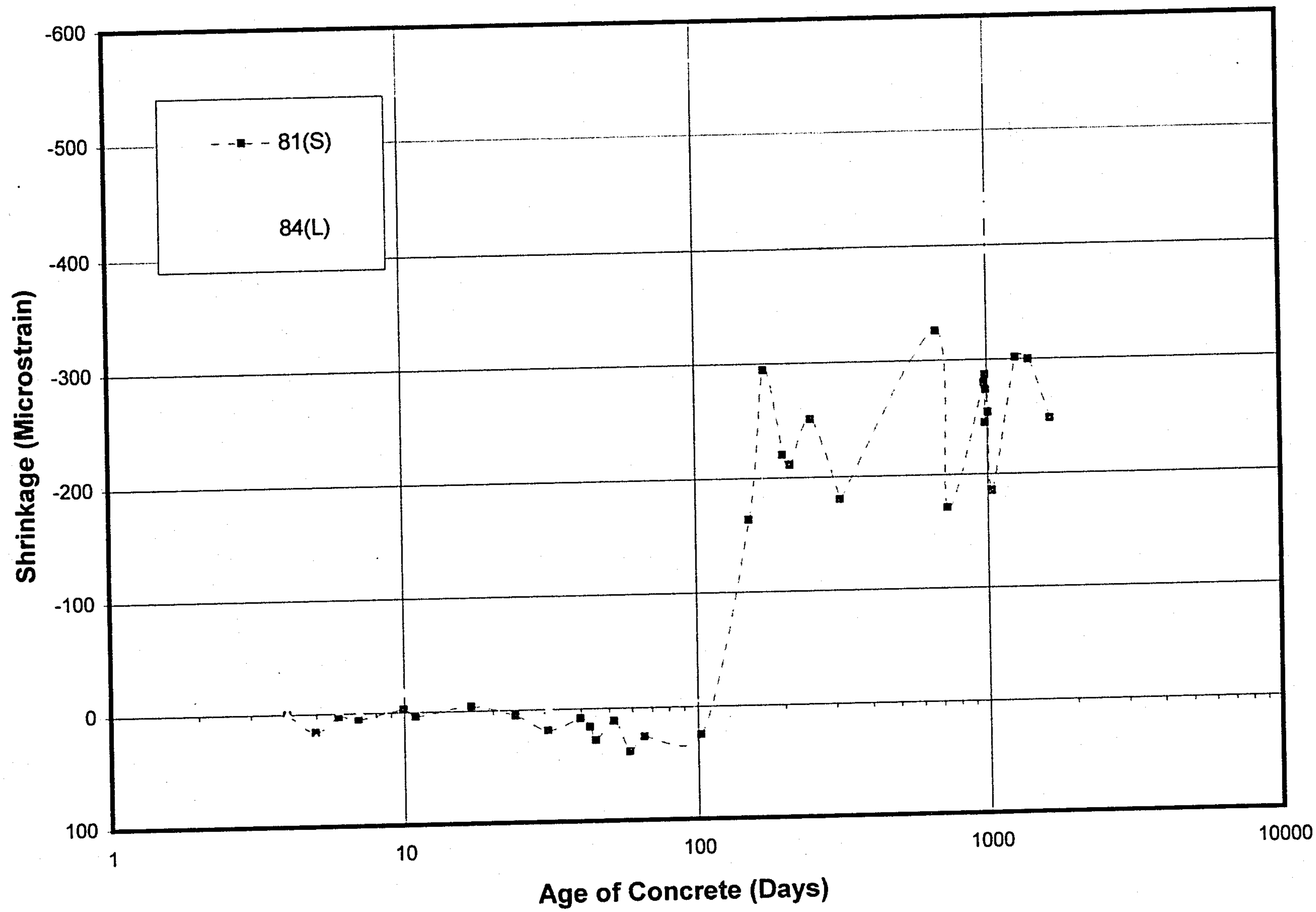


Figure 4-10: Shrinkage of 89 mm Immersed Specimens, Moist cured 3 days

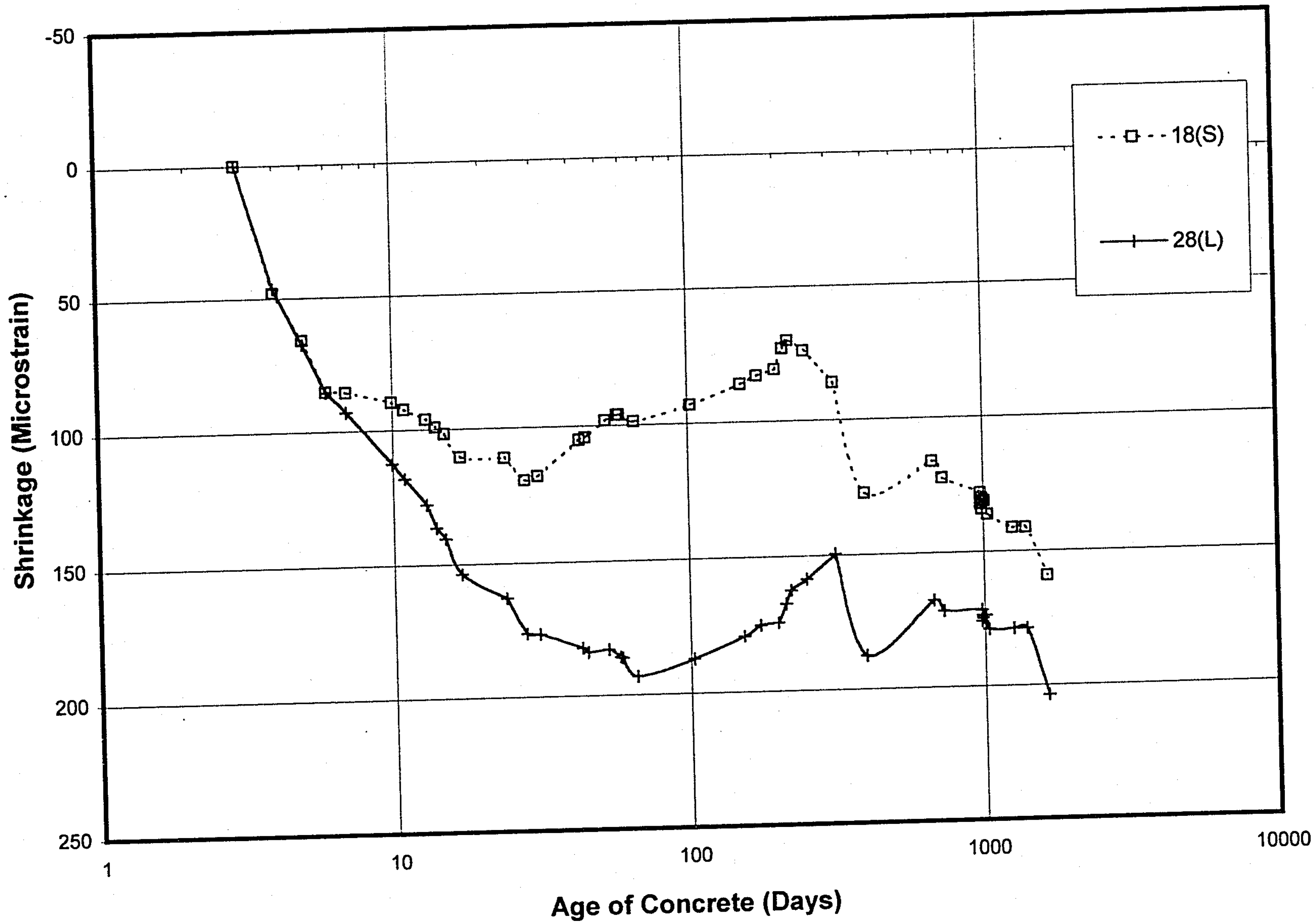


Figure 4-11: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days

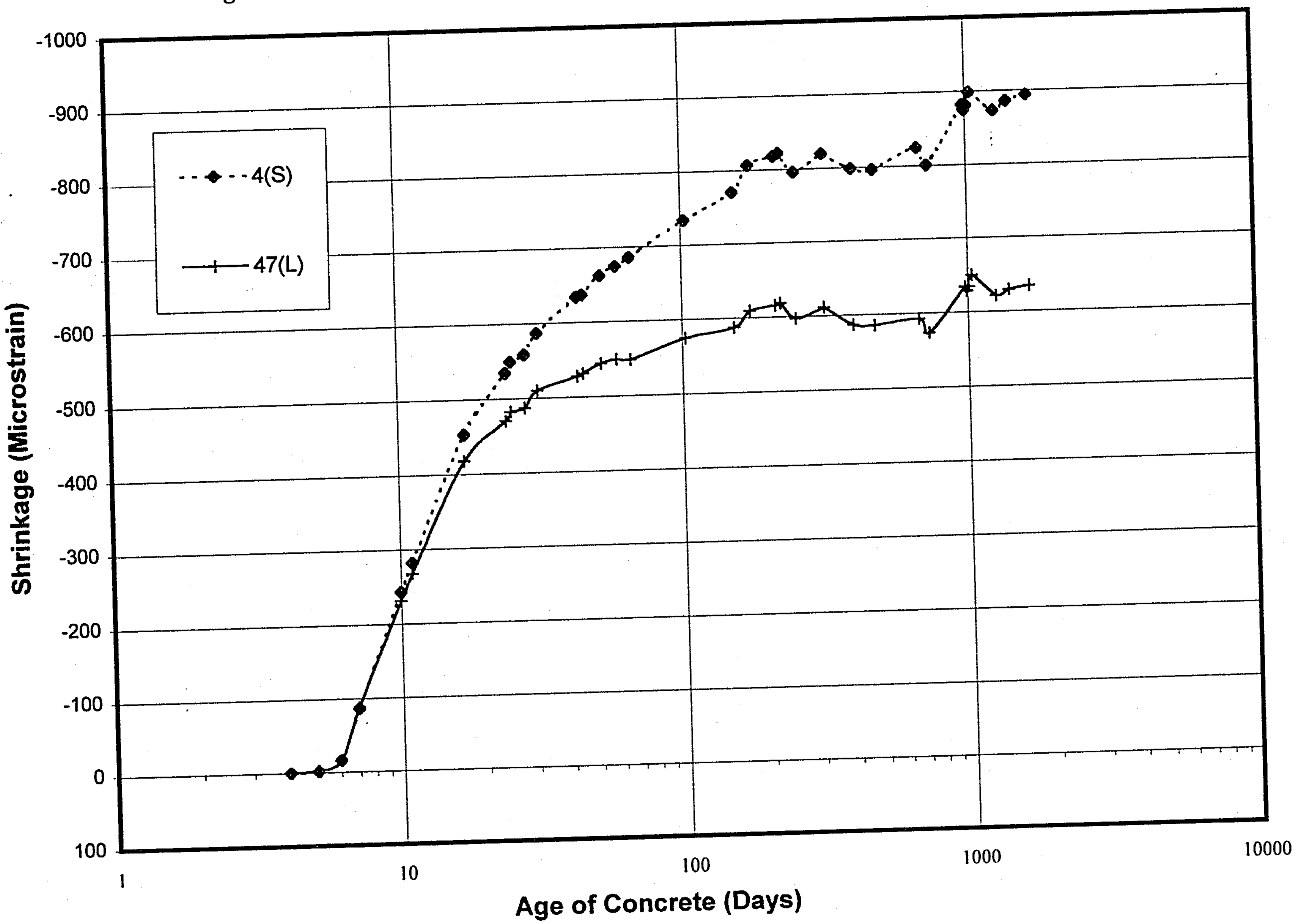


Figure 4-12: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 24/25 days

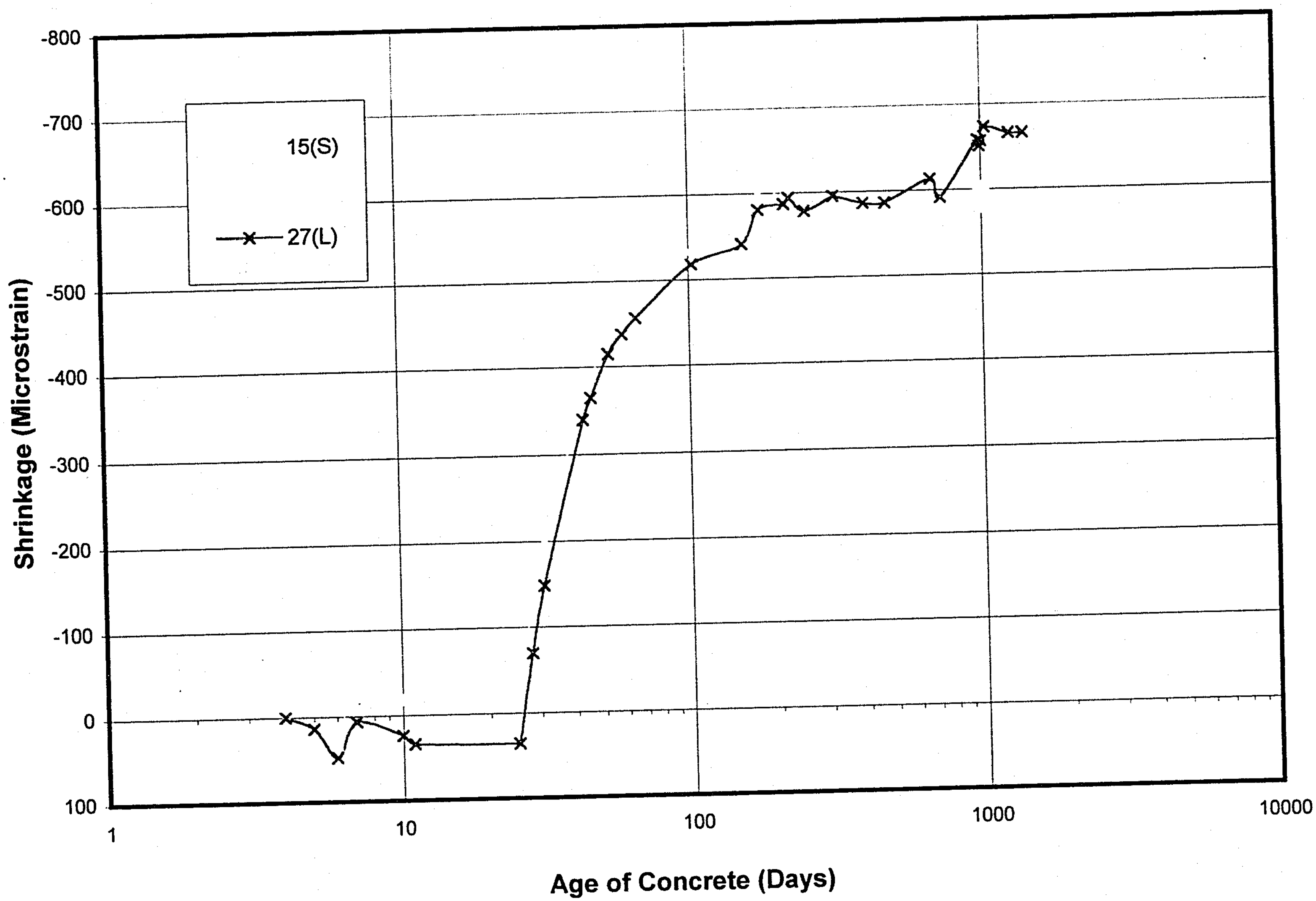


Figure 4-13: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 200 days

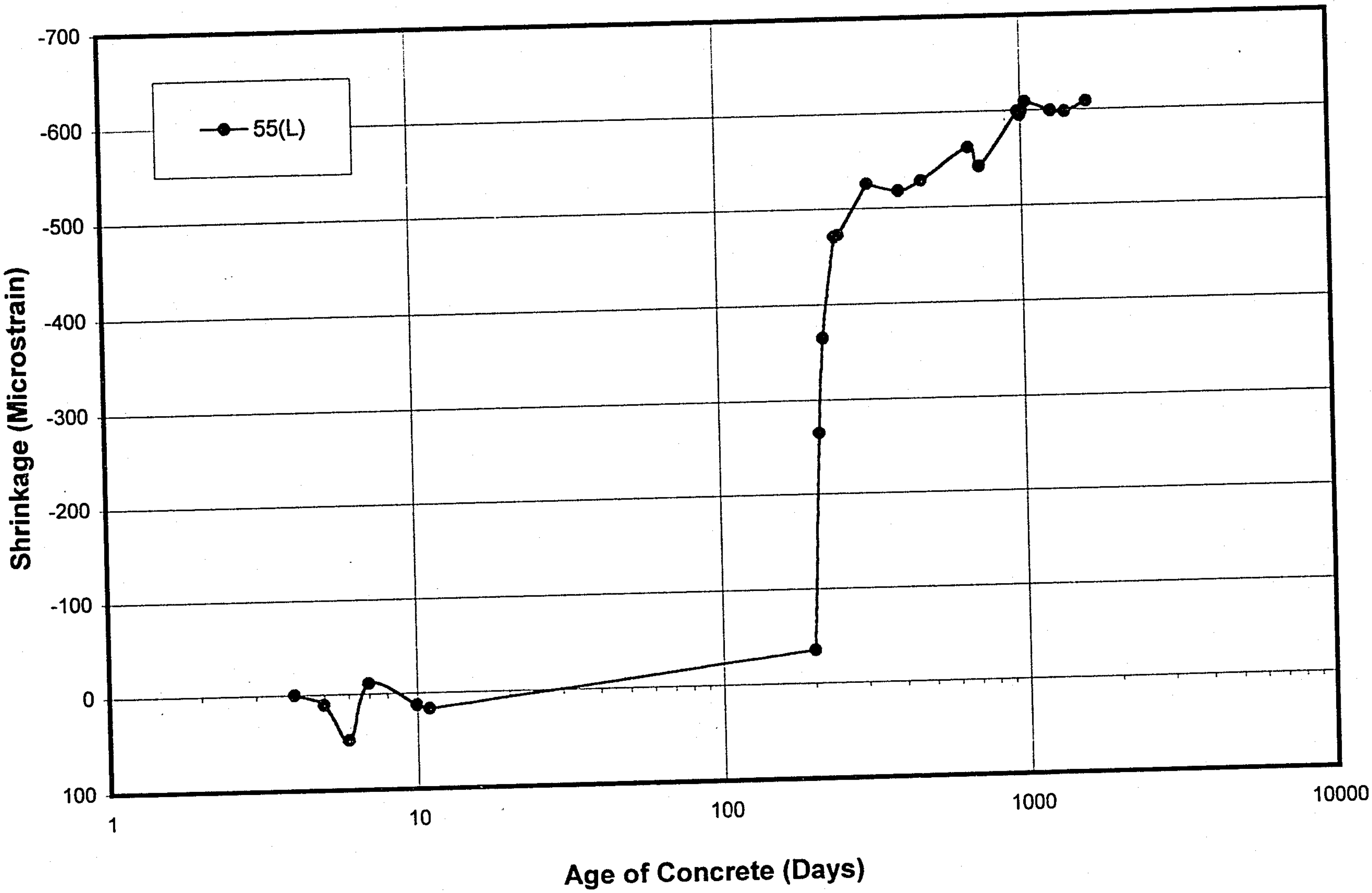


Figure 4-14: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 3 days

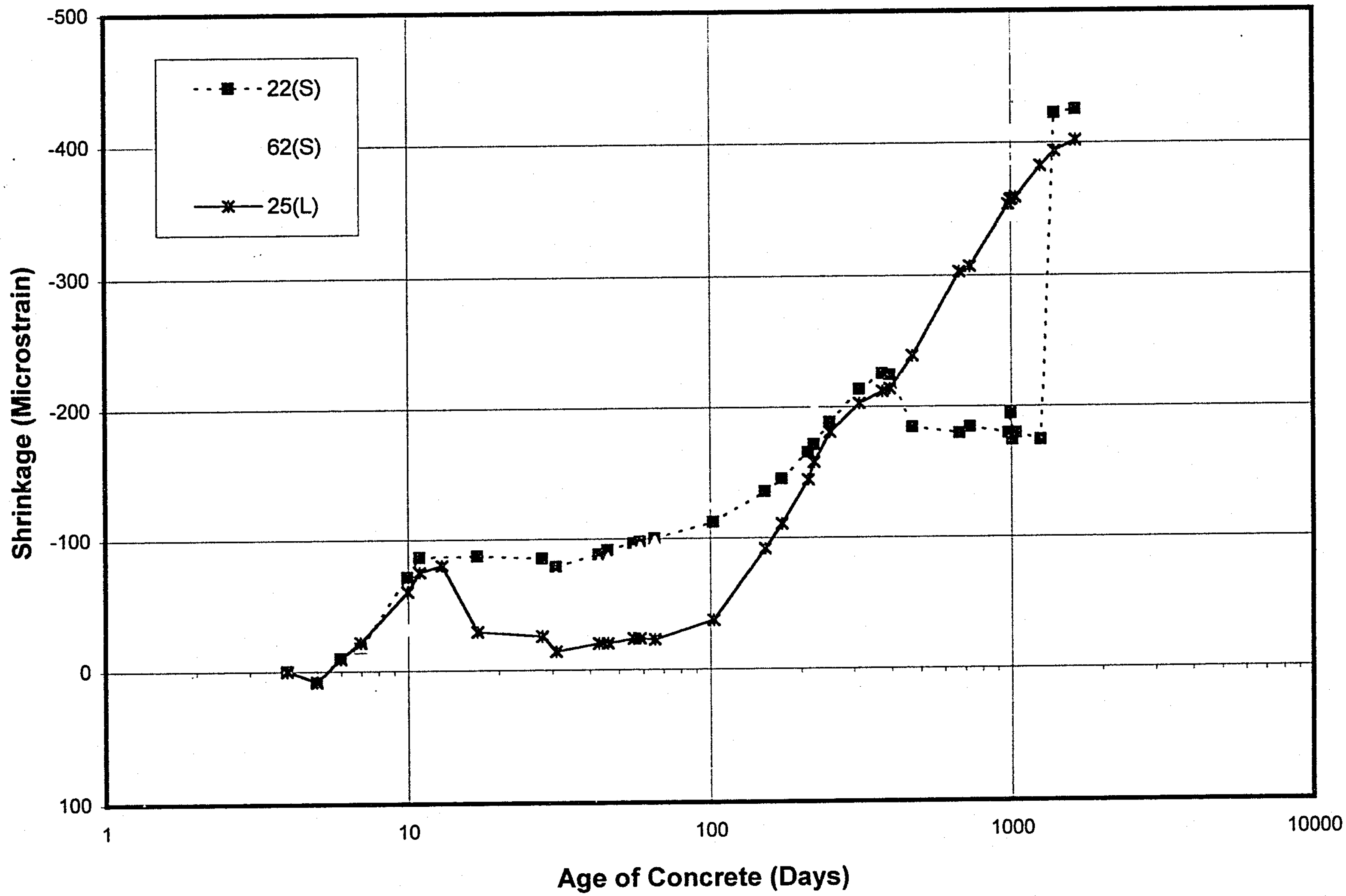


Figure 4-15: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 25 days and Sealed after 25 days

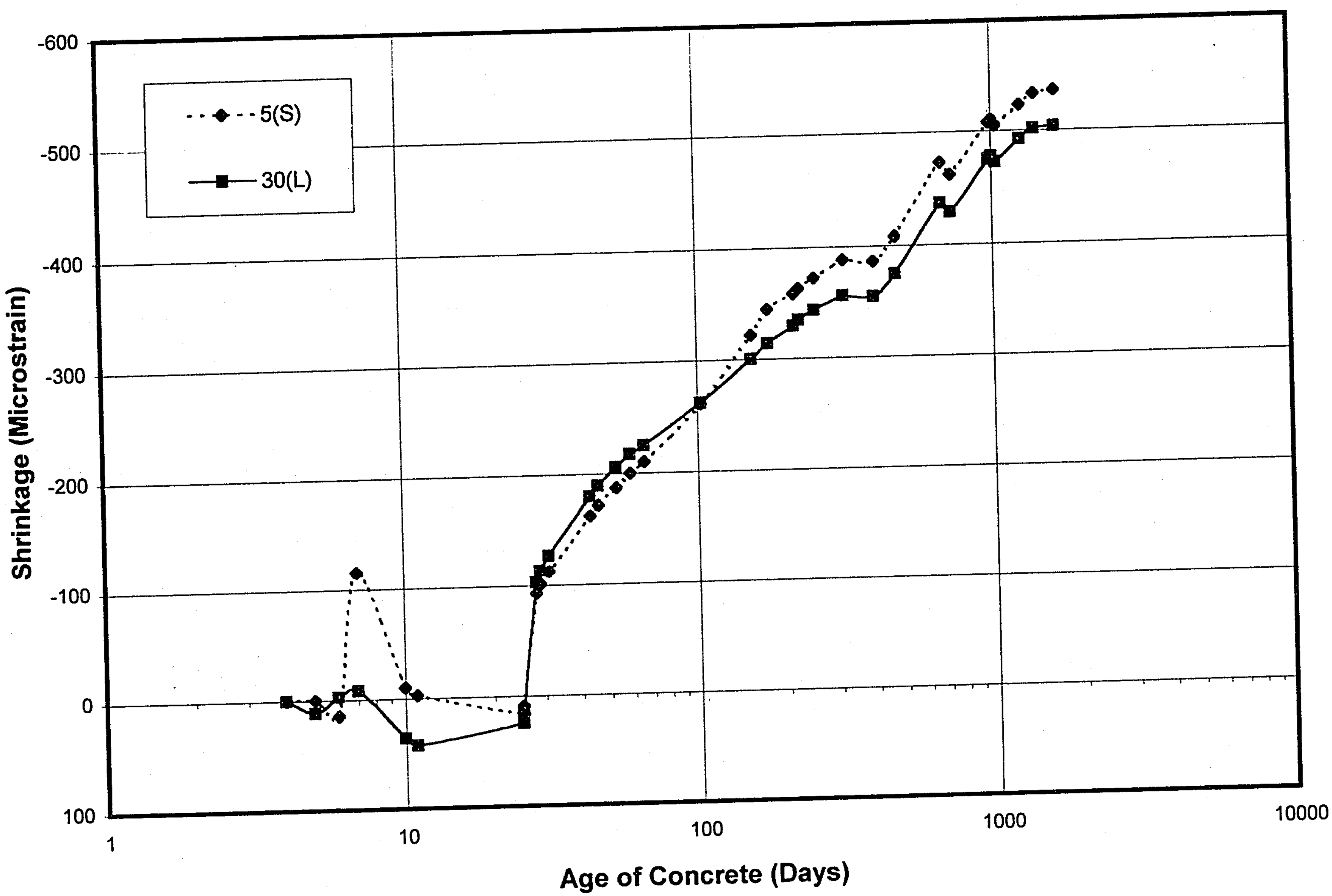


Figure 4-16: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 25 days

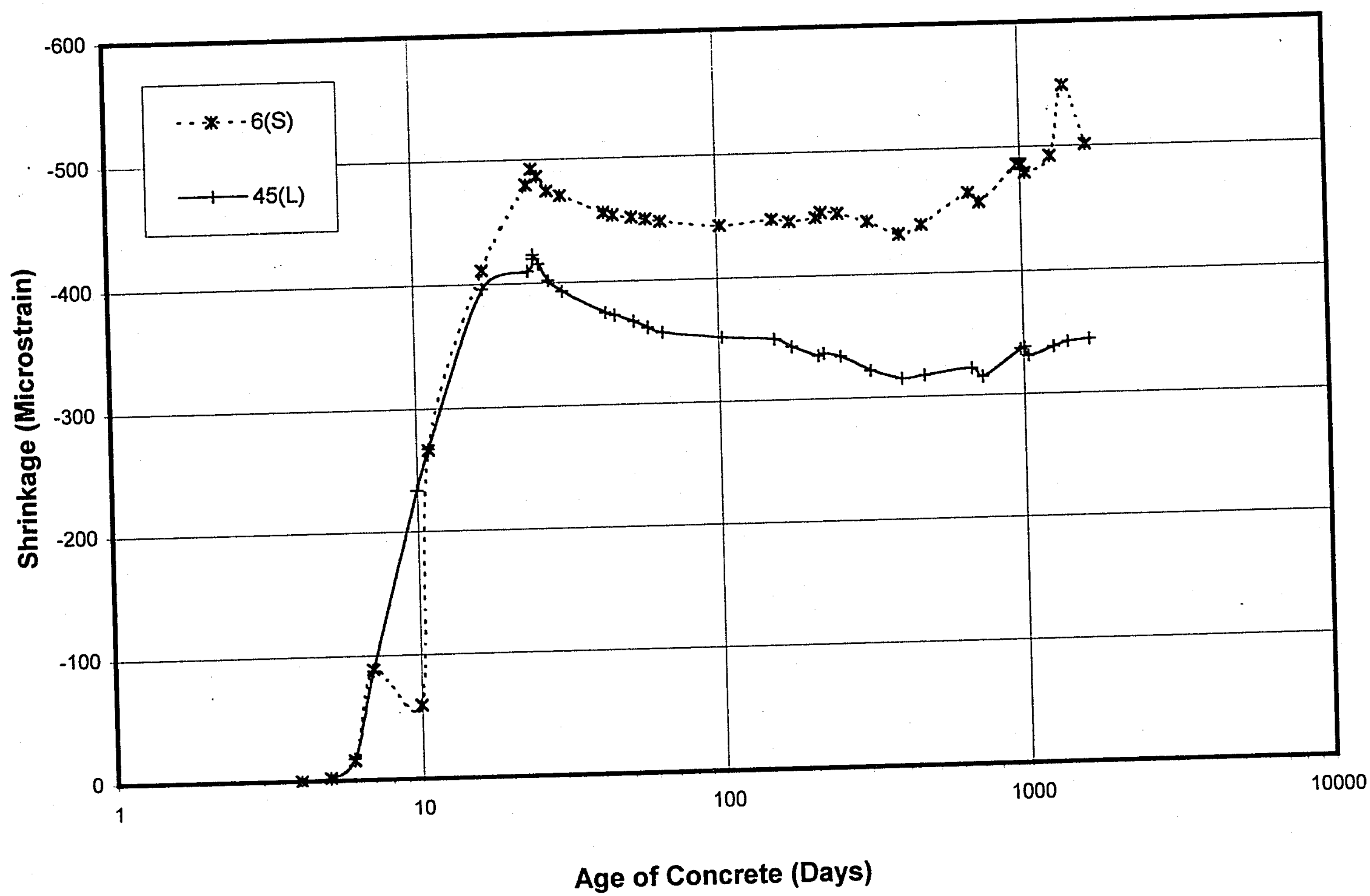


Figure 4-17: Shrinkage of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 200 days

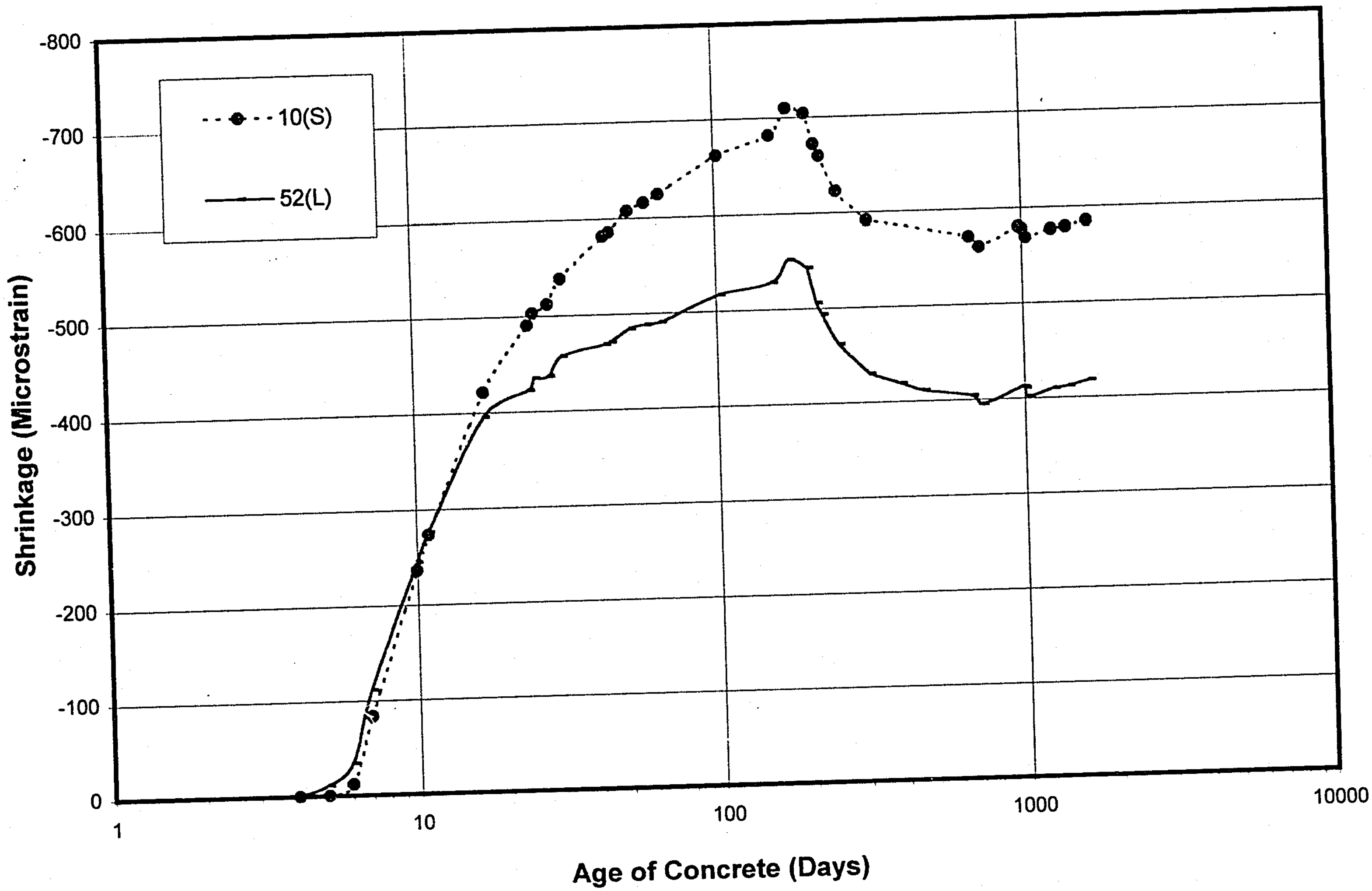


Figure 4-18: Shrinkage of 152 mm Specimens in 50% R.H. Environment, Moist cured 3 days

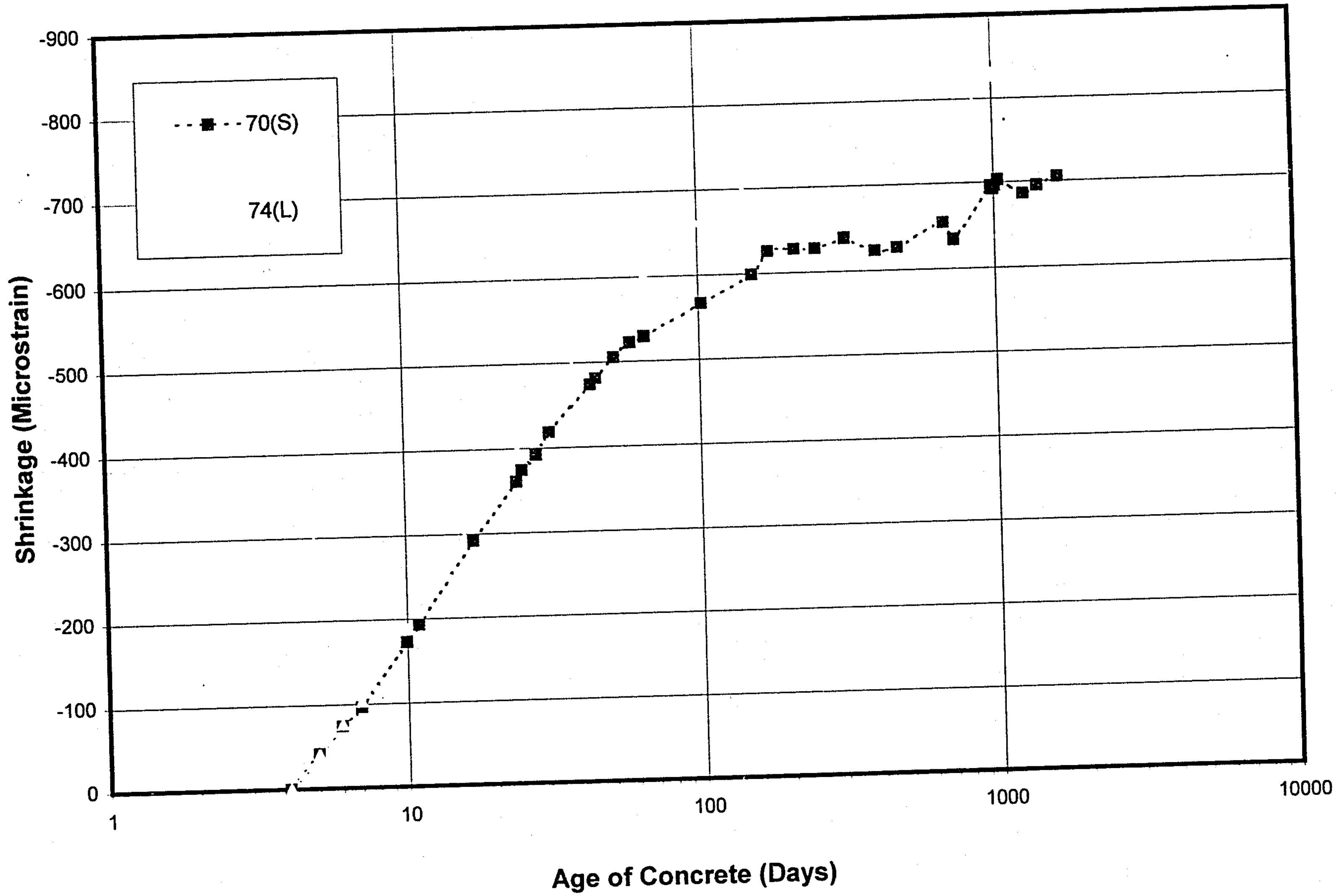


Figure 4-19: Shrinkage of 254 mm Specimens in 50% R.H. Environment, Moist cured 3 days

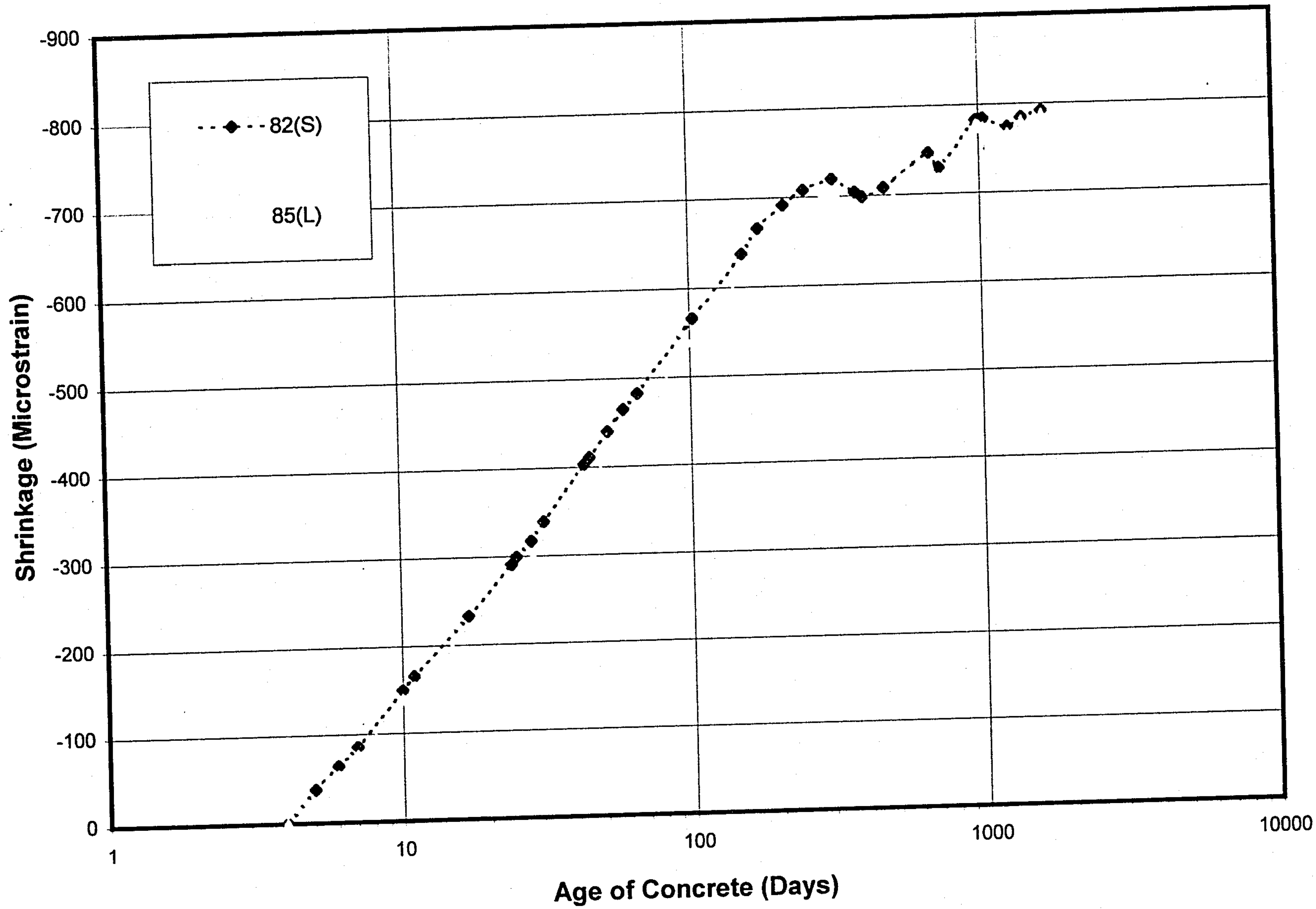


Figure 4-20: Environment Effect - Shrinkage of 89 mm Specimens in Various Environments
Specimen 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days

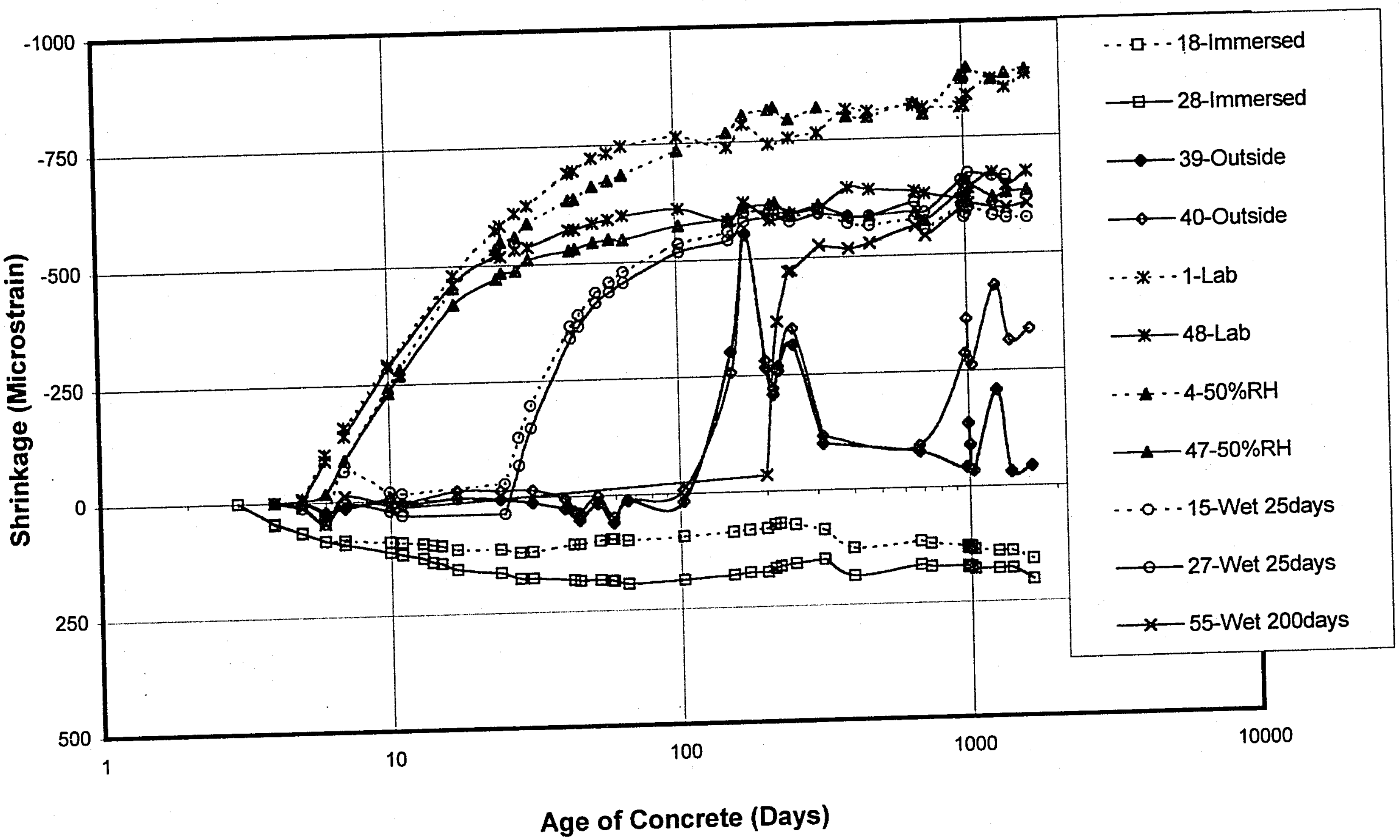


Figure 4-21(a): Environment Effect - All 89 mm Specimens stored in 50 % RH, Specimen 22, 62, 25 sealed after demoulding at 3 days, Specimen 6 & 45 sealed at 25 days, Specimen 10 & 52 sealed at 200 days, Specimen 5 & 30 Moist cured 25 days and sealed 25 days

