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ATHES

**AN EXPERIMENTAL INVESTIGATION INTO SUPERPOSITION
OF CREEP STRAINS FOR CONCRETE**

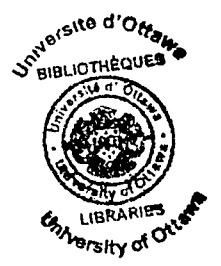
by
Andre O'Brain Brown

A thesis
submitted under the supervision of
Dr. John Gardner

in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in
Civil Engineering

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ABSTRACT

This experimental investigation was performed to examine the validity of the hypothesis of superposition of creep strains by measuring and comparing the time dependent strains of concrete prisms subjected to increasing and decreasing loads, constant loads, and late loads (for unsealed concrete specimens which were dried before loading and sealed concrete specimens kept in a moist room). Three series of specimens were made; one was moist cured for four days, then sealed and the other two series of specimens were moist cured for three and four days respectively, then transferred to a 50% relative humidity room. The conclusions must be read noting that the use of sixteen prism specimens limits the number of specimens available at second and third load events. Use of a single specimen for either shrinkage or compliance measurement is not desirable.

For increasing loads under sealed conditions, it is noticeable that at the second load cycle superposition closely approximates the experimental result. There is a 30% underestimation for the third load cycle. For creep recovery of sealed specimens superposition, considering the calculations involved approximates the experimental results at both 20 days and 87 days.

Two series of specimens exposed to drying were prepared for this phase of the experimental investigation. For drying before loading the results indicate that superposition underestimates the measured strains by 5 - 10% for increasing loads,

experimental strains are greater than calculated strains. Creep recovery was overestimated by 10 - 12%.

It would appear that the application of the superposition rule is valid for basic creep but is less valid for drying creep. Therefore an alternative hypothesis is necessary to predict with more precision the creep strains for concrete subjected to increasing or decreasing loads for drying before loading and sealed conditions.

The influence of compressive load shows very little effect on weight loss compared to specimens without load. These results would indicate that the moisture loss depends only on relative humidity and is not influenced by loading i.e. the seepage theory does not hold.

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NOTATIONS

$C_r(t, t_o, t_1)$	Specific creep recovery at time t under loading age t_o and unloading age t_1
E	Modulus of elasticity
E_{cm28}	Modulus of elasticity of concrete at 28 days (MPa)
E_{cmt}	Modulus of elasticity of concrete at age t (MPa)
E_{cmt_o}	Mean modulus of elasticity of concrete when loading commenced (MPa)
f_{cm28}	Concrete mean compressive strength at 28 days (MPa)
f_{cmt}	Concrete mean compressive strength at age t (MPa)
f_{cmt_o}	Concrete mean compressive strength when loading commenced (MPa)
f_{ck28}	Concrete characteristic strength at 28 days (MPa)
h	Humidity expressed as a decimal
$J(t, t_o)$	Compliance (1/MPa)
K	Shrinkage constant
$R(t, t_o)$	Relaxation (MPa)
S_1	Loaded 7-day specimen
S_2	Loaded 28-day specimen
S_3	Specimen loaded at 7 days and then additional load at 28 days
t_c	Age drying commenced, end of moist curing (days)
t_o	Age of concrete at application of load (days)
t_1	Age of concrete at removal of load (days)
t	Age of concrete
β_E	Parameter for the calculation of f_{cmt} and E_{cmt} , CEB MC90 model
$\beta(t)$	Correction term for effect of time on shrinkage
$\beta_{cr}(t, t_o, t_1)$	Development of creep recovery with time which is associated with loading history
ε_c	Creep strain
ε_1	Deformation (Instantaneous + deferred) due to loading at 7-days under σ_0
ε_2	Deformation (Instantaneous + deferred) due to loading at 28-days under σ_0
$\varepsilon_\sigma(t, t_o)$	Stress-dependent strain (Initial strain + creep strain)
ε_3	Deformation (Instantaneous + deferred) due to successive 7-days and 28-days loadings at under $2\sigma_0$
ε_{sh}	Shrinkage strain
ε_τ	Deformation of a body
$\phi_{cr}(t_o, t_1)$	Final value of creep recovery which is associated with loading history
$\phi(t_o, t_1)$	Creep function
$\Phi(t_c)$	Correction term for effect of drying before loading
$\Phi_r(t, t_o, t_1)$	Correction term for effect of drying before loading
ρ	Density of concrete (kg/m^3)
σ_0	Initial stress value at the beginning of first loading (Mpa)
$d\tau$	Time element
τ	Point in time interval (Instant of time)

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is a composite material with a highly heterogeneous and complex structure. This creates difficulties in constituting exact models of concrete structure from which its behaviour can be reliably predicted. For structural engineers to have better control and prediction of the properties of this material, knowledge of the structure and properties of the individual components and how they relate are critical. The selection of this engineering material for a particular application has to take into account its ability to withstand the applied force over the service life of the structure without excess cracking or deflections. Properties of concrete that are of interest to the structural engineer are strength, durability, cracking, modulus of elasticity, shrinkage and the creep strain under load.

Concrete is formed by the aggregation of loose sand and aggregate held together by the cement paste, which can be described as a highly viscous pseudo liquid. The viscosity of this liquid increases with time because of chemical changes within the structure (crystallization) to form a complete crystalline network of particles. Its resistance to irrecoverable deformation by shear (i.e. when the cement paste hardened) is the result of friction between the grains, which is a function of the applied hydrostatic pressure. Hardened concrete contains approximately 75% (by volume) inert aggregate, hydrated concrete cement paste, free water and voids. The hydrated cement paste

develops as a series of complex, exothermic reactions between the cement powder and the residue of water in the fresh paste. The development of mechanical strength depends upon the degree of completion of the hydration reactions. It must be noted that the mechanical properties of hardened concrete are significantly affected by the curing temperature, water/cement ratio, environmental humidity and composition of the aggregates.

According to Freudenthal and Roll (1957), when load is applied to concrete, there is an initial instantaneous deformation, part of which is perfectly elastic and the other part inelastic. The elastic component of this deformation is due to the formation of an isotropic structure resulting from the cohesion between the aggregate particles and the cement paste, while the inelastic part resulted from the permanent set due to micro-cracks. It is at this stage of applied load, that absorbed water in the gel is expelled to the surface or redistributed within the structure of the concrete by hydrostatic pressure gradient. When the pressure gradient decreases sufficiently so that no more water is expelled or redistributed, the flow of absorbed water ceased, and there is no further creep.

At the removal of applied load, there is an instantaneous recovery, followed by a delayed elastic recovery, which is less than the initial deformation. The deformation due to the flow of absorbed water from cement gel may be completely recoverable, partly recoverable, or irrecoverable, depending on the environmental conditions.

At this stage of removing the load according to Freudental and Roll (1957), expelled water on the surface of concrete can return to the pore spaces of the gel, and cause the gel to expand, and hence full creep recovery due to absorption. However, if the concrete environment is of a low humidity, the expelled water will evaporate. If all the expelled water evaporates before the load is removed, the removal of the load is not accompanied by recovery, and the creep due to the flow of absorbed water is a permanent deformation. Partial evaporation before removal of load results in partial recovery after the load is removed.

Three basic components that influence the structural properties of concrete: the hydrated cement paste, the aggregate, and the transition zone between the cement paste and the aggregate.

Creep and shrinkage, are two time-dependent deformations of concrete that should be considered as two aspects of a single complex physical phenomenon.

1.2 Shrinkage

Shrinkage is a decrease in concrete volume with time and occurs as concrete hardens. This decrease in volume is due to changes in the physico-chemical properties due to the hydration of the cement and loss of moisture. Shrinkage is expressed as a dimensionless strain. Shrinkage can be partially recovered if the relative humidity increases.

Shrinkage includes plastic shrinkage, autogenous shrinkage, drying shrinkage, and carbonation shrinkage.

- a) Plastic shrinkage is due to negative capillary pressures resulting from external influences.
- b) Autogenous shrinkage is caused by the hydration of cement for low water/cement ratio concrete and commences immediately after addition of water to the cement.
- c) Drying shrinkage is due to moisture loss in hardened concrete
- d) Carbonation shrinkage results as the various hydration products form calcium carbonate in the presence of CO_2

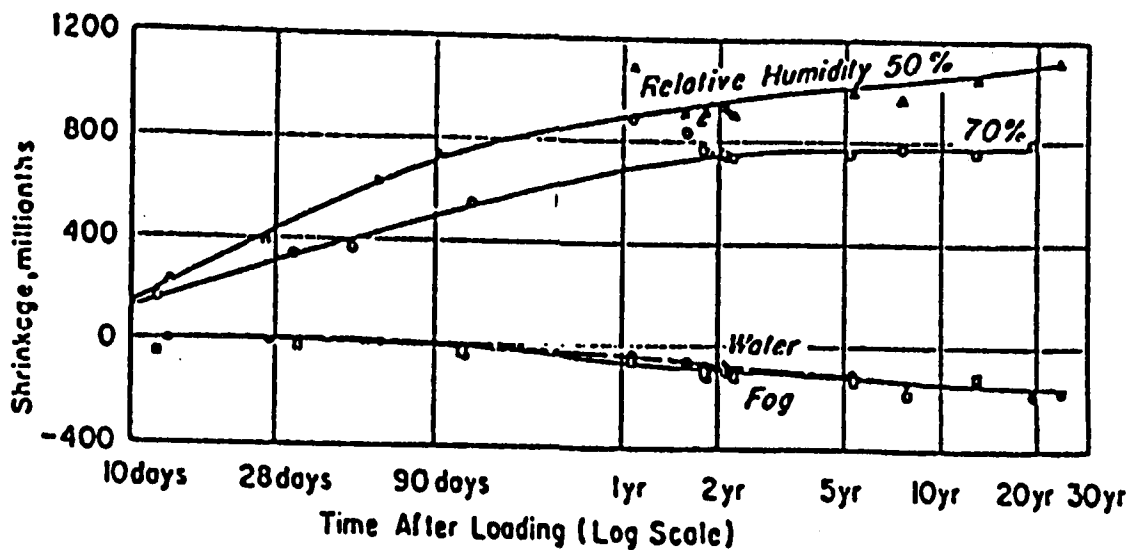


Figure 1.1 Troxell et al (1958) shrinkage experiments

Concrete immersed in water swells (expands). If the ambient humidity is less than some value close to 100 %, concrete will shrink. These behaviors are clearly shown in Figure 1.1 by the results of the shrinkage experiments by Troxell et al. Troxell et al's data

is often used for the illustration of these phenomena, as the duration of the investigation was nearly 25 years.

1.3 Creep

Creep is the time-dependent increase of strain in hardened concrete subjected to sustained stress. It is obtained by subtracting, the sum of the initial instantaneous (usually considered elastic) strain due to the sustained stress, the shrinkage and thermal strain (from an identical load-free specimen) from the total measured strain in a loaded specimen, subjected to the same history of relative humidity and temperature. All materials experience creep, which is often temperature dependent. For concrete, it is necessary to separate the effects of shrinkage from the load-induced strains. Creep is designated as a stress under conditions of steady relative humidity and temperature, assuming the strain at loading (normal elastic strain) as the instantaneous strain at any time.

Creep in the CEB-FIP 1978 Model Code is divided into irreversible creep (plastic flow) and reversible creep (delayed elastic strain). In addition, the plastic flow is subdivided into a component representing flow for the first day under load (initial flow) and subsequent flow.

Creep measured on sealed concrete specimens, where moisture movement is prevented, is termed basic creep. Specimens loaded in a drying environment demonstrate drying creep, in addition to the basic creep and independently measured shrinkage.

- a) Basic creep occurs under the condition of no moisture movement to or from the environment.
- b) Drying creep is the strain remaining after subtracting shrinkage, elastic strain and basic creep from the total measured strain or in simple term, drying creep is the additional creep that is caused in a drying environment after subtracting shrinkage and basic creep.

Any effects of thermal strains resulting from heat of hydration effects have to be removed in all cases.

To measure creep, two nominally identical sets of specimens are made and subject to the same curing regime and environment; one set is not loaded and is used to determine shrinkage while the second set is loaded to 30 % to 40 % of the available concrete strength. Load induced strains are determined by subtracting the shrinkage strains from the strains measured on the loaded specimens. Figure 1.2 shows a set of results published by Troxell et al. Figure 1.1 was taken from this data set.

It is assumed that initial instantaneous strain, the creep strain, and the shrinkage are additive even though they affect each other. This is known as the additive principle. Without this assumption it would be necessary to do creep tests at all the stress levels envisaged in service. The additive relationship is written as:

$$\text{Total strain} = \text{shrinkage} + \text{elastic} + \text{basic creep} + \text{drying creep} \quad (1.1)$$

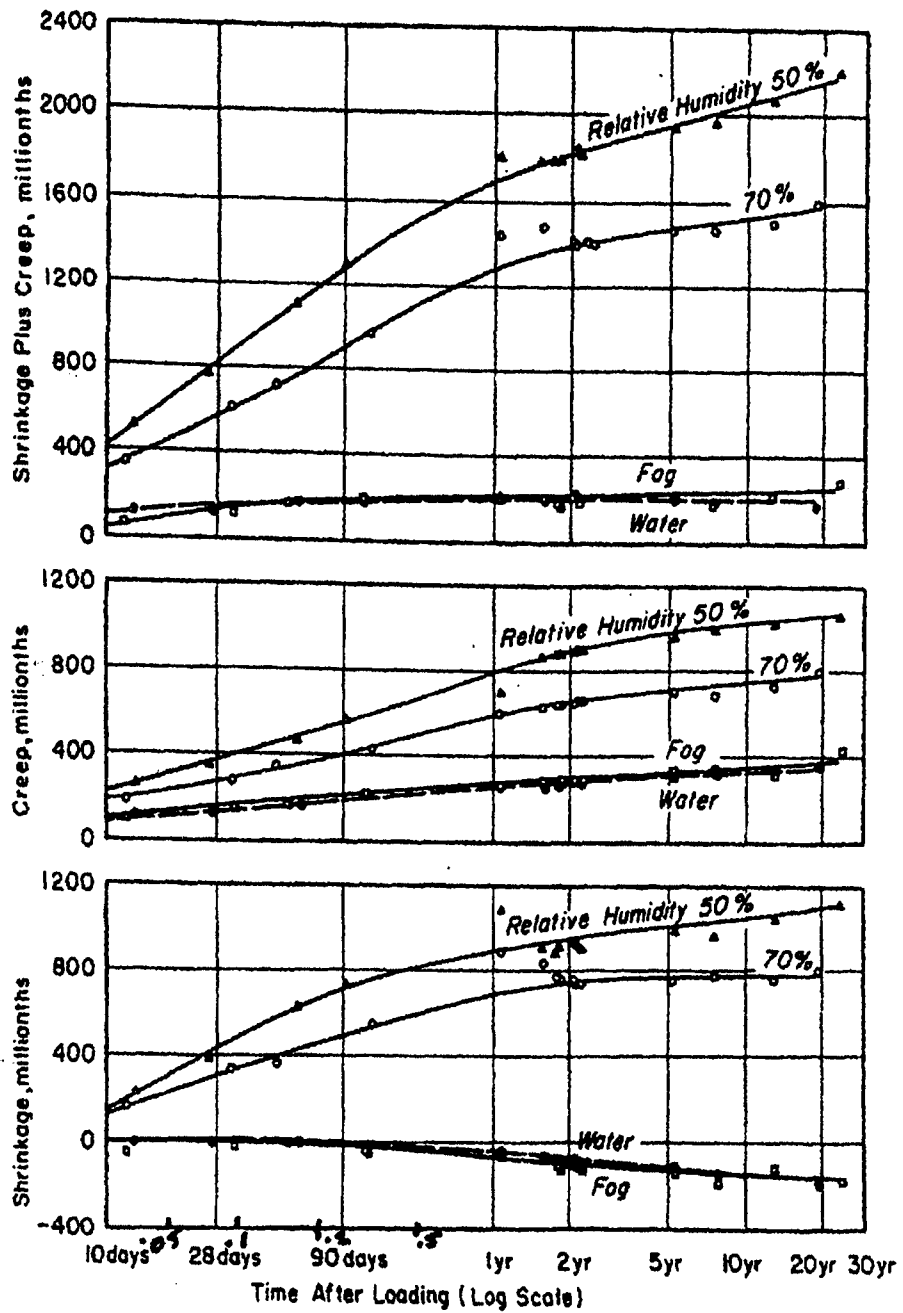


Figure 1.2 Troxel et al Long Duration Results

Total strain, shrinkage strain and immediate strain are measured; the creep strain is obtained by subtraction. Any errors in the measured modulus of elasticity, measured total strain or measured shrinkage strain are all reflected in the calculated creep strain. The immediate strain/unit stress, or its inverse the modulus of elasticity, is dependent upon the rate of loading.

Keeton (1965) in an extensive experimental investigation measured the total deformations of specimens subjected to zero stress (shrinkage) and stresses of 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 of the available strength at relative humidities of 75 %, 50 %, 20 % and immersed in water. Within the stress range of 10 % to 40 % of developed strength, the creep strains were proportional to stress. Extrapolating Keeton's experimental results at stresses of 0.4, 0.3, 0.2 and 0.1 of the available strength (f_{cm28}) to zero stress does not give the measured shrinkage strain but the difference is too small to abandon the principle that shrinkage and creep strains are independent and additive. The measured shrinkage was 965×10^{-6} and the back extrapolated shrinkage was 930×10^{-6} , a difference of 4%.

Experimental research has indicated that creep is approximately proportional to stress provided the stress applied is less than 40 % of the available strength and hence equation (1.1) can be rearranged as follows:

$$Total\ strain = shrinkage + \frac{stress}{E_{cmto}} (1 + basic\ creep\ coef. + drying\ creep\ coef.) \quad (1.2)$$

Specific creep = creep coefficient \times elastic strain

Compliance = (1 + creep coef.) \times elastic strain

E_{cmto} = mean modulus of elasticity at loading

The definition of creep coefficient given above, based upon the modulus of elasticity of the concrete at age of loading, is that used in ACI 209-82.

However, the CEB Model Codes and their derivatives define the creep coefficient with respect to the 28-day modulus of elasticity giving equation 1.3. Obviously, the ACI and CEB creep coefficients are logically and numerically different.

$$Total\ strain = shrinkage + \frac{stress}{E_{cm(t_0)}} + \frac{stress}{E_{cm(28)}} (basic\ creep\ coef. + drying\ creep\ coef.) \quad (1.3)$$

where:

$$E_{cm(28)} = \text{mean modulus of elasticity at 28 days}$$

If the load is reduced or totally removed from a previously loaded concrete there is an immediate elastic recovery of strain followed by recovery of some of the creep strains (a time-dependant recovery) i.e. strain is changed accordingly. The elastic recovery is simply the reciprocal of the modulus of elasticity at the age of unloading. The time-dependant recovery is generally referred as creep recovery. As shown in Figure 1.3, some residual deformation remains after total removal of the load.

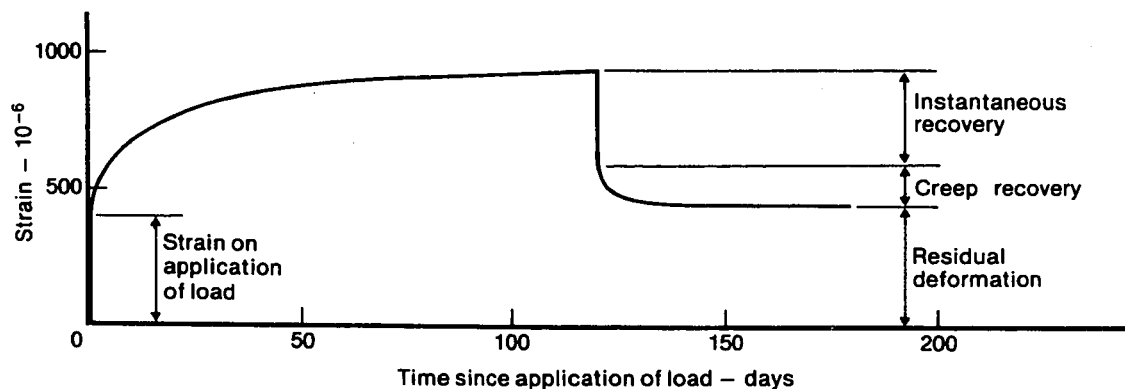


Figure 1.3 Creep Recovery

Experimental results show that the creep recovery is less than 100 %, i.e. the reduction in strain due to adding a negative unit load is less than the increase in strain due to adding a positive unit load to an already loaded specimen.

Structural engineers are often required to predict the behavior of a structure that may be subjected to loads that increase and/or decrease with time. The apparent reversibility of creep led McHenry (1943) to propose the principle of superposition. Creep is considered as a delayed elastic phenomenon in which full recovery is impeded only by further hydration of cement. Whenever a specimen is unloaded, it is treated as a negative load, which induces a creep equal, and opposite to that of a positive load of the same magnitude applied at the same time.

