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MODULUS OF ELASTICITY, CREEP AND SHRINKAGE OF CONCRETE

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16. Abstract

At present, the modulus of elasticity, creep and shrinkage properties of concrete that are used in structural design in Florida are based on the arbitrary available literature or based on the limited research of the locally available material. There is a great need for a comprehensive testing and evaluation of locally available concrete mixes to determine these mechanical and physical properties of Florida normal-weight as well as lightweight concretes, so that correct values for these properties can be used in structural designs.

The main objectives of this study are (1) to design, evaluate and construct creep test apparatuses that are suitable and effective for performing creep tests on Florida concretes, and (2) to evaluate the compressive strength, indirect tensile strength, elastic modulus, drying shrinkage and creep characteristics of typical Florida Class II, IV, V and VI concrete mixes made with normal-weight and lightweight aggregates.

A creep test apparatus was designed, and twelve creep test apparatuses were constructed and set up in the laboratory for use in performing the creep tests in this study. The creep test apparatus was evaluated to be working satisfactorily. An effective procedure for the creep test using this apparatus was developed and documented. This study has generated valuable data and determined general trends on the compressive strength, splitting tensile strength, elastic modulus, drying shrinkage strains and creep coefficient of typical Florida structural concretes made with normal weight and lightweight aggregates.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometres	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		Temperature (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		Temperature (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Problem Statement

At present, the modulus of elasticity, creep and shrinkage properties of concrete that are used in structural design in Florida are based on the arbitrary available literature or based on the limited research of the locally available material. In the absence of creep and shrinkage test results on the specific concretes to be used, an ultimate creep coefficient of 2.0 and an ultimate shrinkage strain of 0.0004 are usually used in designs. The possible errors in the estimation of these parameters can cause a serious problem in the design of pre-stressed concrete structures such as segmental bridges, which requires a more precise estimate of creep strain and shrinkage strain for the concrete. Thus, there is a great need for a comprehensive testing and evaluation of locally available concrete mixes to determine the mechanical and physical properties of Florida normal-weight as well as lightweight concretes, so that correct values for these properties can be used in structural designs. In addition, there is also an immediate need to determine the most effective and practical laboratory test setups and procedures for obtaining the modulus of elasticity, creep and shrinkage properties of structural concretes used in Florida.

Objectives of the Study

The main objectives of this study are (1) to design, evaluate and construct creep test apparatuses that are suitable and effective for performing creep tests on Florida concretes, and (2) to conduct a research testing program to evaluate the compressive strength, indirect tensile strength, elastic modulus, drying shrinkage and creep characteristics of typical Florida Class II, IV, V and VI concrete mixes made with normal-weight and lightweight aggregates. With the time constraint of this two-year study, a total of 10 different concrete mixes were evaluated.

Design and Construction of Creep Apparatuses

The creep test apparatus was designed, and twelve creep test apparatuses were constructed and set up in the laboratory for use in performing the creep tests in this study. In each test frame, three $6'' \times 12''$ cylindrical specimens can be placed on top of one another and cemented together by an epoxy and tested under the same load. The maximum capacity of each creep apparatus is 1.92×10^5 lbf. The maximum stress that can be applied to the $6'' \times 12''$ cylindrical concrete specimens in the creep frame is 6795 psi. Three pairs of gage points with a gage distance of 10 inches are to be placed in each test concrete specimen. A mechanical strain gage (formerly known as Whittemore gage) is to be used to measure the change in distance between the gage points, which is the creep of the concrete specimen during the creep test.

The creep test apparatus was evaluated to be working satisfactorily. An effective procedure for the creep test using this apparatus was developed and documented.

Findings from the Research Testing Program

Ten typical Florida concrete mixes were evaluated in the research testing program for their compressive strength, splitting tensile strength, elastic modulus, shrinkage and creep characteristics. Eight of the ten concrete mixes used a Miami Oolite as the coarse aggregate, while two concrete mixes used a lightweight aggregate Stalite. Four normal-weight concretes and one lightweight concrete used 20% fly ash, while the other four normal-weight concretes and one lightweight concrete used 50 to 70% slag. Tests were run on the concrete specimens up to an age of 91 days.

Major findings from the tests on these ten concrete mixes are summarized as follows:

❖ **On Strength and Elastic Modulus**

1. The compressive strength, splitting tensile strength and elastic modulus of the normal-weight concretes with 20 % fly ash continue to increase significantly beyond 28 days, while those of the normal-weight concretes with 50 to 70% slag level off considerably beyond 28 days.

2. The lightweight concretes have considerably lower compressive strength, splitting tensile strength and elastic modulus than those of the normal-weight concretes with similar w/c and mineral additive.

3. The empirical relationships between compressive strength ($f_c^{'}$) and splitting tensile strength (f_{ct}) for the normal-weight concretes evaluated in this study are as follows:

$$f_{ct} = 7.08 \cdot \sqrt{f_c^{'}}$$

$$f_{ct} = \left(f_c^{'}\right)^{0.72}$$

The second equation was found to fit the data slightly better than the first one.

4. The empirical relationships between compressive strength and elastic modulus for the normal-weight concretes evaluated in this study are as follows:

For 28-day curing, $E = 32.2 \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$

For 91-day curing, $E = 32.8 \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$

For all curing conditions, $E = 33.0 \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$

❖ **On Drying Shrinkage**

5. For the normal-weight concretes containing 20% fly ash, the drying shrinkage decreases as w/c decreases, and as the moist curing time increases from 7 days to 14 days.

6. For the normal-weight concretes containing 50 to 70% slag, the drying shrinkage does not change significantly as the moist curing time increases from 7 days to 14 days.

7. The normal-weight concretes containing 20% fly ash have a significantly higher drying shrinkage than the concretes containing 50 to 70% slag of comparable w/c.

8. For the two lightweight concretes evaluated, the drying shrinkage decreases significantly as the moist curing time increases from 7 days to 14 days.

9. The lightweight concretes have a significantly higher drying shrinkage than the normal-weight concretes.

❖ **On Creep Characteristics**

10. The creep coefficient is generally lower for a concrete with a lower w/c.

11. The creep coefficient of a concrete with slag is generally lower than that for a concrete with fly ash, for comparable w/c.

12. The creep coefficients of lightweight concretes are substantially lower than those of normal-weight concretes.

13. The creep coefficient does not vary linearly with load level. As the load increases from 40% to 50% of ultimate load, the creep coefficient increases more than proportionally.

14. With the exception of Mix 1 with a low w/c of 0.24, the creep coefficients of the other nine concrete mixes appeared to continue to increase significantly beyond 91 days.

15. Three of the ten concrete mixes evaluated had creep coefficients exceeding the value of 2.0 at 91 days. At least two other concrete mixes had predicted creep coefficients exceeding 2.0 at one year.

Recommendations

While this study has generated valuable data and determined general trends on the compressive strength, splitting tensile strength, elastic modulus, drying shrinkage strains and creep coefficient of typical Florida structural concretes made with normal weight and lightweight aggregates, it must be noted that this study was limited in scope due to the constraint of time and budget. Due to the time constraint, no replicate batch of the concrete mixes in the testing program was tested. There is a need to test the replicates of these concrete mixes to establish reliability of the findings and to evaluate the variability of the test results. The creep tests in this study were run only up to 91 days. However, the creep test results from this study indicate that most of concretes still continued to creep considerably at 91 days. There is a need to extend the creep tests beyond 91 days, and preferably to one year, so that the ultimate creep coefficient can be determined more reliably.

Due to the limited scope of this study as described above, the concrete properties as determined from this study should not be recommended for use in structural designs yet at this point. It is recommended that further testing be conducted in the following areas:

(1) Replicate batches of the ten concrete mixes evaluated in this study should be tested to establish reliability of the findings and to evaluate the variability of the test results.

(2) The creep tests should be run up to one year, instead of 91 days.

(3) Structural concretes using other Florida coarse aggregates should also be evaluated.

(4) The effects of the type and amount of mineral admixtures (fly ash, slag and silica fume), and other admixtures should be evaluated.

Chapter 1

INTRODUCTION

1.1Research Need

At present, the modulus of elasticity, creep and shrinkage properties of concrete that are used in structural design in Florida are based on the arbitrary available literature or based on the limited research of the locally available material. For example, the "AASHTO LRFD Bridge Construction Specifications-2001 Interim Revisions" [AASHTO, 2001] specifies that, for the design of continuous prestressed concrete I-girder superstructures, the ultimate creep coefficient should be 2.0 and the ultimate shrinkage strain will take the value of 0.0004, in accordance with the recommendation of ACI 209. The guidelines say that, when mix-specific data are not available, estimates of shrinkage and creep may be made using the provisions of CEB-FIP model or ACI 209 model. However, the guidelines also state that, without results from tests on the specific concretes or prior experience with the materials, the use of the creep and shrinkage values referenced in these Specifications can not be expected to yield results with errors less than ±50%. This possible error can be a more serious problem for design of segmental bridges, which requires a more precise estimate of creep strain and shrinkage strain for the concrete. Furthermore, we do not have enough data available to judge whether the design parameters given by these specifications are in the range for safe design, especially for structural concretes made with Florida aggregates.

Thus, there is a great need for a comprehensive testing and evaluation of locally available concrete mixes to determine these mechanical and physical properties of Florida normal-weight as well as lightweight concretes, especially for the concretes used in pre-stressed concrete structure, so that correct values for these properties can be used in structural design. In addition, there is also an immediate need to determine the most effective and practical laboratory test setups and procedures for obtaining the modulus of elasticity, creep and shrinkage properties of structural concretes used in Florida. This research study was carried out to meet these needs of the FDOT.

1.2 Scope of This Study

This research study had the following main objectives:

(1) To evaluate and determine the most effective laboratory test setups and procedures for determining the modulus of elasticity, creep and shrinkage properties of structural concretes used in Florida.

(2) To construct the necessary creep testing apparatuses and to set up the necessary laboratory testing equipment and data acquisition system at the FDOT Materials Office for evaluation of the modulus of elasticity, creep and shrinkage properties.

(3) To determine the compressive strength, indirect tensile strength, modulus of elasticity, creep and shrinkage of typical Class II, IV, V and VI concrete mixes made with normal-weight and lightweight aggregates used in Florida. With the time constraint of this two-year study, a total of 10 different concrete mixes were evaluated.

(4) To recommend an efficient and reliable laboratory testing procedure for FDOT for determining or verifying the modulus of elasticity, creep and shrinkage properties of Class II, IV, V and VI concrete mixes.

1.3 Scope of This Report

This report presents all the work performed in this project, including (1) a literature review on the factors affecting the elastic modulus, shrinkage and creep of concrete, and existing models for prediction of these mechanical properties, (2) the design and construction of the creep testing apparatuses, (3) the design and conductance of the laboratory testing program, (4) the collection and analysis of the laboratory data, and (5) findings and recommendations from this study.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review on the effects of various factors on the elastic modulus, shrinkage and creep properties of concrete. The existing models for predicting the elastic modulus, shrinkage and creep properties of concrete are also reviewed.

2.2 Elastic Modulus of Concrete

2.2.1 Definition of Elastic Modulus of Concrete

The modulus of elasticity or "Young's Modulus" is defined as the slope of the stress-strain curve within the proportional limit of a material. For a concrete material, the secant modulus is defined as the slope of the straight line drawn from the origin of axes to the stress-strain curve at some percentage of the ultimate strength. This is the value most commonly used in structural design. Since no portion of the stress-strain curve is a straight line, the usual method of determining the modulus of elasticity is to measure the tangent modulus, which is defined as the slope of the tangent to the stress-strain curve at some percentage of the ultimate strength of the concrete as determined by compression tests on $6'' \times 12''$ cylinders. Figure 2-1 shows the stress-strain plot of a concrete as it is loaded and unloaded. From this figure, we can see that the secant modulus is almost identical to the tangent modulus obtained at some lower percentage of the ultimate strength.

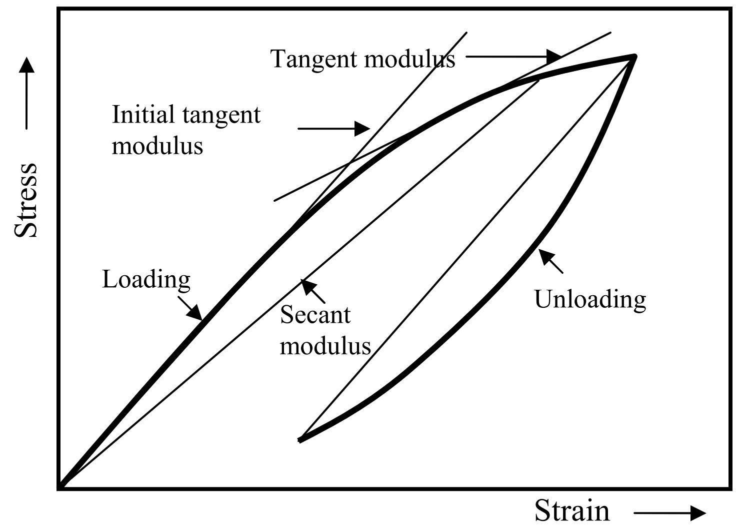


Figure 2-1. Diagrammatic representation of the stress-strain relation for concrete [A.M.Neville, 1996]

2.2.2 Significance of Studying Elastic Modulus of Concrete

The elastic modulus of concrete is a very important mechanical parameter reflecting the ability of the concrete to deform elastically. For example, in prestressed concrete structures, elastic shortening of prestressed concrete is one of the main factors contributing to prestress loss. If a too conservative estimate of elastic shortening was used, the volume of tendon to reach the design prestress would have to be increased, resulting in possible waste of materials and increased cost. Also, prestress loss due to elastic shortening will decrease the capacity of a concrete structure, and even lead to collapse of the structure. In addition, in order to make full use of the compressive strength potential, the structures using high-strength concrete tend to be slimmer and require a higher elastic modulus so as to maintain its stiffness. Therefore, knowledge of the modulus of high strength concrete is very important in avoiding excessive deformation, providing satisfactory serviceability, and achieving the most cost-effective designs.

2.2.3 Influence of Coarse Aggregate on Elastic Modulus of Concrete

Since concrete is a multiphase material, any variation of coarse aggregate content, coarse aggregate type or mix design will result in the change of elastic modulus of concrete. The following sections will review the influence of aggregate content, aggregate type and mix design on the elastic modulus of concrete.

- **Effects of Coarse Aggregate Content on Elastic Modulus**

In a study by A.F.Stock, D.J.Hannant and R.I.T.Williams [Stock et al, 1979], it was reported that for concretes with a fixed w/c of 0.5, as the volume of coarse aggregate varied from 20 to 60 %, the compressive strength of concrete remained almost same, as shown in Figure 2-2. This result is very consistent with the 'W/C law' established by Duff Abrams in 1919. That is to say, for a given mix proportion, the compressive strength of concrete will be determined by its water to cement ratio. This is especially true for normal concrete with compressive strength less than 60 MPa. However, the elastic modulus of the concrete was substantially influenced by the changes in its coarse aggregate content. As shown in Figure 2-3, we can see that the elastic modulus of concrete is remarkably different from that of hardened cement. Also, A.M.Neville [A.M.Neville, 1996] pointed out that, for a concrete of a given strength, because normal weight aggregate has a higher elastic modulus than hydrated cement paste, a higher aggregate content results in a higher modulus of elasticity of the concrete.

