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

by

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To My Parents, My Wife Maria

and

My Daughter Michelle

Abstract

In literature a lot of studies about the prediction of creep and shrinkage of concrete at constant temperature and relative humidity can be found. However, when a concrete structure is built in reality, temperature and relative humidity of the environment vary with location and seasons of construction. So it can be expected that the "moment of casting concrete" has an influence on the evolution of creep and shrinkage of that concrete. In order to acquire information regarding the problem of " the prediction of creep and shrinkage due to a time-varying climate history" a research program is going on at the University of Ottawa. The following parameters are examined: curing period, storage environment, specimen size and age of loading.

Creep and shrinkage testing of two sets of specimens is described. For the size and environment tests, the 89 mm, 152 mm, 254 mm, and 610 mm diameter cylinders were used. 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 ages raging from 24 to 200 days, and 610 mm diameter specimens were loaded at concrete age 24 days in each of the chosen environment. The environment were inside (22°C, variable humidity), 22°C and 50 % relative humidity, outside (uncontrolled temperature and humidity) and immersed in water.

LAB
Tent

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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 and appreciate 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 many cases concrete time-dependent volume changes are several times, to as much as an order of magnitude, greater than the time-independent volume changes. Thus, it is important that engineers and designers not only understand these time-dependent volume changes of concrete, but also understand how they can be measured in the laboratory and how those results should be applied in the design and evaluations of structures in the field.

Time-dependent deformations (creep and drying shrinkage) have a profound influence on the structural behavior of concrete. They are directly related to long-term deflection, losses in prestressing, and cracking. Creep strains may heal cracks but drying shrinkage will not. From a structural point of view, drying shrinkage is an adverse

not favourable

property of concrete. Drying shrinkage is defined as 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 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 controversial. ACI recommendations assume that ultimate shrinkage decreases with increasing member size.

size ↑
shrinkage ↓

The purpose of this report is to present data on the creep and drying shrinkage behavior of normal plain concrete subjected to (a) constant environmental conditions in a laboratory, (b) in a room of 50 % relative humidity, (c) in water, and (d) outdoor exposure in the Ottawa area. These tests were designed to show how compressive creep and drying shrinkage are affected by conditions of curing or storage environment, specimen size, age/duration of loading, and magnitude of compressive strength at age of loading.

1.2 Shrinkage

Shrinkage, after hardening of concrete, is the decrease with time of concrete volume. The decrease is due to changes in the moisture content of the concrete and physico-chemical changes, which occur without stress attributable to action external to the concrete. The converse of shrinkage is swelling, which denotes volumetric increase due to moisture gain in hardened concrete. Shrinkage is conveniently expressed as a dimensionless strain (mm/mm) under steady conditions of relative humidity and temperature. There are three types of shrinkage as described below.

- Plastic shrinkage.
- Drying shrinkage is due to moisture loss in the concrete.
- Autogenous shrinkage is caused by the hydration of 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.

1.3 Creep

The time-dependant increase of strain in hardened concrete, in excess any elastic strain and shrinkage, due to sustained stress is defined as creep. It is obtained by subtracting from the total measured strain in a loaded specimen, 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 which is subjected to the same history of relative humidity and temperature. Creep is conveniently designated at a constant stress under conditions of steady relative humidity and temperature, assuming the strain at loading (nominal elastic strain) as the instantaneous strain at any time.

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 instantaneous strain (elastic and inelastic strains) and the creep strain. 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 caused by drying.

CHAPTER 2

LITERATURE REVIEW AND STANDARD TEST

2.1 Introduction

Concrete gains strength as a result of chemical reactions known as hydration between the cement and water. For a given concrete mixture, strength at any age, and in normal conditions, is related to the degree of hydration. The rate of hydration and, therefore, 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, experimental parameters affect creep in much the same way as shrinkage, the magnitudes of the strains are same, and include a considerable amount of irreversibility.

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

2.2 Prediction Methods

For structural design purposes the existing state of knowledge is summarized in the code provisions of ACI 209-93 and CEB 1990 Model Code. The provisions of these two codes and the method proposed by Gardner are given below for reference.

2.2.1 ACI 209-93

Modulus of Elasticity

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

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

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

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).

$$f'_{c(t)} = f'_{c(28)} \left(\frac{t}{a+bt}\right) \qquad (2-1)$$

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.

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:

$$\varepsilon_{sht} = \frac{t}{35+t}\varepsilon_{shu} \qquad (2-3)$$

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

$$\varepsilon_{sht} = \frac{t}{55+t}\varepsilon_{shu} \qquad (2-4)$$

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

$$\varepsilon_{shu} = 780 \times 10^{-6} \gamma_{sh} \qquad (2-5)$$

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.

Creep

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

$$\phi(t) = \frac{(t-t_0)^{0.6}}{10+(t-t_0)^{0.6}} \phi_u \qquad (2-6)$$

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:

$$K_{RH}=1.27-0.0067RH \qquad (2-7)$$

where RH is the relative humidity in %, and

$$K_{la}=1.25t_0^{-0.118} \qquad (2-8)$$

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

$$\varepsilon_c(t)=\frac{\sigma_0(t_0)}{\mathrm{E}_c(t_0)}(1+\phi(t,t_0)) \qquad (2-9)$$

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.

2.2.2 CEB 1990 Model Code

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

$$\mathrm{E}_c=10000(f_{ck}+8)^{0.33} \qquad (2-10)$$

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.

Shrinkage

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

$$\varepsilon_{cs} = \varepsilon_{cso} \beta_s (t - t_s) \qquad (2-11)$$

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:

$$\varepsilon_{cso} = \varepsilon_s (f_{cm}) \beta_{RH} \qquad (2-12)$$

With

$$\varepsilon_s (f_{cm}) = (250 + \beta_{sc} (75 - f_{cm})) \times 10^{-6} \qquad (2-13)$$

and

$$\beta_{sRH} = 1 - \left(\frac{RH}{100}\right)^3 \qquad (2-14)$$

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:

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

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

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

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

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:

$$\phi(t,t_0)=\phi_0\beta_c(t-t_0) \qquad (2-17)$$

where

ϕ_0: notional creep coefficient (Eq. 2-19)

β_c: coefficient to describe the development of creep with time after loading (Eq. 2-23)

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

$$t_0=\sum\exp(-\frac{4000}{273+T(\Delta t_i)}-13.65)\Delta t_i \qquad (2-18)$$

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

The notional creep coefficient may be estimated from:

$$\phi_0=\phi_{RH}\beta(f_{cm})\beta(t_0) \qquad (2-19)$$

with

$$\phi_{RH} = 1 + \frac{1 - RH/100}{0.08 h_0^{1/3}} \qquad (2-20)$$

$$\beta(f_{cm}) = \frac{21.8}{3 + \sqrt{f_{cm}}} \qquad (2-21)$$

$$\beta(t_0) = \frac{1}{0.1 + t_0^{0.18}} \qquad (2-22)$$

where RH is the ambient relative humidity and h0 is the effective thickness.

The time development function of creep is given by:

$$\beta_c(t - t_0) = \left(\frac{t - t_0}{\beta_H + t - t_0}\right)^{0.3} \qquad (2-23)$$

With

$$\beta_H = 1.5(1 + 0.00012(\frac{RH}{50})^{18})h_0 + 250 \qquad \leq 1500\,mm \qquad (2-24)$$

2.2.3 Gardner-Zhao 1997

Modulus of Elasticity

For analysis purposes the mechanical properties of mature concrete are considered functions of the uniaxial compressive strength. The following equation is proposed for design purposes.

$$E_{cmt} = 3500 + 4300\sqrt{f_{cmt}} \quad MPa \qquad (2\text{-}25)$$

E_{cmt} = mean modulus of elasticity at age t

f_{cmt} = mean concrete strength at age t

It can be noted that equation (2-25) does not include any effects for aggregate stiffness or concrete density. Rather than making allowance for the density of the concrete it is preferable to measure the modulus of elasticity.

Strength Development with Time

If experimental results for the development of concrete strength with time do not exist the following equation can be used.

$$f_{cmt} = f_{cm28} \frac{t^{3/4}}{a + bt^{3/4}} \qquad (2\text{-}26)$$

for Type I cement concrete a = 2.8 and b = 0.77 (2-26a)

Type II cement concrete a = 3.4 and b = 0.72 (2-26b)

Type III cement concrete a = 1.0 and b = 0.92 (2-26c)

f_{cmt} = mean concrete strength at t days

f_{cm28} = mean concrete strength at 28 days

To take account of temperatures other than normal, a 20 °C modified Arrhenius age can be used. The form of equation (2-26) is similar to that recommended by ACI 209-82. Describing the strength development with time of a given cement as Type I is very simplistic. Equation (2-26) can be used to approximate the hydration characteristics of cement-supplementary cementing material combinations.

Shrinkage

The following equation is recommended to calculate the shrinkage, at time t, with correction factors for ambient relative humidity, (a) strength at end of moist curing, (b) strength of concrete, (c) duration since end of moist curing and (d) member size. Expression (c) was normalised to be unity at 20,000 days. For sealed specimens use $\beta(h) = 0$ (ie h = 96%). It should be noted that an ultimate shrinkage strain is not assumed; the strain increases indefinitely.

where h = humidity expressed as a decimal

$$\varepsilon_{sh=} = \varepsilon_{shu}\,\beta(h)\beta(t) \qquad (2-27)$$

$$\beta(h) = (1 - 1.18h^4) \qquad (2-28)$$

$$\varepsilon_{shu} = 900K\underset{(a)}{\left(\frac{f_{cm28}}{f_{cmtc}}\right)^{0.5}}\underset{(b)}{\left(\frac{25}{f_{cm28}}\right)^{0.5}} \times 10^{-6} \qquad (2-29)$$

$$\beta(t) = \underset{(c)}{\left(\frac{6 + \ln(t - t_c)}{16}\right)}\underset{(d)}{\left(\frac{t - t_c}{t - t_c + 0.015(V/S)^2}\right)} \qquad (2-30)$$

t = age of concrete (days)

t_c = age drying commenced, end of moist curing (days)

t_o = age concrete loaded (days)

K = 1 Type I cement, K = 0.70 Type II cement, K = 1.33 Type III cement

V/S = volume/surface ratio (mm)

f_{cm28} = concrete mean compressive strength at 28 days (MPa)

f_{cmtc} = concrete compressive strength when drying commenced (MPa)

f_{cmto} = concrete compressive strength when loading commenced (MPa)

For blended flyash or slag cement concrete, the measured concrete strengths should be used to determine which of equations (2-26a), (2-26b) or (2-26c) best represents the test results to determine the appropriate value of K to be used.

Creep

Effect of Humidity on Creep

As hygral equilibrium has been assumed to be 96% for shrinkage it was assumed that drying creep would be zero at a relative humidity of 96%.

Specific creep = creep coefficient x elastic strain calculated using adjusted concrete strength.

Compliance = measured elastic strain + specific creep.

$$\Phi(t) = \left[\frac{7.27 + \ln(t - t_0)}{17.18}\right] \qquad (2\text{-}31)$$

$$\frac{creep}{coef} = \Phi(t)\Phi(t_c)\left(\frac{f_{cm28}}{f_{cmto}}\right)^{1/2}\left[1.5 + 3\left(\frac{25}{f_{cmto}}\right)^{1/2}(1-1.086\,h^2)\left(\frac{t-t_0}{t-t_0+0.05*(V/S)^2}\right)\right] \quad (2\text{-}32)$$

Equation (2-32) can be used to calculate the creep coefficient. It should be noted that an ultimate creep strain is not assumed; the strain increases indefinitely.

If $t_0 = t_c$

$$\Phi(t_c) = 1$$

When $t_0 > t_c$

$$\Phi(t_c) = \sqrt{1 - \frac{\varepsilon_{sh}(t_0 - t_c)}{\varepsilon_{sh}(20000 - t_c)}}$$

The term $\Phi(t_c)$, models, but does not explain, the *Pickett* effect. The term $\Phi(t_c)$ takes account of drying before loading, which reduces both basic and drying creep. It is accepted that the creep on concrete is related to the evaporable water - the remaining evaporable water is approximated as the fraction remaining potential shrinkage relative to the shrinkage from end of moist curing to 20,000 days.

2.3 Literature Review

Most experimental investigations described in the literature were performed under conditions of constant temperature and humidity. This literature review only describes investigations under non-constant temperature or non-constant relative humidity. These paragraphs deal only with test results on the effect of variable ambient humidity. Few investigations on the influence of changing temperatures on creep and shrinkage of concrete have been published. However, no systematic longtime investigations on the effect of cyclic temperature and humidity changes are known.

Pickett (1942) demonstrated that the rate of creep deformation of 2-in. by 2-in. (51 mm by 51 mm) plain concrete flexural specimens increased each time the specimens were either submerged in water or removed from water.

Hansen (1960) subjected 20-mm deep flexural specimens to cycles of changing humidity, and found that while the shrinkage of unstressed specimens corresponded to shrinkage at the average relative humidity; the creep corresponded approximately to creep of specimens maintained at the lower limit of the relative humidity cycle. The length of the humidity cycle was significant, as was the initial moisture state of the specimens.

Bernhardt (1969) carried out tests on concrete cylinders (diameter 10 cm, height 28 cm) cured at 100 % relative humidity and 20 °C temperature. Uniaxial compressive loads were applied at the ages of 9 to 11 days. The specimens were exposed to four different intervals of drying in air (relative humidity in the laboratory 35 to 55 %) and wetting (immersion in water) in periods for 7 and 14 days. The drying/wetting intervals were 6.75/0.25, 6/1, 5/2, and 12/2 days. It was observed that there was practically no difference in the creep behavior of the specimens, which were exposed to the different drying/wetting intervals in periods of 7 days. In comparison to these series, the creep strains of the speminens with the period of 14 days were found to be approximately 40 % larger. In this investigation no experiments were conducted with a constant average relative humidity. No details are reported on the shrinkage behavior.

The experimental study of *A-Alusi et al.* (1972) measured creep and shrinkage on hollow concrete cylinders (diameter 15.2 cm, height 101.6 cm wall thickness 2.5 cm) which were exposed to cyclic variations of the ambient relative humidity from 100 (fog room) to 50 % at intervals of 14 days with exception of the first moisture interval (7 days). The creep specimens of the tests considered here were uniaxially loaded at the age of 21 days. Creep and shrinkage tests were also conducted at constant relative humidities of 50 and 100 %, however the specimens of the creep tests at 50 % relative humidity were loaded at the age of 27 days after having been preconditioned for 14 days at 50 % relative humidity. No tests were carried out at a constant average relative humidity of 75 %. The tests results showed that after 50 days of loading the creep strains at cyclic ambient conditions are approximate 7 times larger than at constant 100 % relative humidity and approximate 3 times larger than at constant 50 % relative humidity. Shrinkage at a constant environment of 50 % relative humidity was found to be approximately 50 % larger than at variable relative humidity at the end of the dry storage intervals.

Parrot (1976) conducted creep tests on specimens, which were allowed to dry and then wetted. Both drying and wetting lead to significant increases in the rates of creep. Rewetting of the accompanying unstressed shrinkage specimens also leads to recovery of much of the shrinkage strain. He also measured shrinkage strains in outdoor exposed specimens and found seasonal variations of the same nature.

Creep and shrinkage measurements were reported on three steam cured and one moist cured control concrete by *Gamble* (1982). Half of specimens were stored in a constant environment of 70 °F and 50 % RH and half of them were stored outdoors in central Illinois. The shrinkage strains in the outdoor specimens were quite low, corresponding to strains expected at relative humidity values of 80 ~ 90 %, even though the annual humidity was about 70 %. However, the creep strains in the outdoor specimens were much larger than normally would have been associated with the 70 % relative humidity range, and were of the same general magnitude as the creep of companion specimens stored indoors in a constant environment of about 45 ~ 50 %.

In summing up only very limited test data on the effect of cyclic variations of the ambient environment on creep and shrinkage may be found in the literature. The data have been obtained from very different investigations and none of the existing test data present conclusive evidence on the effects under consideration because the experimental programs were not sufficiently complete and comprehensive.

2.4 Test Methods for Creep and Shrinkage

2.4.1 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 deformations). 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.

2.4.2 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.
- Separations exist between strain components from environmental and load conditions.
- Strain gradients are linear (and uniform).

2.4.3 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 behaviour, 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 incertitude 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.

2.4.4 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 from the moment 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 causes 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 loading age.

2.4.5 Basic Creep and Autogenous Shrinkage Curing in ASTM C 512

At the age of moulding 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 is shown in Figure 2-1.

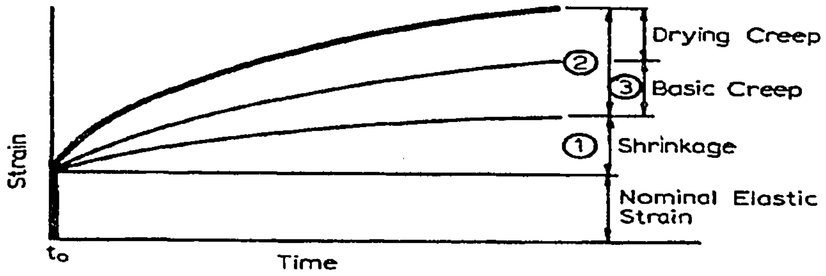


Figure 2-1: Time-dependent deformation in concrete subjected to a sustained load

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.

2.4.6 Standard Moist Curing and Testing Environments

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 for standard compression tests cured under standard condition of 23 ± 1.7 °C and 95 % relative humidity. However, ASTM C512 "Creep of concrete in 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.

2.4.7 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 important 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.

2.4.8 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 technique as used on creep specimens. The end surfaces of all the shrinkage specimens should be sealed to allow radial drying only.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Introduction

This Chapter describes a current 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. Due to the short time since the measurement program commenced results are available only for 300 days since casting. The intention is to continue measurements for 6 years or until the deformations cease to change. 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 or 4 days depending upon the test program. Some specimens were loaded at 3/4 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 before loading, some which were 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 and two 610 mm diameter specimens and eighty standard cylinders were cast. All specimens employed the same 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. 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 test for shrinkage and creep at age of loading and f'_c, and E_c 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 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 %.

The 89, 152 and 254 mm diameter specimens were cast in two lengths with non-instrumental 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 as shown Figure 3-1, and 610 mm (24″) x 1930 mm (3 x 24″ +6″) cylinders as shown 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, and 155 kg water. 65 kg slag, 250 ml retarder and 65 ml air content 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 is initially applied and periodically adjusted, using a hydraulic jack. There were two types of creep frame used for 89 mm specimens as shown in Figure 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 as shown in Figure 3-7, the load is applied and maintained by hydraulic pressure. Figure 3-3~3-7 shows a hydraulic jack during load application.

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 compression strengths 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 place for 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 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-cured room, and outside the building.

3.6 Testing 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 time 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 of specimens were moved to other environments. The descriptions are as follow in Table 3-1~3-4:

3.6.1 Environment of temperature-controlled laboratory

- Both length sets of 89, 152 and 254 mm 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

- Both length sets of 89, 152 and 254 mm specimens were stored outside of 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.

3.6.4 Environment of 50 % RH Room

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

- Four 89 mm diameter specimens were stored in a standard moist curing room after demoulding until 25 days and then sealed and 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 % of relative humidity after demoulding and sealed at 25 days and then maintained in a 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 and sealed at 200 days and then maintained in the 50 % of 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 controlled environment as the creep specimens and close to them, have the same surface area exposed to the environment, the same gage length, and have deformations measured using the same equipment, and technique as used on 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, clearly 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 x 10^{-6} in.) for a specimen with a gage 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 once 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 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 150 mm x 300 mm cylinders were grounded and tested each time. 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 gage 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 gage essentially as described by ASTM C469.

Compressometers with mechanical (analogue) or digital dial gauges are used to measure strain on gage points mounted on the surface of the specimen. For this project, a typical compressometer, which is equipped with a digital dial gage reading is 203 mm (8 in.) between gage 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. Average of three results at age of every loading is given and plotted in the Chapter 4.

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)	Stress, f (MPa)	f/f_{28} (%)
Moist cured for 3 days	89 x 330 (Shrinkage)	1		
	89 x 330 (Creep)	7 (24 days)	8.0	14
	89 x 460 (Shrinkage)	48		
	89 x 460 (Creep)	56 (4 days)	6.0	14
		31 (24 days)	8.0	19
Moist cured for 24 days	89 x 330 (Shrinkage)	17		
	89 x 330 (Creep)	21 (28 days)	8.0	14
	89 x 460 (Shrinkage)	46, 60		
	89 x 460 (Creep)	26 (25 days)	8.0	19
		37 (28 days)	8.0	19
Moist cured for 3 days	152 x 442 (Shrinkage)	68		
	152 x 442 (Creep)	66 (24 days)	8.0	19
	152 x 747 (Shrinkage)	72		
	152 x 747 (Creep)	76 (24 days)	8.0	19
Moist cured for 3 days	254 x 645 (Shrinkage)	79		
	254 x 645 (Creep)	80 (24 days)	8.0	19
	254 x 1153 (Shrinkage)	86		
	254 x 1153 (Creep)	88 (24 days)	8.0	19
Moist cured for 3 days	610 x 1930 (Shrinkage)	111~116*		
	610 x 1930 (Creep)	101~106* (25 days)	8.0	19

Table 3-1: Detail of Creep Specimens in the Lab
* strain gauge No. detailed in Figure 3-2
f applied creep stress, MPa
f_{28} compressive strength after moist cured 28 days

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)	Stress, f (MPa)	f/f_{28} (%)
Moist cured for 3 days	89 x 330 (Shrinkage)	18		
	89 x 330 (Creep)	12 (3 days) 20 (13 days) 64 (200 days)	6.0 8.0 9.64	14 19 22
	89 x 460 (Shrinkage)	28		
	89 x 460 (Creep)	29 (3 days) 23 (13 days) 24 (200 days)	6.0 8.0 9.64	14 19 22

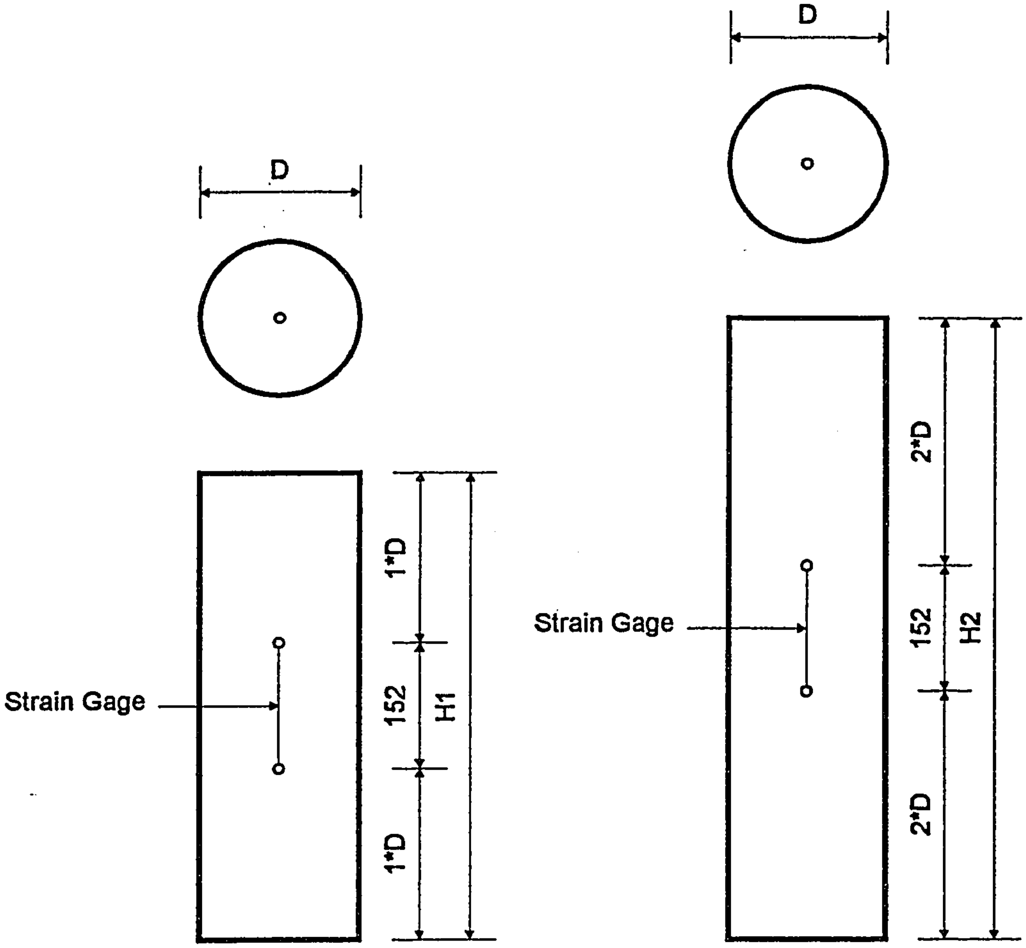
Table 3-2: Detail of Creep Specimens Immersed in Water

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)	Stress, f (MPa)	f/f_{28} (%)
Moist cured for 3 days	89 x 330 (Creep)	19 (24 days) 14 (201 days)	8.0 9.64	19 22
	89 x 460 (Shrinkage)	39, 40		
	89 x 460 (Creep)	53 (4 days) 58 (24 days) 32 (201 days)	6.0 8.0 9.64	14 19 22
Moist cured for 24 days	89 x 330 (Shrinkage)	16		
	89 x 460 (Shrinkage)	49		
	89 x 460 (Creep)	61 (24 days)	8.0	19
Moist cured for 3 days	152 x 442 (Shrinkage)	71		
	152 x 442 (Creep)	67 (24 days)	8.0	19
	152 x 747 (Shrinkage)	73		
	152 x 747 (Creep)	75 (24 days)	8.0	19
Moist cured for 3 days	254 x 645 (Shrinkage)	81		
	254 x 645 (Creep)	78 (201 days)	8.0	22
	254 x 1153 (Shrinkage)	84		
	254 x 1153 (Creep)	87 (201 days)	8.0	22

Table 3-3: Detail of Creep Specimens stored Outside

Curing Condition	Specimen Size (mm)	No. of Specimen (Age of Loading)	Stress, f (MPa)	f/f_{28} (%)
Moist cured for 3 days	89 x 330 (Shrinkage)	4		
	89 x 330 (Creep)	65 (24 days)	8.0	19
		11 (200 days)	9.64	22
	89 x 460 (Shrinkage)	47		
	89 x 460 (Creep)	41 (4 days)	6.0	14
		44 (24 days)	8.0	19
		38 (200 days)	9.64	22
Moist cured for 3 days	152 x 442 (Shrinkage)	70		
	152 x 442 (Creep)	69 (24 days)	8.0	19
	152 x 747 (Shrinkage)	74		
	152 x 747 (Creep)	77 (24 days)	8.0	19
Moist cured for 3 days	254 x 645 (Shrinkage)	82		
	254 x 645 (Creep)	83 (24 days)	8.0	19
	254 x 1153 (Shrinkage)	85		
	254 x 1153 (Creep)	89 (24 days)	8.0	19
Moist cured for 24/25 days	89 x 330 (Shrinkage)	15		
	89 x 330 (Creep)	2 (25 days)	8.0	19
		13(200 days)	9.64	22
	89 x 460 (Shrinkage)	27		
	89 x 460 (Creep)	59 (25 days)	8.0	19
Moist cured for 200 days	89 x 460 (Shrinkage)	55		
	89 x 460 (Creep)	42 (200 days)	9.64	22
Moist cured for 25 days & sealed	89 x 330 (Shrinkage)	5		
	89 x 460 (Shrinkage)	30		
	89 x 460 (Creep)	50 (25 days)	8.0	19
Moist cured for 3 days & sealed 25 days	89 x 330 (Shrinkage)	6		
	89 x 330 (Creep)	3 (25 days)	8.0	19
	89 x 460 (Shrinkage)	45		
	89 x 460 (Creep)	35 (25 days)	8.0	19
Moist cured for 3 days & sealed 200 days	89 x 330 (Shrinkage)	10		
	89 x 330 (Creep)	9 (200 days)	8.0	19
	89 x 460 (Shrinkage)	52		
	89 x 460 (Creep)	36 (200 days)	8.0	19
Moist cured for 3 days & sealed 3 days	89 x 330 (Shrinkage)	22, 62		
	89 x 330 (Creep)	63 (28 days)	8.0	19
		8 (200 days)	9.64	22
	89 x 460 (Shrinkage)	25		
	89 x 460 (Creep)	33 (28 days)	8.0	19
		54 (200 days)	9.64	22