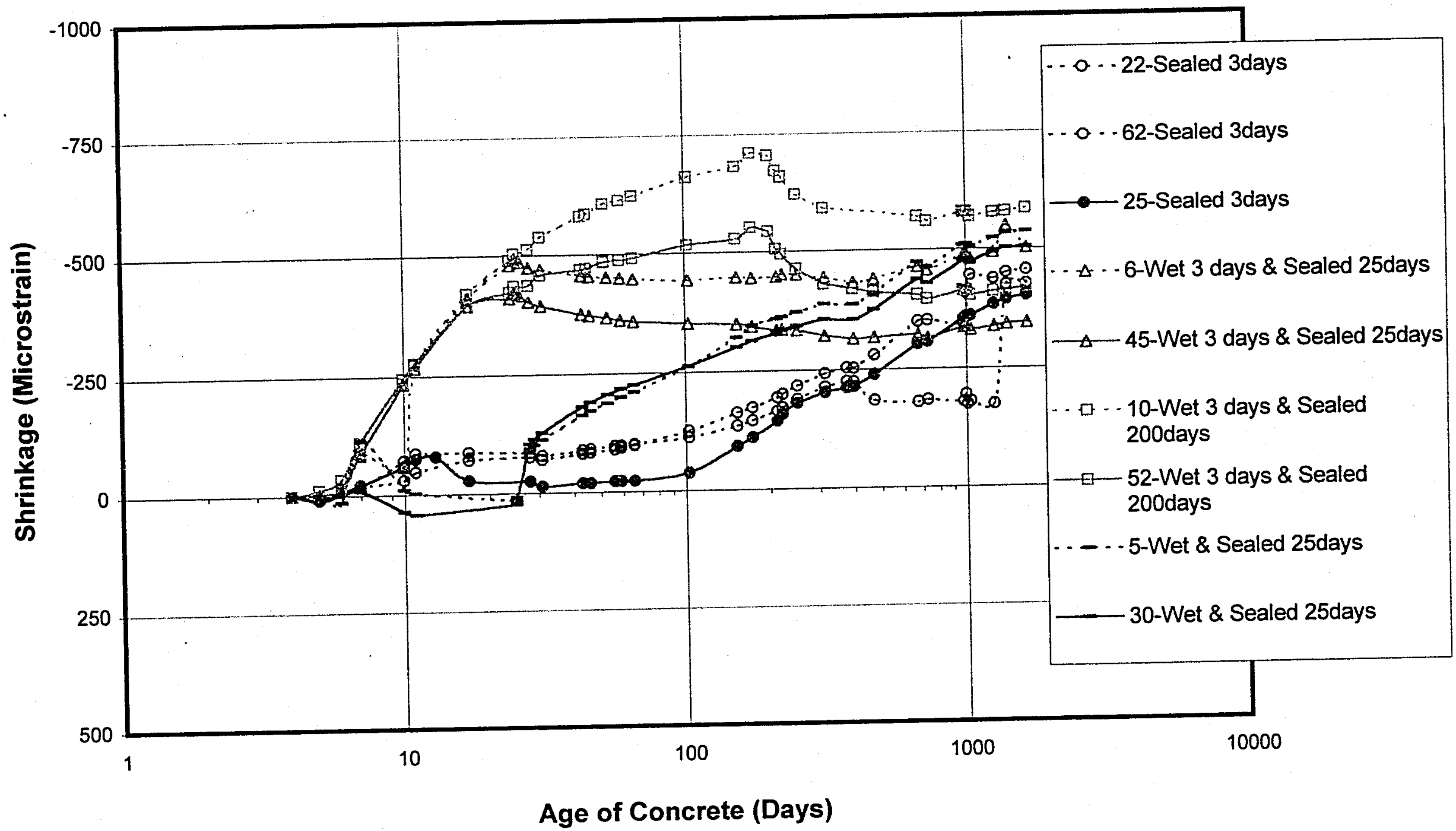


Figure 4-21(b): Environment Effect - All 89 mm Specimens stored in 50 % RH, Specimen 22, 62, 25 sealed after demoulding at 3 days, Specimen 6 & 45 sealed at 25 days, Specimen 10 & 52 sealed at 200 days, Specimen 5 & 30 Moist cured 25 days and sealed 25 days

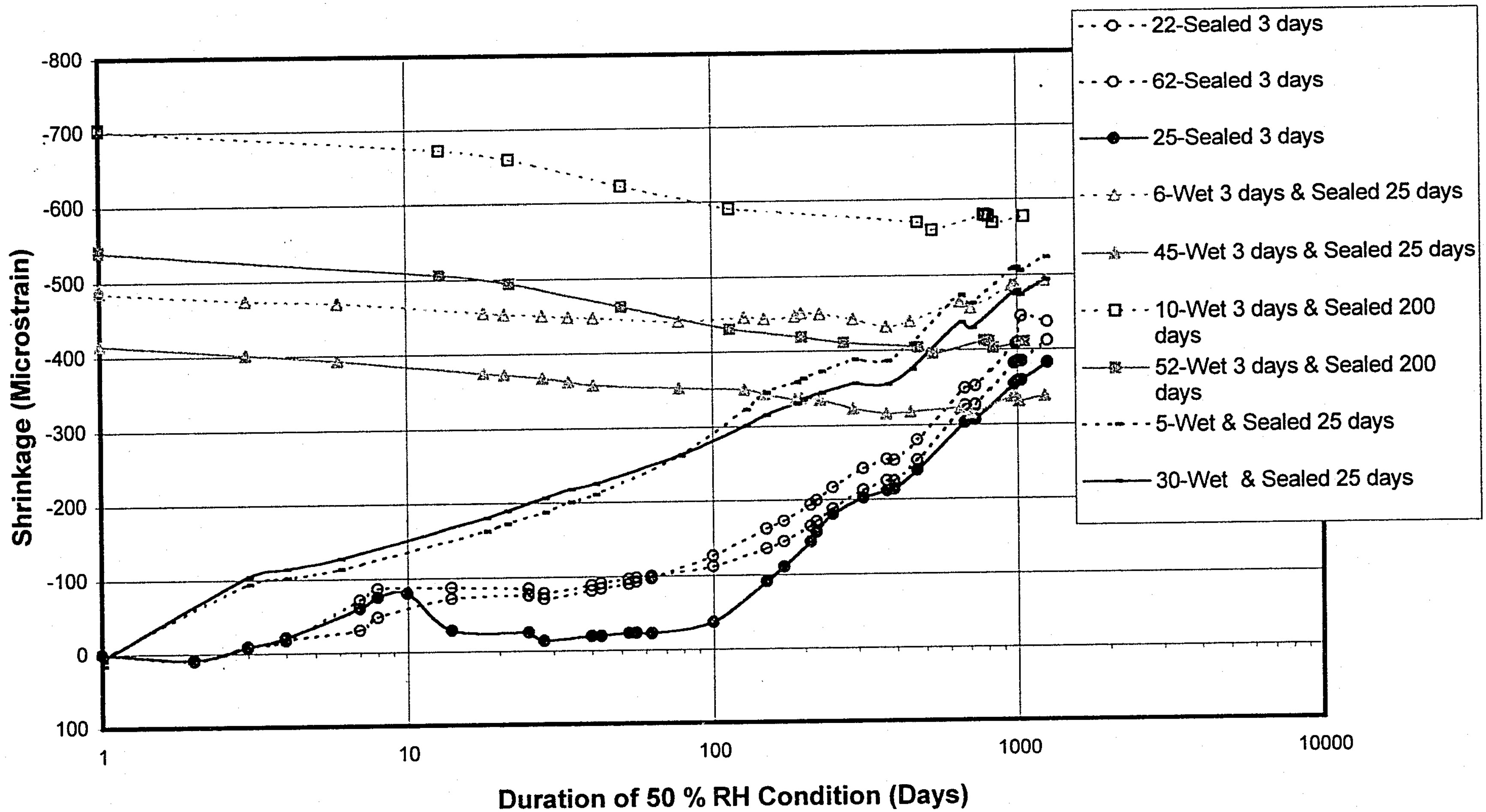


Figure 4-22: Environment Effect - Shrinkage of 152 mm Specimens in Various Environments

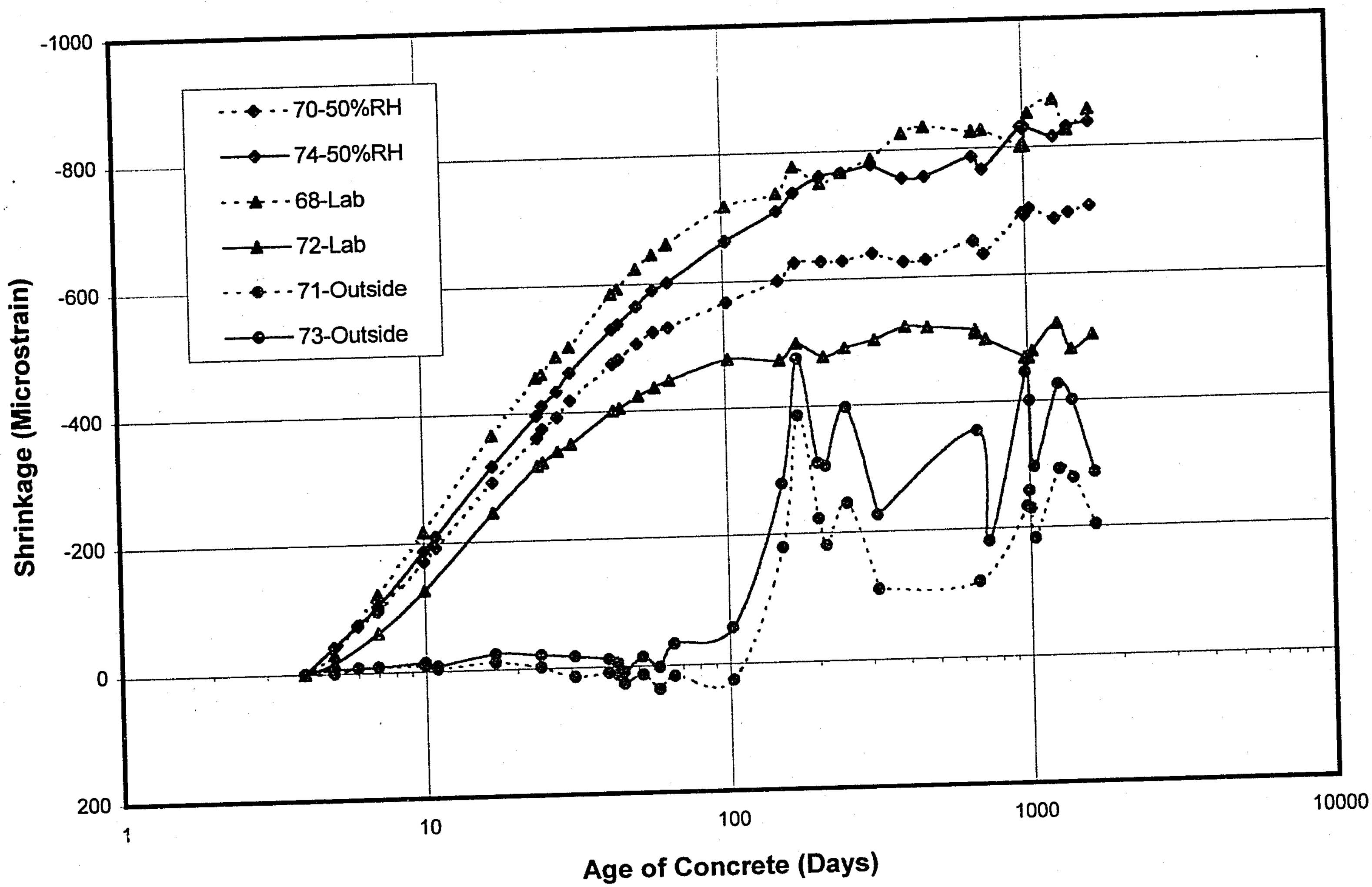


Figure 4-23: Environment Effect - Shrinkage of 254 mm Specimens in Various Environment

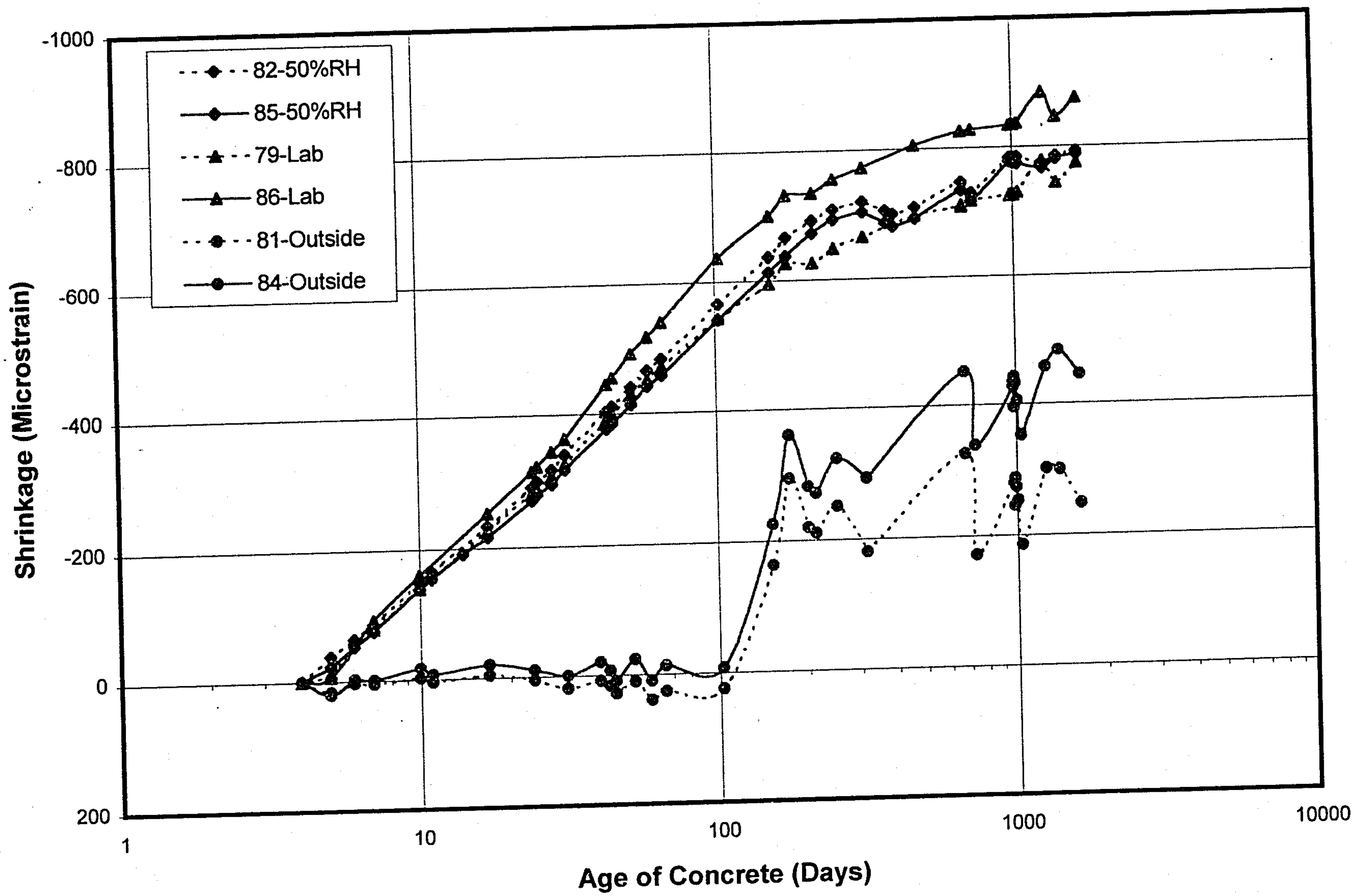


Figure 4-24(a): Longitudinal & Lateral Shrinkage of 610 mm Specimens in the Lab

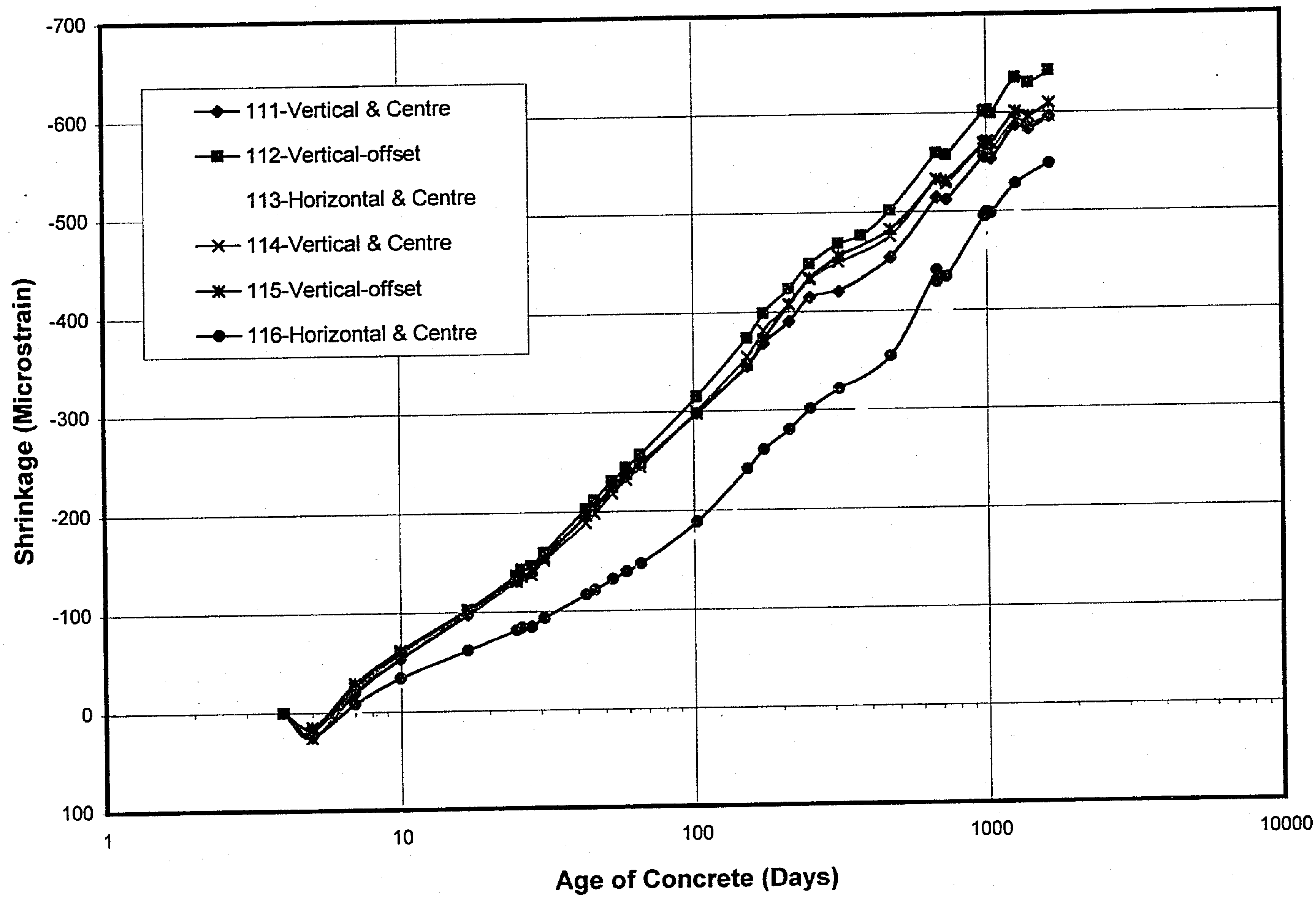


Figure 4-24(b): Longitudinal Shrinkage of 610 mm Specimens in the Lab, Strain gauge 111 & 114 are centre, Strain gauge 112 & 115 are offset of 152 mm

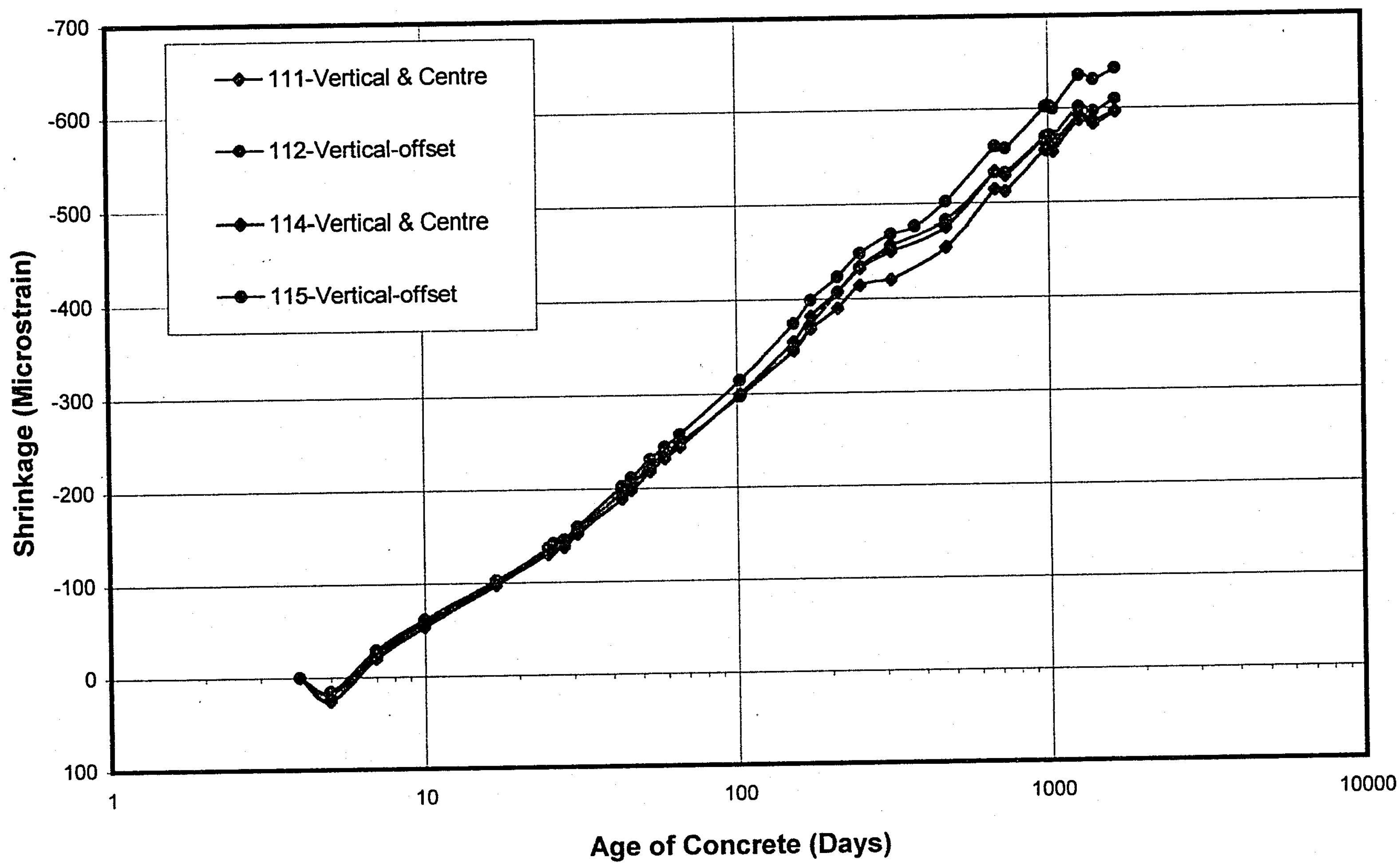


Figure 4-25: Size Effect - Shrinkage of the 89, 152, 254, and 610 mm Specimens in the Lab

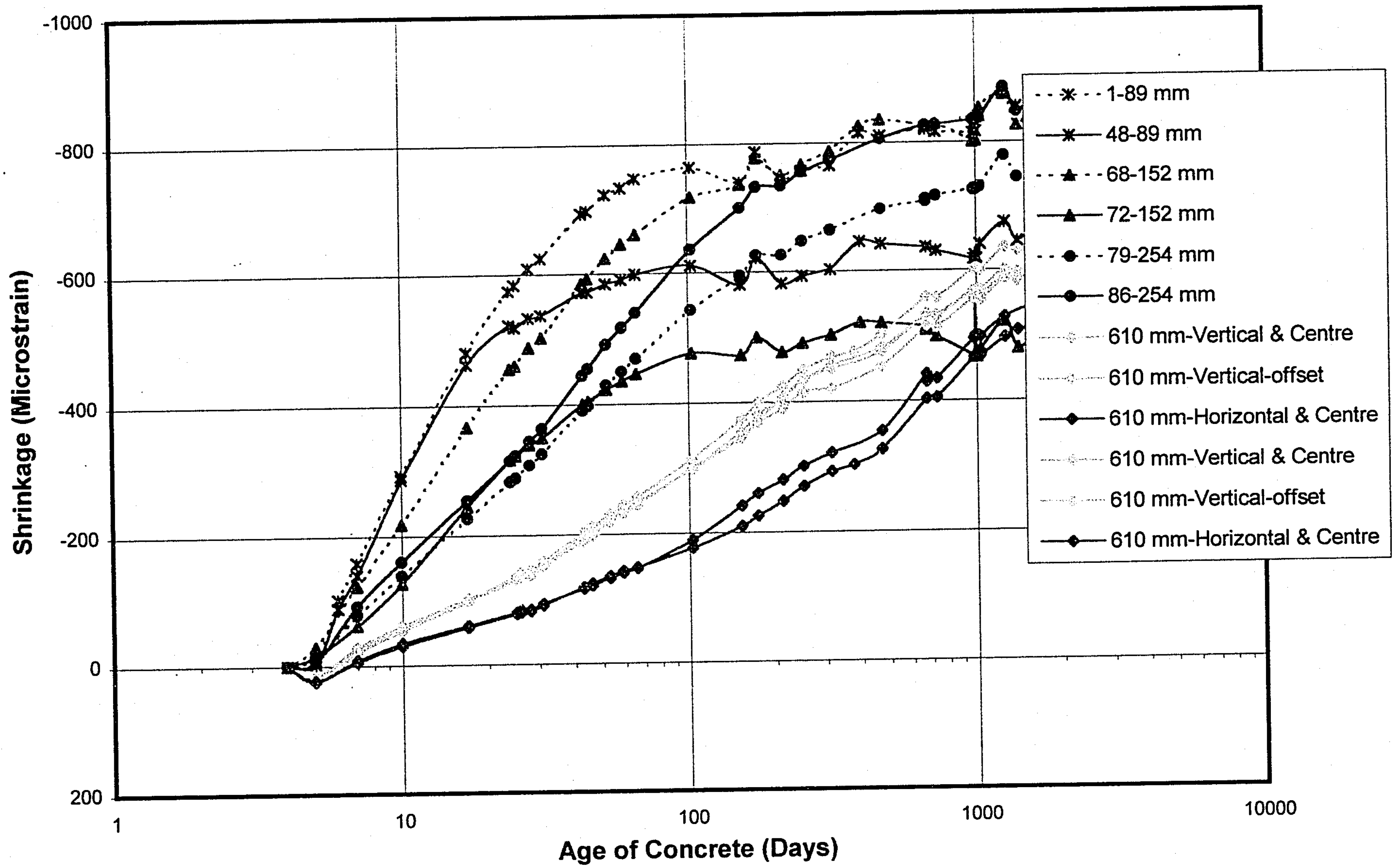


Figure 4-26: Size Effect - Shrinkage of the 89, 152, and 254 mm Specimens Outside Environment

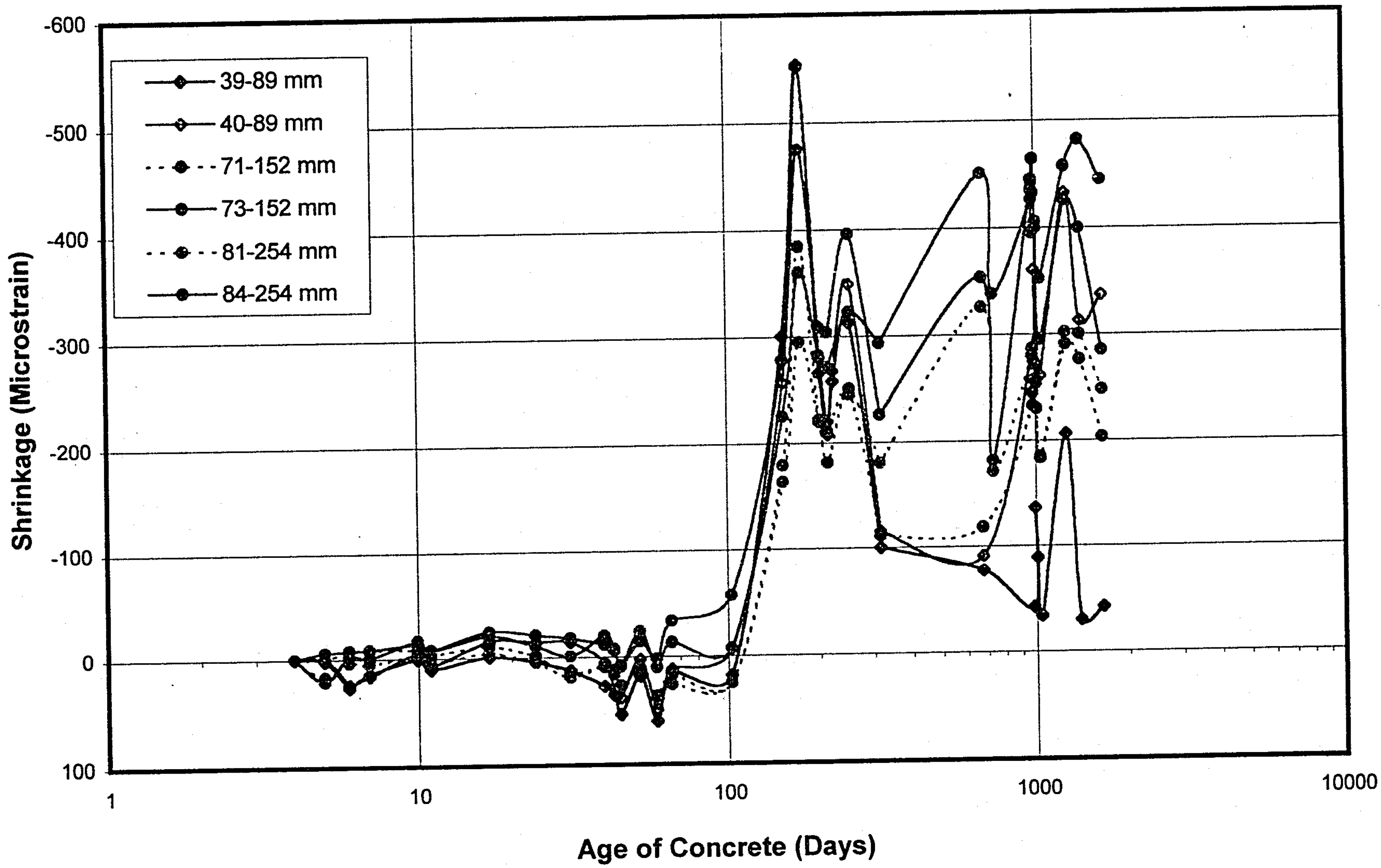


Figure 4-27(a): Size Effect - Shrinkage of the 89, 152, and 254 mm Specimens in 50 % RH, Specimen 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days, all other specimens moist cured 3 days

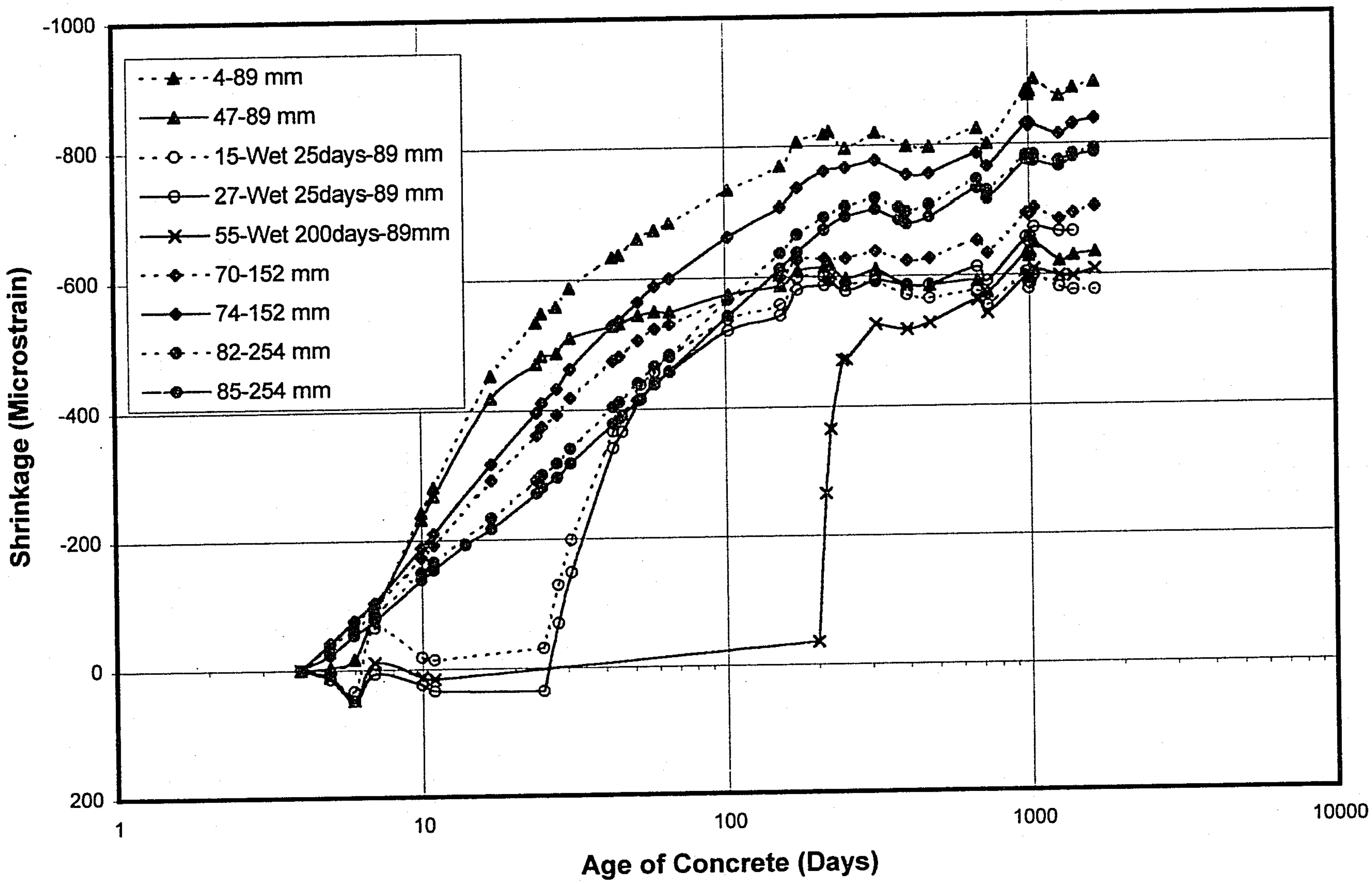


Figure 4-27(b1): Moist Curing Period Effect - Shrinkage of the 89 Specimens in 50 % RH,Specimens 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days, Other specimens moist cured 3 days

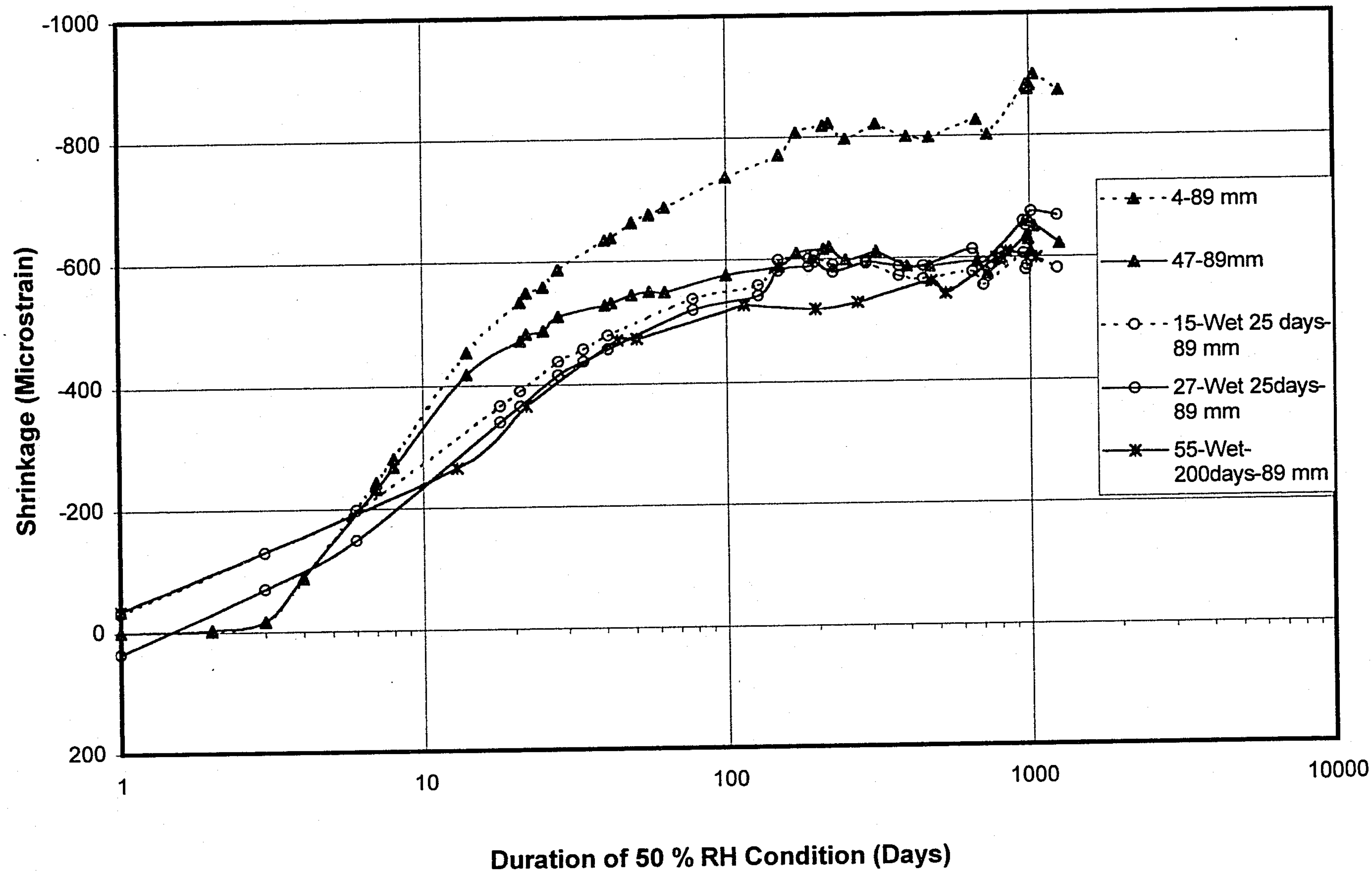
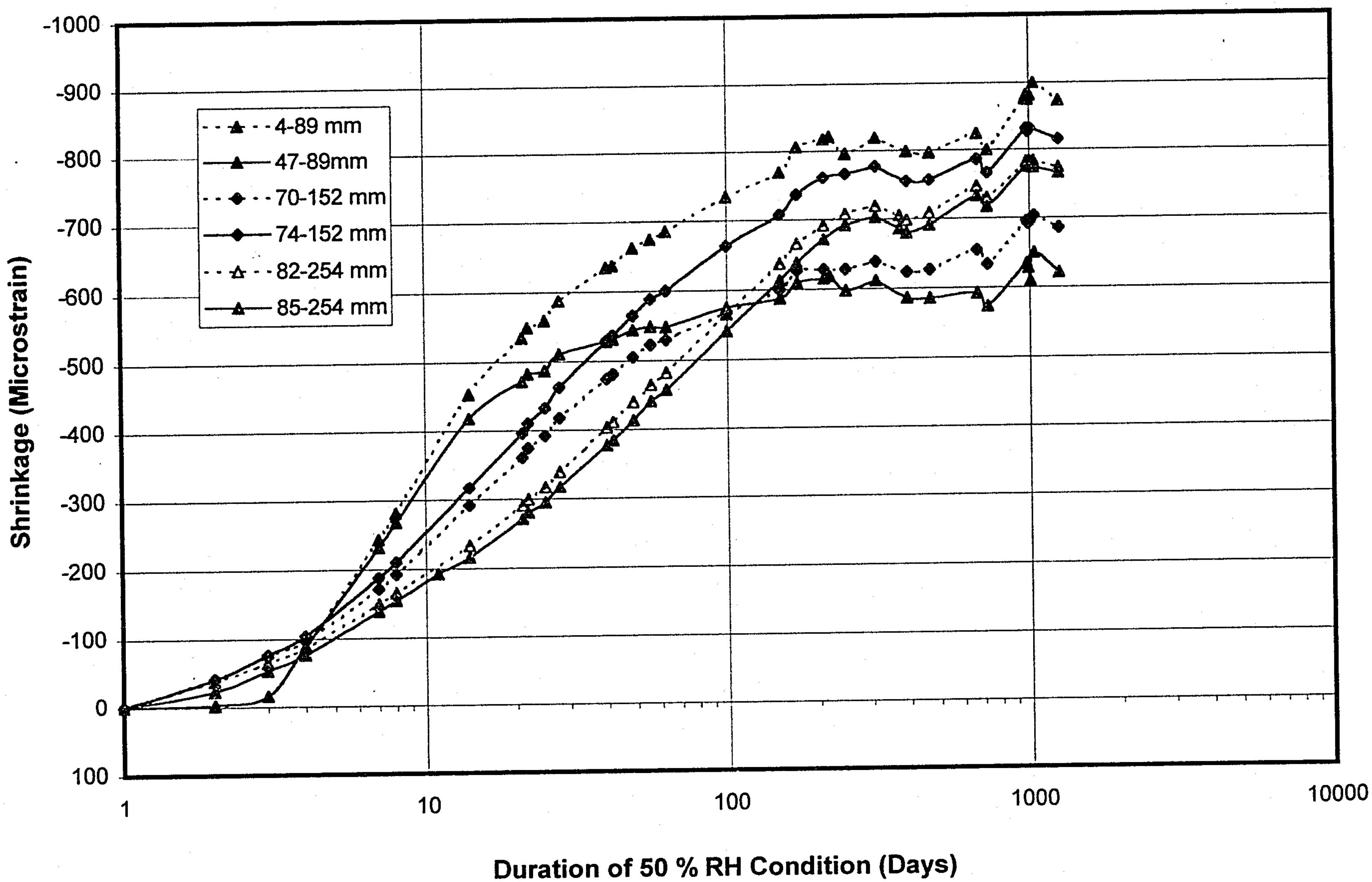


Figure 4-27(b2): Size Effect - Shrinkage of the 89, 152, and 254 mm Specimens in 50 % RH,Specimens 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days, Other specimens moist cured 3 days



CHAPTER 5

CREEP

Creep specimens were loaded at different ages but all were unloaded at 1000 days. Therefore the effect of creep is investigated for durations up to 1000 days.