McHenry (1943) proposed the following hypothesis for superposition of load induced strains: "The strains produced in concrete at any time t by a stress increment applied at any time t_0 , are independent of the effects of any stress applied either earlier or later than t_0 . The increment may be either positive or negative providing stresses which approach the ultimate strength are excluded." For Fig.1.4 this implies that $Q + P = R$.

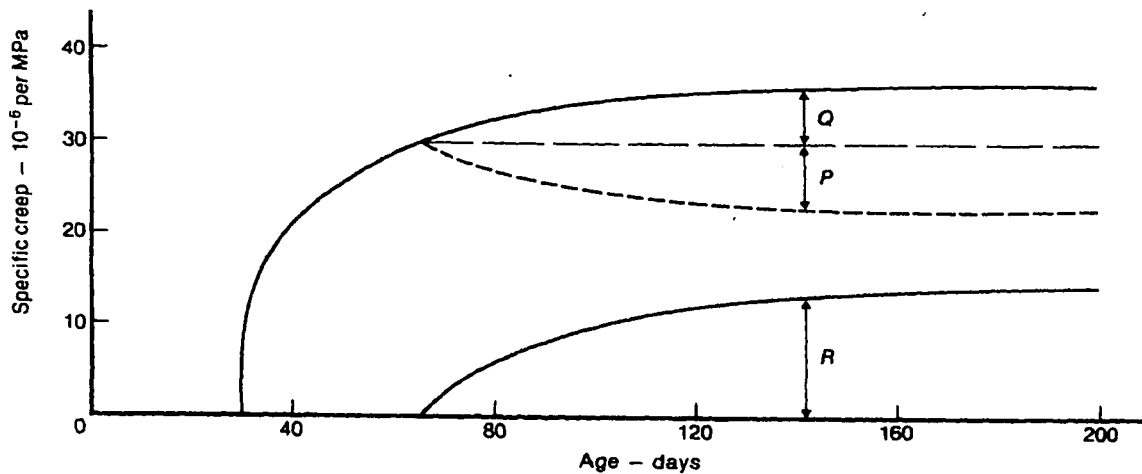


Figure 1.4 Principle of Superposition of Creep Strains

The validity of superposition can be demonstrated by relaxation, creep recovery under decreased loads or creep under increased loads for sealed specimens, specimens dried before loading and specimens loaded before drying. The validity of the hypothesis of superposition could be resolved by experimental research; however, relaxation tests, maintaining the strain constant and measuring the decreasing stress while adjusting for shrinkage in a drying environment, are very difficult.

If drying creep is consequent to moisture being expelled from the concrete due to load, superposition would require on unloading that the concrete absorb all expelled moisture which is difficult to justify. Hence, it would be difficult to accept the hypothesis of superposition for concretes subject to drying under decreasing stresses. Maney (1941) dismissed the seepage theory as a consequence for creep.

Calculating recovery by superposition is subject to more problems than calculating relaxation by superposition. If the moisture does not ingress into the concrete, drying creep would not be recoverable. If recovery is to be calculated by superposition both basic and drying creep compliance curves have to be parallel in time to give a constant compliance after unloading. If as described in Section 1.4, drying before loading reduces both basic and drying creep, it is not yet possible to determine a formulation that permits calculating recovery by superposition in a drying environment. Experimental evidence is inconclusive on whether both drying creep and basic creep are a hundred percent (100%) recoverable.

Precise creep equations to accurately compute creep strain over the duration of a concrete structure are complex. When dealing with concrete any thought of high precision must be dropped at the outset. However, the application of superposition presents a simplistic approach.

1.4 Drying before Loading: Pickett's Paradox

The Pickett Effect, also known as or drying creep is the result of the observation that the time dependent strains measured in a drying environment are larger than the sum of the shrinkage strain plus the creep strain of sealed concrete. Figure 1.5 (Acker 1993), shows that the evaporable water available in the concrete at loading limits both basic and drying creep. Pickett's paradox suggests that a previously dried concrete, specimen (a), exhibits practically no creep, during loading. Specimen (b) highlights the situation where moisture movement is prevented; however, the more evaporable water it contains, the more it creeps.

Specimen (c) that dries during loading shows the most creep, even though it gradually changes from the hydral state of specimen (b) to the hydral state of specimen (a).

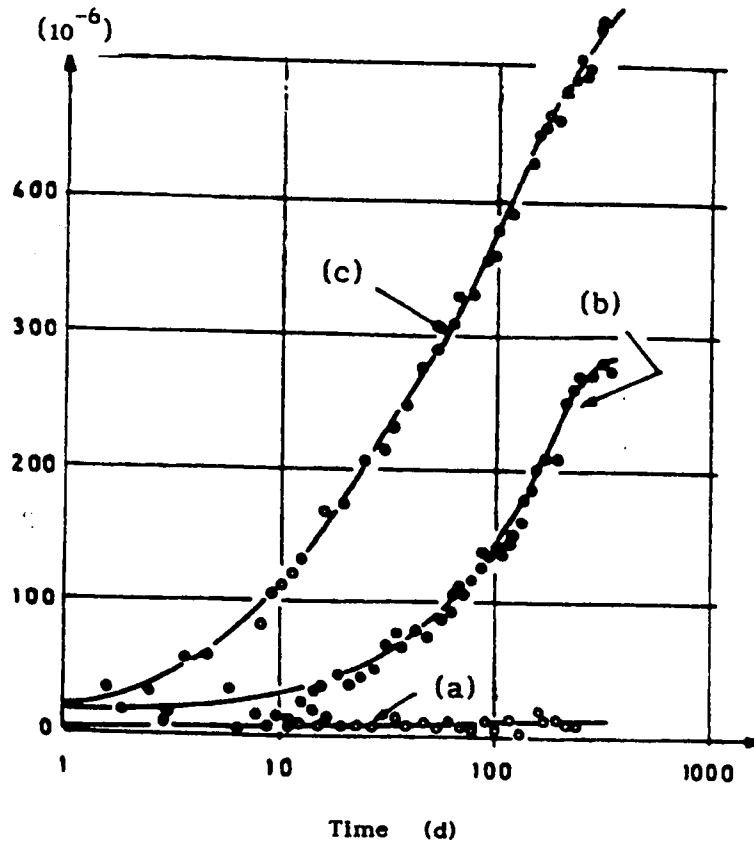


Figure 1.5 Pickett's paradox

Creep under 20 MPa, loaded at 42 days: (a) concrete dried at 40°C for 35 days and sealed, (b) sealed concrete, (c) concrete stored at 20°C and 50 % relative humidity

1.5 Loading History

Several researchers, including Yue L.L. and Taerwe L. (1992), have observed that concrete subjected to sustained load develops higher strength in comparison to identical

specimens stored without load exposed to the same temperature and humidity, due to load strengthening and/or load stiffening.

Loading history influences creep recovery and its rate of development with time. It is commonly assumed that recoverable creep develops rapidly with time, while unrecoverable creep develops slowly. Therefore, under the same loading age or unloading age, when the load history is shorter recoverable creep forms a higher percentage of creep than with a longer load history. Analysis of existing test data by Yue and Taerwe (1993) showed that the initial creep recovery per unit stress is generally smaller than the initial strain per unit stress of previously unloaded concrete at the same concrete age and this is probably due to the application of load which creates a stiffer concrete. It was also observed that initial creep recovery per unit stress at the same unloading age is often larger when loading occurs at an early age, which would indicate that the degree of stiffness is affected by the loading history.

1.6 Concrete as an Engineering Material

Concrete is an age stiffening material that has low tensile strength, shrinks in environments with relative humidities less than 96%-98%, exhibits creep in sealed conditions and additional drying creep in environments with relative humidities less than 96%-98%.

There are three fundamental types of deformation occurring in concrete: elastic, plastic and viscous. These deformations can occur in combination such as elasto-plastic

or visco-elastic. Delayed elasticity can be considered as a form of creep, usually characteristic of a disorderly molecular arrangement. This deformation occurs at a decreasing rate and is fully reversible because the energy producing it is stored in the material and not dissipated. The elasticity caused by the flow of the liquid phase is due to the elastic after-effect.

Plasticity deformation is due wholly to distortion without a volumetric change. This occurs when the potential energy of an external force is larger than the internal thermal energy. Plastic flow is characterized by a plastic limit; below this stress, value there is no flow. When irrecoverable deformation (plastic flow) increases with the duration of applied load, the material is said to flow.

Viscosity is of a material occurs when the potential energy of an external force is relatively small compared with the internal energy of the molecular structure. Viscous flow applies to ideal fluids and requires that the rate of strain (with respect to time t) be proportional to the applied stress. It has been established that concrete has no plastic limit so that in the rheological sense concrete is a fluid. Thus, the irrecoverable time-dependent deformation should be designated as viscous.

According to Hansen (indirect reference from Neville, Dilger and Brooks 1983), the principle of superposition of strains approximately holds for concrete, and this is valid only in elastic or visco-elastic material state as no superposition can be applied to plastic deformation. There is the indication that the time dependent irrecoverable deformation is not

purely viscous but includes some permanent set due to closing of the gel structure. This may be the explanation why superposition overestimates creep recovery.

Under sustained load concrete will creep. The creep on concrete has been hypothesized as due to:

- a) Viscous flow of the cement paste.
- b) Consolidation due the flow of absorbed water from the cement gel through applied pressure.
- c) Delayed elasticity due to the cement paste as a restraint on the elastic deformation of the crystalline structure.
- d) Permanent deformation caused by localized fracture.

1.7 Objective

This experimental investigation was designed to study the validity of the hypothesis of superposition of creep strains by measuring and comparing the time dependent strains of concrete prisms subjected to increasing and decreasing loads, constant loads, and late loads (for unsealed concrete specimens which were dried before loading and sealed concrete specimens kept in moist room). This investigation was an extension of that described by Gardner and Tsuruta (2004) to verify superposition for a third load event and to determine if the recovery of unsealed specimens were similar to the creep of a late loaded sealed specimen. Strains were measured using vibrating wire gages and self-consolidating concrete was used for ease of fabrication.

CHAPTER 2

LITERATURE REVIEW – PREVIOUS RESEARCH

This chapter gives an overview on work done by researchers in the investigation of the validity of the principle of superposition on concrete.

Boltzman (1874) proposed the principle of superposition for simultaneous and successive actions for isotropic materials with deferred elasticity. Quoting from a translation of “Zur Theorie der elastische Nachwirkung”. “I only assumed that the forces which act on the faces of a parallelepiped at a give instant depend not on the present deformations at a given instant but also on former deformations---. More precisely, the force necessary to produce a given deformation is smaller when a deformation has occurred previously in the same direction and is called the reduction in force due to previous deformations. If at any instant τ during the element time $d\tau$ the body has a deformation $\epsilon(\tau)$, it is assumed that the reduction in force which this deformation exerts on the force acting at t is proportional to $d\tau$, to $\epsilon(\tau)$ and to a function of $t - \tau$ separating these two instants”.

“To that I add the hypothesis stating that the influence of deformations, which have occurred at different times, is superposed, that is to say that the lowering of the force having caused a given deformation at a given time will not depend on the states of the in the interval (.)”.

Boltzmann noted that while the principle of superposition is plausible for deformations that are not too large, perhaps it does not longer apply for very large deformations.

Boltzman's theory is widely used in polymer engineering but relatively unknown in concrete technology.

Maney (1941) in a series of experiments presented evidence to support his argument that "plastic flow" or creep, which have been considered to be the inelastic time yield of concrete under low working load ranging from 300-1000 psi (2 - 7 MPa), are negligible when concrete is loaded under the low-stress conditions of ordinary practice. Maney noted the correlation between "plastic flow" and shrinkage and concluded that "plastic flow" is merely a phenomenon of elastic deformation resulting from non-uniform shrinkage.

Maney in one of his experiments demonstrated his argument that water loss is independent of load intensity by comparing the loss of weights between loaded and never loaded plain concrete specimens due to drying out of mix. Six (6) specimens in two groups of three (3) were used. Each specimen had an average weight of 6.13 pounds (2.78 kg). Group No.1 was loaded under a continuous stress of 1000 psi (7 MPa) at 8 days, while group No. 2 was never loaded. In this experiment, great care was taken to assure that both the loaded and never loaded specimens had the same surfaces exposed

and experienced the same humidity condition. The result showed similar losses in weight of both groups and emphasized the fact that moisture loss depends on the surrounding humidity and is not affected by loading. This was contrary to the expectation that if loaded concrete shortened more than unloaded concrete it should lose more moisture by seepage, as well as shrinkage water loss.

Maney in his closing statement from his article "Concrete under sustained Working Load" referred to available evidence which points to the dominance which shrinkage exerts over all time yields occurring under working load conditions. He acknowledged that some "plastic flow" occurred under working load but pointed out that all the important time yields under load which other investigators attribute to "plastic flow" are merely elastic redistributions of stress and strain due to non-uniform shrinkage or warping.

MacHenry (1943) noted that creep occurred equally for increasing and decreasing load increments. MacHenry, who was aware of Boltzman's work, proposed the modern/current principle of superposition for concrete in an article entitled "A new aspect of creep in concrete and its application to design". He stated "The deformation caused in concrete at a time t by a variation in stress applied at a time t_0 are independent of the effects of any other stress applied at a time different from t_0 , before or after. The variation in stress can be negative or positive but must not approach ultimate strength". MacHenry continued his argument by saying "Any appearance of simple finality in this statement is deceptive, for if the statement is verified it may in combination with the

presumption that the sustained modulus is independent of stress intensity and constitute the beginning of a rather extensive analysis of the stress-strain relationship in concrete.

“An immediate inference from the principle is that when a sustained load is removed from concrete which was first loaded and the properties had become constant, the load removal will be followed by an eventual complete recovery of both instantaneous and creep strains. This is because a load removal may be represented by the addition of an equal load of opposite sign. If the two opposing loads are to be maintained indefinitely, it is apparent that the two opposing components, which determine the creep recovery, must asymptotically approach equality and thus will cancel each other eventually.”

Freudenthal and Roll (1958) reported studies on creep and creep recovery of plain concrete under sustained compressive stresses varying between 15% and 65% of the 28-day compressive strength using four series of test data and four different mixes. The 1:1 mix (cement: fine + coarse aggregate) represented an essentially viscous body (cement paste) in which the aggregate was “floating”. The 1:6 mix represented an essentially solid mass of aggregate, the voids were filled by the viscous cement paste. The 1:2.5 mix represented an intermediate concrete, possibly the richest concrete mix still used in a structure. It should be noted that different cement types were used.

Table 2.1 Average Compressive Strength

Mix	Series	Cement:sand:aggregate (By weight)	Comparisons of Average Compressive Strength at 28-Days: psi (MPa)
1:1	1	1:0.4:0.6	9360 (64.53)
1:2.5	1	1:1.0:1.5	6160 (42.50)
1:6	1	1:2.4:3.6	5040 (34.75)
1:1	2	1:0.4:0.6	9070 (62.54)
1:2.5	2	1:1.0:1.5	5670 (39.0)
1:6	2	1:2.4:3.6	5110 (35.23)
1:1	3	1:0.4:0.6	8940 (61.6)
1:2.5	3	1:1.0:1.5	6490 (44.75)
1:6	3	1:2.4:3.6	6100 (42.06)
1:1	4	1:0.4:0.6	8900 (61.36)
1:2.5	4	1:1.0:1.5	6900 (47.53)
1:6	4	1:2.4:3.6	6000 (41.37)
1:4	4	1:1.6:2.4	6370 (43.92)

Curing conditions and test environment were identical for all mixes and test series. The fresh concrete was left in the cylinder molds for approximately 18 hours at ambient laboratory temperature and humidity. The molds were then stripped and the cylinders placed for 14 days in a moist-room at 100% relative humidity and approximately 70°F (22°C). Subsequently the cylinders were stored in an air-conditioned room at 70°F and 60% relative humidity. Temperature and humidity were recorded

during tests so that any variations of creep and shrinkage due to temperature or humidity could be noted. The purpose and procedure of each test series is described below.

The purpose of test *Series 1* was to study the effect a given stress level has on creep for different concrete mixes in comparison to the effect of that stress level upon creep for a given concrete mix.

Series 1, consisted of 4 x 10 inches (100 x 250 mm) cylinders of mixes 1:1, 1:2.5, and 1:6, (cement: fine + coarse aggregate) which had sustained loads of full spring capacity (40 kips or 178 KN) and half spring capacity for 168 days.

In test *Series 2*, the sustained loads were cycled, being applied for 28 days and essentially removed (reduced to 500 lbs or 2.24 KN) for the next 28 days. This loading-unloading sequence was repeated three times. After the third sequence (168 days), loads were re-applied and sustained for an additional 203 days. The purpose was to study the effects of periodically sustained loads upon creep, strength and stiffness, as well as the time-dependent elastic recovery upon unloading (creep recovery).

The purpose for *Test Series 3* was the same as for *Series 1*. The use of 3 inch (75 mm) diameter specimens permitted the application of the same high stress levels as for all three mixes and thus a more direct comparison of the effect of concrete mix upon creep for a given stress level. Use of three stress levels gave a clearer picture of the nonlinearity of the stress-creep relation. Sustained loads of 20, 40, and 60% of the 28-day ultimate

strengths of mixes 1:1, 1:2.5, and 1:6 were applied to 3 x 10 inches (75 x 250 mm) cylinders at 168 days. In addition, a sustained load of 50% of ultimate strength was applied to a 3 x 10 inches (75 x 250 mm) cylinder of mix 1:1 for 168 days. A load of 80% of ultimate strength was applied to a 3 x 10 inches (75 x 250 mm) cylinder of mix 1:6 for 10 days, at which time an explosive failure occurred. A sustained load of full spring capacity (40 kips) was applied to 4 x 10 inches (100 x 250 mm) cylinders of the three mixes. The use of 4-inch (100 mm) diameter cylinder was only for comparison with the results of *Series 1*.

Test *Series 4* was to compare creep predicted by a proposed concrete model, with the actual creep. Sustained loads of 20, 35, 50 and 65 % of the 28-day ultimate strengths of 1:1, 1:2.5, 1:4(1:1.6:2.4), and 1:6 mixes were applied to 3 x 10 inches (75 x 250 mm) cylinders for 210 days. Supplementary compression tests were conducted to determine the effect of sustained load on strength and modulus of elasticity of the concrete. The moduli of elasticity were determined on 6 x 12 inches (150 x 300 mm) cylinders and on the cylinders from the creep rigs. In both cases, the moduli were defined in terms of the unloading stress increment and the corresponding instantaneous strain recovery.

The effect of time alone was to increase the strength of the 4 x 10 inches (100 x 250 mm) and the 6 x 10 inches (150 x 300 mm) cylinders for mixes 1:6 and 1:2.5 respectively. However aging of the rich 1:1 mix was negligible; in some cases, there was a slight decrease in strength (3 x 10 inches (75 x 250 mm) cylinders of *Series 3* at 196 days). This result suggested that with small specimens, rapid drying has a detrimental

effect on the strength of concrete and that size may have some influence upon the aging properties of concrete.

Test Results

The effect of sustained load upon compressive strength was comparatively small for 4 x 10 inches (100 x 250 mm) cylinders. The 3 x 10 inches (75 x 250 mm) cylinders from the 1:6 mix showed an appreciable increase in strength due to sustained loads, while mixes 1:2.5 and 1:1 showed smaller and negligible increases respectively.

The effect of age alone upon the modulus of elasticity for the 6 x 12 inches (150 x 300 mm) cylinders was negligible. The authors noted that this was a direct contradiction of the accepted belief of an increase in the modulus of elasticity with age, where the modulus is defined in the conventional manner as the slope of a secant of the loading stress-strain curve.

Freudenthal and Roll established from their creep test results that the nonlinear behavior of the creep-stress relationship was apparent in all series of mixes. To illustrate this nonlinearity, the average creep was plotted as a function of the specific stress level (ratio of applied stress to the 28-day ultimate strength) with time. The curves of plots average creep versus specific stress showed that creep is a linear function of stress up to stresses of 26 % of ultimate strength of concrete but are nonlinear for higher stresses. This limiting stress is slightly less when the load was sustained for a short period but higher for a longer period. When comparing the creep of different mixes subjected to the

same stress level, it was seen in *Series 3 & 4* that mix 1:2.5 has the largest creep strains and mix 1:6 the smallest. The nonlinearity of the creep due to high stresses was highest for mix 1:1. Creep recovery appears to be complete within a few days after removal of the stress and is a linear function of the previously sustained stress, regardless of the magnitude of that stress level, or the numbers of previous load cycles.

Freudenthal and Roll noted that these results are limited to tests on relatively small cylinders done at the same age and for relatively short periods subject to the same environmental conditions.