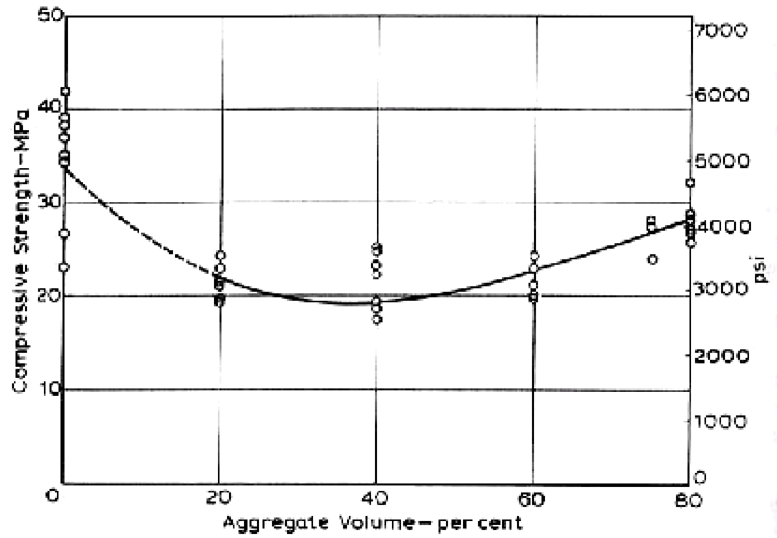


Figure 2-2. Relation between compressive strength and volume of aggregate at W/C= 0.5 [A.F.Stock, D.J.Hannant and R.I.T.Williams, 1979]

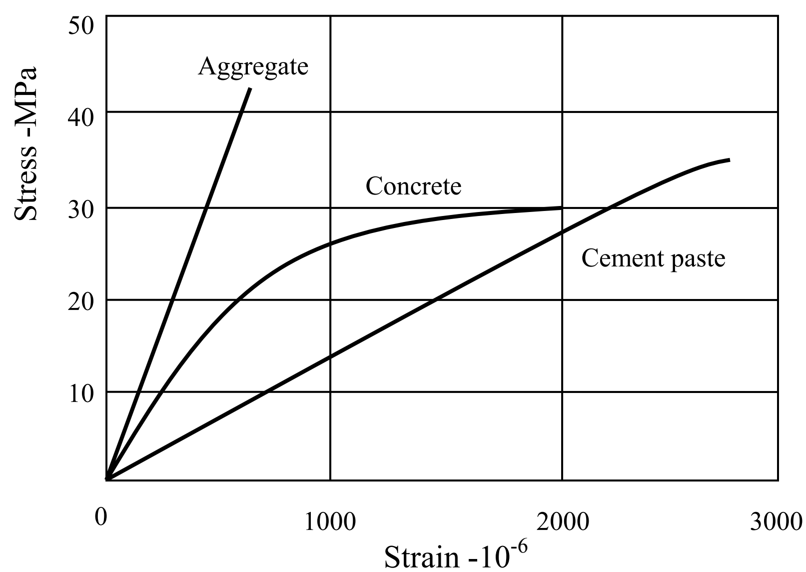


Figure 2-3. Stress-strain relations for cement paste, aggregate and concrete [A.M.Neville, 1996]

In a study by Bertil Persson [Persson, 2001], it was reported that the elastic modulus of self-compacting concrete was the same as that for normal concrete as long as their compressive strengths were the same. However, in the study by Jürg Schlumpf

[Schlumpf, 2004], the elastic modulus of self-compacting concrete was reported to be 20% lower than that of a normal concrete with similar strength. In addition, the findings from the study by J.M.Chi [Chi, 2003] also indicated that the aggregate fraction in concrete had a considerable effect on the elastic modulus of concrete.

❖ **Effects of Coarse Aggregate Type on Elastic Modulus**

Coarse aggregate type is another very important factor affecting the elastic modulus of hardened concrete. Different types of aggregate can have quite distinct effects on elastic modulus. Even different course aggregates of the same type but from different locations can have substantially different properties. The reported findings by F.P.Zhou, F.D.Lydon and B.I.G.Barr [Zhou et al, 1995] show that the coarse aggregate type has a considerable influence on the elastic modulus of concrete. In their study, the effects of expanded clay, sintered fly ash, limestone, gravel, glass and steel aggregate on the elastic modulus of concrete were investigated. Figure 2-4 shows the plot of elastic modulus versus compressive strength of concretes made with different aggregate types. In addition, the study results reported by J.J.Shideler [Shideler, 1957] on concrete mixtures using gravel and expanded clay as aggregate also indicate the same conclusion as reported by F.P.Zhou, F.D.Lydon and B.I.G.Barr [Zhou et al, 1995].

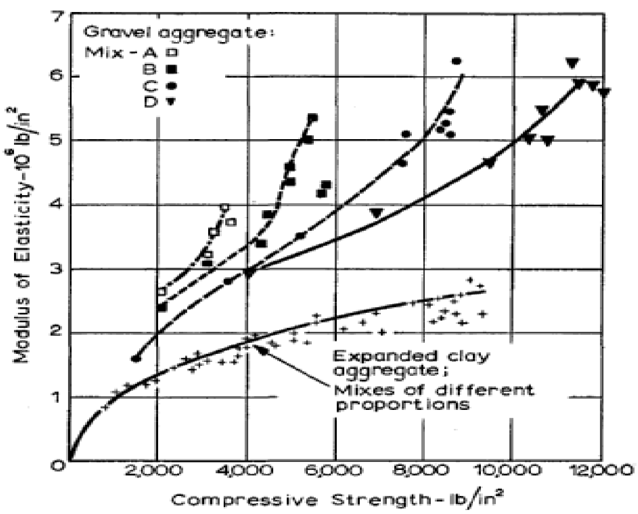


Figure 2-4 Static modulus of elasticity of concrete made with gravel aggregate and expanded clay, and tested at different ages up to one year [J.J.Shideler, 1957]

- **Effects of Mix Design on Elastic Modulus**

Normally, the compressive strength of concrete is the only mechanical property to be considered in the mix design of a concrete. The elastic modulus of concrete is normally predicted by the equation recommended by ACI 318-89. According to the ACI prediction equation, a high compressive strength will give a high predicted elastic modulus. However, from Figure 2-4, it can be seen that a concrete with a higher compressive strength does not necessarily give a higher elastic modulus than a concrete with a lower compressive strength. For example, the elastic modulus of mixture C with a compressive strength of 8,000 psi is similar to that of mixture B with a compressive strength of 5,000 psi. Thus, not only the design strength but also the mix ingredients will have a great influence on the elastic modulus of the concrete.

2.2.4 Models for Predicting Elastic Modulus of Concrete

As mentioned in the literature about the factors affecting elastic modulus of concrete, for a given type of aggregate, although the modulus of elasticity of concrete will increase with the strength of concrete, the factors that affect the modulus of elasticity of concrete do not always have a corresponding effect on the strength of concrete. Thus, there is no universal specification that is possibly applied to relate compressive strength to elastic modulus of concrete.

But, it is still helpful to use models to predict the elastic modulus of concrete. The following sections review a few models for prediction of elastic modulus of concrete.

- **Model recommended by Florida LRFD Guidelines [2002]**

According to this specification, in the absence of more precise data, the modulus of elasticity for concretes with unit weights between 0.090 and 0.155 kcf, can be estimated from the following formula:

$$E_c = 33000 \cdot w_c^{1.5} \cdot \sqrt{f_c^{'}} \qquad \text{[Equation 2.1]}$$

Where

E_c – Elastic modulus in ksi

w_c -unit weight of concrete (kcf)

$f_c^{'}$ -compressive strength of concrete (ksi)

- **Prediction equations recommended by ACI 209**

The prediction equations recommended by ACI for estimating the elastic modulus of concrete are given as follows:

$$E_c = 57000\sqrt{f_c^{'}} \qquad \text{[Equation 2.2]}$$

Where

E_c – Elastic modulus (psi)

$f_c^{'}$-compressive strength of concrete (psi)

This following equation recommended by ACI 318-89 (revised 1992) for structural calculation is applicable to normal weight concrete:

$$E_c = 3.32\sqrt{f_c^{'}} + 6.9 \qquad \text{[Equation 2.3]}$$

Where

E_c – Elastic modulus (GPa)

$f_c^{'}$-compressive strength of concrete (MPa)

The following equation given by ACI 363R-92 is applicable for predicting elastic modulus of concretes with compressive strength up to 83 MPa (12000 psi)

$$E_c = 3.65\sqrt{f_c^{'}} \qquad \text{[Equation 2.4]}$$

Where

E_c – Elastic modulus (GPa)

$f_c^{'}$-compressive strength of concrete (MPa)

- **CEB-FIP Model (1990)**

CEB-FIP Model (COMITE EURO-INTERNATIONAL DU BETON) Code (1990) also offers the following model for prediction of time-dependent modulus of elasticity. The equation is given as follows:

$$E_{ci}(t) = \left(\exp\left(s \cdot \left(1 - \left(\frac{28}{t/t_1} \right)^{0.5} \right) \right) \right)^{0.5} \cdot E_{ci} \qquad \text{[Equation 2.5]}$$

Where

s - A coefficient depending on the type of cement; s = 0.20 for rapid hardening high strength cements, 0.25 for normal and rapid hardening cements, and 0.38 for slow hardening cements.

t - Age of concrete (days).

t_1 - 1 day

E_{ci} = Modulus of elasticity of concrete at an age of 28 days.

2.3 Shrinkage of Concrete

2.3.1 Definition of Shrinkage of Concrete

According to the mechanisms of concrete shrinkage, shrinkage of concrete consists of plastic shrinkage, autogenous shrinkage (a process known as self-desiccation), drying shrinkage, and carbonation shrinkage. Autogenous shrinkage is the consequence of withdrawal of water from the capillary pores by the anhydrous cement particles. Most of the autogenous shrinkage will take place at the early age of hydration of cement. However, for concrete mixtures with a very low W/C ratio, this procedure may last longer if moisture is available. Plastic shrinkage and drying shrinkage are caused by withdrawal of water from concrete under the condition of humidity gradient between the interior of concrete and air. These are the two main factors contributing to cracking of concrete at early age. Carbonation shrinkage is caused by carbonation of calcium hydroxide in the concrete. Thus, carbonation shrinkage normally takes place on the surface of concrete members.

2.3.2 Significance of Studying Shrinkage of Concrete

Shrinkage of concrete is a very important property of concrete to be evaluated. Excessive shrinkage of concrete is connected to cracking of concrete, even failure. At the early age of concrete, due to the low strength of concrete, stresses due to drying shrinkage can cause cracking in the concrete. Shrinkage cracking in concrete can subsequently lead to premature failure of the concrete structure. Cracking in concrete can also lead to increased corrosion rate of steel reinforcement in the concrete structure. The rate at which corrosion occurs and the time to initiate corrosion is significantly influenced by the cracks in the concrete, which increase the permeability of the concrete. For marine concrete or concrete structures close to the coastal region, the penetration of aggressive ions through cracks into the interior of concrete is a very critical factor in causing the corrosion of steel reinforcement.

In addition, for prestressed concrete elements, not only does the shrinkage-induced cracking speed up the corrosion of reinforcement, shrinkage deformation is also one of the main factors contributing to prestress loss.

2.3.3 Effect of Coarse Aggregate on Shrinkage of Concrete

An increase in volume of aggregate in concrete will usually lead to a decrease in cement content, which would lead to reduced shrinkage for the concrete. However, a reduction in cement content does not necessarily cause a reduction in the strength of the concrete. Thus, it is possible to design a concrete with low cement content and low shrinkage without sacrifice of strength.

The following sections will review the influence of aggregate content, aggregate type and aggregate size on shrinkage of concrete.

❖ **Effect of Coarse Aggregate Content on Concrete Shrinkage**

The contribution of coarse aggregate to decrease shrinkage of concrete is attributed to the decrease of cement paste volume in the concrete mix. Figure 2-5 shows the influence of coarse aggregate content on the shrinkage of concrete mixtures with the same curing temperature, relative humidity, and wind velocity.

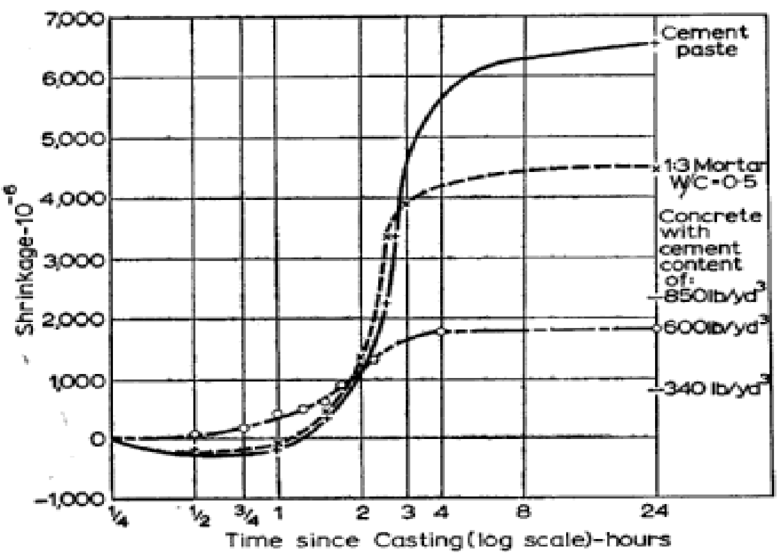


Figure 2-5. Shrinkage of concrete with different cement contents (at a curing temperature of 68°F, 50% relative humidity and wind velocity of 2.25 mph) [R.L'Hermite, 1960]

From Figure 2-5, we can see that, at the early age of concrete, the shrinkage strain of the concrete with a cement content of 850 lb/yd³ (typical cement content for flowable concrete) is almost three times higher than that of concrete mixtures with a cement content of 340 lb/yd^3.

Figure 2-6 shows the influence of aggregate content in concrete on the ratio of the shrinkage of concrete to the shrinkage of cement paste. The shrinkage ratio increases significantly as the aggregate content decreases. The possible reason to explain the effects of coarse aggregate content on shrinkage strain of concrete is shown in Figure 2-7. For the lean concrete mixture with a high coarse aggregate content, the coarse aggregate particles will have point-to-point contacts or even face-to-face contacts with each other. So a concrete with such an aggregate structure will be very effective in resisting stresses caused by cement paste shrinkage. The coarse aggregate particles cannot be pushed more closely under the action of interior stress cause by shrinkage.

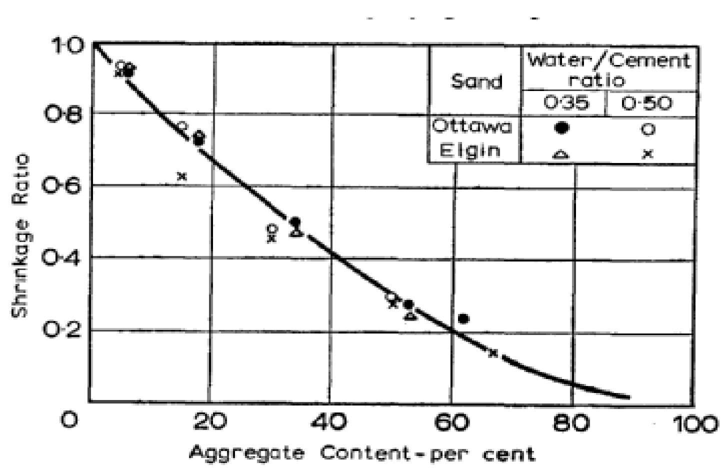
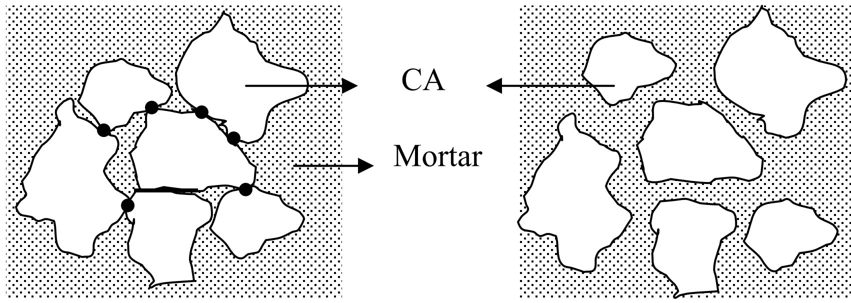


Figure 2-6. Influence of aggregate content in concrete on the ratio of the shrinkage of concrete to the shrinkage of cement paste [G.Pichett, 1956]



a. Lean concrete b. Rich concrete

Figure 2-7. Effect of coarse aggregate content on the shrinkage of concrete

However, for the rich concrete mixture, there are greater distances between the coarse aggregate particles. This condition gives the concrete less resistance to movement caused by shrinkage.