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



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

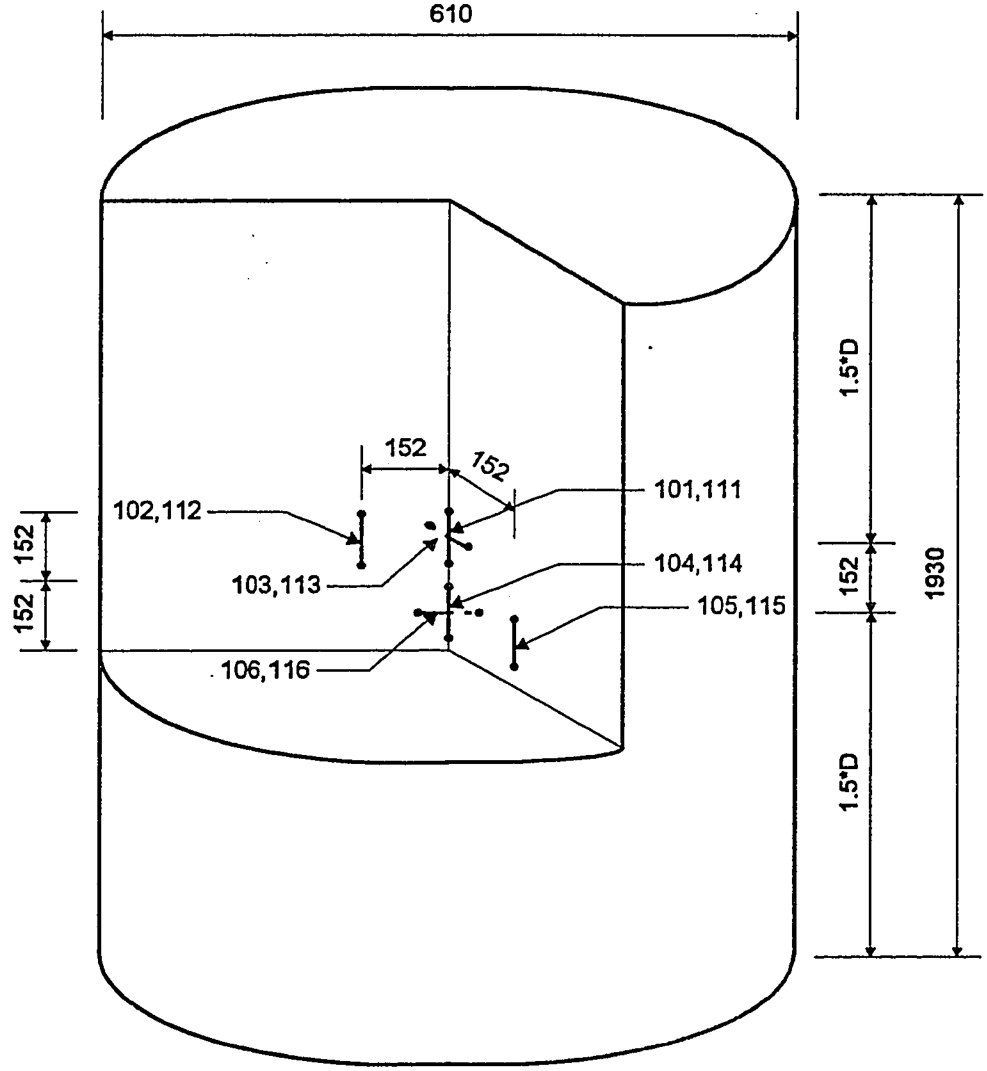


Figure 3-2: Detail of Strain Gauges Location of 610 mm Diameter Specimens

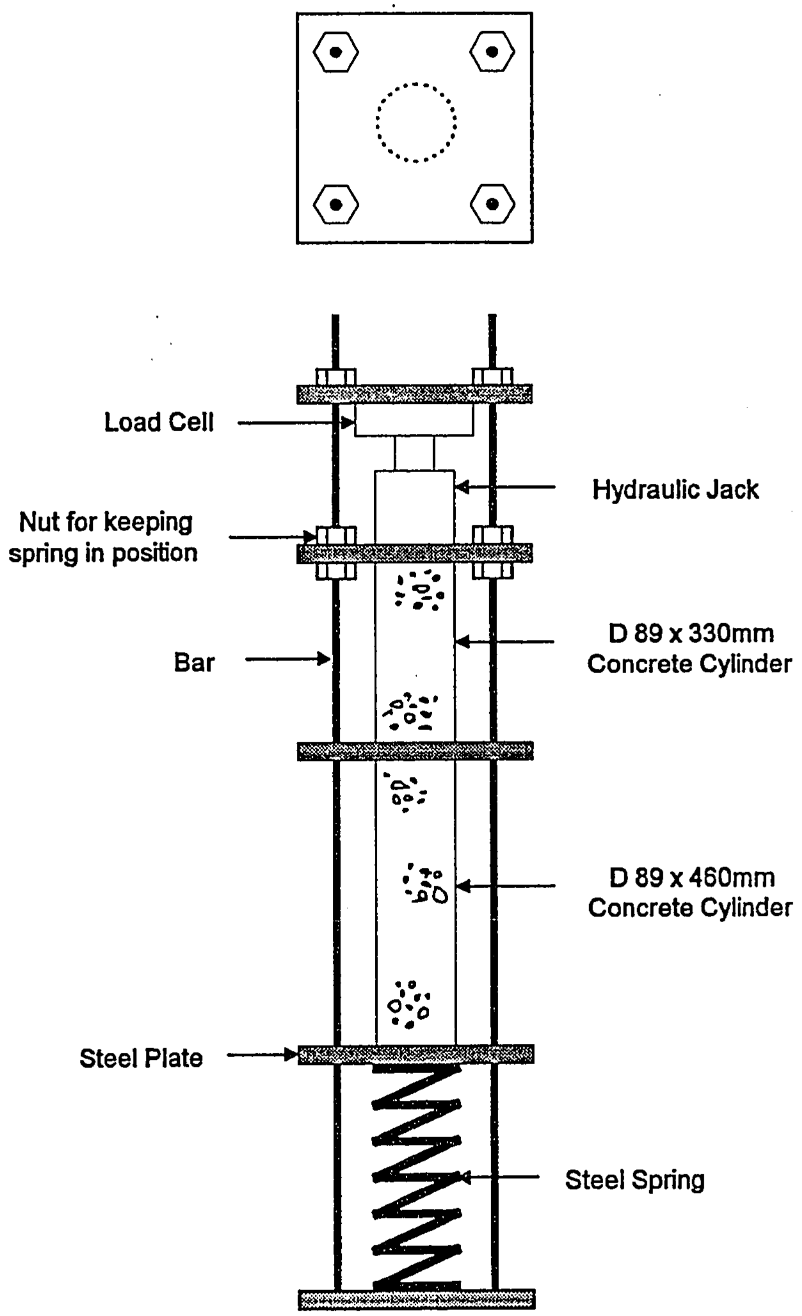


Figure 3-3: Detail of 89 mm Diameter Specimens Creep Frame Type1

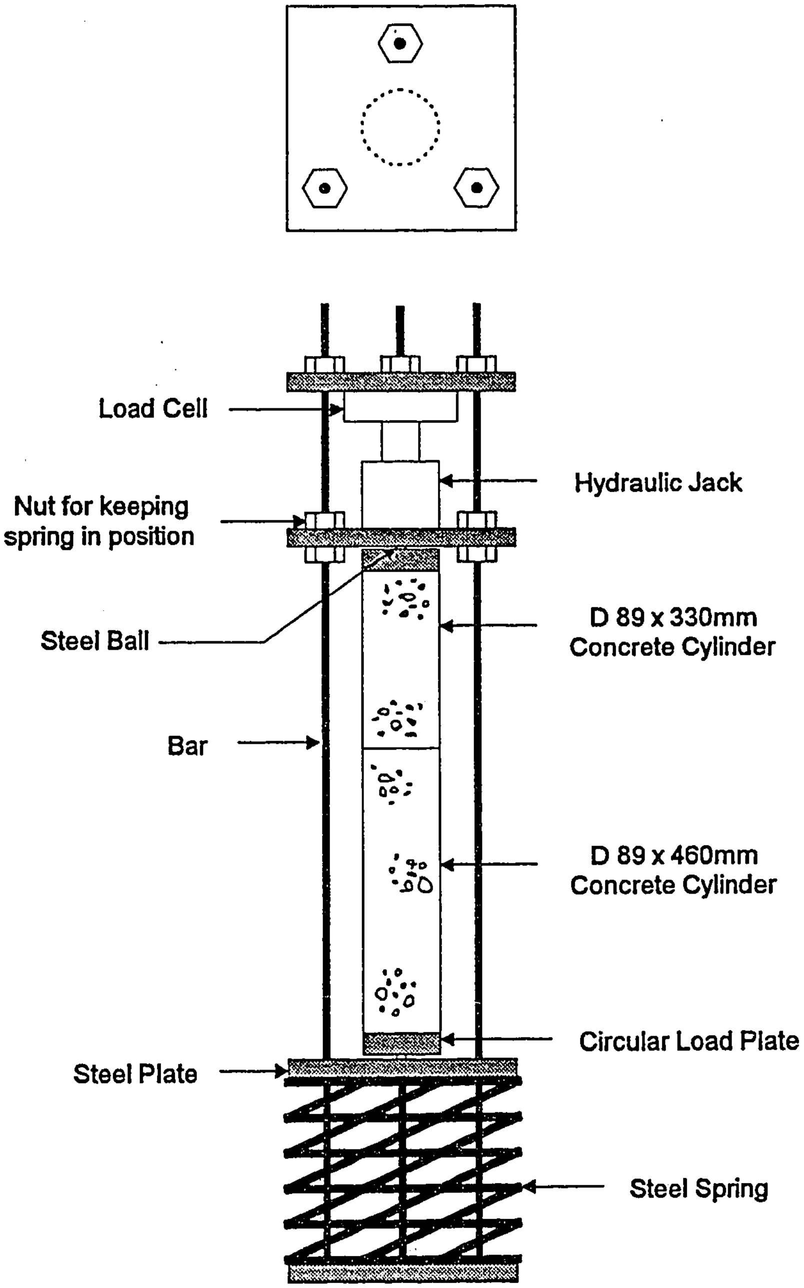


Figure 3-4: Detail of 89 mm Diameter Specimens Creep Frame Type 2

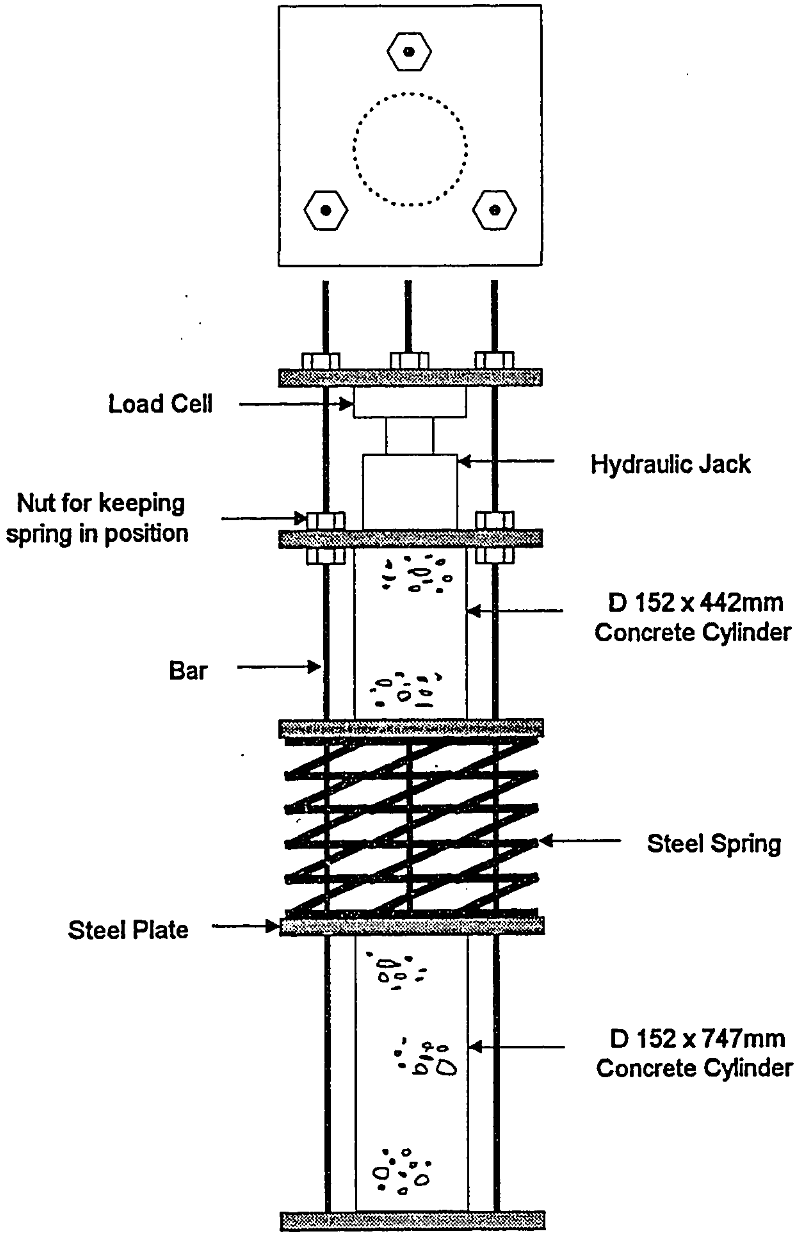


Figure 3-5: Detail of 152 mm Diameter Specimens Creep Frame

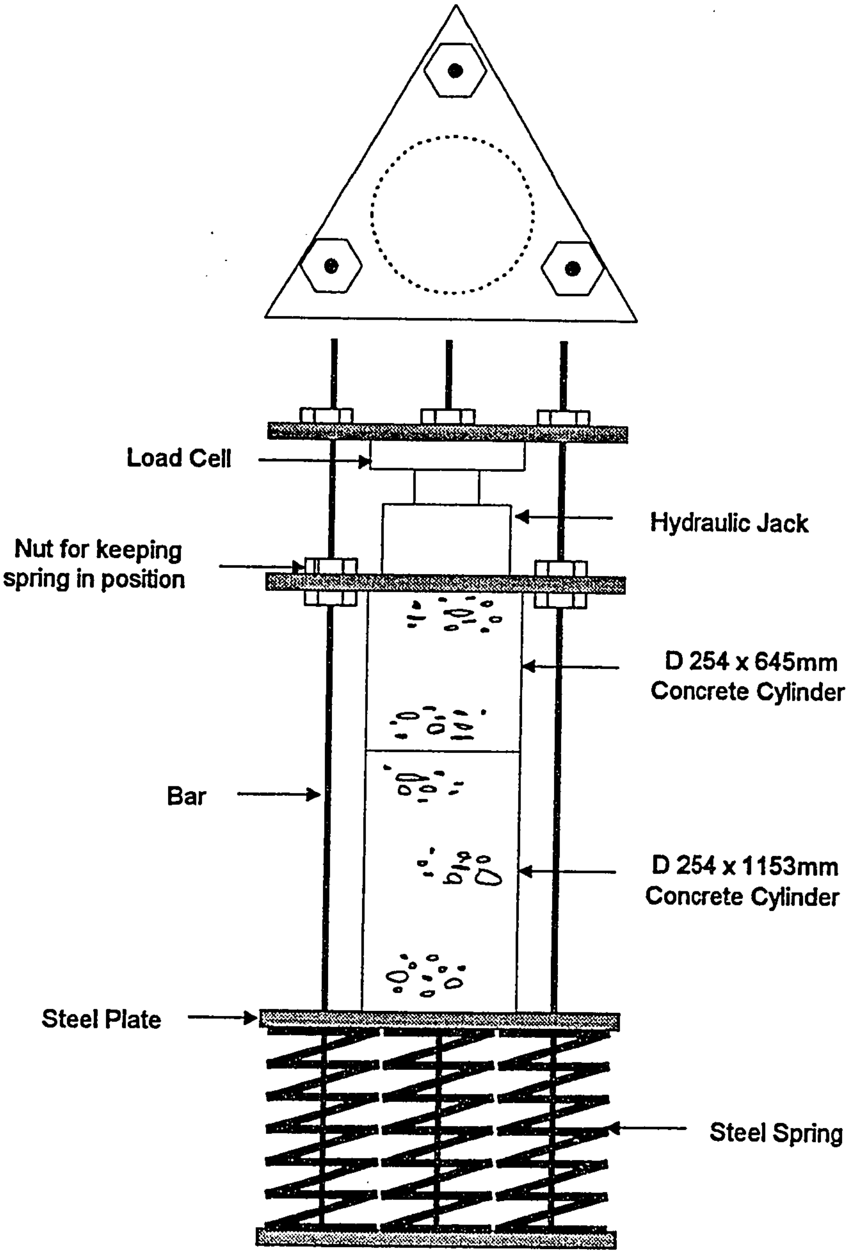


Figure 3-6: Detail of 254 mm Diameter Specimens Creep Frame

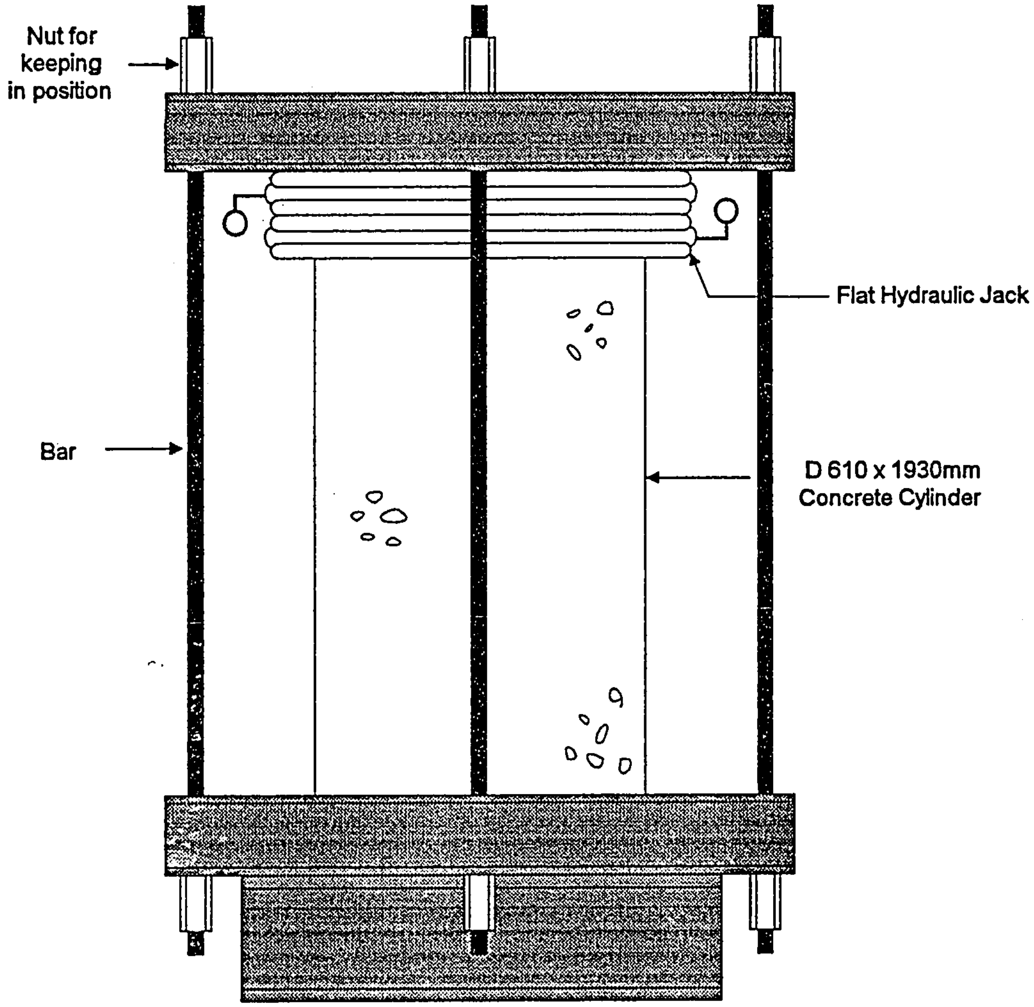


Figure 3-7: Detail of 610 mm Diameter Specimens Creep Frame

CHAPTER 4

MECHANICAL PROPERTIES

In general, the physical tests on the properties of concrete and the mechanical tests on sixty-five concrete specimens were carried out successfully. All test cylinders were stored in the same controlled environment and close to the creep and shrinkage specimens, and were stored the five chosen environments which were in the Lab, 50 % RH room, water tank, moist-cured room, and outside the building as shown in Table 4-1 ~ 4-3. However, there are several remarks that must be mentioned in order to make this paper complete.

4.1 Concrete Strength

In general, the specimens failed in a consistent manner in that the compressive strength increased with increasing time. The lower strength specimens demonstrated considerable plastic deformation before failure occurred. In contrast, older specimens having higher compressive strengths, typically above 40 MPa, exhibited very little plastic strain and the failure was both sudden and explosive. The results of the compression tests with environment and age were given in Table 4-1. To examine the strength results, the compressive strength versus the age of concrete are plotted in Figure 4-1. In general, compressive strength increased with age for all storage environments. However, it must be observed that strength development is grossly affected by environment. The 50 % RH concrete and the laboratory-stored concrete were significantly weaker at 200 days than the sealed and moist cured specimens. Concrete stored outdoors also was considerably weaker at 25 days, which was the middle of January 1998, than concrete stored in the other environments because of below freezing winter temperatures. At 180 days, however, strength of the concrete stored outdoors was equal to the strength of the moist cured and sealed concretes.

4.2 Modulus of Elasticity

The static modulus of elasticity used in the determination of elastic and creep deformations may be determined using methods such as those outlined in ASTM C 469. If such information is not available, the static modulus of concrete at age of loading may be calculated from the mean concrete strength. The measured moduli of elasticity with age and environment are given in Table 4-2. . Modulus of elasticity is defined as the ratio of normal stress to corresponding strain for compressive stress below the proportional limit of material.

Equation 2-25 is a compromise between the recommended equations of ACI 209-82 and ACI 363-94. Figure 4-2 shows relationship between modulus of elasticity and at age of loading with various environments. Two types of compressometer were used for deformation measurements. Measurements taken from 4 to 24 days' were taken using the University compressometer and the 25 to 200 days' measurements were taken using an EMR compressometer. The two results are quite different. The measured modulus of elasticity appears to decrease with time which was not expected and illogical. Hence, little confidence can be placed upon those results.

The relative compressive strengths as a percent of 28 days moist cured concrete strength with age and environment are given in Table 4-3. Figure 4-3 shows the relationship between strength gain and moist curing. The concrete strength increases with age, provided moisture is present for hydration of cement.

$$\textit{percent of } 28 \textit{ days moist cured concrete strength} = \frac{\textit{concrete strength}}{f_{cm28}} \times 100 \qquad (4-1)$$

where f_{cm28} = mean concrete strength at 28 days

Figure 4-4 illustrates relationship between modulus of elasticity and compressive strength at age of loading for various environments. Due to the previously described problems in determining the modulus of elasticity, little credence should be placed on these comparisons. The equations with Eq. 2-1 and Eq. 2-26 versus Eq. 2-25 were very similar in shape.

Age (Day)	Lab	50% RH	Outside	Moist Cured	Immersed	Sealed	Eq. 2-1	Eq. 2-26
1							8.86	12.03
2							15.07	17.64
3	23.55						19.67	21.49
4	26.44						23.22	24.40
5							26.03	26.72
6							28.32	28.63
7							30.22	30.23
8							31.81	31.61
9							33.18	32.81
10							34.36	33.87
11							35.39	34.82
12							36.30	35.66
13					34.88	30.80	37.10	36.43
14							37.82	37.13
15							38.46	37.76
16							39.05	38.35
17							39.57	38.89
18							40.06	39.39
19							40.50	39.85
20							40.90	40.29
21							41.28	40.69
22							41.63	41.08
23							41.95	41.43
24	35.47	35.26					42.25	41.77
25	38.35	38.19	29.16	40.30			42.52	42.09
28				42.95	40.53	39.13	43.26	42.95
30							43.68	43.45
40							45.21	45.40
56							46.61	47.37
60							46.85	47.73
70							47.35	48.49
80							47.72	49.10
84							47.85	49.32
100							48.26	50.03
112							48.49	50.45
140							48.89	51.20
168							49.15	51.75
179	38.46						49.24	51.92
180			48.44			47.84	49.24	51.94
181		42.67			47.47		49.25	51.95
196				49.74			49.34	52.16
200				50.74			49.37	52.21

Table 4-1: Compressive strength (MPa) of at age of loading with various environment

Age (Day)	Lab	50% RH	Outside	Moist Cured	Immersed	Sealed	Eq. 2-25
1							18415
2							21560
3							23435
4	38100						24742
5							25727
6							26506
7							27143
8							27677
9							28132
10							28527
11							28873
12							29179
13					70033	35060	29454
14							29700
15							29924
16							30128
17							30315
18							30487
19							30646
20							30793
21							30931
22							31059
23							31179
24	32021	32901					31291
25	18987	20074	20614	25659			31397
28				22121	21513	20036	31680
30							31845
40							32473
56							33094
60							33207
70							33444
80							33632
84							33697
100							33914
112							34042
140							34270
168							34432
179	17299						34484
180			21179			24666	34489
181		17291			28724		34493
196							34555
200				26935			34570

Table 4-2: Modulus of elasticity (MPa) of at age of loading with various environment

Age (Day)	Lab	50% RH	Outside	Moist Cured	Immersed	Sealed	Eq. 4-1
1							28
2							41
3	55						50
4	62						57
5							62
6							67
7							70
8							74
9							76
10							79
11							81
12							83
13					81	72	85
14							86
15							88
16							89
17							91
18							92
19							93
20							94
21							95
22							96
23							96
24	83	82					97
25	89	89	68	94			98
28				100	94	91	100
30							101
40							106
56							110
60							111
70							113
80							114
84							115
100							116
112							117
140							119
168							120
179	90						121
180			113			111	121
181		99			111		121
196				116			121
200				118			122

Table 4-3: Compressive strength, percent of 28 days moist cured concrete versus various environment

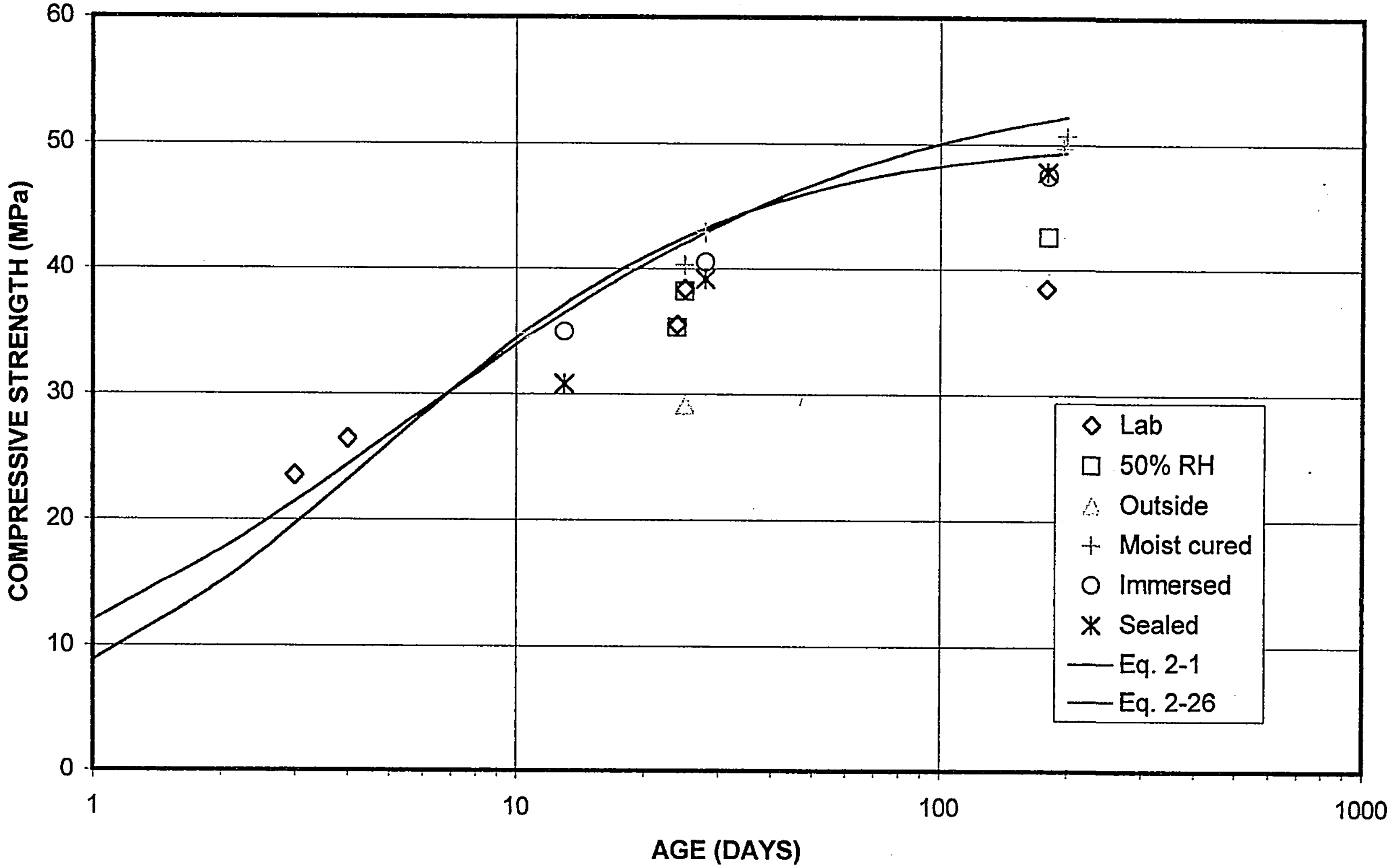


Figure 4-1: Compressive strength of at age of loading with various environment

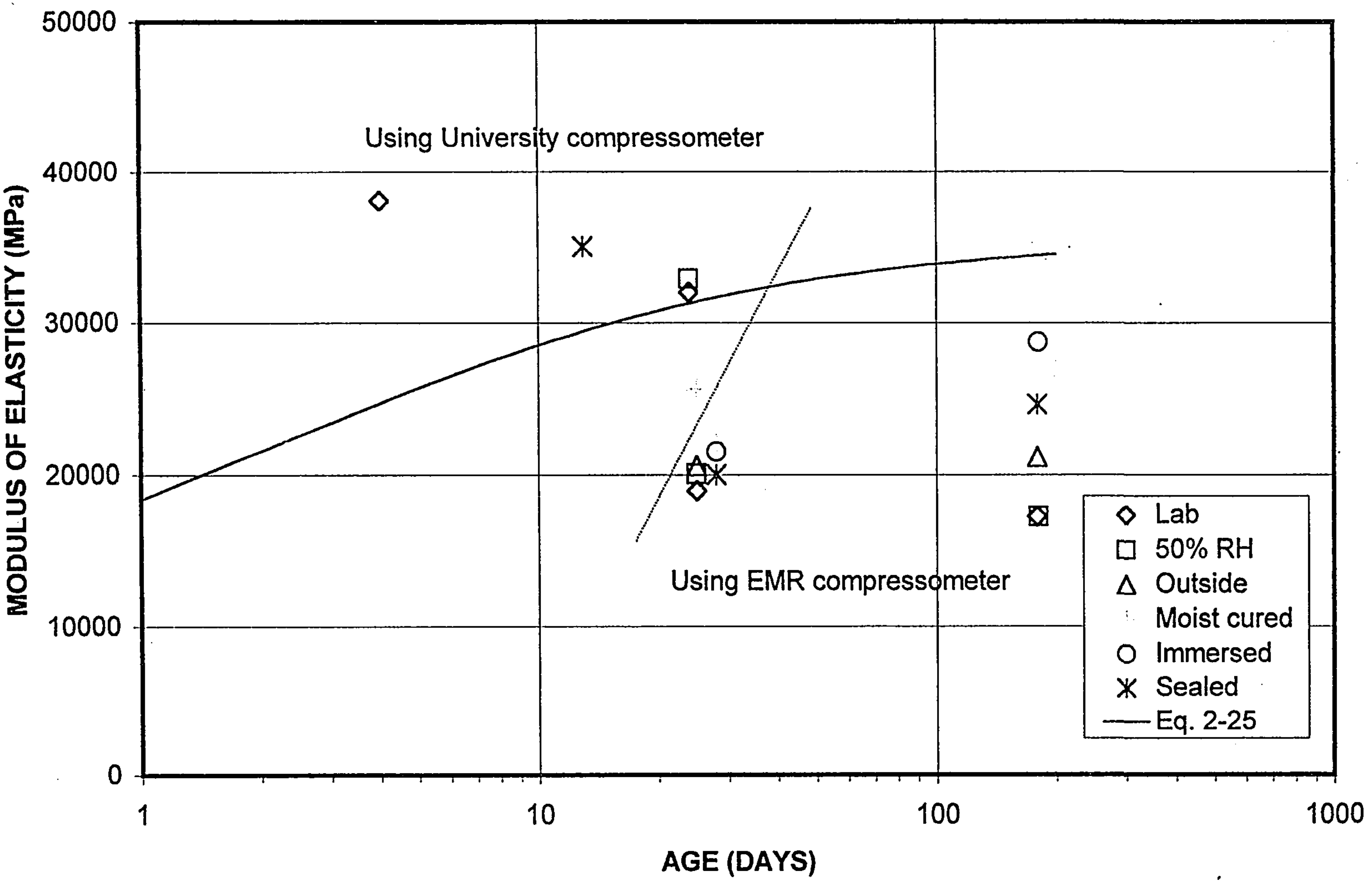


Figure 4-2: Modulus of elasticity of at age of loading with various environment

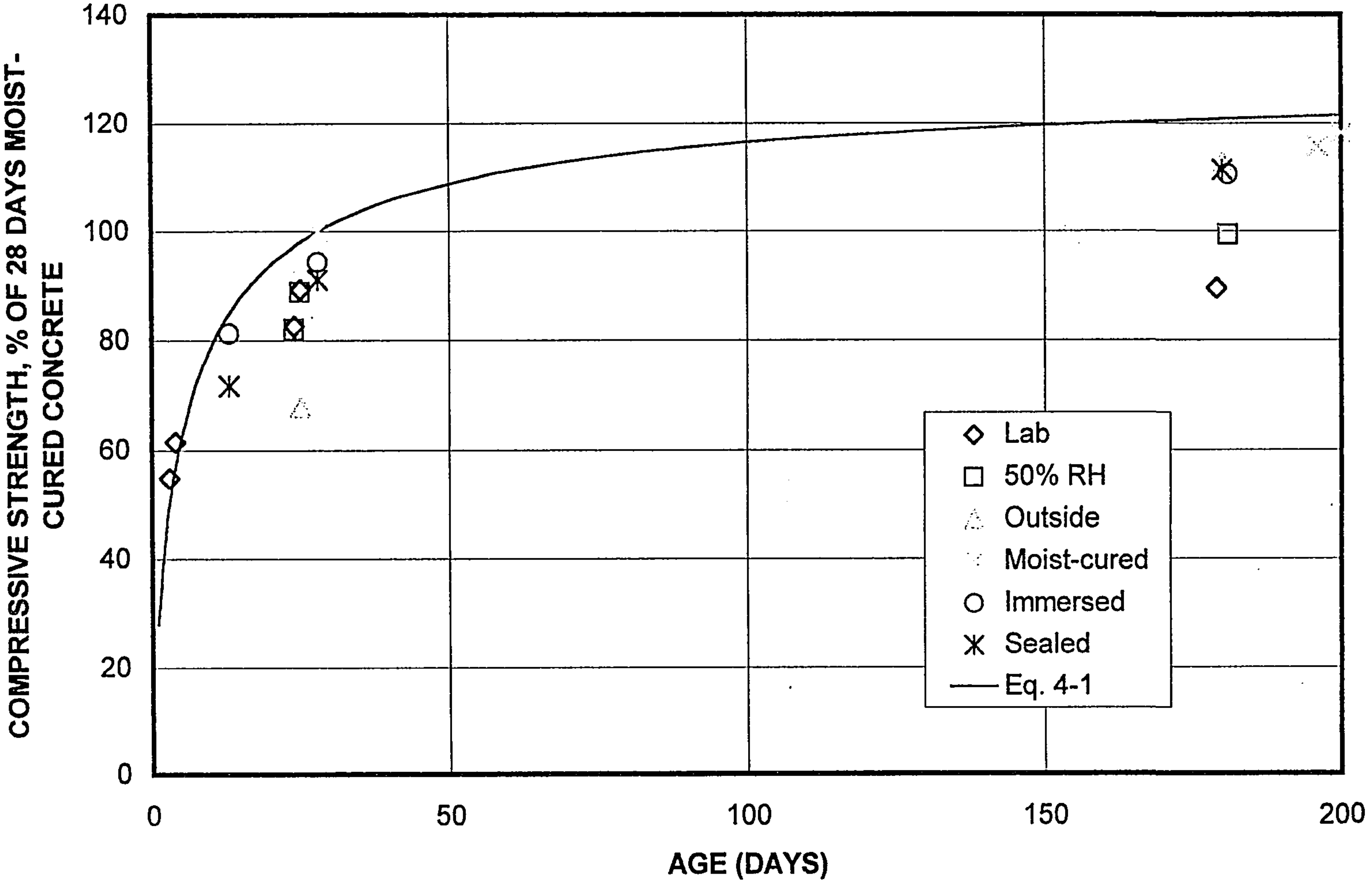


Figure 4-3: Compressive strength, % of 28 days moist cured concrete versus various environment