Ross (1958) noted that concrete structures in use are subjected to variable stress whereas most of the data on creep were obtained from specimens subjected to constant stress. Ross discussed and compared three (3) methods proposed to compute creep under variable stress from the results under constant stress. The methods are:

1. Effective Modulus
2. Rate of Creep
3. Superposition

Plain concrete mix 1:1.6:2:8 was used with rapid hardening Portland cement and a water cement ratio of 0.375 by weight compacted by vibration. This concrete had a 4 inch cube strength of 9600 psi (66.2 MPa) after 28 days at 17°C. The creep specimens were 4 5/8 " diameter (115 mm) cylinders 12 inches (300 mm) inches long; the strength of the concrete in this form was 70% of the cube strength. A simple stressing device was

developed to sustain loads up to 17 tons (17.3 Mg on the concrete) and each test rig incorporated a load dynamometer in the form of a length of mild steel tubing with provision for strain measurements along three gage lengths arranged at 120 degrees intervals around the perimeter. Every loaded specimen was accompanied by an unstressed control to establish the shrinkage under identical atmospheric conditions. All specimens were stored in a chamber maintained at 17 °C and 93% relative humidity.

Specimens subjected to a constant stress of 2000 psi (13.79 MPa) applied at various ages, while other specimens were subjected a stress variation ranging from 545 to 2180 psi (3.76 – 15.03 MPa). The tests were designed to examine the simplest case of stress variation, i.e. a period of constant stress followed by complete removal of load so that recovery of creep under zero stress could be observed. In six (6) other tests, stresses were altered in increasing and decreasing load increments. It was expected that these variations would provide a critical test of the three (3) methods of calculating creep strains.

Results showed that the *effective modulus method* would predict an obvious erroneous value of strain immediately after a sudden change of stress. The effective modulus gave a poor prediction for severe variations, underestimating the strain when the stress is diminishing and visa versa.

Strain curves computed by the *rate of creep method* show an agreement with experimental results, which was surprising in view of the theoretical deficiencies of the

method. It was noticeable that this method cannot predict a creep recovery following a reduction of stress, so that the curvature in the creep-time curve is sometimes wrong. The shape predicted on complete removal of the load, is a horizontal straight line, and is always wrong. Experimental diagrams confirm the theoretical deductions that the rate of creep method overestimates creep under reduced stress.

The strain-time curves computed by *superposition* show fair agreement with experimental results, though not markedly superior to those computed by the rate of creep method. The method of superposition however shows superiority over other methods and gives the best result but one not very different from the approximate result.

Ross reported in his investigation that, the principle of superposition overestimates recovery in concrete subjected to both basic and drying creep.

Polivka, Pirtz and Adams (1964) reported on experimental investigations of creep in mass concrete. In one of their studies, creep characteristics for mass concrete containing six (6) inches (150 mm) maximum size aggregates, were compared with wet-screened concretes from the same mix containing 1 ½ or 3 inches (35 or 75 mm) maximum size aggregates. Specimen sizes used for measuring creep were as follows; mass concrete (6 inches (150 mm) aggregate size) a 30 x 60 inches (750 x 1500 mm) cylindrical specimen, wet-screened concrete 16 x 32 inches (400 x 800 mm) cylinders (3 inches (75 mm) aggregate size), and 6 x 18 inches (150 x 450 mm) cylinders (1 ½ inches (35 mm) aggregate size). All these specimens were loaded at 31 days.

The oil pressure supplied to pressure cells by a fuel injection pump accomplished the loading of creep specimens. An electronic controller was used to maintain pressure in case of power failure. All creep frames were supplied pressure from a single system in order to assure the same sustained pressures at any time. Results showed creep of the concrete to be directly proportional to the paste content of the mix. The wet-screened specimens containing the smaller aggregates had greater paste contents and thereby exhibited greater creep.

Comparison was also made between the creep characteristics of large mass concrete specimens (6 inches (150 mm) maximum aggregate size) and sealed wet-screened mass concrete (1½ inches (35 mm) maximum aggregate size). As would be expected the results showed that the mass concrete exhibited lower creep than the mix containing only the 1½ inches (35 mm) maximum size aggregate.

Two series of investigations were undertaken to determine the effect of loading history on creep and strain recovery. In the Series 1 investigation (three 16x 44 inches (400 x 1115 mm) cylinders), specimens of a mass concrete, wet-screened (3 inches (75 mm) maximum aggregate size) were subjected to initial sustained loads at early ages of 1 day (stress of 80 psi or 0.55 MPa), 3 days (stress of 350 psi or 2.41 MPa), and 7 days (stress of 350 psi). These sustained loads were increased at age 28 days (stress of 800 psi or 5.52 MPa), and maintained until recovery strains were determined at age 412 days. In the second investigation, Series 2, a very lean mass concrete (4½ inches (110 mm) maximum size) was subjected to initial sustained loads at ages of 3, 7, and 28 days.

At 90 days, the sustained loads were increased, and at 300 days the loads were removed and recovery strains were measured. In both studies, concrete specimens not previously loaded were subjected to sustained loads at the age of recovery measurement. These specimens were tested to study the principle of superposition on recovery of concretes having previous load history. The hydraulic loading system permitted all loadings or unloading to be carried out in less than 1 minute. All instantaneous strains and recoveries were determined within 30 to 60 seconds from the time loading started.

The experimental results demonstrated that previous loading history, at early ages of concrete, has a definite effect on creep at later ages. The largest creep rate due to increase in sustained load at 28 days was observed for the specimen initially loaded at 1 day with 80 psi (0.55 MPa); the smallest creep rate was observed for specimens initially loaded at 3 days with 350 psi (2.41 MPa). An intermediate creep rate was observed for the specimen initially loaded at 7 days. The lower the initially applied load, in terms of percentage of compressive strength at later ages, the greater the creep rate due to increase in load at the later ages. It was also demonstrated that the early-age loading history has no appreciable effect on strain recovery of concretes subjected to an increased sustained load over an extended period.

Polivka, Pirtz and Adams concluded with four (4) points.

1. Preloading history influences creep at a later age due to an increase in sustained load. The later age creep rates appear to be dependent on the relative load level at early ages. The lower the initial load with respect to

- the ultimate strength at a later age, then the greater the creep rate at later ages due to increase of the load.
2. Elastic strains, total elastic-plus-creep recovery strains at late ages seem to be independent of the previous load history.
 3. Creep of concrete loaded for the first time, along with creep recovery are essentially identical.
 4. Instantaneous strain recovery and the strain of a concrete loaded for the first time, both occurring at the same age, differ slightly. The instantaneous strain recovery is slightly lower than the strain on loading. Permanent set and change in structure due to sustained load are probably responsible for the difference.

The results of Polivka, Pirtz and Adams demonstrated experimentally that the principle of superposition overestimates recovery of concrete subject to basic creep.

Neville (1970), Maney, and Hansen (indirect reference from Neville, 1970) disputed the seepage theory (external evaporation of moisture) as a possible phenomenon that causes creep due to compressive preload.

Lynam proposed the seepage theory of creep of concrete in 1934. Seepage was described as "a viscous flow of the dispersion medium through and ahead of the disperse phase" due to the application of load. On unloading, there is a partial but immediate recovery, followed by a slow elastic after-effect as seepage is reversed. The seepage

theory arises from the observation that hydrated cement paste is a rigid gel, and when load is applied there is an expulsion of the viscous component from the void in the elastic skeleton; causing a redistribution of stresses from the viscous component to the elastic skeleton. As a result, creep in concrete is taken to be due to seepage of gel water under pore pressure. In this way creep is analogous to shrinkage, except the former is caused by an externally applied pressure, while the latter is a direct vapor pressure differential with the ambient surroundings.

Seed, Lea and Lee (indirect reference from Neville, 1970) also supported the seepage theory. In their explanation, they hypothesized that the application of an external stress to concrete causes a change in the internal vapor pressure and hence in the gel water content, with accompanying volume changes. The rate of seepage depends on the moisture gradient. When water is squeezed out, the stress on the solid increases and the pressure on the water decreases, with a resulting reduction in the rate of expulsion of the water. Creep is a manifestation of the delay in re-establishing the equilibrium between the gel and its surroundings. Creep recovery is simply the tendency to re-establish the original state, after the external load is removed. However full recovery is prevented by the formation of new bonds, and only the gel water is involved in seepage.

A concrete specimen stored in air of 100% relative humidity is exposed to full vapor pressure of water at that temperature. This vapor pressure prevents evaporation and the direction of flow is usually inward since the hygroscopic gel can then take up water. This will continue until, with time, the equilibrium between the outside and the inside

vapor pressure has been reached. As moisture is lost, the gel shrinks owing to the collapse of pore spaces within it. On the other hand, as these pore spaces become filled with water the gel swells. It was stated that since this moisture movement can also be produced by external pressure, it would appear that shrinkage due to loss of moisture and creep due to seepage are interrelated phenomena.

Neville (1970) argued that the seepage theory does not explain the following.

1. Why does concrete dried in air and then subjected to a compressive stress in water creeps about twice as much as concrete stored and loaded in water?
2. Why does the creep of concrete under tension in water is about the same as that under compression in water? (According to the seepage theory it should be smaller under compression)

Neville noted that measured loss of water from concrete subjected to compressive stress is insufficient to account for the quantity of water loss supposed to be by seepage.

Neville, Maney and Mamillan (1982) found out that the amount of water loss from shrinkage specimens were similar to the losses from creep specimens. Hansen found no difference in creep of sealed and unsealed preconditioned specimens subjected to compressive for 453 days at a relative humidity of 60% at 68°F (20°C). He concluded that no external seepage took place.

Gamble and Parrot (1978) investigated the effect of variable stress and variable moisture history on the shrinkage and creep of concrete. To simulate practice, specimens were loaded before drying. Systematic studies of creep in concrete indicated that simultaneous stress and moisture-change gives rise to a total strain in excess of the sum of separate steady-moisture-state creep and shrinkage responses. Basic creep was determined on specimens wrapped in moist toweling.

Gamble and Parrot observed that drying creep was directly proportional to shrinkage and could be related to shrinkage by a single coefficient. For practical purposes, there was good correlation between the coefficient and water/cement ratio and 28 days compressive strength of different mixes. Gamble and Parrott concluded that basic and drying creep are recoverable to the same extent, but only 20% to 25% of the original creep is recoverable.

Mamillan (1982) conducted tests on six (6) batches of concrete where all precautions were taken at the CEBTP Laboratories to make test specimens as identical as possible. Five test specimens were made from each batch. Of the five specimens two were not loaded to measure shrinkage, one was loaded at 7 days, and another was loaded at 28 days. The fifth specimen was loaded at 7 days, with its load doubled at 28 days.

Deformations were measured for 1700 days after casting. Tests were carried out in duplicates as follows:

Series C and F experienced compressive stress of 2.53 MPa

Series A and D experienced compressive stress of 5.07 MPa

Series B and E experienced compressive stress of 7.60 MPa

The aim of this experiment was to verify that after 1700 days the deformation;

$$\epsilon_3 = \epsilon_1 + \epsilon_2$$

where:

ϵ_3 = Deformation (instantaneous + deferred) at 1700 days following successive loadings at 7 days under σ_0 and at 28 days under $2\sigma_0$

ϵ_1 = Deformation (instantaneous + deferred) at 1700 days resulting from loading at 7 days under σ_0

ϵ_2 = Deformation (instantaneous + deferred) at the same date due to loadings at 28 days under σ_0

Mamillan (1982) compared the curve of experimental deformation under the addition of the two stresses, one applied at 7 days, the other at 28 days on the test specimen S_3 , and the theoretical curve obtained from adding the deformations caused by separate loadings at 7 days on the specimen S_1 , and at 28 days on specimen S_2 .

For the six series, with stress of 2.53 Mpa, 5.06 Mpa, 7.60 MPa the curves calculated according to Boltzmann principle are always lower than the experimental curve. This indicates that this principle of superposition under estimates the real deformation. The essential result of Macmillan's research was a deviation of 10% between Boltzmann's Theory and experimental values for increased loads.

Yue and Taerwe (1992 and 1993) published two related papers on creep recovery. Yue and Taerwe commented "It is well known that the application of the principle of superposition in the service stress range yields an inaccurate prediction of concrete creep when unloading takes place. It appears that after a period of compressive creep, the experimental creep recovery is significantly less than predicted by the principle of superposition." Based on a systematic, experimental investigation Yue and Taerwe (1992) highlighted the influence of some factors such as preloaded stress variation levels, loading history, and concrete type on creep recovery. As a simple relationship between creep recovery and elastic strain at loading or its developed creep strain does not exist but the effects of loading history have to be considered to predict creep recovery properly. Hence, the evolution of creep recovery is dependent on the loading age as well as the duration of load. In their extensive research, Yue and Taerwe used concrete made from Portland cement type P40, and had a water/cement ratio of 0.46. The creep specimens and companion specimens were prisms 150mm x 150mm in cross-section and 600 mm in height. After casting, all the specimens were transferred immediately to an air-conditioned room at a temperature of 20°C and a relative humidity of 60% and remained there during the whole test period. The applied stress level before unloading corresponded to a stress/strength ratio ranging from 0.15 to 0.45. The loading age varied from 3 to 91 days, and the unloading age from 28 days to 210 days.

Yue and Taerwe concluded that the application of the superposition rule generally results in a significant over estimation of creep recovery. Yue and Taerwe mentioned that

the non-linear creep recovery behavior of concrete is due to sustained compressive pre-load, called load stiffening.

In their proposed “Two-Function Method”, a linear creep function is used to model the time-dependent deformations due to increased stress on concrete and a separate non-linear creep recovery function is used to represent concrete behavior under decreasing stress. Experimental findings revealed that concrete creeps stains depend linearly upon the sustained constant stress level, and the calculation of creep caused by variable stress within the service limit is often computed base on the principle of superposition. Creep is said to be a delayed elastic phenomenon, whereby the total creep recovery is prevented by further hydration of cement. Removal of load is treated as a negative load, which induces s creep equal and opposite to that which would be caused by a positive load of the same magnitude applied at the same time. Yue and Taerwe’s proposed model used an optimization technique for parameter estimation named Marquardt’s Method. The model includes the following principal features:

- (a) The development of creep with time is characterized by a hyperbolic power function.
- (b) The influence of the preloading history on final creep recovery, as well as on the development of creep recovery with time is considered.
- (c) The creep recovery is assumed independent of temperature, humidity and the sizes of the specimens.
- (d) The material parameters are unaffected by the strength of concrete.
- (e) The prediction model can also be applied to high strength concrete.

The Two-Function Method requires both a creep function and a creep recovery function. For the creep function, the formulation presented in the CEB-FIP Model Code 1990 (MC90) was adopted by Yue and Taerwe in a slightly modified form.

For the creep recovery three different mathematical expressions, such as hyperbolic-power, single-exponential and multi-exponential expression were applied to the following Models. CEB Model Code of 1978 (MC78), the improved CEB Model Code (IMC78) and the Revised Summation Model (RSM). In the MC78 and IMC78 models, creep recovery is considered independent of loading and unloading age. RSM however takes into account the influence of loading history on the development of creep recovery.

The following mathematical model for recovery was proposed.

$$\varepsilon_{cr} = \sigma \phi_{cr}(t_0, t_1) \beta_{cr}(t, t_0, t_1) / E_{cr} \quad (2.4)$$

Final value of creep recovery is estimated by

$$\phi_{cr}(t_0, t_1) = 0.35 / (\sqrt{\alpha}) \quad (2.5)$$

The development of creep recovery with time is predicted by

$$\beta_{cr}(t, t_0, t_1) = [(t - t_1) / (t - t_1 + 300\alpha)]^{0.24} \quad (2.6)$$

Where

$$\alpha = 1 - \exp[-0.1 \{t_0 + 0.05(t_1 - t_0)\}] \quad (2.7)$$

Experimental results yielded discrepancies when compared to predictions by the application of the principle of superposition for creep recovery. The two-function method gives an excellent fit between prediction and experimental results. The deviations

between prediction and experimental that are usually observed when applying the principle of superposition are avoided by making use of one creep function for loading and another for unloading. In the case of unloading, complete removal of stress results in a time-dependent recovery, this reaches a limiting value. Partial removal of stress resulted in two opposite motions. Creep recovery is due to the removal of stress and continued creep due to the remaining stress. The resulting strain will be the algebraic sum of the two time-dependent strains. Based on this consideration, creep strain under variable stress can be calculated by using a creep function for loading and a different one for unloading.

Gardner and Tsuruta (2004) reported an experimental investigation to determine if superposition of creep strain is valid for concretes subjected to drying creep using concrete prisms subjected to uniaxial compression. Three (3) designated conditions were drying before loading, loading before drying and sealed state. Five series of specimens were fabricated. The sizes of the specimens were 100 x 100 x 400 mm concrete prism using vibrating wire gages to measure strains. Series 1, consisted of sixteen (16) specimens, while Series 2, 3, 4, and 5, consisted of 11 specimens. Some of these specimens were sealed and loaded; others were allowed to dry before loading and loaded before drying. Two controlled environment were used namely a 50% and a 95-99% relative humidity rooms and at a temperature between 20 and 23°C. Some specimens were moist cured and loaded in a spring compensating frame as early as 3 or 4 days, while others were late loaded. After forty (40) days some early aged loaded, specimens were unloaded for creep recovery. Stress application varies from 8 MPa to 16 Mpa. Strains were measured at loading 1, 2, 4, 7, 21 and 28 days after loading, and thereafter at

2-week intervals. Loads measured by a load cell were applied with a 400 KN hydraulic jack.

Gardner and Tsuruta concluded that in all the three conditions, drying before loading, loading before drying and sealed, creep recovery was only 70 to 80% of the creep of previously never loaded concrete for loads applied at the same age as the recovery. They further concluded that superposition is not valid for sealed concrete or concrete subjected to drying for situations that involve unloading. The validity of superposition of creep strains of increasing loads depends upon the age at which the concrete was first loaded relative to the duration of moisture curing. For drying before loading and loading before drying, the measured incremental creeps are 10% and 20% larger respectively, than the creep of late loaded specimens. For sealed concrete, the creep due to an incremental increase in load was identical to the creep of the late-loaded concrete.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

This experimental investigation was designed to investigate the validity of the hypothesis of superposition of creep strains by measuring and comparing the time dependent strains of concrete prisms subjected to increasing and decreasing loads, constant loads and late loads (for sealed concrete and concrete specimens which are dried before loading). Three series of specimens were fabricated, identified as Series 'A', Series 'B', and Series 'C'. Each series had sixteen 100 mm x 100mm x 400 mm prisms which were used for shrinkage and creep measurements, with 18-22, 100mm diameter by 200mm cylinders for cylinder strength measurements. Each series was essentially fabricated independent of the other. Some specimens within each series were placed in creep frames, loaded, strains monitored, and shrinkage strains were inferred from unloaded specimens. Loads were applied at three ages, 4 days, 20 days and 87 days for Series A, 3 days, 18 days and 108 days for Series B and 4 days, 18 days and 101 days for Series C. At each loading stage, cylinders that were subjected to the same environment as the prisms were crushed to determine concrete strengths.

Spring compensated creep frames were used with spring stiffnesses and capacities appropriate to the maximum loads applied. It took an average 10-20 minutes to initially load the specimens and unloading had to be done in at least two stages. Uniaxial compressive loads were applied through a load cell, by means of a 450 KN hydraulic jack. The set up is shown in Figure 3.1. Creep prisms were loaded in creep frames using

1" (25 mm) steel plates and either $\frac{5}{8}$ " or 1" (15 or 25 mm) diameter threaded rods as shown in Figure 3.1.