To take out the effect of shrinkage, for each pair of long and short specimens the average shrinkage was used. It is assumed that shrinkage strains and load induced strains are additive:

$$\varepsilon_{total} = \varepsilon_{shrinkage} + \varepsilon_{load}$$

where:

$$\varepsilon_{load} = \varepsilon_{elastic} + \varepsilon_{creep}$$

Hence,

$$\varepsilon_{total} = \varepsilon_{shrinkage} + \varepsilon_{elastic} + \varepsilon_{creep}$$

$$\varepsilon_{total} = \varepsilon_{shrinkage} + \varepsilon_{elastic}\left(1 + \frac{\varepsilon_{creep}}{\varepsilon_{elastic}}\right)$$

$$\varepsilon_{total} = \varepsilon_{shrinkage} + \frac{\sigma}{E_{t0}}(1 + CreepCoefficient)$$

$$\varepsilon_{total} = \varepsilon_{shrinkage} + \frac{\sigma}{E_{t0}}(Modified\ Creep\ Coefficient)$$

where:

Creep Coefficient= $\frac{\varepsilon_{creep}}{\varepsilon_{elastic}}$

Modified Creep Coefficient=1+ Creep Coefficient

"Modified creep coefficient" can also be called "Non-dimensional compliance"

$\sigma = \frac{P}{A} = Compression\ stress\ of\ the\ specimens$

E_{t0} = Modulus of elasticity of concrete at the age of loading

To investigate the effect of creep, graphs of "Age of concrete" versus "Modified creep coefficient" are drawn and the effect of creep is investigated for different parameters.

The five parameters considered in this study on creep were:

- Specimen size (diameter= 89 mm, 152mm, 254mm and 610mm)
- Environment (50% RH, lab, immersed in water, outside and sealed)
- Moist curing period (3 days, 24/25 days and 200 days)
- Length of specimens (short or long)
- Age of loading (3 or 4 days, 13 days, 24, 25 or 28 days and 200 or 201 days)

In addition some of the specimens are sealed after 3, 25 or 200 days.

The way to consider the effect of one of these parameters is, keeping four constant and studying the effect of the changed parameter.

5.1 Effect of Specimen Length on Creep

To investigate the effect of specimen length, the other four parameters are kept constant, and each pair of specimens has been investigated. For example, specimens 7 and 31, which are 89 mm in diameter, kept in a lab environment, moist cured for 3 days and loaded at 24 days. Specimen 7 is short and 31 is long.

Because the 610 mm specimen diameter has only one length (1930 mm), gauges 101, 102, 103, 104, 105 and 106 are not considered.

In the next paragraphs each pair of long and short samples are considered separately to determine the effect of length of specimen on creep during the period of study (1000 days).

5.1.1 Comparing Lab Observations

7 and 31: Lab, moist cured for 3 days, d=89 mm, loaded at 24 days, *Fig.5-1*

a) Modified creep coefficient of short specimen is always larger than the long specimen.
b) For all ages the pattern of modified creep coefficient development seems to be consistent.
c) Up to 43 days (3 to 43 days) the values of modified creep coefficient are very close but a significant difference starts after 43 days.

d) The ratio of measured modified creep coefficient, S/L (short over long) is 1.10 at 1000 days and as mentioned before seems to be approximately constant at all ages.

e) Average modified creep coefficient of long and short specimens is 4.1.

f) *Fig. 5-1* contains specimen 56 too. This specimen was loaded at 4 days and the expectation was that the value of modified creep coefficient be larger than the similar specimens loaded at 24 days (specimens 7 and 31) but was not observed. No significant reason can be suggested for this case.

<u>**21, 26 and 37:** Lab. moist cured for 24 days, d=89mm, loaded at 25/28 days, specimen No.21 is short and 26 and 37 are long. *Fig. 5-2*</u>

A) Comparing **26 and 37** (long ones)

a) Up to 66 days the modified creep coefficient graphs are practically identical.

b) Between 66 and 398 days there seems to be slight difference between the specimens but totally they are completely reasonable.

c) After 398 days the graphs are the same up to the time of unloading.

d) Practically there is no difference observed between these two specimens.

B) **21 and 26** short and long

a) At all ages the value of the modified creep coefficient of the short specimen is smaller than that for the long specimen.

b) The pattern of change is the same in both specimens.

c) The ratio of measured modified creep coefficient, S/L is 0.95.

d) Average of the modified creep coefficient is 3.1.

66 and 76: Lab, moist cured for 3 days, d=152 mm, loaded at 24 days, *Fig.5-3*

a) These two specimens seem to behave exactly like the previous ones in their pattern of behavior.

b) The ratio of measured modified creep coefficient, S/L is 1.14 and is approximately the same at all ages.

c) The average modified creep coefficient of long and short specimens is 3.9, which is comparable with specimens 7 and 31.

80 and 88 Lab, moist cured for 3 days, d= 254 mm, loaded at 24 days, *Fig. 5-4*

a) Both graphs have practically the same values at all ages.

b) The ratio of measured modified creep coefficients, S/L is 0.95.

c) The average modified creep coefficient of long and short specimens is 3.9, which is the same value as the 152 specimens.

101-106 Lab, moist cured for 3 days, d=610 mm, loaded at 25 days, *Fig. 5-5a*

There are three pairs of gauges in these specimens:

Gauges No. 101 and 104 are located vertically on the centerline.

Gauges No. 102 and 105 are located vertically but offset by 150 mm.

Gauges No. 103 and 106 are located horizontally at mid-height of the specimen.

For gauges located on the vertical center line (101 and 104) the same behavior is observed but for vertical offset gauges (102 and 105) it is not correct. The values calculated for these two gauges are 3.1 and 2.4 respectively. This is strange because as concrete is a homogeneous material the expectation is to have the same behavior in these two gauges. However the average of specimens 102 and 105 (vertical center) seems to be the same as the average of 101 and 104 (vertical offset).

Poisson ratio:

$$Poisson\ ratio = \frac{\varepsilon_{Horizontal(laod)}}{\varepsilon_{Vertical(load)}}$$

$$\varepsilon_{Horizontal(load)} = \varepsilon_{Tatal(Hor.)} - \varepsilon_{Shrinkage(Hor.)}$$

$$\varepsilon_{Vertical(load)} = \varepsilon_{Tatal(Ver.)} - \varepsilon_{Shrinkage(Ver.)}$$

Using the above formulas *Fig. 5-5b* is drawn for the "Age of concrete" versus "Poisson ratio". As it can be observed the value of Poisson ratio is "0.18" at almost all ages.

The following results are the averages of modified creep coefficient calculated for the 610 mm specimen:

Gauges 101 and 104, vertical center: 2.65

Gauges 102 and 105, vertical offset: 2.75

Gauges 103 and 106, horizontal center: 2.45

The average modified creep coefficient for all lab specimens, regardless of their size, is 3.54.

5.1.2 Outside Specimens

14 and 32 Outside, moist cured for 3 days, d=89 mm, loaded at 201 days *Fig. 5-6*

a) There is a significant difference between these two specimens, which can be observed from 25 days after the day of loading.

b) Modified creep coefficients calculated at 1000 days are 3.2 and 2.1 for specimen 14 and 32 respectively.

c) An average modified creep coefficient of 2.7 is calculated for these two specimens.

d) The ratio of modified creep coefficient, S/L is 1.52, which is relatively high.

<u>**19 and 58** Outside, moist cured for 3 days, loaded at 24 days, d=89 mm, *Fig. 5-6*</u>

a) The values of modified creep coefficient of these two specimens are practically the same.

b) The pattern of modified creep coefficient changes at day 201 but the values of modified creep coefficient are so close that this change seems to have no effect.

c) Comparing specimens 19 and 58, which have exactly the same characteristics but are loaded at 24 days, the graphs have smaller values of modified creep coefficient than specimens 14 and 32, which is as expected.

d) The ratio of calculated modified creep coefficient, S/L is 1.12.

e) Average modified creep coefficient of long and short specimens is 3.6.

f) Specimen 53, also shown in Fig.5-6, has the same properties as the specimens 14, 32, 19 and 58 but was loaded at 4 days. As expected the modified creep coefficients of this sample are greater than the other four at all ages.

<u>**67 and 75**, Outside, moist cured for 3 days, d=152 mm, loaded at 24 days, *Fig. 5-8*</u>

a) Until day 174, the values of modified creep coefficient are practically the same and no significant difference is observed.

b) From day 174 to day 1000 the modified creep coefficients are different but the pattern of change is similar.

c) The modified creep coefficient of the short specimen is always larger than the longer specimen and a S/L ratio of 1.15 is calculated for modified creep coefficient.

d) Average modified creep coefficient of long and short specimens is 2.8.

78 and 87, Outside, moist cured for 3 days, d=254 mm, loaded at 24 days, *Fig.5-9*

a) For the first 200 days the values of the modified creep coefficients are effectively zero.

b) After 200 days the modified creep coefficients are different but the pattern of change is similar.

c) The ratio of measured modified creep coefficients S/L is 0.87.

d) Average modified creep coefficient of long and short specimens is 2.2.

An average of 2.80 is calculated for the outside specimens regardless of their size.

5.1.3 Immersed Specimens

12 and 29 Immersed, moist cured for 3 days, d=89 mm, loaded at 3 days, *Fig 5-10*

Looking at measurements for these specimens shows:

a) The pattern of change is similar at all ages.

b) The longer specimen has smaller modified creep coefficients.

c) The ratio of modified creep coefficient, S/L is 1.16.

d) Average modified creep coefficient of long and short specimens is 2.1.

20 and 23 Immersed, moist cured for 3 days, d=89 mm, loaded at 13 days, *Fig 5-10*

Looking at measurements for these immersed specimens shows:

a) The pattern of change is similar at all ages.

b) The longer specimen has larger modified creep coefficients.

c) The ratio of modified creep coefficient, S/L is 0.80.

d) Average modified creep coefficient of long and short specimens is 1.8.

64 and 24 Immersed, moist cured for 3 days, d=89 mm, loaded at 200 days, *Fig 5-10*

Looking at measurements for these specimens shows:

a) The pattern of change is almost similar at all ages.

b) The longer specimen has larger modified creep coefficients.

c) The ratio of modified creep coefficient, S/L is 0.67.

d) Average modified creep coefficient of long and short specimens is 1.8.

An average of 1.87 is calculated for the immersed specimens.

5.1.4 50% RH Environment

11 and 38, 50% RH, moist cured for 3 days, d=89 mm, loaded at 200 days, *Fig.5-11*

a) The pattern of increase is similar and the long specimen always has smaller values.

b) The ratio of measured modified creep coefficients S/L is 1.33.

c) An average final modified creep coefficient of 2.1 can be observed.

65 and 44, 50% RH, moist cured for 3 days, d=89 mm, loaded at 24 days, *Fig.5-11*

a) The pattern of increase is similar but the values are far away from each other, which no explanation can be suggested.

b) The graphs of *Fig. 5-11*, show the results of different samples with the same characteristics but loaded at different ages. Looking at these specimens, the curve for specimens 65 and 44 loaded at 24 days, should be located between 11 and 38, loaded at 200 days and specimen 41 loaded at 4 days. Hence it seems that using the average of specimens 65 and 44 is reasonable.

c) The ratio of measured modified creep coefficient S/L is 2.44 cannot be correct and is not used in calculations of short over long ratios.

d) An average ultimate modified creep coefficient of 2.8 can be observed.

2 and 59, 50% RH, moist cured for 24/25 days, d=89 mm, loaded at 25 days *Fig. 5-12*

a) The pattern of modified creep coefficients is similar.

b) The ratio of measured modified creep coefficient S/L is 1.27.

c) Average final modified creep coefficient of the long and short specimens is 2.5.

8 and 54, 50% RH, moist cured for 3 days, d=89 mm, loaded at 200 days and sealed after 3 days, *Fig. 5-14*

a) The pattern of increase in modified creep coefficient is similar but the short one is always less than the long one.

b) The ratio of modified creep coefficient of S/L is 0.74.

c) Average modified creep coefficient of long and short specimens is 1.7, which is 17% less than the similar not sealed specimen. Hence this decrease should be the effect of sealing.

33 and 63, 50% RH, moist cured for 3 days and sealed after 3 days, d= 89 mm, loaded at 28 days, *Fig. 5-14*

a) Up to 200 days the modified creep coefficients are approximately the same.

b) The ratio of measured modified creep coefficient, S/L is 0.82.

c) Average modified creep coefficient of long and short specimens is 2.6, which is almost 7% less than the same specimen but not sealed.

3 and 35, 50% RH, moist cured for 3 days and sealed after 25 days, d=89 mm, loaded at 25 days, *Fig.5-16*

a) Sample No. 35 is completely unreasonable and seems to have wrong results. The modified creep coefficient of 1.0 calculated for 1000 days would indicate there is no creep at 1000 days, which, comparing with the similar specimens which are loaded at the same time and sealed earlier (specimens 33 and 63), is strange.

b) The ratio of measured modified creep coefficient, S/L is 2.1, which as mentioned above is strange and is discarded.

c) The average modified creep coefficient of long and short specimens is 1.6 which comparing to specimens 63 and 33, sealed earlier and loaded at the same time seem to be wrong. Therefore only 2.1, from specimen 3, is used for average.

9 and 36, 50% RH, moist cured for 3 days and sealed after 200 days, d= 89 mm, loaded at 200 days, *Fig. 5-17*

a) Observing the graphs show that there is a significant difference between the results. Modified creep coefficient for 1000 days for these specimens are 1.9 and 1.0, which seem to be wrong.

b) With the assumption that the initial reading was wrong for both specimens, modification was done and the results are shown in the same figure.

c) Average modified creep coefficient of long and short specimens after modification is 1.35.

d) After modification the ratio of short over long of modified creep coefficient is 1.25, which is used in Table 5-1.

69 and 77, 50% RH, moist cured for 3 days, d=152 mm, loaded at 24 days, *Fig. 5-18*

a) The values of modified creep coefficient are similar.

b) Average modified creep coefficient of long and short ones is 3.5.

c) The ratio of modified creep coefficient, S/L is 0.97.

83 and 89, 50% RH, moist cured for 3 days, d= 89 mm, loaded at 24 days, *Fig. 5-19*

a) The pattern of change is the same in both specimens and the short one always has greater values.

b) Average modified creep coefficient of the long and short specimens is 3.8.

c) The ratio of measured modified creep coefficient, S/L is 1.11.

In overall an average modified creep coefficient of 2.92 was obtained for 50% RH specimens not sealed, regardless of the size.

An average of 1.91 is calculated for the 50% RH samples sealed, regardless of size, which is less than the unsealed samples and conforms to what is expected of sealing of specimens.

5.1.5 Conclusion on Length Effect

After looking at each pair of specimens for the length effect on creep, an average of the ratio of short over long specimens and the standard deviation were calculated and are given in Table. 5-1.

Looking in the results of this Table (Average=1.05 and Standard Deviation= 0.22) and noticing that results are half more and half less than average, leads us to the conclusion that the length of specimens does not have a considerable effect on the creep at the ultimate days. (Here 1000 days)

Also as investigated in each single pair of specimens and because of almost always the same pattern in the creep figures of the long and the short pairs, it can be concluded that there is not a major effect for length of specimens at any ages during the consideration of creep values.

In conclusion, it can be said that at all ages, the average of short and long specimens is a good representative of any specimens with the same size, moist curing duration, loading age and the same environment.

In other words all specimens, whatever the length, of the same size (diameter), moist curing period, loading time and same environment, have similar behavior for creep, or the length doesn't have a significant effect on creep.

5.2 Effect of Environment on Creep

To consider the effect of environment on creep, specimen size, moist curing duration and age of loading will be kept constant. The following groups will be discussed. For these graphs the results are plotted as compliance.

5.2.1 Specimens with d=89 mm, Moist Curing Duration of 3 Days, Loaded at 3/4 Days

The results are gathered in Table 5-12 and *Fig.5-20*. The specimens are:

Lab specimens: 56

50% RH specimens: 41

Outside specimens: 53

Immersed specimens: 12 and 29

The table shows that the ultimate creep of lab and 50% RH samples are similar. This time the 50% RH creep is larger by 14 percent. The ratio of lab to outside specimens is 0.61, which was not expected, and no explanation can be suggested. Immersed specimens, which don't have any evaporation of water, have the smallest creep value as expected.

5.2.2 Specimens with d= 89 mm, Moist Curing Duration of 24/25 Days, Loaded at 24/25/28 Days

The results of this group are brought in Table 5-9. The specimens are:

Lab specimens: 26, 37 and 21

50% RH specimens: 59 and 2

Outside specimen: 61

Looking at results it is observed that lab specimens have a larger value of creep by a percentage of 20% in comparison with 50% RH specimens and 45% in comparison with the outside specimens. Again it means that creep in real life is much less than what is experimented in the special conditions of labs. This result is valid if the concrete is cast in winter.

5.2.3 Specimens with d= 89 mm, Moist Curing Duration of 3 Days, Loaded at 24 Days

The results of this group are brought in Table 5-10 and *Fig.5-21*. The specimens are:

Lab specimens: 7 and 31

50% RH specimens: 44 and 65

Outside specimens: 19 and 58

Looking at results it can be said that laboratory stored specimens have greater values of creep by 32% in comparison with 50% RH specimens and 13% in comparison with outside environment specimens.

5.2.4 Specimens with d= 89 mm, Moist Curing Duration of 3 Days, Loaded at 200/201 Days

The specimens are:

50% RH specimens: 11 and 38

Outside specimens: 14 and 32

Immersed specimens: 24 and 64

As shown in Table 5-11 and *Fig.5-22*, the final creep of immersed specimens is smaller than 50%RH. On the other hand the ultimate value of outside specimens is greater than the lab specimens. This is strange and seems to be because of the incorrect reading of specimen 14.

5.2.5 Specimens with d=152 mm, Moist Curing Duration of 3 Days, Loaded at 24 Days

The results are gathered in Table 5-13 and Fig.5-23. The specimens are:

Lab specimens: 66 and 76

50% RH specimens: 69 and 77

Outside specimens: 67 and 75

The table shows that the ultimate creep of lab and 50% RH samples are almost similar and 50% RH creep is smaller by 10 percent. The ratio of lab to outside specimens is 1.4, which is rational.

5.2.6 Specimens with d=254 mm, Moist Curing Duration of 3 Days, Loaded at 24 Days

The specimens are:

Lab specimens: 80 and 88

50% RH specimens: 83 and 89

Table 5-14 and *Fig. 5-24* show the results. The lab ultimate creep is larger by a percentage of 3% than the 50% RH stored specimens.

5.2.7 Conclusion on Environment Effect

In conclusion lab and 50% RH ultimate creeps are almost the same but the lab creep is usually a little larger than the 50% RH values. The average for lab ultimate modified creep coefficient is 3.67 and for 50% RH is 2.92. On the other hand outside ultimate creep with an average modified creep coefficient of 2.80 is less than lab by a ratio of 1.31. This means that if the concrete is cast outside in winter, the amount of creep in a long period is less than what it is in experimental environment. The immersed specimens with an average modified creep coefficient of 1.87 show the importance of evaporation of water in decrease of creep of specimens.

5.3 Effect of Size of Specimen on Creep

As stated before, to understand the effect of size of specimen on creep we should try to keep the other four variables constant. So we consider specimens with the same environment, moist curing period and age of loading. For this discussion the values of the long and short specimens will be averaged.

5.3.1 Lab Specimens

Fig. 5.26 shows the behavior of different samples in lab environment. The moist curing period of 3 days and age of loading of 24/25 days is common for all samples. As stated before, the average value graphs can be used for the following specimens:

d= 89 mm Specimens 7 and 31

d= 152 mm Specimens 66 and 76

d= 254 mm Specimens 80 and 88

d= 610 mm Specimens 101 and 104

Observing the average graphs shows that the pattern of graphs are completely different and are in no way comparable, but as expected the smaller specimens have greater values of creep at any given age. The ultimate values can be compared. The results of this comparison are gathered in Table 5-2.

5.3.2 Outside Specimens

a) Specimens loaded at 24 days: *Fig. 5-27a and 5-27b* shows the same study for the outdoor samples. Again all specimens were placed outside at 3 or 4 days, after a moist curing period of 3 days and were loaded at 24 days. The average graphs can be used for following specimens:

d= 89 mm Specimens 19 and 58

d= 152 mm Specimens 67 and 75

The results are collected in Table 5-3a.

b) Specimens loaded at 201 days: Again the graphs are shown in *Fig. 5-27a and 5-27b*. The specimens were placed outside at 3 or 4 days, after a moist curing period of 3 days and were loaded at 201 days. The average graphs can be used for following specimens:

d= 89 mm Specimens 14 and 32

d= 254 mm Specimens 78 and 87

The results are collected in Table 5-3b.

5.3.3 50% RH Specimens

The same study has been performed in *Fig. 5-28* for 50% RH specimens. The average graphs are used for:

d= 89 mm Specimens 44 and 65

d= 152 mm Specimens 69 and 77

d= 254 mm Specimens 83 and 89

None of these specimens are sealed. The results are shown in Table 5-4.

5.3.4 Conclusion on Size Effect

Looking at the results as a group shows that, increasing the diameter in the same environment, moist curing period and age of loading, creep will become smaller. Table 5-2 shows that in lab environment increase of the diameter of the specimen always resulted in decrease of the value of creep. Tables 5-3a and 5-3b show the same result for the outdoor environments. These conform to what is expected because increase of size will result in less evaporation of moisture which makes the inside concrete better in quality and causes less creep.

Looking in the results of Table 5-4 shows that for 50% RH increase of diameter resulted in more creep, which is strange, and no explanation is suggested.

5.4 Effect of Sealing on Creep

A separate study can be performed of the effect of sealing on creep of specimens in 50% RH, of the same size of d=89 mm and moist cured for 3 days and sealed after 3, 24/25 and 200 days. The results are shown in Tables 5-5a and 5-5b and *Fig. 5-21* and *5-22*. Each table contains specimens with the same age of loading.

The following specimens are investigated:

50% RH, d= 89 mm, moist cured for 3days, loaded at 28 days, sealed after 3 days, Specimens 33 and 63

50% RH, d= 89 mm, moist cured for 3 days, loaded at 28 days, sealed after 25 days, Specimens 3 and 35

50% RH, d= 89 mm, moist cured for 3days, loaded at 200 days, sealed after 3 days, Specimens 8 and 54

50% RH, d= 89 mm, moist cured for 3days, loaded at 200 days, sealed after 200 days, Specimens 9 and 36

Looking in the results of Table 5-5a and 5-5b, it can be observed that the creep of samples sealed after 3 days is less than those sealed after 25 days and those sealed after 25 days are less than those sealed after 200 days. This conforms to what was expected. Another deduction is that the amount of decrease for the specimens sealed after 3 days to those sealed after 25 days is much more than the ratio of decrease for specimens sealed after 25 days to the ones sealed after 200 days.

5.5 Effect of Moist Curing Duration on Creep

To study the effect of moist curing duration on creep of concrete, the size, environment and age of loading are kept constant and the average of long and short specimens are used.

5.5.1 Lab Specimens

The following specimens are used for lab:

d=89 mm, moist cured for 3 days, loaded at 24 days, Specimens 7 and 31

d=89 mm, moist cured for 24 days, loaded at 25/28 days, Specimens 21, 26 and 37

The results are collected in Table 5-6. Increasing the duration of moist curing from 3 to 24 days causes a decrease of about 24% in creep.

5.5.2 Outside Specimens

The outdoor environment specimens considered are as follows:

d=89 mm, moist cured for 3 days, loaded at 24 days, Specimens 19 and 58

d=89 mm, moist cured for 24 days, loaded at 24 days, Specimen 61

The results are given in Table 5-7. As expected, increasing the period of moist curing from 3 days to 24 days causes a decrease of 53% in creep, which is really noticeable and is twice as much as the lab specimens.

5.5.3 50% RH Specimens

Tables 5-8a, 5-8b and 5-8c show the effect of moist curing duration on the specimens stored in 50% RH. In 50% RH there are three different groups of specimens:

Group 1: d=89 mm, moist cured for 3 days, loaded at 24/25 days, Specimens 44 and 65

d=89 mm, moist cured for 24 days, loaded at 24/25 days, Specimens 59 and 2

Group 2: d=89 mm, moist cured for 3 days, loaded at 200 days, Specimens 11 and 38

d=89 mm, moist cured for 24/25 days, loaded at 200 days, Specimen 13

d=89 mm, moist cured for 200 days, loaded at 200 days, Specimen 42

Group 3: d=89 mm, moist cured for 3 days, loaded at 25 days, sealed after 25 days, Specimens 3 and 35

d=89 mm, moist cured for 25 days, loaded at 28 days, sealed after 25 days, Specimen 50

The result of groups 1, 2 and 3 are gathered in Tables 5-8a, 5-8b and 5-8c respectively.

As it can be observed for all specimens kept in 50% RH environment, increase of moist curing duration has caused the decrease of creep effect. Only specimen 13 seems to have wrong result.

5.5.4 Conclusion on Moist Curing Duration Effect

In conclusion, increasing the duration of moist curing from 3 days to 25 days, and form 25 to 200 days, reduces creep. Because the number of specimens moist cured for 200 days is only one, no significant result can be suggested for the ratio of decrease from 3 to 24 and 24 to 200 days.

On the other hand the most significant effect was for the samples stored outside which means that in real life we have less problem with creep, if the moist curing period is increased.

5.6 Effect of Age of Loading on Creep

To study the effect of age of loading on creep of concrete, the size, environment and age of moist curing duration are kept constant and the average of long and short specimens are used for comparison.

5.6.1 Immersed Specimens

The specimens used for immersed environment are as follows:

d=89 mm, moist cured for 3 days, loaded at 3 days, Specimens 12 and 29

d=89 mm, moist cured for 3 days, loaded at 13 days, Specimens 20 and 23

d=89 mm, moist cured for 3 days, loaded at 200 days, Specimens 64 and 24

The results are given in Table 5-15. Increasing the age of loading from 3 to 13 days causes a reduction of 14% whereas increasing the age of loading from 24 to 200 days doesn't have a significant effect on creep. The graphs are compared in *Fig.5-10.*

5.6.2 Lab Specimens

The following specimens are used for lab:

d=89 mm, moist cured for 3 days, loaded at 4 days, Specimens 56

d=89 mm, moist cured for 3 days, loaded at 24 days, Specimens 7 and 31

The results are collected in Table 5-15. Increasing the age of loading causes the creep to become larger, which is quite strange. This may be bad observation of the first reading of specimen 56. The graphs are compared in *Fig. 5-1.*

5.6.3 Outside Specimens

The specimens used for outdoor are as follows:

d=89 mm, moist cured for 3 days, loaded at 4 days, Specimen 53

d=89 mm, moist cured for 3 days, loaded at 24 days, Specimens 19 and 58

d=89 mm, moist cured for 3 days, loaded at 201 days, Specimens 14 and 32

The results are given in Table 5-15. Increasing the age of loading from 3 to 24 days causes a reduce of 40% whereas increasing the age of loading from 24 to 200 days causes a reduction of only 25%. *Fig. 5-6* shows the comparison of the graphs.

5.6.4 50% RH Specimens

Table 5-15 shows the effect of moist curing duration on the specimens stored in 50% RH. In 50% RH there are two different groups of specimens:

Group 1: d=89 mm, moist cured for 3 days, loaded at 4 days, Specimen 41

d=89 mm, moist cured for 3 days, loaded at 24 days, Specimens 65 and 44

d=89 mm, moist cured for 3 days, loaded at 200 days, Specimens 11 and 38

Group 2: d=89 mm, moist cured for 3 days, sealed after 3 days, loaded at 28 days, Specimens 63 and 33

d=89 mm, moist cured for 3 days, sealed after 3 days, loaded at 200 days, Specimen 8 and 54

The results are gathered in Tables 5-15.

In the first group, change of age of loading from 4 to 24 days causes a decrease of 29% whereas from 24 to 200 days a decrease of 25%. In the second group(sealed specimens), the increase of age of loading from 28 days to 200 days causes a decrease of 35%.

5.6.5 Conclusion on Effect of Age of Loading

In conclusion, increasing the age of loading from 3 days to 25 days, and from 25 to 200 days, reduces creep. It seems that the decrease of creep is more when the age of loading changes from 3 to 24 than from 24 to 200 days.

Table 5-1: Effect of length on creep

No of Specimen	Diameter (mm)	Short or Long	Moist Cured (days)	Environment	Age of Loading (days)	Creep Coefficient at 1000 days	Average of Pairs	Average of Environments	Short/Long Ratio
20	89	S	3	Immersed	L13	1.6			
23	89	L	3	Immersed	L13	2.0	1.8		**0.80**
12	89	S	3	Immersed	L3	2.2			
29	89	L	3	Immersed	L3	1.9	2.1		**1.16**
64	89	S	3	Immersed	L200	1.4			
24	89	L	3	Immersed	L200	2.1	1.8	**1.87**	**0.67**
7	89	S	3	Lab	L24	4.3			
31	89	L	3	Lab	L24	3.9	4.1		**1.10**
21	89	S	24	Lab	L28	3.0			
26	89	L	24	Lab	L25	3.1			
37	89	L	24	Lab	L28	3.2	3.1		**0.95**
66	152	S	3	Lab	L24	4.1			
76	152	L	3	Lab	L24	3.6	3.9		**1.14**
80	254	S	3	Lab	L24	3.8			
88	254	L	3	Lab	L24	4.0	3.9	**3.67**	**0.95**
14	89	S	3	Outside	L201	3.2			
32	89	L	3	Outside	L201	2.1	2.7		**1.52**
19	89	S	3	Outside	L24	3.8			
58	89	L	3	Outside	L24	3.4	3.6		**1.12**
67	152	S	3	Outside	L24	3.0			
75	152	L	3	Outside	L24	2.6	2.8		**1.15**
78	254	S	3	Outside	L201	2.0			
87	254	L	3	Outside	L201	2.3	2.2	**2.80**	**0.87**
2	89	S	24/25	Tent	L25	2.8			
59	89	L	24/25	Tent	L25	2.2	2.5		**1.27**
11	89	S	3	Tent	L200	2.4			
38	89	L	3	Tent	L200	1.8	2.1		**1.33**
65	89	S	3	Tent	L24	3.9			
44	89	L	3	Tent	L24	1.6	2.8		
69	152	S	3	Tent	L24	3.4			
77	152	L	3	Tent	L24	3.5	3.5		**0.97**
83	254	S	3	Tent	L24	4.0			
89	254	L	3	Tent	L24	3.6	3.8	**2.92**	**1.11**
3	89	S	3, Sealed after 25 days	Tent	L25	2.1			
35	89	L	3, Sealed after 25 days	Tent	L25	1.0	2.1		
8	89	S	3, Sealed after 3 days	Tent	L200	1.4			
54	89	L	3, Sealed after 3 days	Tent	L200	1.9	1.7		**0.74**
9	89	S	, Sealed after 200 day	Tent	L200	1.5			
36	89	L	, Sealed after 200 day	Tent	L200	1.2	1.4		**1.25**
63	89	S	3, Sealed after 3 days	Tent	L28	2.3			
33	89	L	3, Sealed after 3 days	Tent	L28	2.8	2.6	**1.91**	**0.82**
								Mean=	**1.05**
								S.D=	**0.22**

Table 5-2: Effect of size for specimens stored in lab, moist cured 3 days, loaded at 24/25 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Age of Loading (days)	Creep Coefficient at 1000 days	Ave.
7	89	S	Lab	3	L24	4.3	
31	89	L	Lab	3	L24	3.9	4.1
66	152	S	Lab	3	L24	4.1	
76	152	L	Lab	3	L24	3.6	3.9
80	254	S	Lab	3	L24	3.8	
88	254	L	Lab	3	L24	4.0	3.9
101	610	–	Lab	3	L25	2.6	
104	610	–	Lab	3	L25	2.7	2.7
Ave.							3.6
Coefficient of Variation							18.2 %

Table 5-3a: Effect of size for specimens stored outside, moist cured 3 days, loaded at 24 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Age of Loading (days)	Creep Coefficient at 1000 days	Ave.
19	89	S	Outside	3	L24	3.8	
58	89	L	Outside	3	L24	3.4	3.6
67	152	S	Outside	3	L24	3.0	
75	152	L	Outside	3	L24	2.6	2.8
Ave.							3.2
Coefficient of Variation							17.7 %

Table 5-3b: Effect of size for specimens stored outside, moist cured 3 days, loaded at 201 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Age of Loading (days)	Creep Coefficient at 1000 days	Ave.
14	89	S	Outside	3	L201	3.2	
32	89	L	Outside	3	L201	2.1	2.7
78	254	S	Outside	3	L201	2.0	
87	254	L	Outside	3	L201	2.3	2.2
Ave.							2.4
Coefficient of Variation							14.7 %

Table 5-4: Effect of size for specimens stored in 50% RH, moist cured 3 days, loaded at 24 days

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Age of Loading (days)	Creep Coefficient at 1000 days	Ave.
44	89	L	50% RH	3	L24	1.6	
65	89	S	50% RH	3	L24	3.9	2.8
69	152	S	50% RH	3	L24	3.4	
77	152	L	50% RH	3	L24	3.5	3.5
83	254	S	50% RH	3	L24	4.0	
89	254	L	50% RH	3	L24	3.6	3.8
Ave.							3.3
Coefficient of Variation							16.0 %

Table 5-5a: Effect of sealing on specimens stored in 50% RH, moist cured 3 days, loaded at 25/28 days,d=89 mm

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Age of Loading (days)	Sealed after (days)	Creep Coefficient at 1000 days	Ave.
33	89	L	50% RH	3	L28	S3	2.8	
63	89	S	50% RH	3	L28	S3	2.3	2.5
3	89	S	50% RH	3	L25	S25	2.1	
35	89	L	50% RH	3	L25	S25	1.0	1.6
Ave.								2.0
Coefficient of Variation								32.3 %

Table 5-5b: Effect of sealing on specimens stored in 50% RH, moist cured 3 days, loaded at 200 days,d=89 mm

No.	Diameter (mm)	Short or Long	Environment	Moist Curing Period (days)	Age of Loading (days)	Sealed after (days)	Creep Coefficient at 1000 days	Ave.
8	89	S	50% RH	3	L200	S3	1.4	
54	89	L	50% RH	3	L200	S3	1.9	1.7
9	89	S	50% RH	3	L200	S200	1.9	
36	89	L	50% RH	3	L200	S200	1.0	1.5
Ave.								1.6
Coefficient of Variation								9.1 %

Table 5-6: Effect of moist curing period for specimens stored in lab, d=89mm

No.	Diameter (mm)	Short or Long	Environment	Age of Loading (days)	Moist Curing Period (days)	Creep Coefficient at 1000 days	Ave.
7	89	S	Lab	L24	3	4.3	
31	89	L	Lab	L24	3	3.9	4.1
21	89	S	Lab	L28	24	3.0	
26	89	L	Lab	L25	24	3.1	
37	89	L	Lab	L28	24	3.2	3.1
Ave.							3.6
Coeff. of Variation							19.6 %

Table 5-7: Effect of moist curing period for specimens stored outside, d=89mm

No.	Diameter (mm)	Short or Long	Environment	Age of Loading (days)	Moist Curing Period (days)	Creep Coefficient at 1000 days	Ave.
19	89	S	Outside	L24	3	3.8	
58	89	L	Outside	L24	3	3.4	3.6
61	89	L	Outside	L24	24	1.7	1.7
Ave.							2.7
Coeff. of Variation							50.7 %

Table 5-8a: Effect of moist curing period for specimens stored in 50% RH, d=89mm, loaded at 24/25 days

No.	Diameter (mm)	Short or Long	Environment	Age of Loading (days)	Moist Curing Period (days)	Creep Coefficient at 1000 days	Ave.
44	89	L	50% RH	L24	3	1.6	
65	89	S	50% RH	L24	3	3.9	2.8
2	89	S	50% RH	L25	24	2.8	
59	89	L	50% RH	L25	24	2.2	2.5
Ave.							2.6
Coeff. of Variation							6.7 %

Table 5-8b: Effect of moist curing period for specimens stored in 50% RH, d=89mm, loaded at 200 days

No.	Diameter (mm)	Short or Long	Environment	Age of Loading (days)	Moist Curing Period (days)	Creep Coefficient at 1000 days	Ave.
11	89	S	50% RH	L200	3	2.4	
38	89	L	50% RH	L200	3	1.8	2.1
13	89	S	50% RH	L200	24/25	2.6	2.6
42	89	L	50% RH	L200	200	1.6	1.6
Ave.							2.1
Coeff. of Variation							23.8 %

Table 5-8c: Effect of moist curing period for specimens stored in 50% RH, d=89mm, loaded at 25 days,sealed after 25 days

No.	Diameter (mm)	Short or Long	Environment	Age of Loading (days)	Moist Curing Period (days)	Creep Coefficient at 1000 days	Ave.
3	89	S	50% RH	L25	3	2.1	
35	89	L	50% RH	L25	3	1.0	1.6
50	89	L	50% RH	L28	25	1.1	1.1
Ave.							1.3
Coeff. of Variation							24.0 %

Table 5-9: Effect of environment for specimens moist cured 24/25 days,loaded at 25 days, d=89 mm

No.	Diameter (mm)	Short or Long	Moist curing period (days)	Age of Loading (days)	Environment	Creep Coefficient at 1000 days	Ave.
26	89	L	24	L25	Lab	3.1	
37	89	L	24	L28	Lab	3.2	
21	89	S	24	L28	Lab	3.0	*3.1*
2	89	S	24/25	L25	Tent	2.8	
59	89	L	24/25	L25	Tent	2.2	*2.5*
61	89	L	24	L24	Outside	1.7	*1.7*

Table 5-10: Effect of environment for specimens moist cured 3 days, loaded at 24 days, d=89 mm

No.	Diameter (mm)	Short or Long	Moist curing period (days)	Age of Loading (days)	Environment	Creep Coefficient at 1000 days	Ave.
7	89	S	3	L24	Lab	4.3	
31	89	L	3	L24	Lab	3.9	*4.1*
44	89	L	3	L24	Tent	1.6	
65	89	S	3	L24	Tent	3.9	*2.8*
19	89	S	3	L24	Outside	3.8	
58	89	L	3	L24	Outside	3.4	*3.6*

Table 5-11: Effect of environment for specimens moist cured 3 days,loaded at 200 days, d=89 mm

No.	Diameter (mm)	Short or Long	Moist curing period (days)	Age of Loading (days)	Environment	Creep Coefficient at 1000 days	Ave.
11	89	S	3	200	Tent	2.4	
38	89	L	3	200	Tent	1.8	*2.1*
14	89	S	3	201	Outside	3.2	
32	89	L	3	201	Outside	2.1	*2.7*
24	89	L	3	200	Immersed	2.1	
64	89	S	3	200	Immersed	1.4	*1.8*

Table 5-12: Effect of environment for specimens moist cured 3 days,loaded at 3/4 days, d=89 mm

No.	Diameter (mm)	Short or Long	Moist curing period (days)	Age of Loading (days)	Environment	Creep Coefficient at 1000 days	Ave.
56	89	L	3	L4	Lab	3.1	*3.1*
41	89	L	3	L4	Tent	3.6	*3.6*
53	89	L	3	L4	Outside	5.1	*5.1*
12	89	S	3	L3	Immersed	2.2	
29	89	L	3	L3	Immersed	1.9	*2.1*

Table 5-13: Effect of environment for specimens moist cured 3 days, loaded at 24 days, d=152 mm

No.	Diameter (mm)	Short or Long	Moist curing period (days)	Age of Loading (days)	Environment	Creep Coefficient at 1000 days	Ave.
66	152	S	3	L24	Lab	4.1	
76	152	L	3	L24	Lab	3.6	*3.9*
69	152	S	3	L24	Tent	3.4	
77	152	L	3	L24	Tent	3.5	*3.5*
67	152	S	3	L24	Outside	3.0	
75	152	L	3	L24	Outside	2.6	*2.8*

Table 5-14: Effect of environment for specimens moist cured 3 days, loaded at 24 days, d=254 mm

No.	Diameter (mm)	Short or Long	Moist curing period (days)	Age of Loading (days)	Environment	Creep Coefficient at 1000 days	Ave.
80	254	S	3	L24	Lab	3.8	
88	254	L	3	L24	Lab	4.0	*3.9*
83	254	S	3	L24	Tent	4.0	
89	254	L	3	L24	Tent	3.6	*3.8*

Table 5-15: Effect of age of loading on creep

No of Specimen	Diameter (mm)	Short or Long	Moist Cured (days)	Environment	Age of Loading (days)	Creep Coefficient at 1000 days	Average of Pairs
12	89	S	3	Immersed	L3	2.2	
29	89	L	3	Immersed	L3	1.9	2.1
20	89	S	3	Immersed	L13	1.6	
23	89	L	3	Immersed	L13	2.0	1.8
64	89	S	3	Immersed	L200	1.4	
24	89	L	3	Immersed	L200	2.1	1.8
56	89	L	3	Lab	L4	3.1	3.1
7	89	S	3	Lab	L24	4.3	
31	89	L	3	Lab	L24	3.9	4.1
53	89	L	3	Outside	L4	5.1	5.1
19	89	S	3	Outside	L24	3.8	
58	89	L	3	Outside	L24	3.4	3.6
14	89	S	3	Outside	L201	3.2	
32	89	L	3	Outside	L201	2.1	2.7
2	89	S	24/25	Tent	L25	2.8	
59	89	L	24/25	Tent	L25	2.2	2.5
13	89	S	24/25	Tent	L200	2.6	2.6
41	89	L	3	Tent	L4	3.6	3.6
65	89	S	3	Tent	L24	3.9	
44	89	L	3	Tent	L24	1.6	2.8
11	89	S	3	Tent	L200	2.4	
38	89	L	3	Tent	L200	1.8	2.1
63	89	S	3	Tent	L28	2.3	
33	89	L	3	Tent	L28	2.8	2.6
8	89	S	3	Tent	L200	1.4	
54	89	L	3	Tent	L200	1.9	1.7

Figure 5-1: Modified Creep Coefficient of 89 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 56 loaded at 3 days, Specimen 7 &31 loaded at 24 days