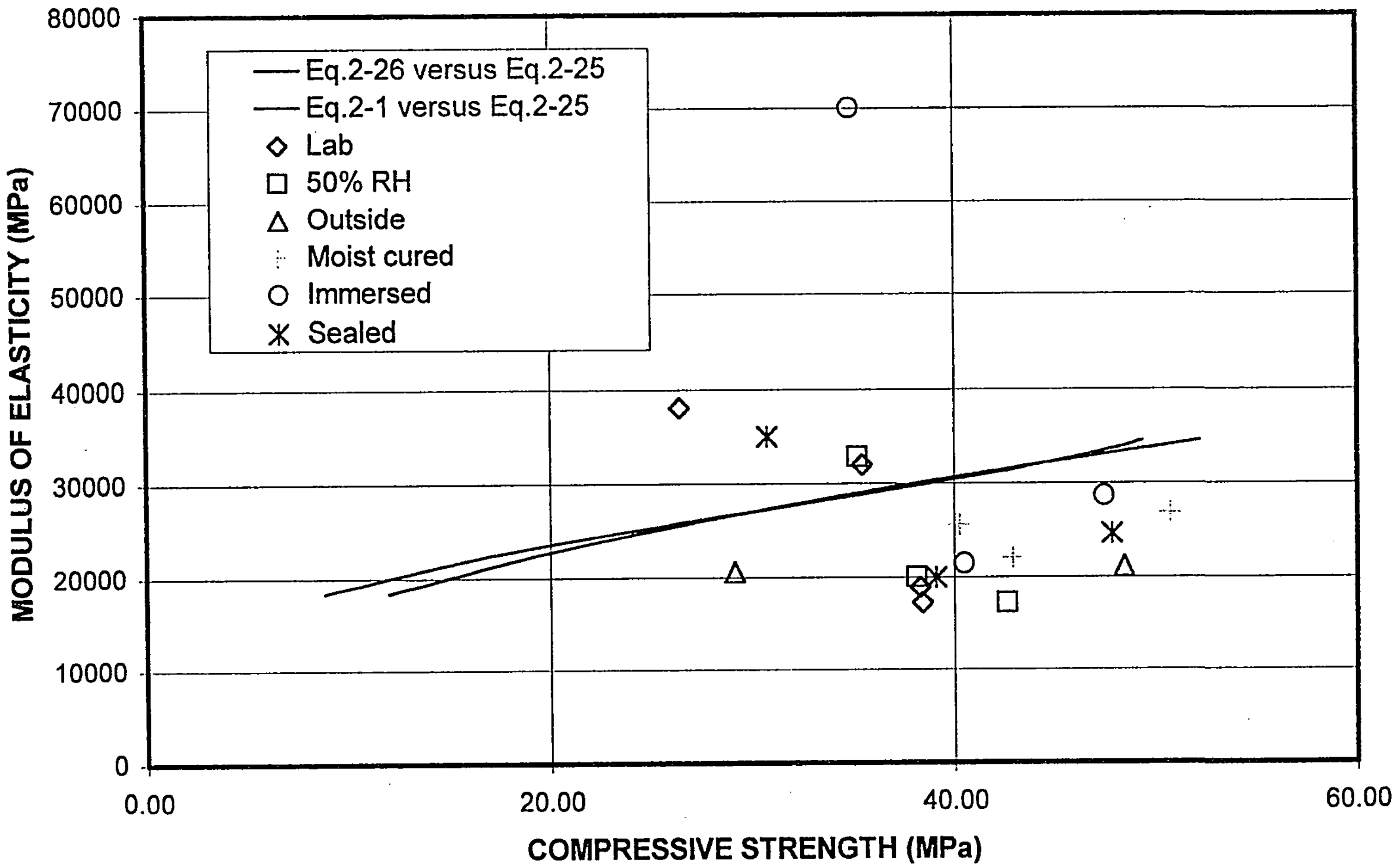


Figure 4-4: Modulus of elasticity versus compressive strength with various environment

CHAPTER 5

TIME DEPENDENT DEFORMATIONS

To determine the long-term response of a concrete structure subjected to load, it is necessary to take account of the time dependent effects of shrinkage and creep. Although shrinkage and creep have been studied for many decades, the roles are not fully understood because of the complexities.

Although creep is observed for all materials, the fundamental basis for creep of concrete must be quite different from that 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 of concrete are similar, experimental parameters affect creep in much the same way as shrinkage, the magnitudes of the strains are similar, and include a considerable amount of irreversibility. Concrete is an age hardening material – its strength and stiffness increase with time.

5.1 Total Strains of Test Specimens

The object of this study was to examine the influence of environment and specimen size on creep and shrinkage of concrete.. Figures 5-1 to 5-19 show measured total strain with age and environment. Each figure includes elastic deformation, shrinkage and creep. The continuous lines in all graphs stand for the long specimens and the dotted lines represent the short specimens.

Figures 5-1 to 5-5 show total strains with age for 89, 152, 254 and 610 mm diameter specimens in the temperature-controlled, uncontrolled-humidity lab. Total strains of the 89 mm diameter specimens moist cured 3 days is shown in Figure 5-1. In general, the total strains of the short and long specimens are similar except for the 152 mm diameter specimens. The total strains of 254 mm diameter, long and short specimens are quite similar as shown in Figure 5-4. However, the total strains of 152 mm diameter long and short specimens are significantly different as shown in Figure 5-3. Figure 5-5 presents the strains measured on the 610 mm diameter specimens; the dotted lines represent the creep specimen gauges and the continuous lines the unloaded specimen.

Figures 5-6 to 5-9 show total strains with age for 89, 152 and 254 mm diameter specimens stored outdoors. Figures 5-28 and 5-29 show the measured outside temperatures which varied from minus 17 °C to plus 30 °C. All graphs of strains of specimens stored outside are very similar with a definite dependency to below freezing temperatures. The strains of specimens measured during winter were very small. As shown in Figure 5-6, the total strains of early age loaded specimens are greater than late age loaded specimens. Overall, there were no significant differences between long and short specimens.

Figure 5-10 shows the total strains of 89 diameter mm specimens immersed in water after 3 days moist curing and loaded at 3, 13 and 200 days. Cement paste, or concrete, cured continuously in water from the time of casting exhibits a net increase in volume and weight. This swelling is due to absorption of water by the cement gel particles with a resultant swelling pressure. The swelling of concrete is considerably smaller than the shrinkage of concrete in a 50% relative humidity environment.

Figures 5-11 to 5-19 illustrate the measured total strains with age for 89, 152 and 254 mm diameter specimens in the 50 % RH environment. Figure 5-11 shows the total strains of 89 mm diameter specimens moist cured 3 days and loaded at various ages. Figure 5-12 gives total strains of 89 mm diameter specimens moist cured 24/25 days. The short and long specimen instantaneous strains are quite similar at 25 days but the total strains of specimens 2 and 59 are significantly different at 315 days. Figure 5-13 shows the total strains of 89 mm diameter specimens moist cured 200 days and then subjected to load. Figure 5-14 shows the total strains of 89 mm diameter specimens moist cured 3 days and then sealed and loaded at various ages. In general, there is no significant difference of total strains of long and short specimens in Figures 5-14 and 5-15. There are illogical curves for creep specimens as shown in Figures 5-16 and 5-17 because there are significant strain differences between the long and short specimens.

The total strains of the unloaded 152 mm and 254 mm diameter specimens are similar as shown in Figure 5-18 and 5-19. However, the total strains of loaded specimens are anomalous, because the strains of 254 mm diameter specimens are slightly greater than those of the 152 mm diameter specimens.

5.2 Factors Affecting Shrinkage

It is known that shrinkage of concrete is influenced by numerous factors, among which the most important are drying-out time, member size, relative humidity and temperature of the environment and period of curing. Therefore, studying these individually influencing factors is essential to understanding shrinkage phenomena. All specimens cured for 3 days with wetted burlap in the lab. However, most of shrinkage specimens were stripped by 4 days except immersed and 3 days creep specimens because of taking time for stripping all specimens. Hence, most of shrinkages of specimens zero at 4 days except immersed specimens.

The temperature in the structural laboratory ranged form 19 °C and 20 % RH in December 1997 to 25 °C and 65 % RH in July 1998. The temperature in the tent enclosure, which was located in the structural laboratory, ranged from 19 °C to 25 °C. Controlling the relative humidity was very difficult with the measured RH's ranging from 40 % to 60 %.

Sealed specimens, all 89 mm diameter, were sealed with a bitumen sheet sealer. The effectiveness of the sealing is uncertain and will be checked later by immersing some specimens in water and measuring any change in strain.

The specimens stored outside were subjected to Ottawa climate. The temperatures measured by the transducers in the specimens are shown in Figure 5-28 and 5-29. These specimens were stripped at 3 or 4 days and then stored outside.

5.2.1 Influence of Curing and Storage Conditions

To discuss the influence of curing and storage conditions on shrinkage, both duration since end of moist curing and relative humidity of the storage environment are considered. The general effect of environment of specimens upon shrinkage is shown in Figures 5-20 through 5-24. Observation of Figure 5-20 shows that the shrinkage of 89 mm diameter specimens in various environments at 315 days is a function of relative humidity, duration of moist curing and temperature. The specimens stored outside exhibited no shrinkage for the first 100 days, during which time the temperatures were below zero degrees. The immersed specimens swelled through the period of test, however all other environment specimens shrank. Figure 5-20 also illustrates the greater absolute magnitude of shrinkage compared with swelling in water. The shrinkage of specimens stored outside depends upon the outside temperature and its humidity as shown in Figure 5-28 and 5-29; the relative humidity was uncontrolled.

Figure 5-21 shows the shrinkage of sealed specimens sealed at different ages with different durations of moist curing. The shrinkage after 3 days curing is essentially constant for 100 days and then increased with time. This could be due to imperfect sealing of specimens. Specimens moist cured for 3 days, than allowed to dry and sealed at 25/200 days, the strain of concrete decreased with time as shown Figure 5-21(b) indicating some autogenuous shrinkage. The shrinkage of concrete moist cured for 25 days moist curing and then sealed increased steadily indicating imperfect sealing..

Figures 5-22 and 5-23 show the shrinkage of 152 mm and 254 mm diameter specimens in the lab, outside and 50 % RH. The shrinkage of both lab and 50 % RH specimens is similar because the temperatures were identical and relative humidities were also similar. However, the shrinkage of specimens stored outside depends upon temperature as shown in Figure 5-28 and 5-29.

Figure 5-24 presents the shrinkage measured on the 610 mm diameter specimens in the lab. It is interesting to observe that the shrinkage measured in the lateral direction is only 60 to 70 % of that measured in the longitudinal direction at 315 days. All longitudinal strains of concrete are similar. Both the lateral and longitudinal strains increased with time. There are no significant differences in shrinkage measured by the gages located on the centerline in the longitudinal direction and those 152 mm offset in the longitudinal direction as shown in Figure 5-24(b).

5.2.2 Size Effects

The rate of water loss is obviously controlled by the length of the path of traveled water, which is expelled during shrinkage. Figures 5-25 to 5-27 show size effect for each environment on shrinkage. Figure 5-25 shows shrinkage of 89, 152, 254 and 610 mm diameter specimens in the lab. The rate of shrinkage of the smaller diameter specimen at early ages is greater than the rate of shrinkage of larger diameter specimen. It is hard to distinguish the effect of size on the specimens stored outside as shown Figure 5-26. The concrete seems to respond more to temperature changes than specimen size. Figure 5-27 shows shrinkage of 89, 152 and 254 mm diameter specimens in 50 % RH. At a constant RH, the size of specimens determines the rate of drying shrinkage. The shrinkage strains of smaller size specimens is greater than that of larger size specimens over the test duration. It is believed that the increase in the dimensions of specimens will delay the process of drying shrinkage, however, it doesn't seem to reduce the ultimate shrinkage because the strains of most of specimens are similar at 315 days.

5.2.3 Outdoor Average Temperature during the Test

Figures 5-28 and 5-29 show average outside temperature during the test period with time plotted on both log and normal scale. It is obvious that the concrete specimens were responding to temperature changes in weather as shown in Figures 5-20, 5-22, 5-23, and 5-26. After 3 days moist and warm curing, all specimens were moved outside the building on December 8, 1997. The outside temperature was below zero degrees until March 18, 1998.

5.2.4 Shrinkage Summary

It is interesting to observe that the shrinkage measured in the lateral direction of the 610 mm diameter specimen, Figure 5-24, and is only 60 to 70 % of that measured in the longitudinal direction at 315 days.

Table 5-1 summarizes the 315 days shrinkages with specimen size and storage environment. All values were taken average of long and short specimens.

5.3 Factors Influencing Creep

Creep cannot be measured directly. Creep is determined by subtracting shrinkage and the initial strain at loading (or normal elastic strain) from the total strain. However, for sealed, non-drying, concrete members, it may be argued that creep can be measured without the need to correct for shrinkage; however, others suggest that autogenous shrinkage should be subtracted from the creep strains.

The creep coefficient is the ratio of creep to elastic strain. Care should be taken when using creep coefficients, as calculated strains are strongly dependent on the modulus of elasticity used to determine this value. The creep coefficient is dimensionless.

The compliance function is defined as strain per unit stress and typically presented in units of strain/MPa. For the creep tests the stresses applied stress were approximately 25% of the cylinder strength at the age of loading. The stresses applied are given in Tables 5-1 to 5-4. Applied stress for 3 or 4 days creep specimens was 6 MPa, for 13 or 24 or 25 days creep specimens was 8 MPa, and for 200 or 201 days creep specimens was 9.64 MPa. The compliance function includes initial or elastic strains. Specific creep is equal to the total deformation per unit stress, minus the elastic strain per unit stress. It should be noted that the compliance function and specific creep have the same units, however, the compliance function includes strains due to elastic shortening, while specific creep does not. In general, the compliance of all graphs was calculated by subtracting shrinkage of the same diameter and length specimens from the measured total deformation.

5.3.1 Influence of Curing and Storage Conditions

Basically the factors influencing shrinkage will influence creep in the same way. Figure 5-27(a) shows the creep compliance versus age curves for the 89 mm diameter specimens in various environments. The creep strains measured on specimens stored outdoors are significantly different from those in other environments. Figures 5-30 to 5-34 illustrate compliance of various size specimens, at loaded at different ages and stored in different environments. Figure 5-30 shows compliance of 89 mm diameter specimens loaded at 3 or 4 days in various environments. The compliance of specimen stored outside is significantly greater than compliance of other environmental specimens. The compliance of immersed specimens is constant with the time. Outside drying cycles can increase microcracking in the transition zone and thus increase creep as shown in Figure 5-30 and 5-33. Figure 5-31 shows compliance of 89 mm diameter specimens at loaded at 24 or 25 days in various environments. In this graph, the compliance of lab stored specimens is greater than compliance of specimens stored in other environments. Compliance of specimens of sealed 3 days after curing is greater than compliance of specimens of sealed 25 days after curing. Figure 5-32 shows compliance of 89 mm diameter specimens loaded at 200 or 201 days in various specimens. The compliance of immersed specimens is less than the compliance of specimens in the other environments. Figure 5-33 shows the effect of environment on the measured compliance of 152 mm diameter specimens loaded at 24 days. Figure 5-34 shows measured compliance of 254 mm diameter specimens loaded at 24 or 201days in various environments. Figure 5-35 shows compliance of 610 mm diameter specimens at 25 days of loading in the lab. Under uniaxial compression, creep occurs not only in the longitudinal direction but also in the lateral direction. This is referred to as lateral creep or Creep Poisson's Ratio.

5.3.2 Size Effects

Figures 5-36 to 5-38 illustrate size effect on compliance with environment. The compliance of small specimens is greater than the compliance of large specimens except

610 mm diameter specimens in the lab as shown in Figure 5-36. Therefore, large size specimens slow down the process of diffusion of the absorbed water, thus, decrease creep. The compliance of longitudinal direction of 610 mm diameter specimens is greater than the compliance of 254 mm diameter specimens.

The compliance of outside specimens loaded at 4 days is generally greater that of specimens loaded at 24 days and 201 days as shown in Figure 5-37(a). Figure 5-37(b) shows the same information plotted against time since loading.. The compliances of 24 and 201 days loaded concrete are similar.

Figure 5-38 gives the compliances of 89, 152 and 254 mm diameter specimens in 50 % RH at 25 days loading. The compliance of 89 mm diameter specimens is slightly greater than compliance of 152 and 254 mm diameter specimens.

5.3.3 Compliance Summary

The measured compliance results are very inconsistent. The elastic compliance is simply the reciprocal of the elastic modulus i.e. should be approximately 50 microstrain. Regardless of specimen size the elastic compliances should be similar. As mentioned in section 4.2 major difficulties were experienced in measuring modulus of elasticity. Any elastic compliances significantly greater than 50 microstrain must be regarded with suspicion. Unfortunately this includes many of the compliance results. Part of the problem was because the CTL 89mm diameter creep frames use a single spring, Figure 3-

3 and were used without a ball to allow the load to be concentric with the specimens. In general the compliances measured on the larger specimens appear more consistent than the results obtained from the 89mm diameter specimens.

From Figure 5-35 it can be noted that the elastic Poisson's Ratio is 0.2 and the creep Poisson's Ratio somewhat larger at 0.3.

Regardless of specimen size the early duration compliance curves are parallel as shown in Figures 5-34(b) and 5-37(b).

For statistical reliability multiple replicates should be used for both shrinkage and creep specimens. Practical necessity will probably limit the number of replicates to 5 which would allow a small sample standard deviation to be calculated.

Specimen Size (mm)	Storage Environment	Moist Cured Days	Shrinkage (10^{-6})
89	Laboratory	3	683
89		24	652
152		3	644
254		3	718
610		3	449
89	Immersed in water	3	-118
89	50 % RH	3	716
89		24/25	593
89		200	526
152		3	708
254		3	711
89	Outside	3	108
89		24	-82
152		3	168
254		3	237

Table 5-1: Summaries the measured shrinkage strains at 315 days with specimen size and environment

Figure 5-1: 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

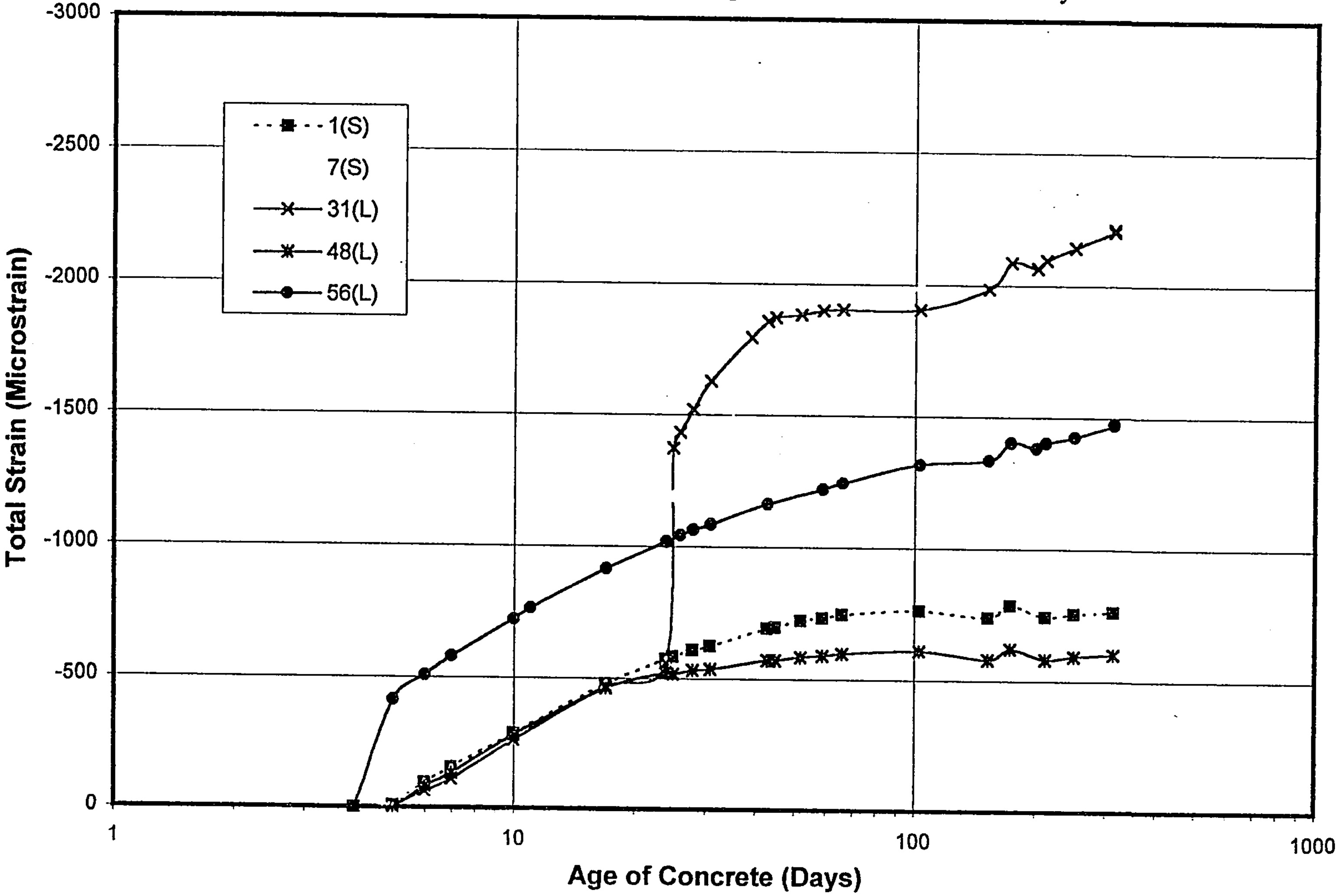


Figure 5-2: Total Strain of 89 mm Specimens in Lab Environment, Moist cured 24 days
Specimen 26 loaded at 25 days, Specimen 21 & 37 loaded at 28 days

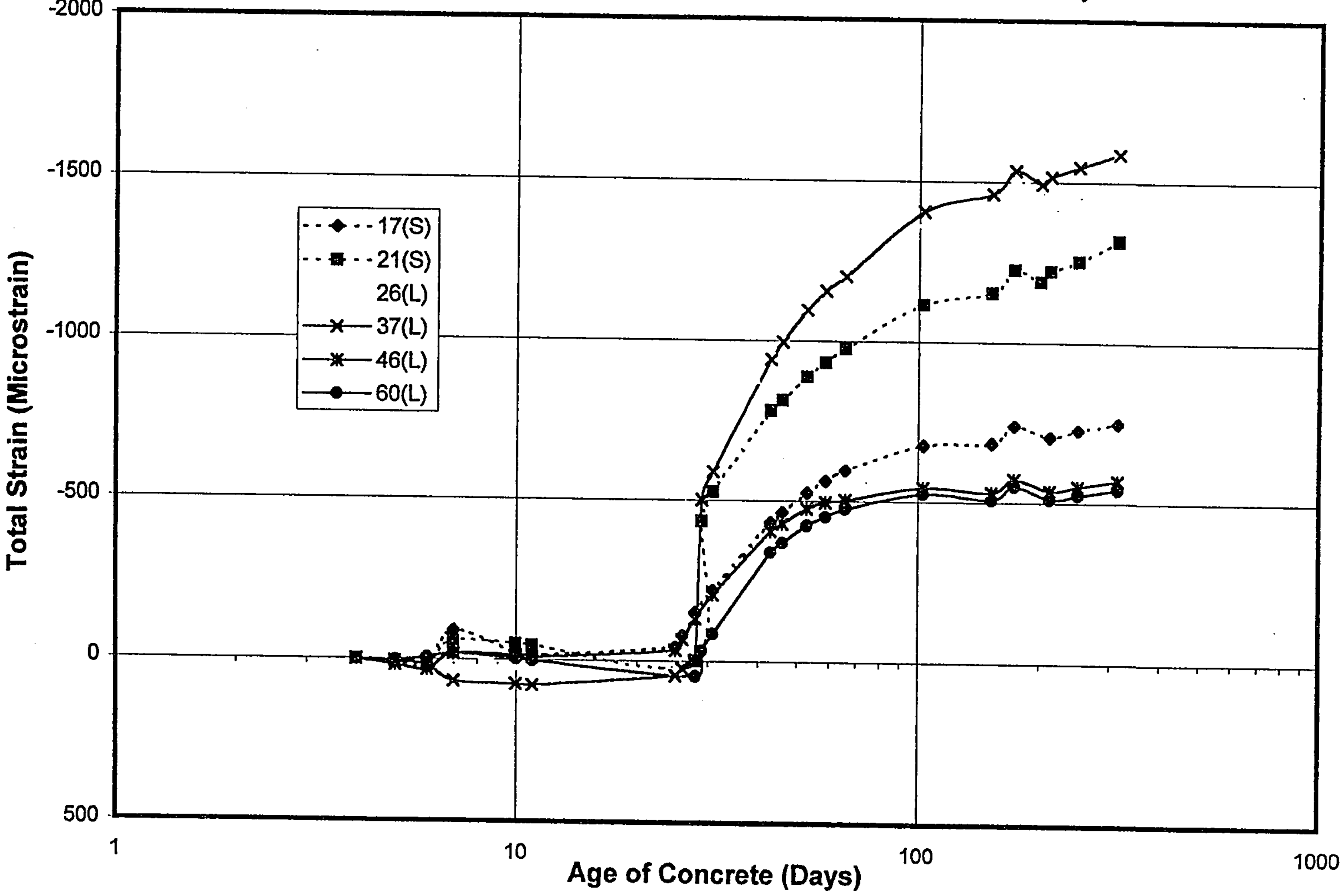


Figure 5-3: Total Strain of 152 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 66 & 76 loaded at 24 days

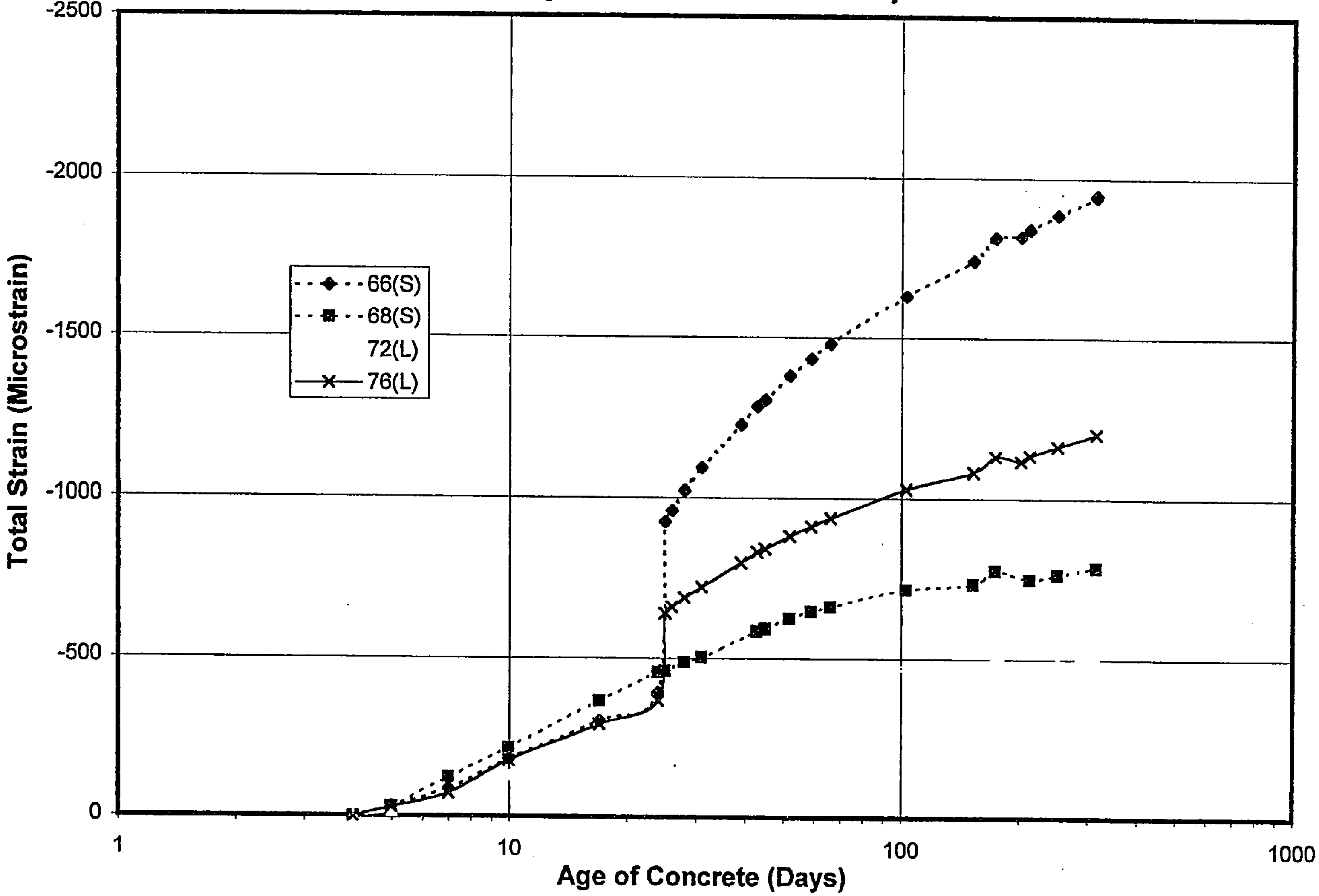


Figure 5-4: Total Strain of 254 mm Specimens in Lab Environment, Moist cured 3 days
Specimen 80 & 88 loaded at 24 days