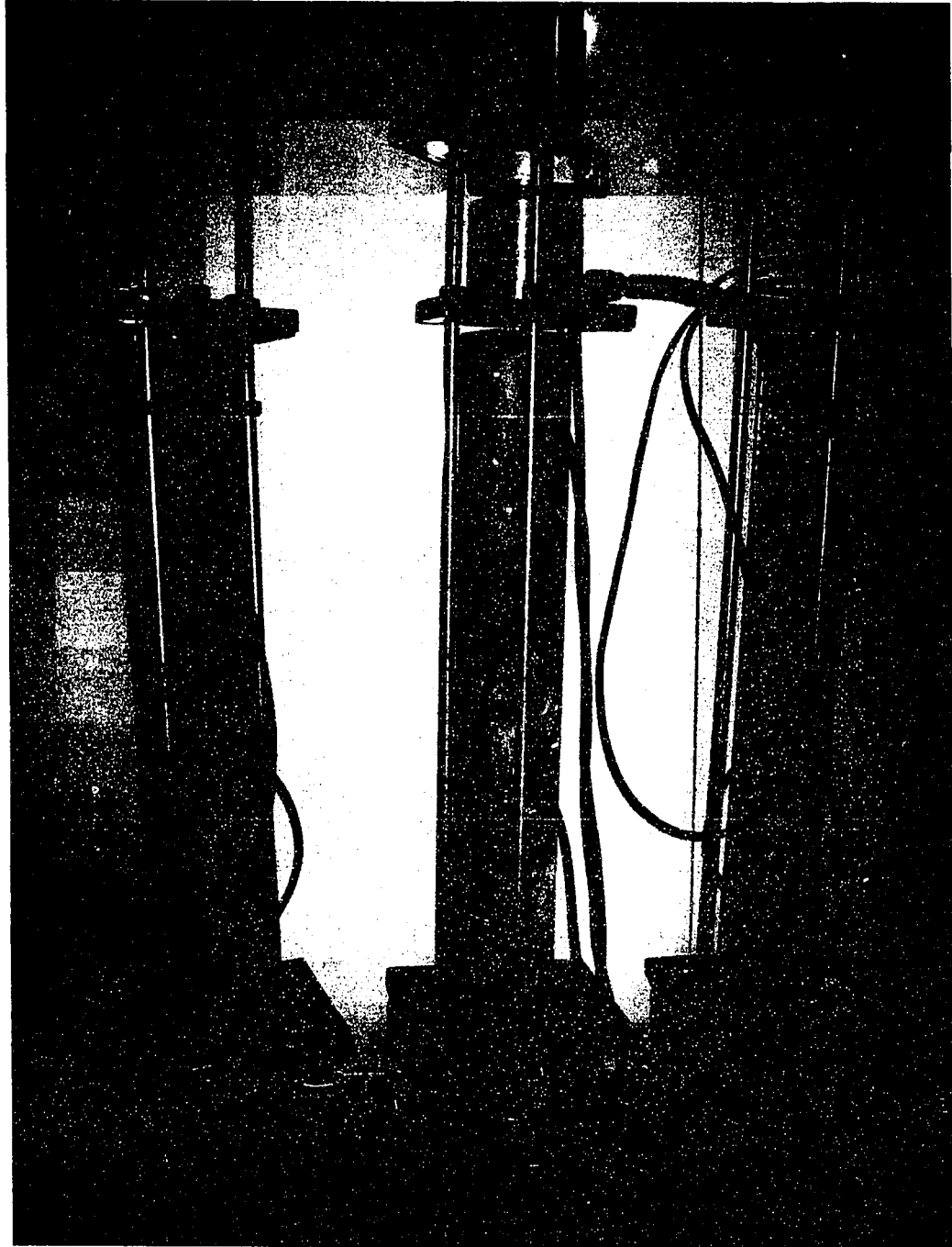


Figure 3.1. Specimens in Creep Frames

To apply a load, the jack was positioned as shown, the reaction (top) plate bolted in place and the jack pressurized to load the specimens. The low spring stiffness meant that the jack had to extend to a considerable distance to apply the required initial load to the specimens. Load adjustment required very little movement. Unloading required that the jack had to be extended before the reaction plate was bolted into position. As the jack travel was only 50 mm, unloading could be done in one step (extension) for a 70 KN load but required two or three extensions for 100 KN and 200 KN loads.

Strains were measured by Roctest model EM5 vibrating wire strain gages which were positively located during casting on a thin wire cradle as shown in Figure 3.2, gauge length 171 mm, using a Geokon model GK 403 readout device. The gages had a range of 3000 microstrain and were specified to be set up to read 500 microstrain in tension and 2500 microstrain in compression. For this experiment, recorded strain readings were done on the initial day of loading, 1, 2, 4, 7, 14, 21, 28 days after loading and thereafter at 2-4 week intervals.

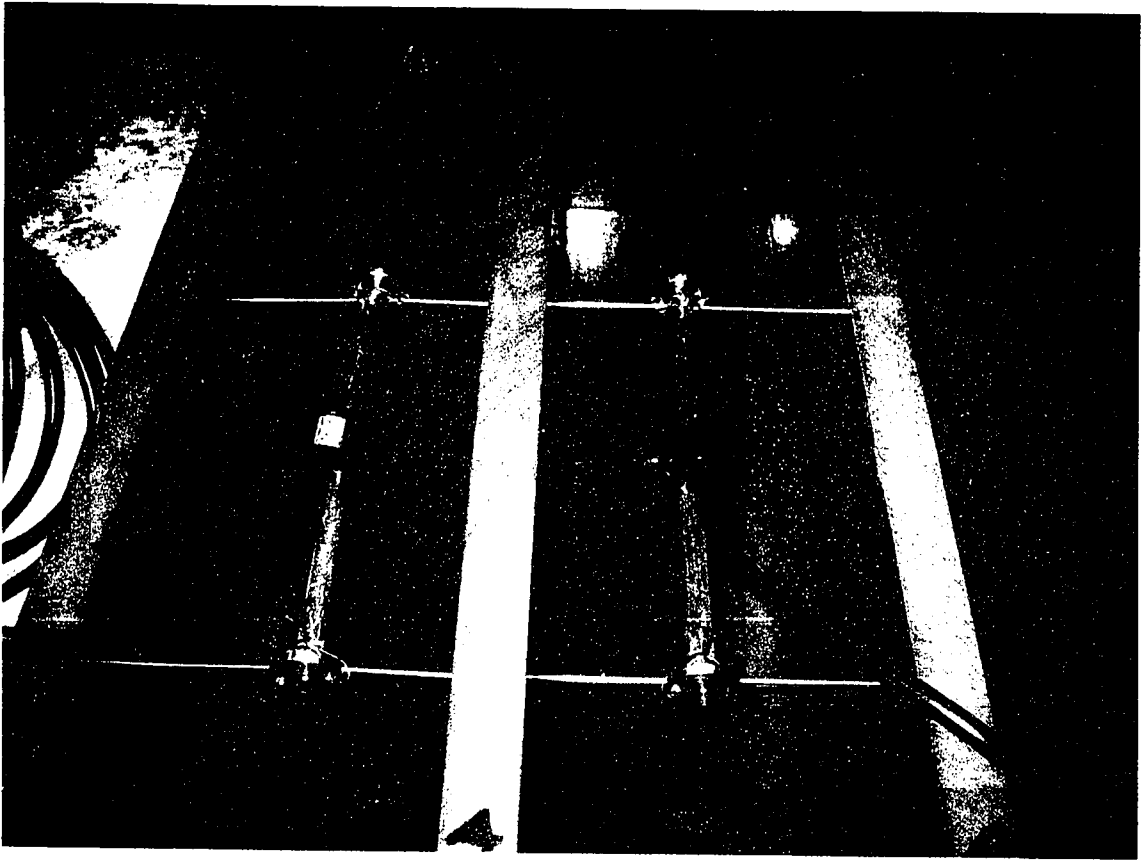


Figure 3.2. Vibrating Wire Gauges in Mold before Casting

Two environmental temperature controlled rooms, located in the concrete laboratory of the University of Ottawa Colonel By engineering building, were used. The moist room was maintained at a relative humidity of 95%- 98% and the 50% relative humidity room was maintained at a nominal relative humidity of 45-55% and a temperature between 20°C and 23°C. Sealed specimens were wrapped in two or three layers of self-adhesive aluminum tape and stored in the 95-98% relative humidity room.

Series A specimens were kept in the 95-98% relative humidity room and sealed at an age of 4 days. Series B specimens were moist cured for 3 days and transferred to the 50% relative room. Series C was essentially a repeat of Series B except specimens were moist cured for 4 days before being transferred to the 50% relative humidity room and all prisms were weighed after demoulding to establish an initial value in weight in order to determine the weight loss due to drying or any weight gain in sealed specimens.

Strains were recorded for all specimens. The loads on the creep frames were adjusted to their prescribed value, the load locked in and strains measured. The jack and load cell were removed and strains measured again.

To investigate stress-stiffening, four (4) concrete cylinders of Series C were conditioned by loading to 55 KN at 4 days and yielded a compressive strength of 64.1 MPa at 101 days, some 7% larger in strength than the cylinders stored unloaded in the same environment. Stress stiffening is a phenomena reported by other investigators including Yue and Taerwe (1993).

3.1 Fabrication and testing

The mix proportions used for all series were for self-compacting concrete with a slump flow of at least 600 mm.

The mixing procedure for these concrete mixtures consisted of homogenizing the sand and the coarse aggregate for one minute before introducing one-third of the mixing

water along with aqueous AEA (air-entraining agent). The cement was then added followed by the super plasticizer and one-third of the water. After three minutes of mixing, the other admixtures diluted with the remaining water were introduced, and the concrete was mixed for two additional minutes.

The concrete mixture proportions per cubic meter were 450 kg/m³ St. Lawrence HSFC cement which contains 8% silica fume, 810 kg/m³ of sand 810 kg/m³ of 10 mm aggregate and 189 kg/m³ of water. Three admixtures were used in proportions of 6 L/m³ of EUCON 37, an ASTM 494 Type F superplasticizer, 2.5 L/m³ of EUCON-NIVO "L", a self-compacting liquid admixture, and 1.125L of EUCON DX, a ASTM C494 Type A water reducing admixture. An air-entraining agent Airextra (ASTM C- 260) was also used to obtain the specified air content in the fresh concrete mixtures. All the admixtures were used in the form of aqueous solution. All series were made using the same brand of cement, same aggregates by the same personnel using the same equipment. No segregation between mortar and coarse aggregate was observed for any mixture.

In this experiment, the mixing machine had the capacity to produce 0.10 m³ (cubic metre) concrete for a single batch that limited the number of specimens that could be used.

Table 3.1 Series A - Mix Design (0.1m³)

Material	Quantity	Comments
Cement	45 kg	St Laurent
Sand	81 kg	
Aggregate	81 kg	
Water Content	16.425 kg	
Water / Cement Ratio	0.365	
Admixtures		
EUCON 37	0.6 litre	ASTM 494 Type F superplasticizer
Air-extra	22.5 millilitres	ASTM C-260
EUCON-NIVO 'L'	0.25 litre	
EUCON DX	112.5 millilitres	ASTM C 494 Type A

NB. The originally designed water content was 17.0 kg. By observation, this mix appeared to have too much water and so water content was further reduced by 565 g.

Table 3.2 Series B - Mix Design (0.1m³)

Material	Quantity	Comments
Cement	45 kg	St Laurent
Sand	81 kg	
Aggregate	81 kg	
Water Content	17.39 kg	
Water / Cement Ratio	0.39	
Admixtures		
EUCON 37	0.6 litre	ASTM 494 Type F superplasticizer
Air-extra	22.5 millilitres	ASTM C-260
EUCON-NIVO 'L'	0.25 litre	
EUCON DX	112.5 millilitres	ASTM C 494 Type A

Table 3.3 Series C - Mix Design (0.1m³)

Material	Quantity	Comments
Cement	45 kg	St Laurent
Sand	81 kg	
Aggregate	81 kg	
Water Content	17.95 kg	
Water / Cement Ratio	0.40	
Admixtures		
EUCON 37	0.6 litre	ASTM 494 Type F superplasticizer
Air-extra	22.5 millilitres	ASTM C-260
EUCON-NIVO 'L'	0.25 litre	
EUCON DX	112.5 millilitres	ASTM C 494 Type A

Specimens were cast and compacted in the horizontal position resulting in one trowelled face and three moulded faces. Cylinders, 100 mm in diameter and 200 mm high, cast in plastic moulds were used to measure concrete strengths. The ends of these cylinders were ground before crushing.

Even though self-compacting concrete was used for all specimens, prisms and cylinders were vibrated on a vibrating table. These specimens were then moved into the moist room, 95% to 98% relative humidity, within one hour of fabrication. The moulds were covered with polyethylene to avoid direct contact of water with the free surfaces of the specimens.

Series A

Series 'A' had sixteen (16) 100 x 100 x 400 mm prism specimens. These specimens and eighteen (18) cylinders were cast on February 27, 2004. All prisms and cylinders were taken to the 95-98% relative humidity room within an hour of casting where they were covered with polythene sheet coverings to be moisture cured for four days. On Monday March 01, 2004, prisms were demoulded and sealed with self-adhesive aluminum tape and remained in this room throughout the duration of the investigation. The specimens were loaded at previously chosen ages to the stresses shown in Table 3.4. Four cylinders were crushed to determine concrete strength.

Ten specimens were loaded to 100 KN after four (4) days. These specimens were identified with tag numbers 729, 739, 731, 740, 736, 746, 732, 744, 730, 745, while specimens 738, 747, 750, 727, 726, 737, were initially retained for shrinkage. Strains were measured at 0 day, which was four (4) days after casting and measurements were taken 1, 2, 4, 7, 14, etc. days after loading. At each measuring time the strains were read, the loads were adjusted to their prescribed value and strains measured again. Strains were measured again after the frames had been bolted up and the jack removed.

On March 18th 2004, when the concrete was twenty (20) days old, the loads on specimens 729, 739, 731, 740, 736, and 746 were increased to 200 KN, specimens 730 and 745 were unloaded, and specimens 732 and 744 were maintained at their initial load. Previously unloaded specimens 726 and 737 were loaded to 100 KN. Four cylinders were ground and crushed to determine concrete strength.

On May 24th, 2004, 87 days after casting, previously never loaded specimens 747 and 750 were loaded to 110 KN. Specimens 739 and 731 were measured, load adjusted and strains measured again, unloaded and weighted and transferred to a higher capacity frame with one 1" inch (25 mm) diameter rods and reloaded to 200 KN and strains measured again. The load on these specimens was then increased to 240 KN and strains again measured. Strains were measured on specimens 729 (9592g) and 740 (9832.5g), load was adjusted and strains measured, load removed and strains measured, then specimens were finally weighed. Four cylinders from this batch were crushed.

Table 3.4 Series A - Loading Schedule and Measured Weights

Series A Sealed in wet room. Cast 2004-02-27 Tag #	4 days status 2004-03-02 MPa	20 day status 2004-03-18 MPa	87 day status 2004-05-24 Mpa (grams)	334 day status 2005-01-26 Mpa	Sealed and stored in 95- 98% RH room
<i>f_{cm}</i> (MPa)	41.9	67.4	72.4	84.0	
727	0	0	0	0	
738	0	0	0	0	
747	0	0	11	11	
750	0	0	11	11	
726	0	10	10	10	
737	0	10	10	10	
732	10	10	10	10	
744	10	10	10	10	
730	10	0	0	0	
745	10	0	0	0	
736	10	20	20	20	
746	10	20	20	20	
739	10	20	24	24	Unloaded, moved and reloaded at 87 days
731	10	20	24	24	
729	10	20	0 (9592)	0	
740	10	20	0 (9832.5)	0	

Results - Series A

The logic of the test procedure for Series A is outlined in Table 3.4. All prisms and cylinders were moist cured in their moulds, top surface covered with sheet polyethylene, in the 95-99% relative humidity room for 4 days. These prisms were sealed with two or three layers of aluminized foil while cylinders were stored in their plastic moulds with the upper surface sealed with aluminized foil and kept in the 95-98% relative humidity room. Average concrete cylinder strengths (f_{cmt}) measured at 4, 20, 87

and 334 days are given on line 2 of Table 3.4. The measured total strains for all specimens, identified by specimen number, are plotted against logarithmic time in Figure 3.3. Sixteen curves are too many to analyze by inspection. Although loaded specimens were done in pairs, there appears to be slight scattering of individual curves when compared with its counterpart.

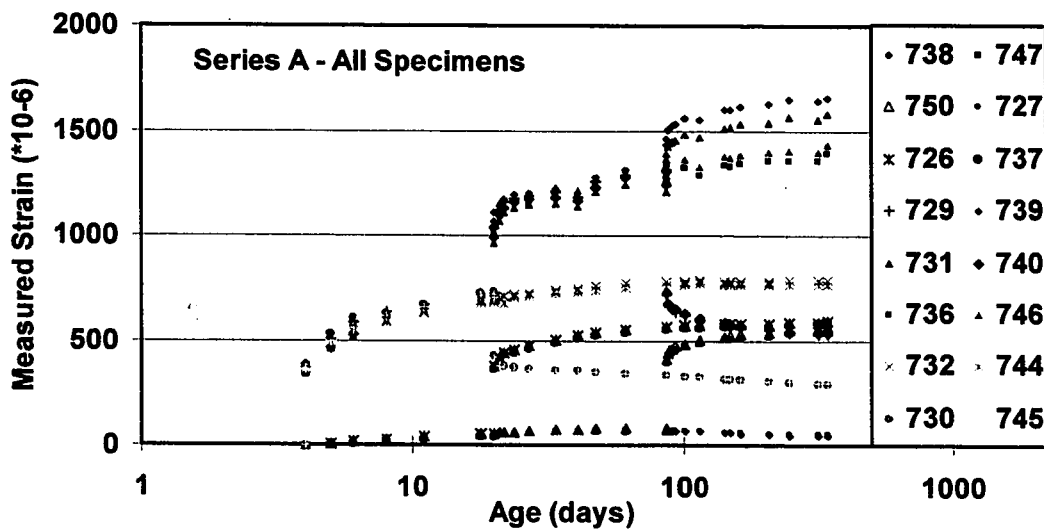


Figure 3.3 All Specimens for Series A

Shrinkage strains plotted in Figure 3.4 indicate some scatter even though all specimens were from the same batch. The shrinkage strains are much smaller than the load-induced strains and are shown at a larger scale in this Figure. It can be observed that after one hundred (100) days, there seems to be some shrinkage recovery; however, the magnitude of the recovery is only 25×10^{-6} micro strain, which is very small for any significant impact.

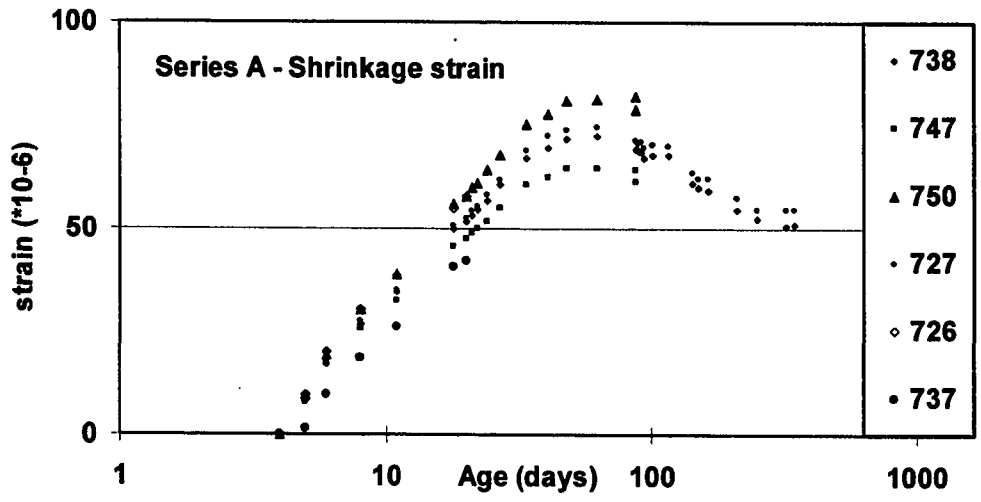


Figure 3.4 All Shrinkage Specimens in Series A

The load induced strains for the creep specimens are shown in Figure 3.5.

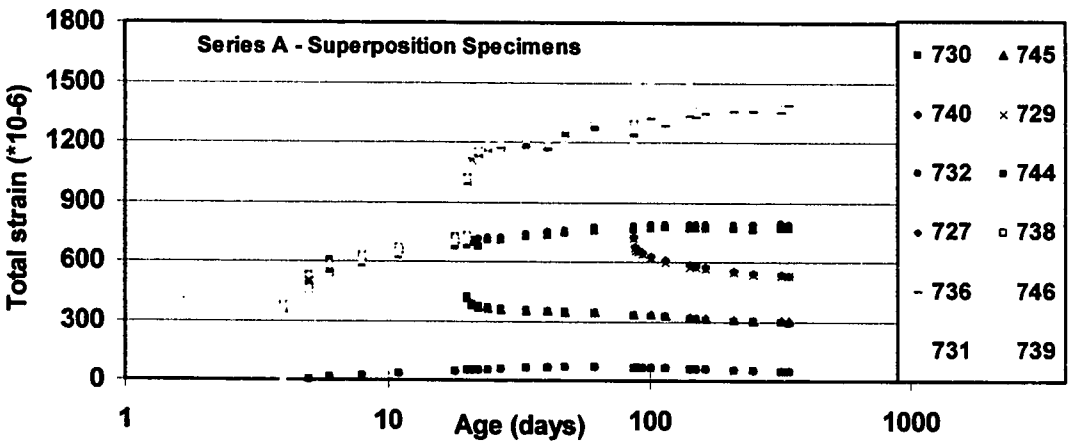


Figure 3.5 Series A – Superposition Specimens

The load induced strains for the 4 days, 20 days and 87 days conventional creep specimens are shown in Figure 3.6; it must be noted that the applied stresses were 10 MPa, 10 MPa and 11MPa respectively for the three load cycles. The results are as

expected with load induced strains decreasing with increasing age of loading. Concrete strengths were measured on cylinders that were 100 mm in diameter by 200 mm long and subjected to the same environments as the prisms.