- **Effects of Coarse Aggregate Type on Concrete Shrinkage**

The skeleton of coarse aggregate in a concrete can restrain the shrinkage of the cement matrix. If the skeleton of coarse aggregate in the concrete is stiffer, the shrinkage strain of concrete will be less. The elastic modulus of the aggregate determines the extent of restraining action to the shrinkage of concrete. For example, the shrinkage of a concrete made with a steel aggregate will be lower than the one made with a normal aggregate. Similarly, the shrinkage of a concrete made with expanded shale aggregate will be higher than the one made with a normal aggregate.

As shown in Figure 2-8, the study by G.E.Troxell, J.M.Raphael and R.E.Davis [Troxell et al, 1958] shows that, for a fixed mix proportion, there is a considerable variation in the shrinkage strain of the resulting concrete batched with coarse aggregate of different types. This phenomenon is due very likely to the difference in modulus of elasticity among aggregates of different types. Generally speaking, the elastic property of aggregate determines the degree of restraint to the cement matrix. This conclusion has also been confirmed by T.W. Reichard [Reichard, 1964]. A normal natural aggregate is usually not subject to shrinkage. However, there exist rocks that can shrink up to the same magnitude as the shrinkage of concrete made with non-shrinking aggregate.

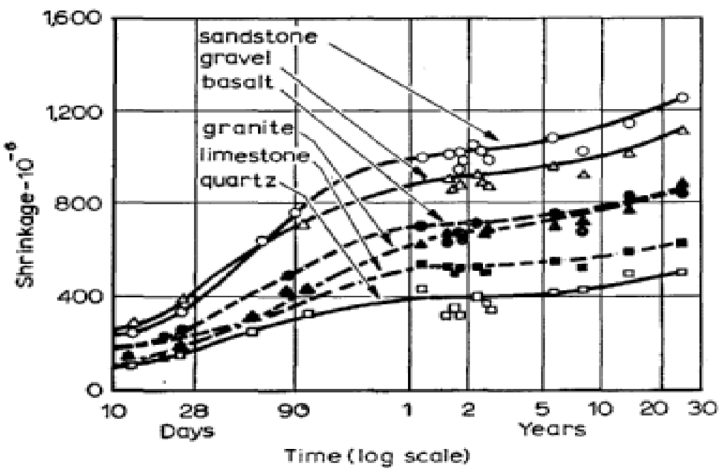


Figure 2-8 Shrinkage of concrete of fixed mix proportion but made with different aggregate and stored in air at 70 °F and relative humidity of 50% [G.E.Troxell, J.M.Raphael and R.E.Davis, 1958]

- **Effects of Size and Shape of Coarse Aggregate on Concrete Shrinkage**

Aggregate size and shape also affect the shrinkage of hardened concrete. The study by J.Bisschop, L.Pel, and J.G.M.van Mier [Bisschop, 2000] indicates that the total length and the depth of micro cracking caused by shrinkage of concrete will increase with larger aggregate size.

2.3.4 Models to Predict Concrete Shrinkage

The shrinkage prediction models offered by LRFD Guidelines, CEB-FIP model code (1990) and ACI-209 (1992) are reviewed in the following sections.

❖ **Prediction equation given by LRFD Guidelines**

For moist cured concretes devoid of shrinkage-prone aggregate, based on the equation recommended by ACI 209 [1992] the modified prediction formula may be taken as:

$$\varepsilon_{sh} = -k_s k_h \left(\frac{t}{35.0+t}\right) \cdot 0.51 \times 10^{-3} \qquad \text{[Equation 2.6]}$$

Where

ε_{sh} – time-dependent shrinkage

t -drying time in days

k_s -size factor; k_s = 1.0 for 6×12 inch cylinder

k_h -humidity factor

❖ **CEB-FIP Model for shrinkage strain prediction**

In this model, the effects of cement type, ambient relative humidity, compressive strength of concrete, and size effect of specimen on shrinkage strain of concrete are taken into consideration. The total shrinkage strain may be estimated by the following equation:

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cs0} \cdot \beta_s(t-t_s) \qquad \text{[Equation 2.7]}$$

Where

$\varepsilon_{cs}(t,t_s)$ – Time dependent total shrinkage strain

ε_{cs0} - Notational shrinkage coefficient

$\beta_s(t-t_s)$ - Coefficient to describe the development of shrinkage with time

ε_{cs0} can be estimated by the following equation:

$$\varepsilon_{cs0} = \left(160 + 10\beta_{sc}\left(9 - \left(\frac{f_{cm}}{f_{cmo}}\right)\right)\right) \times 10^{-6} \quad \beta_{RH} \qquad \text{[Equation 2.8]}$$

Where

β_{sc} - A coefficient which depends on the type of cement: $\beta_{sc} = 4$ for slowly hardening cements; 5 for normal or rapid hardening cements; 8 for rapid hardening high strength cements.

f_{cm} -The mean compressive strength of concrete at the age of 28 days.

f_{cmo} =1 MPa

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

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

Where

$$\beta_{sRH} = 1 - \left(\frac{RH}{RH_0}\right)^3$$

RH - The relative humidity of the ambient environment (%).

RH_0 -100%

$\beta_s(t - t_s)$ can be estimated by the following equation:

$$\beta_s(t - t_s) = \left(\frac{\frac{(t - t_s)}{t_1}}{350 \cdot \left(\frac{h}{h_0}\right)^2 + \frac{t - t_s}{t_1}}\right)^{0.5} \qquad \text{[Equation 2.9]}$$

Where

$h = \frac{2A_c}{u}$ - The notational size of member (in mm), where A_c is the cross-sectional area

(mm^2) and u is the perimeter (mm) of the member in contact with the atmosphere.

h_0 -100 mm

t_1 -1 day

- **Prediction Model Recommended by ACI-209 Report** [1992]

The concrete shrinkage prediction model recommended by ACI-209 (1992) is shown by the following equation:

$$(\varepsilon_{sh})_t = \frac{t}{35+t}(\varepsilon_{sh})_u \qquad \text{[Equation 2.10]}$$

Where

$(\varepsilon_{sh})_t$ - Time dependent shrinkage strain

$(\varepsilon_{sh})_u$ - Ultimate shrinkage strain

t - Time in days

If there is no available shrinkage data from the concrete to be evaluated, the ultimate shrinkage strain, $(\varepsilon_{sh})_u$, can be assumed to be the following:

$$(\varepsilon_{sh})_u = 780 \times 10^{-6} \times \gamma_{sh} \qquad \text{[Equation 2.11]}$$

where

γ_{sh} - a product of all the applicable correction factors for the testing conditions other than the standard condition; γ_{sh} = 1 under standard testing condition.

γ_{sh} is obtained by multiplying the ultimate shrinkage strain under the standard condition by the appropriate correction factors as described in the following:

(1) Correction factors for the effect of initial moist curing

The correction factor is equal to 1.0 for concrete cylinders moist cured for 7 days, and 0.93 for that moist cured for 14 days.

(2) Correction factor for the effect of ambient relative humidity

The following formulas are given for use in obtaining the correction factor for shrinkage test performed under the condition of ambient relative humidity greater than 40%.

$$\gamma_\lambda = 1.40 - 0.0102\lambda \text{, for } 40 \le \lambda \le 80$$

$$\gamma_\lambda = 3.00 - 0.030\lambda \text{, for } 80 \le \lambda \le 100$$

where

γ_λ - Correction factor for the effect of relative humidity

λ - Relative humidity

(3) Correction factor for the effects of specimen size

The correction factor in consideration of the specimen size effect (γ_{vs}) is given by the following equation:

$$\gamma_{vs} = 1.2\exp(-0.12 \cdot \frac{v}{s})$$

where

γ_{vs} - Correction factor for the effects of specimen size

$\frac{v}{s}$ - Volume-surface area ratio of the specimen in inches

(4) Correction factor for concrete composition

Various equations for calculating the correction factors for the effects of the slump of the fresh concrete, aggregate content, cement content and air content of the concrete have also been given in this model.

2.4 Creep of Concrete

2.4.1 Definition of creep of hardened concrete

Figure 2-9 shows a plot of strain versus time for a concrete that was loaded for some time and then unloaded. The permanent strain that remains after the load has been taken off is called the creep strain. The creep strain consists of two main components. The first component is the true or basic creep, which occurs under the conditions of no moisture movement to or from the ambient medium. The second component is the drying creep, which is caused by drying. Normally, the creep strain that is considered in structural design is the sum of basic creep strain and drying creep strain.

Due to the difficulty to differentiate delayed elastic strain from creep strain and the convenience to build a numerical model to simulate time-creep strain curve with the delayed elastic deformation included, the total creep strain would usually include both the delayed elastic deformation and permanent creep deformation. The approach is usually taken since the delayed elastic strain is usually very small compared with the total creep strain.

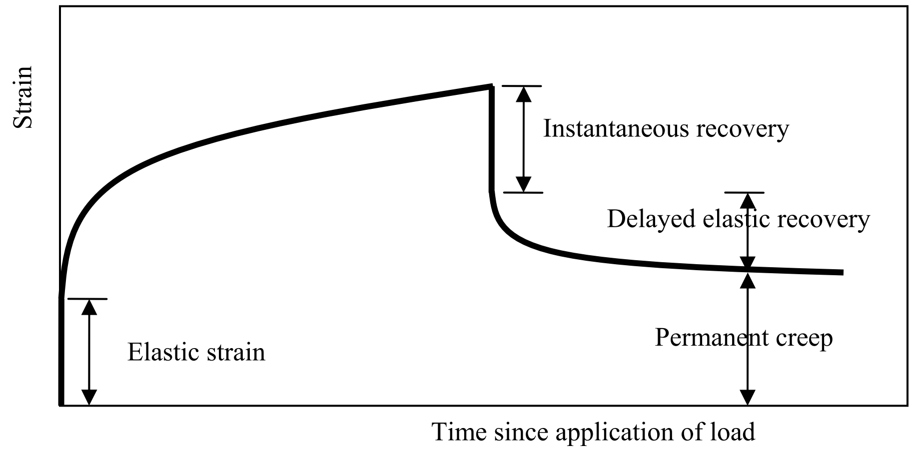


Figure 2-9. Typical strain-time plot of concrete under a sustained load and after release of load

2.4.2 Significance of Studying Creep Behavior of Concrete

Creep in concrete can have both positive as well as negative effects on the performance of concrete structures. On the positive side, creep can relieve stress concentrations induced by shrinkage, temperature changes, or the movement of supports. For example, in indeterminate beam with two fixed ends, creep deformation will be very helpful in reducing tensile stress caused by shrinkage and temperature variation.

On the other hand, in some concrete structures, creep can do harm to the safety of the structures. Creep can lead to an excessive deflection of structural members, buckling or other serviceability problems, especially in high-rise building, eccentrically loaded columns and long bridges. In mass concrete, creep may be a cause of cracking when a restrained concrete mass undergoes a cycle of temperature change due to the development of heat of hydration and subsequent cooling. For prestressed concrete structures, such as composite bridges, pre-stressed shells, or continuous girders, the desirable creep of concrete would be as low as possible. Heavily pre-stressed members and long members are particularly susceptible to large volume changes. If a pre-stressed member is restrained in position prior to the majority of the volume change has taken place, the pre-stressed members will exert excessive forces on its connections and supporting structures that could cause a structural failure.

2.4.3 Effect of Aggregate on Creep of Hardened Concrete

Aggregates play an important role in creep of concrete. Coarse aggregate reduces creep deformation by reducing the cement paste content and restraining the cement paste against contraction. Generally, concretes made with an aggregate, which is hard and dense and have low absorption and high modulus of elasticity, are desirable when low creep strain is needed.

K. M. Alexander, G. M. Bruere and I. Ivanusec studied the influence of 23 aggregate types on creep deformation of concrete [Alexander et al, 1980]. Creep tests were conducted in a controlled environment at 23 °C and 60 % relative humidity. Creep tests were conducted for six months after a 28-day water cured period in lime-saturated water to allow for minimal effects of hydration. Strains were measured using longitudinal gages on two opposite faces of the prism with a gage length of 100 mm (4 in). The conclusion shows that aggregates with a lower absorption will produce concrete with a lower creep deformation. It was further determined that the aggregate with a high elastic modulus will produce low creep values.

T.M.Collins [Collins, 1989] examined the creep property of high strength concrete. Creep tests were conducted according to ASTM C 512. The results demonstrated that a concrete with a larger aggregate size and lower paste content would provide a lower creep strain. Also as shown in Figure 2-10, the study by G.E.Troxell, J.M.Raphael, and R.E.Davis [Troxell et al, 1958] indicates that the creep strains of the concrete mixtures with different types of aggregate will behave differently. The highest creep value is obtained from the concrete made with sandstone aggregate, and the lowest creep value is obtained from the concrete made with limestone. Rüsch et al [Rüsch, 1963] found an even greater difference between the creep strains of concretes made with different aggregates. After 18 months under the load at a relative humidity of 65%, the maximum creep strain of the concrete made with sandstone was five times higher than the minimum creep strain of the concrete made with basalt.

In addition, the conclusion on the effect of coarse aggregate content on creep of concrete is also confirmed by the tests on lightweight aggregate concrete. The study by Mehmet Gesoğlu, Turan Özturan and Erhan Güneyisi [Gesoğlu et al, 2004] shows that concretes containing higher lightweight coarse aggregate content had a lower creep strain at all W/C.

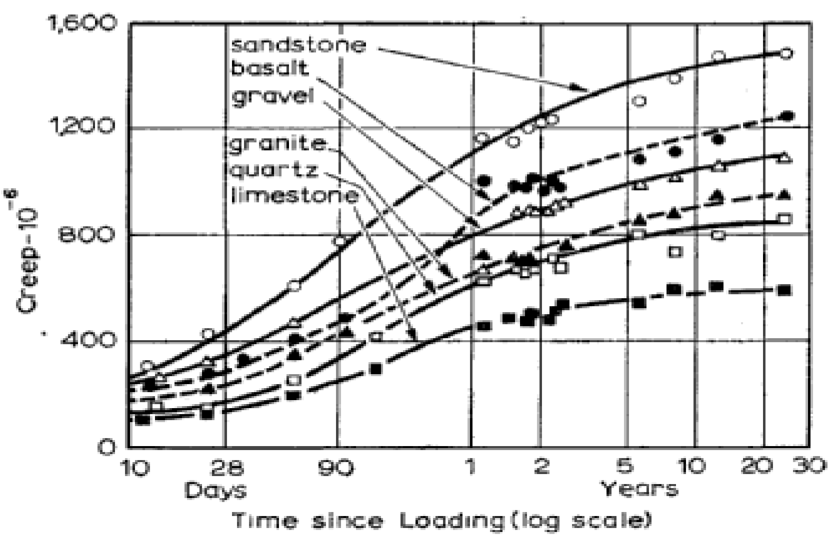


Figure 2-10. Creep of concrete of fixed mix proportion but with different aggregate (loaded at the age of 28 days, and stored in air at 70 ^{o}F and relative humidity of 50 %) [G.E.Troxell, J.M.Raphael, and R.E.Davis, 1958]

Creep tests done by Hua, C. [Hua, 1995] on pure hardened cement pastes and on a reference concrete (made with the same paste) also show that creep is reduced by the presence of aggregate.

Creep of cement paste is the main source of the total creep strain of concrete. Thus, decreasing the cementitious content of concrete is an effective measure to reduce creep strains in concrete.

2.4.4 Models to Predict Creep Strain of Concrete

Regardless of which creep models, either rheological model or numerical model, are used for predicting the relationship between creep strain and time, none of them can give us an accurate prediction. The complicated effects of concrete ingredients as well as the environmental conditions on creep behavior make the satisfying prediction nearly unapproachable. Even though some models were well-established and proper to predict creep behavior of some concretes, they only can be applied to the concretes with the given mix-proportions as well as raw materials.