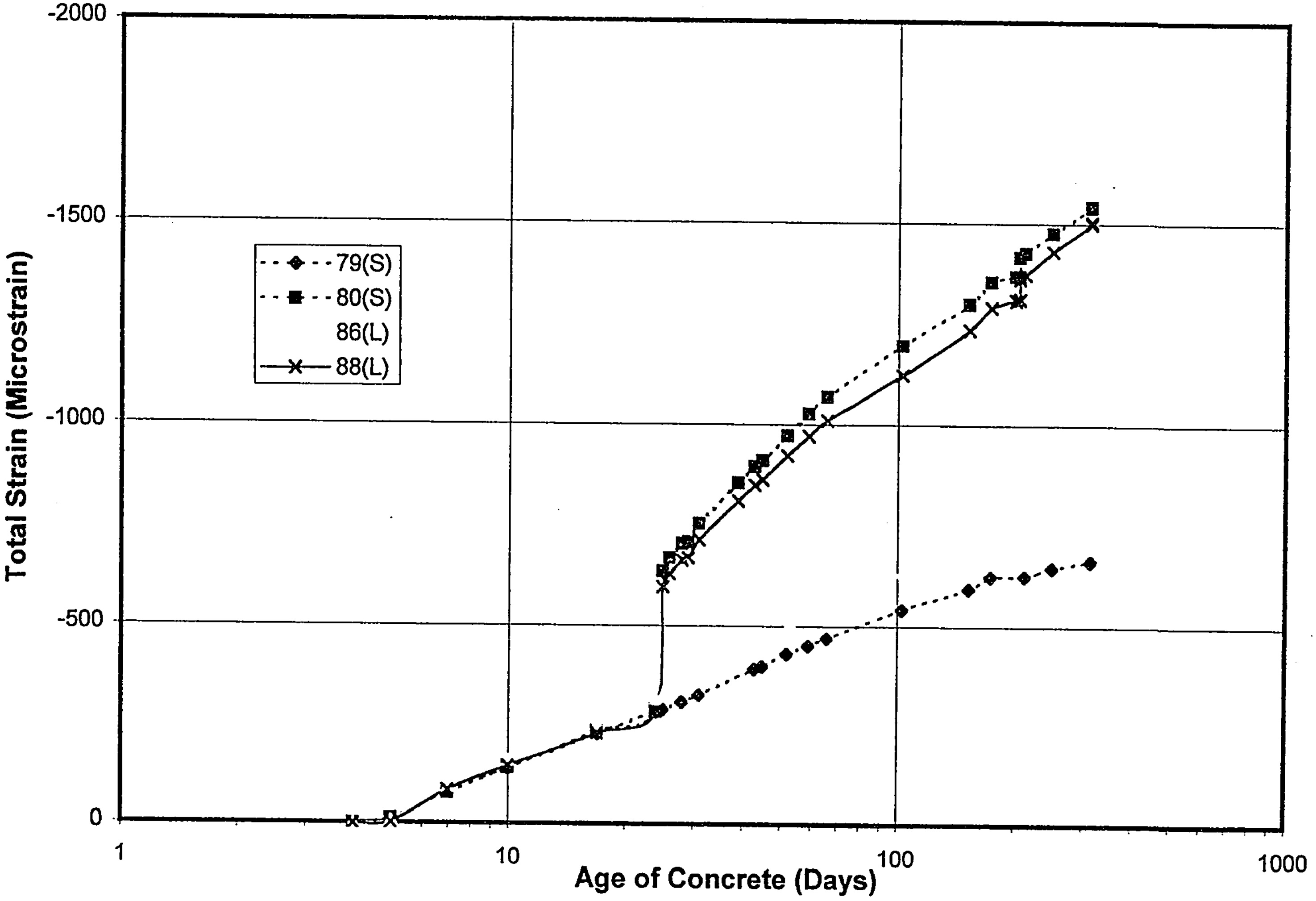


Figure 5-5: Total Strain of 610 mm Specimens in Lab Environment, Moist cured 3 days
Specimens 101~106 loaded at 25 days

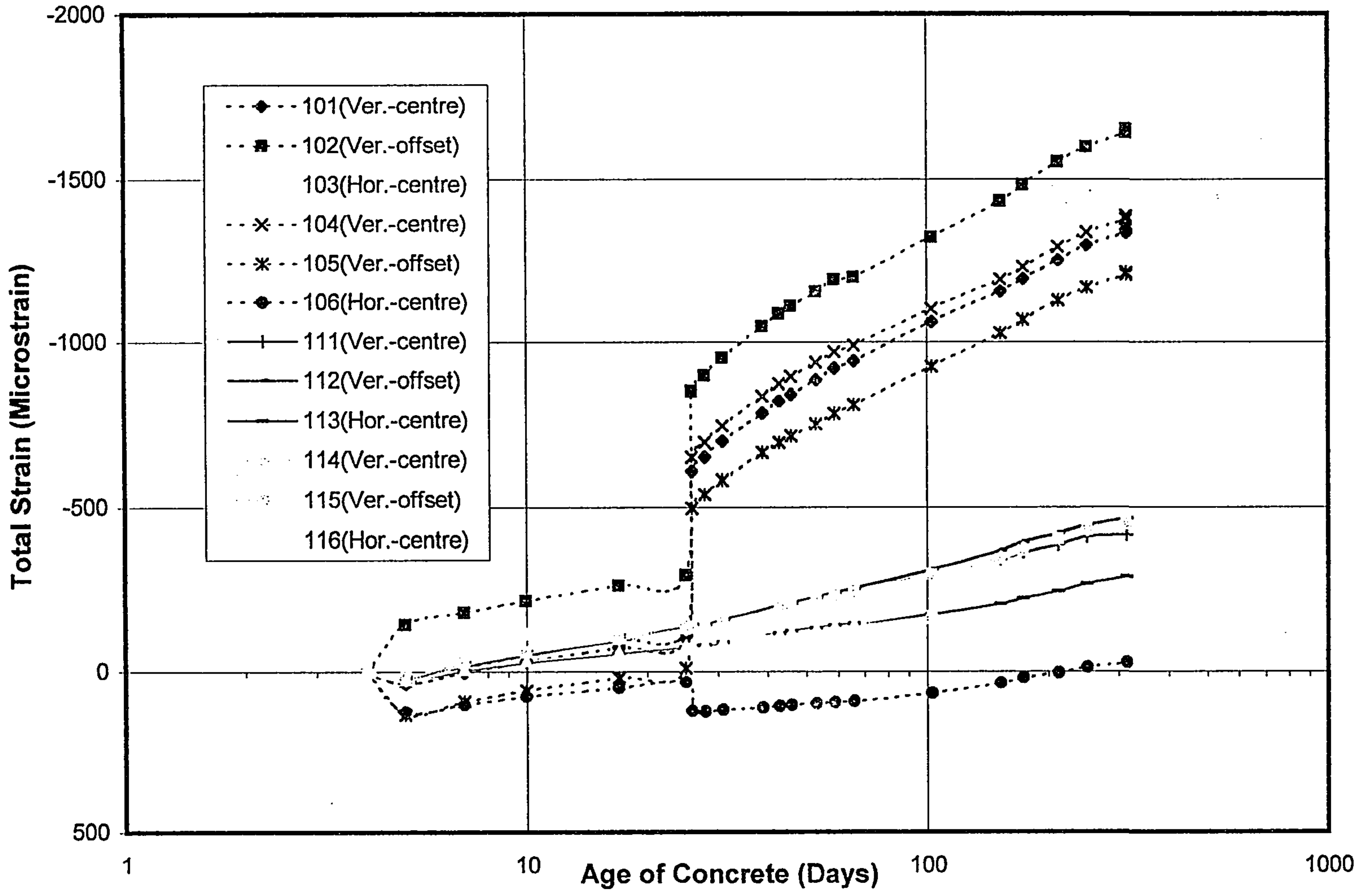


Figure 5-6: Total Strain of 89 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 53 loaded at 4 days, Specimen 19 & 58 loaded at 24 days, Specimen 14 & 32 loaded at 201 days

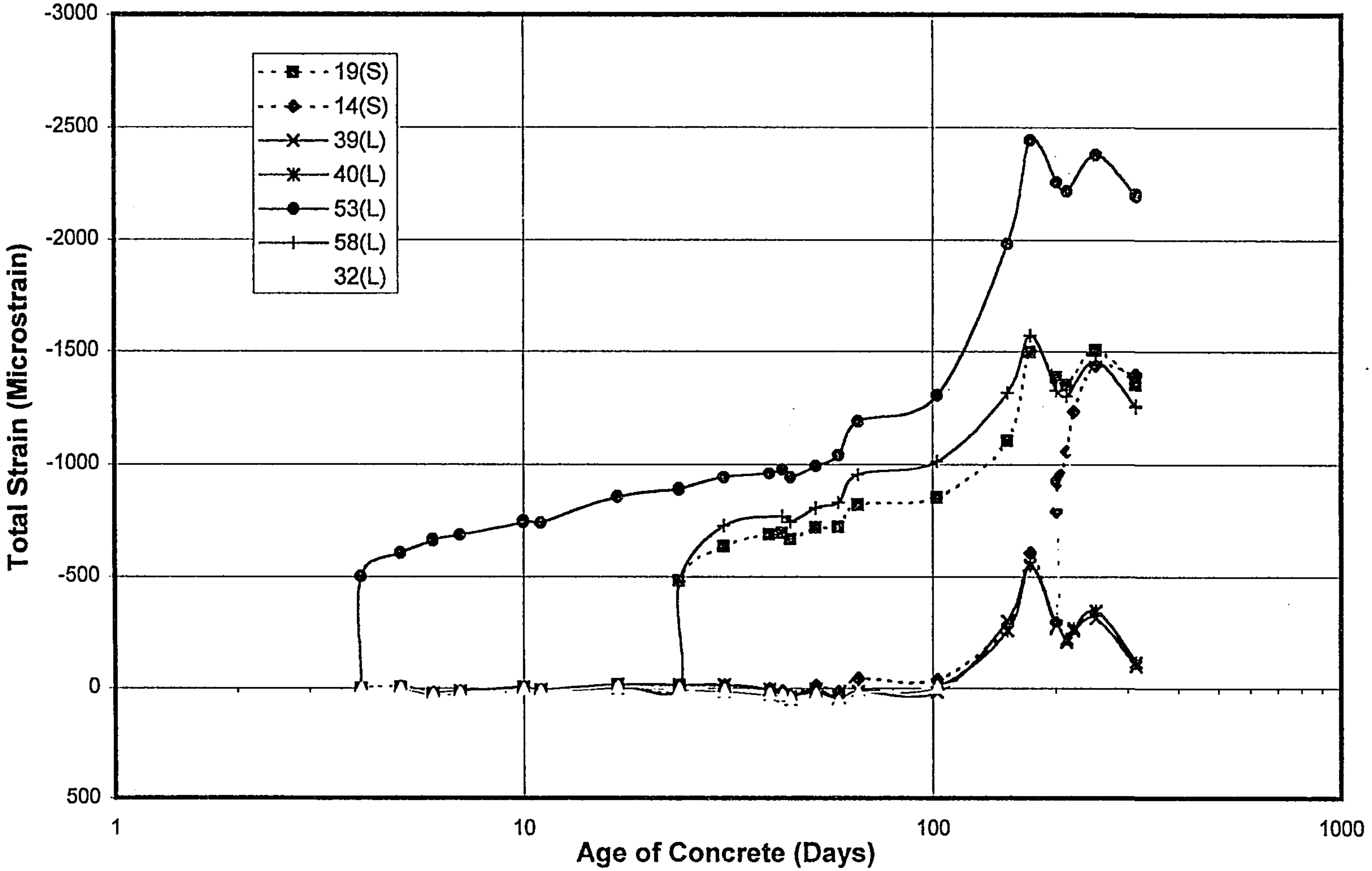


Figure 5-7: Total Strain of 89 mm Specimens Outdoor Environment, Moist cured 24 days
Specimen 61 loaded at 24 days

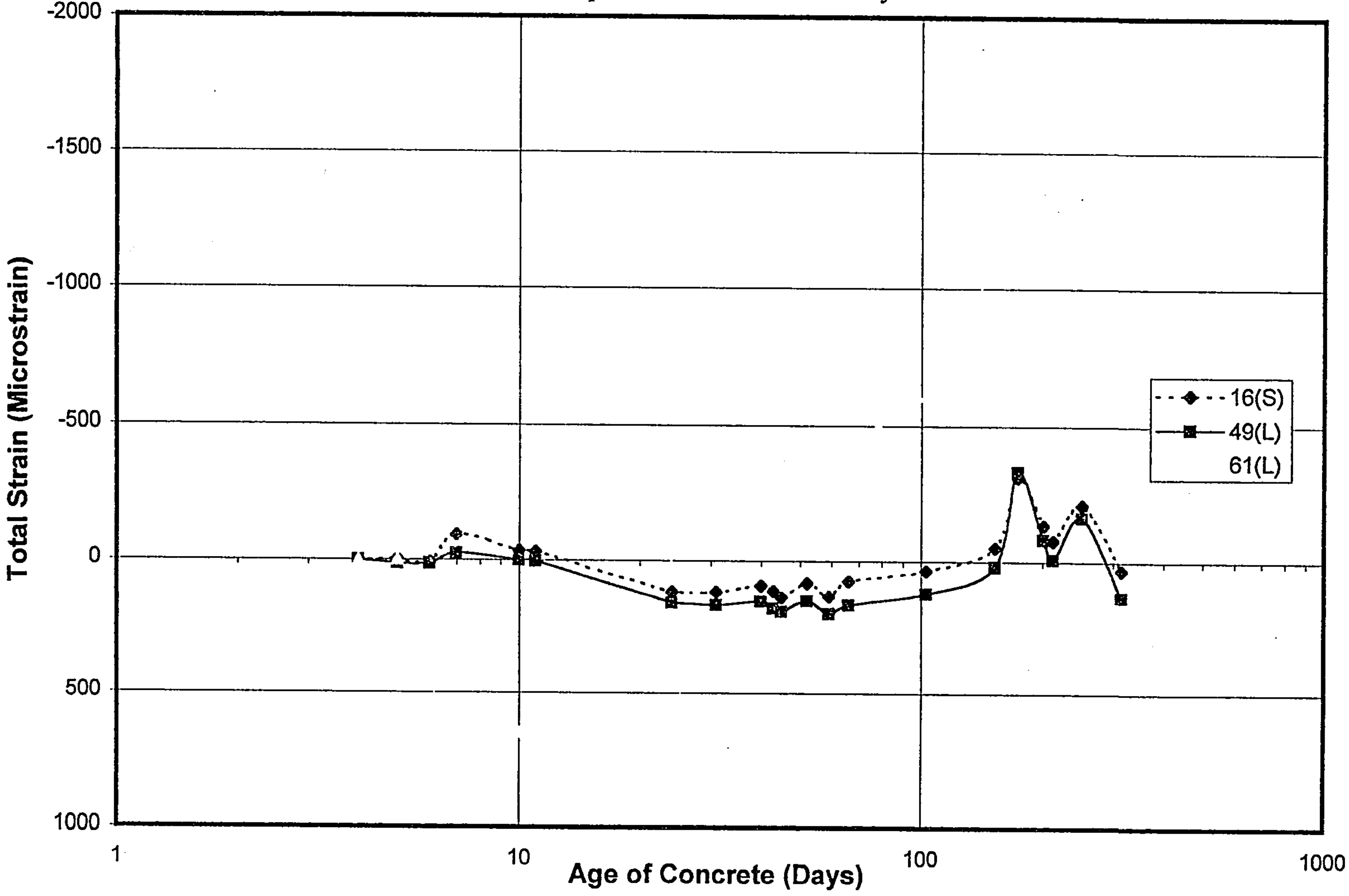


Figure 5-8: Total Strain of 152 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 67 & 75 loaded at 24 days

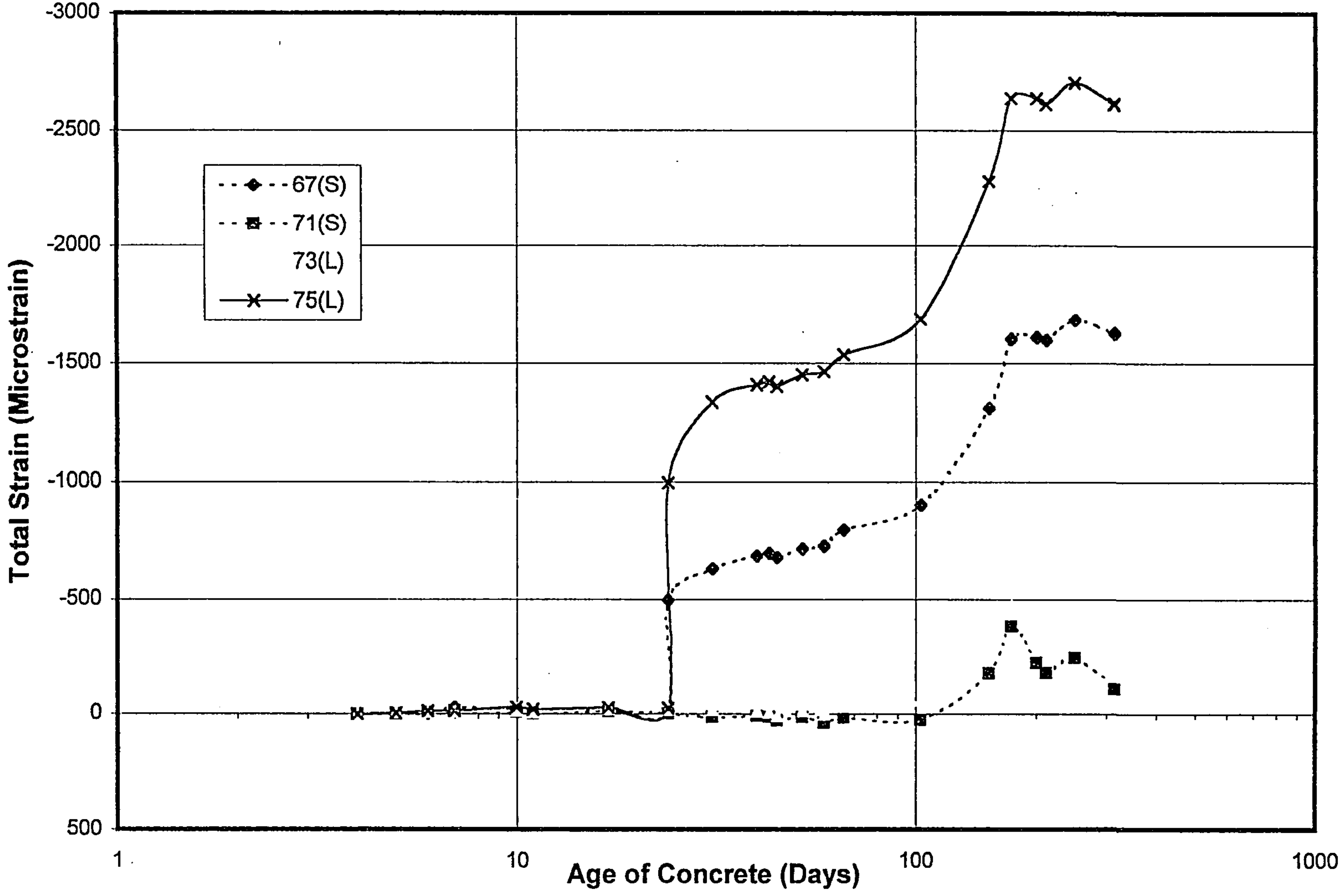


Figure 5-9: Total Strain of 254 mm Specimens Outdoor Environment, Moist cured 3 days
Specimen 78 & 87 loaded at 201 days

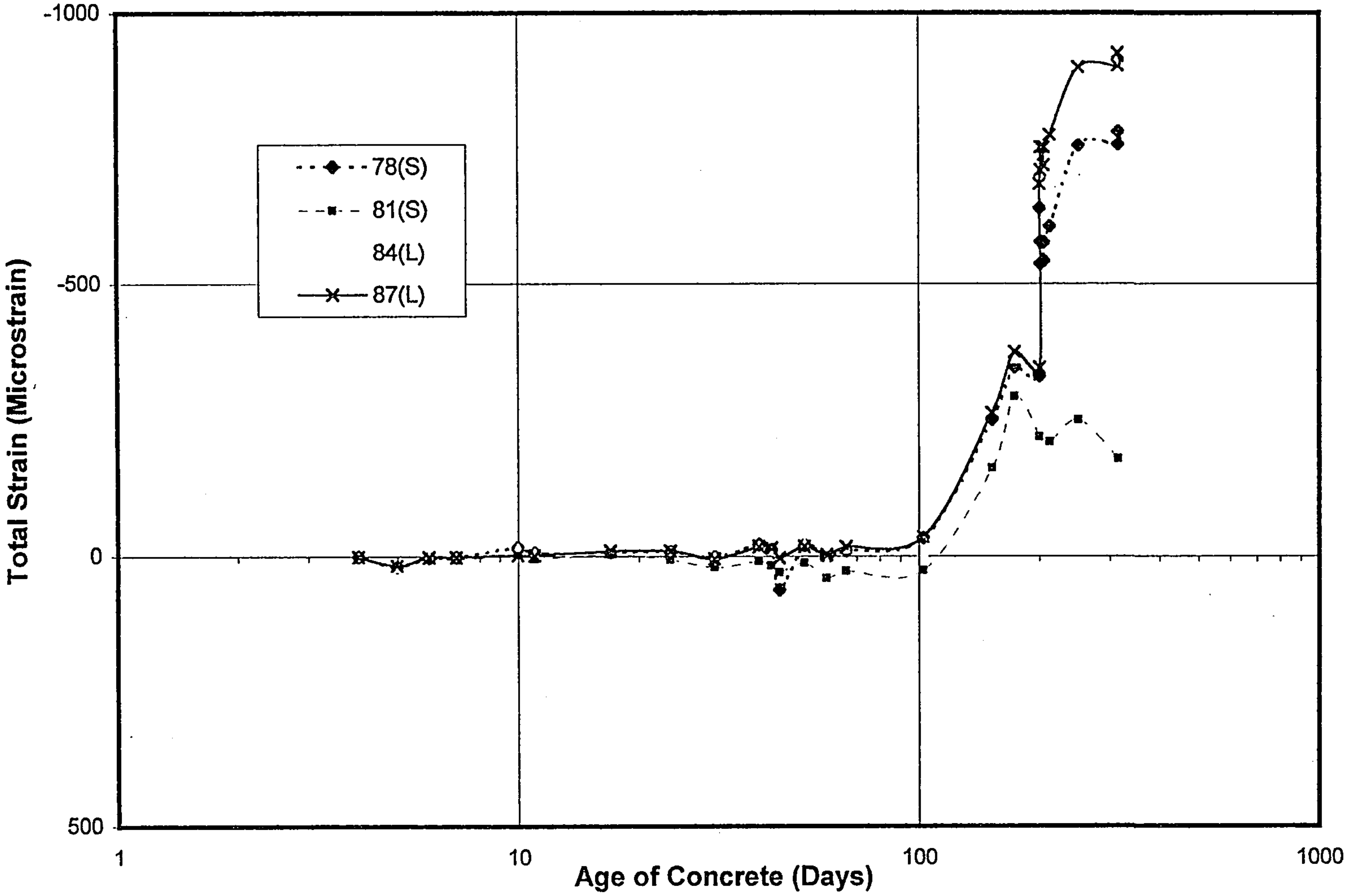


Figure 5-10: Total Strain of 89 mm Immersed Specimens, Moist cured 3 days, Specimen 12 & 29 loaded at 3 days, Specimen 20 & 23 loaded at 13 days, Specimen 64 & 24 loaded at 200 days

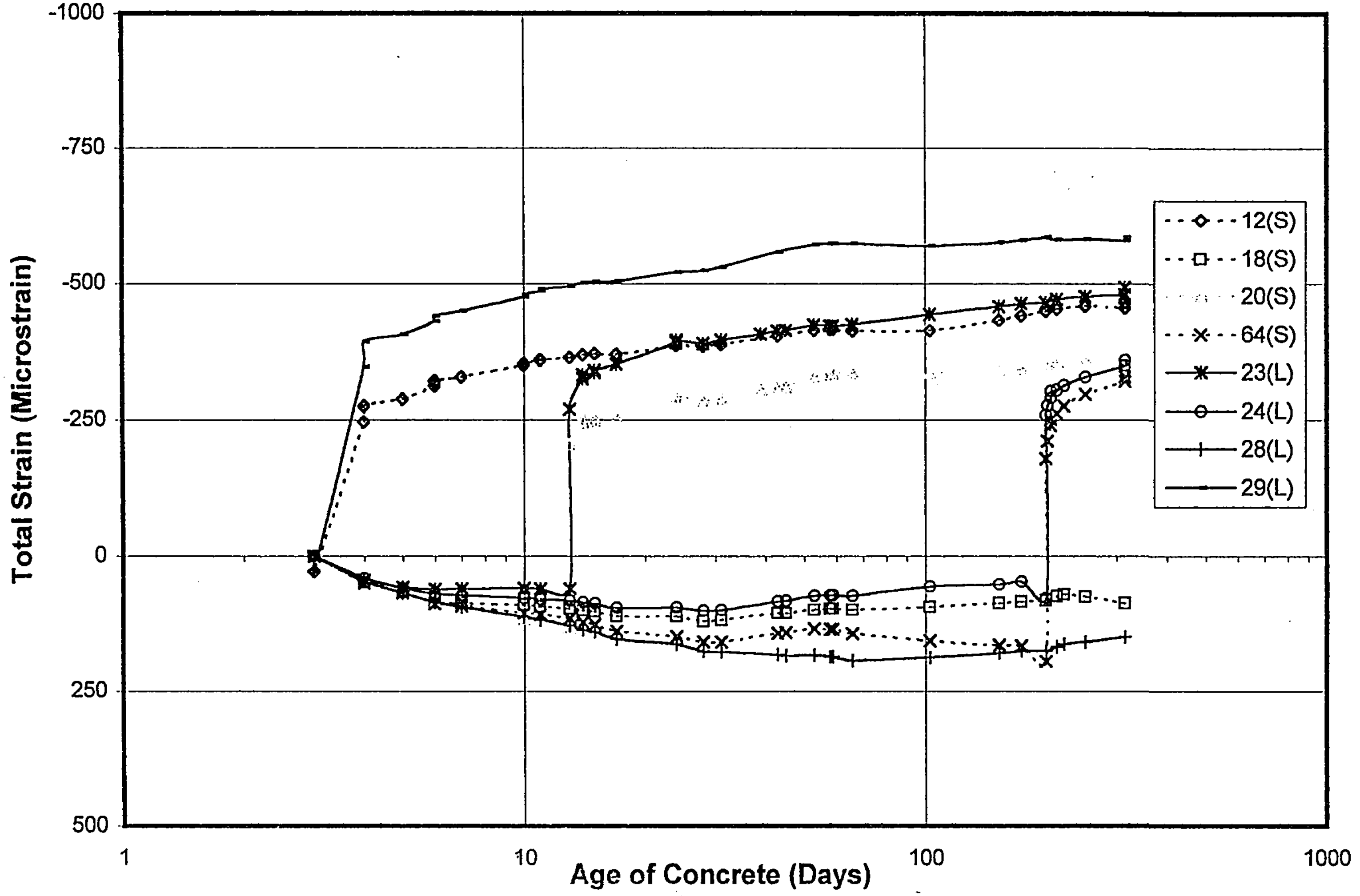


Figure 5-11: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 41 loaded at 4 days, Specimen 65 & 44 loaded at 24 days, Specimen 11 & 38 loaded at 200 days

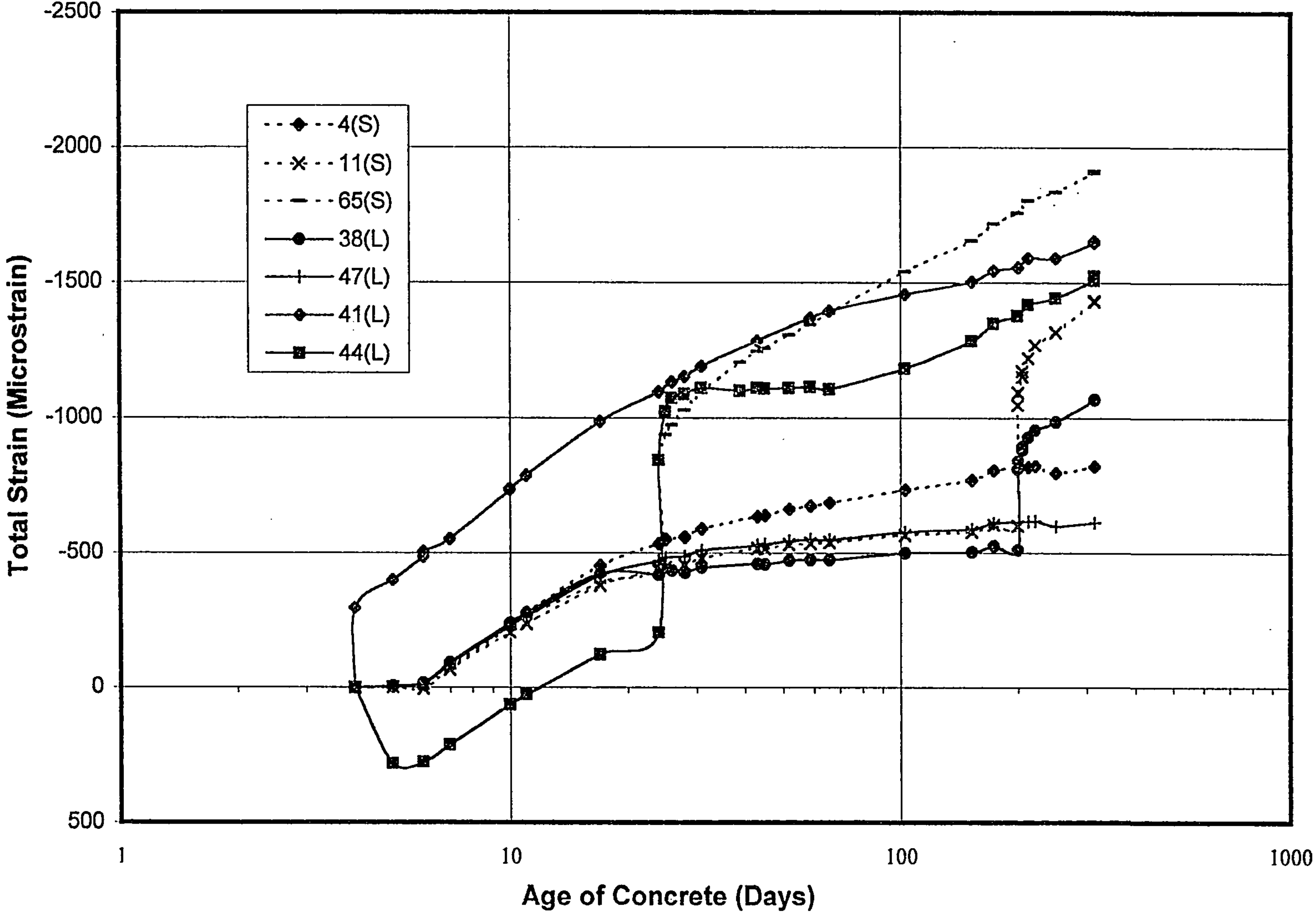


Figure 5-12: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 24/25 days Specimen 2 & 59 loaded at 25 days, Specimen 13 loaded at 200 days