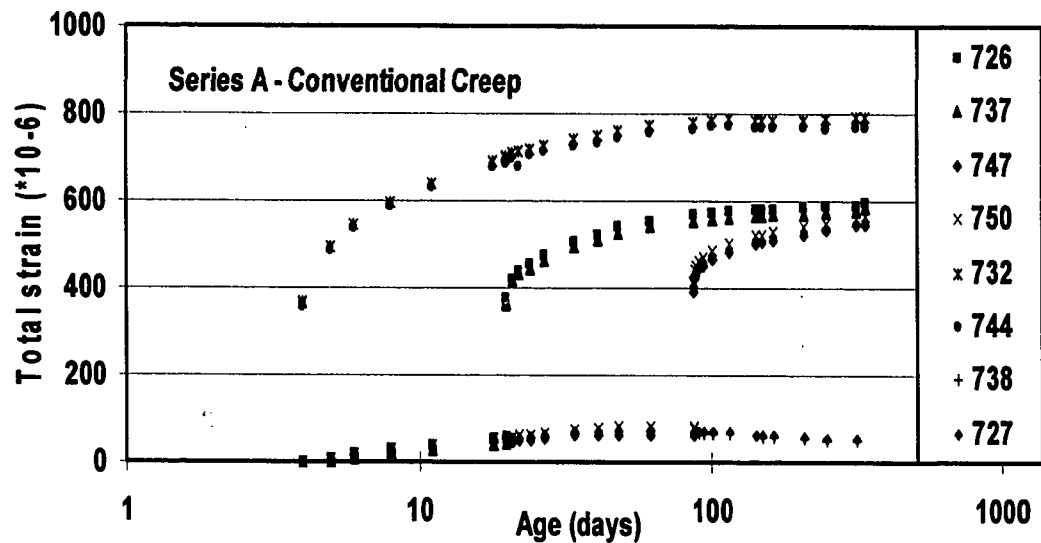


Figure 3.6 Conventional Creep Specimens for Series A

Series B

On March 26th 2004, sixteen prism specimens for Series “B”, and eighteen cylinders were cast. Within an hour of casting, the moulds were moved to the 95-98% relative humidity room and covered with polyethylene to avoid direct contact of water with the free surfaces of the specimens. On March 29th 2004, three (3) days after casting, the prisms and cylinder specimens were demoulded and placed in the 50% relative humidity room. Six specimens, identified with the tag numbers 710, 715, 722, 723, 713 and 711, were loaded to 70 KN. Strains were measured at loading day 0, three (3) days

after casting. Loads were adjusted and strains measured at 1, 2, 4, 7, 14 days after loading and so on. The remaining specimens 716, 725, 717, 714, 721, 720, 712, 719, 724 and 718, were retained for shrinkage.

On April 13th 2004, the second load event took place, specimens 722 and 723 were unloaded (18d/0 KN), and specimens 713 and 711 had their load increased to 140 KN (18d /140 KN). Never loaded specimens 712 and 720 were loaded to 70 KN (18d/70 KN) and remained in the 50% relative humidity room (dry room) with four specimens reserved for shrinkage. To investigate the suggestion by Gardner and Tsuruta (2004) that the recovery of sealed and drying specimens are similar, specimens 716, 721, 724 and 725 were sealed with self-adhesive aluminum tape, weighed and placed in the 95-98% relative humidity room. Specimens 716 and 725 were used for shrinkage and specimens 721 and 724 were loaded to 70 KN (18d/70 KN). As will be discussed later the sealed, never loaded specimens showed decreased shrinkage (expansion).

On July 12th 2004, 108 days after casting, the third load event was performed. Specimens 710,715,711 and 713 (108d/0 KN) were unloaded. Specimen 719 was loaded to 140 KN (108d/ 140 KN) in a frame with specimen 766 of Series "C". Specimen 714 remained in the dry room for shrinkage. Specimens 724 and 721 were kept under their load of 70 MPa.

Specimens 711, 718, were weighed and moved to the 95%-98% relative humidity room (wet room) exposed, unsealed, to absorption of water. Specimen 717 was sealed, weighed and placed in the wet room. Specimen 712 had its load increased to 140 KN

(108d/140KN). Specimen 720 was unloaded from its initial frame, reloaded at 70 KN, with specimen 749 (Series "C") and remained in the 45-50% relative humidity room (dry room).

Results - Series B

The logic of the test procedure for Series B is given in Table 3.5. All prisms and cylinders were moist cured for three (3) days in their moulds, top surface covered with sheet polyethylene, in the 95-99% relative humidity room. Concrete cylinders mean characteristic strengths (f_{cm}) measured at 3, 18 and 108 days are presented in Table 3.5.

Table 3.5 Series B - Loading Schedule and Measured Weights

Series B Cast 2004-03-26	3 day status 2004-03-29 MPa	18 day status 2003-04-13 Mpa (grams)	108 day status 2004-07-12 Mpa (grams)	253 day status 2004-12-07 Mpa (grams)	306 day status 2005-01-26 Mpa (grams)
fcu	36.8	55.1	55.9	Cured in 50% RH after 4 days moist curing	
710	7	7		Specimens broke under unloading at 108 days	
715	7	7			
722	7	0	0		
723	7	0	0	0	0
711	7	14	0 wet (9153.5)	0 wet (9252)	0 wet
713	7	14	0 dry	0	0 (9082.5)
716	0	0 sealed (9300.5)	0 sealed (9327.5)	0 sealed (9328.5)	0 sealed (9326.5)
725	0	0 sealed (9365)	0 sealed (9367)	0 sealed (9367)	0 sealed
714	0	0	0	0	0 (9126.25)
718	0	0	0 wet (9119.5)	0 wet (9226)	0 wet
719	0	0	14 with 766	14	0 (9149.5)
712	0	7	14 with 764 (9099/w9179)	14	0 (9184.5)
720	0	7	7 with 749	7	0 (9225.5)
717	0	0	0 sealed (u9099/w9179)	0 sealed (9192)	Seal later found to be discontinuous
721	0	7 sealed	7 sealed	7 sealed	0
724	0	7 sealed	7 sealed	7 sealed	0

The measured strains for all specimens, identified by specimen number, are plotted against logarithmic time in Figure 3.7.

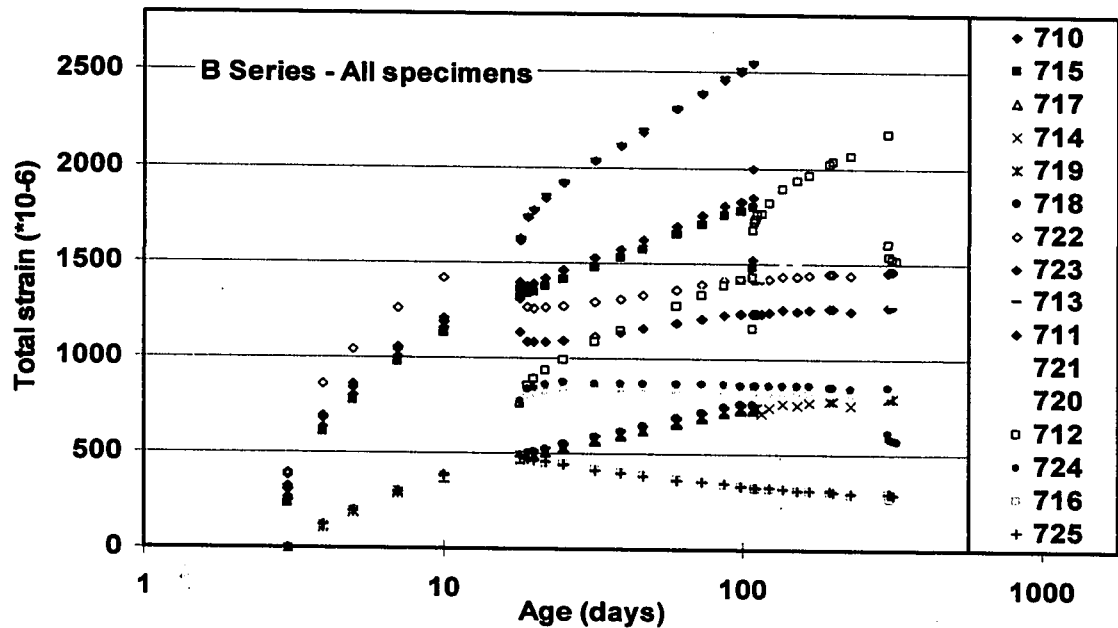


Figure 3.7 All Specimens for Series B

The drying shrinkage strains, which are smaller than the load-induced strains are shown to a larger scale in Figure 3.8. The measurements of the shrinkage strains for specimens 716 and 725 show unexpected results. These two specimens were sealed and transferred to the moist room after 18 days. This behavior cast some doubt to level of confidence in all our sealed specimens and was the reason the weights of all specimens in Series C were monitored.

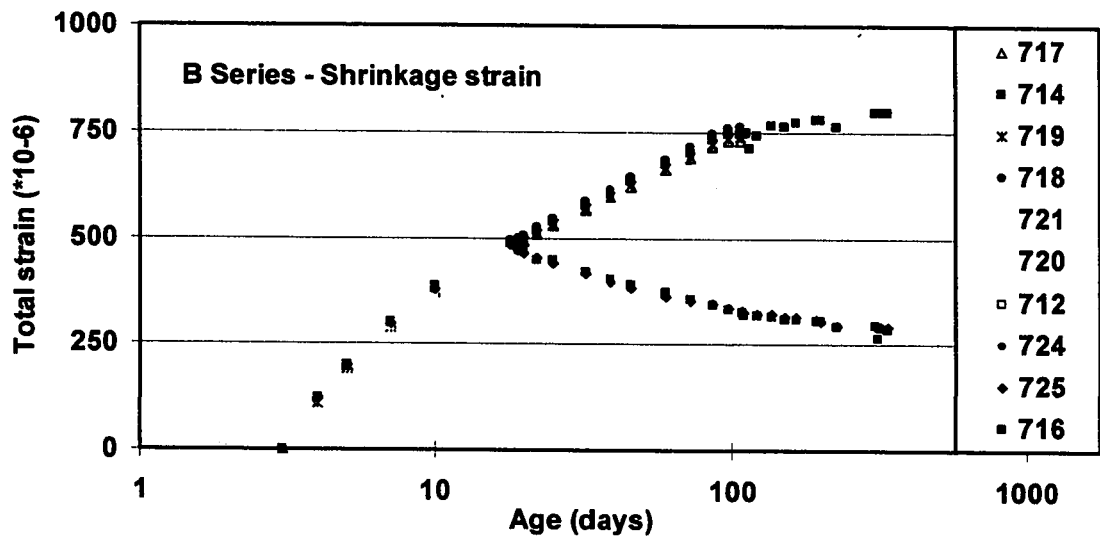


Figure 3.8 All Shrinkage Specimens in Series B

Specimen 717, (a drying shrinkage specimen) which was carefully sealed and place sealed in the wet room showed an unusual result; on later inspection it was found that the sealing on this specimen was discontinuous allowing a possible easy ingress of moisture. Applied stresses and measured weights are given in Table 3.5.

The load induced strains for the 3 days, 18 days and 108 days loaded specimens are shown in Figure 3.9; it must be noted that the applied stresses were 7 MPa, 7 MPa and 14 MPa respectively for the three ages.

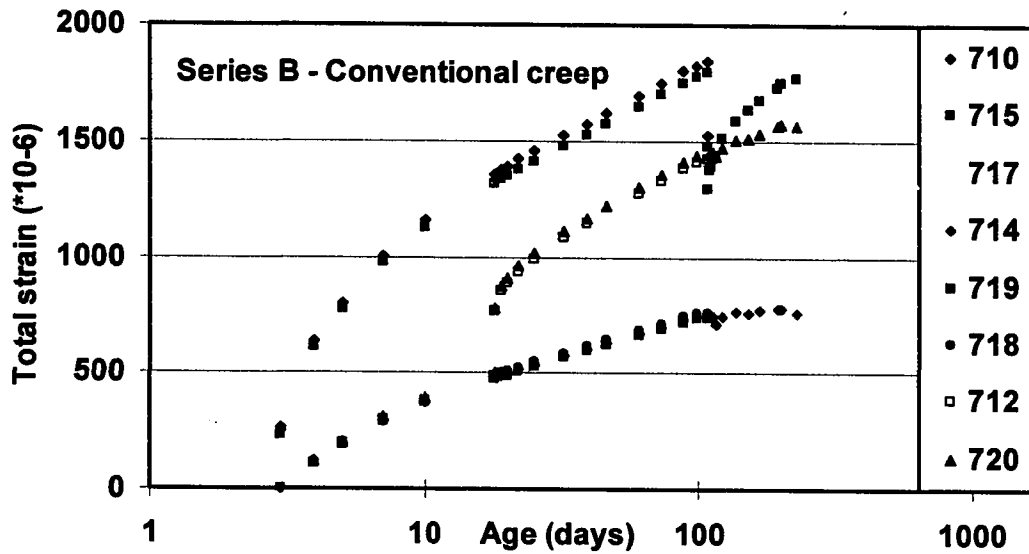


Figure 3.9 Conventional Creep Specimens for Series B

Total measured strains for never loaded specimens, late-loaded specimens at 18 days are shown in Figure 3.10. In this Figure, the shrinkage strains of the unsealed specimens are 165% of the sealed specimens. In addition, in this Figure, it can be observed that the load-induced strains of unsealed specimens are 80% to those of the sealed specimens. This unexplained phenomenon needs to be investigated.

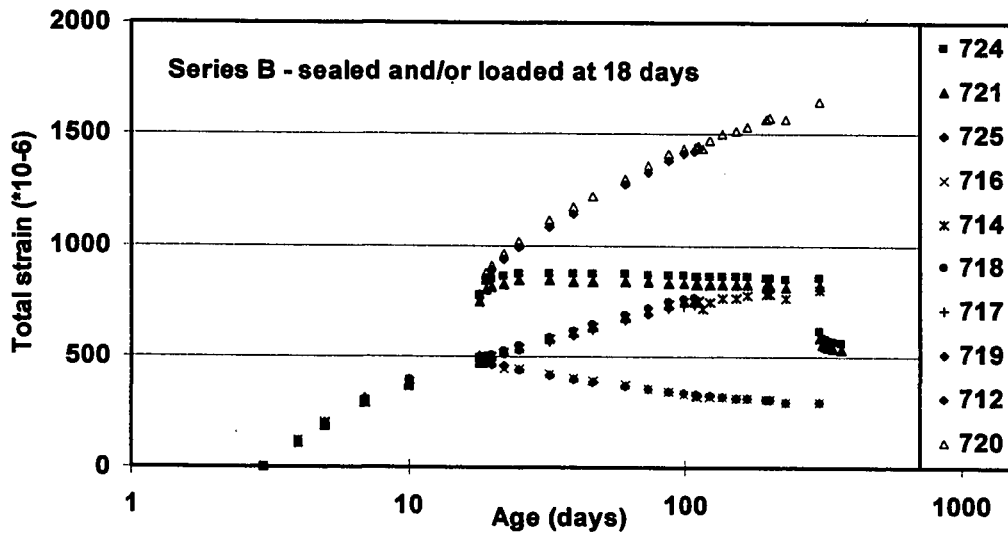


Figure 3.10 Sealed and / or Loaded at Loaded at 18-days Series B

Figure 3.11 shows the strains of specimens 710, 715, 722, 723, 713, and 711 loaded to 7 MPa after 3 days of moisture curing. Specimens 722, 723 were placed in the same loading frame, however during the first fourteen days under load, specimen 722 shows a marked deviation with its counterpart/ companion specimen 723, although both specimens experienced the same level of stress. The deviation in profile remains distinct even in its creep recovery stage. There is no known explanation for this behavior at this time.

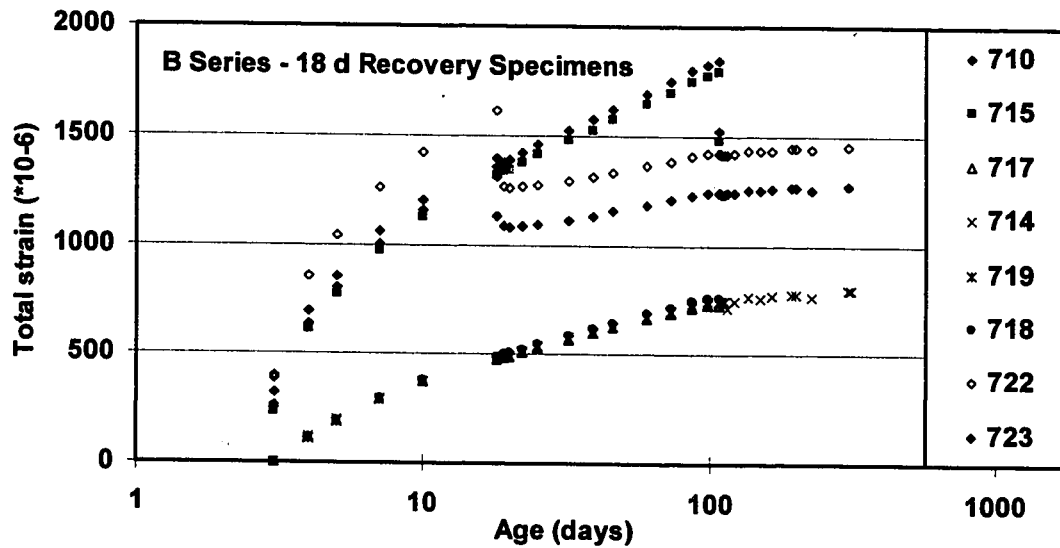


Figure 3.11 Recovery of Specimens at 18-days for Series B

Series C

On April 2nd 2004, Series "C" was cast, moisture cured for four (4) days. As the measurements of the Series B shrinkage strains for specimens 716 and 725 sealed at 18 days showed unexpected results, the weights of all specimens in Series C were monitored. On April 6th 2004, all sixteen specimens were demoulded, weighed and placed in the 50% relative humidity room (Dry Room). Eight specimens were loaded to 70 KN (4d/70KN), for the first load cycle, namely 766 (9397g), 741 (9597g), 733 (9494.5g), 764 (9520g), 743 (9469.5g), 772 (9396g), 728 (9466.5g) and 761 (9482g). Twenty concrete cylinders were demoulded and moved to the 50% relative humidity room (Dry Room). Four cylinders were crushed, four cylinders were loaded to 60KN and twelve cylinders were stored without load. The remaining specimens, 735 (9533.5g), 742 (9524g), 757 (9486g), 754 (9442.5g), 768 (9480.5g), 734 (9505g), 749 (9387g) and 748 (9516g) were initially retained as shrinkage specimens.

On April 20th 2004, second load cycle, specimens 733 (9418.5g), 764 (9445g), 772 (9321g) and 743 (9396g) were unloaded (18d/ 0KN). Specimens 733 and 764 remained unloaded in the dry room while specimens 772 and 743 were unloaded, weighted, sealed, reweighed and placed in the wet room. Specimens 728 and 761 were maintained their initial load. Specimens 741, 766, had their load increased to 140 KN (18d/140 KN). Specimens 754 (9366.5g), 768 (9401.5g), were weighed, sealed, moved to the wet room and loaded for the first time to 70 KN (18d/70 KN), while specimens 735 and 742 remained in the dry room, but were loaded to 70 KN (18d/70 KN). Specimens 734 (9515g) and 748 (9526g), were weighed, sealed, re-weighted and placed in the wet room for shrinkage. The two remaining specimens 749 and 757 were kept for shrinkage in the dry room. Six cylinders were crushed.

On July 12th 2004, with concrete specimens 101 days old, the third load cycle commenced. Specimen 741 was measured, load adjusted and strains measured again, unloaded, weighted and transferred to a 1" (25 mm) diameter rod frame, 140 KN load applied and strains measured again, the load was increased to 210 KN and strain again measured. Specimen 766 was unloaded, weighted, placed in a frame with specimen 719, (Series "B"), and reloaded to a load of 140 KN, while specimen 764 was placed in another frame with specimen 712, (Series "B") (108d/140KN), and was reloaded to 140 KN. Specimens 728 (9320g), 761 (9345g), 735 (9396.5g) and 742 (9388g) were unloaded and weighed. Specimens 728 and 735 were reloaded to 70 KN and placed in the same frame, in the dry room. Specimens 733 (9349g) and 764 (9444.5g) remained in the dry room. Specimen 757 (9342g) remained in the dry room as the only shrinkage specimen.

Specimen 749, was placed in a frame with specimen 720, (Series "B"), and loaded to 70 KN (108d/70 KN). Specimens 772 and 743 remained sealed in the wet room.

Results - Series C

The logic of the test procedure for Series C is given in Table 3.6. All prisms and cylinders were moist cured for four (4) days in their moulds, top surface covered with sheet polyethylene, in the 95-99% relative humidity room as in other series.