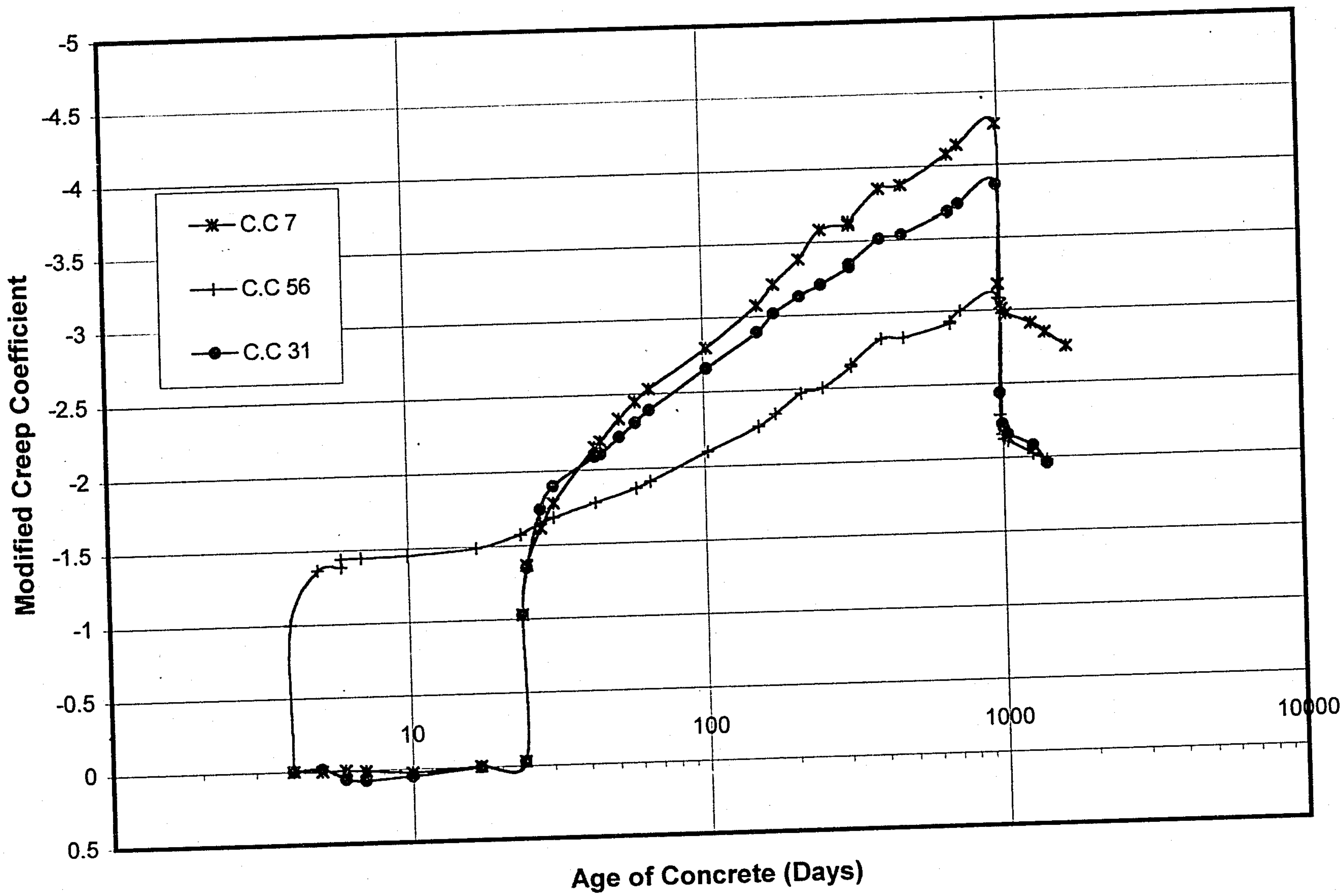


Figure 5-2: Modified Creep Coefficient of 89 mm Specimens in Lab Environment, Moist cured 24 days
Specimen 26 loaded at 25 days, Specimen 21 & 37 loaded at 28 days

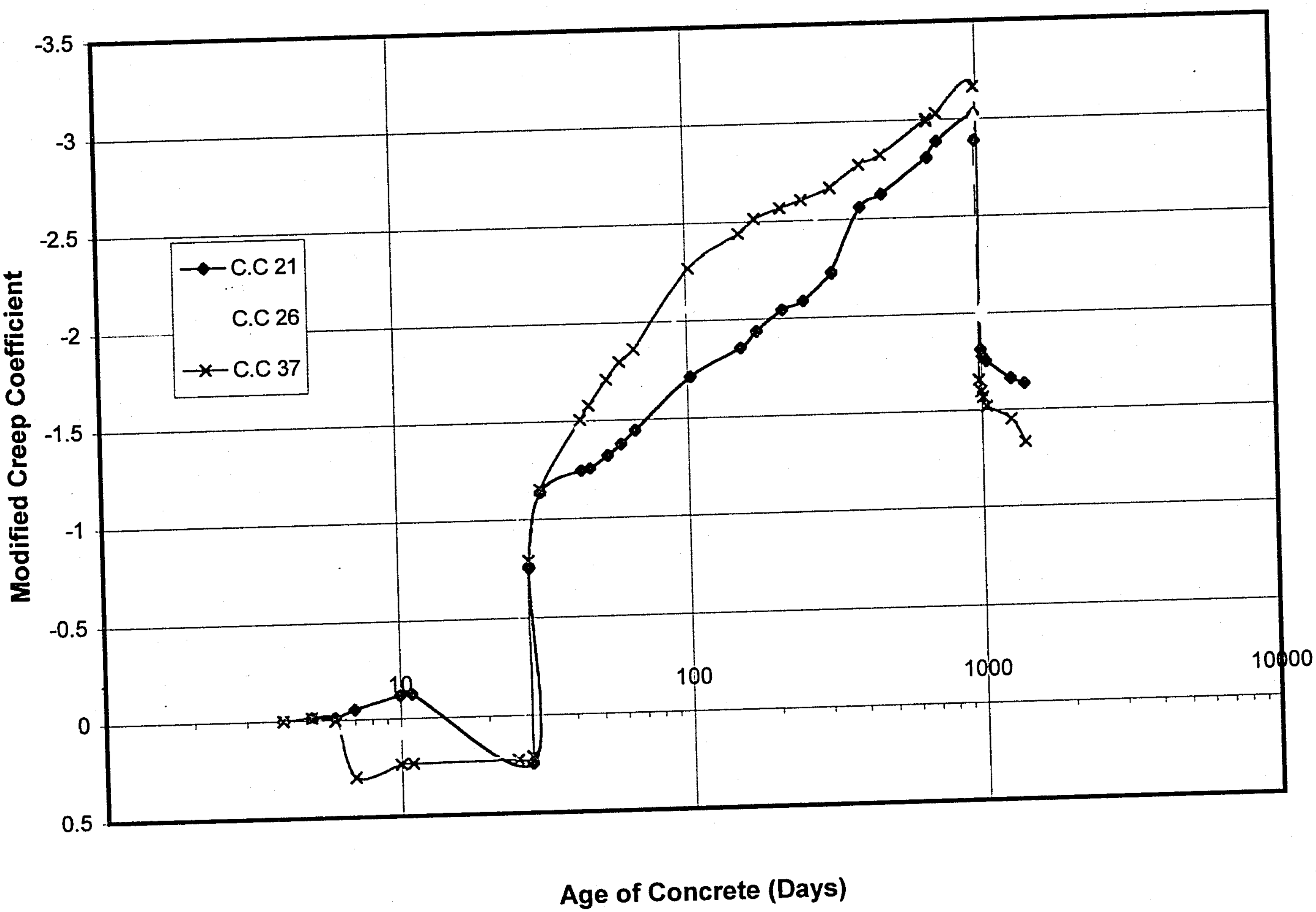


Figure 5-3: Modified Creep Coefficient of 152 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 66 & 76 loaded at 24 days

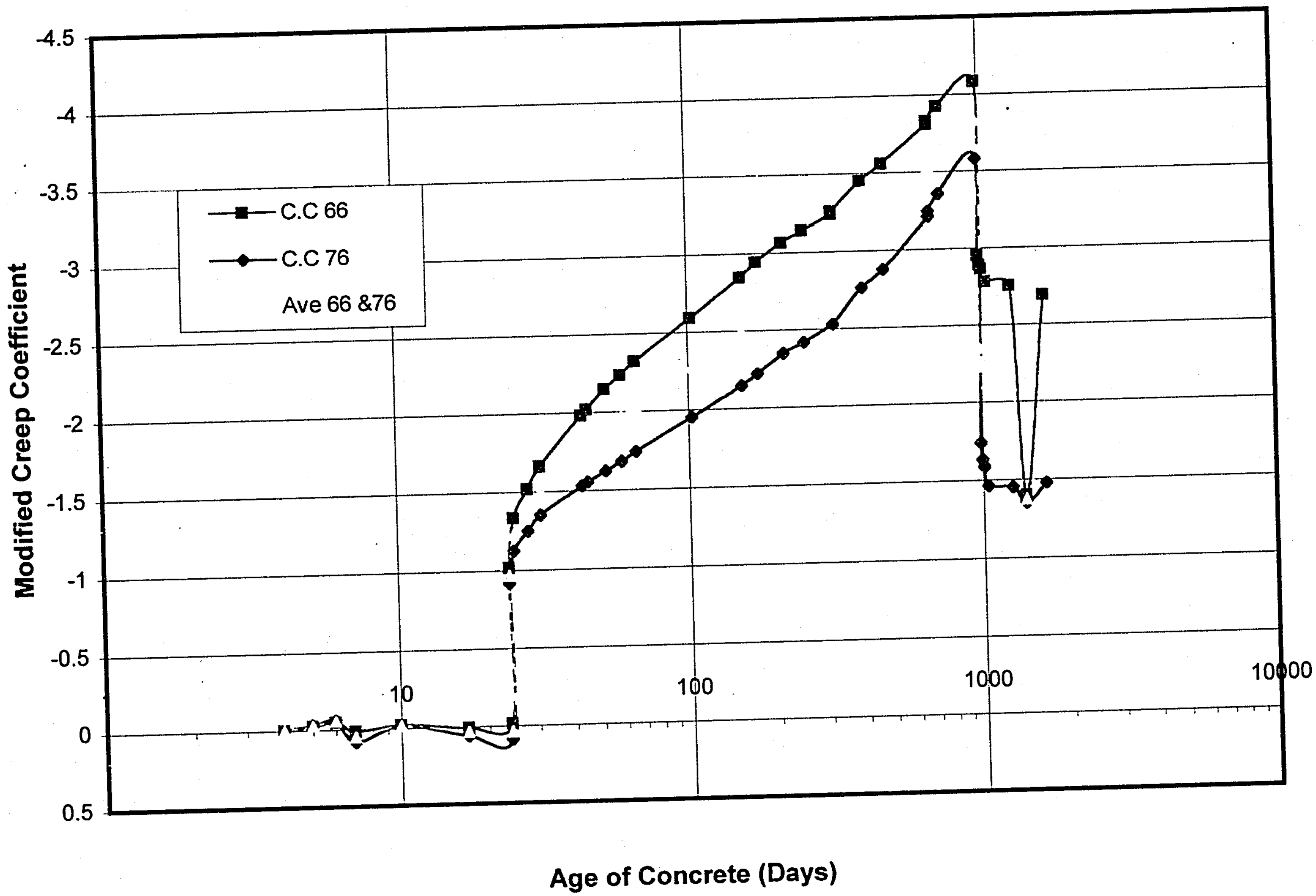


Figure 5-4: Modified Creep Coefficient of 254 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 80 & 88 loaded at 24 days

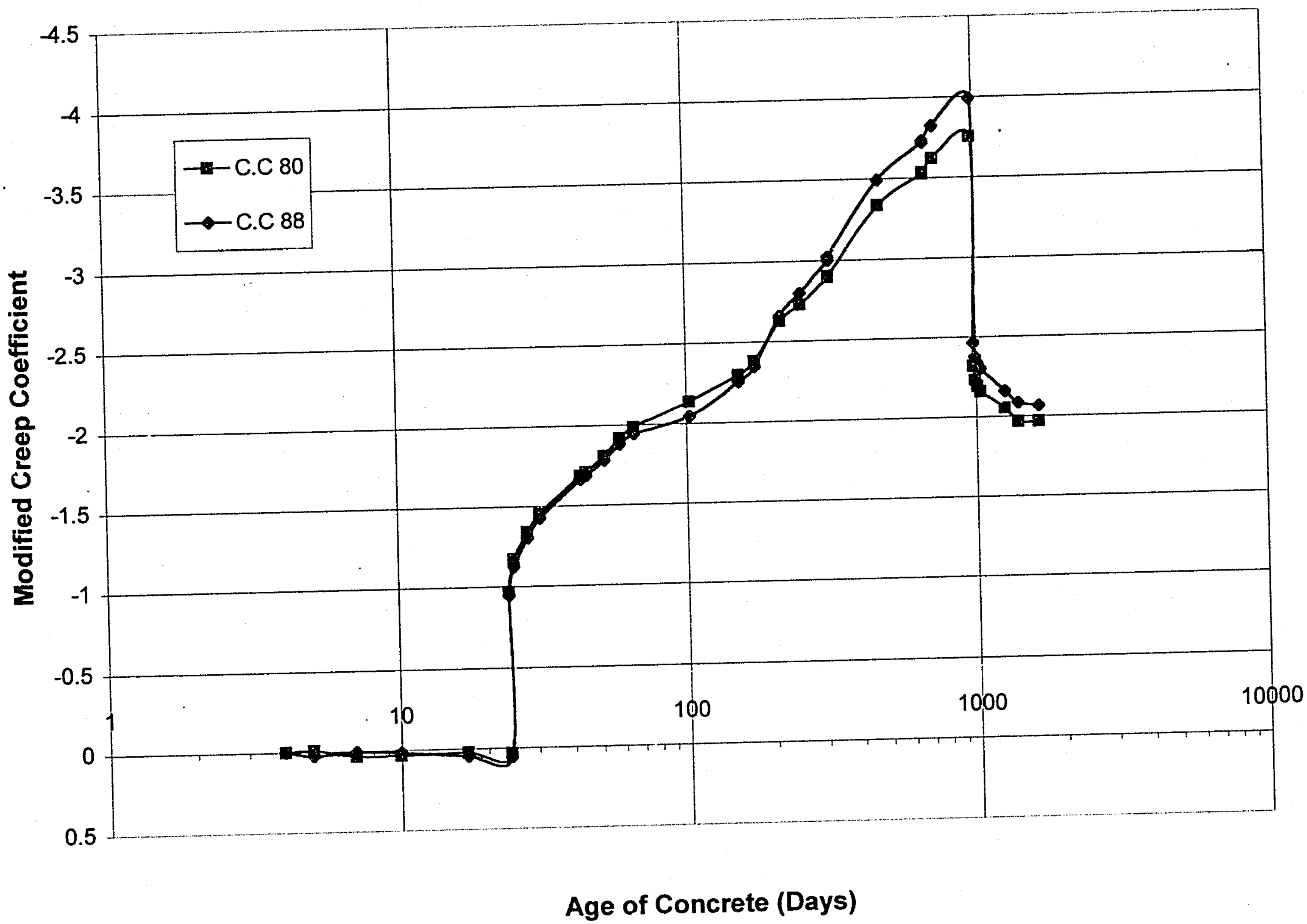


Figure 5-5(a): Modified Creep Coefficient of 610 mm Specimens in Lab Environment, Moist cured 3 days
Specimens 101~106 loaded at 25 days

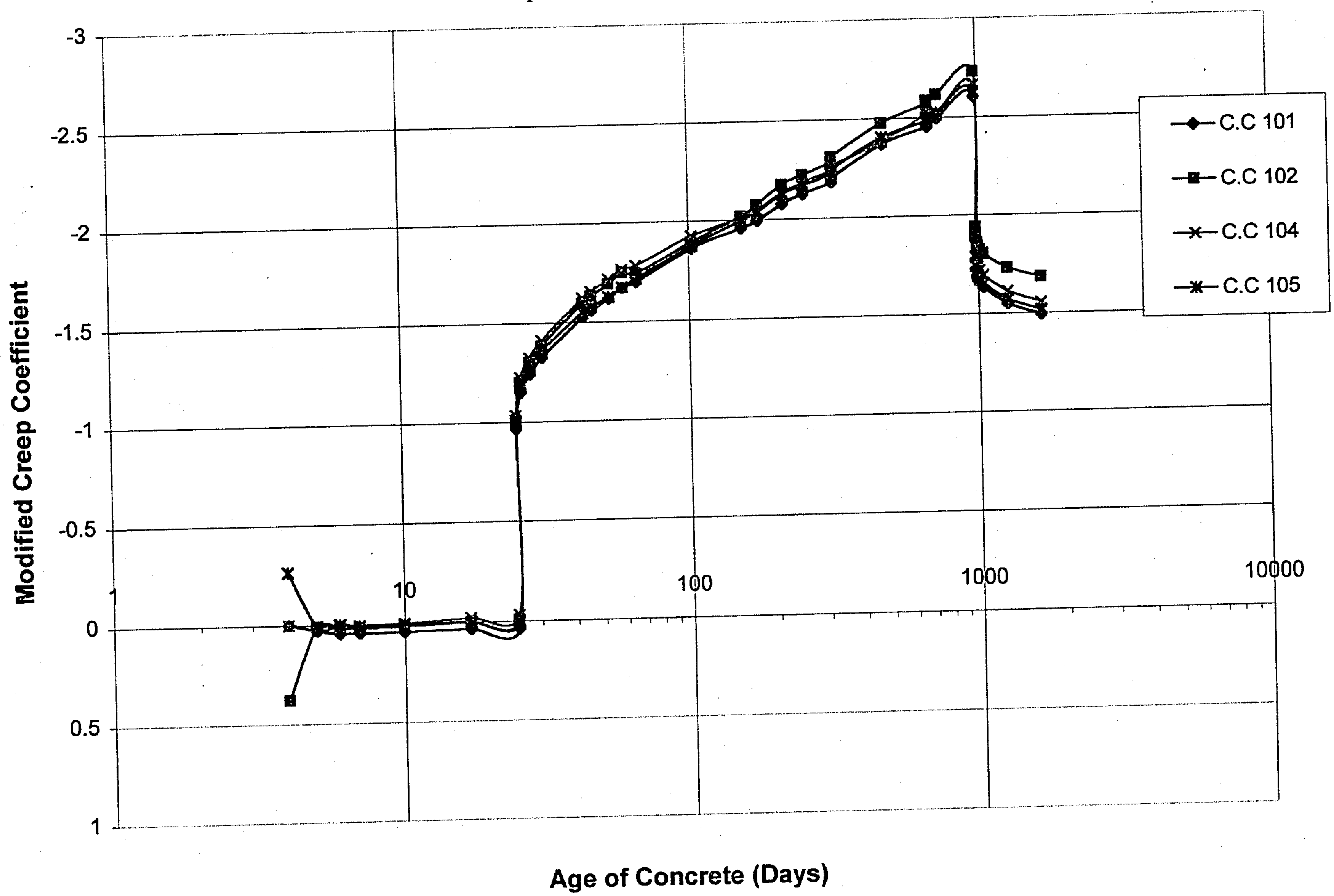


Figure 5-5(b): Poisson Ratio of 610 mm Specimens in Lab Environment, Moist cured 3 days

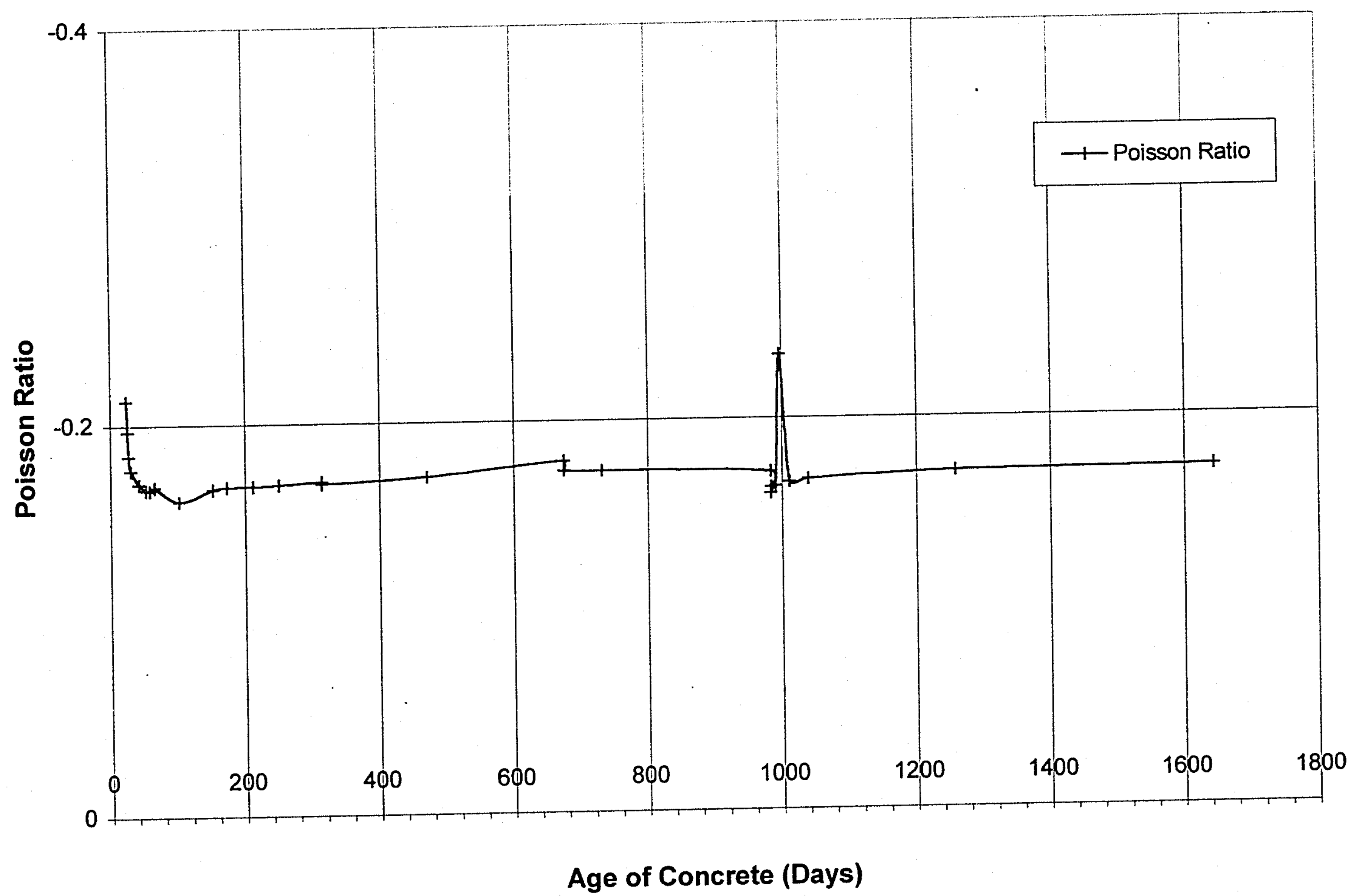


Figure 5-6: Modified Creep Coefficient of 89 mm Specimens Outdoor Environment, Moist cured 3 days Specimen 53 loaded at 4 days, Specimen 19 & 58 loaded at 24 days, Specimen 14 & 32 loaded at 201 days

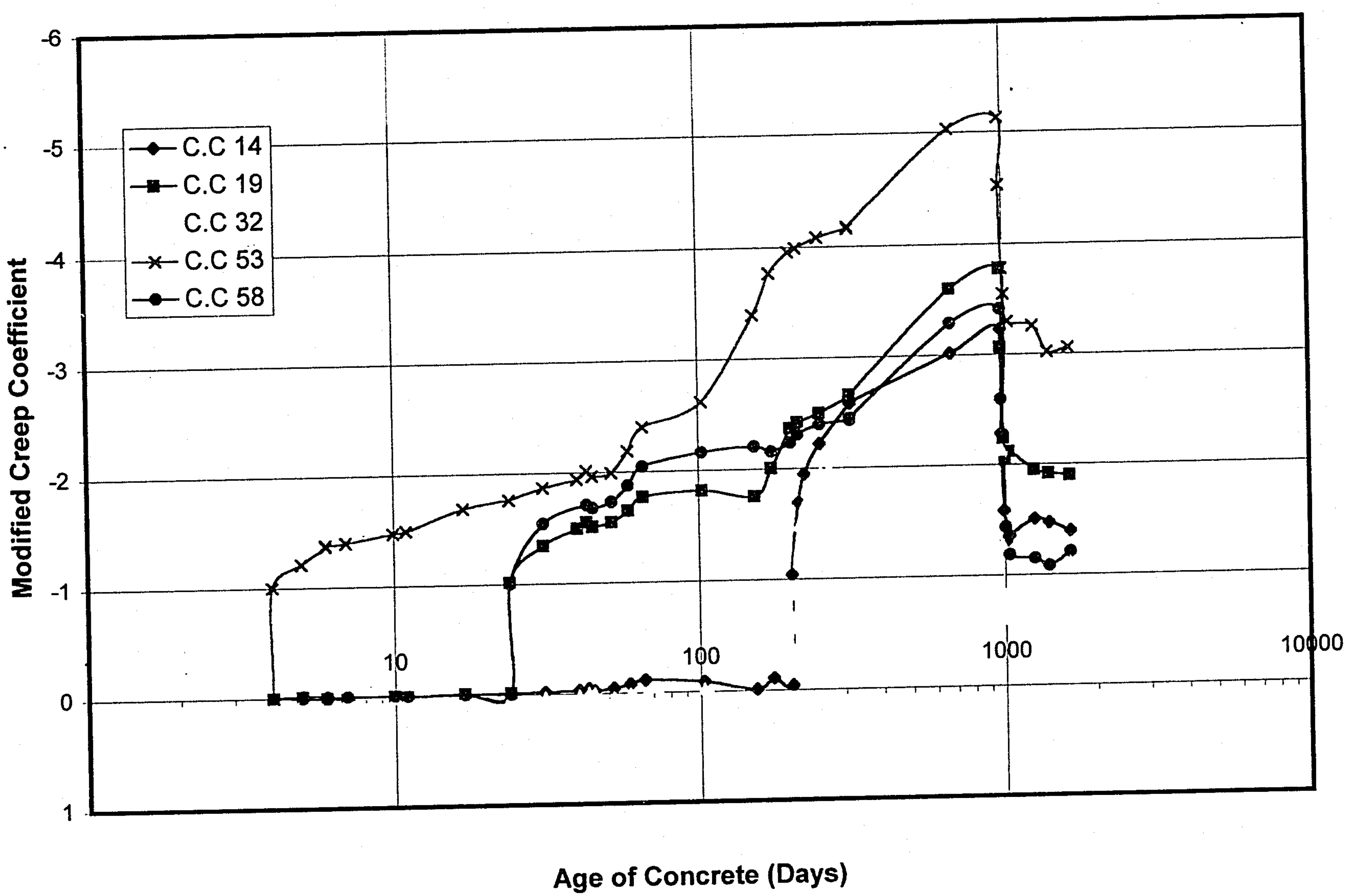


Figure 5-7: Modified Creep Coefficient of 89 mm Specimens Outdoor Environment, Moist cured 24 days
Specimen 61 loaded at 24 days

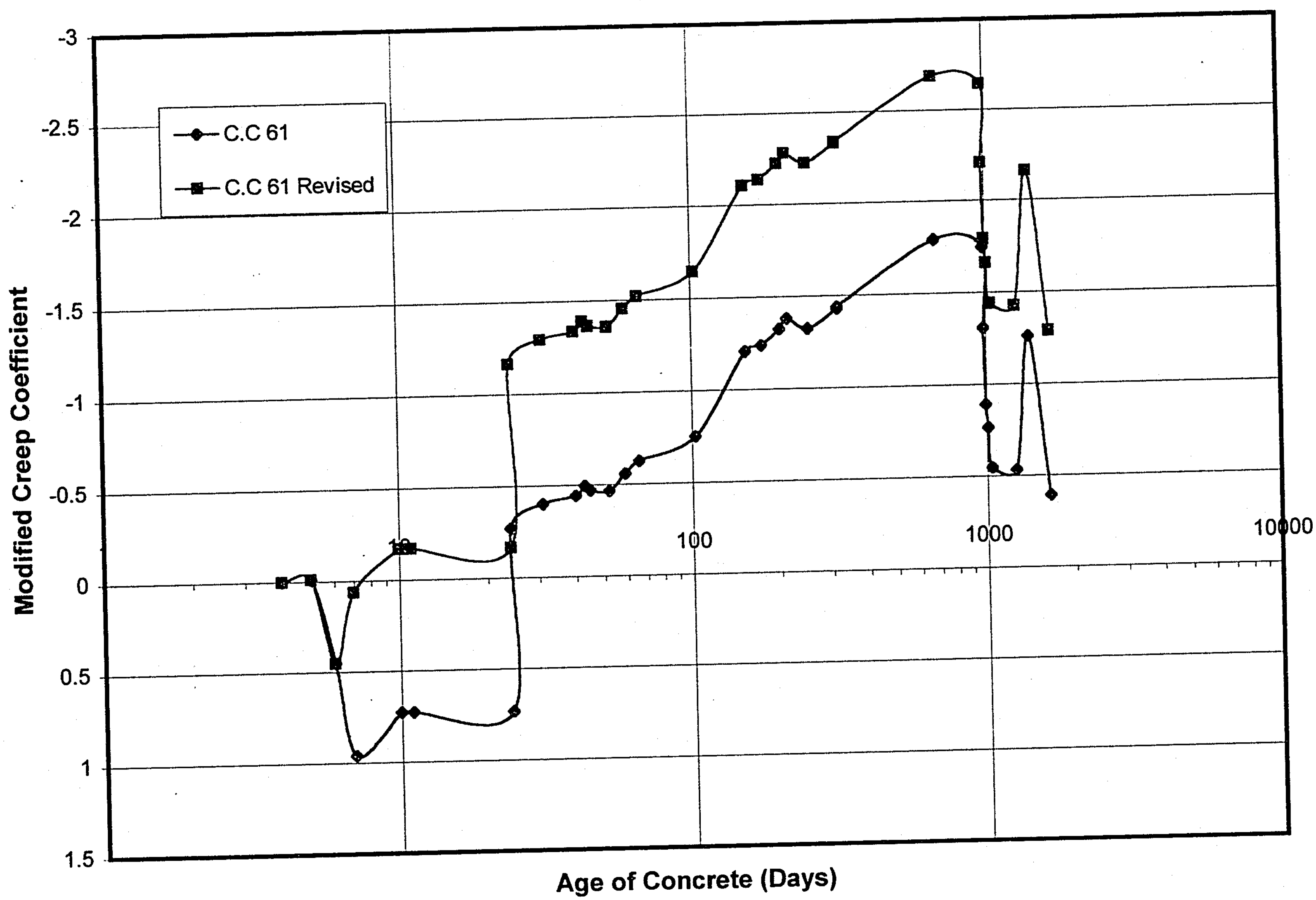


Figure 5-8: Modified Creep Coefficient of 152 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 67 & 75 loaded at 24 days

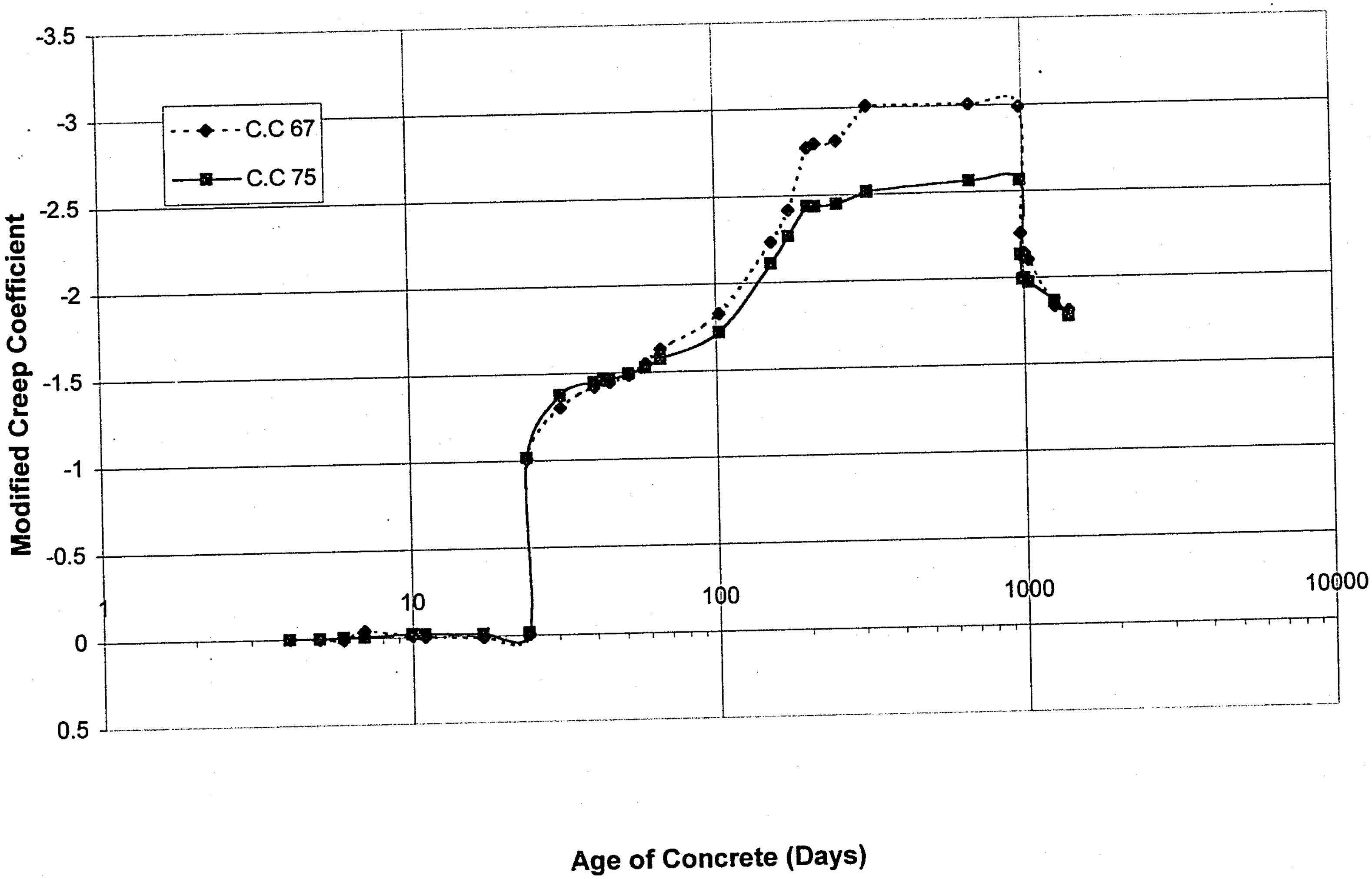


Figure 5-9: Modified Creep Coefficientof 254 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 78 & 87 loaded at 201 days

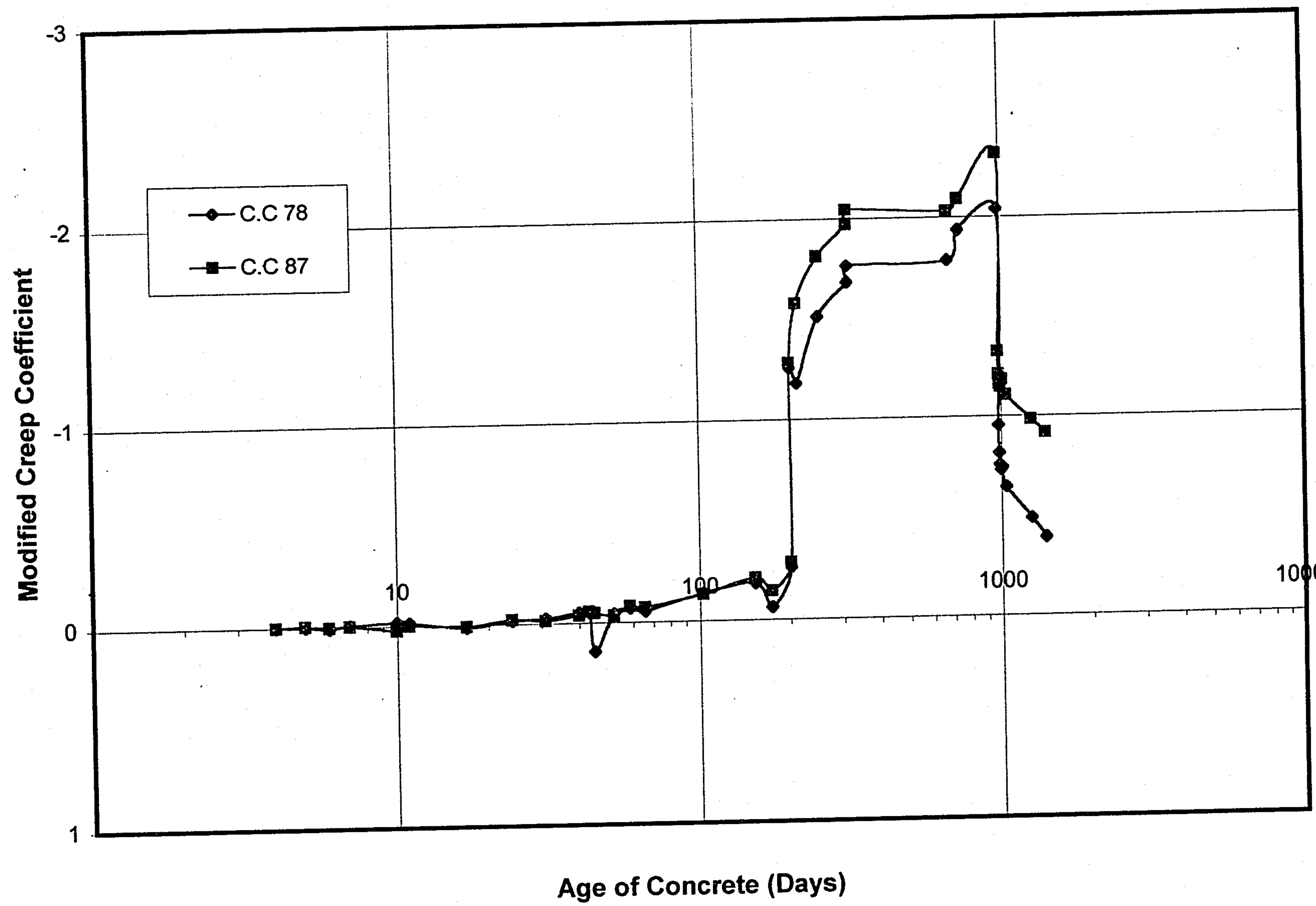


Figure 5-10: Modified Creep Coefficient of 89 mm Immersed Specimens, Moist cured 3 days, Specimen 12 & 29 loaded at 3 days, Specimen 20 & 23 loaded at 13 days, Specimen 64 & 24 loaded at 200 days

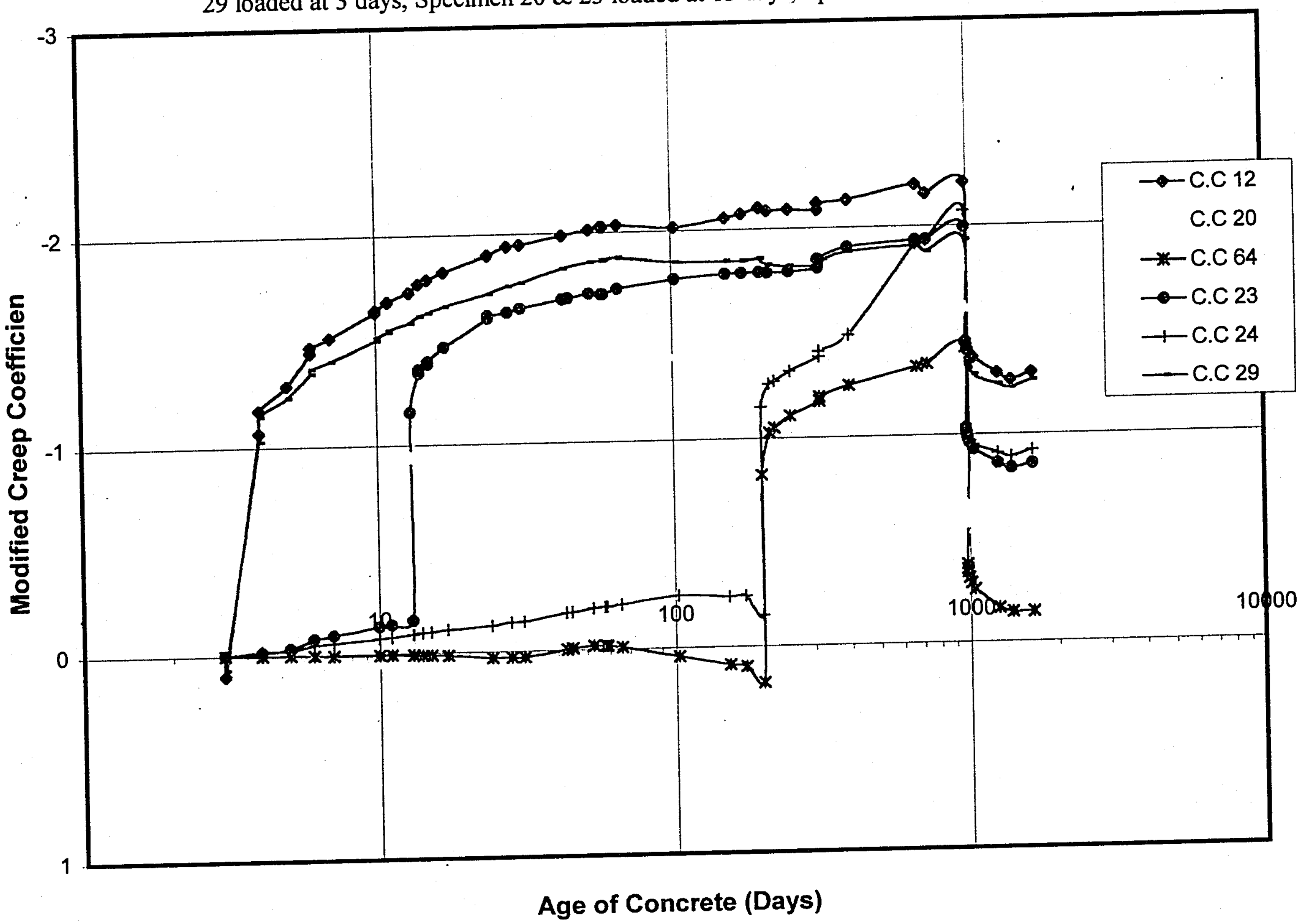


Figure 5-11: Modified Creep Coefficient of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days Specimen 41 loaded at 4 days, Specimen 65 & 44 loaded at 24 days, Specimen 11 & 38 loaded at 200 days

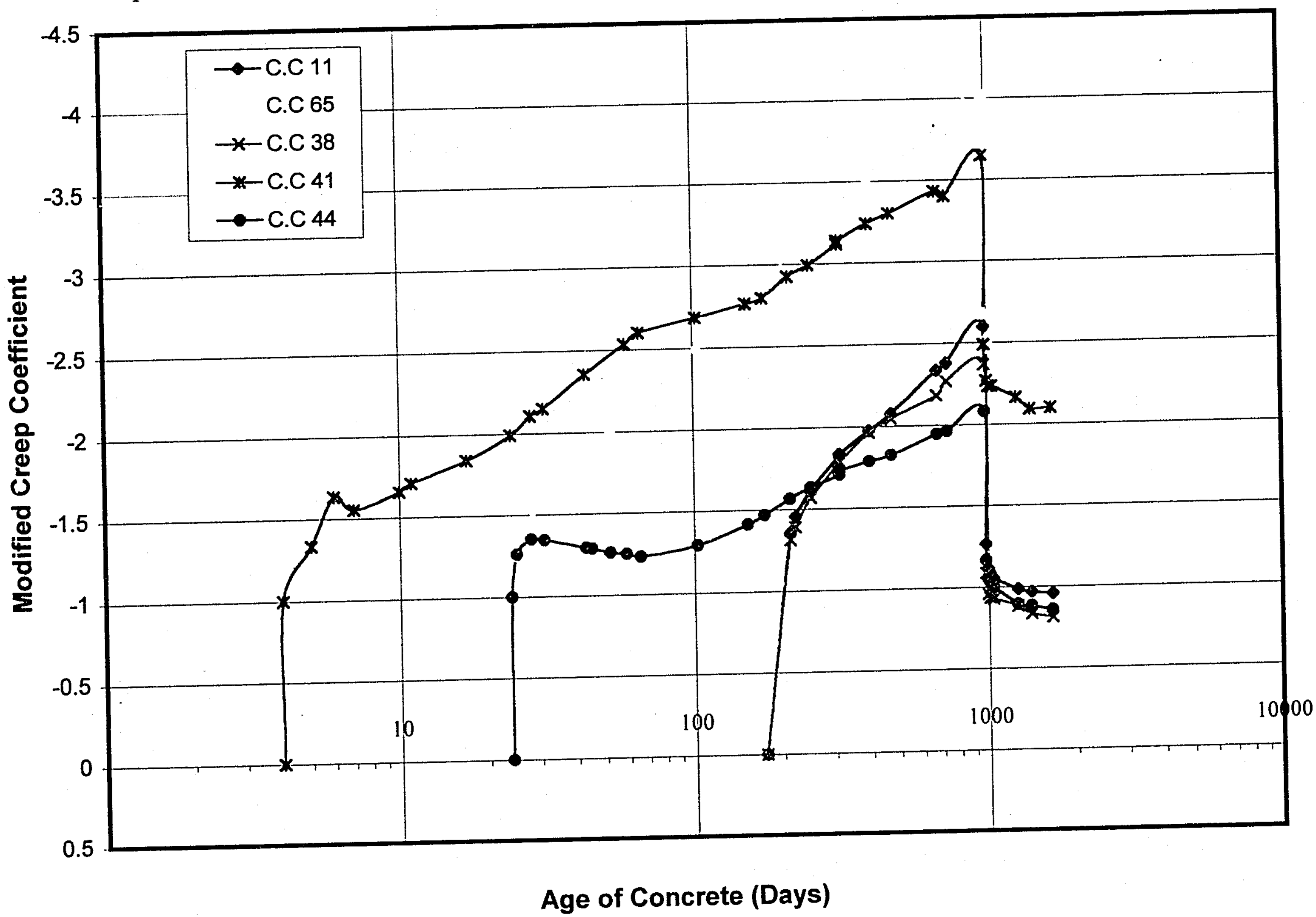


Figure 5-12: Modified Creep Coefficient of 89 mm Specimens in 50% R.H. Environment, Moist cured 24/25 days Specimen 2 & 59 loaded at 25 days, Specimen 13 loaded at 200 days