However, when creep data are not available for specific concrete and there is no condition to perform creep test, prediction equations can be used to get some estimates of the creep strains. Three models for prediction of creep strain of concrete are reviewed in the following sections.

- **Equation given by LRFD Guidelines (FDOT, 2002)**

This method of determining creep is taken from Collins and Mitchell [1991]. This method based on the commendation of ACI Committee 209 is modified by additional recently published data. According to this method, the creep coefficient may be taken as:

$$\varphi(t,t_1) = 3.5k_c k_f \left(1.58 - \frac{H}{120}\right) t_1^{-0.118} \cdot \frac{(t-t_1)^{0.6}}{10.0+(t-t_1)^{0.6}} \qquad \text{[Equation 2.12]}$$

Where

$$k_f = \frac{1}{0.67 + \left(\frac{f_c'}{9}\right)}$$

H -relative humidity (%)

k_0 -factor for the effect of the volume to surface ratio

k_f -factor for the effect of concrete strength

t -maturity of concrete (day)

t_1 -age of concrete when load is initially applied (day)

❖ **C.E.B-F.I.P Model Code (1990)**

In this model, the creep strain can be predicted by the following equation:

$$\varepsilon_{cr}(t,t_0) = \frac{\sigma_c(t_0)}{E_{ci}} \cdot \phi_{28}(t,t_0) \qquad \text{[Equation 2.13]}$$

Where

$\varepsilon_{cr}(t,t_0)$ - Creep strain at time t

$\sigma_c(t_0)$ -Applied stress

$\phi_{28}(t,t_0)$ - Creep coefficient

E_{ci} - Modulus of elasticity at the age of 28 days

The modulus of elasticity can be estimated by the following equation:

$$E_{ci} = \alpha_E \cdot 10^4 \cdot (\frac{f_{ck} + \Delta f}{f_{cmo}})^{\frac{1}{3}}$$ [Equation 2.14]

where

f_{ck} - Characteristic strength of concrete (in MPa)

$\Delta f = 8MPa$

$f_{cmo} = 10MPa$

$\alpha_E = 2.15 \times 10^4 MPa$

The creep coefficient $\phi_{28}(t, t_0)$ can be calculated as follows:

$$\phi_{28}(t, t_0) = \phi_0 \cdot \beta_c(t - t_0)$$ [Equation 2.15]

Where

ϕ_0 - Notational creep coefficient.

β_c - Coefficient to describe the development of creep with time after loading

t - Age of concrete in days

t_0 - Age of concrete when loaded in days

The notational creep coefficient can be estimated as follows:

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

$$\phi_{RH} = 1 + \frac{1 - RH / RH_0}{0.46 \cdot (h / h_0)^{1/3}}$$

$$\beta(f_{cm}) = \frac{5.3}{\sqrt{f_{cm} / f_{cmo}}}$$

$$\beta(t_0) = \frac{1}{0.1 + (t_0 / t_1)^{0.2}}$$

Where

$f_{cm} = f_{ck} + \Delta f$,

h - Notational size of the member (in mm) $= 2A_c / u$.

A_c - Cross-sectional area (in mm^2)

u - Perimeter of the member in contact with the atmosphere (in mm)

h_0 - 100 mm.

RH - Relative humidity of the ambient environment (in %).

RH_0 - 100%

t_1 - 1 day.

$$\beta(t - t_0) = \left[\frac{(t - t_0)/t_1}{\beta_H + (t - t_0)/t_1} \right]^{0.3}$$

$$\beta_H = 150 \cdot \left[1 + \left(1.2 \cdot \frac{RH}{RH_0} \right)^{18} \right] \cdot \frac{h}{h_0} + 250 \le 1500$$

❖ **Model of ACI 209** [ACI 209 Committee, 1992]

In the ACI 209 (1992) model, the creep coefficient is estimated as follows:

$$\phi_{28}(t,t_0) = \phi_\infty(t_0) \cdot \frac{(t-t_0)^{0.6}}{10+(t-t_0)^{0.6}}$$ [Equation 2.16]

Where

$\phi_{28}(t,t_0)$ - Creep coefficient at time t

$\phi_\infty(t_0)$ - Ultimate creep coefficient

t_o - Time of loading

The ultimate creep coefficient can be expressed as:

$$\phi_\infty(t_0) = \gamma_c \cdot \phi_\infty$$ [Equation 2.17]

The constant $\phi_\infty = 2.35$ is recommended. The correction factors γ_c consist of the following terms:

$$\gamma_c = \gamma_{la} \cdot \gamma_{RH} \cdot \gamma_{at} \cdot \gamma_s \cdot \gamma_\rho \cdot \gamma_a$$

Where

γ_{la} - Correction factor for loading age. For loading ages later than 7 days and moist cured concrete, $\gamma_{la} = 1.25 \cdot (t_0)^{-0.118}$. For loading ages later than 1-3 days and steam cured concrete, $\gamma_{la} = 1.13 \cdot (t_0)^{-0.094}$

γ_{RH} - Correction factor ambient relative humidity. For ambient relative humidity greater than 40%, $\gamma_{RH} = 1.27 - 0.0067 \cdot RH$. (*RH* is the ambient relative humidity in %)

γ_s - Correction factor for slump of fresh concrete. $\gamma_s = 0.82 + 0.00264 \cdot S_l$ (S_l is slump in mm)

γ_ρ - Correction factor for fine to total aggregate ratio. $\gamma_\rho = 0.88 + 0.0024 \cdot \rho_a$ (ρ_a is fine to total aggregate ratio)

γ_a - Correction factor for air content. $\gamma_a = 0.46 + 0.09 \cdot a_a$ (a_a is air content)

γ_{at} - Correction factor for thickness of member. When the average thickness or volume to surface ratio of a structural member differs from 150 mm or 38 mm, respectively, two methods are offered for estimating the factor of member size γ_{at} :

(1) average-thickness method

For an average thickness of a member smaller than 150 mm, the factors are given by ACI-209 Report. For an average thickness of a member larger than 150 mm and up to about 300 to 380 mm, the correction factor for thickness is given as:

$\gamma_{at} = 1.14 - 0.00092 \cdot h_a$ During the first year after loading

$\gamma_{at} = 1.10 - 0.00067 \cdot h_a$ For ultimate values

Where

h_a = Average thickness of a member in mm.

(2) volume-surface ratio method

$$\gamma_{at} = \frac{2}{3} \cdot \left[1 + 1.13 \cdot e^{-0.0213 \cdot (\frac{v}{s})} \right]$$

Where

$\frac{v}{s}$ = Volume to surface ratio in mm.

Chapter 3

DESIGN OF CREEP TEST APPARATUS

3.1 Introduction

The creep test apparatus was designed, and twelve creep test apparatuses were constructed and set up in the laboratory for use in performing the creep tests in this study. This chapter describes the design of the creep test apparatus, and its auxiliary tools, which include a gage-point positioning guide for positioning gage points on a creep test specimen, and an alignment frame for aligning the specimens in a vertical direction when they are cemented together with an epoxy.

3.2 Creep Test Apparatus

3.2.1 The Design

The design for the creep test apparatus is shown in Figure 3-1. In each test frame, three $6'' \times 12''$ cylindrical specimens are placed on top of one another and cemented together by an epoxy and tested under the same load. The load is applied by means of a hydraulic jack (with a maximum capacity of 200,000 lbs) and monitored by a load cell with a digital readout indicating the load applied. When the desired load is reached, the nuts on the threaded rods are turned so that they are snugly pressing against the plate underneath the hydraulic jack so as to hold the plate in that position and thus holding the applied load. After the nuts are positioned properly to hold the applied load, the jack and the load cell can be removed from the test frame and used to set the load on another test frame.

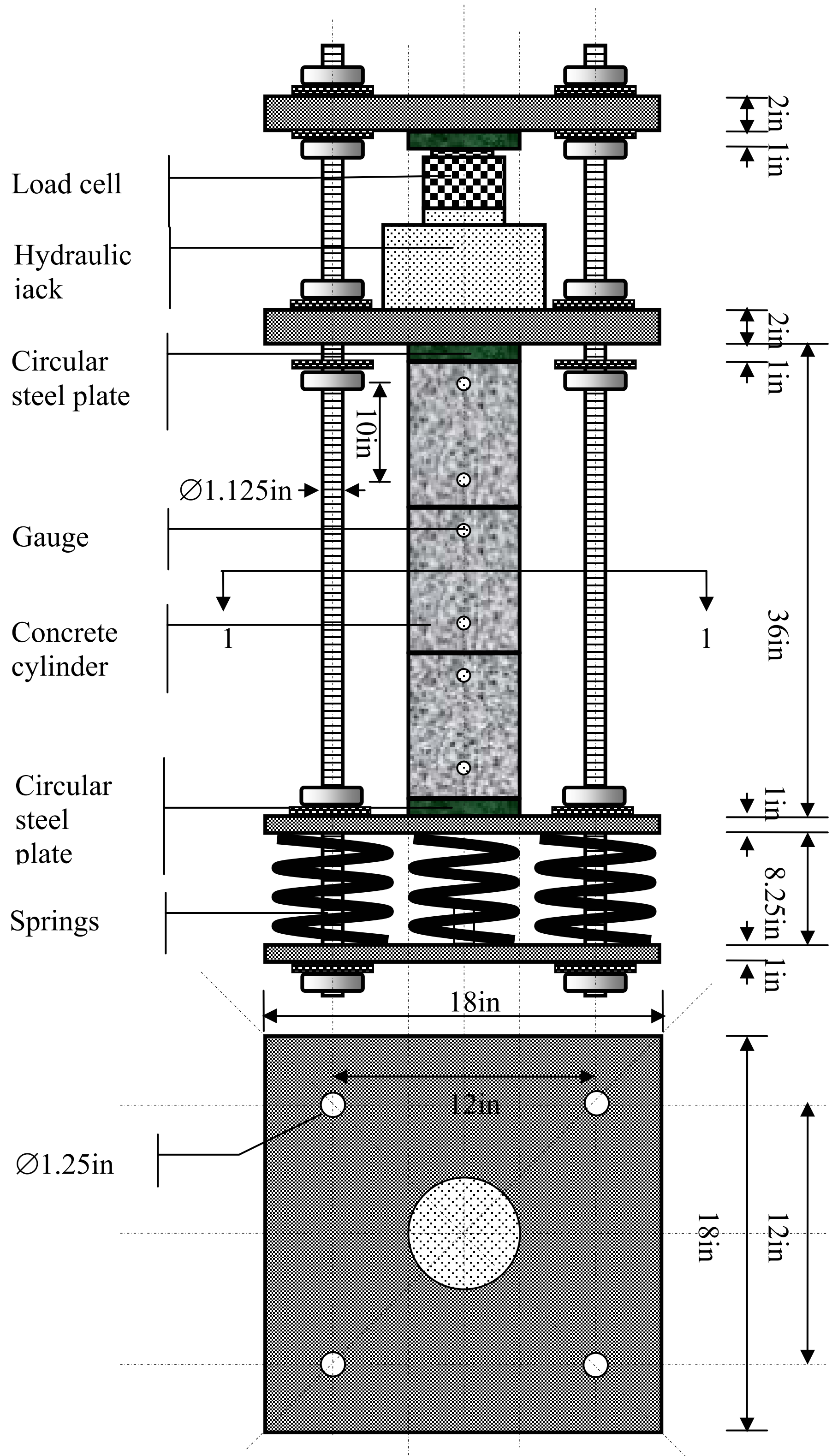


Figure 3-1. Creep Test Apparatus

The springs in the creep frame help to maintain the load that is applied to the concrete specimens, as the concrete specimens creep under load. Up to 9 sets of springs can be used in this test frame. Figure 3-2 shows the positions of the springs in the test frame. Each set of springs consists of a smaller spring fitting inside a larger spring. The reason for using up to 9 sets of springs instead of using a smaller number of springs is mainly due to cost consideration. With this design, standard railroad springs, which are much less expensive than custom-made springs, can be used. This design also has the advantage that when a smaller load is applied, a smaller number of springs can be used so as to maintain the applied load better.

3.2.2 Maximum Capacity of the Creep Apparatus

The spring constant of the larger spring, k_l, is 9822 lbf/in, while the spring constant of the smaller spring, k_s, is 3314 lbf/in. The maximum travel distance, S, for both springs is 1.625 in. If all nine sets of springs are used, the maximum load, C_{max}, that the springs can hold can be calculated to be:

$$C_{max} = 9 \times (k_l + k_s) \times S = 1.92 \times 10^5 \text{ lbf} \qquad \text{[Equation 3.1]}$$

Thus, the maximum capacity of this creep apparatus is $1.92 \text{ X } 10^5$ lbf . The maximum stress, σ_{max} that can be applied to the $6'' \times 12''$ cylindrical concrete specimens in the creep frame can be calculated to be:

$$\sigma_{max} = C_{max} / (\pi \times 3^2) = 6795 \text{ psi} \qquad \text{[Equation 3.2]}$$

In consideration that the concrete test specimens may be loaded up to 50% of its ultimate compressive strength in the creep test, this creep apparatus can be used to test concretes with a maximum ultimate compressive strength of 13,590 psi.

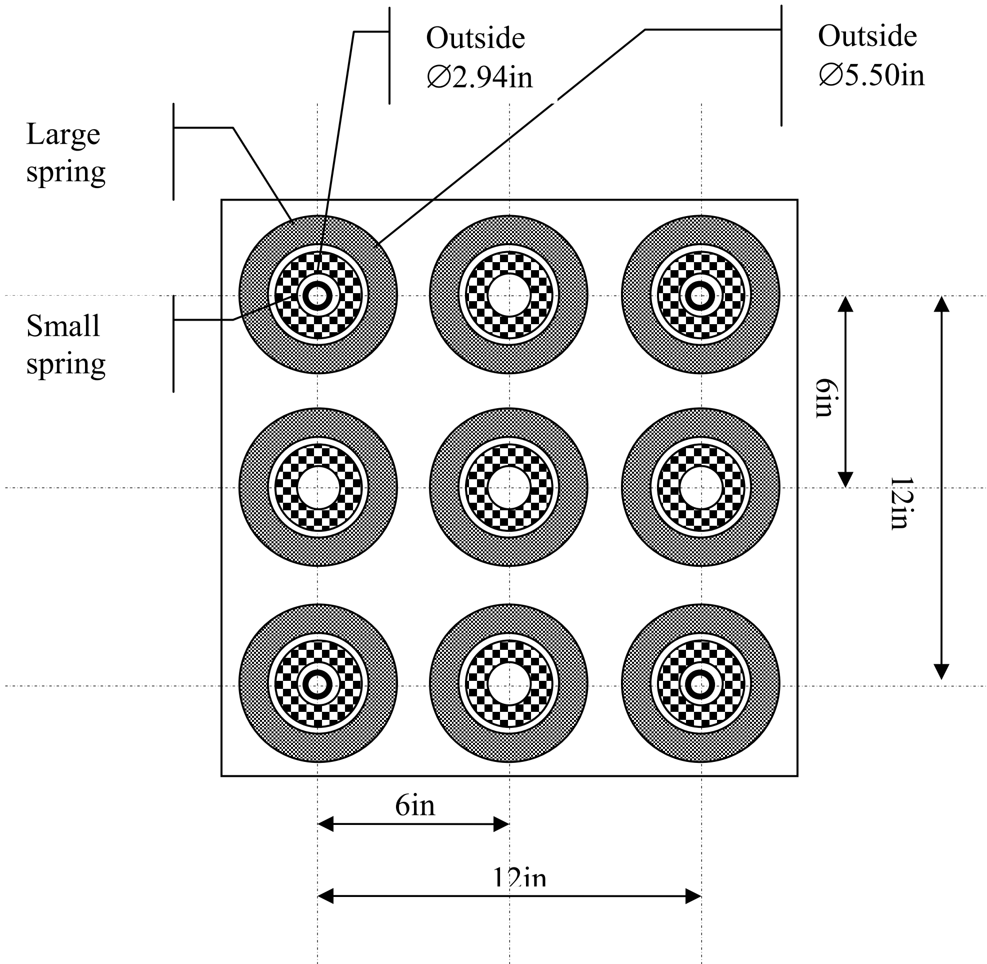


Figure 3-2. Positions of springs on the steel plate

3.2.3 Load Relaxation due to Creep of Concrete

As the concrete specimens creep under the sustained load in the creep frame, the load applied on concrete will be reduced. The load relaxation due to the creep deformation of the concrete specimens can be calculated by multiplying the total creep deformation by the total spring constant of the springs, as follows:

Load Relaxation = (Total Spring Constant) × (Creep Deformation)

= (Total Spring Constant) × (Creep Strain) × 3 × 12 in.