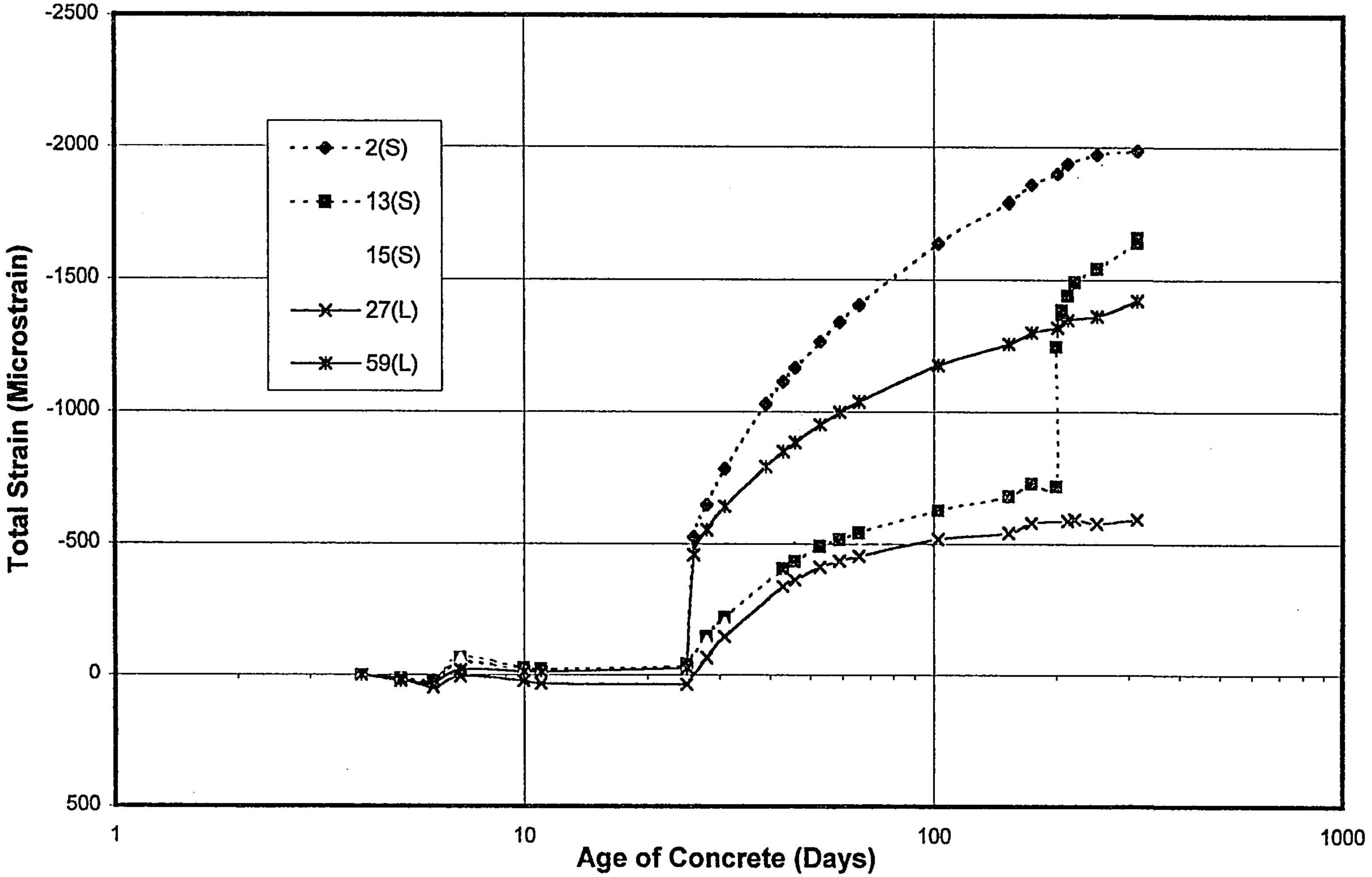


Figure 5-13: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 200 days
Specimen 42 loaded at 200 days

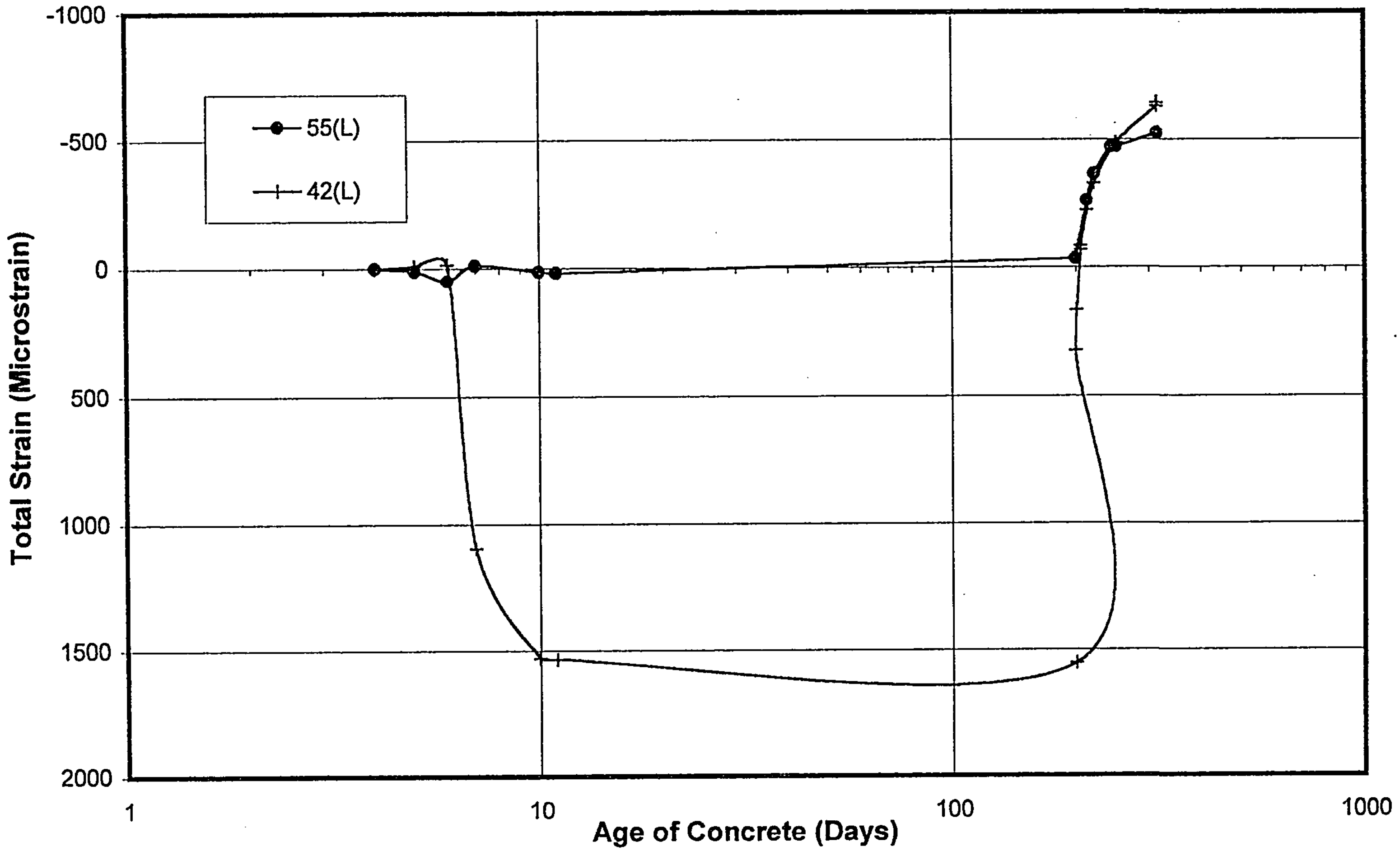


Figure 5-14: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 3 days, Specimen 63 & 33 loaded at 28 days, Specimen 8 & 54 loaded at 200 days

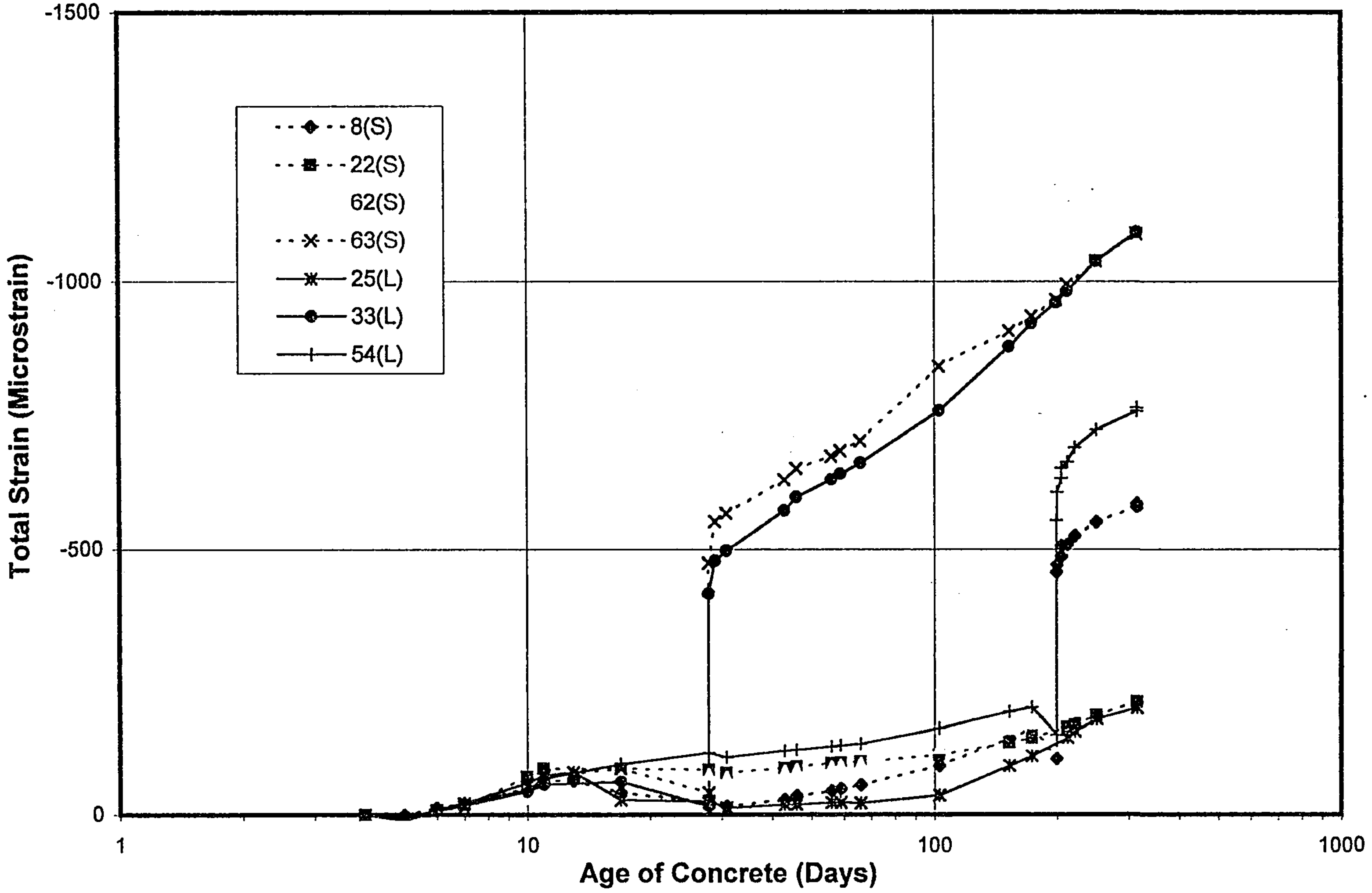


Figure 5-15: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 25 days and Sealed after 25 days, Specimen 50 loaded at 25 days

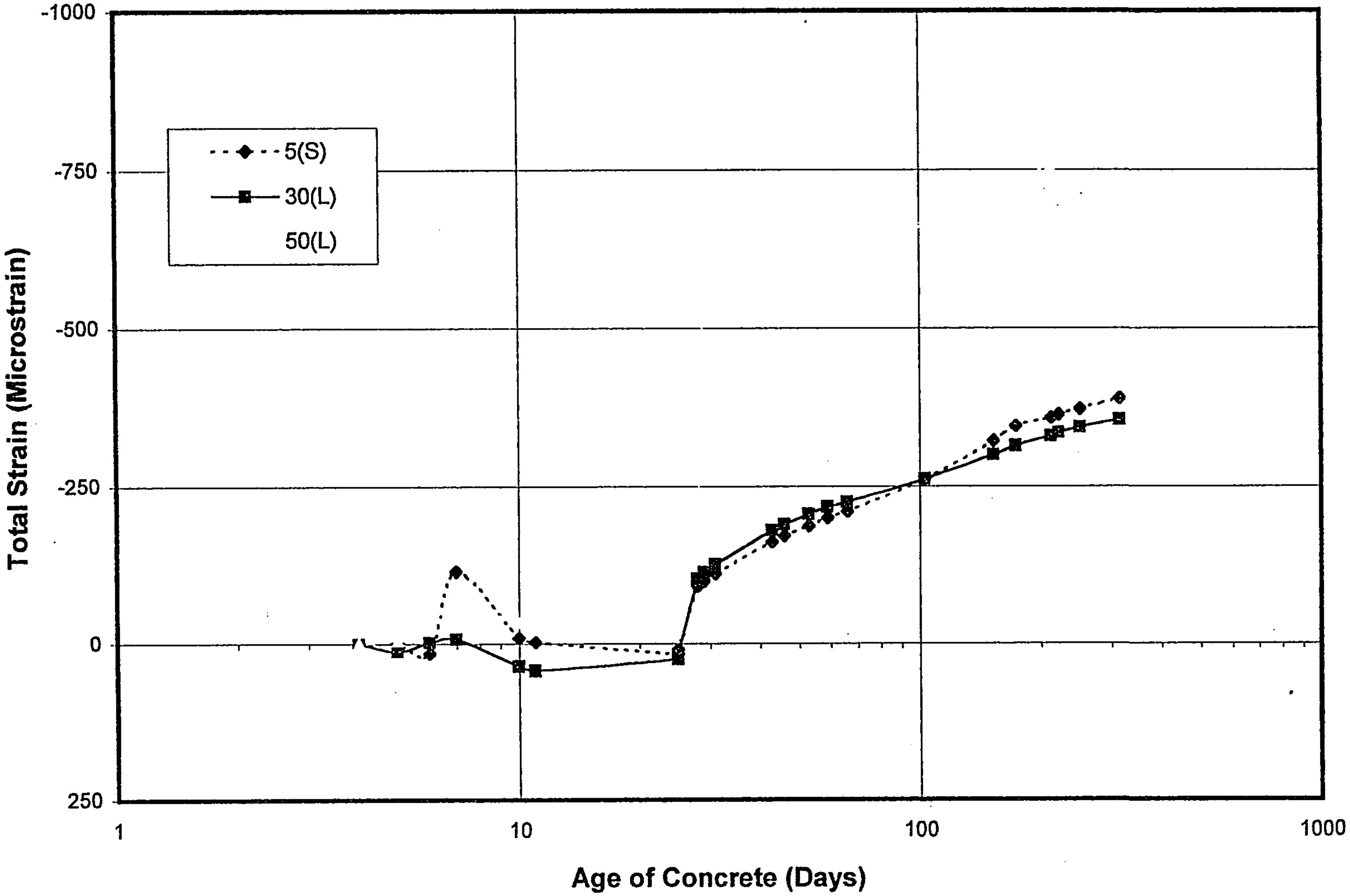


Figure 5-16: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 25 days, Specimen 3 & 35 loaded at 25 days

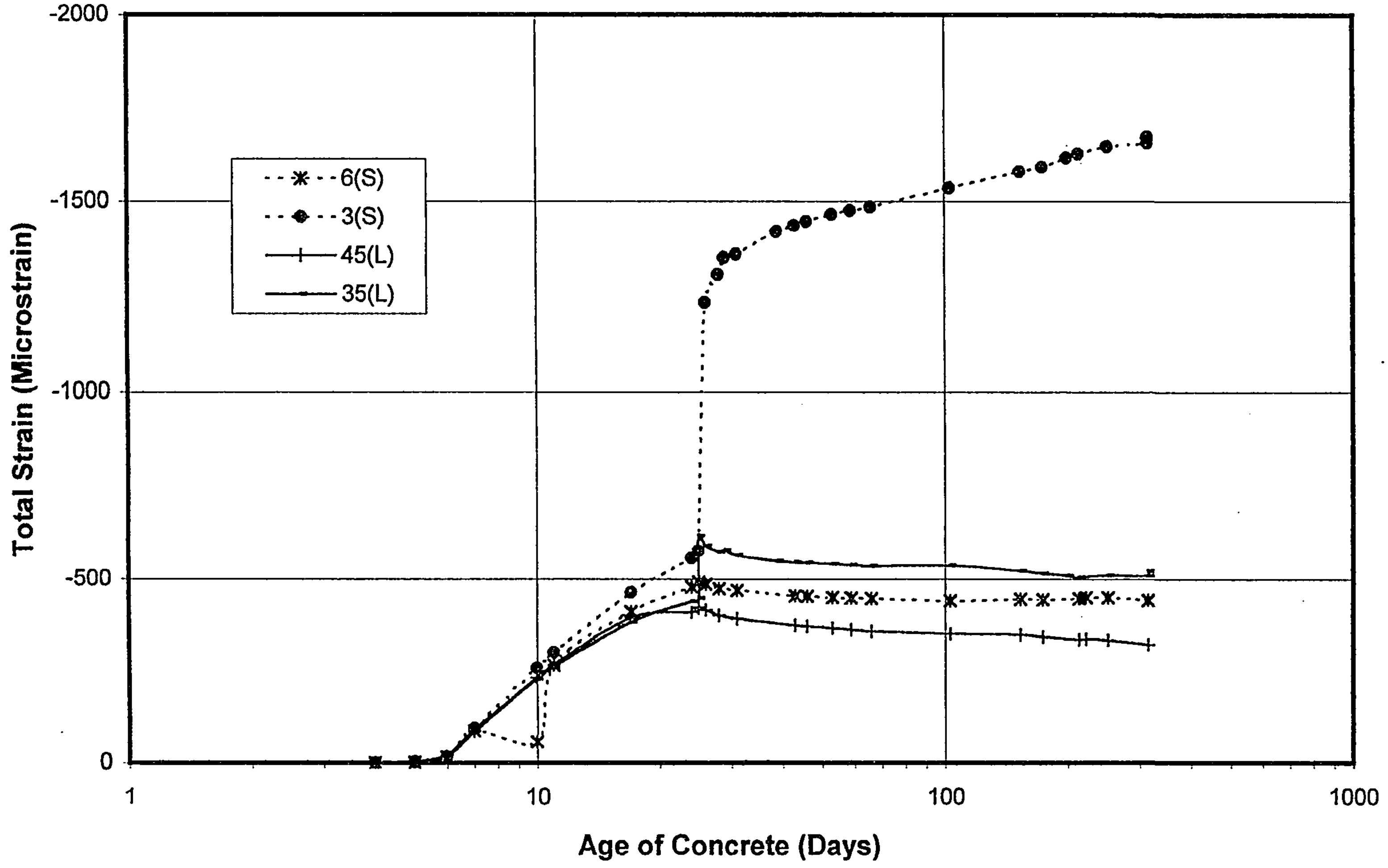


Figure 5-17: Total Strain of 89 mm Specimens in 50% R.H. Environment, Moist cured 3 days and Sealed after 200 days, Specimen 9 & 36 loaded at 200 days

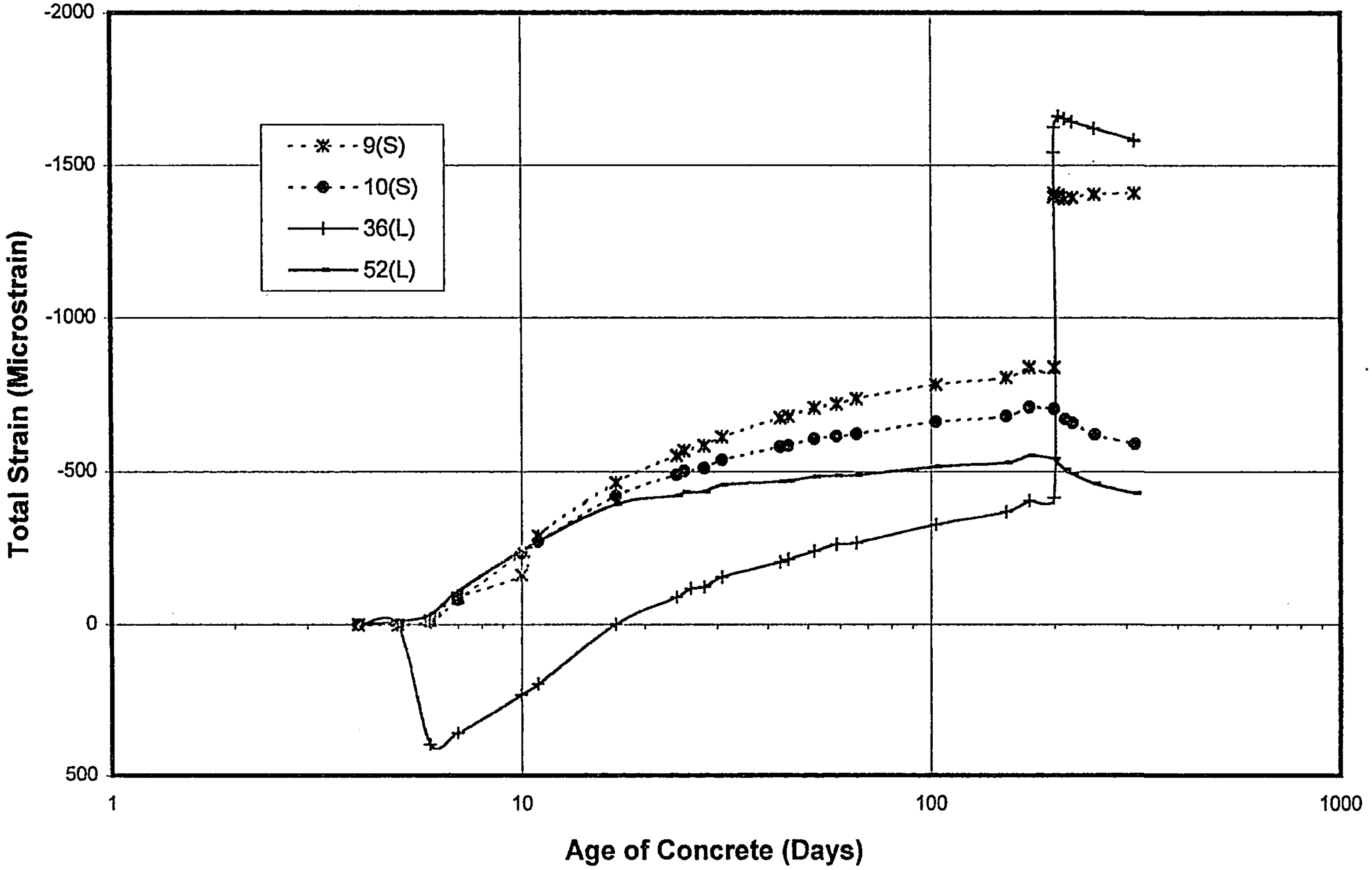


Figure 5-18: Total Strain of 152 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 69 & 77 loaded at 24 days

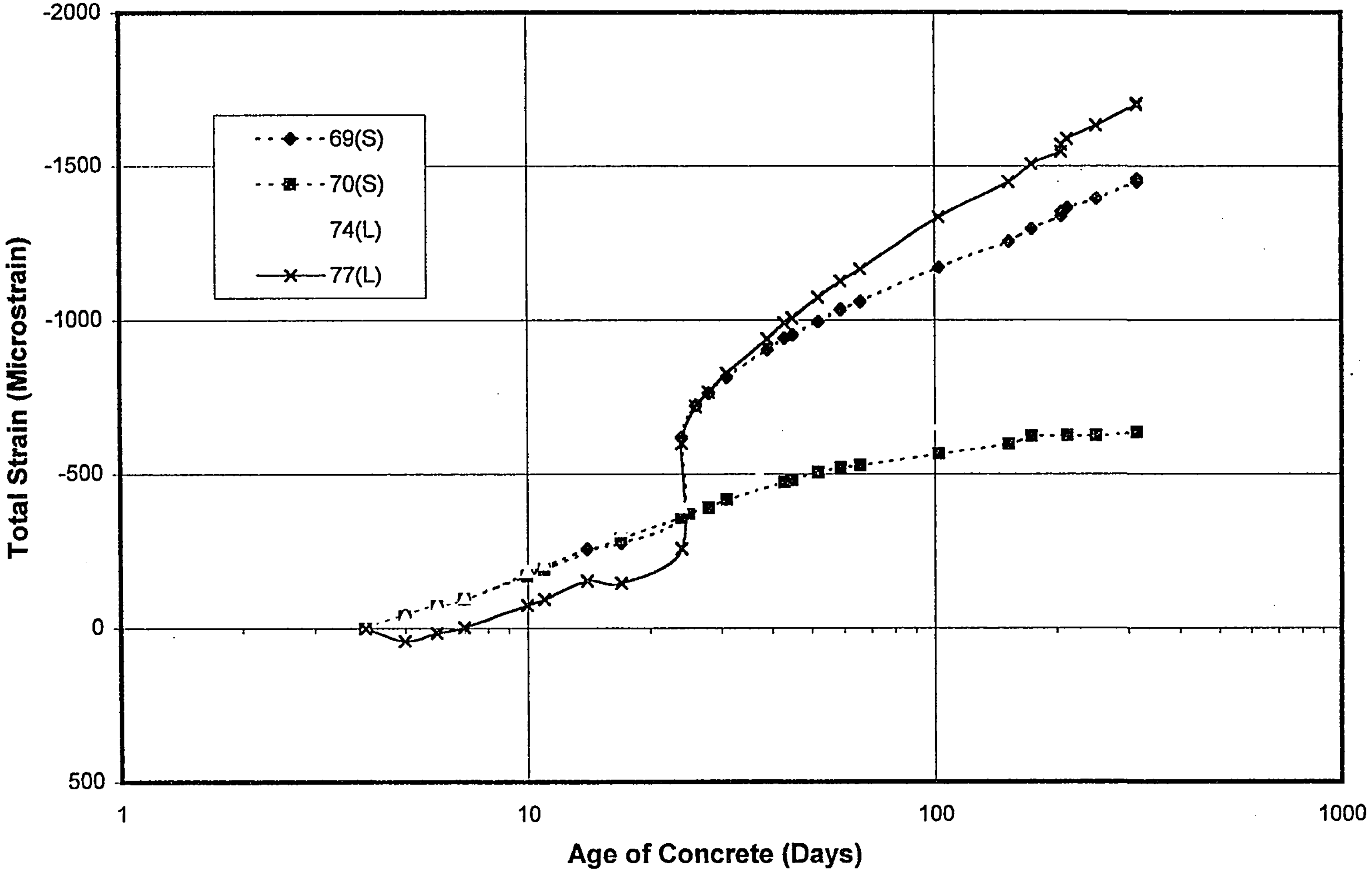
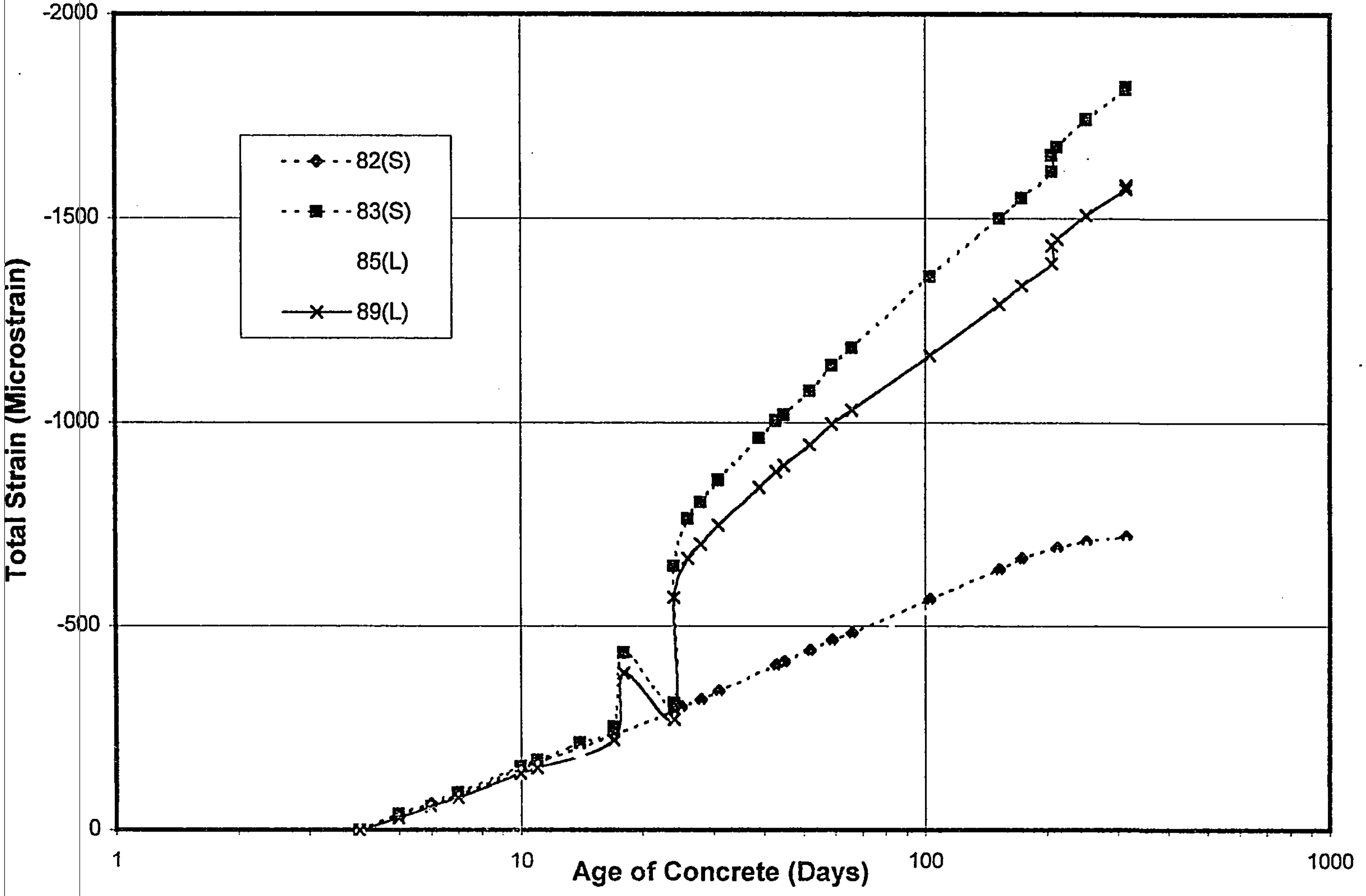


Figure 5-19: Total Strain of 254 mm Specimens in 50% R.H. Environment, Moist cured 3 days
Specimen 83 & 89 loaded at 24 days