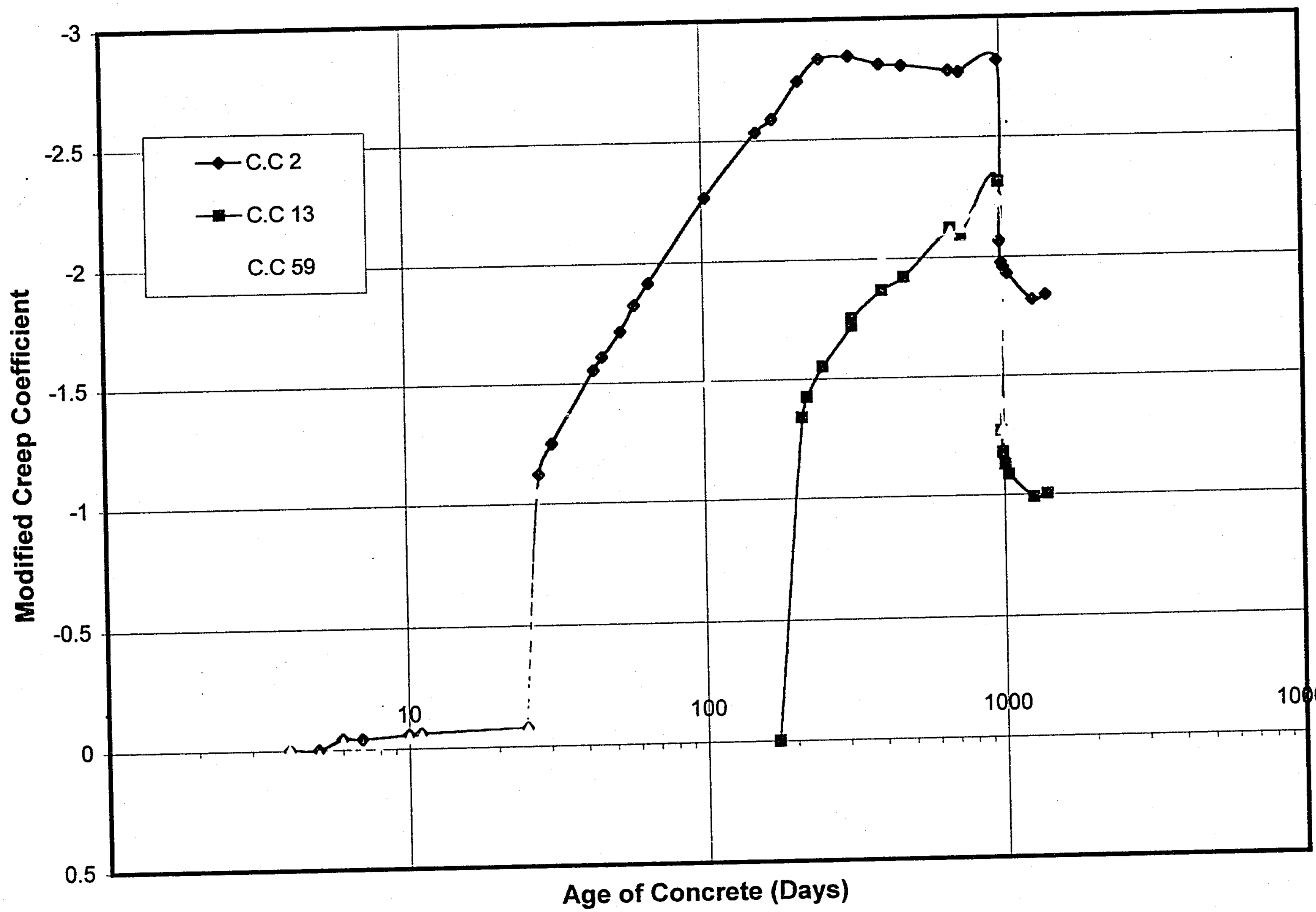


Figure 5-13: Modidfied Creep Coefficient of 89 mm Specimens in 50% R.H. Environment, Moist cured 200 days
Specimen 42 loaded at 200 days

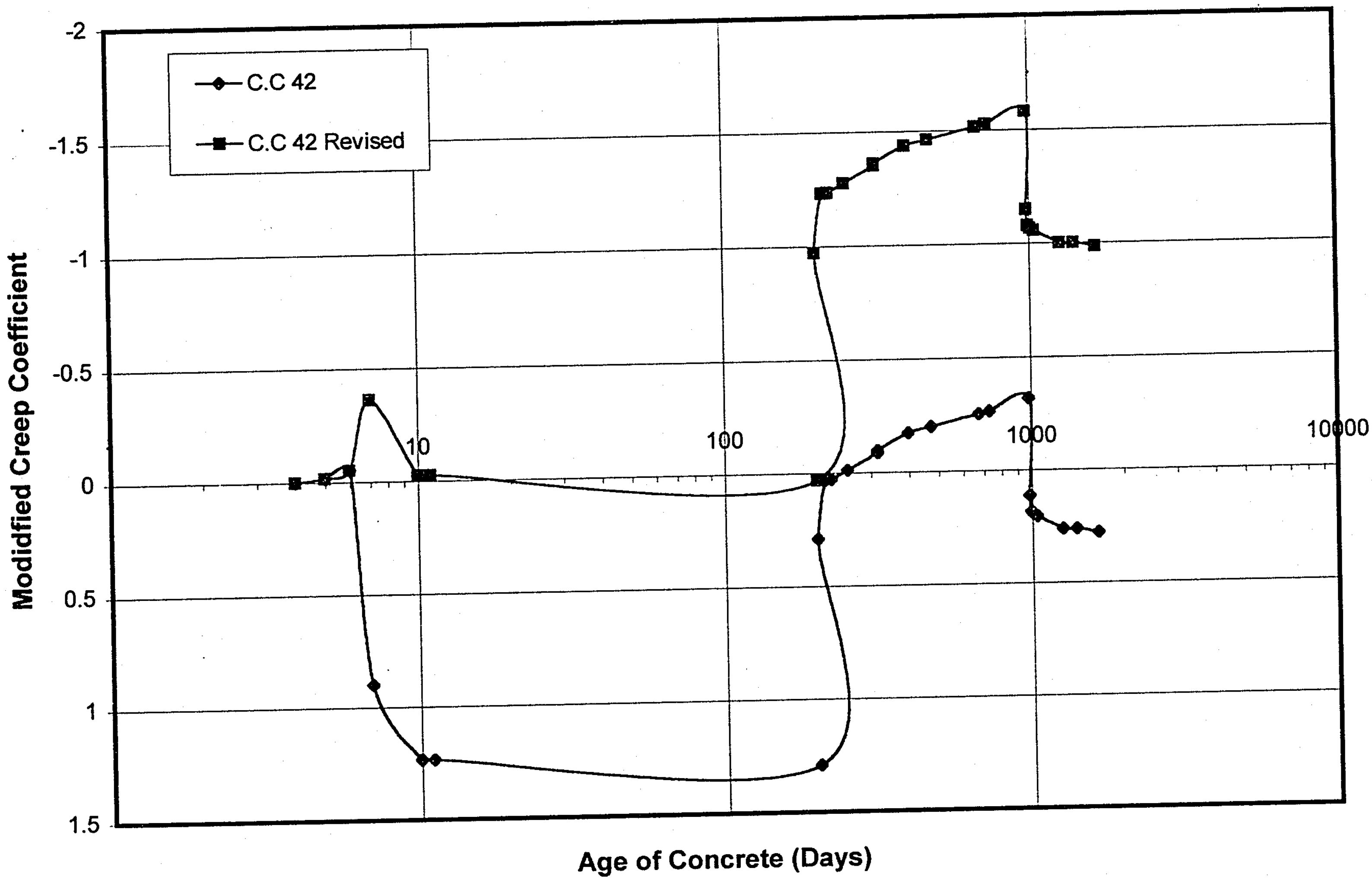


Figure 5-14: Modidfied Creep Coefficient of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 3 days, Specimen 63 & 33 loaded at 28 days, Specimen 8 & 54 loaded at 200 days

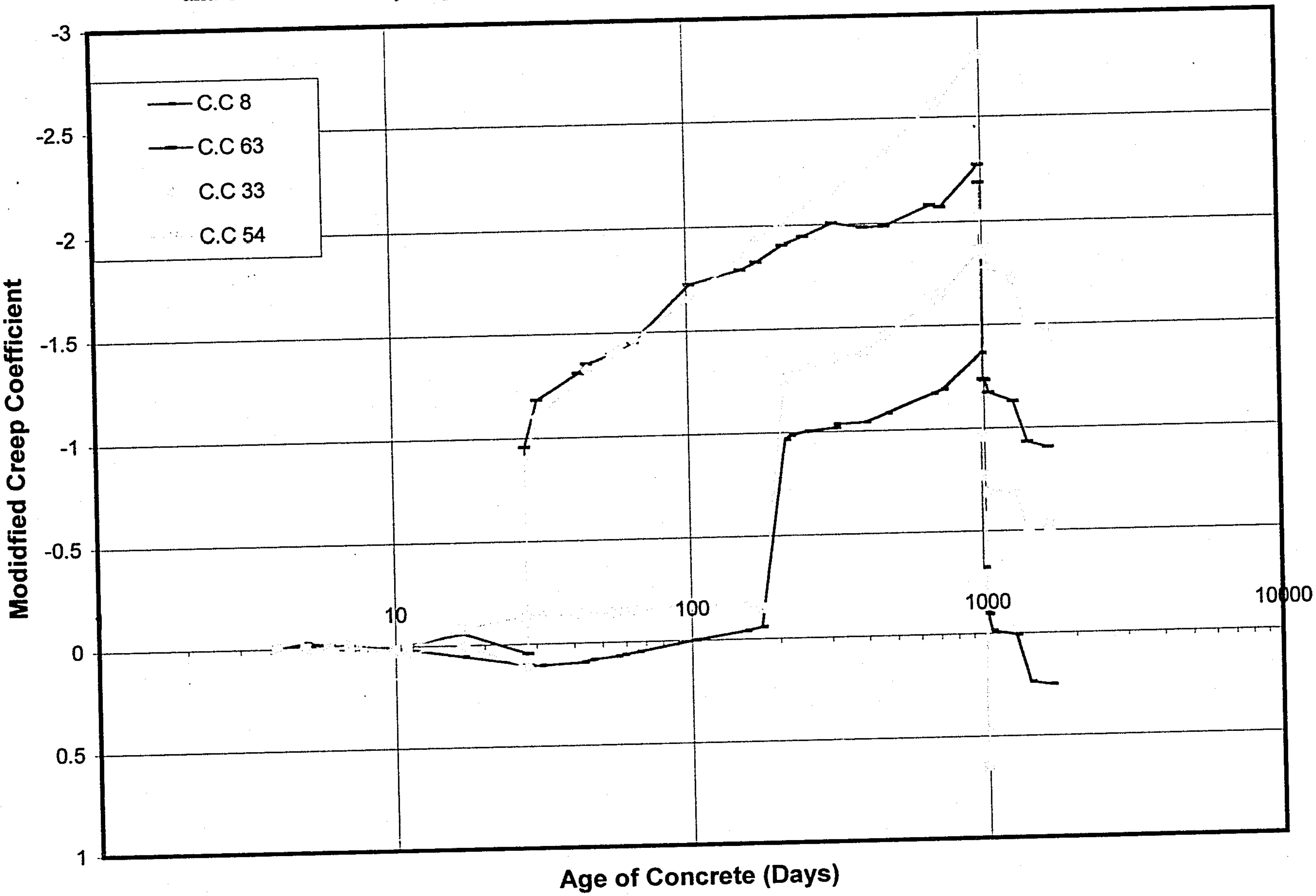


Figure 5-15: Modidfied Creep Coefficient of 89 mm Specimens in 50% R.H. Environment, Moist cured 25 days and Sealed after 25 days, Specimen 50 loaded at 25 days

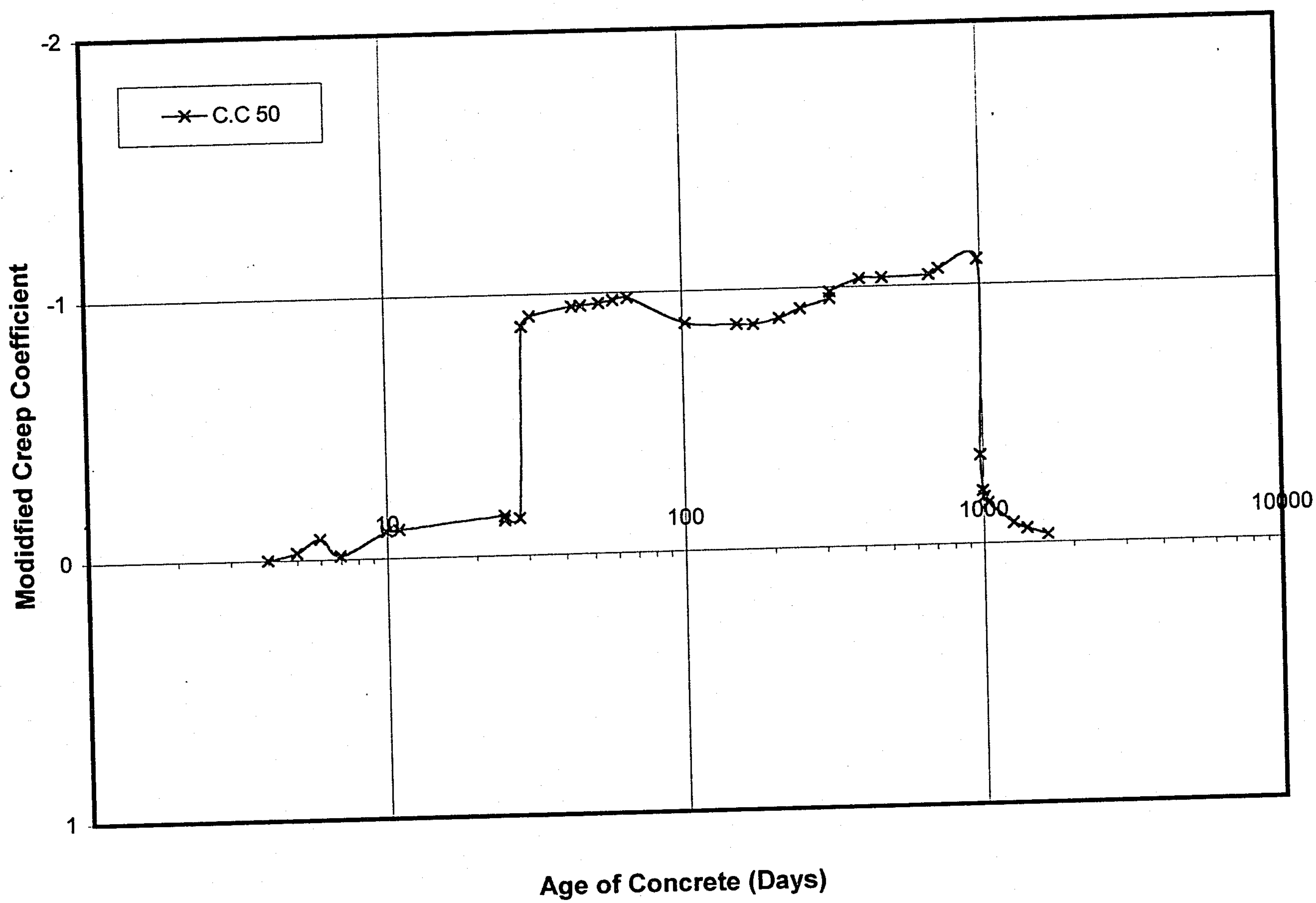


Figure 5-16: Modidfied Creep Coefficient of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 25 days, Specimen 3 & 35 loaded at 25 days

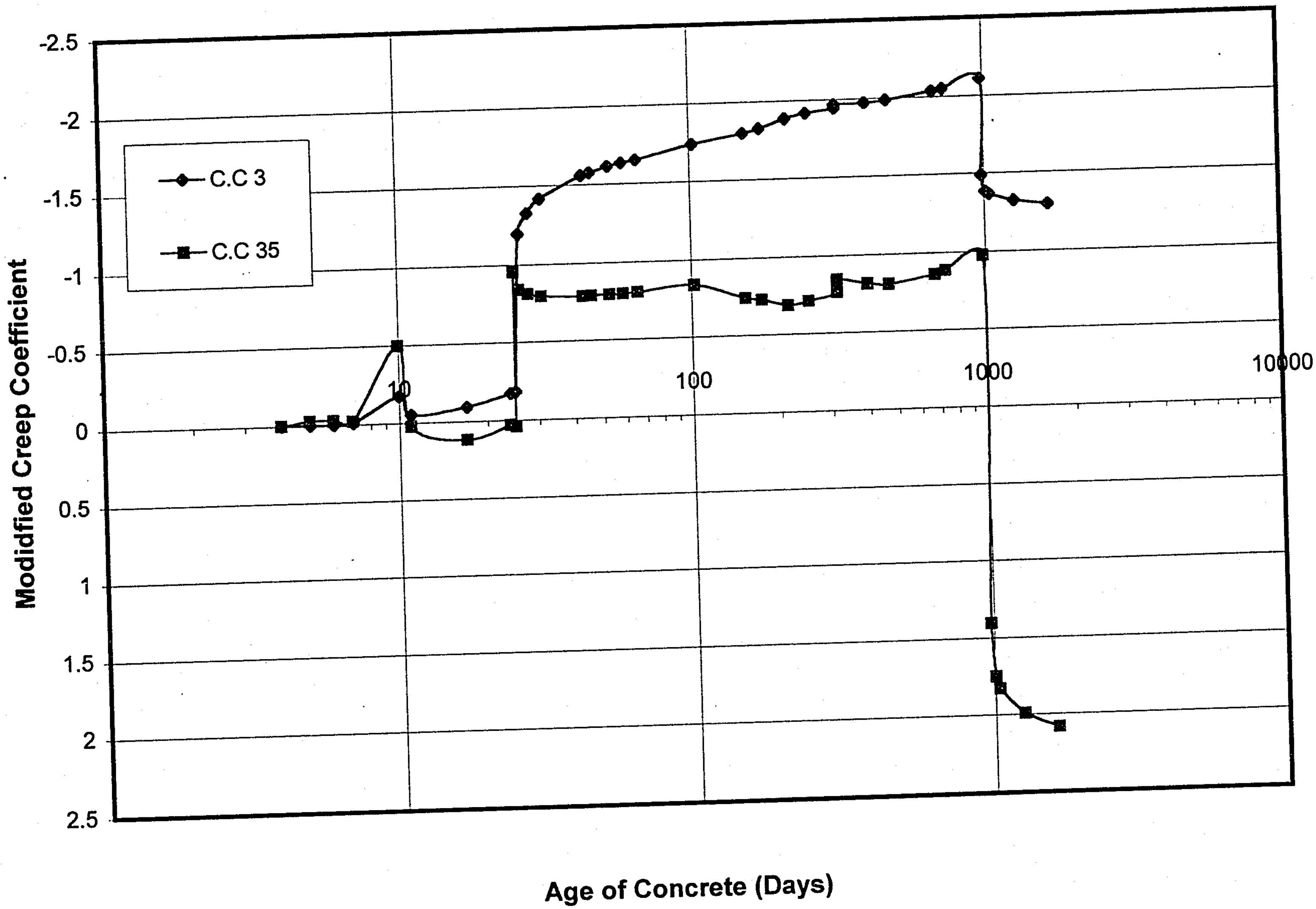


Figure 5-17: Modidfied Creep Coefficientof 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 200 days, Specimen 9 & 36 loaded at 200 days

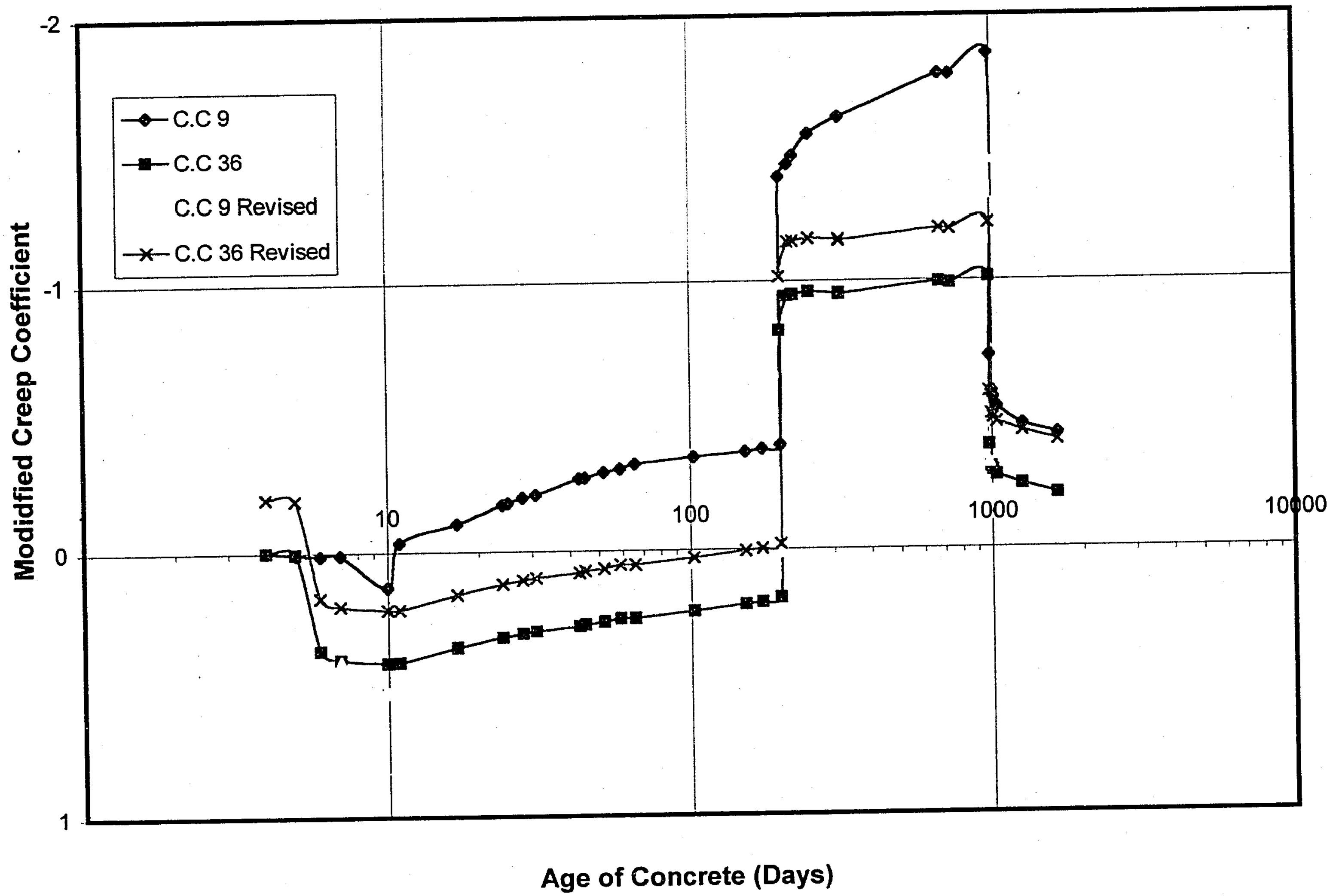


Figure 5-18: Modfied Creep Coefficient of 152 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 69 & 77 loaded at 24 days

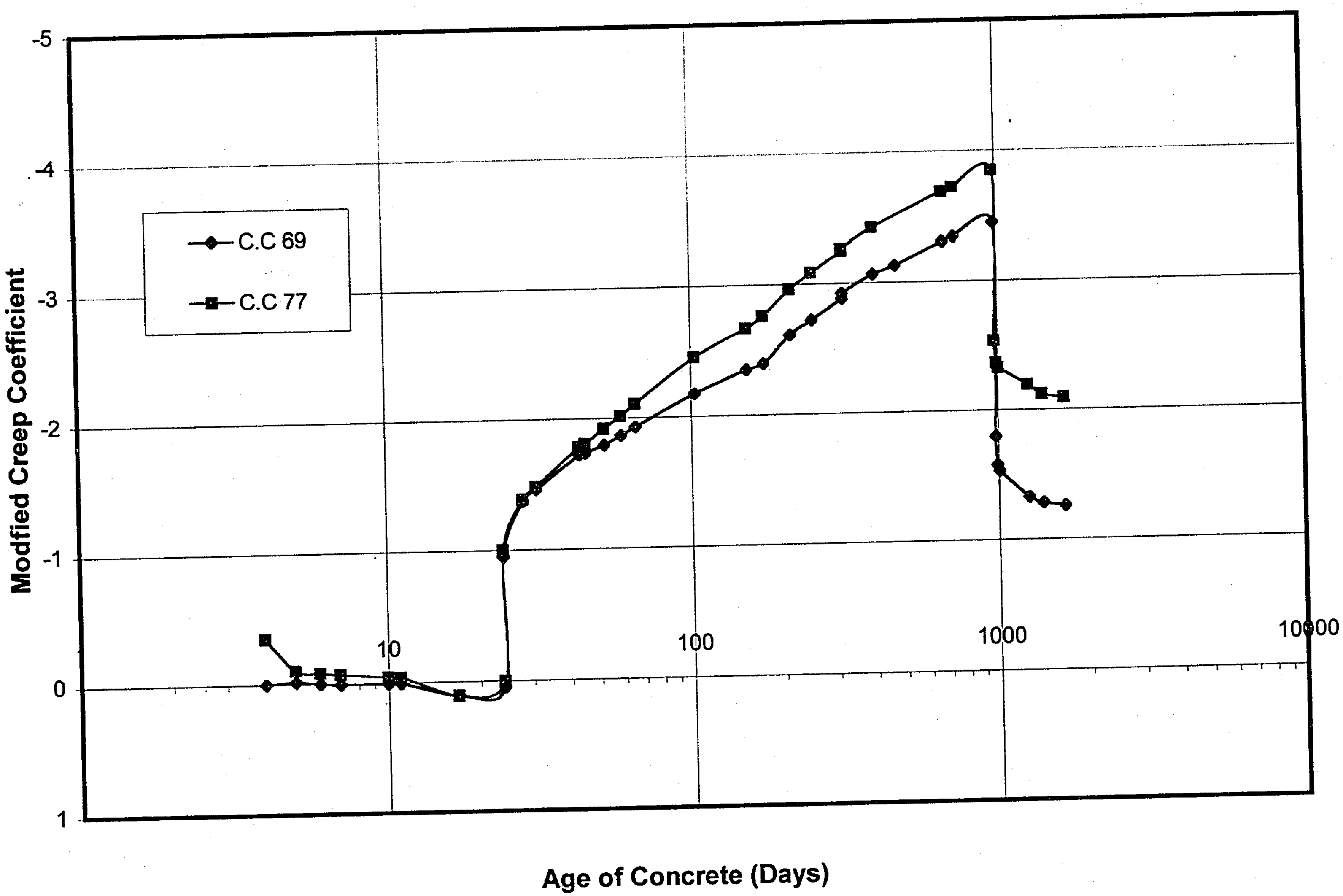


Figure 5-19: Modfied Creep Coefficient of 254 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 83 & 89 loaded at 24 days

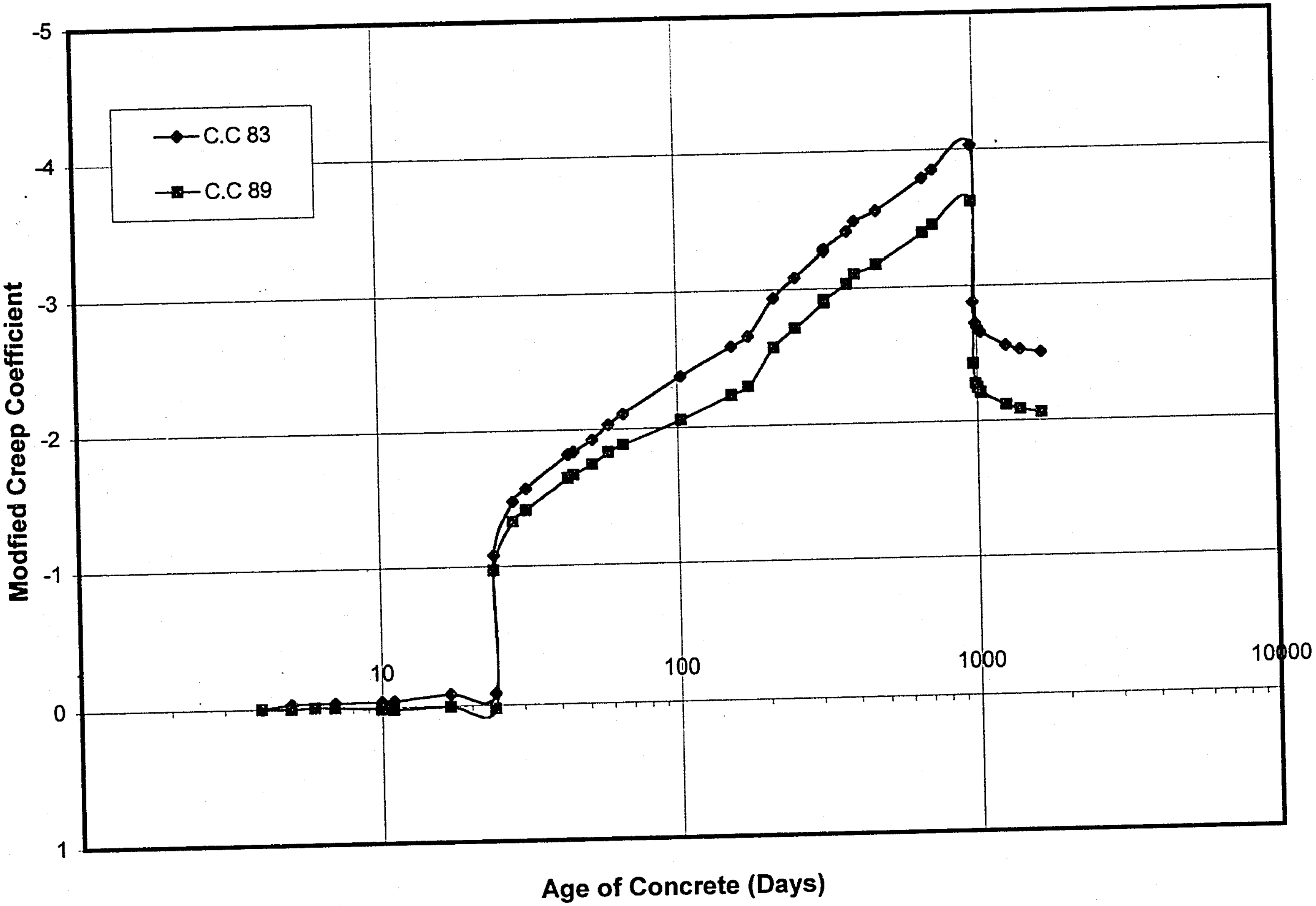


Figure 5-20: Environment Effect - Modified Creep Coefficient of 89 mm Specimens Loaded at 3/4 days in Various Environments

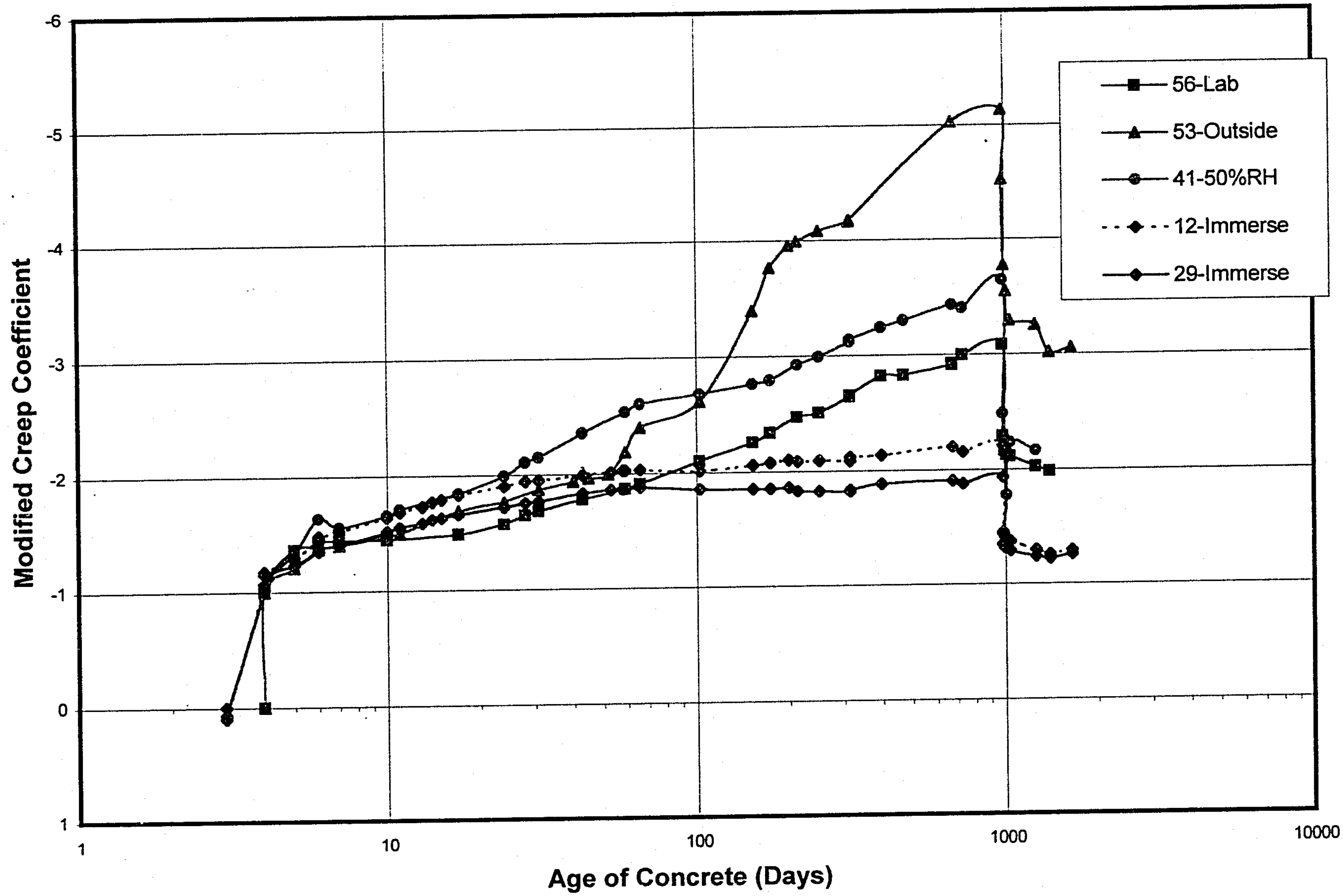


Figure 5-21: Environment Effect - Modified Creep Coefficient of 89 mm Specimens Loaded at 24/25 days in Various Environments

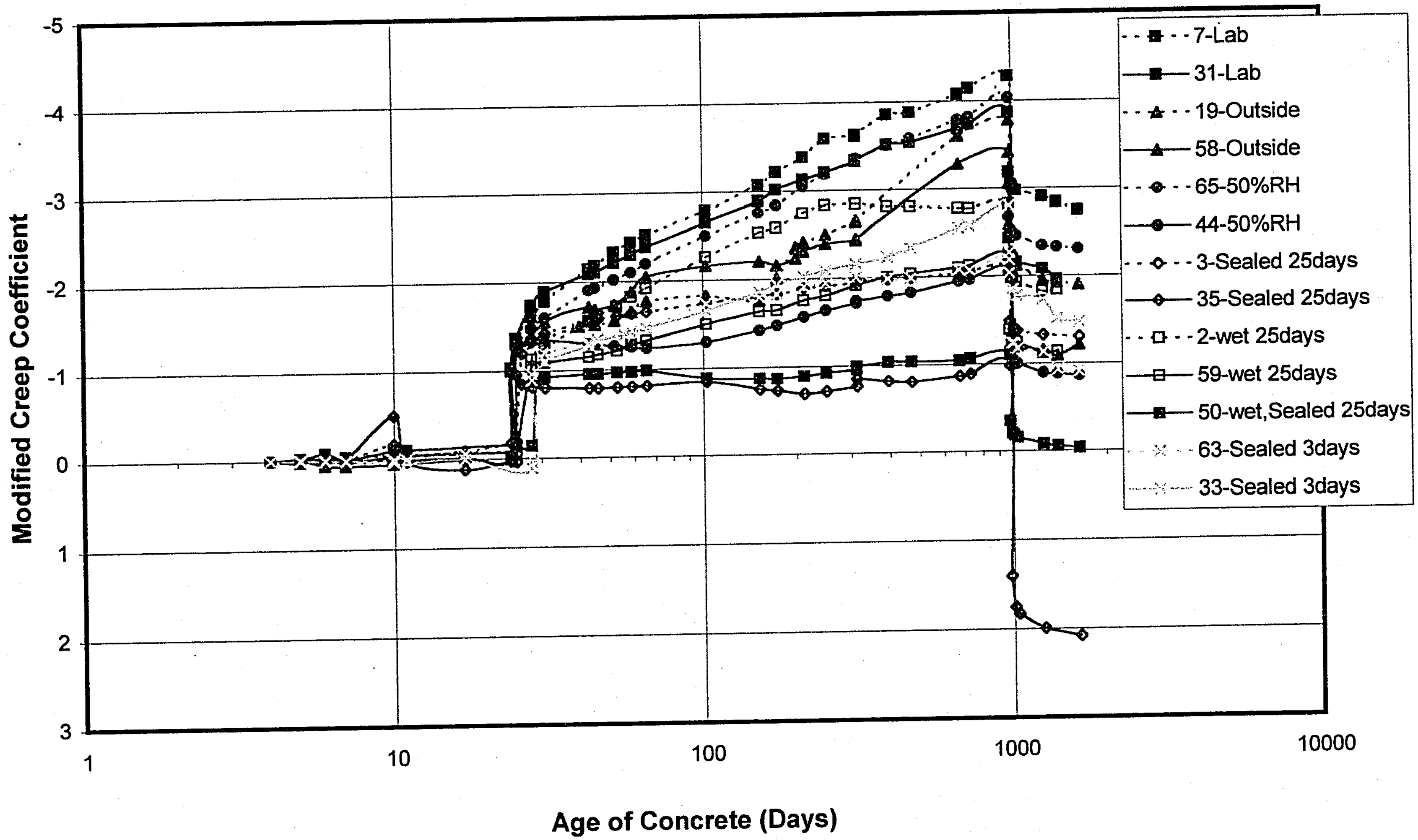


Figure 5-22: Environment Effect -Modified Creep Coefficient of 89 mm Specimens Loaded at 200/201 days in Various Environments

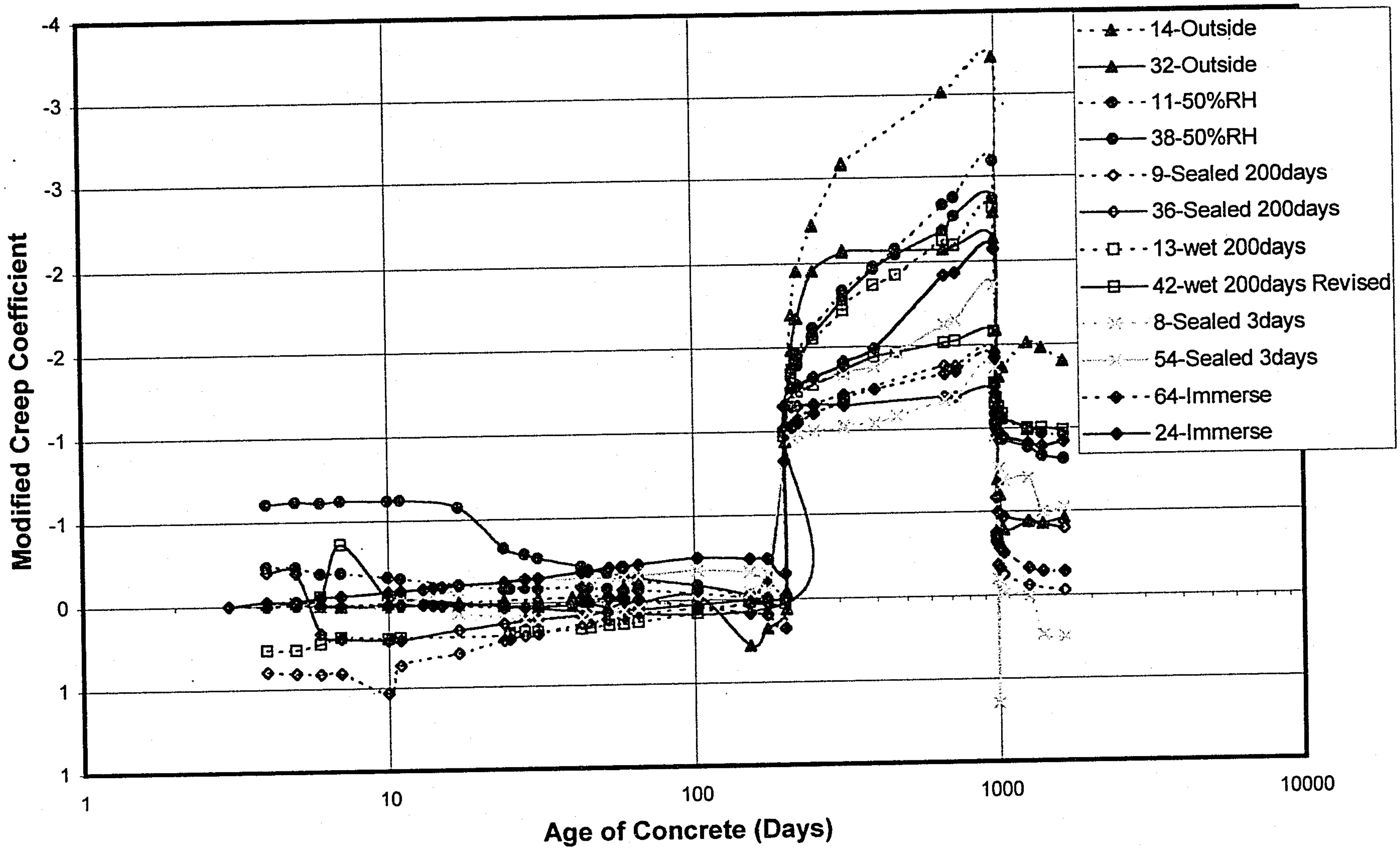


Figure 5-23: Environment Effect -Modified Creep Coefficient of 152 mm Specimens Loaded at 24 days in Various Environments