When all nine sets of springs are used, the total spring constant is equal to 118,224 lbf/in. Table 3-1 presents the load relaxation of the creep frame for various values of creep strains for the case when all nine sets of springs are used. The % load relaxation for an assumed load of 150,000 lbf was also calculated and shown in the table.

Table 3-1 Load relaxation in the creep apparatus due to creep strain of concrete

Creep strain	0.5×10^{-5}	1.0×10^{-4}	5.0×10^{-4}	1.0×10^{-3}	2.0×10^{-3}
Load relaxation (lbs)	210	420	2100	4200	8400
% of 150,000 lbs	0.14	0.28	1.4	2.8	5.6

As seen from Table 3-1, re-adjustment of load is necessary to maintain the load constant on the concrete specimens if the creep strain of the concrete specimens is very high.

3.2.4 Stresses in the Steel Rods of the Creep Apparatus

When the concrete specimens are loaded in the creep frame, each of the four steel rods will carry one quarter of total load. The steel rods are 1.125 in. in diameter and are made of a high-strength alloy steel with a yield strength of 105,000 psi. If the concrete specimens were loaded up to the maximum capacity of the creep apparatus of 192,000 lbf, the maximum stress in the steel rods would be equal to:

$$192{,}000 / (4 \times 0.5625^2 \times \pi) = 48{,}300 \text{ psi}$$

This maximum possible stress in the steel rod is less than half of the yield strength of the steel of 105,000 psi.

3.2.5 Circular Steel Plates

As the concrete specimens are loaded in the creep frame, the rectangular steel plates, which are at the top and bottom of the test specimens, are deflected slightly. To keep the loading surfaces flat and the test specimens vertical when the load is applied, two 1-inch thick circular steel plates with a diameter of 6 inches are placed on the top and bottom of the stack of concrete test specimens, as shown in Figure 3-1.

3.3 Gage-Point Positioning Guide

Three pairs of gage points with a gage distance of 10 inches are to be placed in each test concrete specimen. A mechanical strain gage (formerly known as Whittemore gage) is to be used to measure the change in distance between the gage points, which is the creep of the concrete specimen during the creep test.

A gage-point positioning guide, as shown in Figure 3-3, was designed for use in positioning the gauge-points on the plastic cylinder mold. The guide can be placed around a $6'' \times 12''$ cylinder mold. By tightening the six screws on the guide, the precise locations for the three pairs of gage points, with a gage distance of 10 inches, can be marked conveniently on the mold. Figure 3-4 shows the picture of gauge-position guide. Figure 3-5 shows a picture with the plastic cylinder mold inside the gauge-position guide.

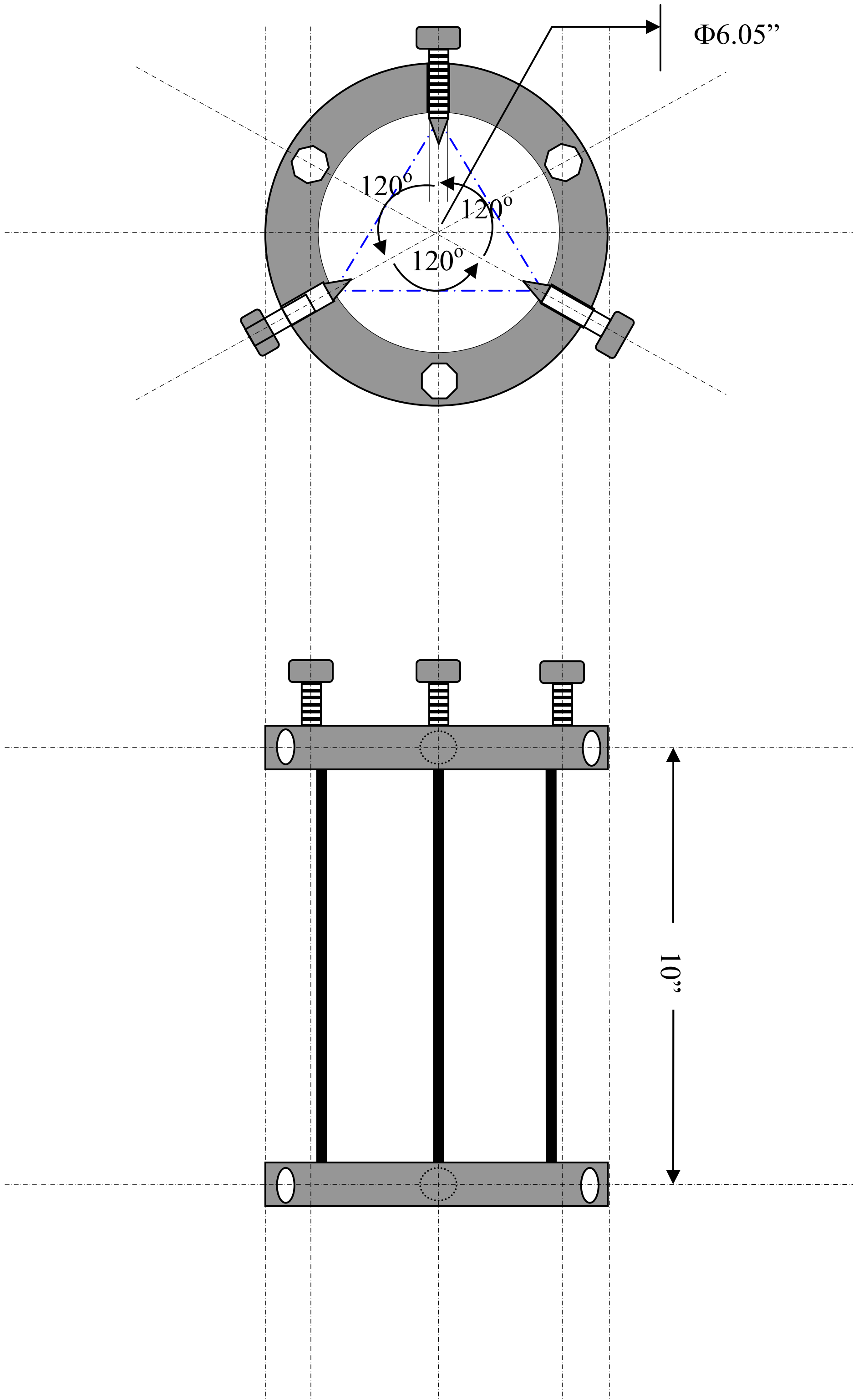


Figure 3-3. Gage-point positioning guide

Figure 3-4. Gauge-position guide

Figure 3-5. Plastic cylinder mold inside gauge-position guide

3.4 Alignment Frame

An alignment frame was designed and constructed to be used to align the concrete specimens in a vertical direction when they are placed in the test frame and cemented together with an epoxy. Figure 3-6 shows the design of the alignment frame. The alignment frame consists of one piece of angle steel and one piece of channel steel with three pieces of $0.5'' \times 2'' \times 10''$ steel plates welded on them respectively. They are connected together by using 6 steel rods. The use of the alignment frame is described in Chapter 4.

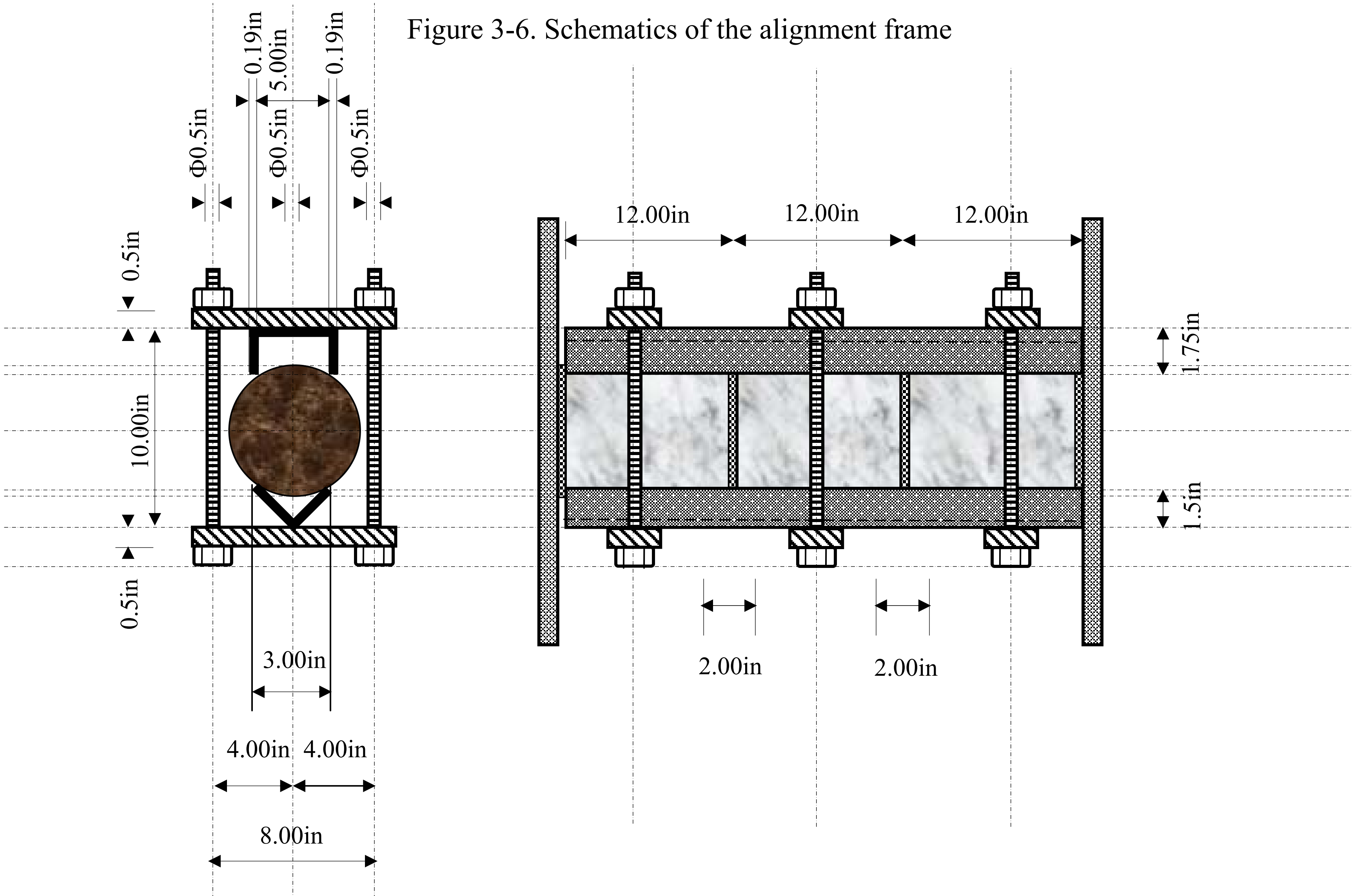


Figure 3-6. Schematics of the alignment frame

Chapter 4

EXPERIMENTAL PROGRAMS

4.1 Introduction

This chapter describes the mix proportions and the mix ingredients of the concrete mixtures evaluated in this study. The method of preparation of the concrete mixtures, fabrication of the test specimens and testing procedures used in this study are also presented.

4.2 Concrete Mixtures Evaluated

4.2.1 Mix Proportions

Typical Class II, IV, V and VI concrete mixtures made with normal-weight and lightweight aggregates used in Florida were selected to be evaluated for their mechanical properties, including compressive strength, splitting tensile strength, modulus of elasticity, shrinkage behavior and creep characteristics.

Because of time constraint, only ten mixtures were investigated. Two different types of coarse aggregates produced in Florida, including a normal-weight limestone aggregate and a lightweight aggregate, were used in this study. The mix proportions for the ten mixtures tested are presented in Table 4-1.

Table 4-1. Mix proportions of the ten concrete mixtures evaluated

No. of Mix	W/C	Cement (lbs/yd^3)	Fly ash (lbs/yd^3)	$\frac{Flyash}{Flyash+Cement}$	Slag (lbs/yd^3)	$\frac{Slag}{Slag+Cement}$	Water (lbs/yd^3)	FA (lbs/yd^3)	CA (lbs/yd^3)	Admixtures	
										AE	WRDA /ADVA
Mix-1	0.24	799.9	200.1	20%	---	---	236.0	931.4	1678.7	7.5 OZ	(WRDA60)-30OZ (ADVA120)-60OZ
Mix-2	0.31	602.1	149.9	20%	---	---	235.3	952	1238.6	9.6 OZ	(WRDA64) -30OZ
Mix-3	0.33	656.1	143.9	20%	---	---	265.6	905.3	1740	12.0 OZ	(WRDA60) -30OZ
Mix-4	0.33	400	---	---	400	50%	262	1062	1750	6.0 OZ	(WRDA60)-24OZ (ADVA120)-48OZ
Mix-5	0.41	494	123	20%	---	----	254	1175	1747	0.5 OZ	(WRDA60)-33.4OZ
Mix-6	0.39	282	---	---	423	60%	275	853	1300	8.8 OZ	(WRDA64)-31.7OZ
Mix-7	0.36	380	---	---	380	50%	270	1049	1736	1.9 OZ	(ADVA120) -38OZ
Mix-8	0.41	197	---	---	461	70%	267	1121	1750	4.6 OZ	(WRDA60)-32.9OZ
Mix-9	0.44	306	---	---	306	50%	269	1206	1710	3.1 OZ	(WRDA60)-30.6OZ
Mix-10	0.37	600	152	20%	---	---	278	1000	1774	2.0 OZ	(WRDA60) -56OZ

Note: AE-air entraining admixture

4.2.2 Mix Ingredients

The mix ingredients used in producing the concrete mixtures are described as follows:

- **Water**

Potable water is used as mixing water for production of the concrete mixtures.

- **Cement**

Type-I Portland cement from CEMEX Company was used. The physical and chemical properties of the cement used are shown in Table 4-2 and Table 4-3.

- **Fly ash**

The fly ash used in this study was provided by Boral Company. The physical and chemical properties of the fly ash used are shown in Table 4-4.

- **Slag**

The slag used in this study was provided by Lafarge Company. Its physical and chemical properties are shown in Table 4-5.

- **Fine aggregate**

The fine aggregate used was silica sand from Goldhead. The physical properties of the fine aggregate are shown in Table 4-6. The gradation of the fine aggregate is shown in Figure 4-1. The fine aggregate was oven-dried before it was mixed with the other mix ingredients in the production of the concrete mixtures.

- **Coarse aggregates**

Two different coarse aggregates were used in this study. One was a normal weight Miami Oolite. The other coarse aggregate was a lightweight aggregate called Stalite. The physical properties of these two coarse aggregates are displayed in Table 4-7. The gradation of the Miami Oolite used is shown in Figure 4-2. The gradation of the Stalite lightweight aggregate is shown in Figure 4-3. The coarse aggregates were soaked in water for at least 48 hours and then drained off the excess water before they were mixed with the other mix ingredients in the production of the concrete mixtures.

- **Air-entraining admixture**

The air-entraining admixture used was Darex AEA from W.R. Grace & Co. Darex AEA is a liquid admixture for use as an air-entraining admixture, providing freeze thaw durability. It contains a catalyst for more rapid and complete hydration of Portland cement. As it imparts workability into the mix, Darex AEA is particularly effective with slag, lightweight, or manufactured aggregates which tend to produce harsh concrete.