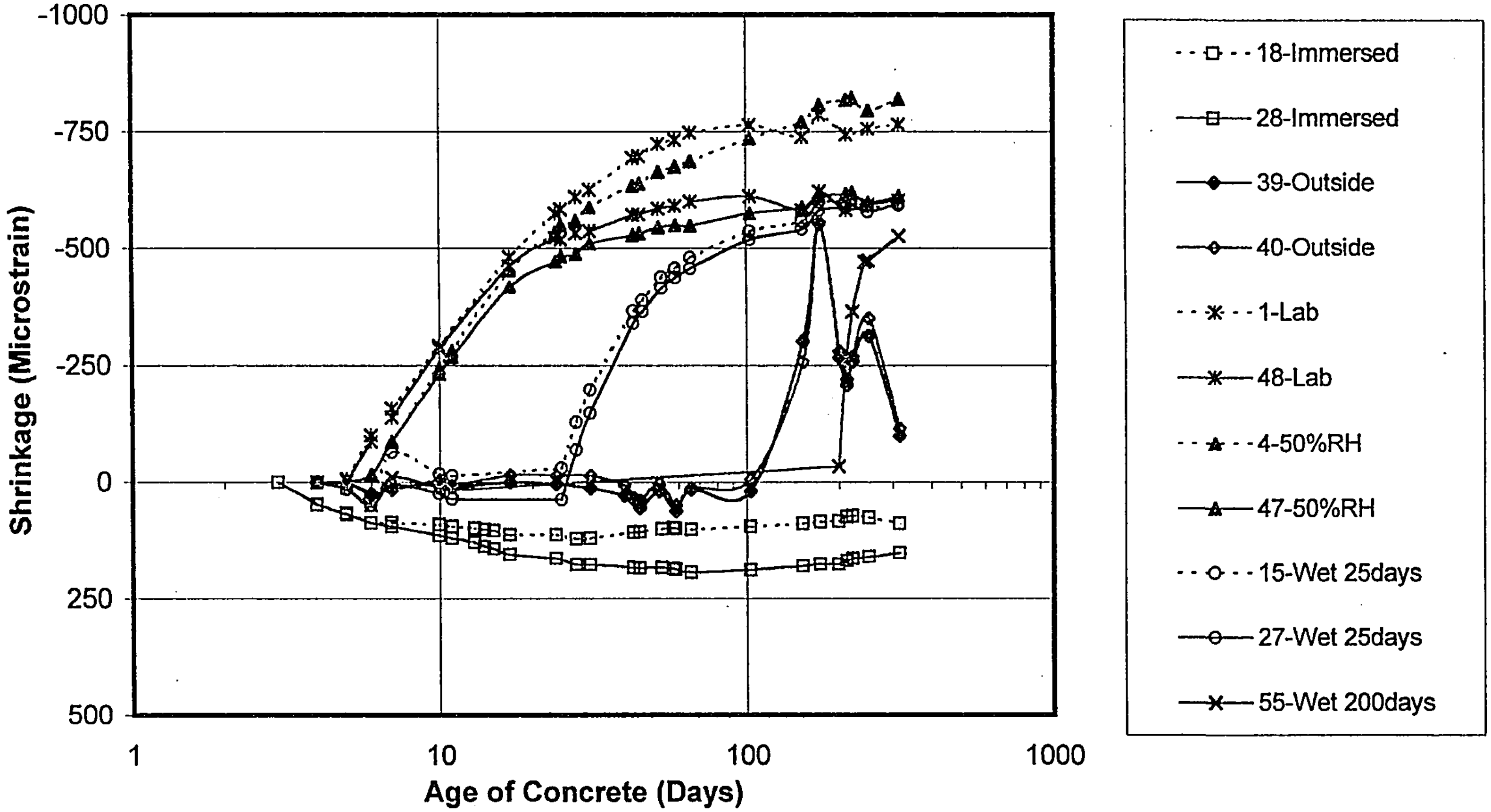


Figure 5-20: Environment Effect - Shrinkage of 89 mm Specimens in Various Environments
Specimen 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days

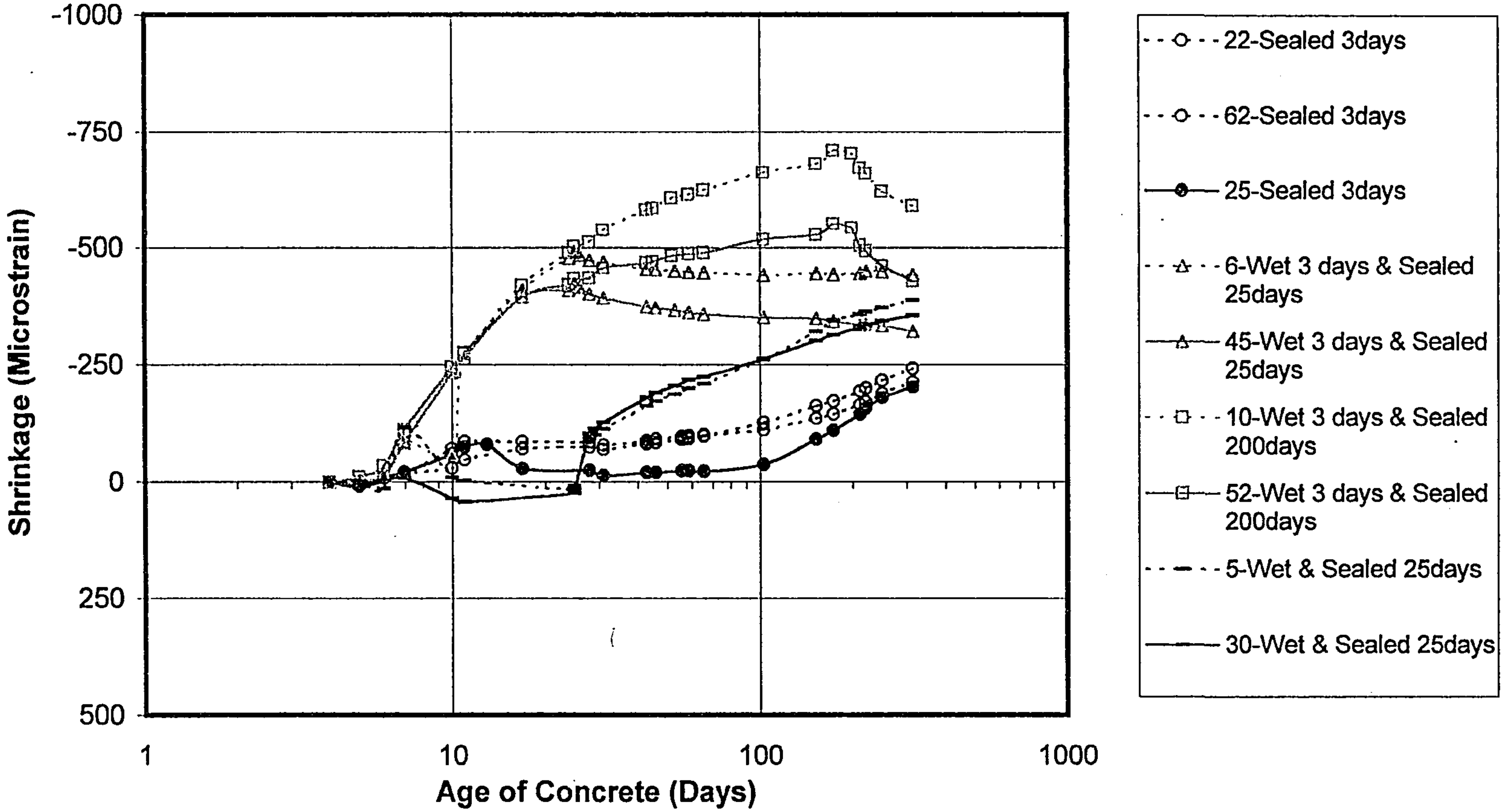


Figure 5-21(a): Environment Effect - All 89 mm Specimens stored in 50 % RH, Specimen 22, 62, 25 sealed after demoulding at 3 days, Specimen 6 & 45 sealed at 25 days, Specimen 10 & 52 sealed at 200 days, Specimen 5 & 30 Moist cured 25 days and sealed 25 days

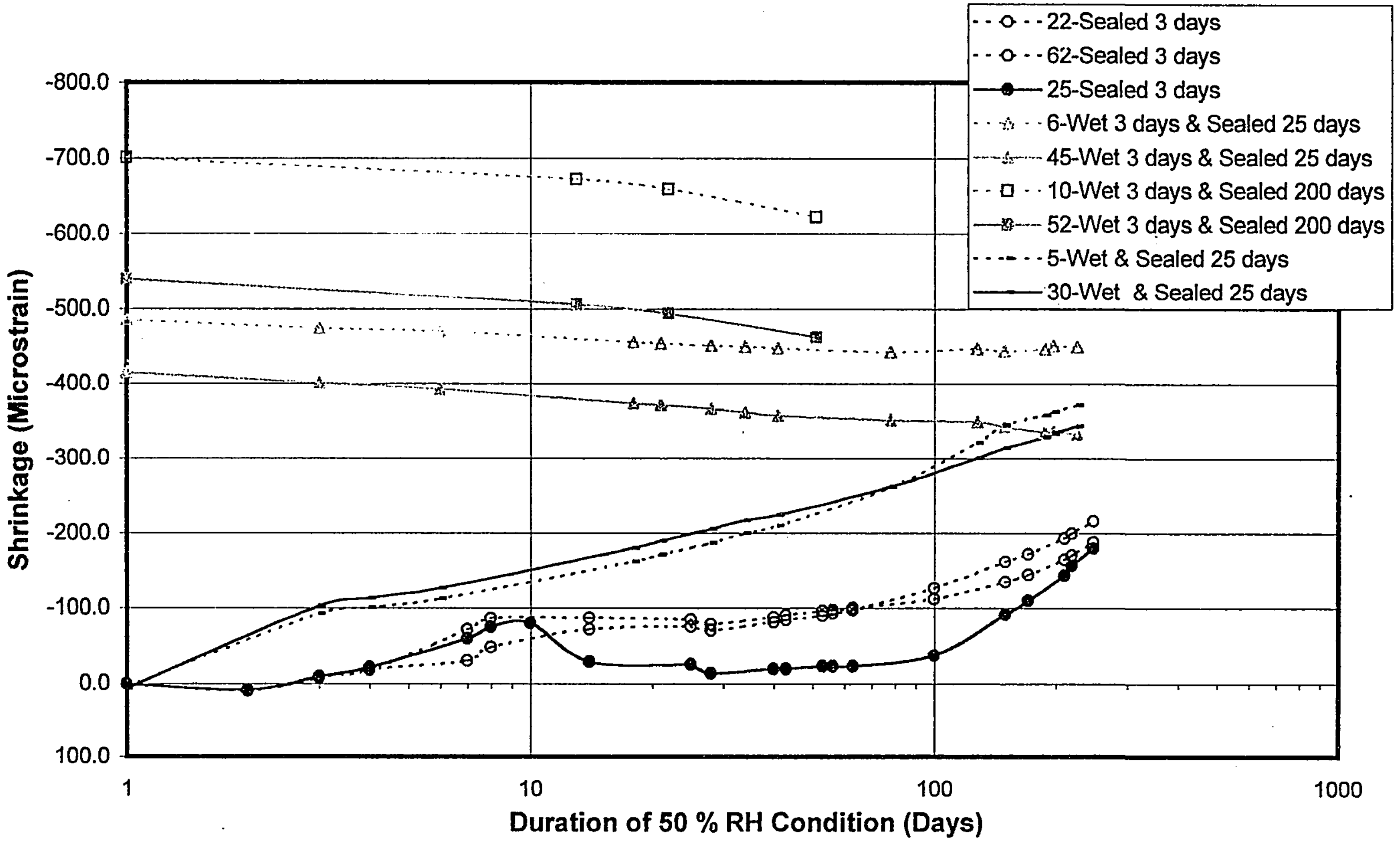


Figure 5-21(b): Environment Effect - All 89 mm Specimens stored in 50 % RH, Specimen 22, 62, 25 sealed after demoulding at 3 days, Specimen 6 & 45 sealed at 25 days, Specimen 10 & 52 sealed at 200 days, Specimen 5 & 30 Moist cured 25 days and sealed 25 days

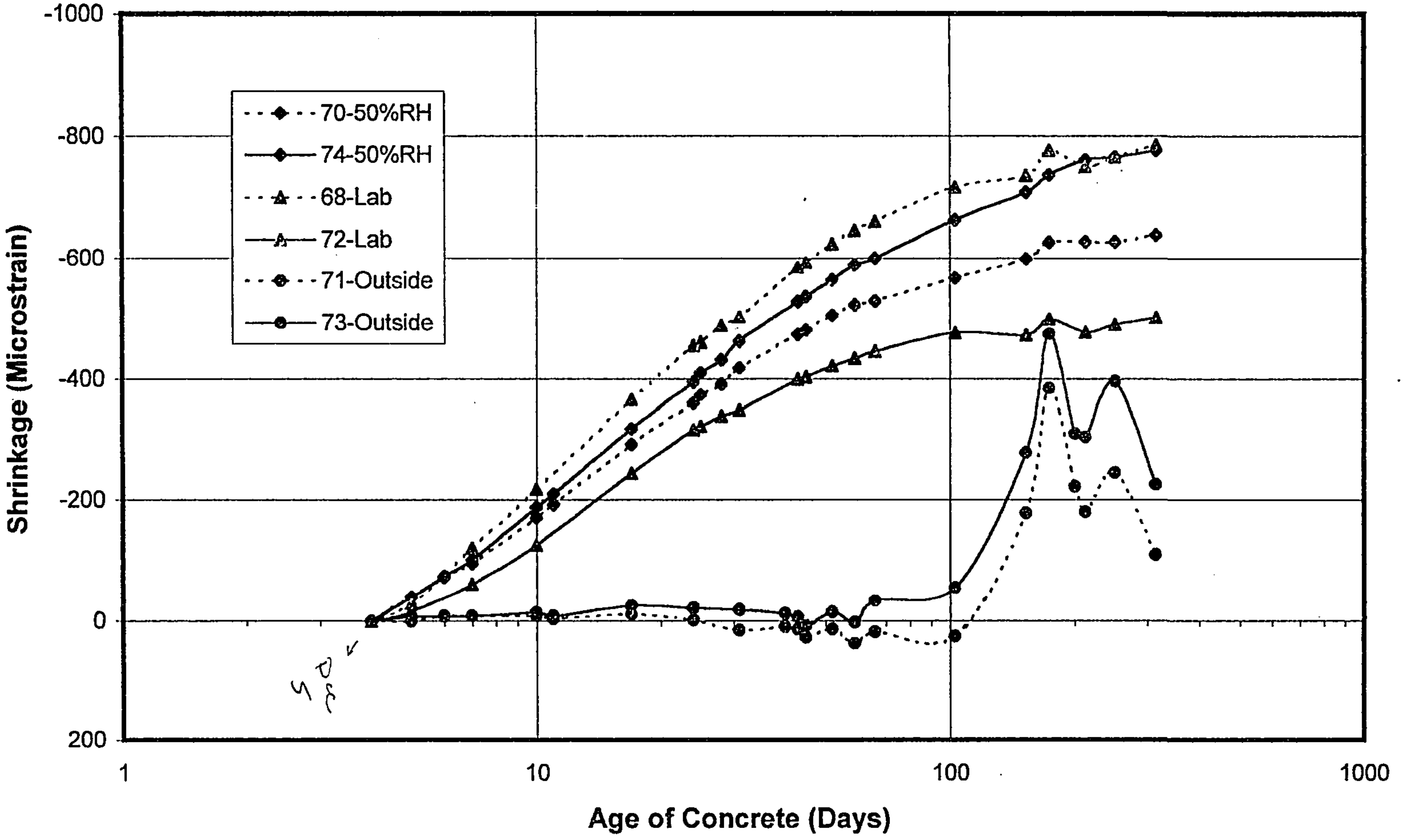


Figure 5-22: Environment Effect - Shrinkage of 152 mm Specimens in Various Environments

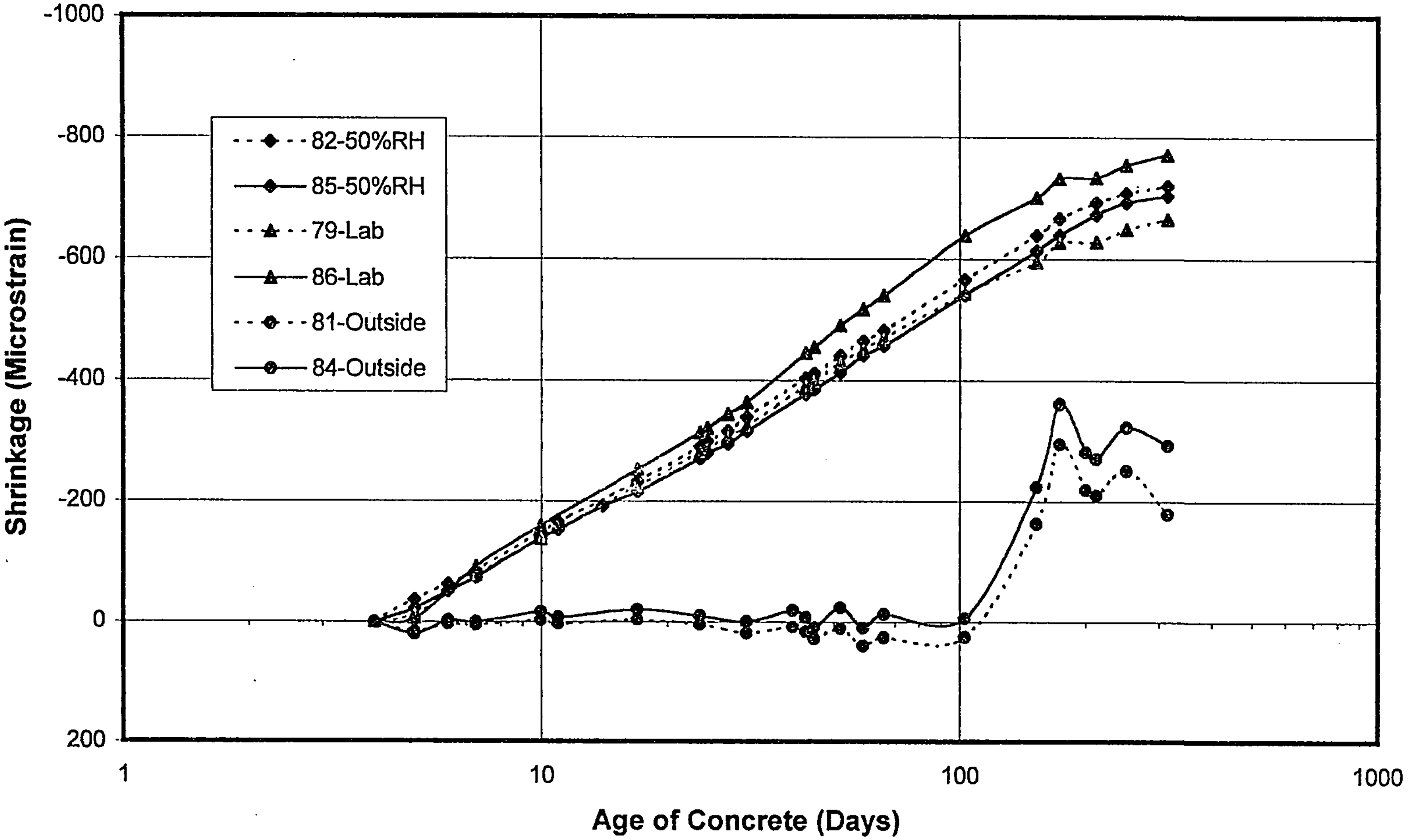


Figure 5-23: Environment Effect - Shrinkage of 254 mm Specimens in Various Environment

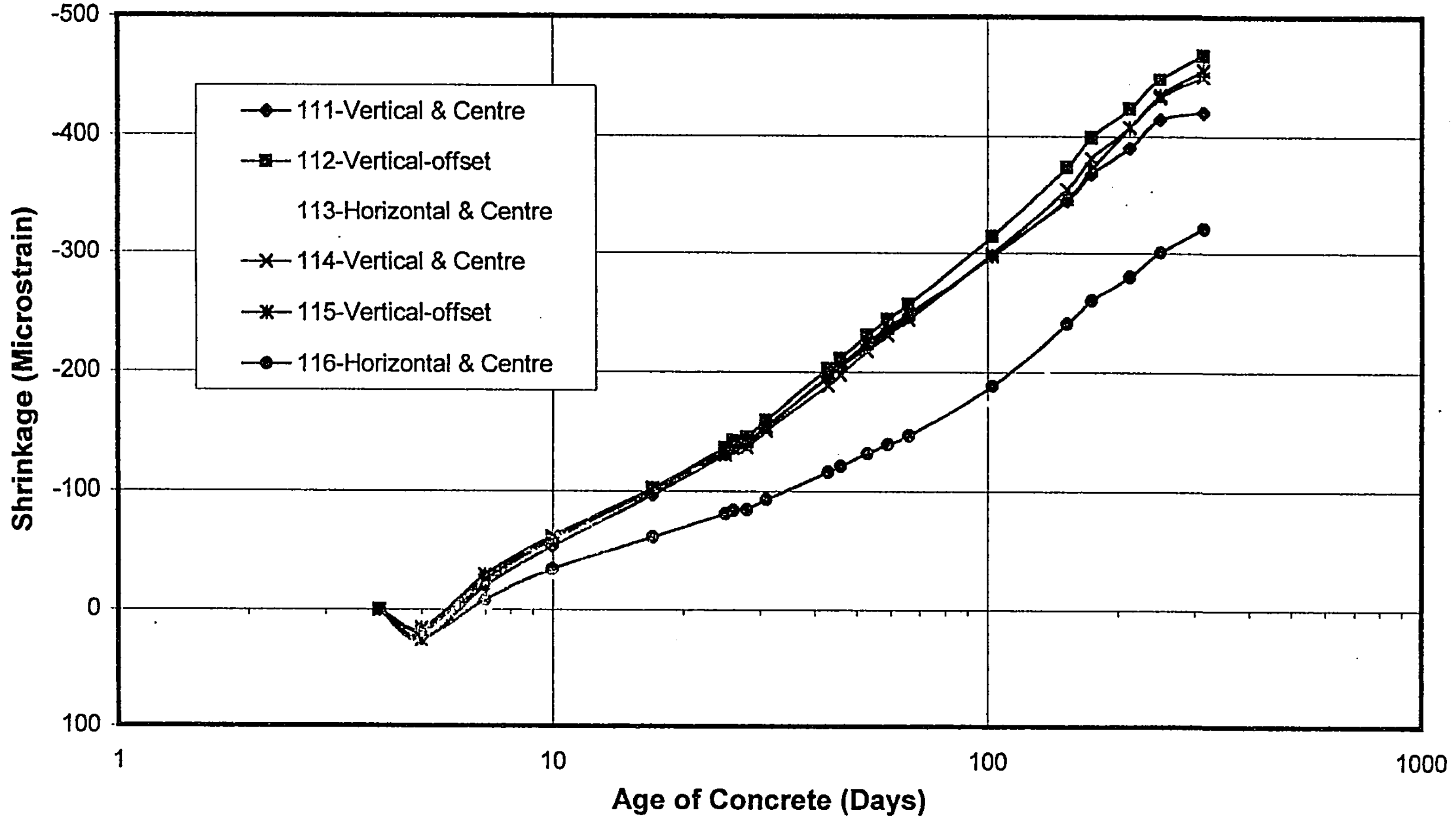


Figure 5-24(a): Longitudinal & Lateral Shrinkage of 610 mm Specimens in the Lab

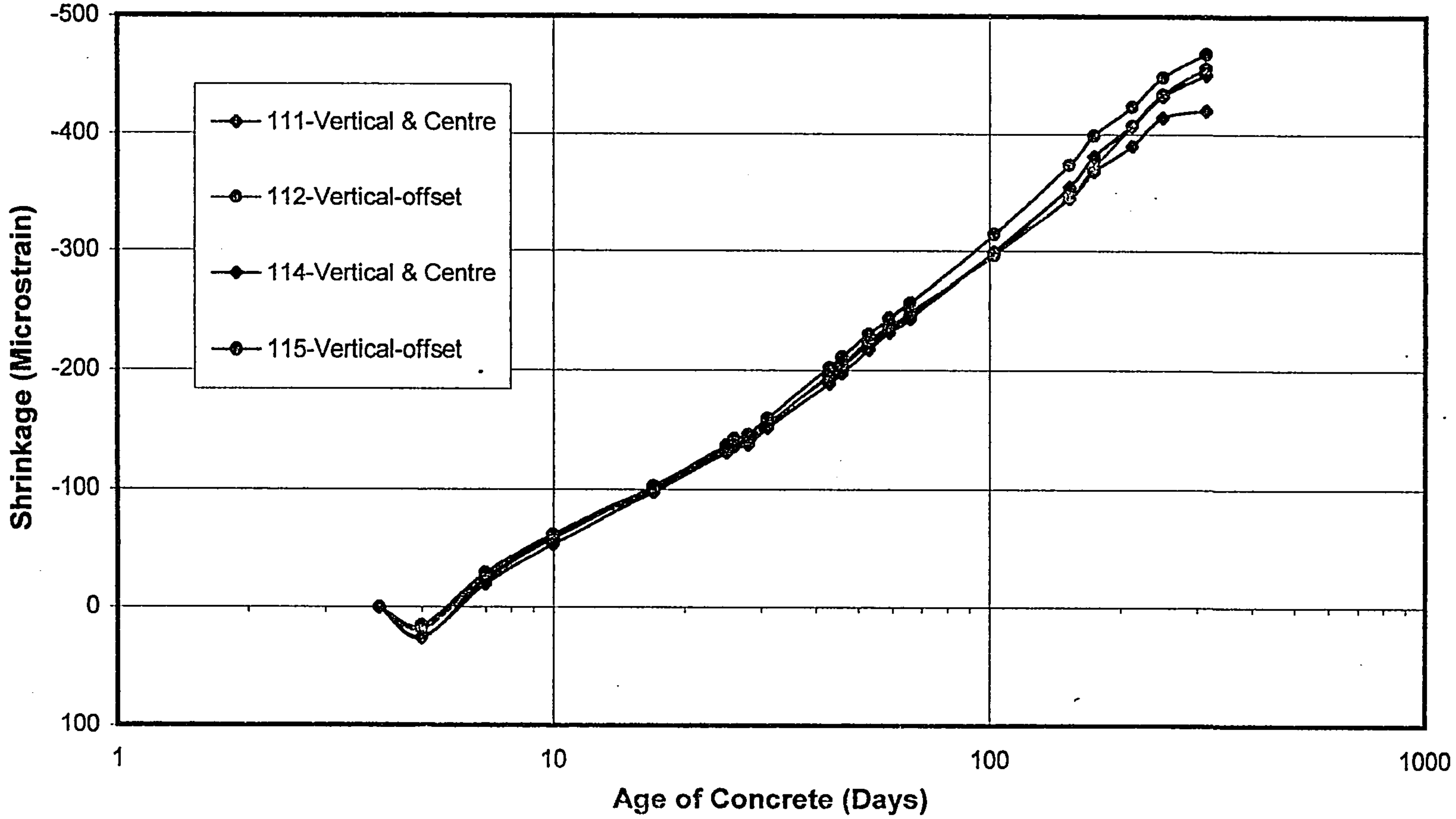


Figure 5-24(b): Longitudinal Shrinkage of 610 mm Specimens in the Lab, Strain gauge 111 & 114 are centre, Strain gauge 112 & 115 are offset of 152 mm

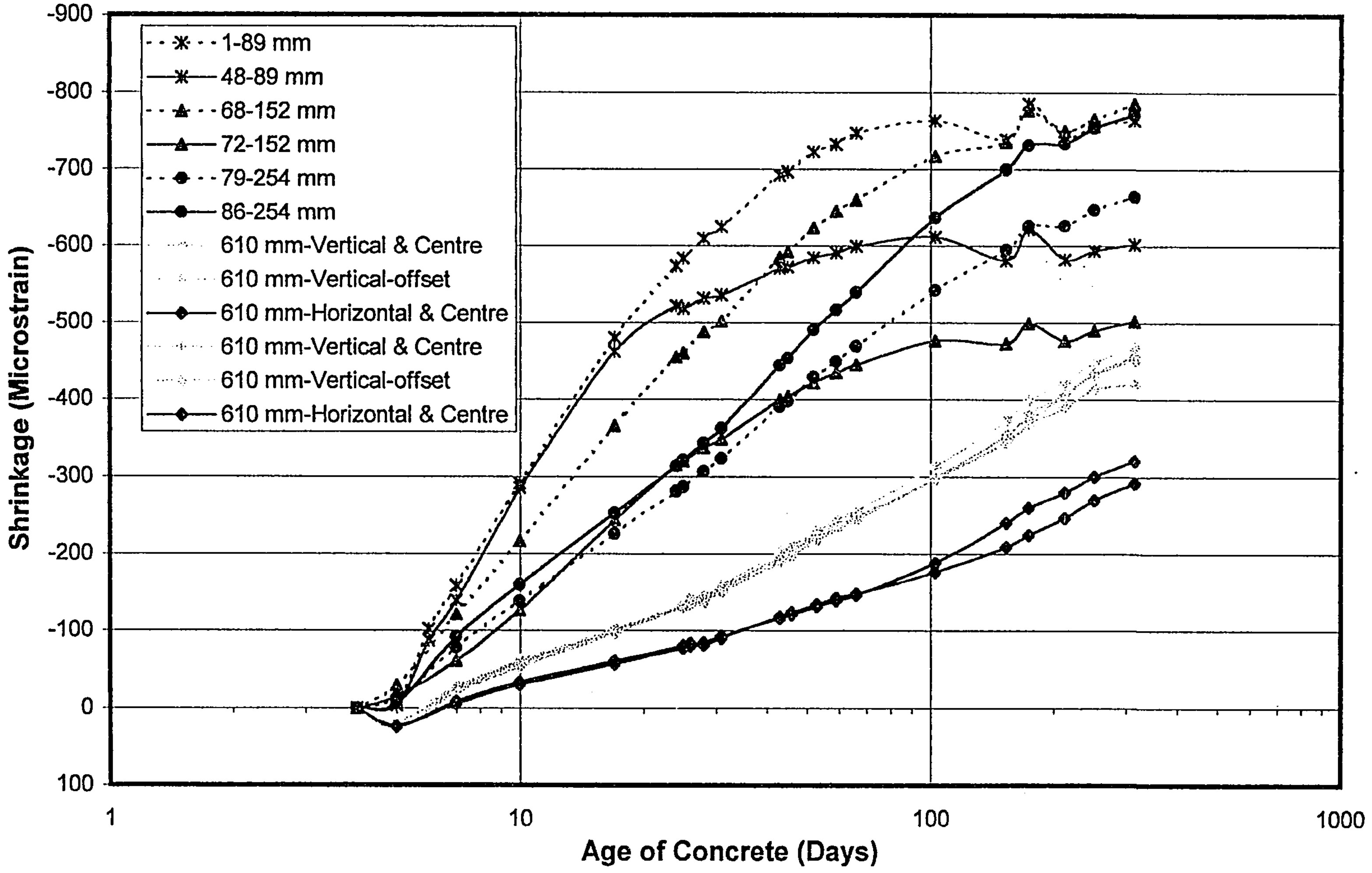


Figure 5-25: Size Effect - Shrinkage of the 89, 152, 254, and 610 mm Specimens in the Lab

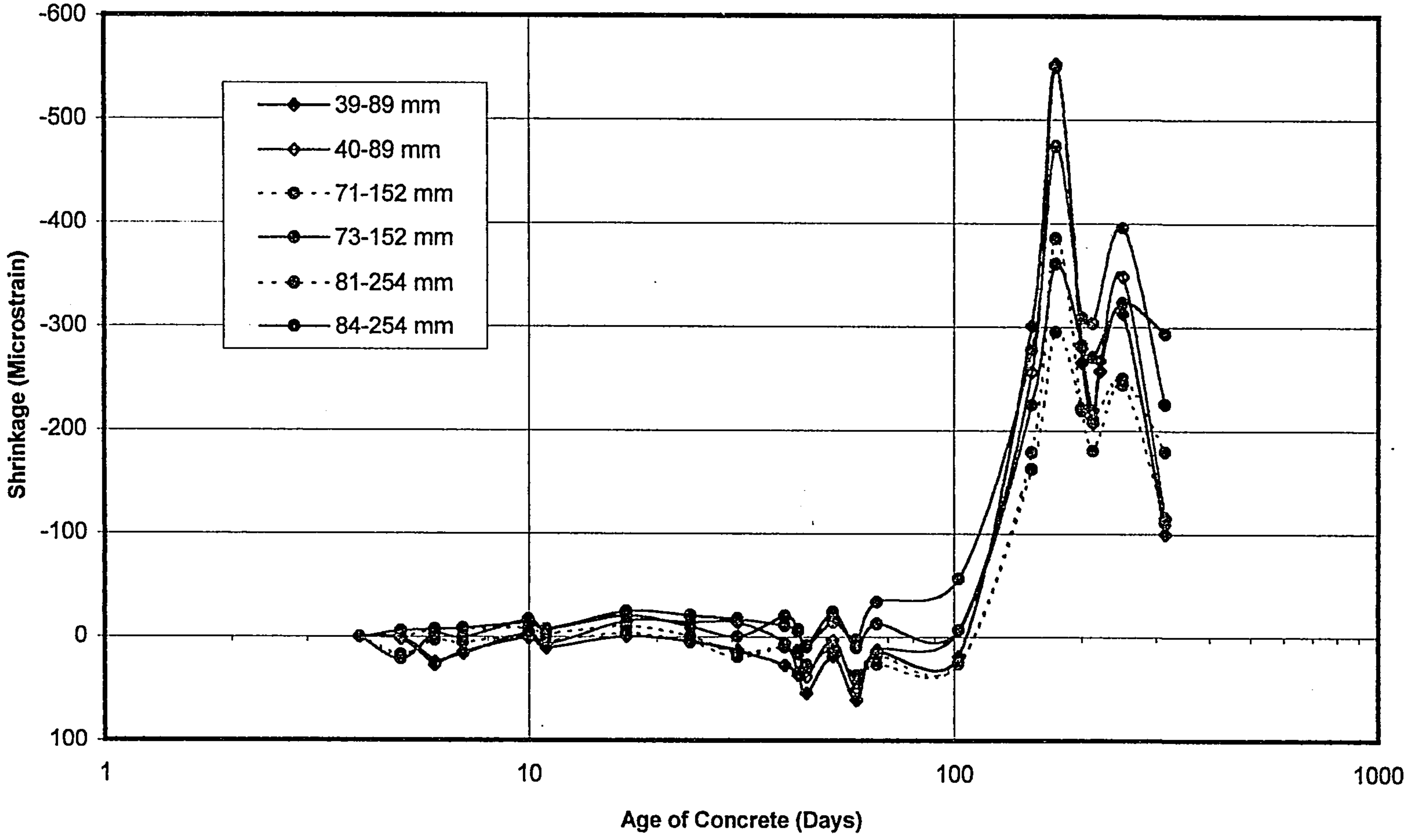


Figure 5-26: Size Effect - Shrinkage of the 89, 152, and 254 mm Specimens Outside Environment