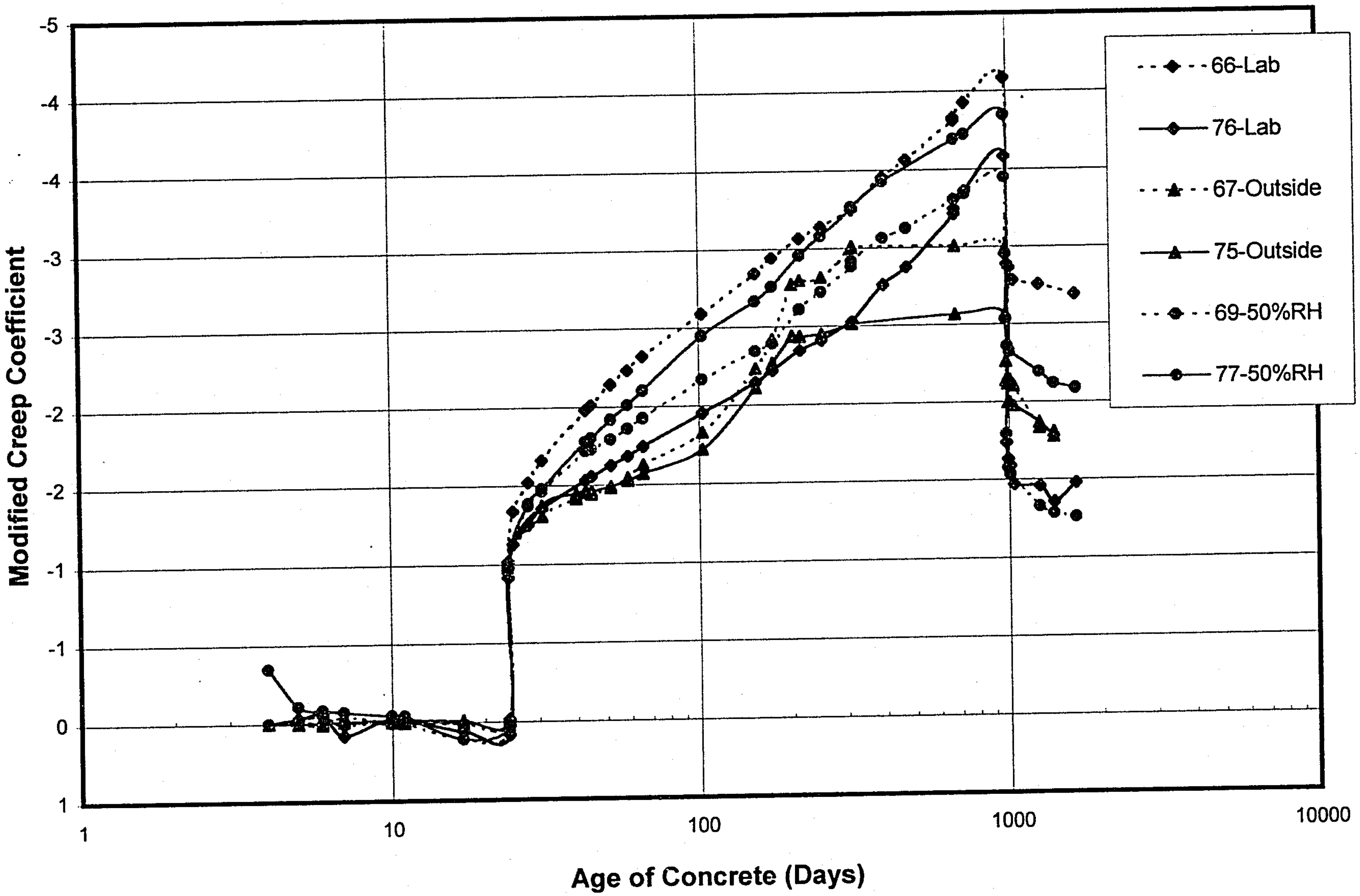


Figure 5-24(a): Environment Effect - Modified Creep Coefficient of 254 mm Specimens Loaded at 24/201 days in Various Environments

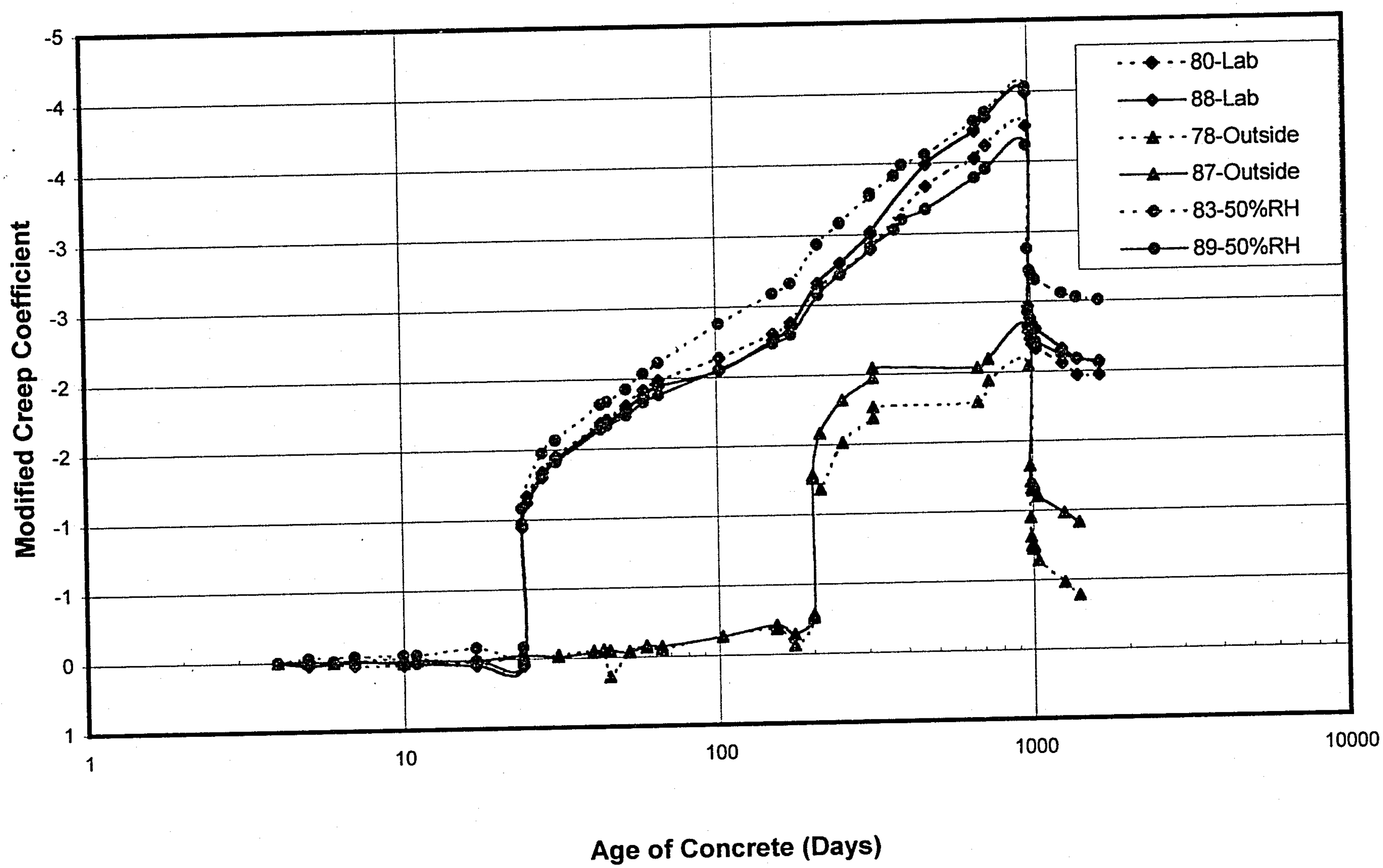


Figure 5-24(b): Environment Effect-Modified Creep Coefficient of 254 mm Specimens

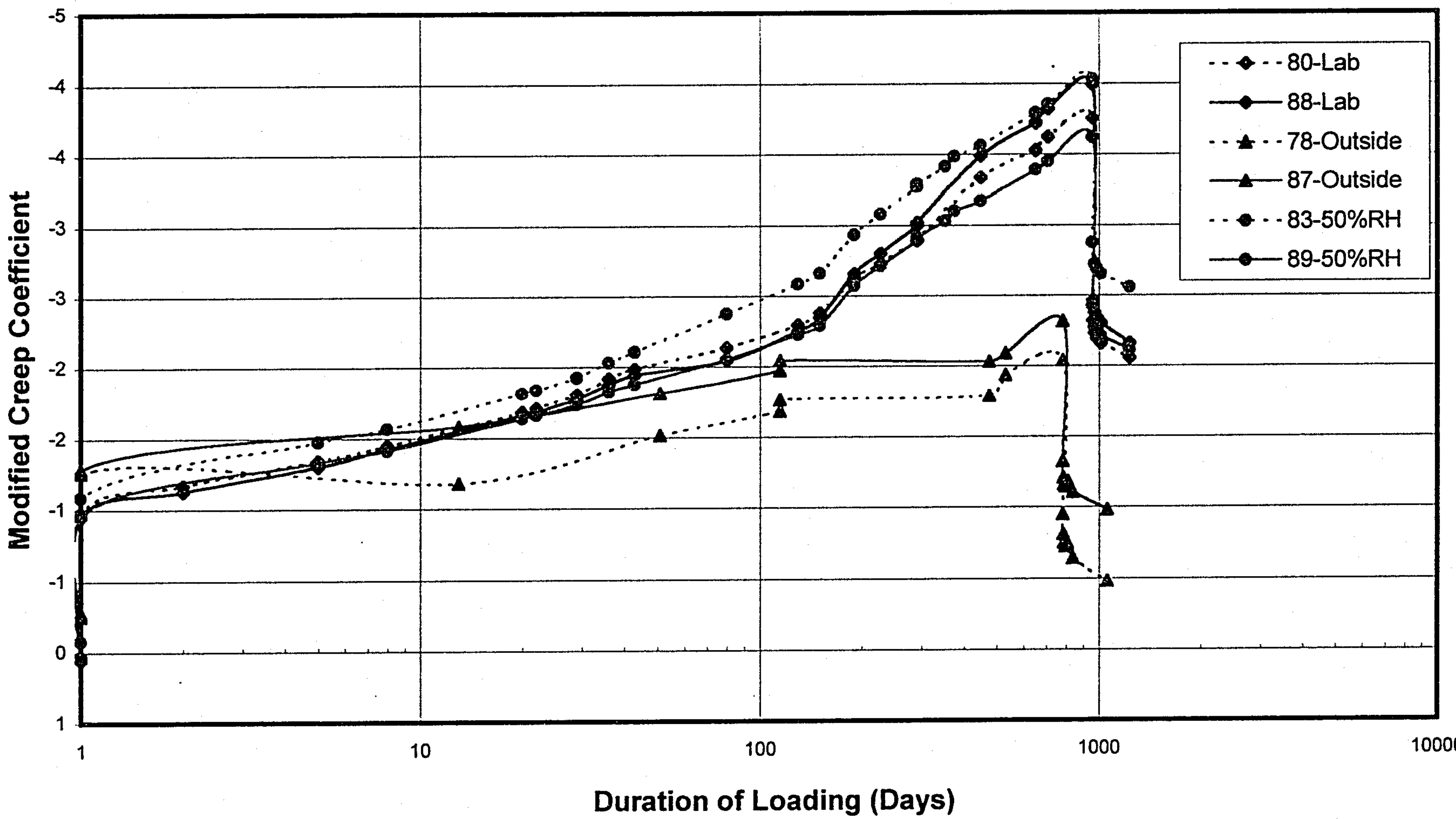


Figure 5-25: Modified Creep Coefficient of 610 mm Specimens Loaded at 25 days in the L

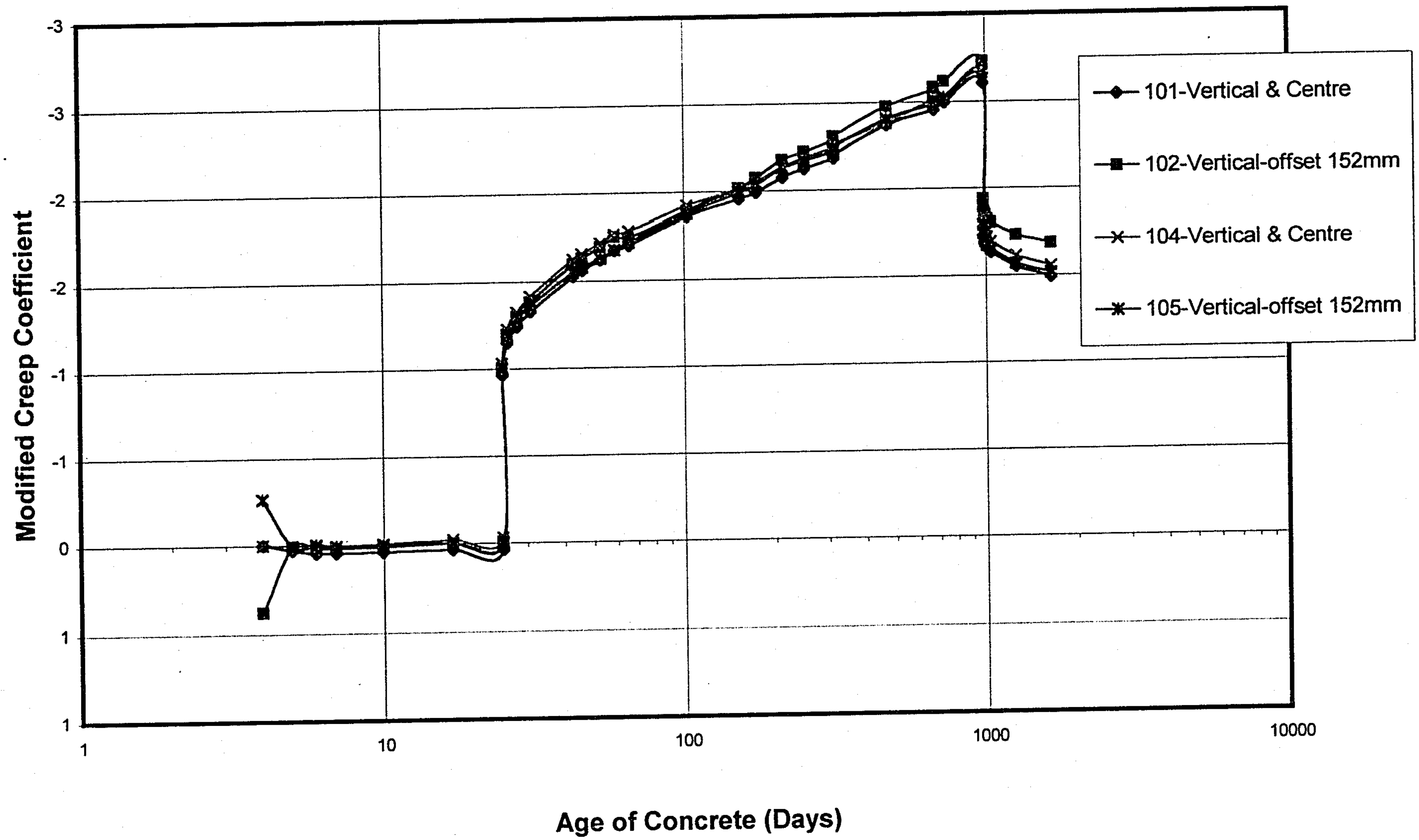


Figure 5-26: Size Effect -Modified Creep Coefficient of 89, 152, 254 and 610 mm Specimens in the Lab Loaded at 24 days

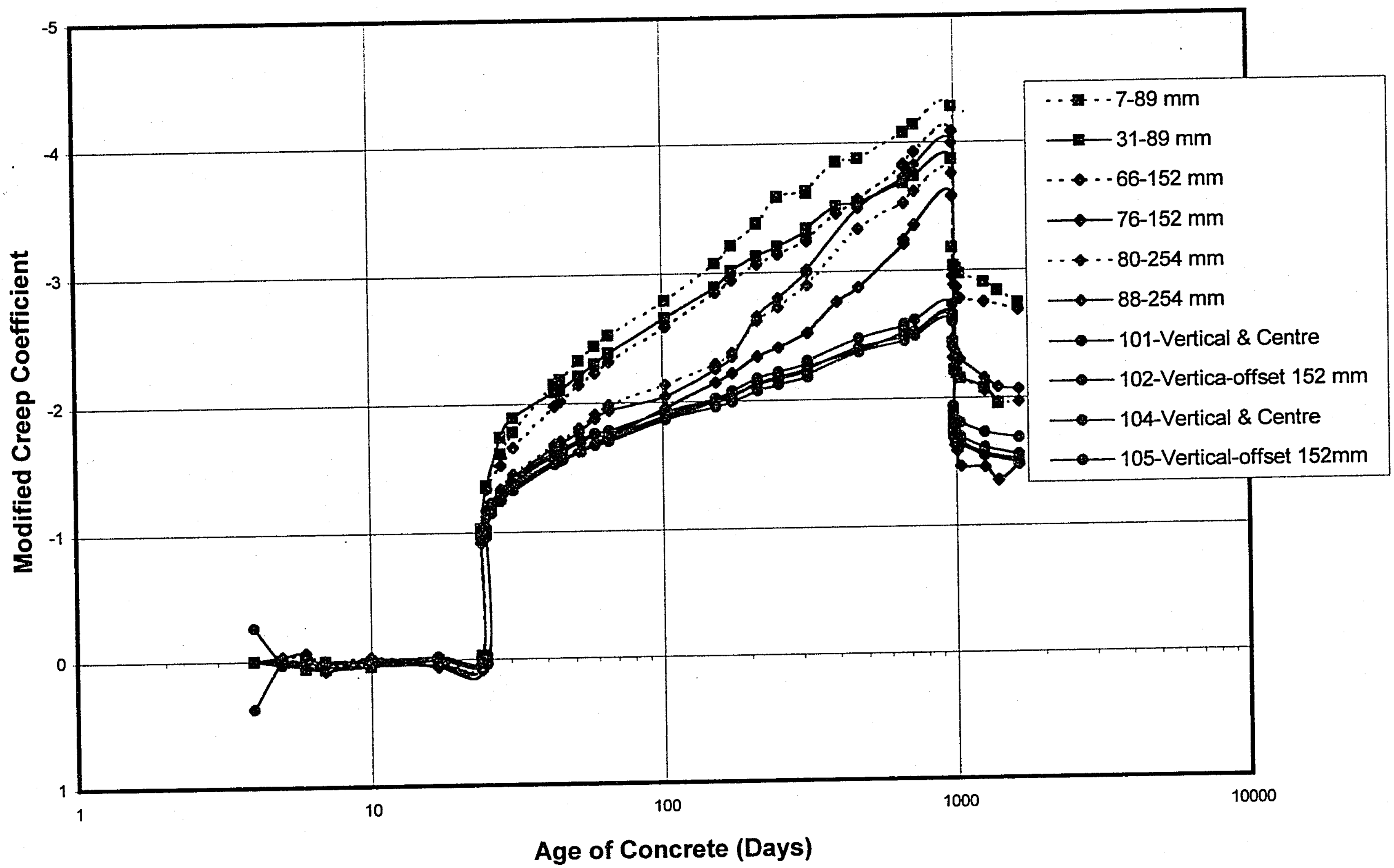


Figure 5-27(a): Size Effect - Modified Creep Coefficient of 89, 152 and 254 mm Specimens Outside, Moist cured 3 days, Loaded at 4, 24, and 201 days

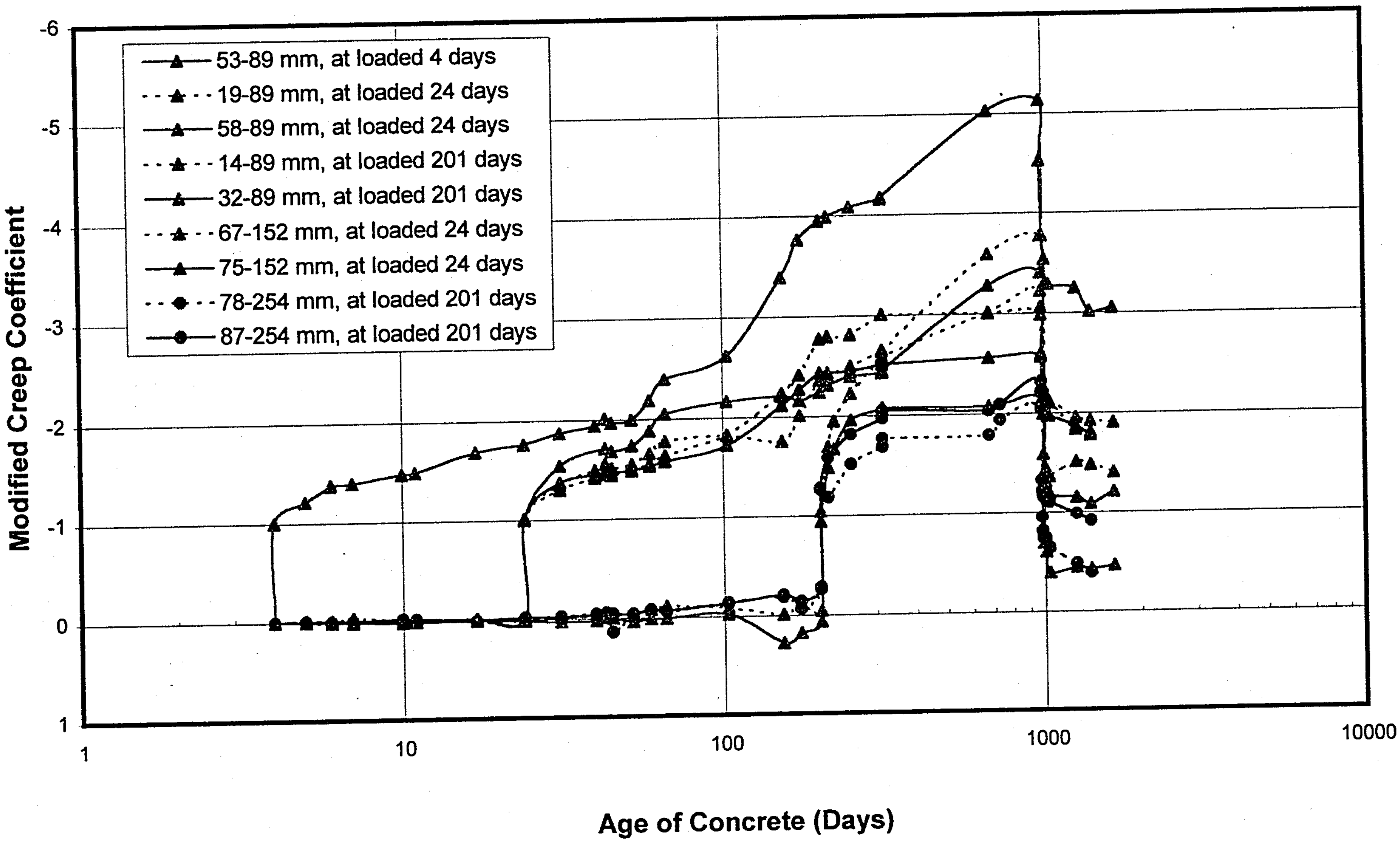


Figure 5-27(b): Size Effect - Modified Creep Coefficient of 89, 152 and 254 mm Specimens Outside
Moist cured 3 days, Loaded at 4, 24, and 201 days

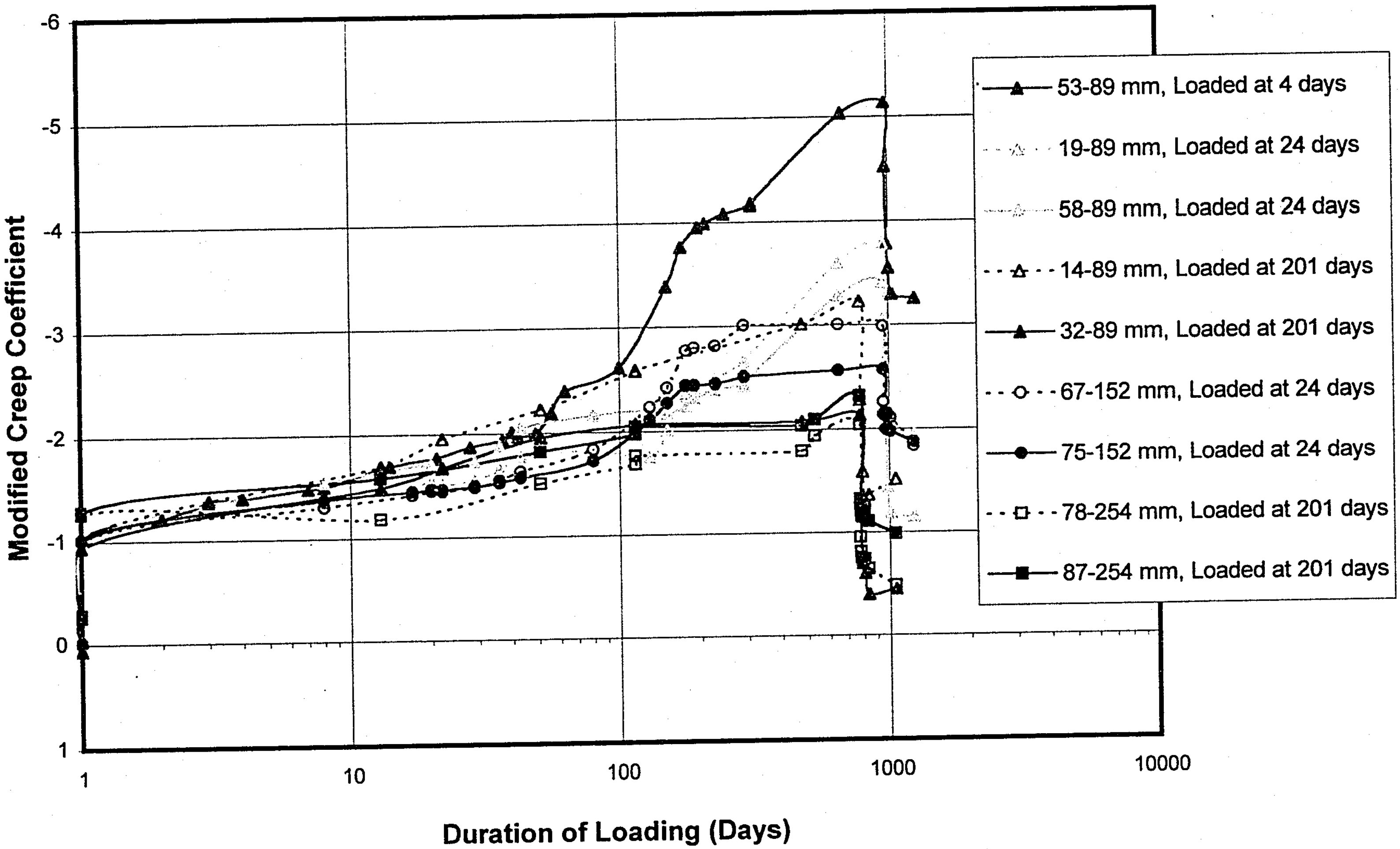
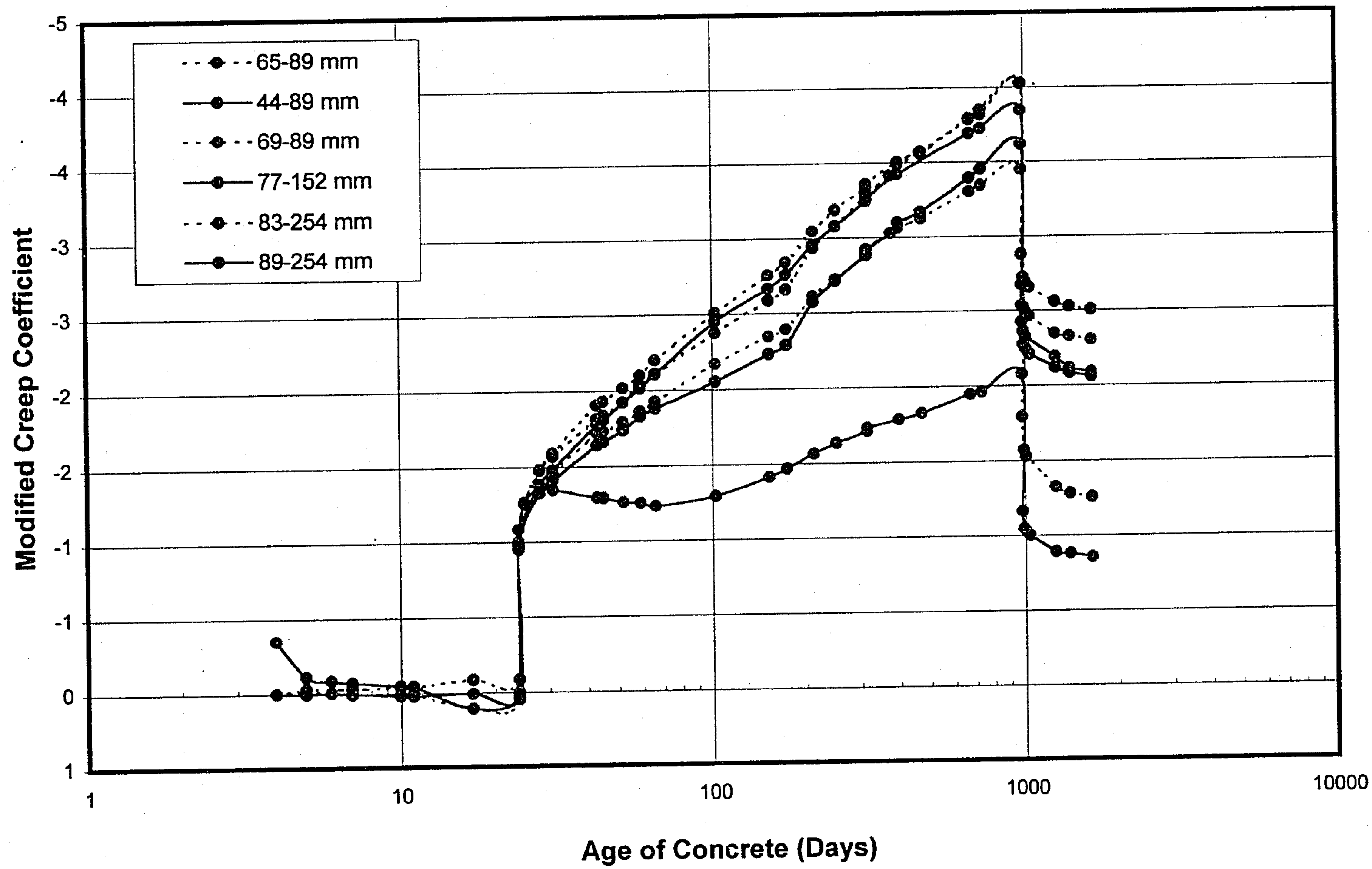


Figure 5-28: Size Effect -Modified Creep Coefficient of 89, 152 and 254 mm Specimens in 50 % RH Environments,
Loaded at 25 days



CHAPTER 6

CREEP RECOVERY

This chapter considers the creep recovery of the specimens in different environments.

All creep specimens were unloaded at 984 days. Figures 6-1 to 6-19 show the modified creep coefficients, based upon the initial elastic strain of creep specimens in different environments and under different moist curing durations, age of loading and size. All graphs are drawn to normal time scale so that creep recovery can be considered better.

The modified creep coefficients of different specimens exactly before and after unloading are collected in Table 6-1 and the difference of the two values is given. Looking at the average of the difference of modified creep coefficients (-0.99) leads us to the conclusion that elastic recovery is the same as the elastic strain at age of loading. The expectation was that elastic recovery should be less than elastic strain of loading.

Looking in the graphs of creep recovery shows that after unloading the values of modified creep coefficient is almost constant and only a slight decrease can be observed. The expectation was that the shape of recovery be the same as the creep, whilst the graphs show that creep recovery has not taken place so effectively.

In conclusion it can be said that elastic recovery has almost taken place completely whilst the creep recovery is effectively zero.

Table 6-1: Elastic Recovery of Creep Specimens

No of Specimen	Environment	C.C 1 Before Loading	C.C 2 After Loading	Elastic Recovery
2	TENT	-2.8	-2.1	-0.7
3	TENT	-2.1	-1.5	-0.6
7	LAB	-4.3	-3.2	-1.1
8	TENT	-1.4	-0.3	-1.1
9	TENT	-1.9	-0.7	-1.2
11	TENT	-2.4	-1.0	-1.4
12	IMMERSED	-2.2	-1.5	-0.7
13	TENT	-2.6	-1.5	-1.1
14	OUTSIDE	-3.2	-2.3	-0.9
19	OUTSIDE	-3.8	-3.1	-0.7
20	IMMERSED	-1.6	-0.7	-0.9
21	LAB	-2.9	-1.8	-1.1
23	IMMERSED	-2.0	-1.0	-1.0
24	IMMERSED	-2.1	-1.0	-1.1
26	LAB	-3.0	-2.0	-1.0
29	IMMERSED	-1.9	-1.4	-0.5
31	LAB	-3.9	-2.4	-1.5
32	OUTSIDE	-2.1	-1.3	-0.8
33	TENT	-2.8	-2.0	-0.8
35	TENT	-1.0	1.4	-
36	TENT	-1.0	-0.4	-0.6
37	LAB	-3.2	-1.7	-1.5
38	TENT	-1.8	-0.5	-1.3
41	TENT	-3.6	-2.5	-1.1
42	TENT	-0.3	0.1	-0.4
44	TENT	-1.6	-0.7	-0.9
50	TENT	-1.1	-0.3	-0.8
53	OUTSIDE	-5.1	-4.5	-0.6
54	TENT	-1.9	-1.0	-0.9
56	LAB	-3.1	-2.3	-0.8
58	OUTSIDE	-3.4	-2.6	-0.8
59	TENT	-2.2	-1.4	-0.8
61	OUTSIDE	-1.7	-0.9	-0.8
63	TENT	-2.2	-1.2	-1.0
64	IMMERSED	-1.4	-0.4	-1.0
65	TENT	-3.9	-2.6	-1.3
66	LAB	-4.1	-3.0	-1.1
67	OUTSIDE	-3.0	-2.2	-0.8
69	TENT	-3.4	-1.8	-1.6
75	OUTSIDE	-2.6	-2.1	-0.5
76	LAB	-3.6	-1.7	-1.9
77	TENT	-3.5	-2.2	-1.3
78	OUTSIDE	-2.0	-1.0	-1.0
80	LAB	-3.8	-2.3	-1.5
83	TENT	-4.0	-2.9	-1.1
87	OUTSIDE	-2.3	-1.3	-1.0
88	LAB	-4.0	-2.5	-1.5
89	TENT	-3.6	-2.4	-1.2
101	LAB	-2.6	-1.8	-0.8
102	LAB	-3.1	-2.3	-0.8
103	LAB	-1.1	-0.2	-0.9
104	LAB	-2.7	-1.8	-0.9
105	LAB	-2.4	-1.5	-0.9
106	LAB	-3.8	-2.9	-0.9
Average				-0.99

Figure 6-1: Creep Recovery of 89 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 56 loaded at 3 days, Specimen 7 &31 loaded at 24 days

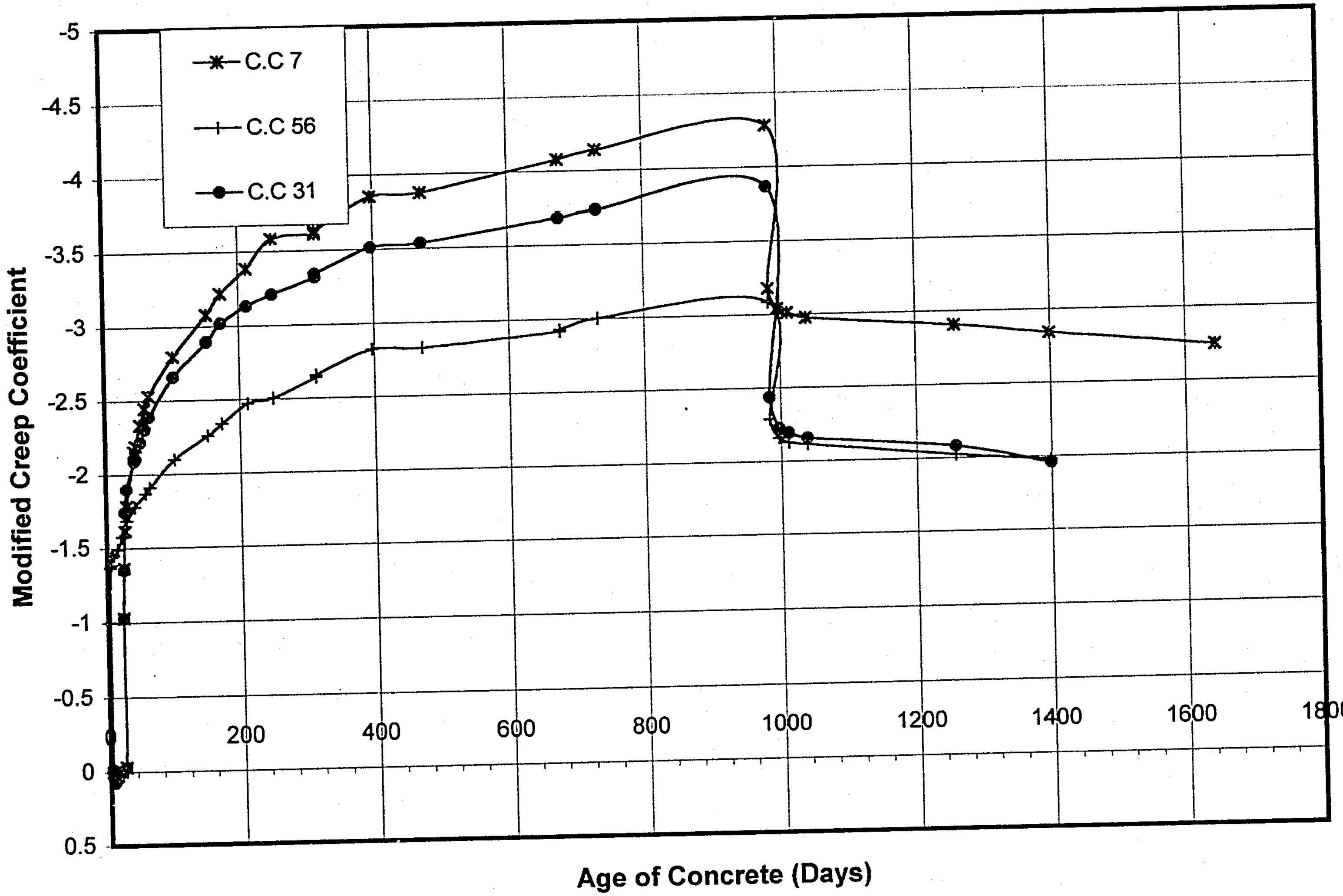


Figure 6-2: Creep Recovery of 89 mm Specimens in Lab Environment, Moist cured 24 days
Specimen 26 loaded at 25 days, Specimen 21 & 37 loaded at 28 days

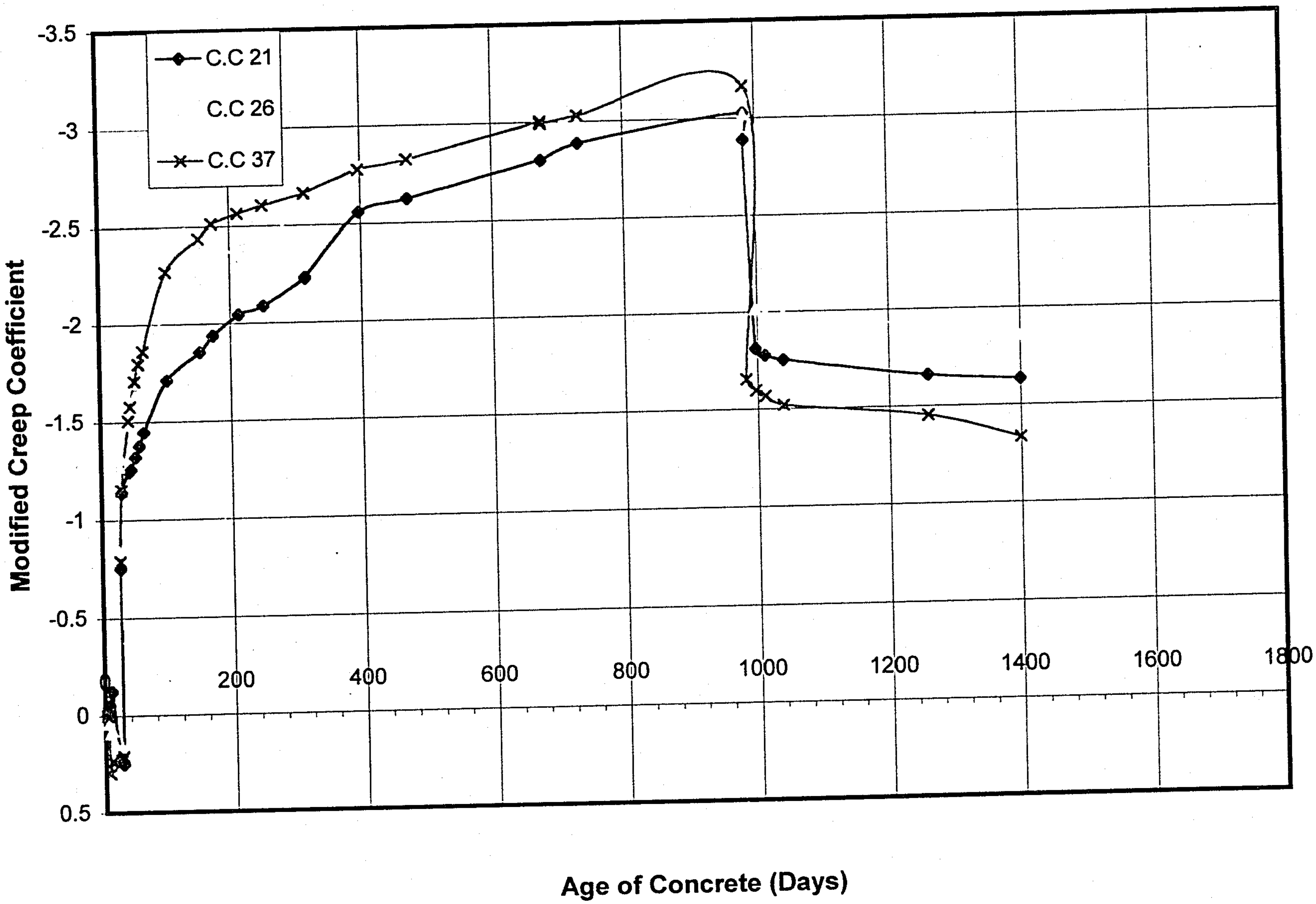


Figure 6-3: Creep Recovery of 152 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 66 & 76 loaded at 24 days