- **Water-reducing admixture**

The water-reducing admixture used included WRDA60, WRDA64, and ADVA120 from W.R.Grace & Co.

WRDA 60 is a polymer based aqueous solution of complex organic compounds producing a concrete with lower water content (typically 8-10% reduction), improved workability and higher strengths. It can be used in ready mix, job site and concrete paver plants for normal and lightweight concrete. It also can be used in block, precast and prestress work. In addition, it offers significant advantages over single component water reducers and performs especially well in warm and hot weather climates to maintain slump and workability in high ambient temperatures.

WRDA 64 is a polymer based aqueous solution of organic compounds producing a concrete with lower water content (typically 8-10% reduction), greater plasticity and higher strength. WRDA 64 performs especially well in concrete containing fly ash and other pozzolans.

4.3 Preparation of Concrete Specimens

The concrete mixtures used in this study were produced in the laboratory using a 27-cubic feet pan mixer. A picture of the mixer used is shown in Figure 4-4. Thirteen (13) cubic feet of fresh concrete was produce per batch. Fifty Eight (58) $6'' \times 12''$ cylindrical specimens were made from each batch of concrete. The following procedures were followed:

(1) Measure out the coarse aggregate and fine aggregate, and two thirds of the water and the air-entraining admixture. Place them into the mixer and mix for 1 minute.

(2) Measure out the cement, mineral admixtures, high-range water reducer and the rest of the water. Place them into the mixer and mix for three minutes, followed by a 2-minute rest. After a 2-minute rest, another 3-minute mixing will follow.

(3) Perform a slump test (ASTM C143) to determine whether or not the target slump has been reached. If the target slump is not satisfied, add some more water and/or water-reducing admixture to adjust slump of the fresh concrete. Re-mix the fresh concrete for two more minutes. Then, perform another slump test to check if the target slump has been reached. Repeat this procedure until the target slump is achieved.

Table 4-2. Physical properties of Type I cement

Loss on Ignition (%)	Insoluble Residue (%)	Setting Time (min)	Fineness (m^2/kg)	Compressive Strength at 3 days (psi)	Compressive Strength at 7days (psi)
1.5%	0.48%	125/205	402.00	2400 psi	2930 psi

Table 4-3. Chemical ingredients of Type I cement

Ingredients	SiO_2	Al_2O_3	CaO	SO_3	Na_2O-K_2O	MgO	Fe_2O_3	C_3A	C_3S	C_2S	C_4AF+C_2F
(%)	20.3%	4.8%	63.9%	3.1%	0.51%	2.0%	3.3%	7%	59%	13.8%	15.8%

Table 4-4. Physical and chemical properties of fly ash

SO_3 (%)	Oxide of Si, Fe, Al (%)	Fineness (%) (ASTM C430)	Strength(7d) (ASTM C109)	Strength (28d) (ASTM C109) (%)	Loss on Ignition (%) (ASTM C311)	% of Water (ASTM C-618)
0.3	84	32	N/A	78	4.3	102

Table 4-5. Physical and chemical properties of slag

SO_3 (%)	Oxide of Si, Fe, Al	Fineness (%) (ASTM C430)	Strength(7d) (%) (ASTM C109)	Strength (28d) (ASTM C109) (%)	Loss on Ignition (%) (ASTM C311)	% of water (ASTM C-618)
1.7%	N/A	4	92%	129	N/A	N/A

Table 4-6. Physical properties of fine aggregate

Fineness Modulus	SSD Specific Gravity	Apparent Specific Gravity	Bulk Specific Gravity	Absorption
2.30	2.644	2.664	2.631	0.5%

Table 4-7. Physical properties of coarse aggregates

Aggregate	SSD Specific Gravity	Apparent Specific Gravity	Bulk Specific Gravity	Absorption
Miami Oolite	2.431	2.541	2.360	3.03%
Stalite	1.55	-	-	6.6%