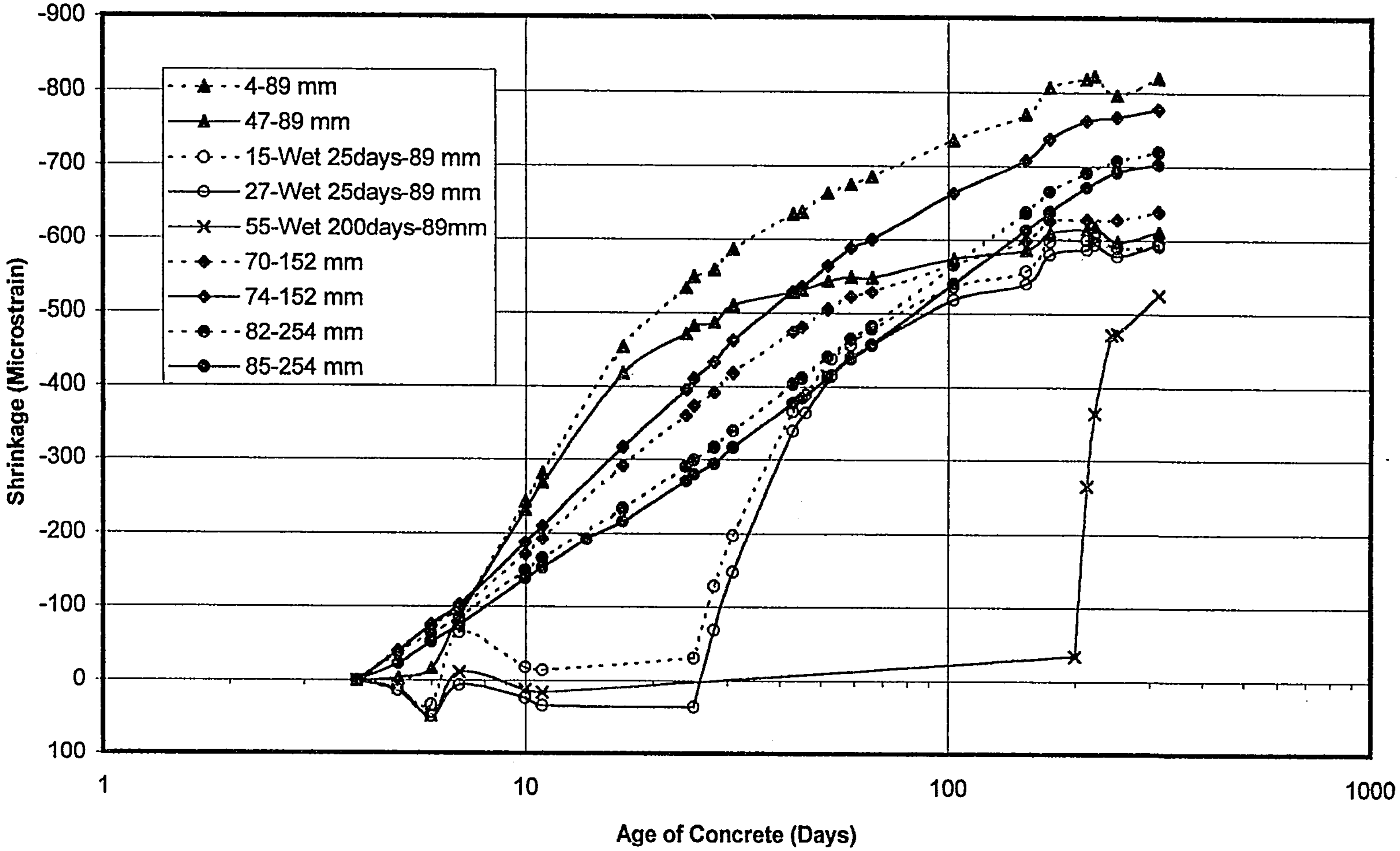


Figure 5-27(a): Size Effect - Shrinkage of the 89, 152, and 254 mm Specimens in 50 % RH, Specimen 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days, all other specimens moist cured 3 days

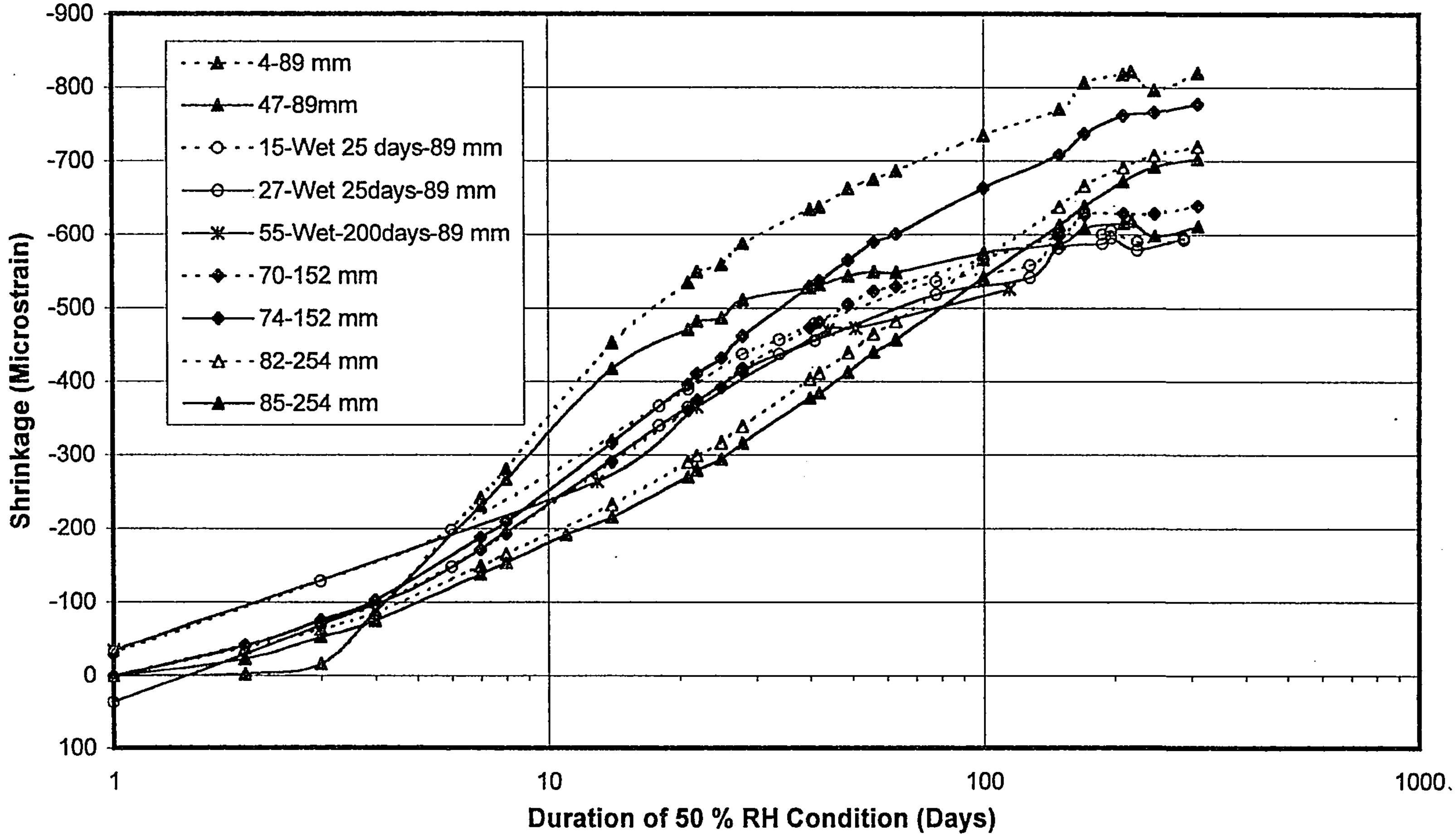


Figure 5-27(b): Size Effect - Shrinkage of the 89, 152, and 254 mm Specimens in 50 % RH, Specimen 15 & 27 Moist cured 25 days, Specimen 55 Moist cured 200 days, Other specimens moist cured 3 days

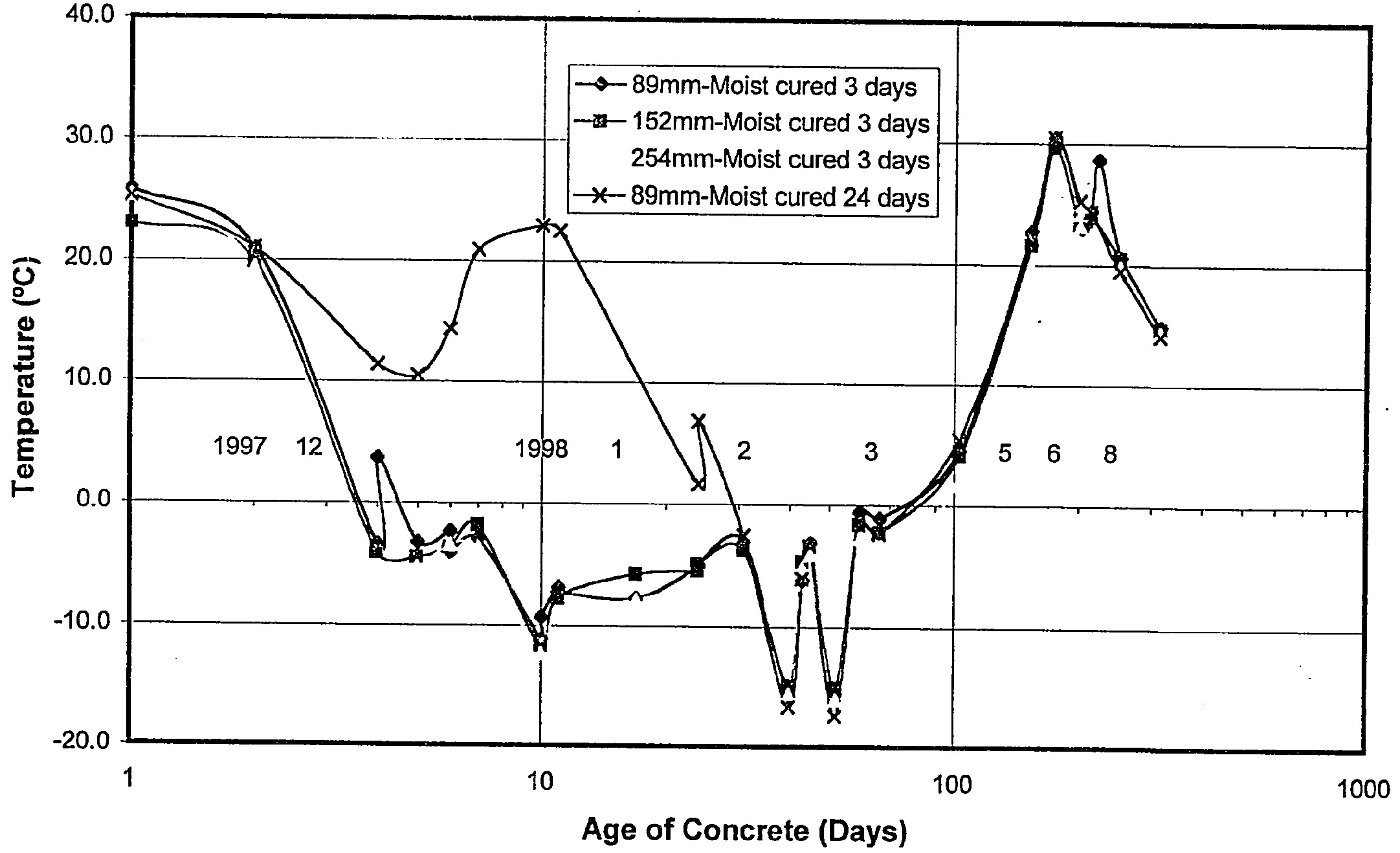


Figure 5-28: Average Temperature Outside during the test period (log scale)
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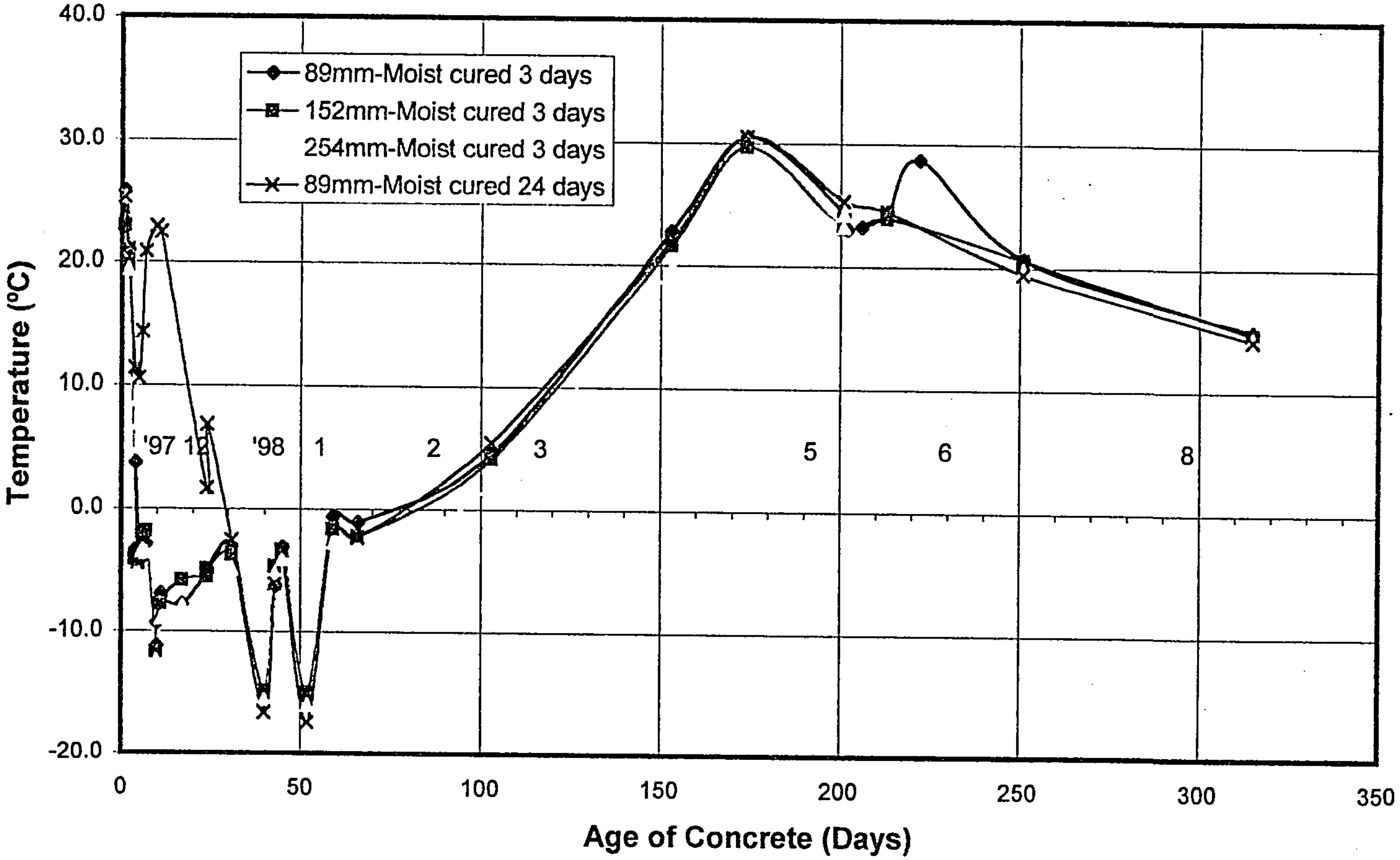

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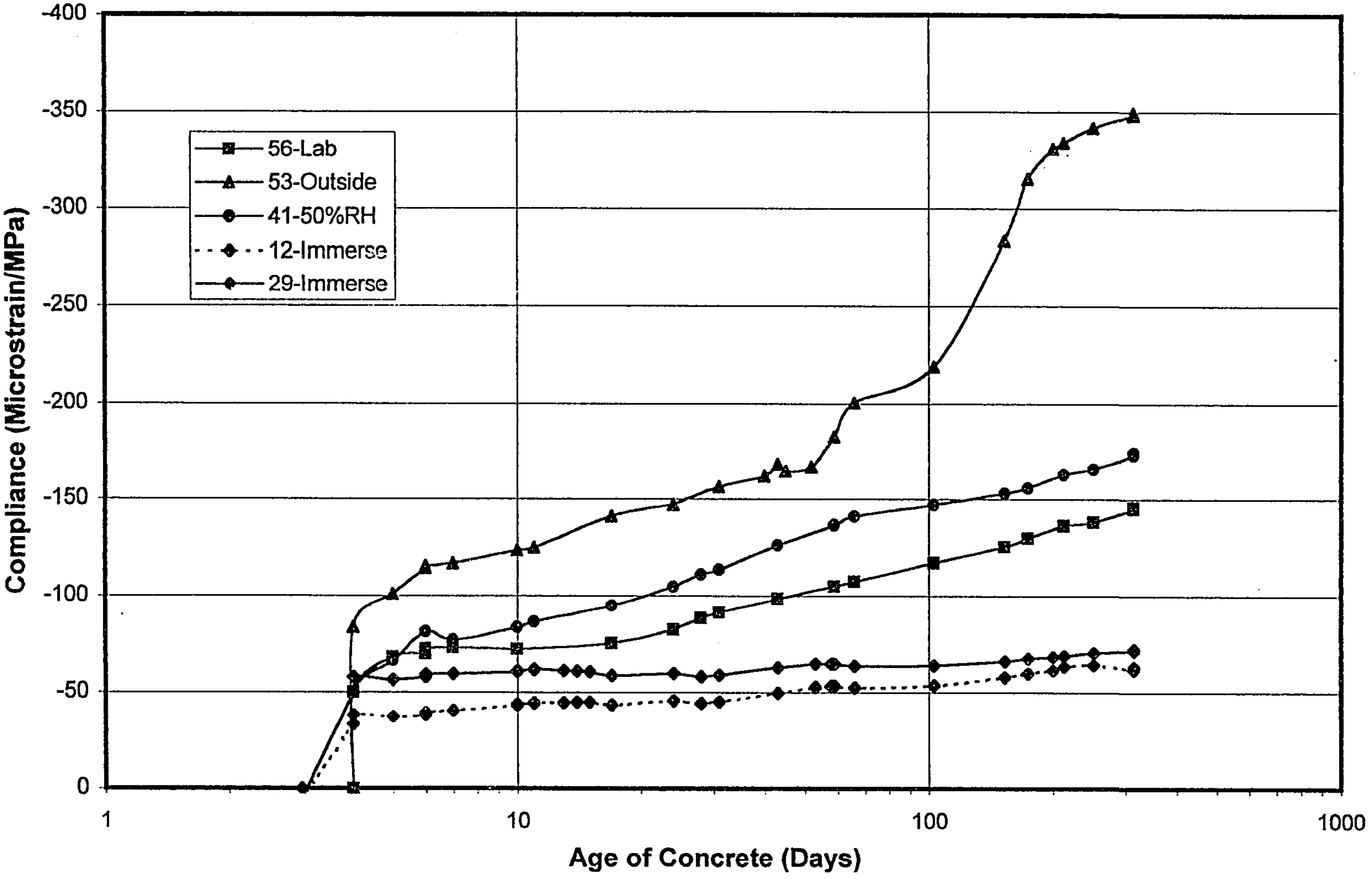

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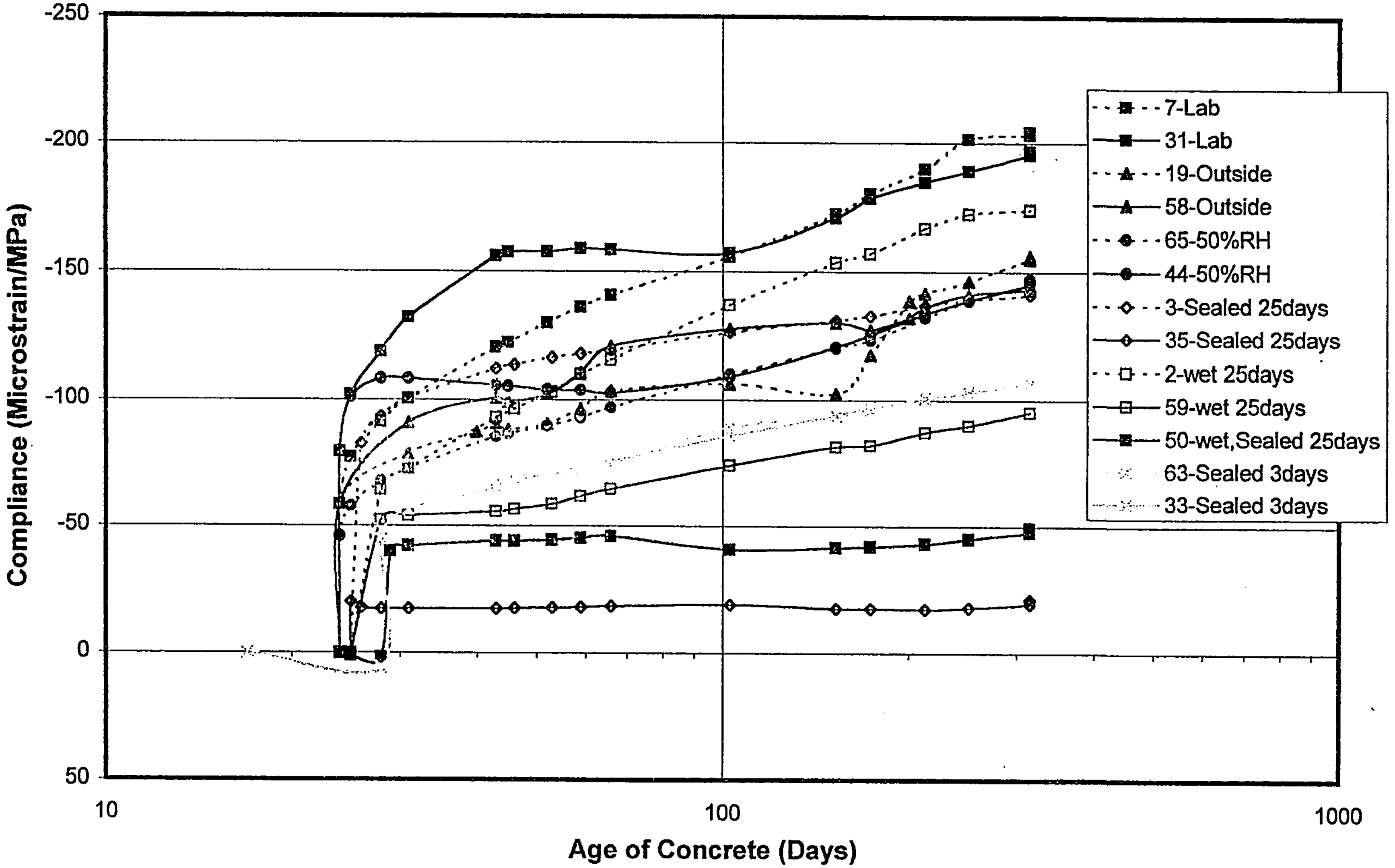


Figure 5-32: Environment Effect - Compliance of 89 mm Specimens Loaded at 200/201 days in Various Environments

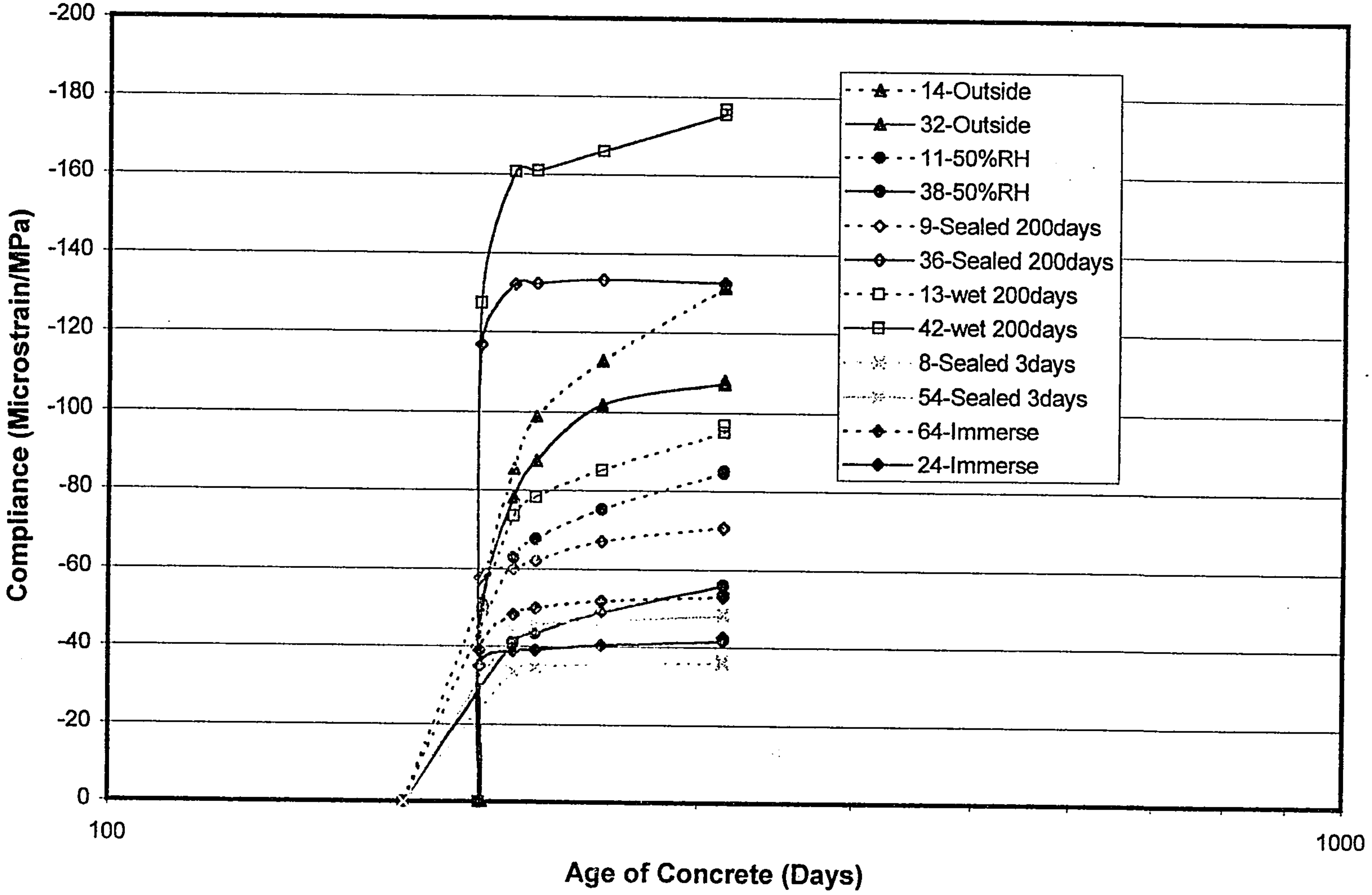
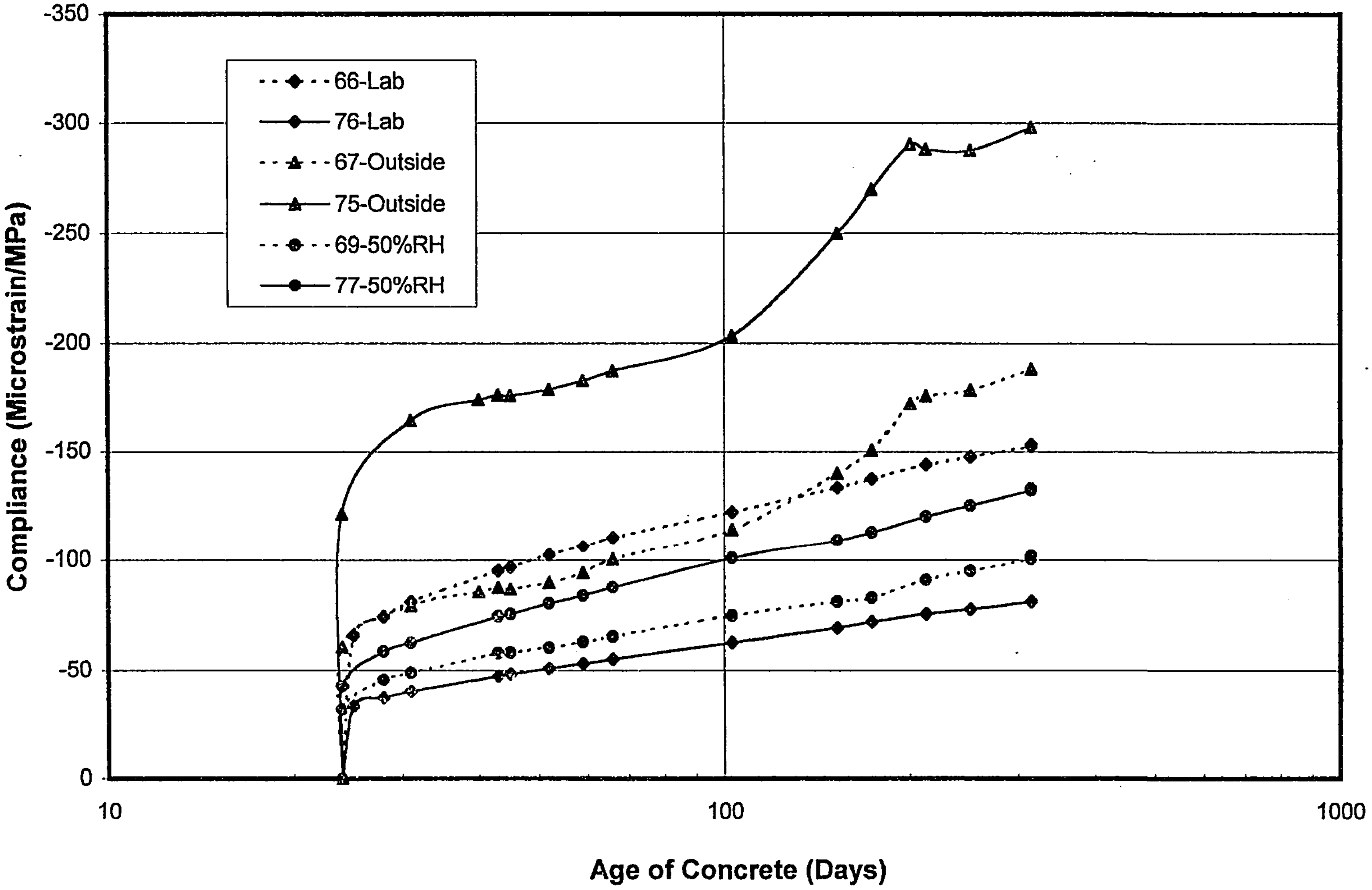