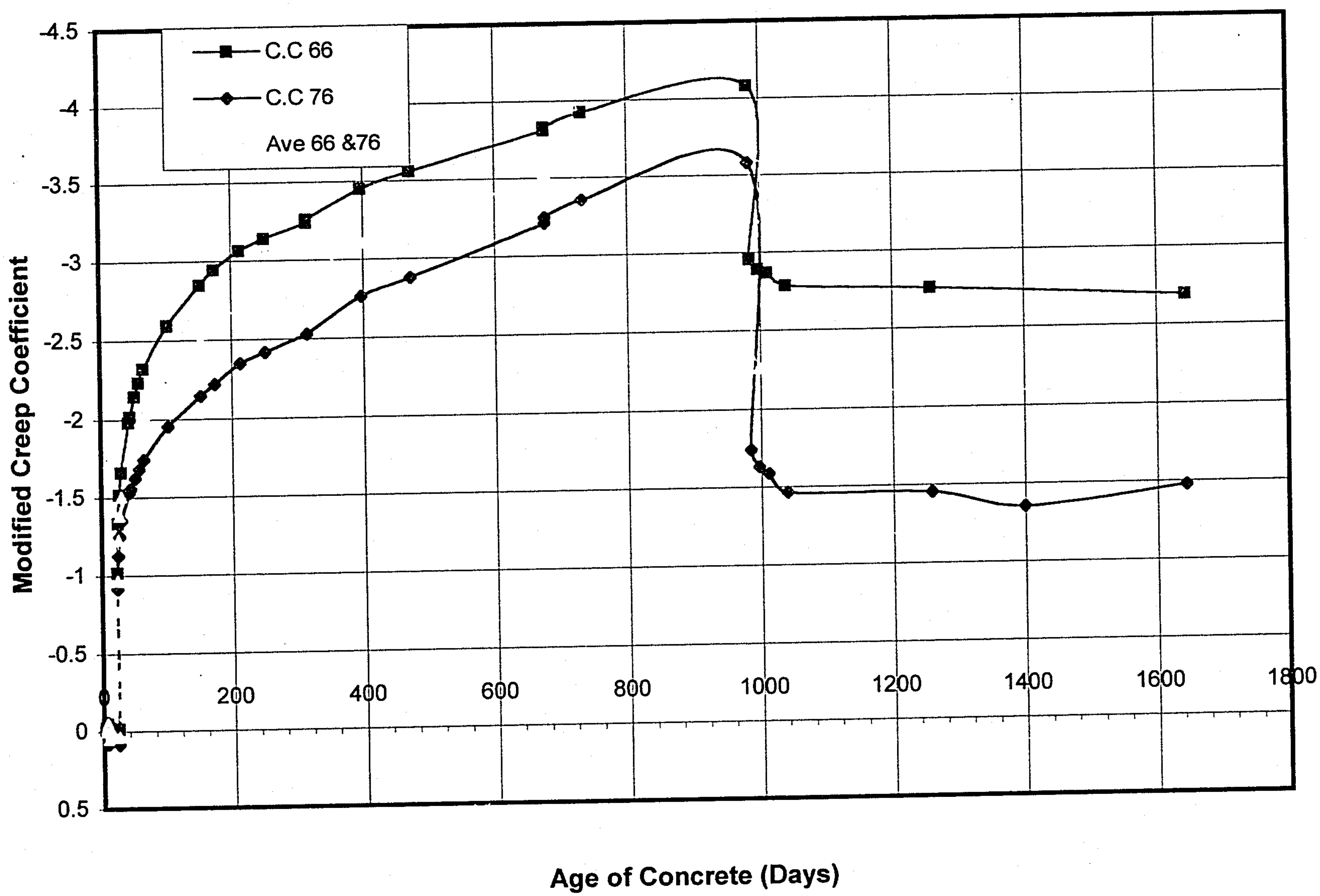


Figure 6-4: Creep Recovery of 254 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 80 & 88 loaded at 24 days

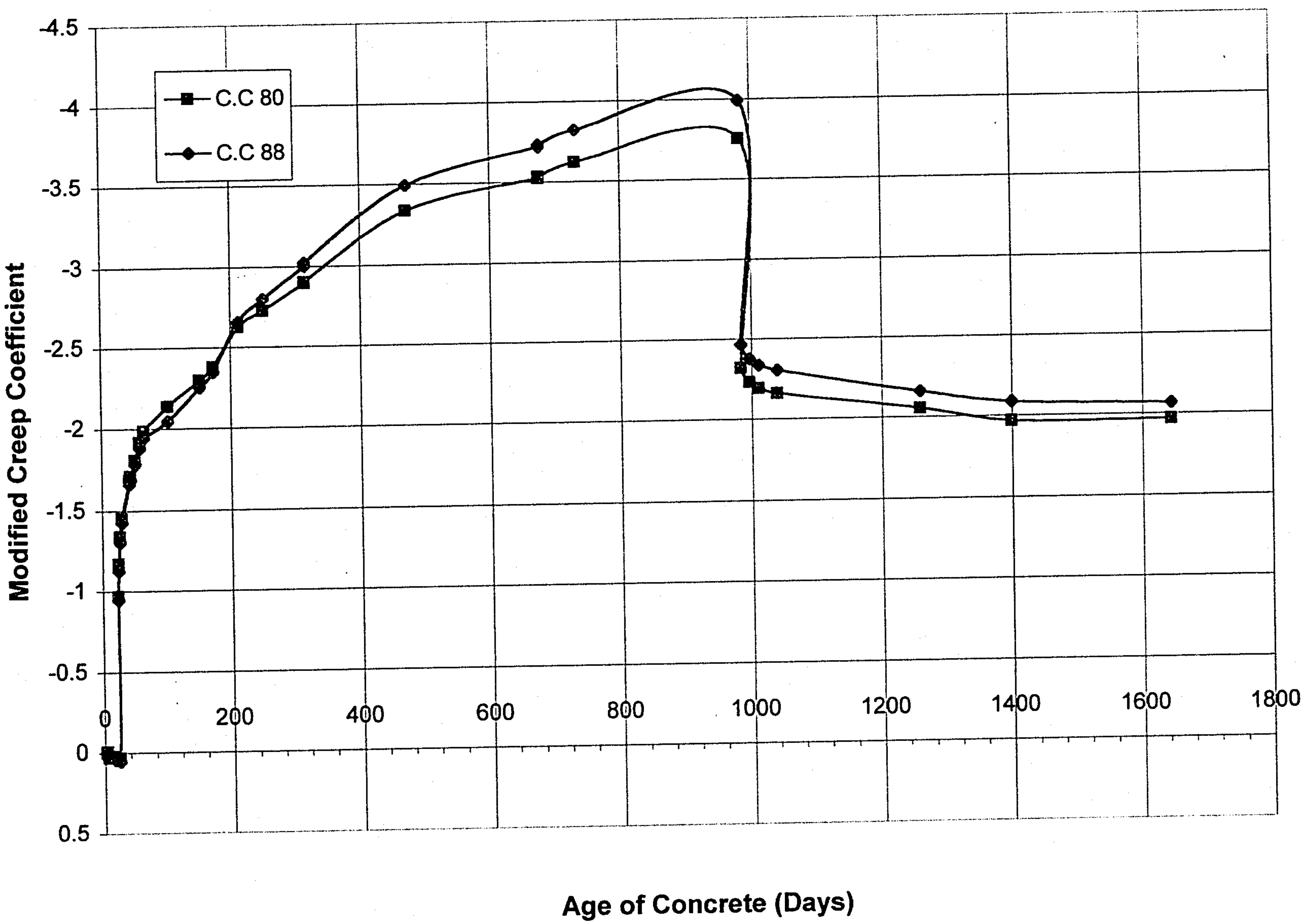


Figure 6-5: Creep Recovery of 610 mm Specimens in Lab Environment, Moist cured 3 days
Specimens 101~106 loaded at 25 days

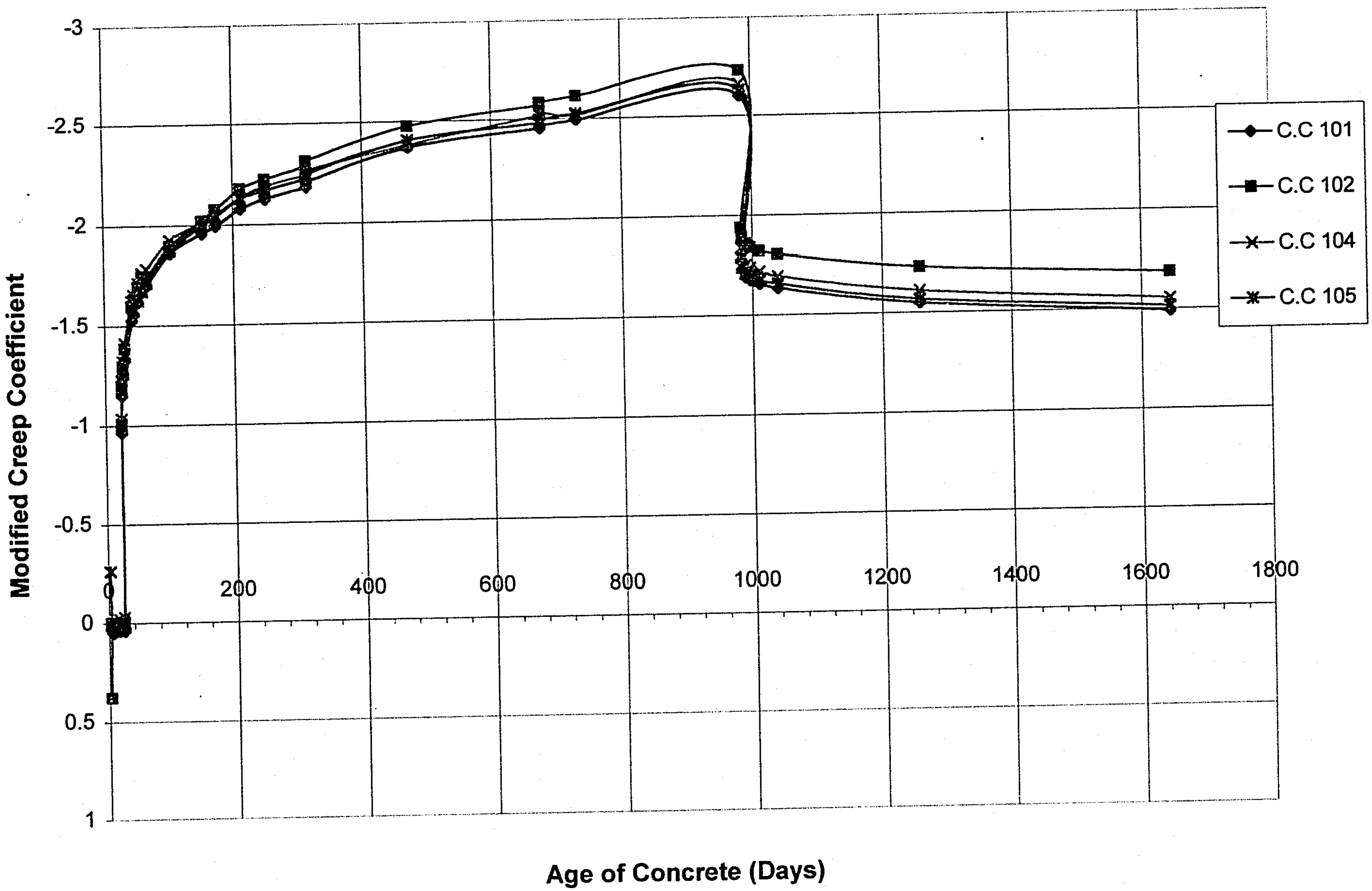


Figure 6-6: Creep Recovery of 89 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 53 loaded at 4 days, Specimen 19 & 58 loaded at 24 days, Specimen 14 & 32 loaded at 201 days

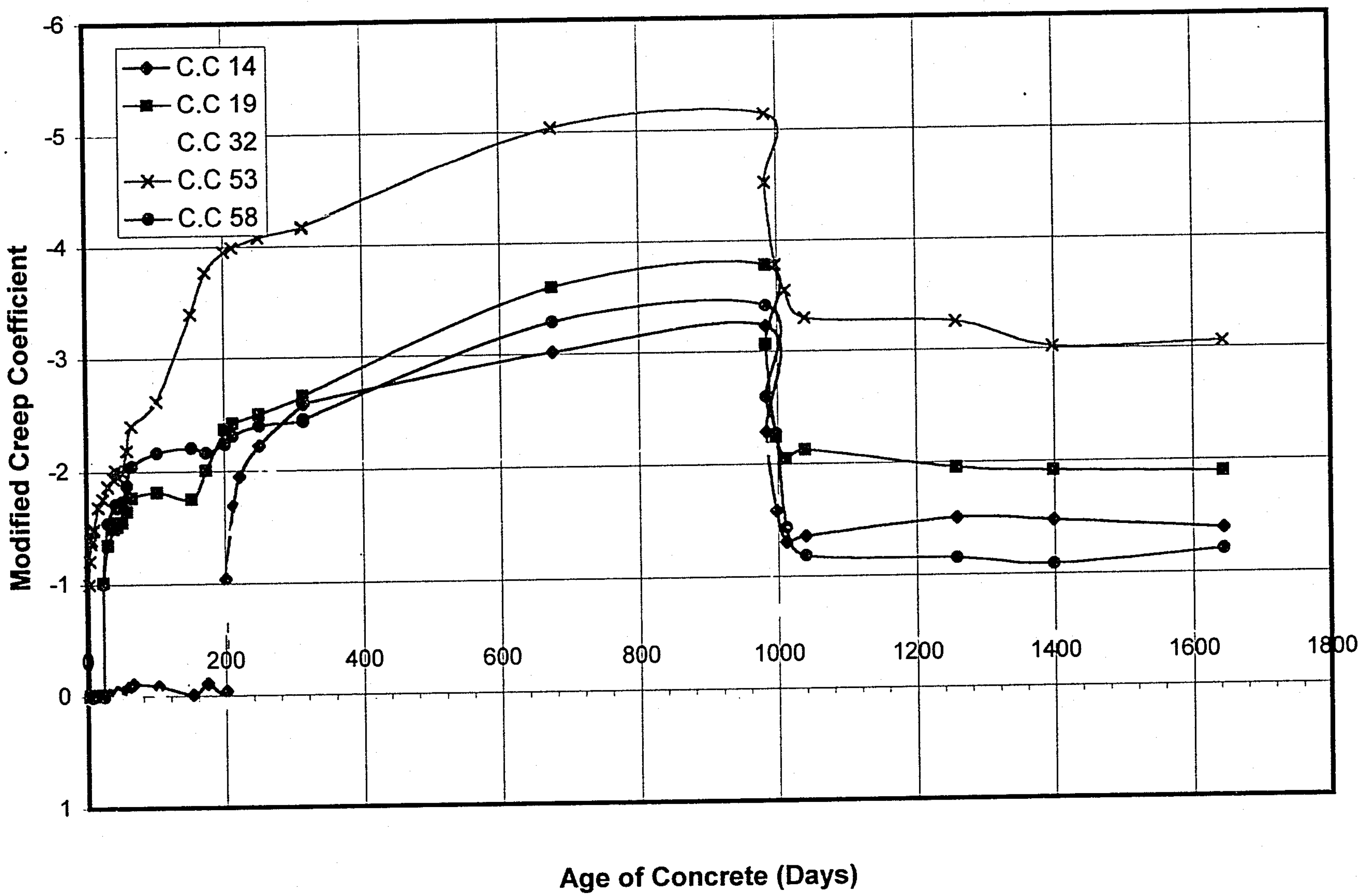


Figure 6-7: Creep Recovery of 89 mm Specimens Outdoor Environment, Moist cured 24 days
Specimen 61 loaded at 24 days

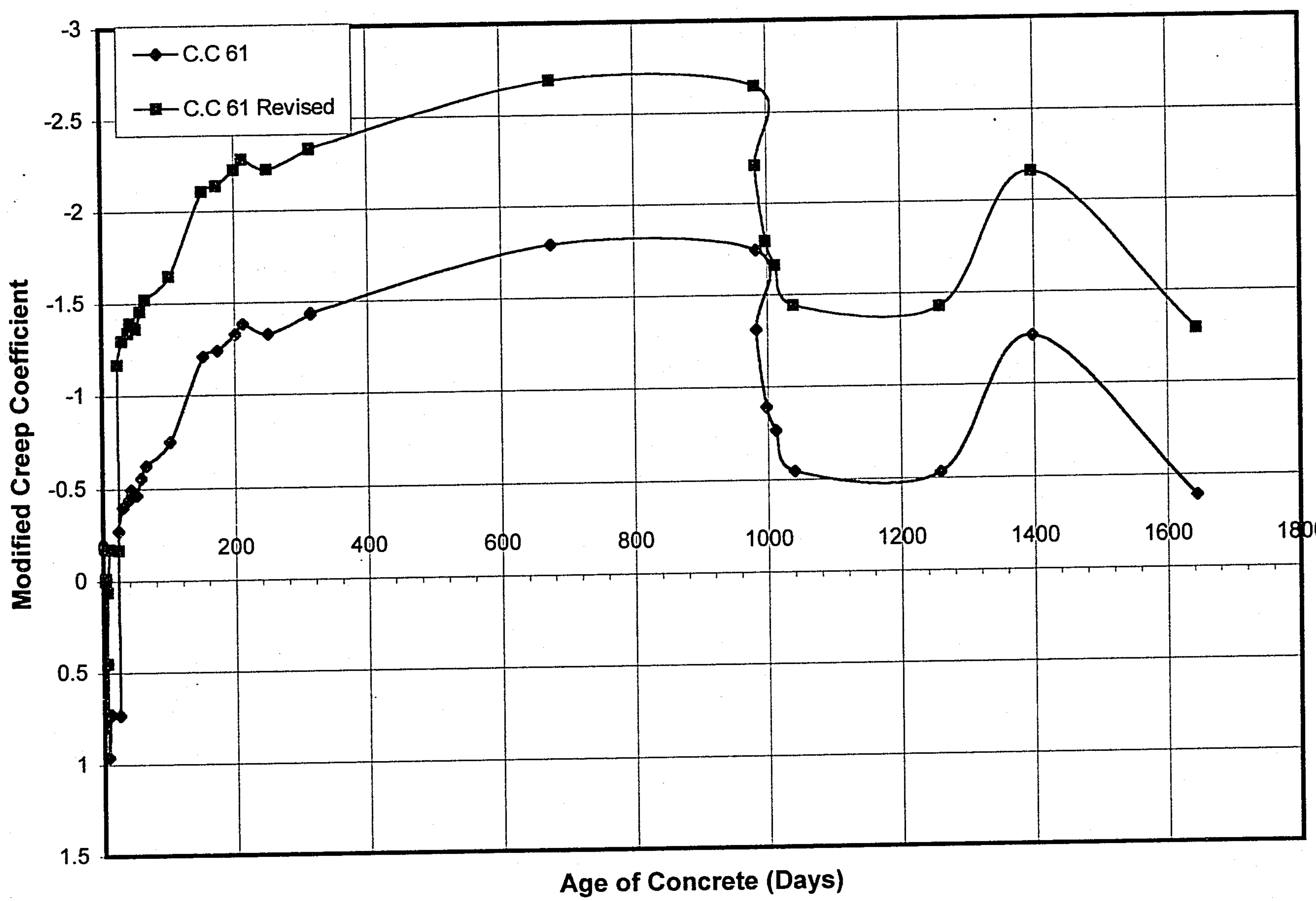


Figure 6-8: Creep Recovery of 152 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 67 & 75 loaded at 24 days

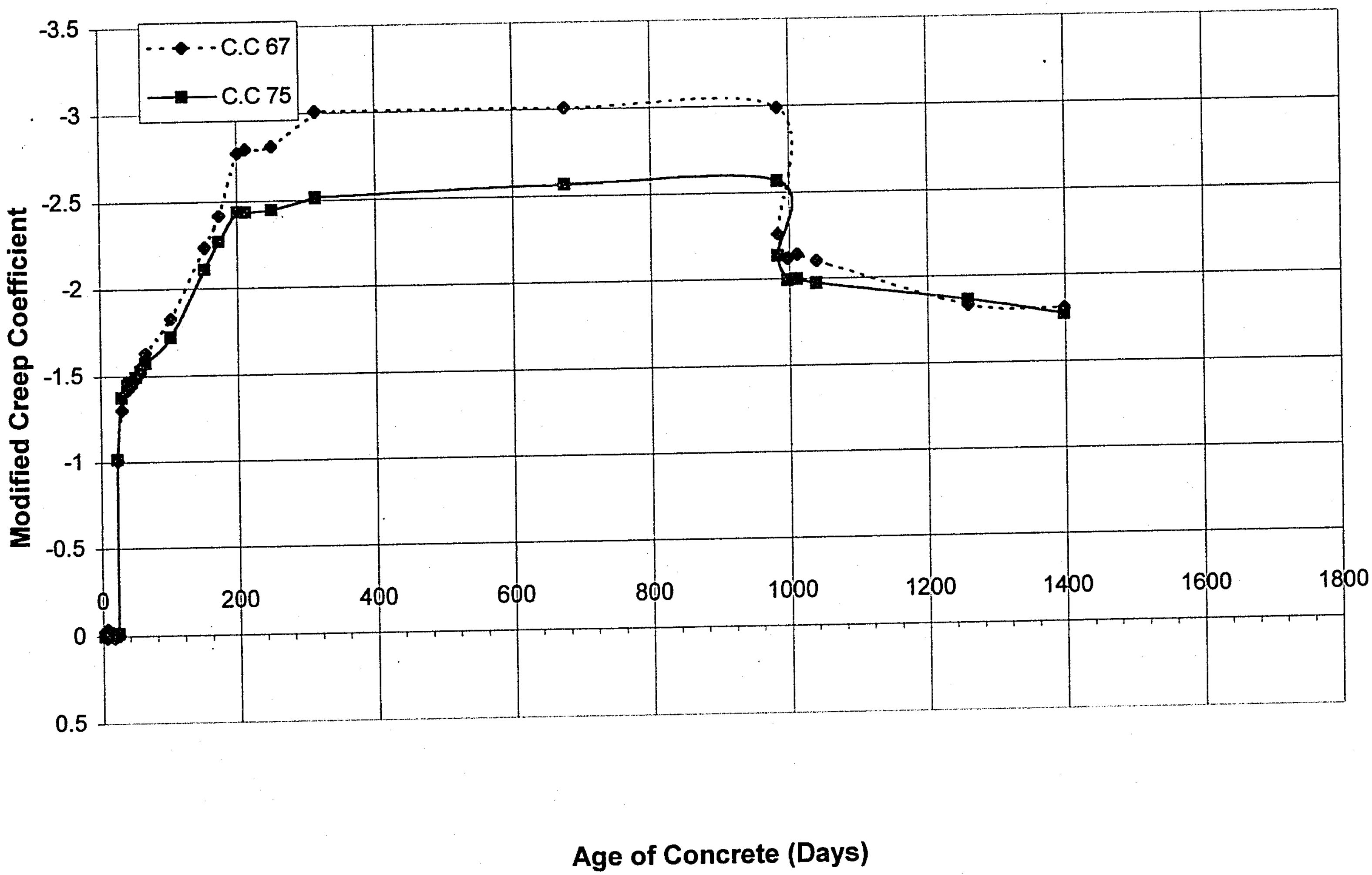


Figure 6-9: Creep Recovery of 254 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 78 & 87 loaded at 201 days

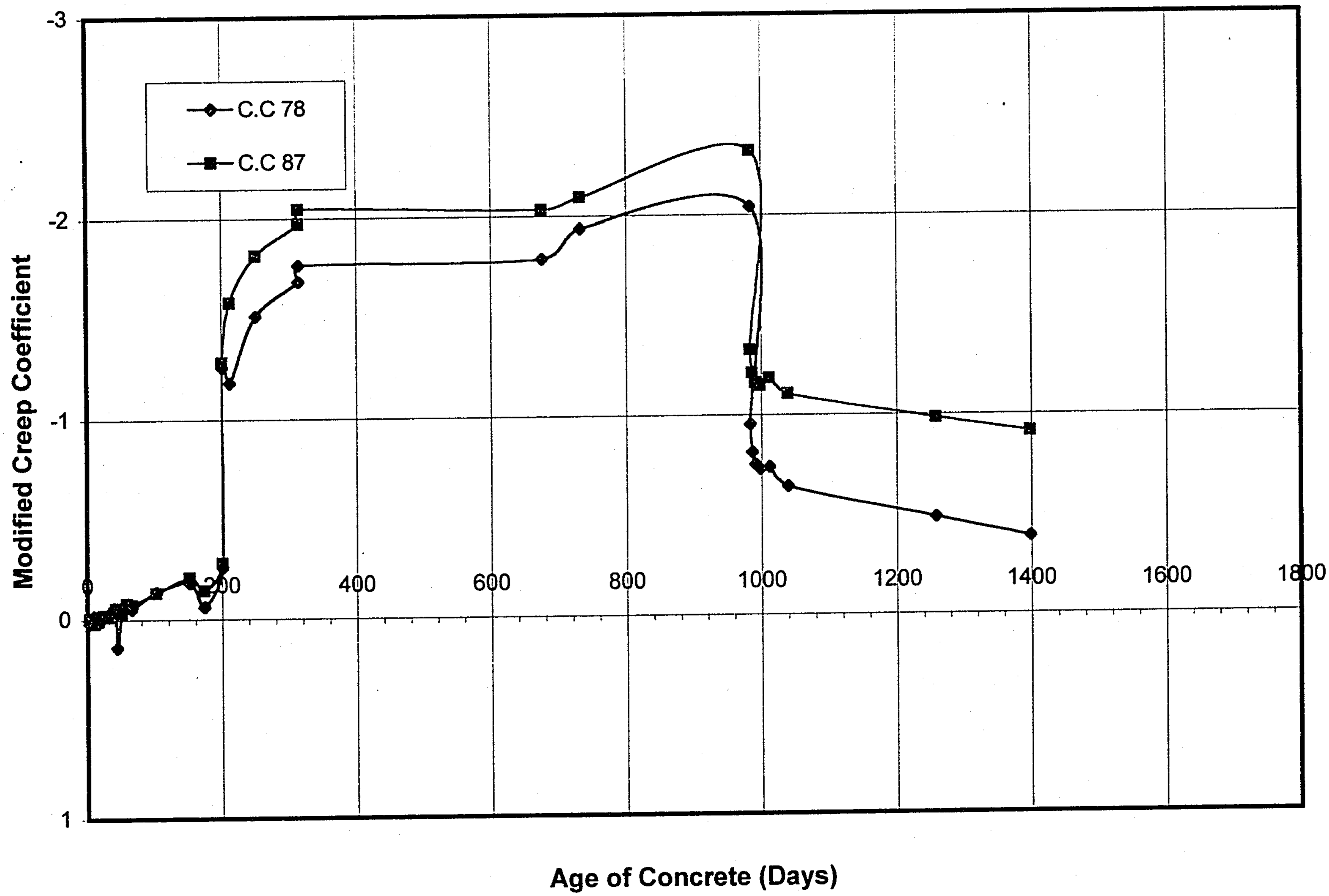


Figure 6-10: Creep Recovery of 89 mm Immersed Specimens, Moist cured 3 days, Specimen 12 & 29 loaded at 3 days, Specimen 20 & 23 loaded at 13 days, Specimen 64 & 24 loaded at 200 days

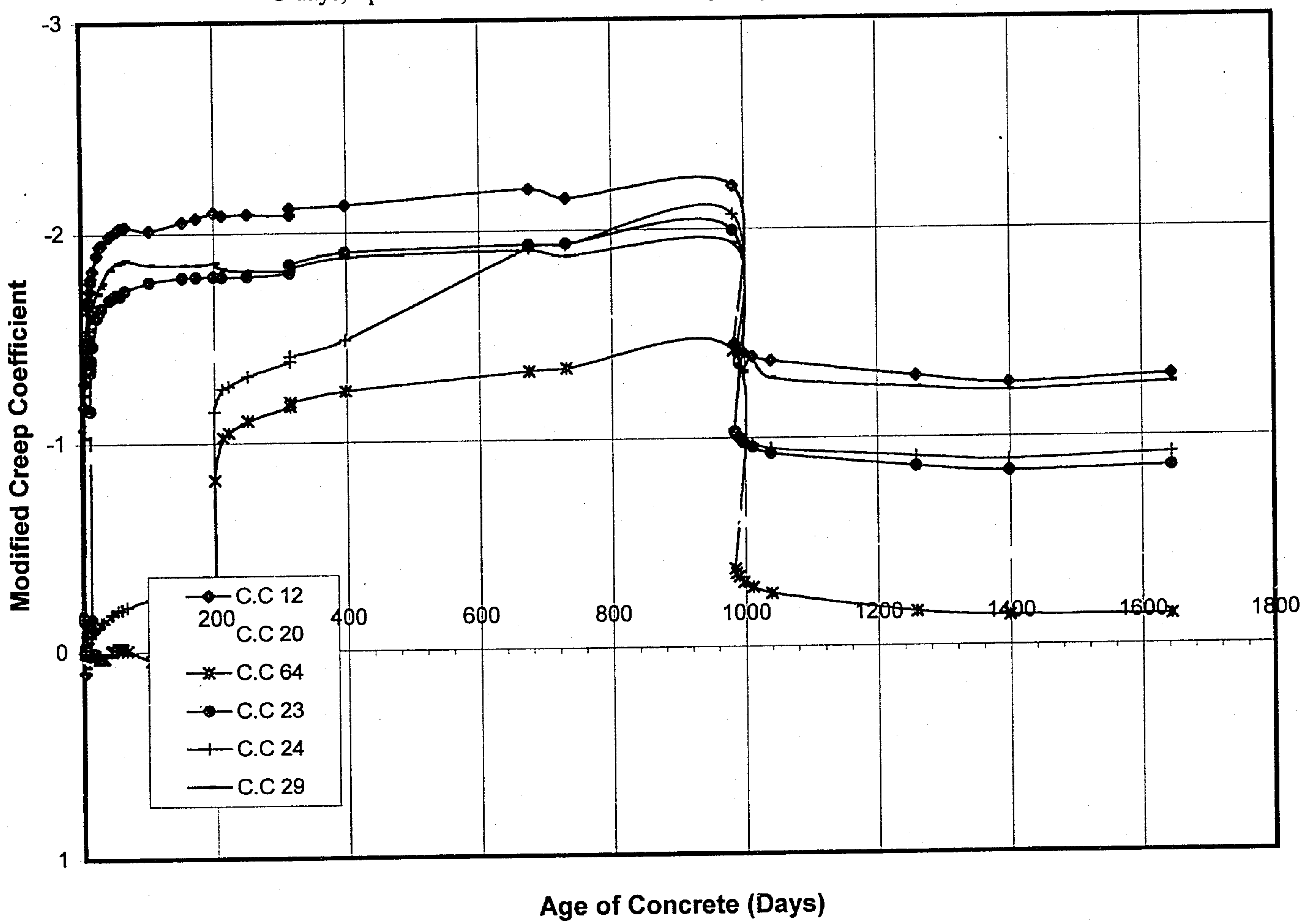


Figure 6-11: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 41 loaded at 4 days, Specimen 65 & 44 loaded at 24 days, Specimen 11 & 38 loaded at 200 days

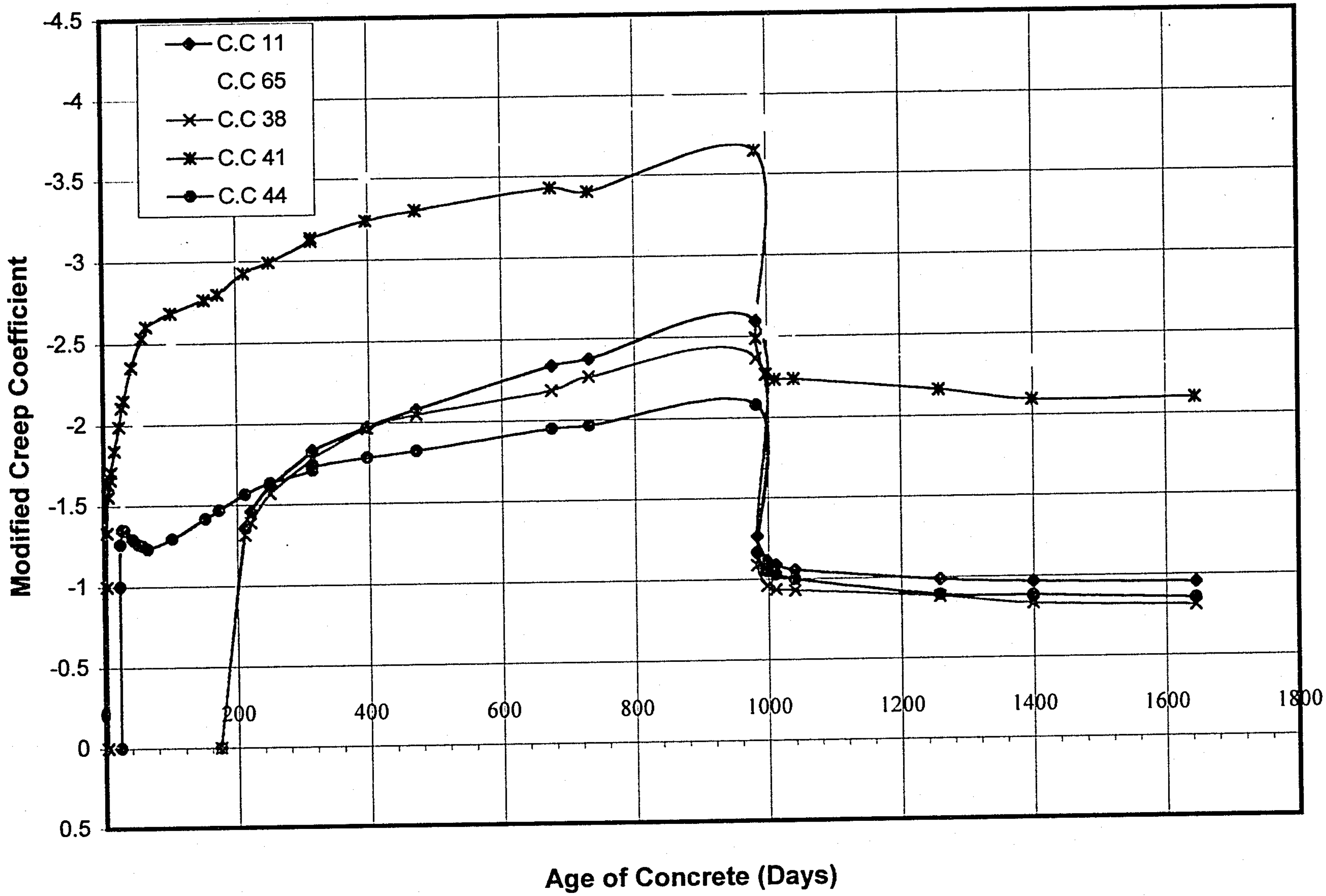


Figure 6-12: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 24/25 days
Specimen 2 & 59 loaded at 25 days, Specimen 13 loaded at 200 days

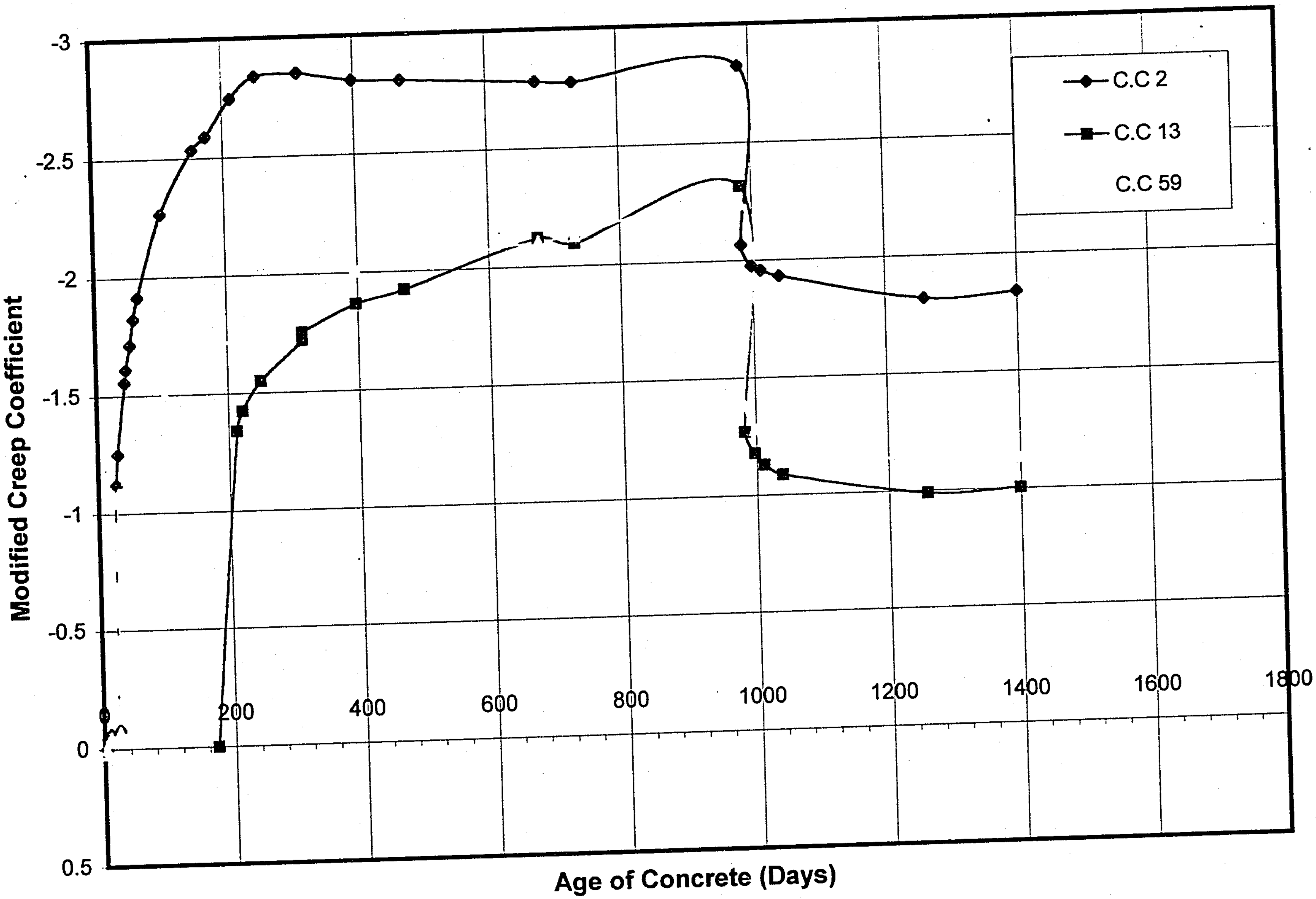


Figure 6-13: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 200 days
Specimen 42 loaded at 200 days

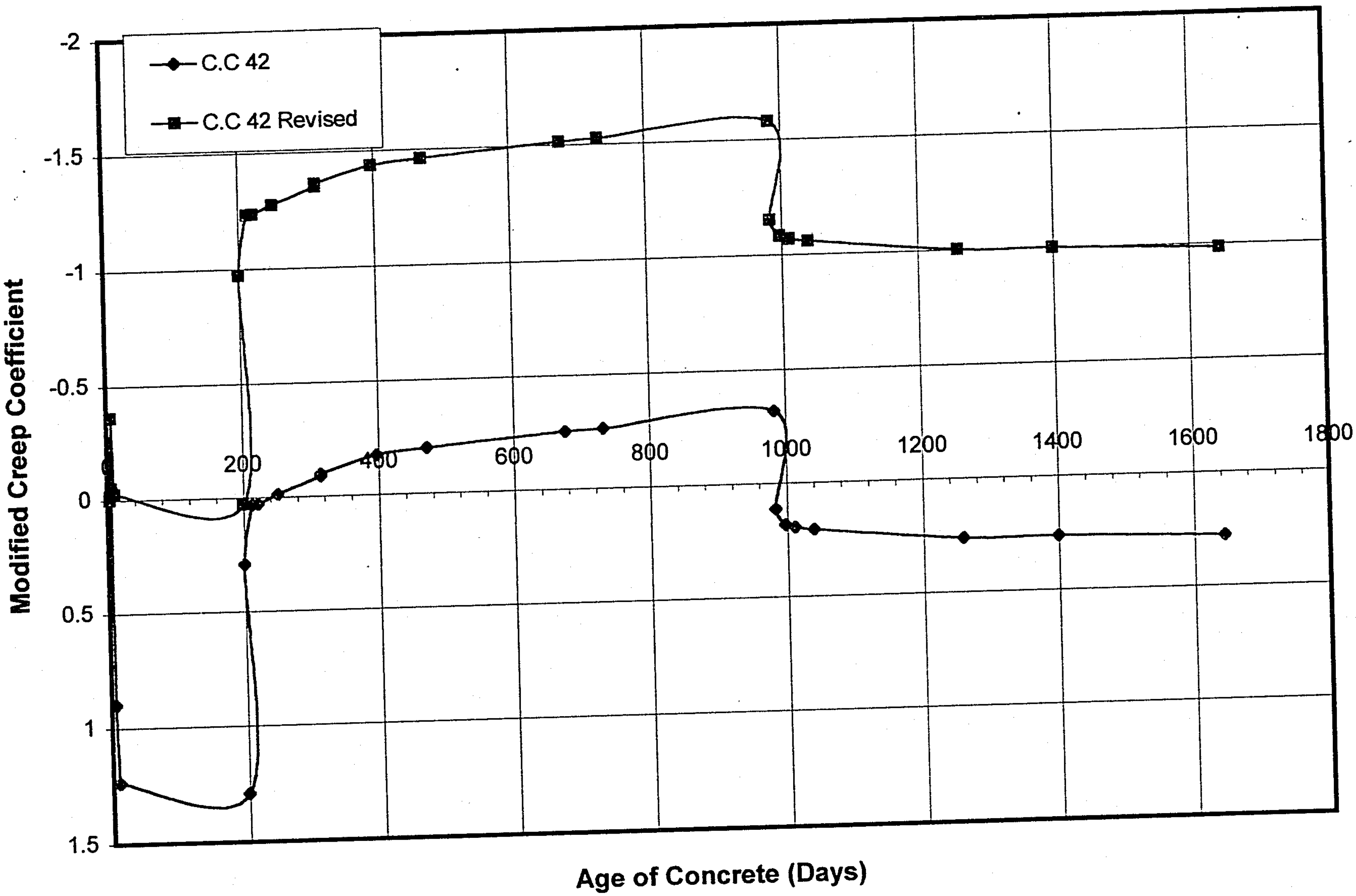


Figure 6-14: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 3 days, Specimen 63 & 33 loaded at 28 days, Specimen 8 & 54 loaded at 200 days

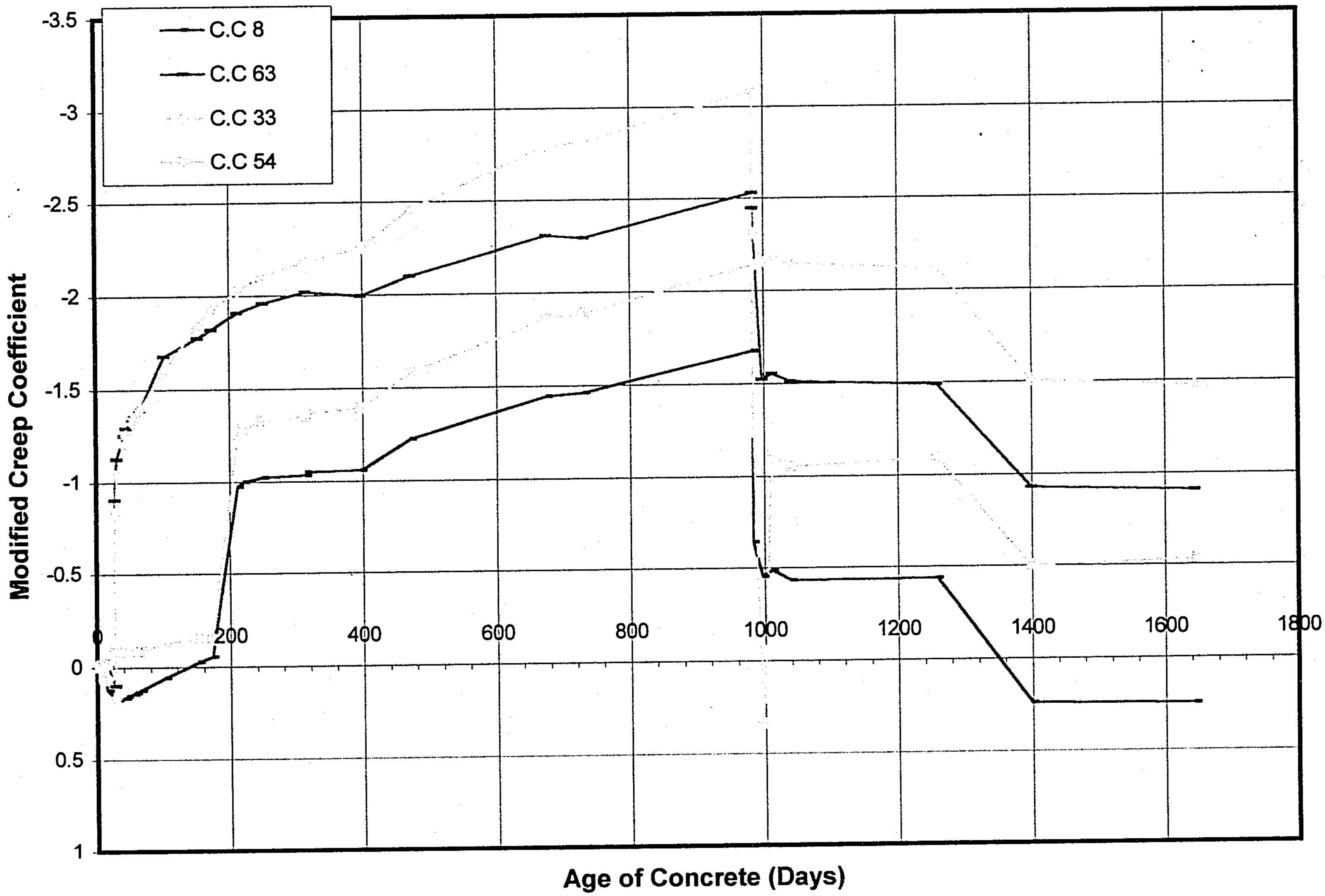


Figure 6-15: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 25 days and Sealed after 25 days, Specimen 50 loaded at 25 days