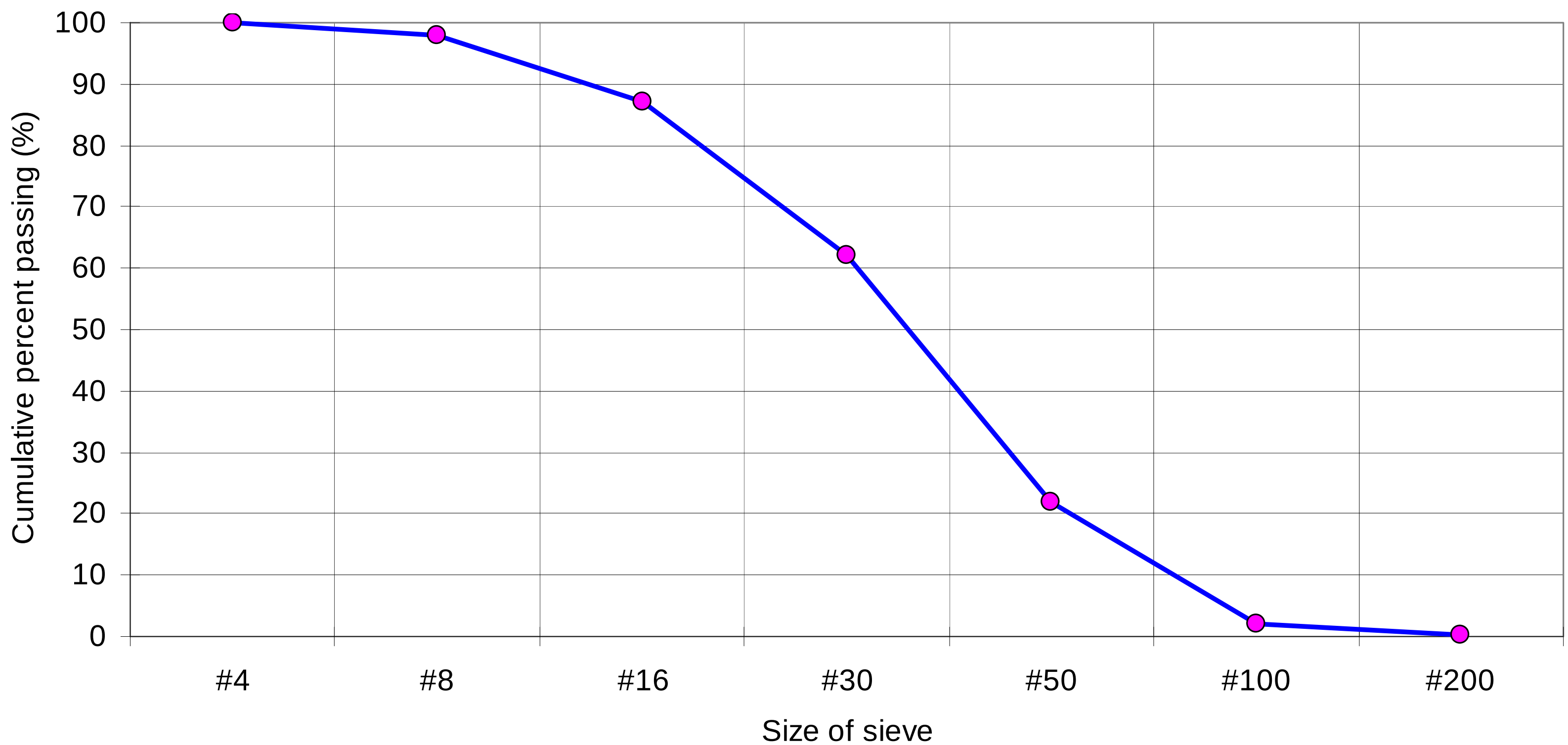


Figure 4-1. Gradation of Goldhead sand

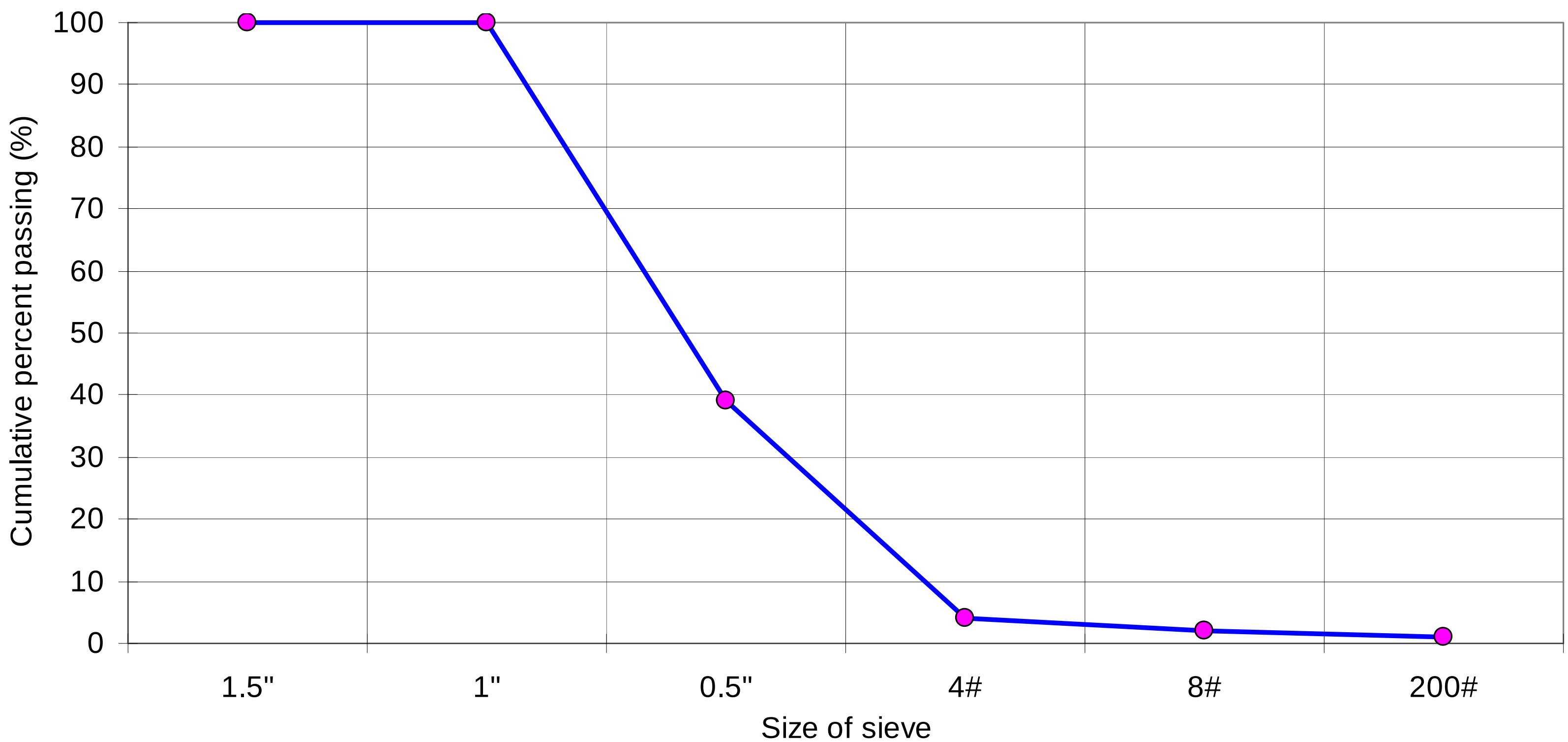


Figure 4-2. Gradation of Miami Oolite coarse aggregate

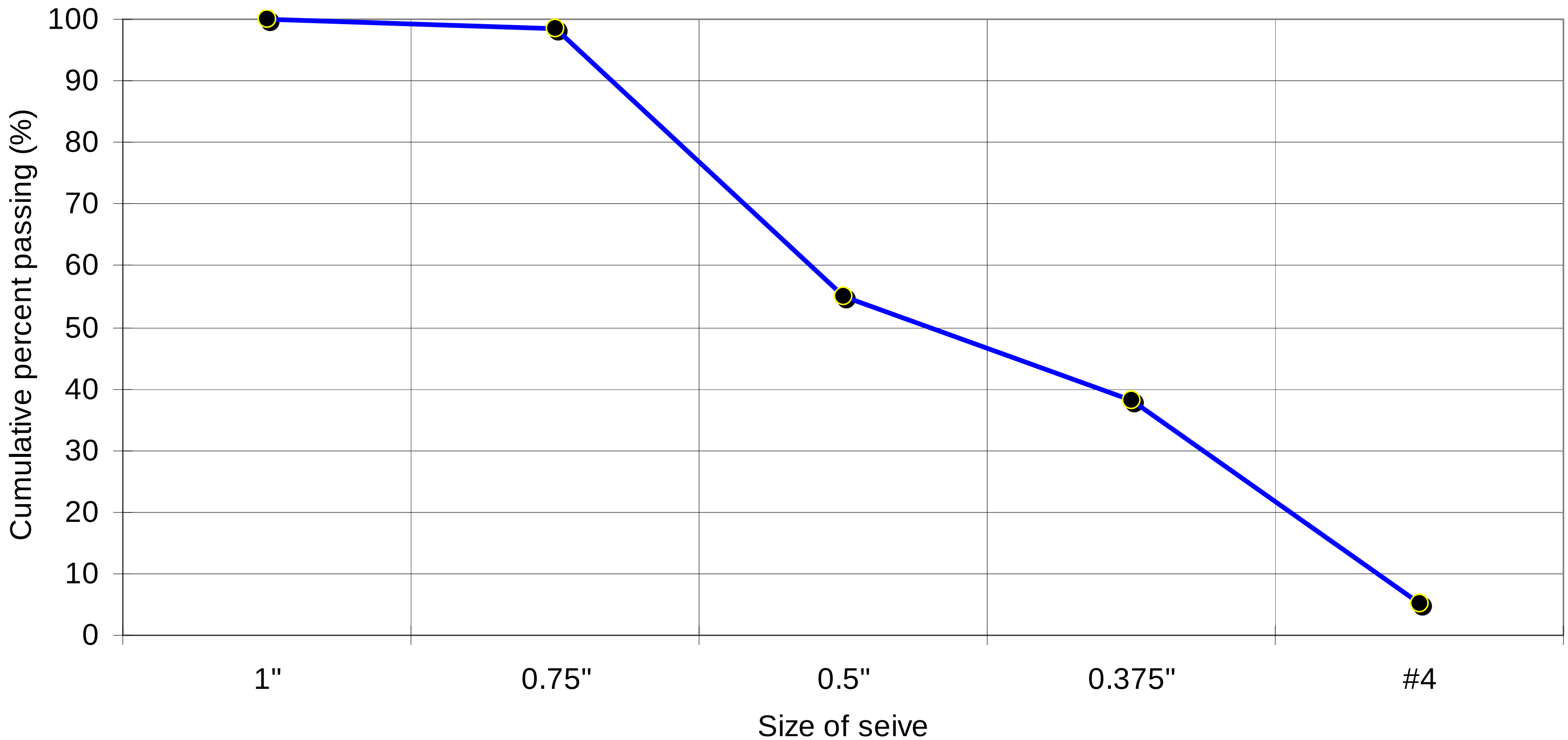


Figure 4-3. Gradation of stalite lightweight aggregate

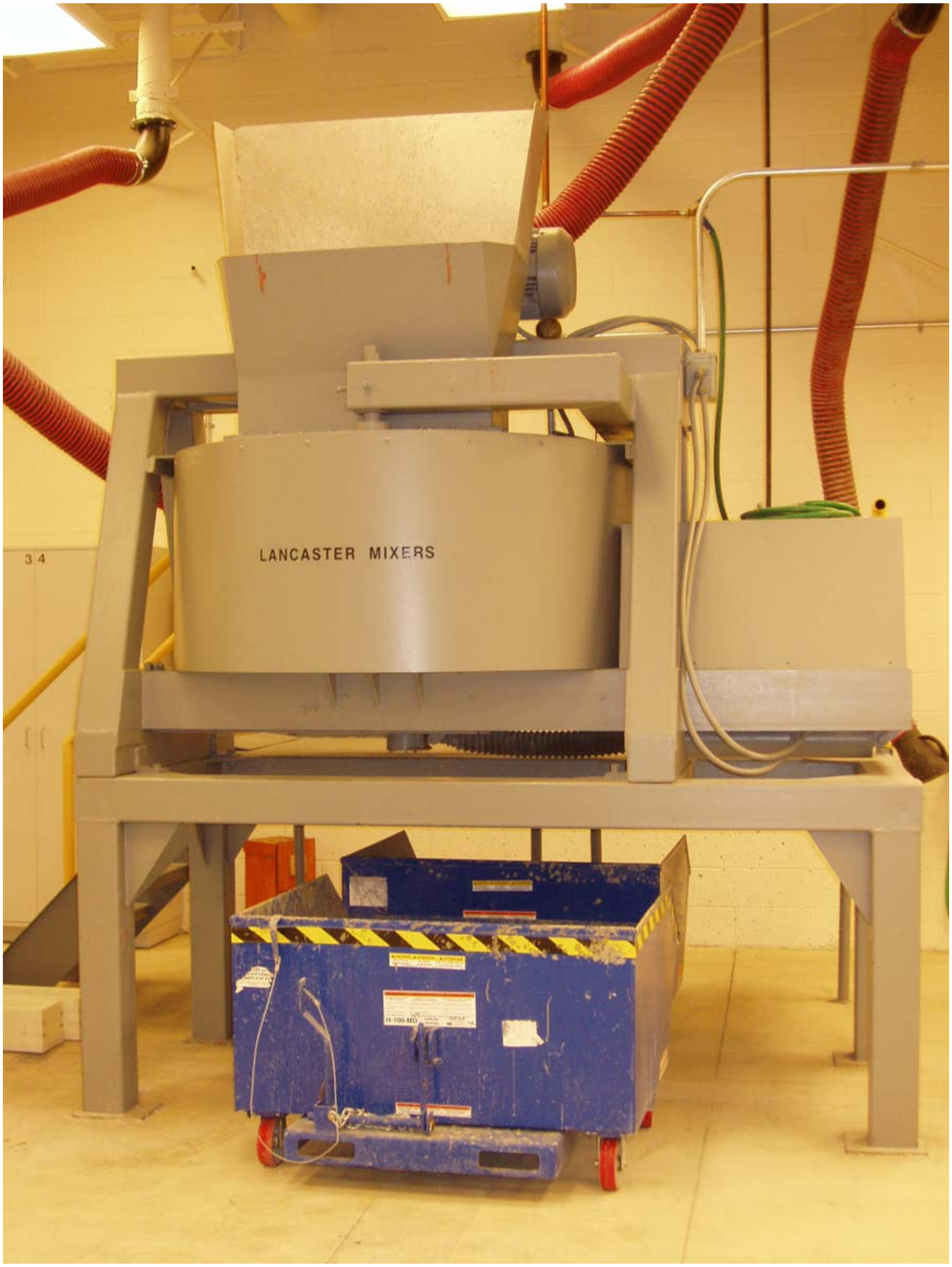


Figure 4-4. Concrete mixer used in this study

(4) After the mixing procedure is completed, place the fresh concrete into $6'' \times 12''$ plastic cylinder molds. If the slump of the fresh concrete is less than 7 inches, fill each cylinder mold to one third of its height, and place the mold on a vibrating table for 45 seconds. Then fill the mold to another one third of its height, and place the mold on the vibrating table for 45 seconds. Then fill the mold fully, and place the mold on the vibrating table for 45 seconds. If the slump is more than 7 inches, fill each cylinder mold in three layers, and rod each layers manually 25 times, as specified in ASTM C31.

(5) Finish the surface of each concrete specimen with a trowel. Cover the top of the cylinder with a plastic sheet to keep moisture from evaporating.

(6) Allow the concrete to cure in the cylinder molds for 24 hours before demolding. For concretes with very low compressive strength at 24 hours, allow another 24 hours of curing in the mold before demolding.

(7) Place the demolded concrete specimens in the standard moist curing room for the specified curing times until testing.

4.4 Curing Conditions for Concrete Specimens

The concrete specimens for compressive strength test, splitting tensile strength test, and elastic modulus test were cured in the standard moist room until the age to be tested. Two different curing conditions were applied to the concrete specimens for shrinkage and creep tests. The first one is to cure the concrete specimens for 7 days in the moist room and followed by room condition for another 7 day. The second one is to cure the concrete specimens for 14 days in the moist room and followed by room condition for another 14 days.

4.5 Tests on Fresh Concrete and Properties of fresh concrete

The tests to be run on fresh concrete are shown in Table 4-8.

Table 4-8. The testing program on fresh concrete

Test	Slump	Air Content	Unit Weight	Setting Time	Temperature
Test Standard	ASTM C143	ASTM C 173	ASTM C138	ASTM C403/C 403M	ASTM C 1064

They are described as follows:

- **Slump test**

Slump test was performed in accordance with ASTM C143 standard. The slump value was used to evaluate the consistency of fresh concrete.

- **Air content test**

Air content test was performed in accordance with ASTM C 173 standard. The volumetric method was employed for this test.

- **Unit weight test**

The procedure of ASTM C138 standard was followed in running the unit weight test. This test was carried out to verify the density of concrete mixtures for quality control.

- **Setting time test**

ASTM C403/C 403M standard was followed to perform the setting time test. The mortar specimen for the setting time test was obtained by wet-sieving the selected portion of fresh concrete through a 4.75mm sieve. The Proctor penetration probe was employed for running this test. In this test, the initial setting time is determined when the penetration resistance equals 500 psi, and the final setting time is determined when the penetration resistance reaches 4000 psi.

❖ **Temperature test**

Temperature of the fresh concrete was determined in accordance with ASTM C 1064 standard. This test was used to ensure that the temperature of the fresh concrete was within the normal range, and that there was no unexpected condition in the fresh concrete. A digital thermometer was used to monitor the temperature of the concrete.

❖ **Properties of fresh concrete**

The properties of the fresh concrete for each of the ten mixtures are presented in Table 4-9.

Table 4-9. Properties of fresh concrete

Mix Number	Slump (in)	Air Content (%)	Unit Weight (lbs/yd^3)	Setting Time		Mixture Temperature (^oF)
				Initial	Final	
mix-1	9.75	1.25	145.52	7h 0min	8h 50min	81
mix-2	2.5	3.0	117.7	5h 35min	7h 20min	80
mix-3	4.25	4.5	137.7	---	---	73
mix-4	9.0	3.75	141.6	---	---	78
mix-5	2.0	2.50	143.9	4h 55min	7h 15min	76
mix-6	2.75	5.25	109.3	7h 45min	10h 0min	78
mix-7	5.50	2.25	141.4	3h 10min	4h 55min	81
mix-8	5.75	5.5	138.0	---	---	79
mix-9	3.00	3.75	140.36	---	---	76
mix-10	3.00	2.0	143.8	---	---	74

4.6 Tests on Hardened Concrete

The tests to be run on the hardened concrete specimens are given in Table 4-10.

Table 4-10. The testing program on hardened concrete

Test	Compressive Strength	Splitting Tensile Strength	Elastic Modulus	Shrinkage	Creep
Test Standard	ASTM C 39	ASTM C 496	ASTM C 469	Described in report	Described in report

These tests are described as follows:

❖ **Compressive strength test**

Compressive strength test is a routine test to evaluate the mechanical property of concrete. The test results can be used as a basis for quality control of concrete proportioning, mixing, and placing operations.

The test procedure of ASTM C 39 standard was followed. For each concrete mixture, three replicate $6'' \times 12''$ cylindrical specimens were tested for their compressive strength at the age of 3, 7, 14, 28, 56, and 91 days, with a total of 18 specimens tested. Before testing, the concrete cylinders were either sawed or ground at the ends in order to keep the two end surfaces even so as to support the load uniformly.

The compressive strength of the test specimen is calculated by dividing the maximum load attained from the test by the cross-sectional area of the specimen, as shown by the following equation:

$$f_i = \frac{p_i}{\pi \cdot r^2} = \frac{4 p_i}{\pi \cdot D^2} \qquad \text{[Equation 4.1]}$$

Where

f_i – Ultimate compressive strength of cylinder i, psi;

p_i – Ultimate compressive axial load applied to cylinder i, lbs;

D – Diameter of cylinder specimen, in.

The average value of compressive strength from three cylinders will be taken as the compressive strength of the concrete.

❖ **Splitting tensile strength test**

The testing procedure of ASTM C 496 standard was followed in running the splitting tensile strength test. The concrete cylinders with the same dimension as that used for compressive strength test were employed for the split tensile strength test. The same curing conditions as those for the compressive strength test were used for the splitting tensile strength test. Three replicate specimens were tested at each of the curing times, which were 3, 7, 14, 28, 56, and 91 days. A total of 18 specimens per concrete mixture were tested for splitting tensile strength.

Before testing, four lines were drawn on the sides of each specimen to mark the edges of the loaded plane. The marked lines were used to help align the test specimen before the load was applied. Figure 4-5 shows the loading configuration for this test.

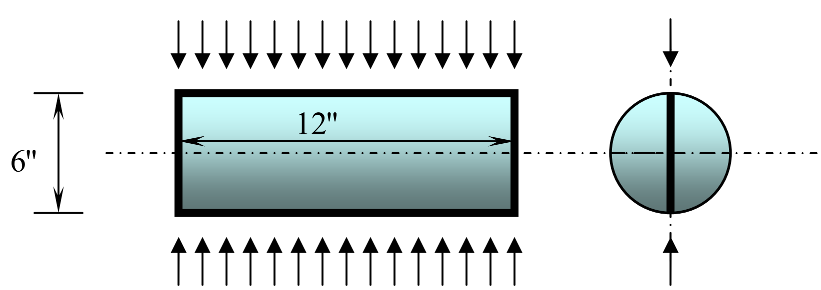


Figure 4-5 Loading configuration for splitting tensile test

The splitting tensile strength of a cylinder specimen can be calculated by the following equation:

$$T_i = \frac{2p_i}{\pi \cdot l \cdot D} \qquad \text{[Equation 4.2]}$$

Where

T – Split tensile strength of cylinder i, psi;

p_i – Maximum applied load to break cylinder i, lbf.

l – Length of cylinder, in;

D – Diameter of cylinder, in.

The splitting tensile strength of concrete will take the average value of splitting tensile strengths of three cylinders.

Due to the sensitivity and susceptibility of the splitting tensile strength to the effects of internal flaws, such as voids, the results of some splitting tensile strength tests may be unusually low and may need to be discarded. For this reason, five extra concrete cylinders were prepared for use in repeating this test if needed.

❖ **Elastic modulus test**

The testing procedure of ASTM C 469 standard was followed to determine the elastic modulus of the concrete specimens. In this method, the chord modulus of elasticity of concrete cylinders is determined when a compressive load is applied on a concrete cylinder in longitudinal direction. Figure 4-6 shows the equipment used to perform elastic modulus test. A compressometer equipped with a linear variable differential transformer (LVDT) was used to measure the deformation of the concrete cylinder during a compression test. The load and deformation data were recorded by means of a computer data acquisition system. Throughout the test, the ambient temperature and relative humidity were maintained at 73 ºF and 100%, respectively.

Figure 4-6. Test set-up for performing the elastic modulus test

Before performing the compressive strength test, two of three concrete cylinders used to perform compressive strength test were evaluated in the elastic modulus test. Prior to the test for modulus of elasticity, one of the three concrete cylinders was broken first to determine the compressive strength of concrete in accordance with ASTM C39 standard. Then, 40% of ultimate compressive strength of concrete specimen was applied on the concrete cylinders to perform the elastic modulus test. The cylinders for the modulus of elasticity test were loaded and unloaded three times. The data from the first load cycle were disregarded. The average value from the last two times was recorded as the elastic modulus of the concrete. The elastic moduli of concrete at the ages of 3, 7, 14, 28, 56, and 91 days were evaluated.

- **Shrinkage test**

For each concrete mixture, six $6'' \times 12''$ concrete cylinders were made to evaluate its shrinkage behavior. The cylinders were cured under the two different conditions. Three cylinders were cured for 7 days in the standard moist room, and then followed by a room condition curing for another 7 days. Another three cylinders were cured for 14 days in the moist room, and then cured for another 14 days in room condition.

Three pairs of gauge points, which were spaced 10 inches apart, were placed on each of concrete cylinder. A gauge-point guide (as shown in Figure 3-4) was used to position the gauge points on the plastic cylinder mold before the concrete was placed. Figure 4-7 shows a picture of the concrete cylinders with the gauge points attached on them after the molds have been removed.

A Whittemore gauge (as shown in Figure 4-8) was used to measure the change in the distance between the gage points as the concrete cylinder shrinks. The Whittemore gauge has a resolution of 0.0005 in.

Three sets of measurements were taken from each specimen. A total of nine sets of measurements were taken from the three replicate specimens for each concrete mixture.

Measurements were taken every day in the first week, and then once a week up to three months. The original distances between the gauges were measured immediately after the plastic mold was removed. The shrinkage measurement was taken as soon as

Figure 4-7. Concrete cylinders with gauge point installed on them

the cylinders were brought out of the moist room. The shrinkage test was run under the conditions of the temperature of 73 ºF and 75% relative humidity. The shrinkage strain was taken as the average of the nine readings from the three replicate cylinders, and can be expressed as follows:

$$\varepsilon_{sh} = \frac{1}{9}\sum_{i=1}^{9}\frac{(l_i - l_0)}{l_0} \qquad \text{[Equation 4.3]}$$

Where

l_i – Measured distance between ith pair of gage points

l_0 – Original distance between ith pair of gage points measured immediately after demolding.

Figure 4-8. Whittemore gauge

❖ **Creep test**

The preparation of specimens for the creep test was the same as that for the shrinkage test specimens, which was described in the previous section. Each creep test specimen contained three pairs of gage points, which were placed 10 inches apart from each other. For each concrete mixture, twelve $6''\times12''$ cylinders were made to evaluate its creep behavior. Two curing conditions and two load levels were used. The two curing conditions were the same as those used on the specimens for the shrinkage test, as described in the previous section. The two load levels used include (1) 40% of the ultimate compressive strength of concrete at the loading age, and (2) 50% of the ultimate compressive strength of concrete at the loading age. Three replicate specimens were used for each combination of curing condition and load level.

Three replicate specimens were to be loaded in one creep apparatus. The following test procedures were followed:

(1) For each set of three specimens to be loaded in a creep frame, cap one end of two specimens with sulfur.

(2) Using the alignment frame, stack the three replicate specimens vertically on top of one another, with the ends with the sulfur capping at the top and the bottom of the stack. Cement the specimens together at the interface with a high strength and high modulus Epoxy, Sikadur 32 or 33. The Sikadur 32 or 33 epoxy was prepared by mixing a Part A (resin) with Part B (hardener). Apply the mixture within 15 minutes. A minimum of 24 hours is needed for curing of the epoxy before the specimens can be loaded in the creep apparatus. Steps (1) & (2) must be done one day before the specimens are to be loaded in the creep frame.

(3) Put the stack of three concrete specimens into the creep frame and adjust creep frame and concrete specimen to make sure the specimens are centered and vertical.

(4) Set up hydraulic jack and load cell in the creep frame, and check the position of hydraulic jack to make sure that it is in line with concrete specimens in order to avoid loading the concrete specimens eccentrically.

(5) Apply the load through the hydraulic jack up to the target load. This should be done with a minimal amount of time in order to obtain a more accurate

instantaneous deformation of the concrete. Otherwise, substantial early creep deformation may take place before the initial reading can be taken.

(6) After the target load is reached, tighten the four nuts on the top of the steel plate that is below the hydraulic jack uniformly to hold the load on the specimens.

(7) Take initial readings with the Whittemore gage immediately after loading. Then take the measurement every day in the first week, and then once a week till 91 days.

(8) Due to the load relaxation caused by shrinkage and creep deformation of the specimens, the load applied on specimens has to be adjusted in order to maintain the load as constant as possible. Adjust the load once a day in the first week, and then once a week in the first month, and then every month.