Table 3.6 Series C - Loading Schedule and Measured Weights

Series C Cast 2004-04-02 tag #	4 day status 2004-04-02 Mpa (grams)	18 day status 2004-04-20 Mpa (grams)	101 day status 2004-07-12 Mpa (grams)	245day status 2004-12-07 Mpa (grams)	299 day status 2005-01-26 Mpa (grams)
f_{cmt}	47.6	64.0	60.4		
f_{cmt}			64.1	Cylinders preloaded at 7 MPa until crushing	
757	0 (9486.0)	0 (9410.0)	0 (9342)	0 (9330.5)	0 (9326.5)
749 with 720	0 (9387)	0 (9311.5)	7 (9246.0)	7	0 (9218.5)
735 with 728	0 (9533.5)	7 (9456)	7 (9396.5)	7	0 (9369.5)
742	0 (9524.0)	7 (9447.3)	0 (9388)	0 (9369.5)	0 (9365.0)
741	7 (9597.0)	14	21 (9457)	Exceeded strain limit of gauge at 115 days	
728 with 735	7 (9466.5)	7	7 (9320)	7	0 (9298)
761	7 (9482.0)	7	0 (9345)	0 (9324.5)	0 (9319.5)
733	7 (9494.5)	0 (9418.5)	0 (9349)	0 (9336.5)	0 (9331.5)
764 with 712	7 (9520.0)	0 (9445.0)	14 (9377.5)	14	0 (9349.5)
766 with 719	7 (9397.0)	14	14 (9260.0)	14	0 (9230.0)
734	0 (9505.0)	0 sealed (u9424/w9513)	0 sealed (9517.5/9520)	0 sealed (9522.5)	0 sealed (9521.0)
748	0 (9516.0)	0 sealed (u9437.5/w9526)	0 sealed (9541.5/9546)	0 sealed (9546.5)	0 sealed (9545.5)
772	7 (9396.0)	0 sealed (u9321/w9432.5)	0 sealed (9437.0)	0 sealed (9436.5)	0 sealed (9435.5)
743	7 (9469.5)	0 sealed (u9396g/w9524)	0/0 (sealed)	0/9546.0 (sealed)	0 sealed (9528.0)
754	0 (9442.5)	7 sealed (u9366.5/p11516)	7 sealed	7 sealed	0 sealed (p11532.0)
768	0 (9480.5)	7 sealed (u9402/p11542.0)	7 sealed	7 sealed	0 sealed (p11560.0)

u unwrapped w wrapped p wrapped with end plates

The measured strains for all specimens are identified by specimen number and are plotted against logarithmic time in Figure 3.12.

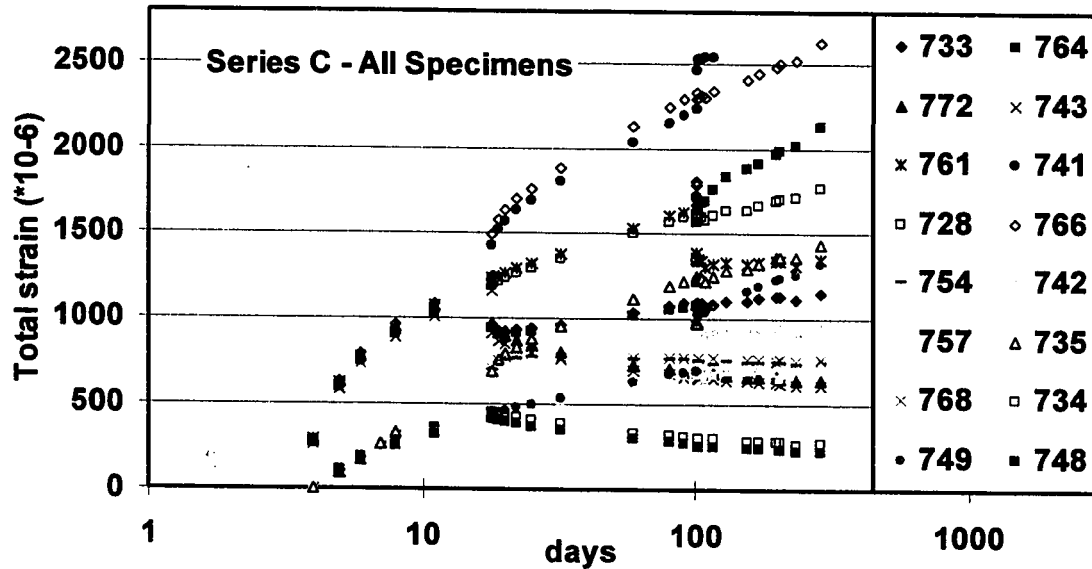


Figure 3.12 All Specimens for Series C

Drying shrinkage strain specimens in Figure 3.13 reveal again that the response of the never loaded, sealed specimens, 734 and 748, tend to suggest possible moisture absorption, this is also suggested by increased weights as shown in Table 3.6.

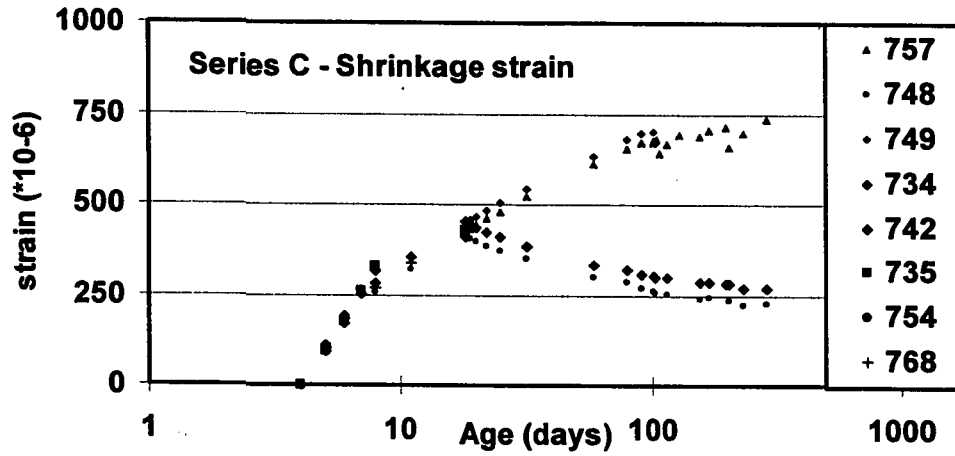


Figure 3.13 All Shrinkage Specimens in Series C

The strains of all drying specimens are shown in Figure 3.14

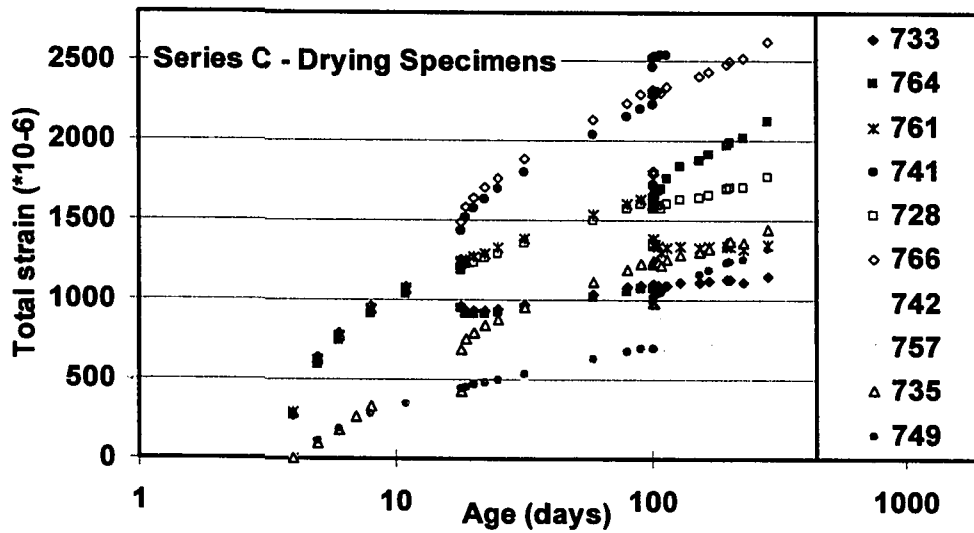


Figure 3.14 Drying Specimens for Series C

The load induced strains for the 3 day, 18 day and 101 day loaded specimens are shown in Figure 3.15. The measured strains show a dip when the specimens were unloaded, weighted and reloaded.

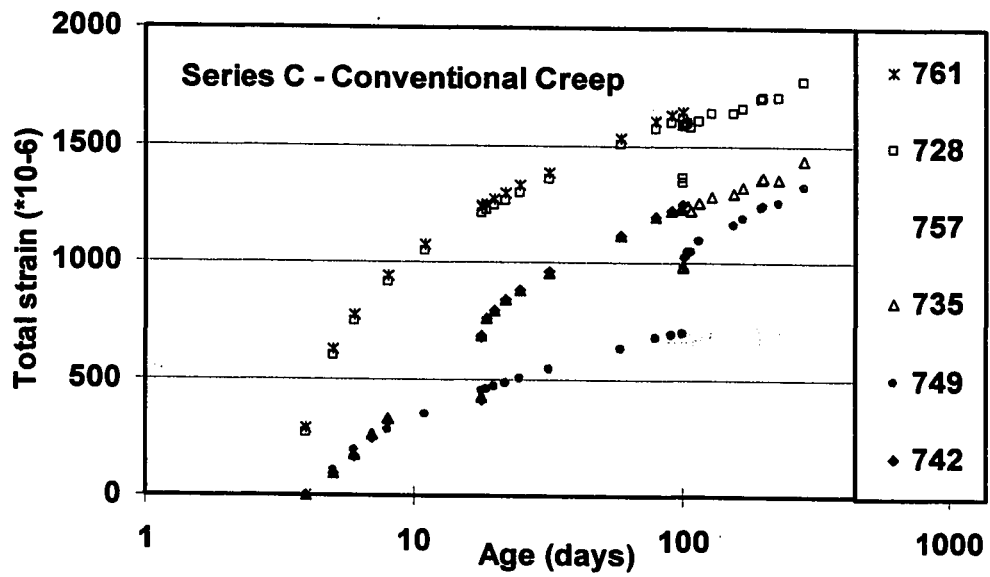


Figure 3.15 Conventional Creep Specimens for Series C

The strain responses of all the specimens dried for 18 days and then sealed are given in Figure 3.16. The never loaded specimens, 748 and 734, show a reduction in shrinkage, i.e. an expansion, while the specimens sealed and loaded specimens 768 and 754, shows negligible changes in strain after loading, as if the expansion due to the sealing offsets the creep.

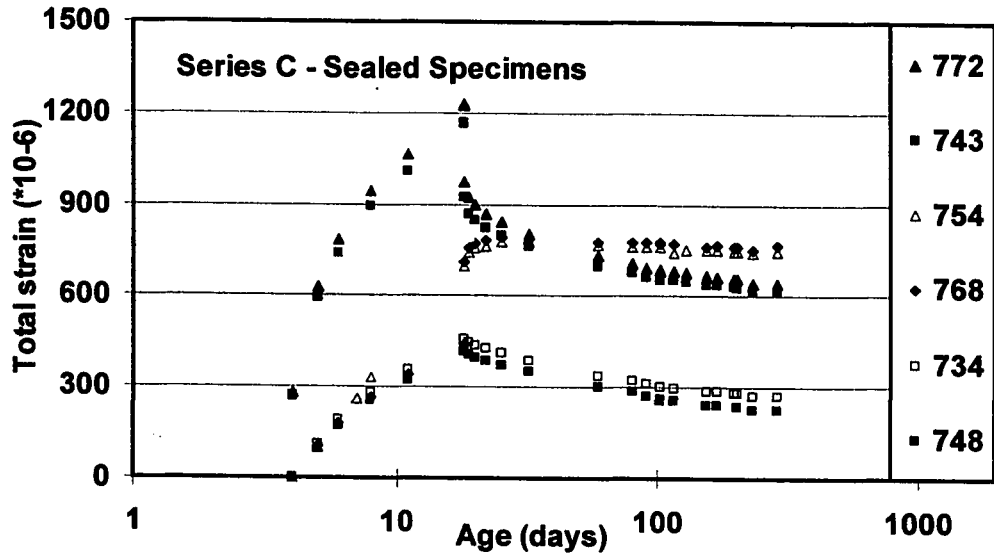


Figure 3.16 Sealed Specimens Series C

Figure 3.17 shows the strains of the specimens that were unloaded at 18 days, unsealed and sealed, and the companion never loaded specimens. In this Figure the creep recovery of unsealed specimens are 83% of those of the sealed specimens.

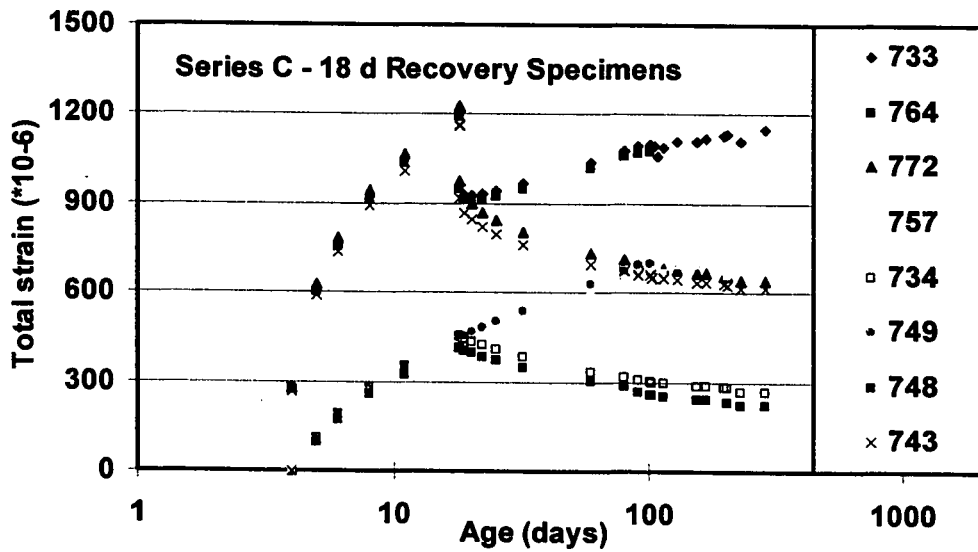


Figure 3.17 Recovery of Specimens at 18-days for Series C

Figures 3.13, 3.18 show the shrinkage strains of unsealed specimens to be 175% to those of the sealed. The load-induced strains of unsealed specimens are 80% of the sealed specimens. These are similar observed result that occurred in Series B

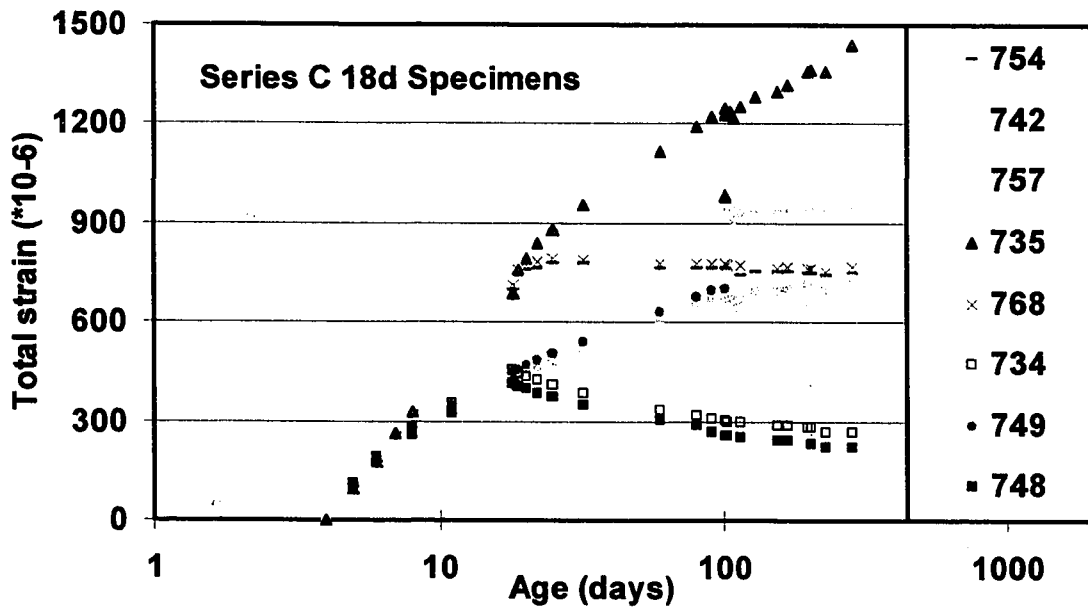


Figure 3.18 Sealed and / or Loaded at 18-days Series C

In Table 3.7 the measured weight, losses for shrinkage specimens are compared with those of creep specimens. Specimen 757 after 299 days had a weight loss of 159.5 grams. Specimen 742 (loaded at 18 days, unloaded at 101 days), had at weight loss of 159 grams. Specimens 735 and 749, loaded at 18 and 101 days respectively, had losses of 164 grams and 168 grams. Specimens 733, 761, loaded at 7 days but unloaded at 18 and 101 days respectively, had losses of 162.5 grams and 163 grams. Specimen 728 had a constant stress of 7 MPa, after 299 days its loss in weight was 168 grams. Specimen 766 had its load increased at 18 days; weight loss at 299 day was 167 grams.

Table 3.7 Series C - Weight Loss

Series C tag #	4 day initial weight in grams	18 day weight loss in grams	101 day weight loss in grams	299 day weight loss in grams
757 (Shrinkage)	9486.0	76	144	159.5
749 (Creep) Late Load	9387	75.5	141	168.5
735 (Creep) Late Load	9533.5	77.5	136.5	164
742 (Creep)	9524.0	76.5	136	159
728 (Creep) Const. Load	9466.5	-	146.5	168
761 (Creep)	9482.0	-	137	162.5
733 (Creep)	9494.5	76	145.5	163
764 (Creep) Incr. Load	9520.0	75	142.5	170.5
766 (Creep) Incr. Load	9397.0	81	137	167
734	9505.0 Sealed	81	76.5	71.5
748	9516.0 Sealed	78.5	63	59
772	9396.0 Sealed	75	70.5	72
743	9469.5 Sealed	73.5	-	69.5
754	9442.5 Sealed	76	-	60
768	9480.5 Sealed	78.5	-	60

u unwrapped

w wrapped

p wrapped with end plates (average weight of plate 2020 grams)

Average moisture lost in shrinkage specimens for the first 18 days was 77.4 grams compared with 76.1 grams for the creep specimens. This difference in average weight loss could have been the direct result of top and bottom metal end plates, which were placed on the creep specimens, and would suggest, that they created a possible retardation of any moisture evaporation at these ends.

The following specimens were allowed to dry for 18 days then weighed, sealed and transferred to the wet room and weight losses observed after 281 days. Specimens 734,748 (never loaded) average weight loss was 66.25 grams. Specimens 772,743 (loaded at 7 days, unloaded at 18 days) average weight loss was 70.25 grams. Specimens 754,768 (late loaded at 18 days) average weight loss was 60 grams. The influence of compressive load shows very little effect on weight loss compared to specimens without load and therefore reveals some other common denominator, which is responsible for these losses.

These results indicate that moisture loss depends on relative humidity and is not influenced by loading. Maney, G. A. (1941), Mamillan, M., (1970) made a similar observations from experiments to examine the seepage theory which had been suggested to be a physical phenomenon influencing creep.

Preloaded cylinders under compression showed a 7 % gain in strength over time when tested at 101 days. Yue and Taerwe (1993) referred to this stiffened behavior of concrete under compression in a number of their experiments.

The strain measurements of Series B and C, never-loaded specimens sealed and transferred to the moist room after 18 days exhibited expansion. This behavior cast doubt to level of confidence in all sealed specimens and was the reason the weights of all specimens in Series C were monitored.

CHAPTER 4

DISCUSSION OF RESULTS

The concretes of all three series were nominally identical. The measured concrete strengths are given in Table 4.1. The differences in strength were due to the difficulty in controlling the moisture content of the sand.

Table 4.1 Measured Concrete Strengths

Series "A"		Series "B"		Series "C"		Series "C" Preloaded Cylinders	
Age (days)	Strength (MPa)	Age (days)	Strength (MPa)	Age (days)	Strength (MPa)	Age (days)	Strength (MPa)
4	41.9	3	36.8	4	47.60	-	-
20	67.4	18	55.1	18	64.0	-	-
87	72.4	108	55.9	101	60.4	101	64.1
334	84.0						

In series A, we see the effect of continuous moist curing on the development of the compressive strength of concrete; i.e. there was a significant accruing of characteristic strength after 28 days.

Previous researchers such as Yue and Taerwe (1993) have noted that the strength of cylinders stored under load is greater than the strength of cylinders stored without load. Four cylinders of Series C were stored under a stress of 7 MPa and tested at 101

days. The strength of the preloaded cylinders was 7% higher than the cylinders stored without load in the same environment.

It was observed that while the characteristic strength of Series A increases under long duration of moisture curing, the strength of the Series B and C concretes moist cured for 3 and 4 days and then stored in a 50% relative humidity environment did not increase significantly after 18 days. As the strength gain after moist curing is humidity and dependent.

To analyze superposition of creep strains it is assumed that shrinkage strains and creep strains are additive and for increased loads that superposition is valid. Unfortunately, using superposition to demonstrate superposition is a circular argument. Each series was analyzed in the same manner. Load induced strains were determined by subtracting the average shrinkage strains from the average of the measured total strains of similarly loaded specimens and are plotted using a natural time axis. Any errors or problems in measuring shrinkage are reflected in the load-induced strains.

To check for consistency, the shrinkage strains of Series B and Series C are plotted in Figure 4.1. Series B was moist cured for three (3) days and Series C moist cured for four (4) days. The results are similar.