Figure 5-33: Environment Effect - Compliance of 152 mm Specimens Loaded at 24 days in Various Environments



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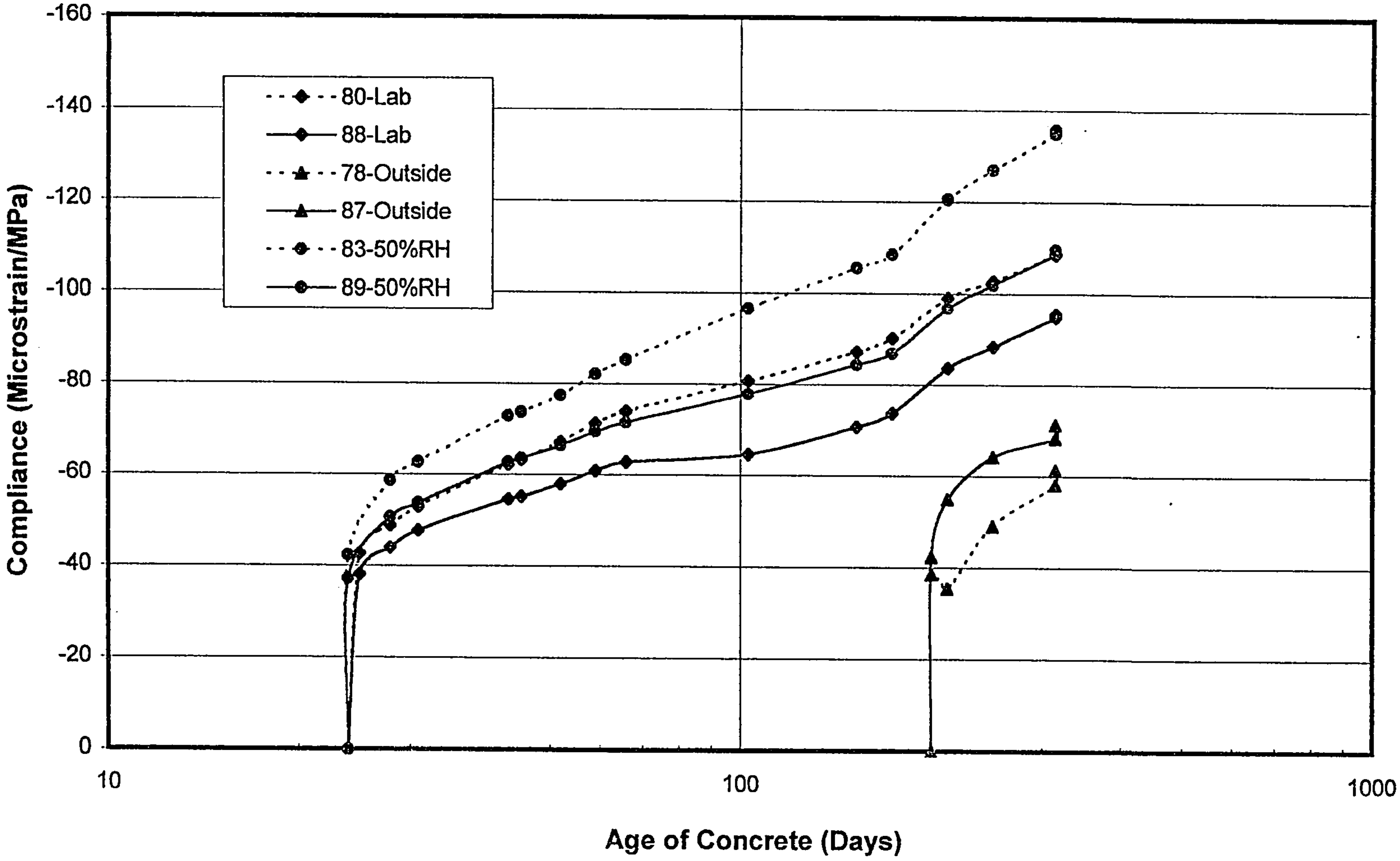

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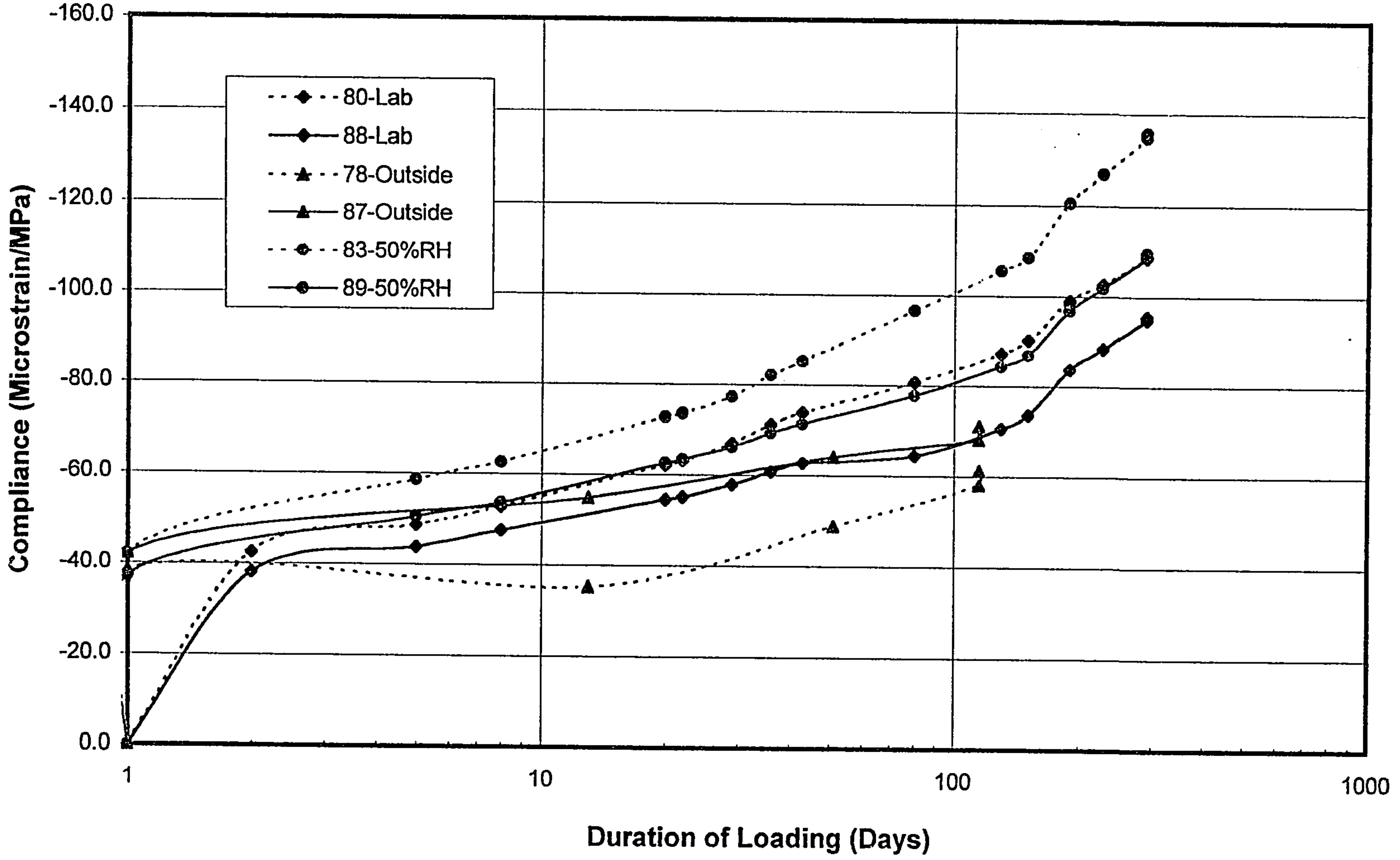

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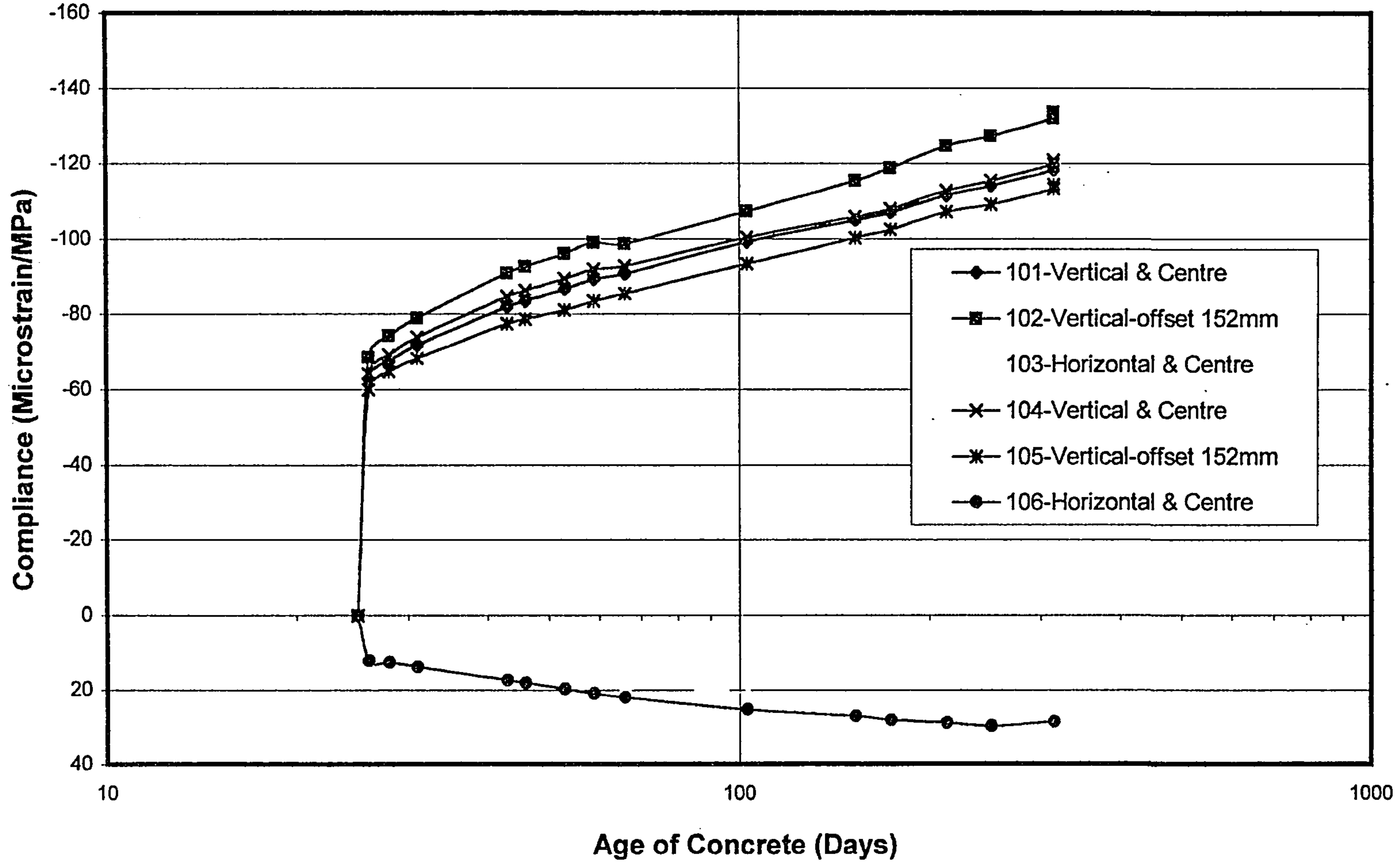

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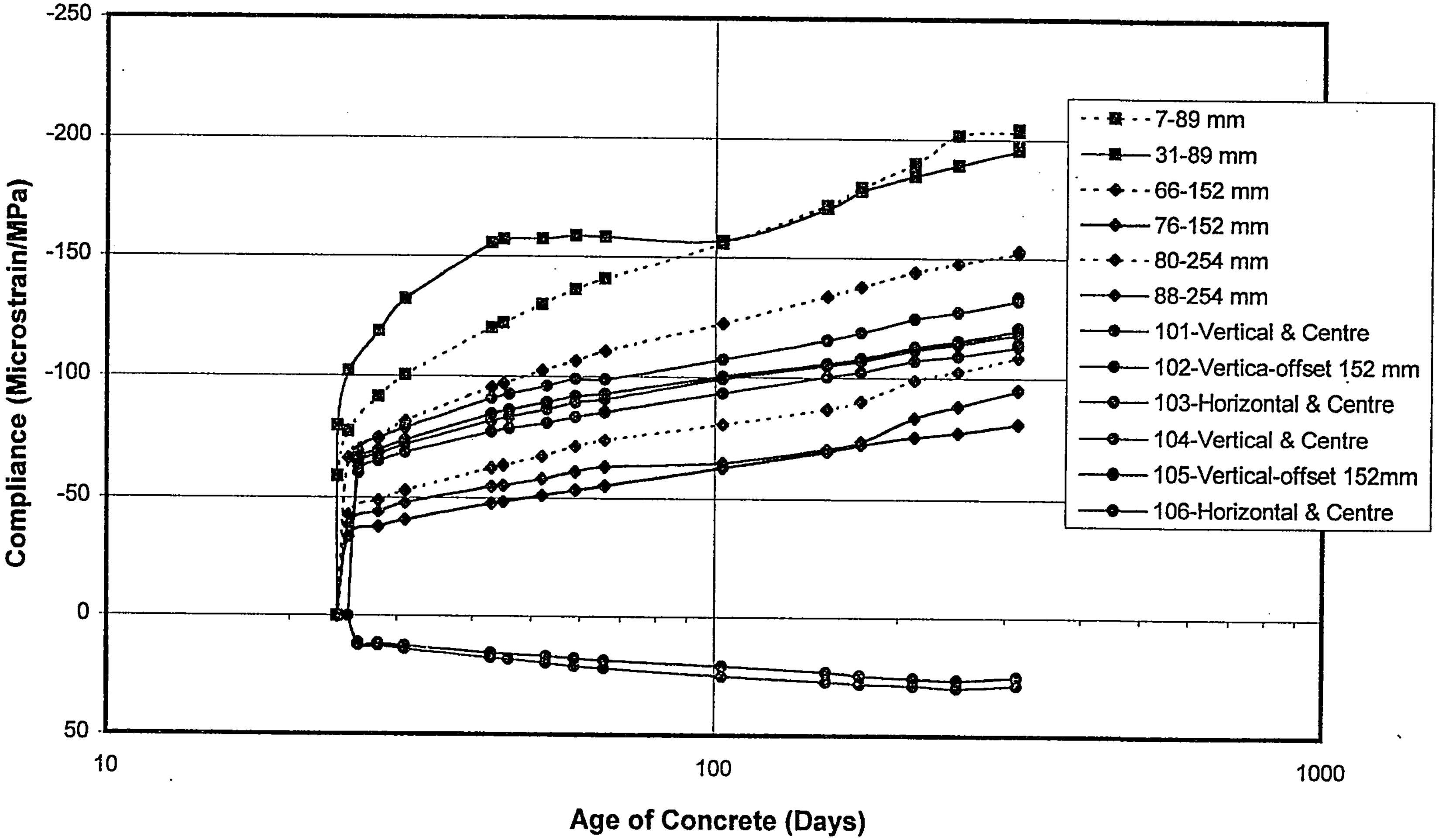

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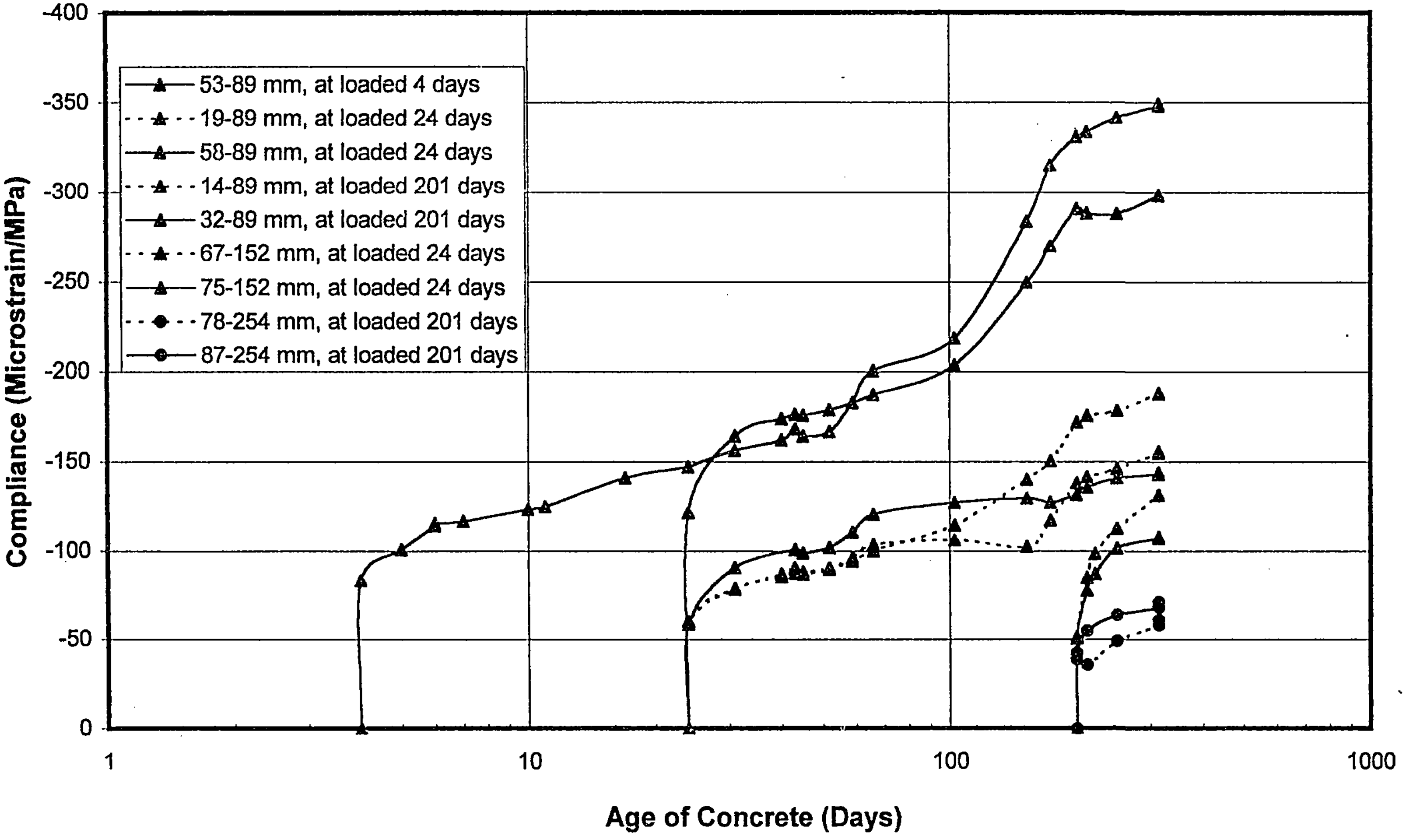

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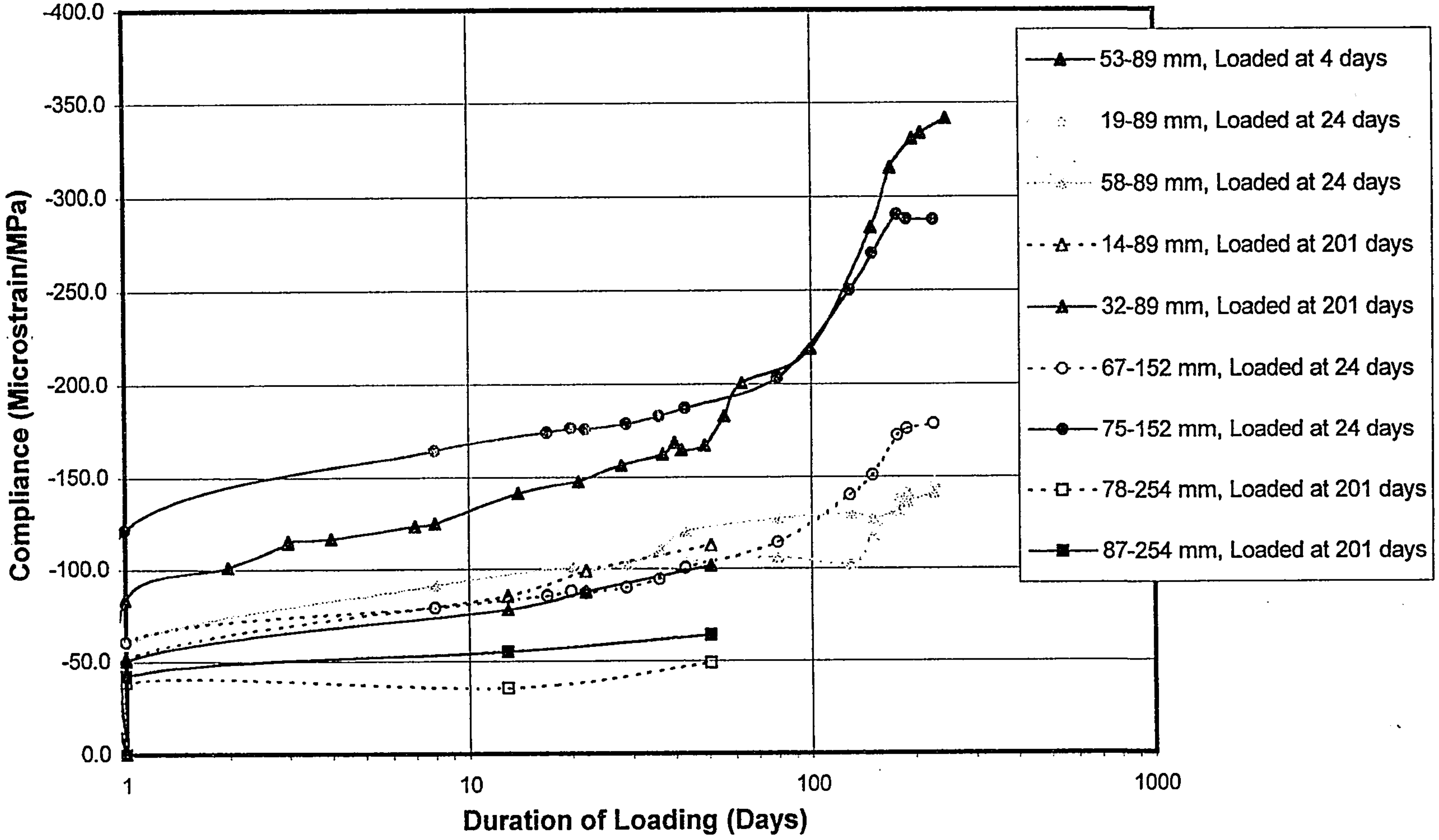

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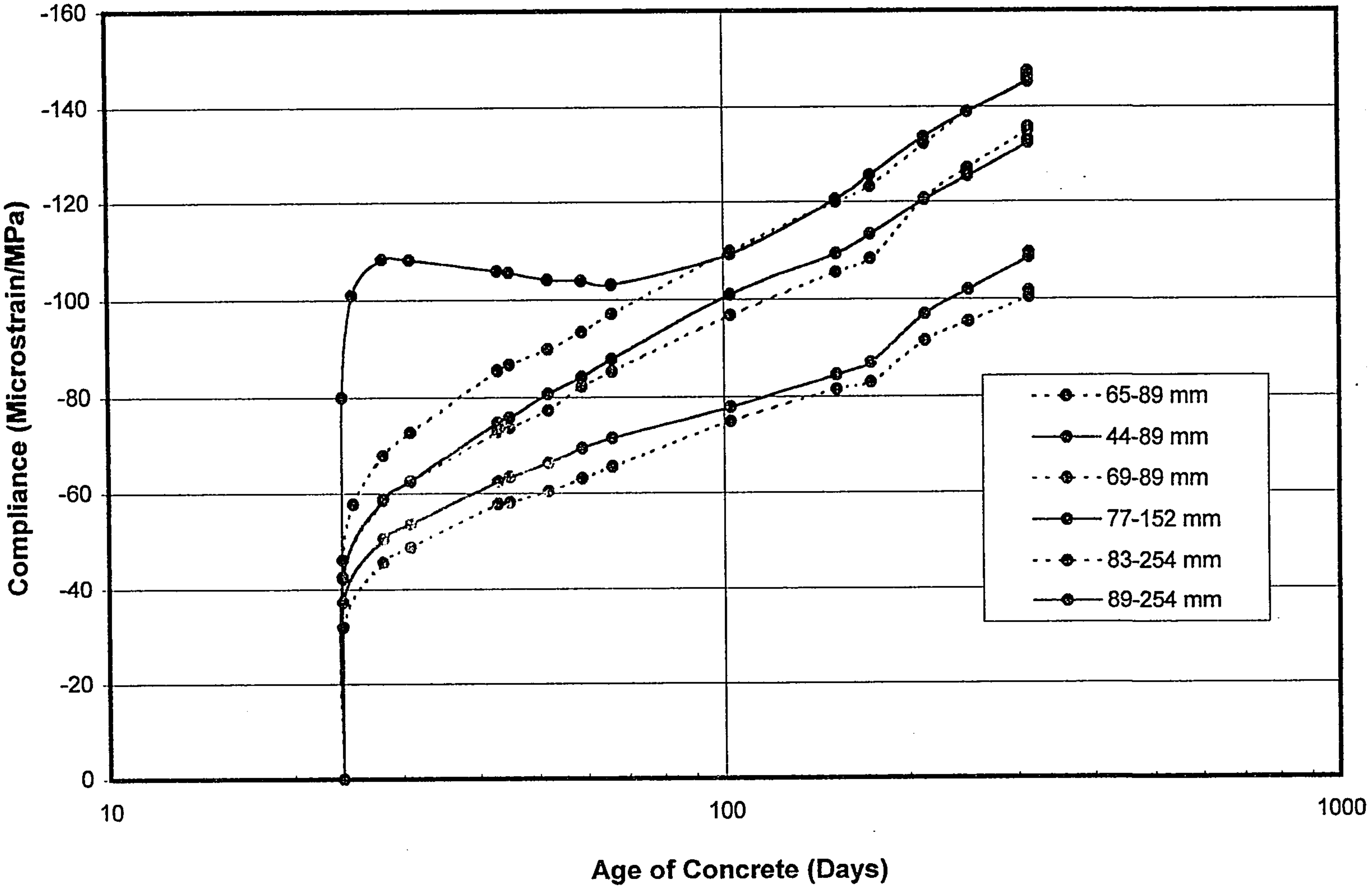

CHAPTER 6

CONCLUSIONS

The primary purpose of this investigation was to examine how the mechanical properties (strength and deformation) of concrete vary with age and curing environment.

6.1 Conclusions

The advantage of using a single concrete mix is totally outweighed by the difficulties of casting, stripping, preparing end surfaces and loading samples within a sufficiently negligible time span. Future experimental research should be divided into smaller projects using multiple batches of concrete made with the same stockpiled aggregates and cement, using the same machinery and the same labour force.

The ends of compression specimens should be ground to ensure they are plane, parallel and perpendicular to the specimen axis.

Measurement of modulus of elasticity by ASTM C 469 is not easy and it is difficult to have confidence in the measured results.

Measurement of shrinkage and creep strains by surface extensometers is time consuming and financially not possible in a university environment. Measurement by cast-in-place vibrating wire strain gauges is very convenient - however the gauges must be carefully aligned and maintained in place during placement of the concrete.

In this investigation the elastic strains measured on the creep specimens are nearly twice those expected. This will checked at the end of the experiment by measuring the elastic recovery on unloading the specimens.

The efficacy of the bitumastic sealer for the sealed specimens is doubtful as the specimens appear to be shrinking. After completion of the investigation the sealed specimens will be immersed in water to check if the seal is watertight. Sealed specimens should be stored in a 96% relative humidity environment to reduce the relative humidity potential across the seal.

Sealed shrinkage specimens should always be made and monitored even if autogenous shrinkage is not expected.

For statistical reliability multiple replicates are required. Practical necessity will probably limit the number to 5 that would enable a sample standard deviation to be calculated.

Specimen lengths of one diameter between the ends and the measurement length were found to give the similar results as specimens with two diameter end zones. While the ends of shrinkage specimens should be sealed the use of a soft seal on the ends of creep specimens should be avoided.

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Day 1 was 1997/12/06

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Reference

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

- Neville, A.M., Properties of Concrete, Pitman Publishing Inc., 1981.

- Neville, A.M., Concrete Technology, Longman Science & Technical, 1987.

- Sau, P., A study on the effect of casting and curing temperature on mechanical properties of concrete, M.Eng. Thesis, Dept. of Civil Engineering, Univ. of Ottawa, Canada, 1984.

- Bazant, Z.P., Mathematical Modeling of Creep and Shrinkage of Concrete, John Wiley and Sons, 1988.

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

- Troxell, G.E., Raphale, J.M. and Vavis, R.E., Long time creep and shrinkage tests of plain and reinforced concrete, ASTM Proc. 58, pp. 1101-1120, 1958.

- Troxell, G.E., Davis, H.E., Kelly, J.W., Composition and Properties of Concrete, McGrraw-Hill Book Co., 1968.

- Metha, P.K., Concrete Structure, Properties, and Materials, Prentice-Hall, 1986.

- Zhao, J., Mechanical Properties of Concrete at Early Ages, M.A.Sc. Thesis, Dept. of Civil Engineering, Univ. of Ottawa, Canada, 1990.

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

- Carreira, D.J., Testing for Concrete Creep and Shrinkage, 1998.

- Hansen, T.C. and Mattock, A.H., Influence of size and shape of member on shrinkage and creep of concrete, ACI Journal, No. 63, pp. 267~290, 1966.

- Gardner, N.J. and Zhao, J.W., Creep and Shrinkage Revisited, ACI Materials Journal, pp.236~246, 1993.

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

- Robertson, I.N., Creep and Shrinkage Prediction Models: a Case Study, 1997.
- ACI Committee 209, Factors Affecting Shrinkage, Creep and Thermal Expansion of Concrete and Simplified Models to Predict Strains, 1997.
- Muller, H.S. and Pristl, M., Creep and Shrinkage of Concrete at Variable Ambient Condition, RILEM Proceeding, pp. 15~26, 1993.
- Khan, A.A., Cook, W.D. and Mitchell, D., Creep, Shrinkage, and Thermal Strains in Normal, Medium, and High-Strength Concretes during Hydration, ACI Materials Journal, pp.156~163, 1997.
- Hobbs, D.W., Influence of specimen geometry upon weight change and shrinkage of air-dried concrete specimens, Magazine of Concrete Research, Vol. 29, No. 99, pp.70~80, 1997
- Almudaiheen, J.A. and Hansen, W., Effect of Specimen Size and Shape on Drying Shrinkage of Concrete, ACI Materials Journal, pp.130~135, 1987.
- Hansen, W. and Almudaiheen, J.A., Ultimate Drying Shrinkage of Concrete-Influence of Major Parameters, ACI Materials Journal, pp.217~223, 1987.
- Bryant, A.H. and Vadhanavikkit, C., Creep, Shrinkage-Size, and Age at Loading Effects, ACI Materials Journal, pp.117~123, 1987.
- Mortelmans, F. and Vandewalle, L., Influence of Variable Temperature and Relative Humidity on the Creep and Shrinkage of Concrete, RILEM Proceeding, pp. 247~252, 1993.
- Kosmatka, S.H., Panarese, W.C., Gissing, K.D. and Macloed, N.F., Design and Control of Concrete Mixtures, CPCA 6th Canadian Edition, 1995.
- Gamble, W.L, Creep of Concrete in Variable Environments, ASCE, pp. 2211~2221, 1982.