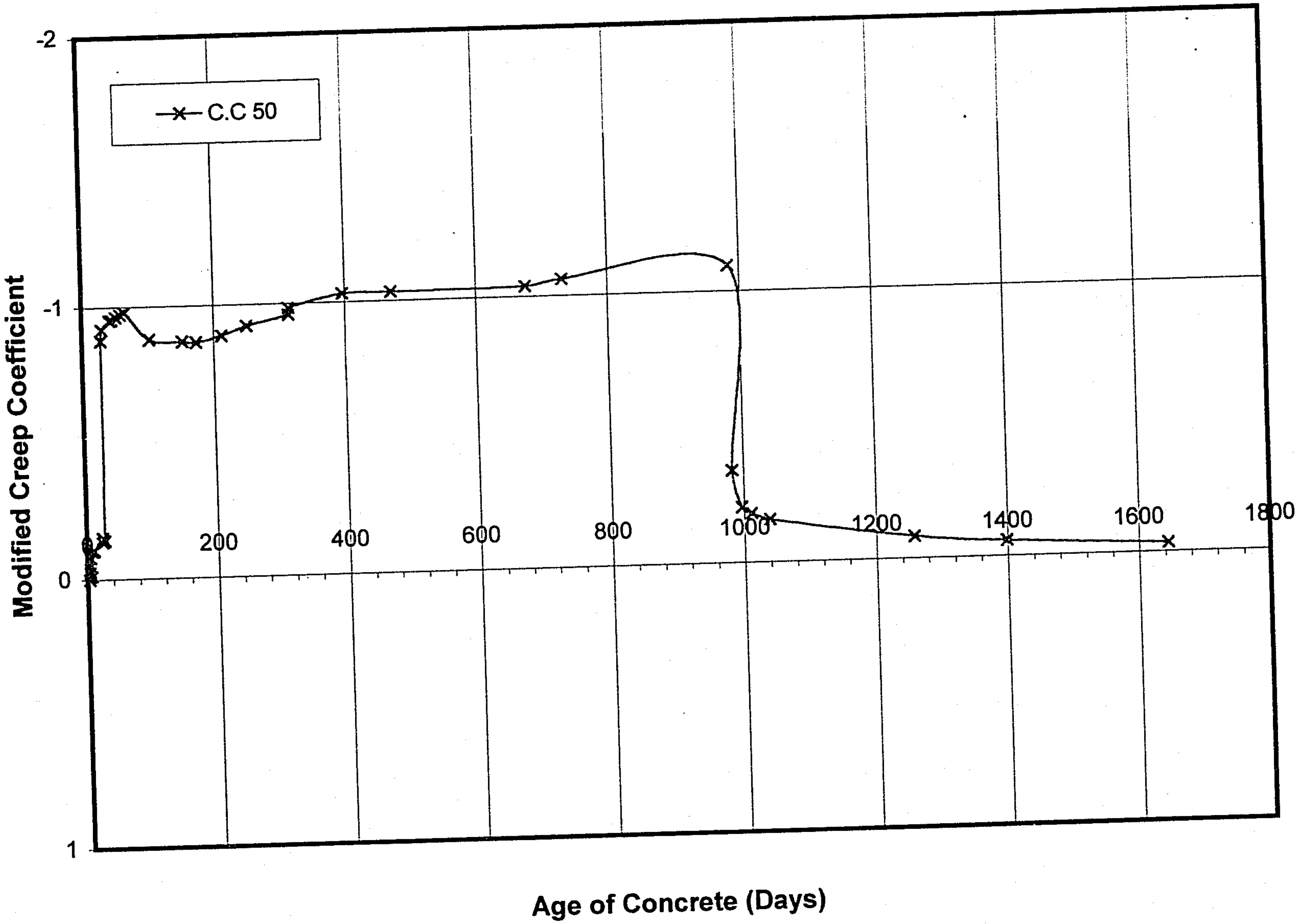


Figure 6-16: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 25 days, Specimen 3 & 35 loaded at 25 days

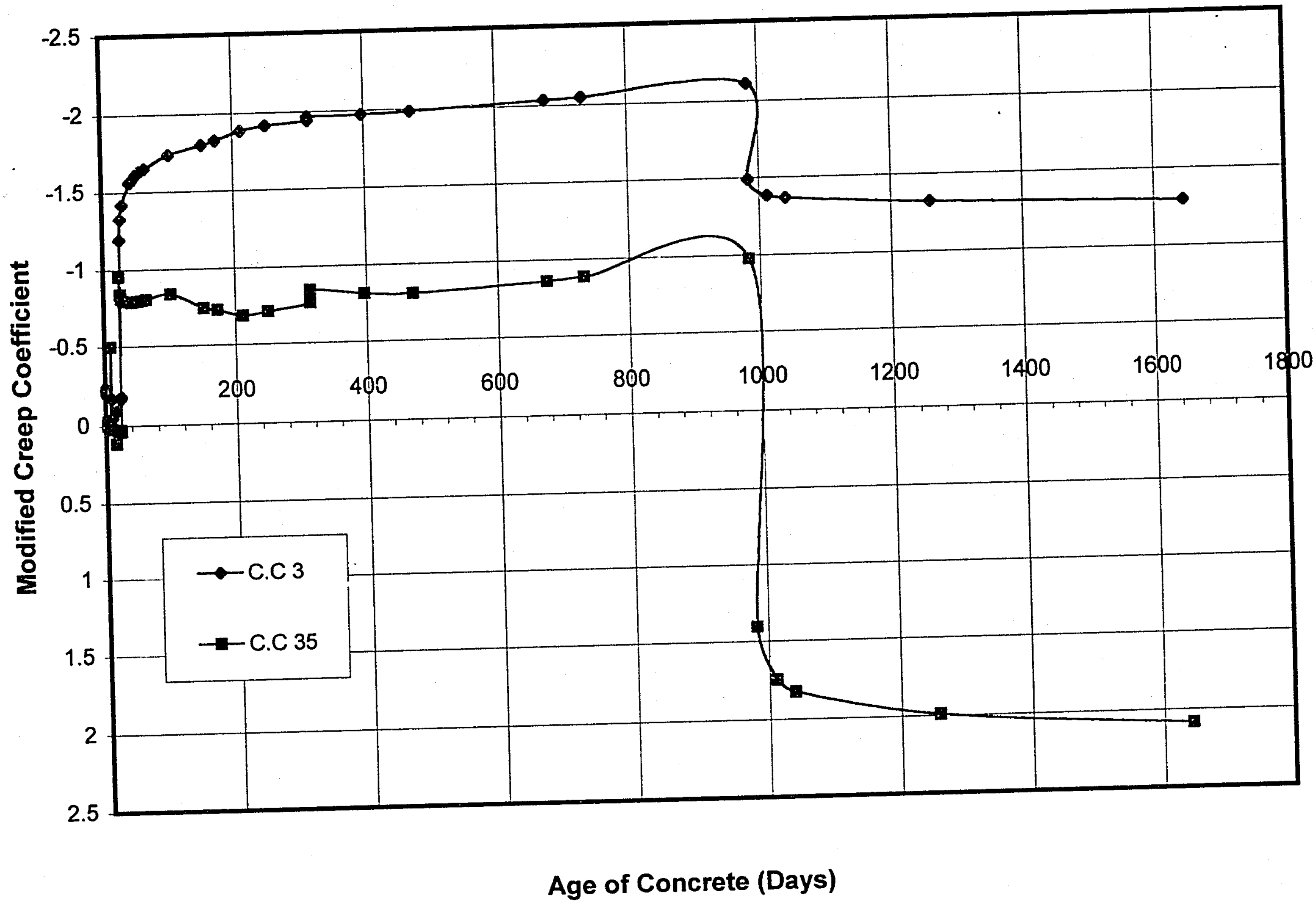


Figure 6-17: Creep Recovery of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 200 days, Specimen 9 & 36 loaded at 200 days

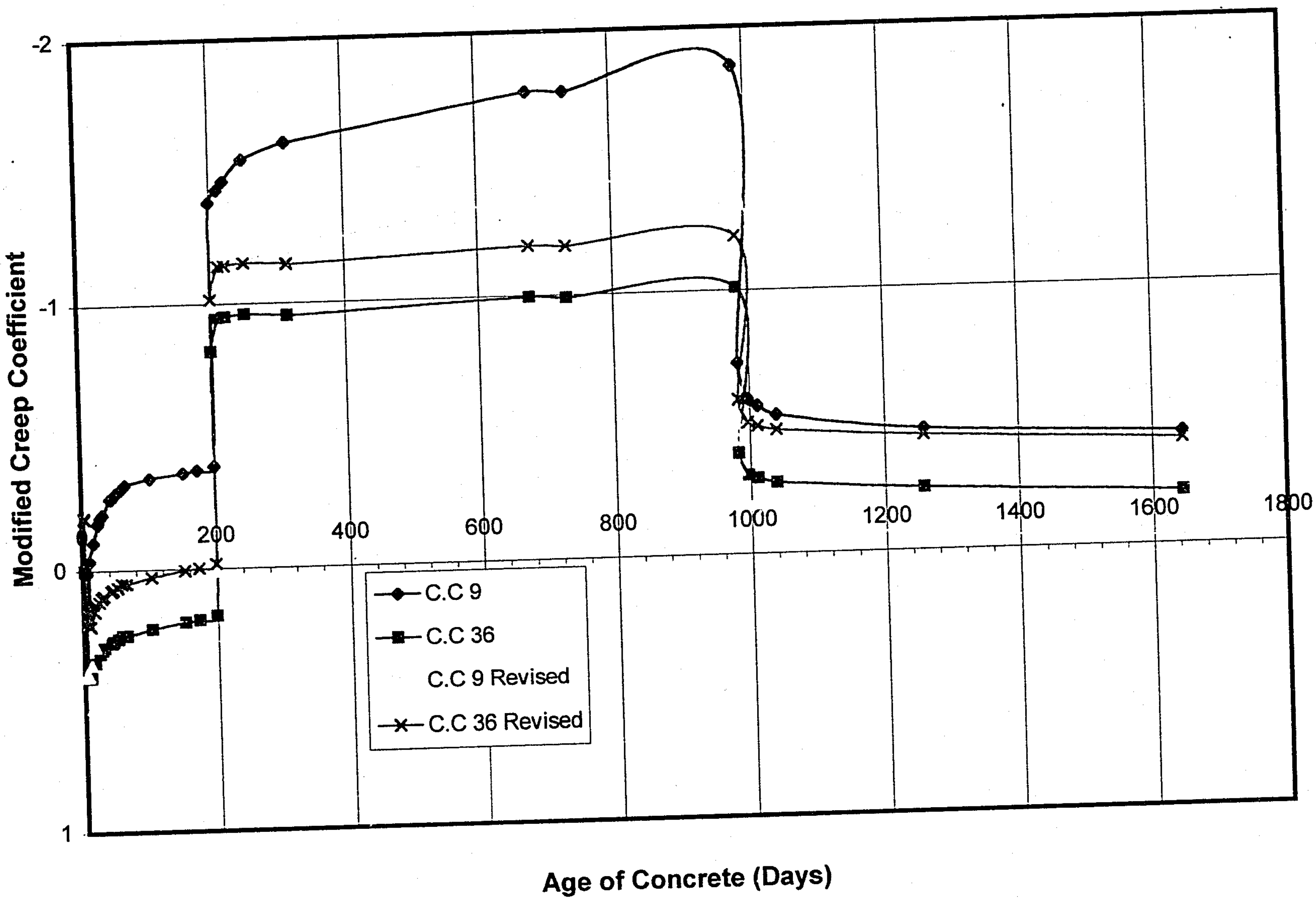


Figure 6-18: Creep Recovery of 152 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 69 & 77 loaded at 24 days

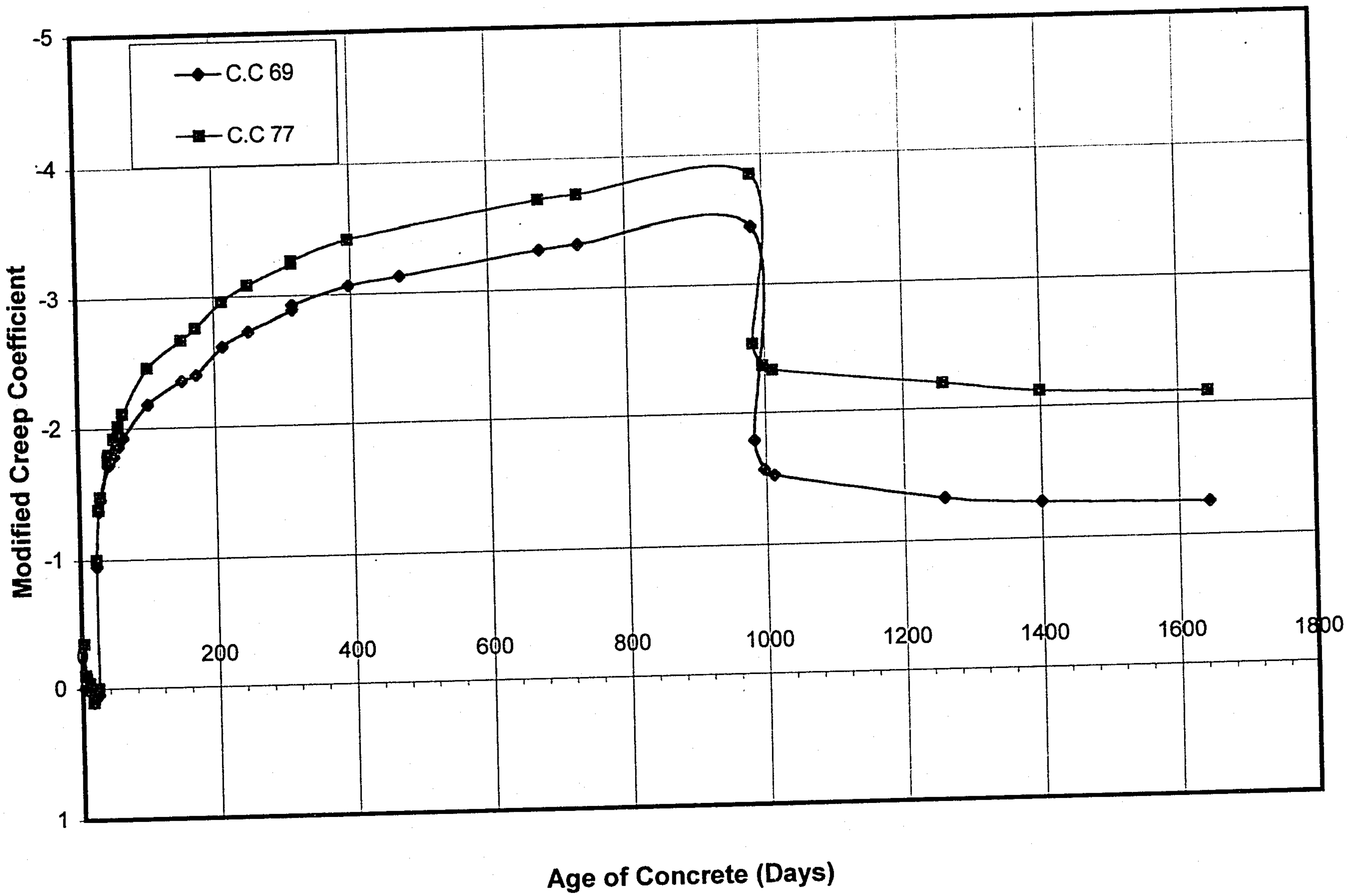
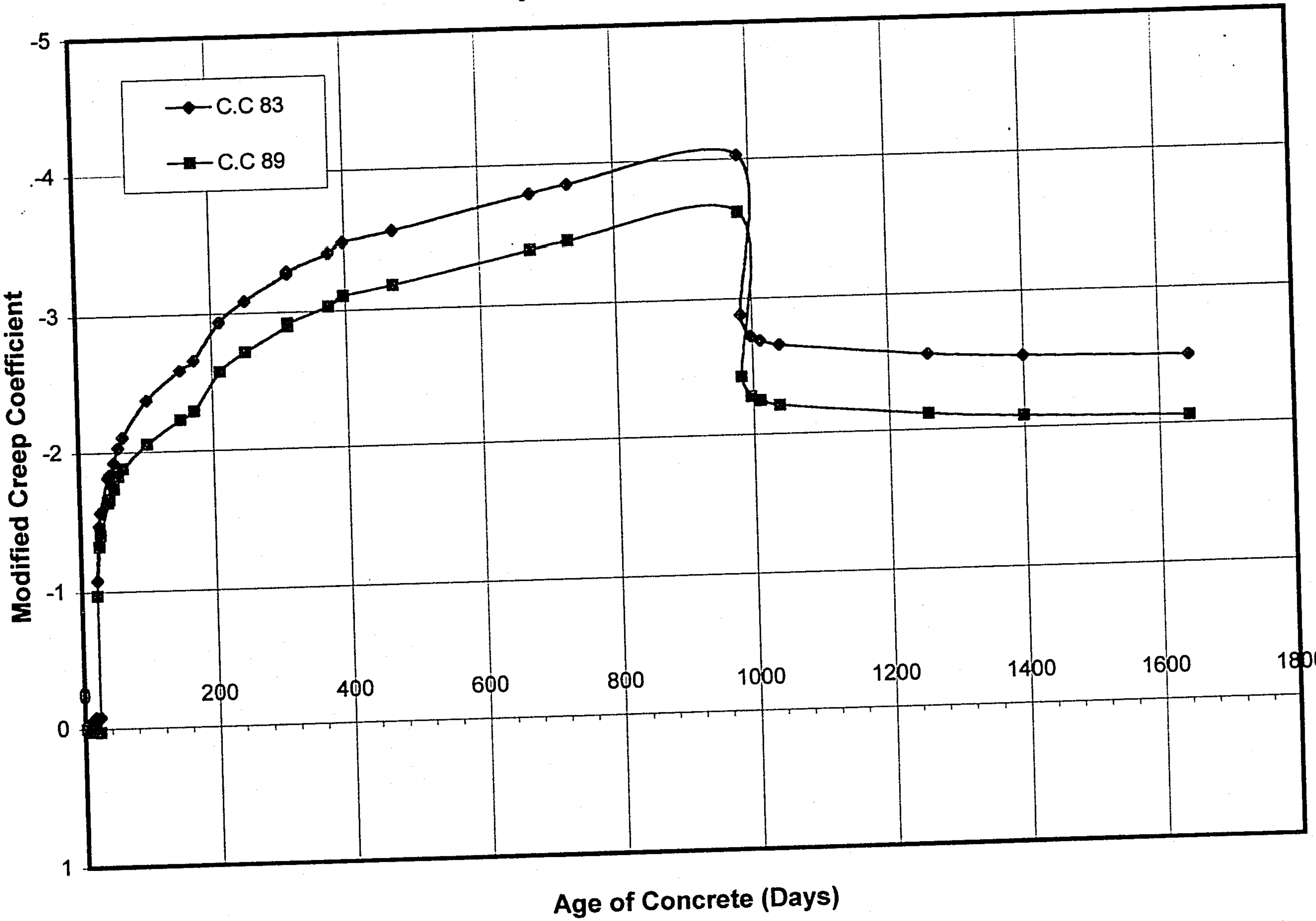


Figure 6-19: Creep Recovery of 254 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 83 & 89 loaded at 24 days



CHAPTER 7

CONCLUSIONS

The first observation is that using only two replicates was unfortunate as the variation between measured values on nominally identical specimens was, in some cases, large. A problem with long-term measurement is that any problems or errors in the initial reading distort all the subsequent calculations.

As the degree of hydration controls porosity and hence concrete strength it will influence shrinkage and creep. The measured concrete strength varied significantly with storage environment.

On average, the effect of the specimen length, two specimen diameters plus gauge length or four specimen diameters plus gauge length, was not significant for either shrinkage or creep measurements. Immersed specimens swelled and hence did not have shrinkage

Increasing specimen size (diameter) increased slightly the values of the last measured shrinkage.

For the specimens stored in the 50% RH environment, the laboratory and immersed approached an ultimate limiting value ie the rate of increase in shrinkage/swelling after 1000 days was small.

Sealing specimens, even after some drying, reduces the measured shrinkage.

Increasing the duration of moist curing from 3 days to 25 days, reduces shrinkage but increasing the duration of moist curing from 25 days to 200 days has little effect.

Storing specimens outside (specimens were cast December 1997) reduced shrinkage considerably. Whether the conclusion is valid for concrete cast in summer is not known.

Although the compressive strength of specimens stored outside was slightly smaller than the identical ones stored in the lab in the first days, the ultimate compressive strength of concrete was much larger for specimens outside. The shrinkages of the specimens stored outside were 50% of the specimens stored in the 50% RH environment.

The compressive strengths of concretes stored in the laboratory and 50% RH environments have similar values but 50% RH shrinkage was slightly smaller shrinkages.

Creep is reduced by increasing specimen diameter, duration of moist curing and the age of loading. The lower the relative humidity the larger the creep.

As sealing decreased creep. Sealing is more effective if it is done in the first few days after casting.

Specimens stored outside had much significantly smaller creeps. Lab and 50% RH had almost similar creeps but 50% RH was slightly smaller. Immersed specimens had a considerably small value of creep.

The elastic and creep Poisson's ratio of the concrete used was 0.18.

The creep of the immersed specimens became asymptotic with time after some 1000 days of loading. However the creep of none of the specimens exposed to drying reached an ultimate value in the observation period.

As expected, creep of the immersed and sealed specimens was less than the specimens exposed to drying.

Creep in a drying environment becomes less as specimen size is increased – as none of the specimens reached a constant ultimate value.

APPENDIX

1 ACI 209-93

1.1 Modulus of Elasticity

By using statistical analysis, *Pauw* found that modulus of elasticity was affected by the density and the compressive strength of concrete

$$E_c = 33\omega^{3/2}\sqrt{f'_{cm}} \qquad (1)$$

where, E_c: static modulus of elasticity of concrete in psi

ω: air-dry density of concrete at time of test, psf

f'_{cm}: mean compressive strength of concrete at time of test, psi

1.2 Strength Development

The rate of gain of strength of concrete is affected by cement type, temperature, water cement ratio, and curing regime. ACI Committee 209 proposed the following equation to represent the rate of strength gain for concrete moist cured at 73.4 ± 3 °F (23 ± 1.7 °C).

$$f'_{c(t)} = f'_{c(28)} \left(\frac{t}{a + bt}\right) \qquad (2)$$

Where, $f'_{c(t)}$ is the compressive strength at age t days, a and b are coefficients, with 4 and 0.85 for Type I (CSA Type 10) cement concrete, 2.3 and 0.92 for Type III (CSA Type 30) cement concrete. In this project, however, the concrete was made using Type I cement and slag

1.3 Shrinkage

ACI Committee 209 endorsed the empirical method to predict shrinkage behavior developed by *Branson*. The shrinkage after 7 days curing for moist cured concrete is given by:

$$\varepsilon_{sht} = \frac{t}{35 + t} \varepsilon_{shu} \qquad (3)$$

Similarly, shrinkage after 1 to 3 days curing for steam-cured concrete is given by:

$$\varepsilon_{sht} = \frac{t}{55 + t} \varepsilon_{shu} \qquad (4)$$

Where t is the time in days after shrinkage is considered, that is, after the end of the initial moist curing; ε_{sht} is the shrinkage at time t, and ε_{shu} is the ultimate shrinkage

$$\varepsilon_{shu} = 780\times10^{-6}\,\gamma_{sh} \qquad (5)$$

Where, γ_{sh} represents the product of correction factors for non-standard conditions, of which ambient relative humidity, member minimum thickness, concrete consistency, fine aggregate content, cement content and air content are considered. However, these equations should not be applied for this study because the concrete was only moist cured 3 days.

1.4 Creep

For moist cured concrete, loaded age of 7 days, the creep coefficient $\phi(t)$ at time t can be estimated from

$$\phi(t) = \frac{(t-t_0)^{0.6}}{10+(t-t_0)^{0.6}}\phi_u \qquad (6)$$

where, t_0 is the age of concrete at time of load in days

ϕ_u is the value of the ultimate creep coefficient

As for shrinkage, the problem lies in determining a suitable value for ϕ_u. ACI Committee 209 recommends an average value of 2.35 if experimental data are not available for an estimation of ϕ_u in the standard condition. Correction factors can be used to adjust for different conditions: relative humidity and age of loading:

$$K_{RH} = 1.27 - 0.0067 RH \qquad (7)$$

where RH is the relative humidity in %, and

$$K_{la} = 1.25 t_0^{-0.118} \qquad (8)$$

Under sustained stress, the strain increase with time due to creep and total strain – instantaneous plus creep – at time t (> t_0), can be calculated from

$$\varepsilon_c(t) = \frac{\sigma_0(t_0)}{E_c(t_0)}(1 + \phi(t, t_0)) \qquad (9)$$

where $\sigma_c(t_0)$ is the concrete stress and $E_c(t_0)$ is the modulus of elasticity of concrete at age t_0, the time of application of the stress.

2 CEB 1990 Model Code

2.1 Modulus of Elasticity

The modulus of elasticity of concrete is regarded as proportional to the cube root of its strength. The CEB expression is based on the specified characteristic cylinder strength (f'_{ck}) at 28 days

$$E_c = 10000(f_{ck} + 8)^{0.33} \qquad (10)$$

where, E_c: tangent modulus of elasticity of concrete at an age of 28 days, MPa

f_{ck}: the characteristic cylinder strength at an age of 28 days, MPa

The additional 8 MPa is introduced to this expression in an attempt to compensate for the different between the specified characteristic strength and actual mean strength of the concrete produced.

2.2 Shrinkage

The recently proposed CEB-FIP Model Code 1990 presented the following model for shrinkage prediction:

$$\varepsilon_{cs} = \varepsilon_{cso} \beta_s (t - t_s) \tag{11}$$

where, ε_{cso}: national shrinkage coefficient

β_s: coefficient to describe the development of shrinkage with time

t: age of concrete in days

t_s: age of concrete in days at the beginning of shrinkage

The notional shrinkage coefficient may be obtained from:

$$\varepsilon_{cso} = \varepsilon_s (f_{cm}) \beta_{RH} \tag{12}$$

With

$$\varepsilon_s (f_{cm}) = (250 + \beta_{sc}(75 - f_{cm})) \times 10^{-6} \tag{13}$$

and

$$\beta_{sRH} = 1 - (\frac{RH}{100})^3 \tag{14}$$

with RH in %.

$\beta_{RH} = -1.55\ \beta_{sRH}$ for $40\ \% \leq RH < 99\ \%$

$\beta_{RH} = 0.25$ for RH > 99 %

where, f_{cm} is the compressive strength of concrete in MPa at the age of 28 days

β_{sc}: coefficient which depends on type of cement, with

$\beta_{sc} = 3$ for normal or slowly hardening cement

$\beta_{sc} = 5$ for rapid hardening cement

$\beta_{sc} = 9$ for rapid hardening high strength cement

The development of shrinkage with time in given by:

$$\beta_s(t - t_s) = \left(\frac{t - t_s}{0.035h_o^2 + t - t_s}\right)^{0.5} \qquad (15)$$

where h_o is national size of member in mm, defined as:

$$h_o = \frac{2A_c}{u} \qquad (16)$$

Where Ac is the cross section and u is the perimeter of the member in contact with the atmosphere.

2.3 Creep

The recently proposed creep prediction model in CEB-FIP Model Code 1990 is significantly simplified from those proposed in previous CEB model codes. The creep coefficient may be calculated from:

$$\phi(t, t_0) = \phi_0 \beta_c(t - t_0) \qquad (17)$$

where

ϕ_0: notional creep coefficient (Eq. 19)

β_c: coefficient to describe the development of creep with time after loading (Eq.23)

The age of concrete at loading t_0 should be adjusted by Arrhenius function to take account of curing temperatures other than 20 °C:

$$t_0 = \Sigma \exp(-\frac{4000}{273 + T(\Delta t_i)} - 13.65)\Delta t_i \qquad (18)$$

where $T(\Delta t_i)$ is temperature in °C during the time period Δt_i.

The notional creep coefficient may be estimated from:

$$\phi_0 = \phi_{RH} \beta(f_{cm}) \beta(t_0) \qquad (19)$$

with

$$\phi_{RH} = 1 + \frac{1 - RH/100}{0.08 h_0^{1/3}} \qquad (20)$$

$$\beta(f_{cm}) = \frac{21.8}{3 + \sqrt{f_{cm}}} \qquad (21)$$

$$\beta(t_0) = \frac{1}{0.1 + t_0^{0.18}} \qquad (22)$$

where RH is the ambient relative humidity and h_0 is the effective thickness.

The time development function of creep is given by:

$$\beta_c(t - t_0) = \left(\frac{t - t_0}{\beta_H + t - t_0}\right)^{0.3} \quad (23)$$

with

$$\beta_H` = 1.5(1 + 0.00012(\frac{RH}{50})^{18})h_0 + 250 \qquad \leq 1500\,mm \quad (24)$$

3 GL2000

The model is basically a modified Atlanta 97 (Gardner 2000), influenced by CEB MC90. The compliance expression is based on the modulus of elasticity at 28 days instead of the modulus of elasticity at the age of loading. This model includes a term for drying before loading, which applies to both basic and drying creep.

3.1 Required Parameters

- Age drying commenced, end of moist curing (days);
- Age of concrete loading (days);
- Concrete mean compressive strength at 28 days (MPa);
- Concrete mean compressive strength at loading (MPa)
- Modulus of elasticity of concrete at 28 days (MPa);
- Modulus of elasticity of concrete at loading (MPa);
- Relative humidity expressed as a decimal;

- Volume to surface ratio (mm).

If experimental values are not available the relationship between the specific/characteristic compressive strength f_{ck} (ACI specific strength 1 in 10 below specified value, CEB characteristic strength is lower 5% value) and the mean compressive strength fcm estimated from;

$$f_{cm28} = 1.1 f_{ck28} + 5.0 \quad \text{(MPa)} \tag{25}$$

If experimental values are not available, the modulus of elasticity and the strength development with time can be calculated using the equations 26 and 27.

3.2 Modulus of Elasticity

$$E_{cmt} = 3500 + 4300\sqrt{f_{cmt}} \quad \text{(MPa)} \tag{26}$$

3.3 Strength Development with Time

$$f_{cmt} = f_{cm28} \frac{t^{3/4}}{a + bt^{3/4}} \tag{27}$$

The constants a and b are related to the cement type, refer to the Table1.

Table 1: *a* and *b* as a function of the cement type, GL2000 model

Cement type	a	b
Type I	2.8	0.77
Type II	3.4	0.72
Type III	1.0	0.92

If experimental results are available the cement type is determined from the strength development characteristic of the concrete regardless of the nominal designation of the cement by matching which of the coefficients best represents the measured strength development.

3.4 Shrinkage

The shrinkage strain ε_{sh} can be calculated using 28:

$$\varepsilon_{sh} = \varepsilon_{shu}\beta(h)\beta(t) \tag{28}$$

Where ε_{shu} is the ultimate shrinkage strain, $\beta(h)$ is a correction term for effect of humidity and $\beta(t)$ is a correction term for effect of time.

$$\varepsilon_{shu} = 900\times10^{-6} K\left(\frac{30}{f_{cm28}}\right)^{1/2} \tag{29}$$

$$\beta(h) = (1-1.18h^4) \tag{30}$$

$$\beta(t) = \left(\frac{t-t_c}{t-t_c+0.12(V/S)^2}\right)^{1/2} \tag{31}$$

K is the shrinkage constant, which depends on the cement type, refer to Table 2. At a relative humidity of 0.96, there is no shrinkage. At higher relative humidities, swelling occurs.

Table 2: *K* as a function of the cement type, GL2000 model

Cement type	K
Type I	1.00
Type II	0.75
Type III	1.15

If experimental results for strength development are available, the shrinkage term can be improved by interpolating *K* from Table 2, using the experimentally determined cement type characteristic

3.5 Compliance Equations

The compliance is composed of two parts: The elastic strain and the creep strain. The elastic strain is simply the reciprocal of the modulus of elasticity at the age of loading and the creep strain is the creep coefficient divided by the modulus of elasticity at 28 days, as expressed in Equation 32.

$$J(t,t_o)=\frac{1}{E_{cmto}}+\frac{\phi_{28}}{E_{cm28}} \tag{32}$$

where ϕ_{28} is the creep coefficient and is calculated using Equation 33

$$\phi_{28} = \Phi(t_c)\left(2\frac{(t-t_o)^{0.3}}{(t-t_o)^{0.3}+14}+\left(\frac{7}{t_o}\right)^{0.5}\left(\frac{t-t_o}{t-t_o+7}\right)^{0.5}+2.5(1-1.086h^2)\left(\frac{t-t_o}{t-t_o+0.12(V/S)^2}\right)^{0.5}\right)$$

(33)

The creep coefficient includes three terms. The first two terms are required to calculate basic creep and the third term is for drying creep. Similar to the shrinkage expression, at a relative humidity of 0.96, there is no drying creep, only basic creep. $\Phi(t_c)$ is the correction term for the effect of drying before loading.

If $t_o = t_c$

$$\Phi(t_c) = 1 \tag{34}$$

When $t_o > t_c$

$$\Phi(t_c) = \left[1-\left(\frac{t_o-t_c}{t_o-t_c+0.12(V/S)^2}\right)^{0.5}\right]^{0.5} \tag{35}$$

To calculate relaxation, $\Phi(t_c)$ remains constant at the initial value throughout the relaxation period. For creep recovery calculations, $\Phi(t_c)$ remains constant at the value at the age of loading

4 Bazant-Baweja B3 Model

The B3 model is the latest variant in a number of shrinkage and creep prediction methods developed by Bazant and his co-workers at Northwestern University.

4.1 Required Parameters

- Age drying commenced, end of moist curing (days);
- Age of concrete loading (days);
- Aggregate content in concrete (kg/m^3);
- Cement content in concrete (kg/m^3);
- Cement type;
- Concrete mean compressive strength at 28 days (MPa);
- Curing condition;
- Modulus of elasticity of concrete at 28 days (MPa);
- Relative humidity expressed as a decimal;
- Shape of specimen;
- Volume to surface ratio (mm);
- Water content in concrete (kg/m^3).

4.2 Shrinkage

The shrinkage strain is calculated using the following equation:

$$\varepsilon_{sh} = \varepsilon_{sh\infty} k_h S(t) \qquad (36)$$

where $\varepsilon_{sh\infty}$ is the time dependence of ultimate shrinkage, k_h is the humidity dependence given in Table 5 and $S(t)$ is the time curve.

$$\varepsilon_{sh\infty} \approx \alpha_1 \alpha_2 [0.019 w^{2.1} f_{cm28}^{-0.28} + 270] \times 10^{-6} \qquad (37)$$

where w is the water content in kg/m^3, α_1 and α_2 are constants related to the cement type and curing condition.

Table 3: α_1 as a function of the cement type, B3 model

Type of cement	α_1
Type I	1.00
Type II	0.85
Type III	1.10

Table 4: α_2 as a function of the curing condition, B3 model

Curing method	α_2
Steam cured	0.75
Cured in water	1.00
Cured at 100 % humidity	1.00
Sealed during curing	1.20

Table 5: Humidity dependence, B3 model

Relative humidity	k_h
$h < 0.98$	$1 - h^3$
$h = 1.00$	-0.2
$0.98 < h < 1.00$	Linear interpolation

$$S(t) = \tanh\left[\left(\frac{t - t_c}{\tau_{sh}}\right)^{1/2}\right] \quad (38)$$

where

$$\tau_{sh} = 0.085 t_c^{-0.08} f_{cm28}^{-0.25}\left[2k_s(V/S)\right]^2 \quad (39)$$

k_s is the cross-section shape correction factor, in Table 6.

Table 6: k_s as a function of the cross-section shape, B3 model

Cross-section shape	k_s
Infinite slab	1.00
Infinite cylinder	1.15
Infinite square prism	1.25
Sphere	1.30
Cube	1.55

4.3 Compliance

The compliance $J(t,t_o)$ is calculated from:

$$J(t,t_o) = [q_1 + C_o(t,t_o) + C_d(t,t_o,t_c)] \tag{40}$$

where q_1 is the instantaneous strain, $C_o(t,t_o)$ is the compliance function for basic creep and $C_d(t,t_o,t_c)$ is the compliance function for drying creep.

The instantaneous strain is calculated using the modulus of elasticity of concrete at 28 days.

$$q_1 = 0.6 / E_{cm28} \tag{41}$$

The basic creep is composed of three terms, an ageing viscoelastic term, a non-ageing viscoelastic term and an ageing flow term.

$$C_o(t,t_o) = q_2 Q(t,t_o) + q_3 \ln[1+(t-t_o)^n] + q_4 \ln(t/t_o) \tag{42}$$

q_2 is the ageing viscoelastic compliance parameter. The cement content and the concrete mean compressive strength at 28 days are required to calculate this parameter.

$$q_2 = 185.4 \times 10^{-6} c^{0.5} f_{cm28}^{-0.9} \tag{43}$$

$$Q(t,t_o) = Q_f(t_o)\left[1+\left(\frac{Q_f(t_o)}{Z(t,t_o)}\right)^{r(t_o)}\right]^{-1/r(t_o)} \tag{44}$$

$Q(t,t_o)$ is a binomial integral, which is multiplied by the parameter q_2 to obtain the ageing viscoelastic term. The three following equations can be used to approximate the binomial integral.

$$Q_f(t_o) = [0.086(t_o)^{2/9} + 1.21(t_o)^{4/9}]^{-1} \tag{45}$$

$$Z(t,t_o) = (t_o)^{-m} \ln[1 + (t - t_o)^n] \tag{46}$$

$$r(t_o) = 1.7(t_o)^{0.12} + 8 \tag{47}$$

q_3 is the non-ageing viscoelastic compliance parameter and q_4 is the ageing flow compliance parameter. These parameters are a function of the concrete mean compressive strength at 28 days, the cement content, the water to cement ratio and the aggregate cement ratio.

$$q_3 = 0.29 q_2 (w/c)^4 \tag{48}$$

$$q_4 = 20.3 \times 10^{-6} (a/c)^{-0.7} \tag{49}$$

The compliance function for drying creep is defined by Equation 49. This equation accounts for drying before loading. The drying before loading is considered only for drying creep.

$$C_d(t,t_o,t_c) = q_5[\exp\{-8H(t)\} - \exp\{-8H(t_o)\}]^{1/2} \tag{50}$$

q_5 is the drying creep compliance parameter. This parameter is a function of the concrete mean compressive strength at 28 days, water content, type of cement, method of curing and $\varepsilon_{sh\infty}$, the ultimate shrinkage strain.

$$q_5 = 0.757 f_{cm28}^{-1} \left| \varepsilon_{sh\infty} \times 10^6 \right|^{-0.6} \tag{51}$$

$$\varepsilon_{sh\infty} \approx -\alpha_1 \alpha_2 [0.019 w^{2.1} f_{cm28}^{-0.28} + 270] \times 10^{-6} \tag{52}$$

The values of α_1 and α_2. are given in Tables 3 and 4.

$H(t)$ and $H(t_o)$ are spatial averages of pore relative humidity. Equations 53 to 54 are required to calculate $H(t)$ and $H(t_o)$.

$$H(t) = 1 - (1 - h)S(t) \tag{53}$$

$$H(t_o) = 1 - (1 - h)S(t_o) \tag{54}$$

$S(t)$ and $S(t_o)$ are the time functions for shrinkage and tau_{sh} is the shrinkage half-time

$$S(t) = \tanh\left[\left(\frac{t - t_c}{\tau_{sh}}\right)^{1/2}\right] \tag{55}$$

$$S(t_o) = \tanh\left[\left(\frac{t_o - t_c}{\tau_{sh}}\right)^{1/2}\right] \tag{56}$$

$$\tau_{sh} = 0.085 t_c^{-0.08} f_{cm28}^{-0.25}\left[2k_s(V/S)\right]^2 \tag{57}$$

k_s is the cross-section shape correction factor, given in Table 6.

NOTATION

a	Strength gain coefficient
b	Strength gain coefficient
c	Cement content of concrete, B3 model (kg/m3)
E	Modulus of elasticity
E_{cm28}	Modulus of elasticity of concrete at 28 days (MPa)
E_{cmt}	Modulus of elasticity of concrete at age t (MPa)
E_{cmto}	Modulus of elasticity of concrete when loading commenced (MPa)
f_{cm28}	Concrete mean compressive strength at 28 days (MPa)
f_{cmt}	Concrete mean compressive strength at age t (MPa)
f_{cmtc}	Concrete mean compressive strength when drying commenced (MPa)
f_{cmto}	Concrete mean compressive strength when loading commenced (MPa)
f_{ck28}	Concrete characteristic strength
h	Humidity expressed as a decimal
J(t,to)	Compliance (1/MPa)
K	Shrinkage constant
R(t,to)	Relaxation (MPa)
t	Age of concrete (days)

t_c	Age drying commenced, end of moist curing (days)
t_o	Age of concrete loading (days)
t_u	Age of concrete unloading (days)
V/S	Volume to surface ratio (mm)
$\beta(h)$	Correction term for effect of humidity on shrinkage
$\beta t)$	Correction term for effect of time on shrinkage
$\varepsilon_{c\sigma}(t)$	Stress dependant strain at time t
ε_{sh}	Shrinkage strain
ε_{shu}	Notional ultimate shrinkage strain
ϕ	Creep coefficient
ϕRH	Correction term for effect of humidity on creep, CEB MC90 model
$\phi(tc)$	Correction term for effect of drying before loading
ρ	Density of concrete (kg/m3)
$\sigma_c(t)$	Variable stress at time t

REFERENCES

- ACI Committee 209, Factors Affecting Shrinkage, Creep and Thermal Expansion of Concrete and Simplified Models to Predict Strains, 1997.

- ACI Committee 209R-92, Prediction of Creep, Shrinkage and Temperature Effects on Concrete Structures, ACI Publication Part 1, pp.209R-1~209R-47, 1993.

- Annual Book of ASTM Standards, Concrete and Mineral Aggregates, Section 4 Construction, Volume 04.02, 1985.

- Bazant, Z.P., and Baweja, S. (1995). "Creep and Shrinkage Prediction Model for Analysis and Design of Concrete Structures - Model B3." *Materials and Structures*, RILEM, Paris, France, Vol. 28, pp. 357-365, 415-430, 488-495.

- CEB-FIP Model Code 1990, Bulletin D'Information, 1990.

- CEB-FIP Model Code for Concrete Structures, 1991, Bulletin d'Information No. 199, Comite Euro-International du Beton, Lausanne, 201pp.

- Gardner N.J. and Lockman M. J. (2001), "Design Provisions for Drying Shrinkage and Creep of Normal Strength Concrete", ACI Materials Journal, Title No. 98-M18, March-April 2001,pp.159-169. Discussion ACI Materials Journal January-February 2002 p11.

- Gardner, N.J., Design Provisions for Shrinkage and Creep Revisited, ACI Conference, 1998.

- Jungsuck (Ben) Huh, (1998) "Influence of Environment and Size on the Creep and Drying Shrinkage of Concrete" M.Eng thesis, University of Ottawa

- Lockman M.J, (2000) "Compliance, Relaxation and Creep Recovery of Normal Strength Concrete" M.Sc.A. thesis, University of Ottawa

- Neville, A.M., Concrete Technology, Longman Science & Technical, 1987.

- Neville, A.M., Dilger, W.H., and Brooks, J.J. (1983). "Creep of Plan and Structural Concrete." *Longman Group Limited*, Essex, England, 361 pages.

- Neville, A.M., Properties of Concrete, Pitman Publishing Inc., 1981.

- RILEM Shrinkage and Compliance Data Bank.