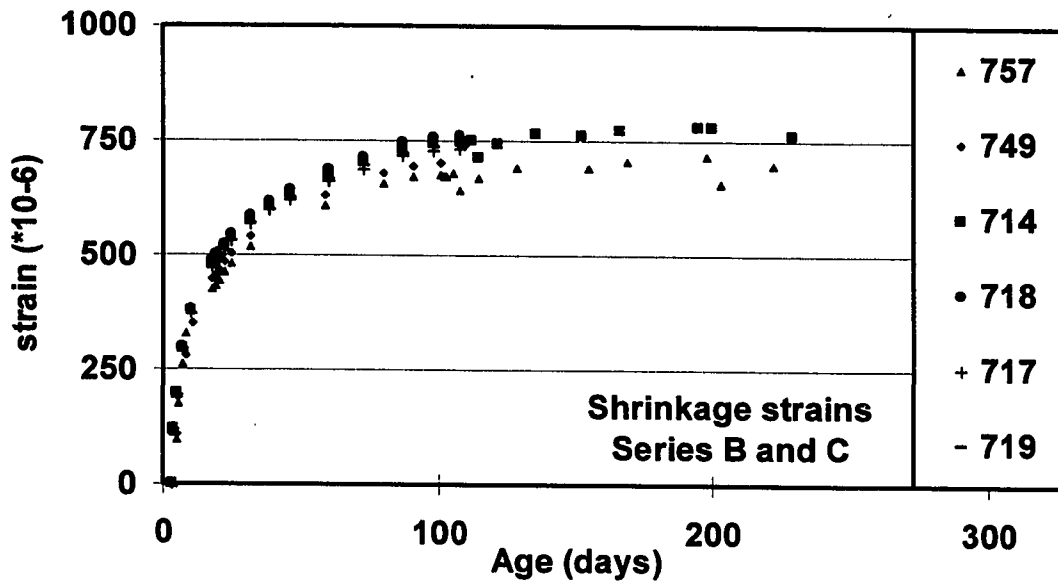


Figure 4.1 Shrinkage Strains Series B & C

Making use of equation (1.2) in Chapter 1, *compliance* is defined as the measured average shrinkage strains subtracted from the total average measured strains divided by the compressive stress.

Specific creep strains are defined as the measured average shrinkage and elastic strains subtracted from the total average measured strains divided by the compressive stress.

At this time no logical explanation has been found for the recovery of shrinkage of the sealed Series B and C specimens sealed at 18 days, Figures 3.10 and 3.16 and so no discussion of these late sealed specimens is included.

Series A - Sealed Specimens

Figure 4.2 shows the average compliances for the maintained load specimens loaded at 4, 20 and 87 days. The results are as expected with the later loaded specimens showing smaller compliance with increased age of loading.

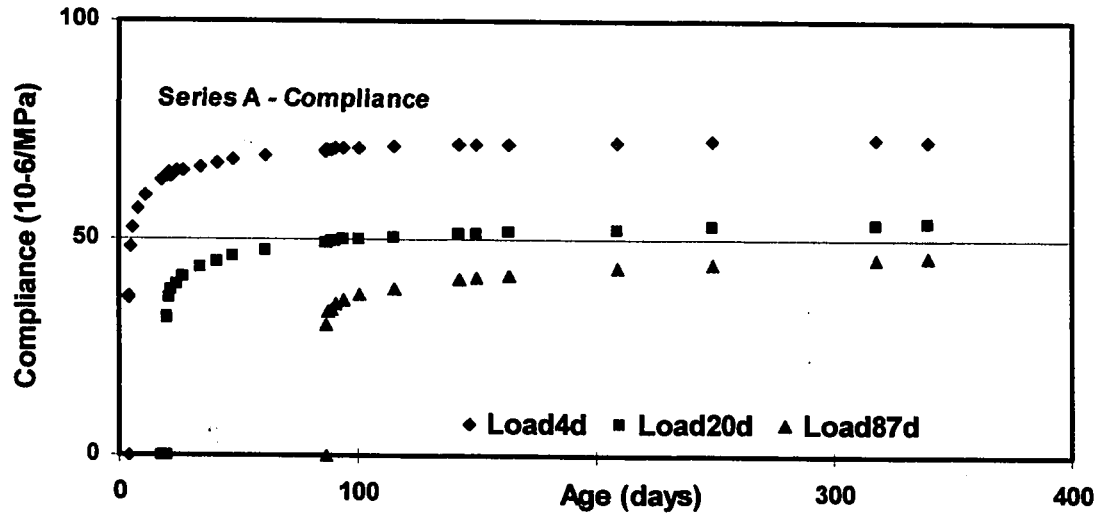


Figure 4.2 Compliance Strains for Series A

The average measured load induced strains of the specimens; which is the measured total strain of loaded specimens less the measured strain of never loaded specimens (shrinkage), are shown in Figure 4.3.

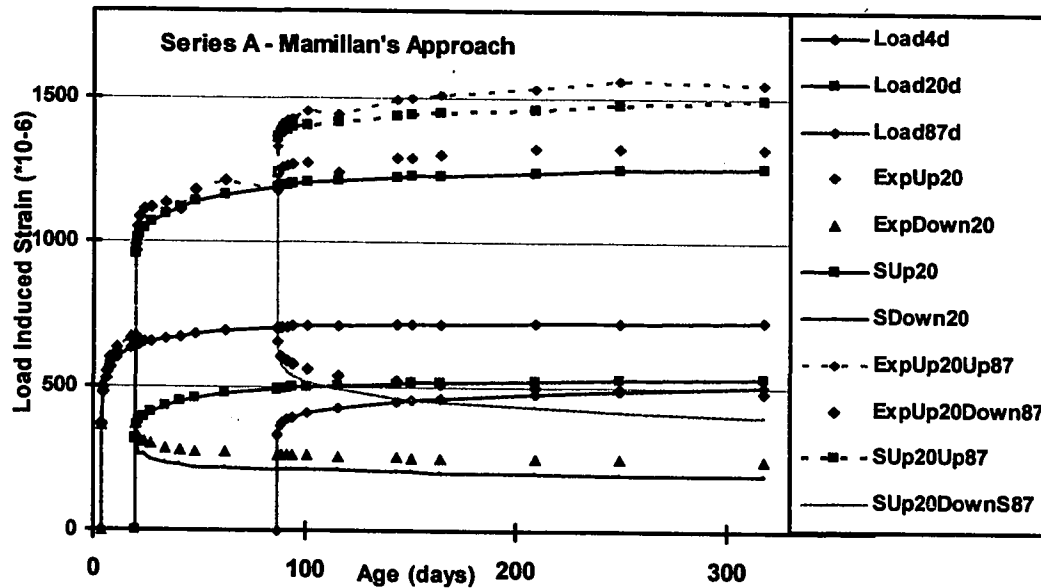


Figure 4.3 Mamillan's Approach of Superposition for Series A

Mamillan (1982) suggested examining the validity of superposition by simply adding, subtracting shrinkage and correcting for load magnitude, the strains from early age loads to the strains for late age loads and comparing the result with experimental result for the combined loads. These curves, indicated by continuous lines, are also shown in Figure 4.3 allowing direct comparison.

Noting the scatter of the results just before the second loading in Figure 4.3, the values after the second loading are replotted in Figure 4.4 as the specific creep after the second loading cycle, which is obtained by subtracting measured shrinkage and elastic strain from measured total strain divided by the compressive stress. In Figure 4.4, 20-day is used as the x-origin and the 20-day strain value as the y-origin and represent the 20-day load event results for the whole measurement period.

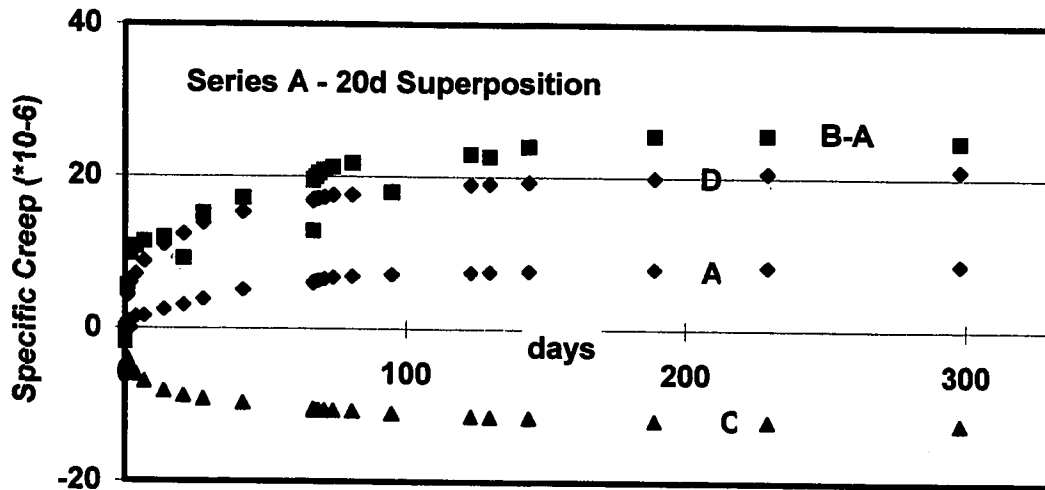


Figure 4.4 Superposition for 20-day load specimens Series A

In Figure 4.5 a comparison of incremental specific creeps B-A (increased load) and A-C (recovery) relative to the specific creep of D, the maintained late-loaded specimens, is shown. Due to accumulative errors, subtracting one specific creep from another accumulates uncertainties and gives some degree of inaccuracy. However, if superposition is valid, the two Curves B-A and A-C should be in coincident with the line of equality. The curves approximate the line of equality.

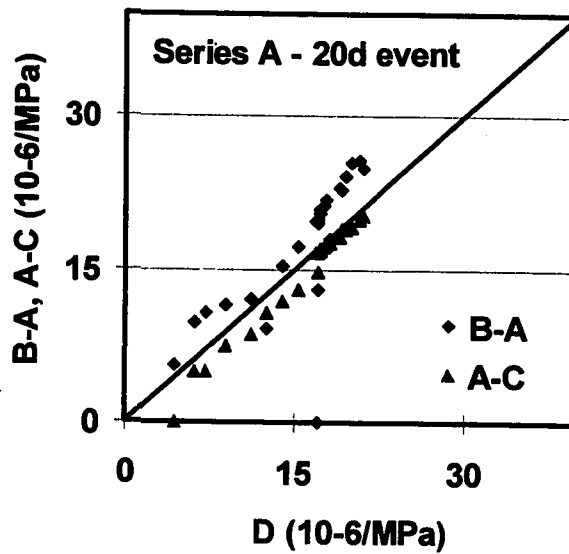


Figure 4.5 Validity of Superposition for 20-day Load Cycle

Figure 4.6 gives the incremental strains after the third load cycle using day 87 as the x origin and the 87-day strain value as the y origin. Figure 4.7 shows the comparisons of the incremental specific creeps B-A (increased load) and A-C relative (recovery) to the specific creep of the maintained late-loaded specimens, D.

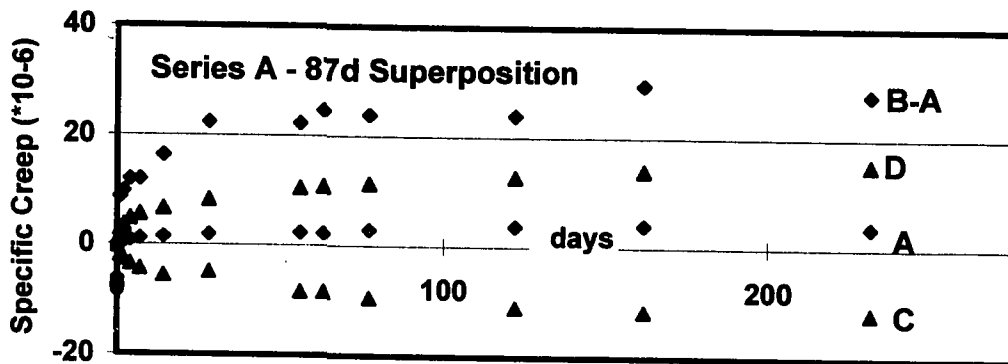


Figure 4.6 Superposition of 87-day load specimens Series A

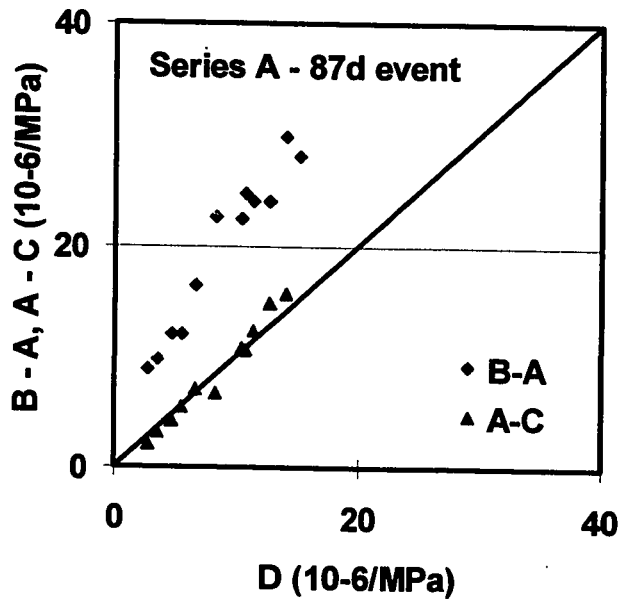


Figure 4.7 Validity of Superposition for 87-day Load Cycle

Observing both Figures 4.4 and 4.6 it appears that the late loaded, D, specific creeps are smaller than expected. This is probably a consequence of the large elastic strain evident in Figure 4.2.

In Series A, the results indicate that superposition underestimated strains due to increased loads for both the second and third load cycles. For the second load cycle, there is a 7% underestimation, while at the third cycle it is 30%. For creep recovery however, superposition overestimates recovery by 5% at the second load stage, but correctly predicted recovery at the third load stage.

Series B - Drying Creep

Figure 4.8 shows the average compliances for the maintained load specimens loaded at 3, 18 and 108 days. The results are as expected showing the later loaded specimens having a smaller compliance with increased age of loading. Also, as expected, the drying compliances are larger than the sealed compliances shown in Figure 4.2.

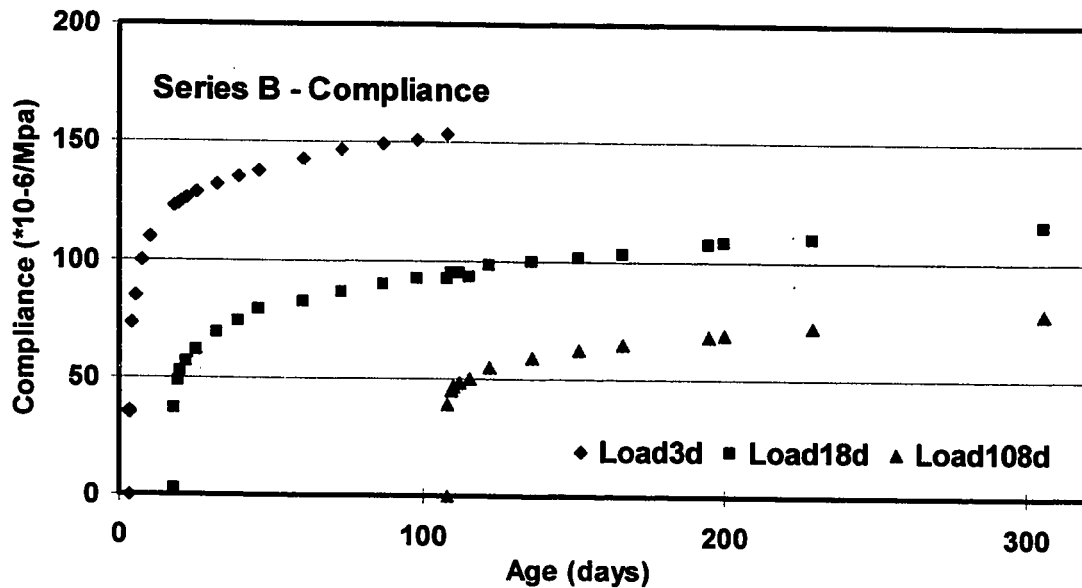


Figure 4.8 Compliance Strains for Series B

Mamillan's approach for load-induced strains for 3 days and 18 days is shown in Figure 4.9. These curves, indicated by continuous lines, are also shown allowing direct comparison. This shows very close result for increased load; however, recovery is quite different.

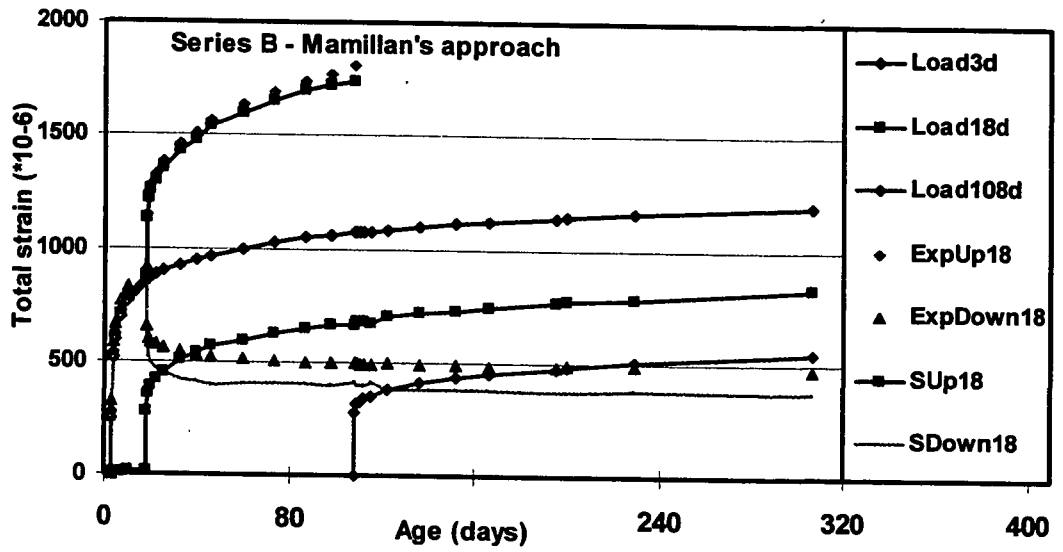


Figure 4.9 Mamillan's Approach of Superposition for Series B

Figure 4.10 shows the specific creep after the second event (18 days) for loading, increased loads and unloading.

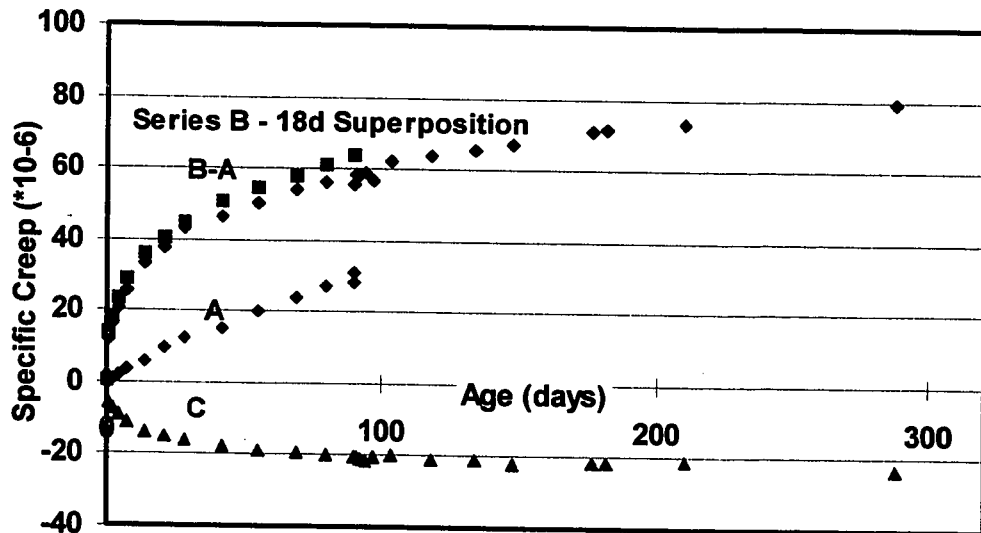


Figure 4.10 Superposition of 18-day Loaded Specimens for Series B

Figure 4.11 shows the comparisons of the incremental specific creeps B-A (increased load) and A-C (recovery) relative to the specific creep of D, the maintained late-loaded specimens, is shown. Again, if superposition is valid, the Curves B-A and A-C should be in coincident with the line of equality. Results are plotted only for the period prior to concrete age of 108 days due to the 18 day maintained load specimens having broken in handling.

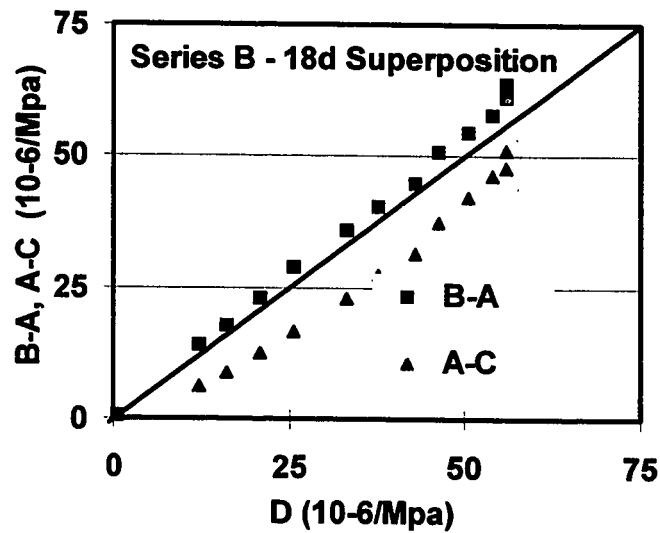


Figure 4.11 Validity of Superposition for 18-day Load Cycle Series B

For Series B results indicate that superposition underestimated the strains due to increased loads by less than 5% but overestimates recovery. This recovery is 90% of predicted value.

Series C - Drying Creep

Figure 4.12 shows the average compliances for the maintained load specimens loaded at 4, 18 and 101 days. The results are logically similar to those of Series A and B. Small deviation in curves at 101 days is probably the result of the process of unloading/reloading or relocation of specimens.

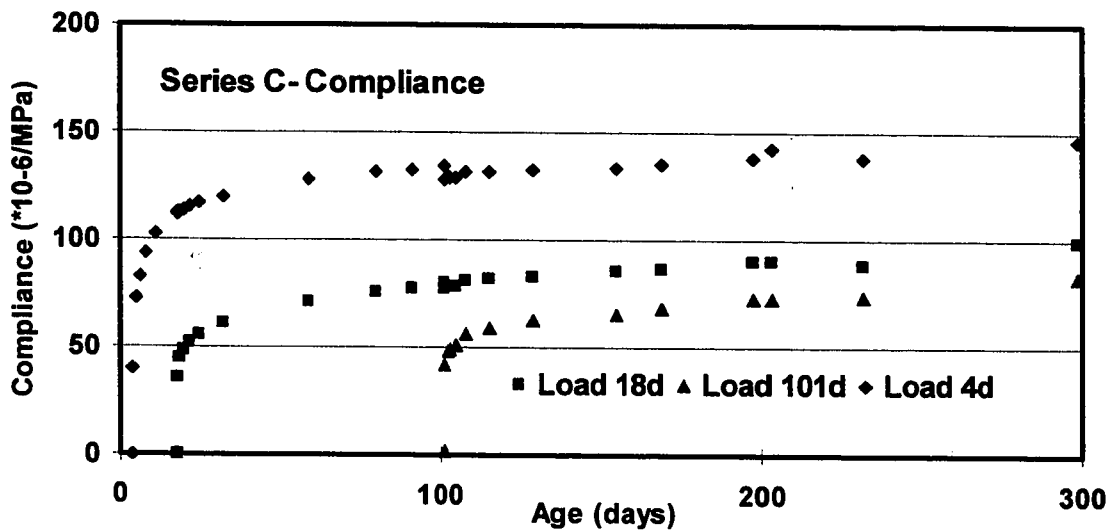


Figure 4.12 Compliance Strains for Series C

The average experimentally measured load induced strains of the specimens derived from measured total strain of loaded specimens less the measured strain of never loaded specimens are shown in Figure 4.13. Also shown are the results calculated using Mamillan's approach. These curves, indicated by continuous lines, are also shown allowing direct comparison. This shows deviation after 18 days for increased load, and after 100 days for creep recovery.

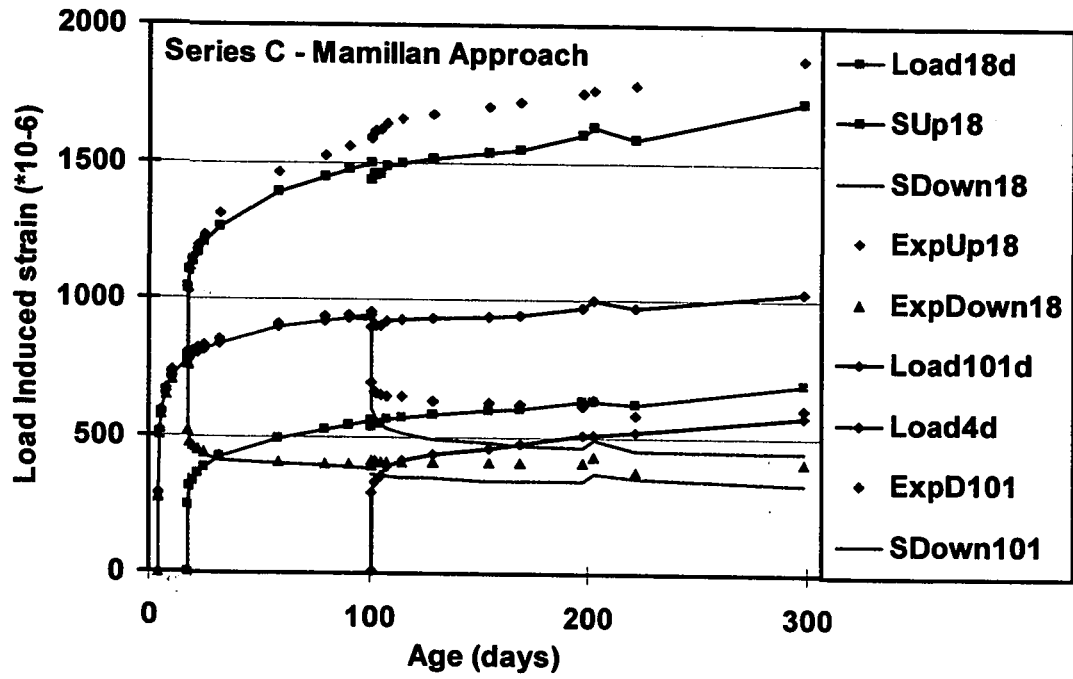


Figure 4.13 Mamillan's Approach of Superposition for Series C

Figure 4.14 shows the specific creep after the second loading cycle, which is obtained by subtracting measured shrinkage and elastic strain from measured total strain divided by the compressive stress.

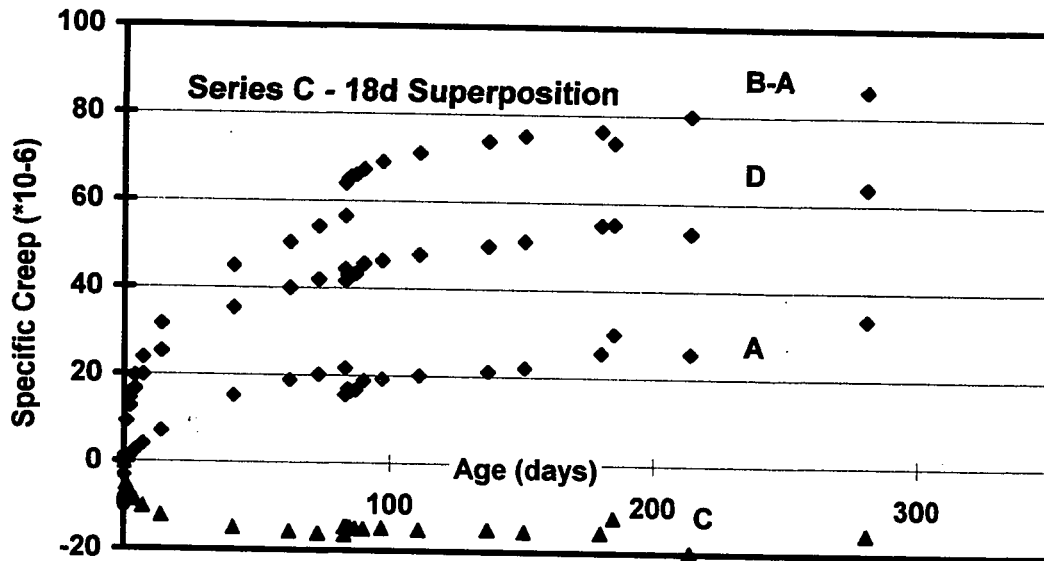


Figure 4.14 Superposition of 18-day loaded Specimens for Series C

Figure 4.15, compares early-loaded incremental specific creep B-A (increased load) and A-C (recovery) relative to the specific creep of the maintained late-loaded specimens (D). The “jump” in the curves is the consequence of averaging two specimens before 101 days and single specimens after.

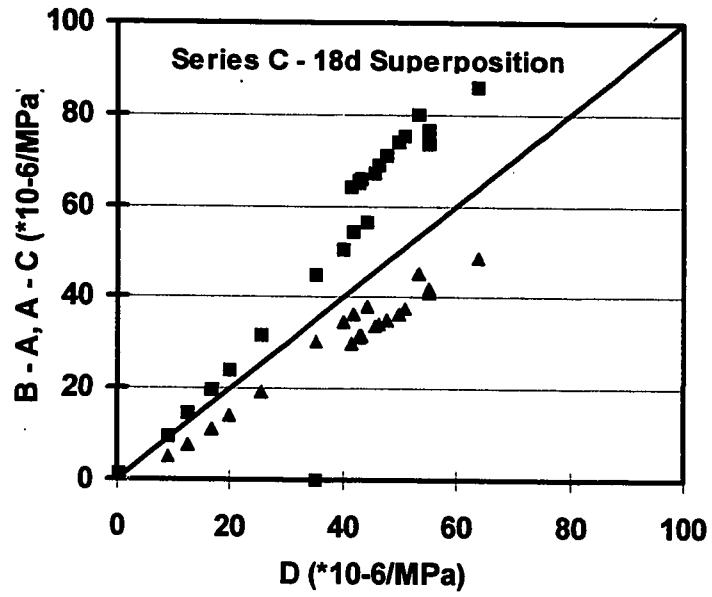


Figure 4.15 Validity of Superposition for 18-day Load Cycle Series C

Specific creep strains of the specimens loaded at 101 days (third load cycle) are shown in Figure 4.16.

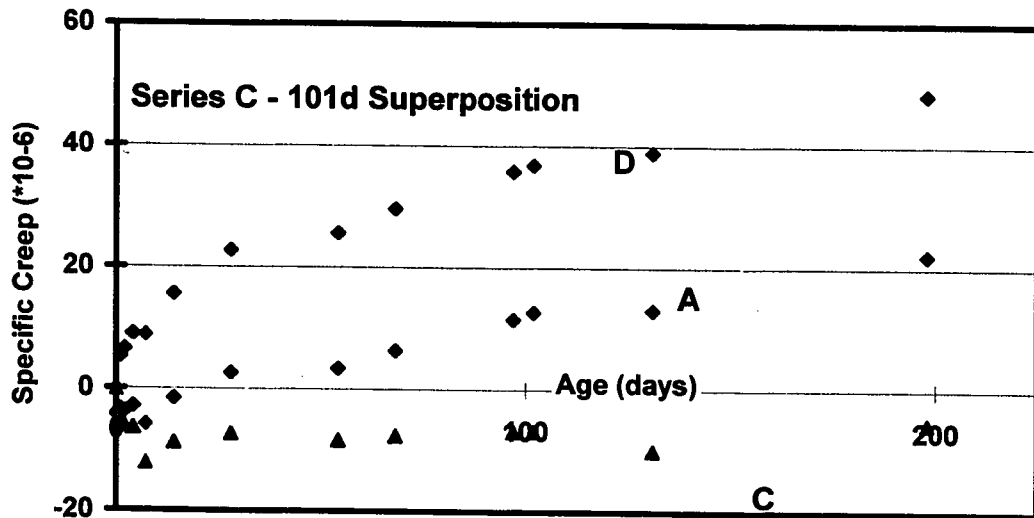


Figure 4.16 Superposition for 101-day loaded specimens Series C

Figure 4.17 shows the comparison of incremental recovery A-C relative to the specific creep of the late-loaded specimens D. At this stage, there was only a single specimen available so a more meaningful comparison was not possible.

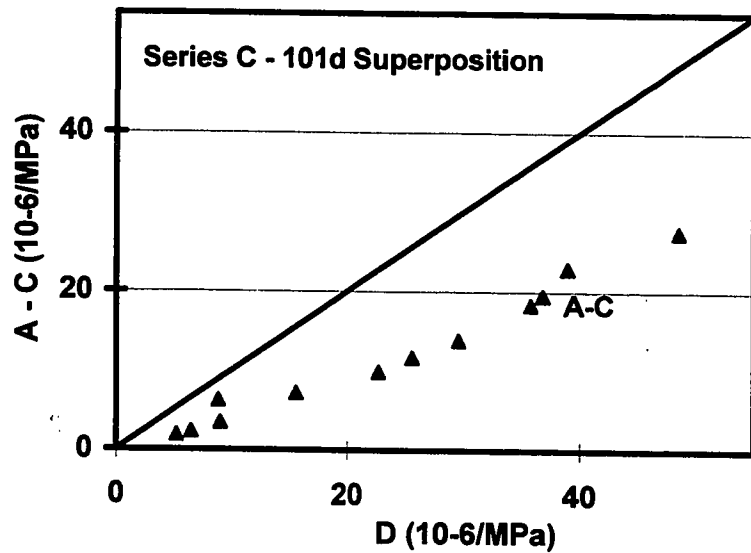


Figure 4.17 Validity of Superposition for 101-day Load Cycle Series C

For Series C, the results indicate that superposition underestimated strains due to increased loads for the second by approximately 15% but overestimates recovery by 11%. Superposition overestimates creep recovery for in the third load cycle. This recovery is 78% of the predicted values.

Yue and Taerwe suggested that creep recovery should be described by a different equation than creep due to increasing load. Their proposed equation, derived from experimental results on concretes removed from the molds after one day and then stored

at 20°C and 60% relative humidity, does not have a humidity dependency suggesting only basic creep is recoverable. The recoveries calculated by Yue and Taerwe's expression are plotted on Figure 4.18 and compared with recoveries for Series A, B, and C. Yue and Taerwe did not investigate recovery of sealed specimens.

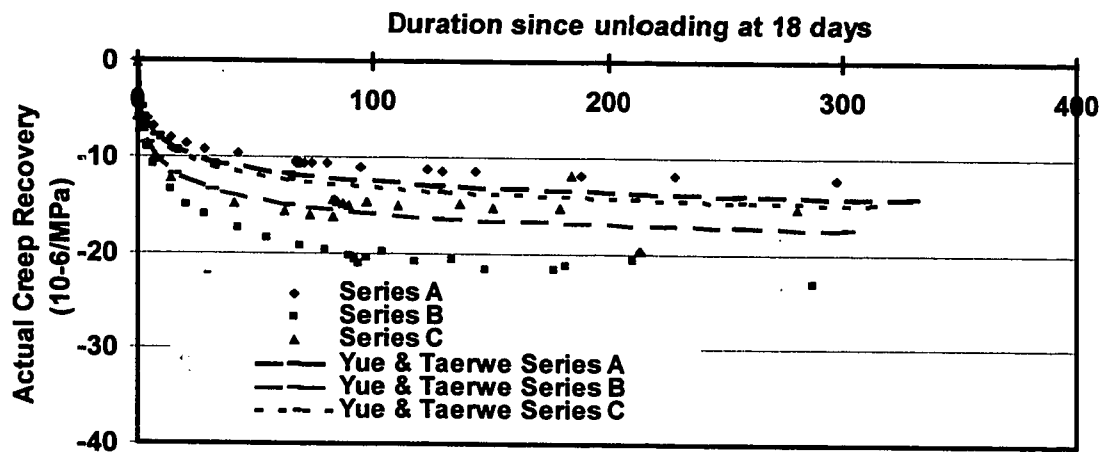


Figure 4.18 Comparison of Creep Recovery; Series A, B & C

Possible Sources of Errors

1. Compliance is calculated by subtracting shrinkage from total strain and dividing by the applied stress. The consequence of subtracting a large number from another large number includes the errors of both previous measurements. Determining immediate/elastic strain is difficult as it is stress rate dependent. To determine creep the immediate strain, with its own uncertainties, is subtracted from the compliance.

2. The process of loading or unloading was not always instantaneous, and at times was longer than anticipated, and in stages. The inability to properly control the process of unloading at every instance had some effect on the accuracy of elastic recoveries measured.
3. Unloading and relocating of specimens, to permit weighing, required that the specimens be accurately placed along the same axis of loading as before; however, repositioning these specimens for further reloading was done at the operators' discretion or judgment.
4. At times the monitoring of maintained load required the a little higher load than that previously set, in order to release the nuts on the loading frames.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This experimental investigation was designed to examine the validity of the hypothesis of superposition of creep strains by measuring and comparing the time dependent strains of concrete prisms subjected to increasing and decreasing loads, constant loads, and late loads (for unsealed concrete specimens which were dried before loading and sealed concrete specimens kept in a moist room). Three series of specimens were made; one was moist cured for four days and then sealed and two series of specimens were moist cured for three and four days respectively and then transferred to a 50% relative humidity room. The conclusions must be read noting that the use of sixteen prism specimens, limits the number of specimens available at second and third load events. Use of a single specimen for either shrinkage or compliance measurement is not desirable.

Compliance is calculated by subtracting shrinkage from total strain and dividing by the applied stress. The consequence of subtracting a large number from another large number includes the errors of both previous measurements. To determine creep the immediate strain, with its own uncertainties, is subtracted from the compliance. Determining the validity of superposition by comparing the creep strains due to increased loading or creep recovery with the creep strains of late loaded specimens is very sensitive because both quantities involve subtraction and consequently to accumulation of experimental errors.

Superposition Sealed specimens

For increasing loads under sealed conditions, it is noticeable that at the second load cycle superposition closely approximates the experimental result. There is a 30% underestimation for the third load cycle. However, these specimens were unloaded and transferred to a higher capacity creep frame. For creep recovery of sealed specimens superposition, considering the calculations involved approximates the experimental results at both 20 days and 87 days.

Superposition Drying Specimens

Two series of specimens exposed to drying were prepared for this phase of the experimental investigation. For drying before loading the results shown in Figures 4.9 and 4.11 (Series B, second load cycle) indicate that superposition underestimates the measured strains by 5% for increasing load, experimental strains are greater than calculated strains. Creep recovery was overestimated by 12%. The results in Figures 4.13 and 4.15 (Series C, second load event) indicate that superposition underestimates creep strain for increasing load by 15%, and overestimates recovery by 10%. The results from Series B & C in general are consistent with results from previous investigation done by Gardner and Tsurata (2004). The manipulated data for the third load cycle shown in Figures 4.16 and 4.17, superposition overestimates creep recovery by 25%. However, the use of single replicates limits the validity of this conclusion.

It would appear that the application of the superposition rule is valid for basic creep in some aspect as indicated but is less valid for drying creep. Therefore an

alternative hypothesis is necessary to predict with more precision the creep strains for concrete subjected to increasing or decreasing loads for drying before loading and sealed conditions.

Creep Recovery

Yue and Taerwe (1992) concluded that after a period of compressive creep, the creep recovery is significantly less than predicted by the principle of superposition. In general it seems that the validity of superposition depends on the age and duration of load application. Yue and Taerwe who suggested that creep recovery should be described by a different equation than that of creep due to load. Experimental results for Series B & C, drying conditions, are larger than those derived from the proposed equation by Yue and Taerwe (1992).

Other Considerations

Average moisture lost in the Series C shrinkage specimens for the first 18 days was 77.4 grams compared with 76.1 grams for the Series C creep specimens. This small difference in average weight loss could have been the direct result of top and bottom metal end plates, which were placed on the creep specimens, and would suggest, that they created a possible retardation of any moisture evaporation at these ends. The influence of compressive load shows very little effect on weight loss compared to specimens without load. These results would indicate that the moisture loss depends only on relative humidity and is not influenced by loading. Drying creep does not depend only on the expulsion of moisture to its surroundings. Maney (1941) and Mamillan (1970) made

similar observations from experiments to examine the seepage theory, which had been suggested to be a physical phenomenon influencing creep.

Even though the concrete mixes were nominally identical, the measured strength of continuously moist cured Series A concrete was significantly higher, 20%, than Series B and C concretes. This behavior, which has been reported elsewhere, must have an influence on the creep of concrete.

A demonstration of load strengthening, using four cylinders of Series C, showed an increase of 7% compared with unloaded cylinders. Freudenthall and Roll (1958) and Yue and Taerwe (1993) referred to this stiffened behavior of concrete under compression in a number of their experiments.

The strain measurements of Series B and C not loaded specimens sealed and transferred to the moist room after 18 days exhibited expansion. This behavior cast doubt to the level of confidence in all pre-dried, sealed specimens and was the reason the weights of all specimens in Series C were monitored. The results of Series A specimens which were sealed immediately after moist curing, concrete saturated in a 96-98% relative humidity environment are as expected.

Recommendations

Because creep is calculated by subtraction of shrinkage and immediate strain from the total strain of loaded specimens, multiple specimens should be used to enable

meaningful statistical averages to be calculated. In particular, shrinkage has to be determined accurately. The assumption that shrinkage and creep are additive should be examined. The effects of load stiffening should be considered.

In addition, for future experiments of similar nature, a single hydraulic loading system that permits all loadings or unloading to be carried out in less than 1 minute would be very useful.

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