The creep strain was calculated by subtracting the shrinkage strain from the the total strain as follows:

$$\varepsilon_C = \varepsilon_T - \varepsilon_S = \frac{1}{9}\left(\sum_{i=1}^{9}\frac{l_i^T - l_{0(i)}^T}{l_{0(i)}^T} - \sum_{i=1}^{9}\frac{l_i^S - l_{0(i)}^S}{l_{0(i)}^S}\right) \qquad \text{[Equation 4.4]}$$

Where

ε_C – Creep strain of concrete

ε_T – The sum of creep strain and shrinkage strain

ε_S – Shrinkage strain of concrete

l_i^T – The measurement taken from the i^{th} pair of gage points for creep test

$l_{0(i)}^T$ – The initial length of the i^{th} pair of gage points for creep test

l_i^S – The measurement taken from the i^{th} pair of gage points for shrinkage test

$l_{0(i)}^S$ – The initial length of the i^{th} pair of gage points for shrinkage test

i – No. of pair of gage points from 1 to 9

The creep coefficient is calculated by taking the ratio of creep strain of the concrete at the testing age to the computed elastic strain of the concrete at the same curing age. It can be expressed as follows:

$$C_{cr} = \frac{\varepsilon_C}{\varepsilon_E} \qquad \text{[Equation 4.5]}$$

Where

C_{cr} – Creep coefficient

ε_C – Creep strain of concrete

ε_E – Elastic strain of concrete

Chapter 5

RESULTS OF STRENGTH AND ELASTIC MODULUS TESTS

5.1 Introduction

This chapter presents the analysis of the results of compressive strength, splitting tensile strength and elastic modulus tests on the ten concretes mixes evaluated in this study. The relationships among these three mechanical properties were also evaluated and presented in this chapter.

5. 2 Results of Compressive Strength Tests

The average compressive strengths at various curing times of the ten concrete mixes evaluated are displayed in Table 5-1. The individual compressive strength values are shown in Table A-1 in Appendix A.

Figure 5-1 shows the compressive strength development with time for the four concrete mixes containing 20 % fly ash. It can be seen that these fly ash mixes continue to grow in compressive strength up to 91 days. Mix 1, with a W/C of 0.24, has a compressive strength of about 12,400 psi at 91 days. The other three fly ash mixes with a W/C of 0.37 to 0.41 were close to each other in compressive strength, and have a compressive strength of 9,100 to 9,900 psi at 91 days.

Figure 5-2 shows the compressive strength development with time for the four concrete mixes containing ground blast furnace slag as an additive. Three mixes contain

50% slag while one contains 70 % slag. It can be seen that strength development levels off after about 28 days. The two mixes containing 50 % slag and with a W/C of 0.33 and 0.36 (Mix 4 & Mix 7) have a compressive strength of 10,200 to 10,800 psi at 91 days. The two mixes with a W/C of 0.41 and 0.44 (Mix 8 and Mix 9) have a compressive strength of 8,200 to 8,700 psi at 91 days. Mix 8 with 70% slag gives a slightly lower compressive strength than Mix 9 with 50% slag, even though its W/C is lower. This can be explained by the higher slag and lower cement content of Mix 8.

Figure 5-3 shows the compressive strength development with time for the two mixes using the lightweight aggregate Stalite. In comparison with the plots on Figures 5-1 and 5-2, it can be seen that the lightweight concretes have a relatively lower compressive strength as compared with the normal weight concretes with similar w/c and mineral additives. Mix 2, with a lightweight aggregate, a W/C of 0.36 and 20% fly ash, has a compressive strength of around 8,100 psi at 91 days, as compared with 9,100 to 9,900 psi for normal weight concretes with similar w/c and mineral additive. Mix 6, with a lightweight aggregate, W/C of 0.39 and 60% slag has a compressive strength of around 7,300 psi at 91 days, as compared with 8,200 to 8,700 psi for normal-weight concretes with similar W/C and mineral additive.

Table 5-1. Compressive strengths of the ten concrete mixtures evaluated (psi)

Mix Number	Age of Testing (days)					
	3	7	14	28	56	91
mix-1	N/A	10314	11087	11562	12068	12401
mix-2	3717	4963	5995	6827	7342	8101
mix-3	5700	6746	7487	7917	8663	9083
mix-4	6373	8637	9475	10117	10247	10248
mix-5	4879	6073	7183	7940	8810	9310
mix-6	1927	3543	5063	6183	7067	7313
mix-7	6203	8580	9613	10233	10527	10787
mix-8	2380	5277	6747	7637	8203	8210
mix-9	3177	5693	6940	7930	8317	8663
mix-10	5243	6713	7853	8650	9317	9923

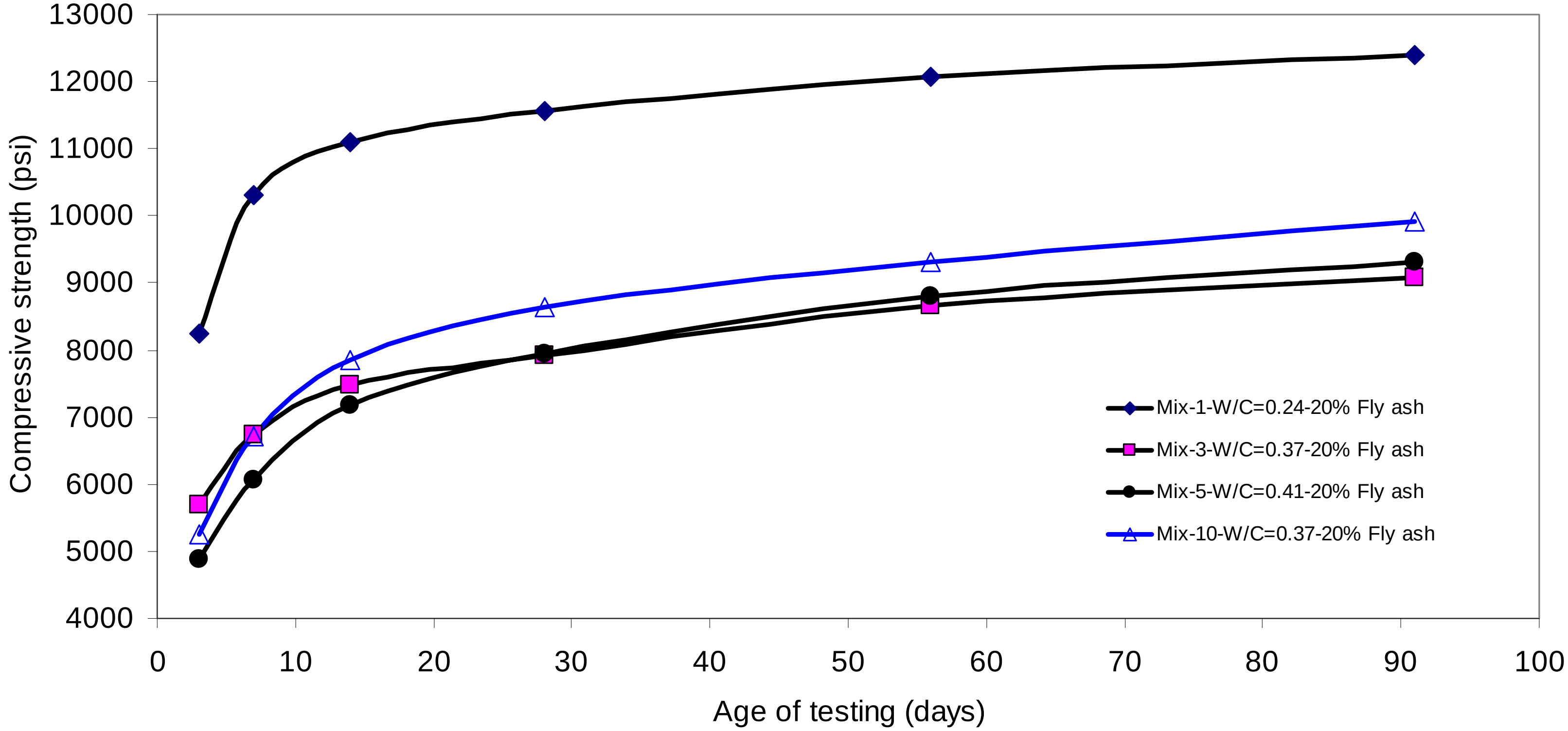


Figure 5-1. Development of compressive strength of concretes with fly ash as mineral additive

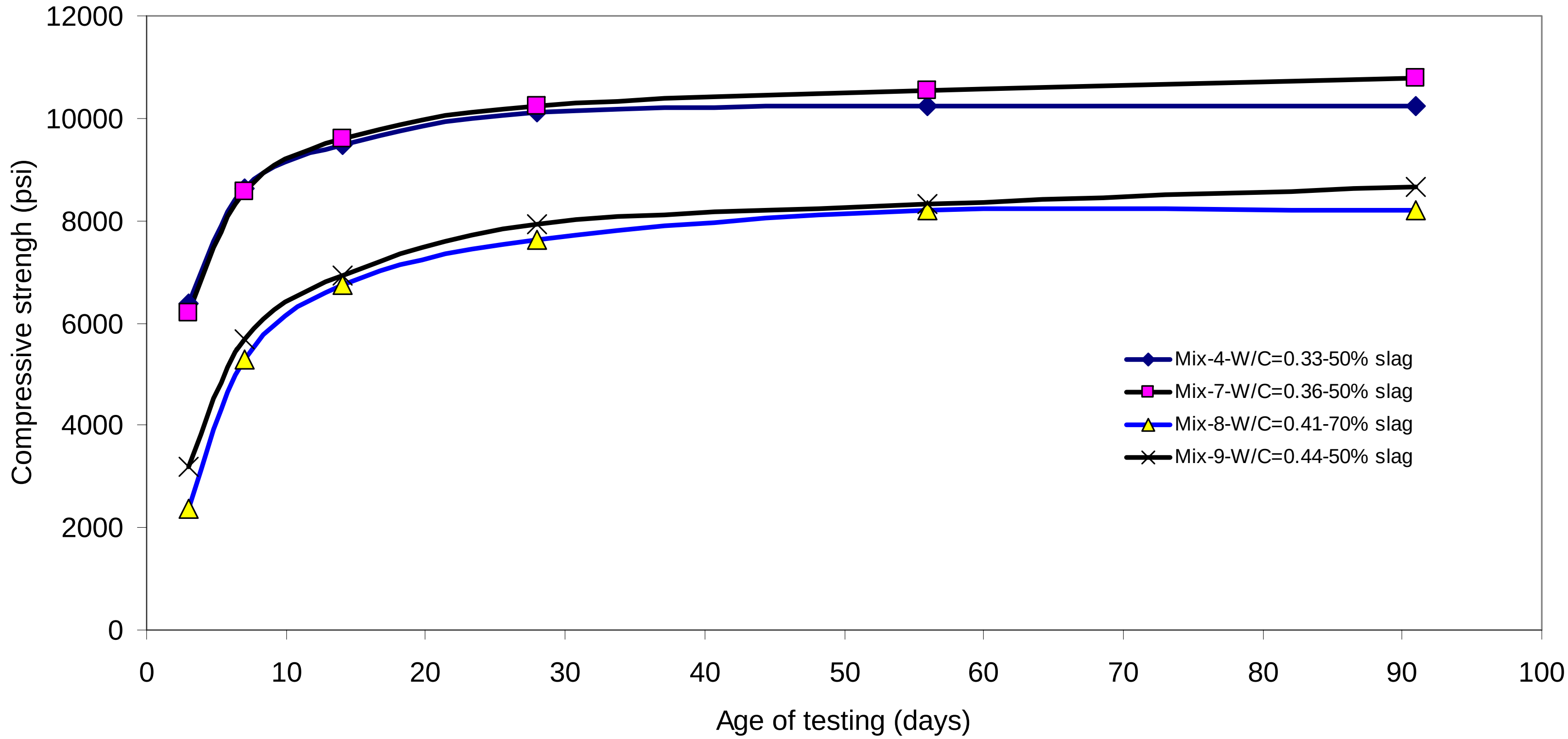


Figure 5-2. Development of compressive strength of concretes with slag as mineral additive

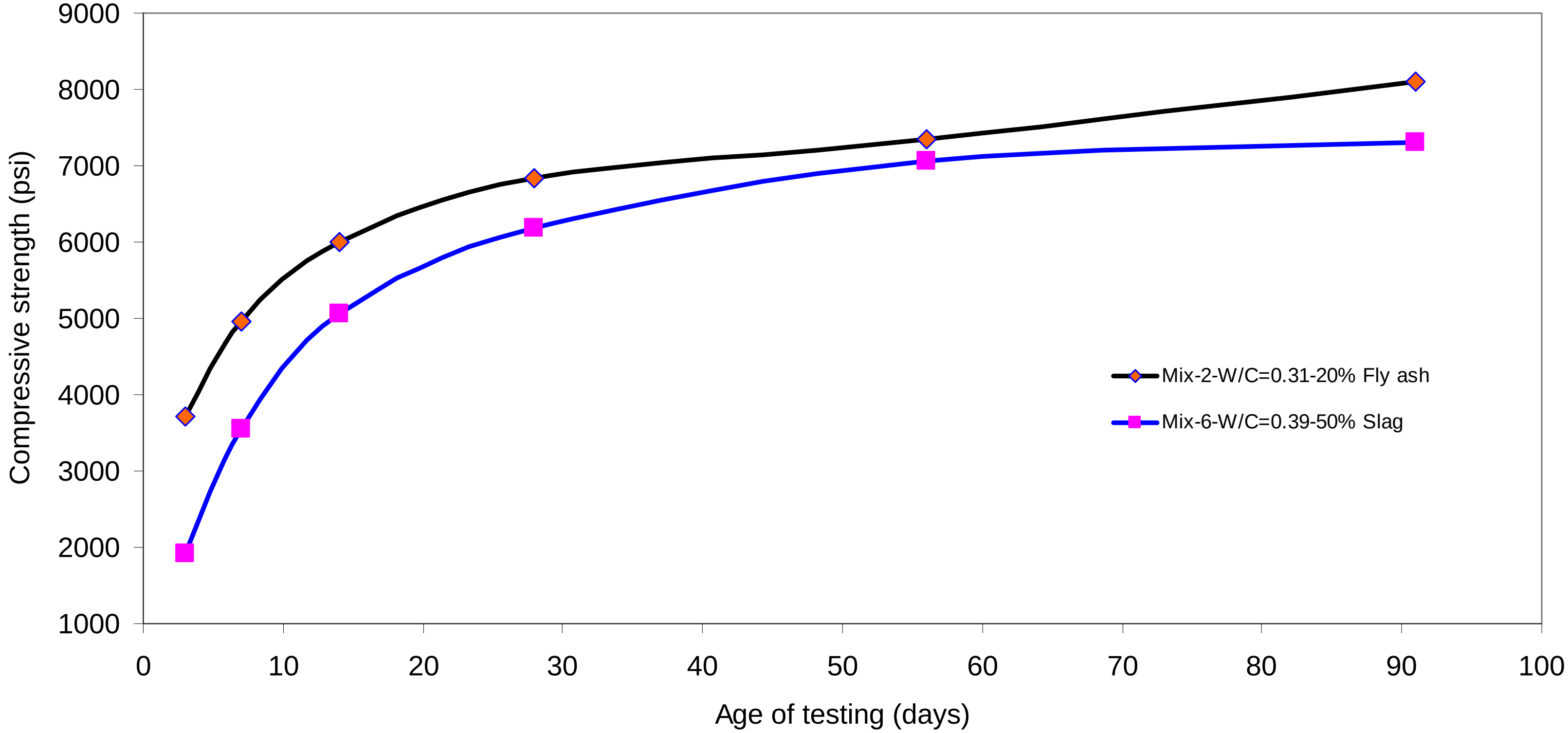


Figure 5-3. Development of compressive stength of lightweight aggregate concrete with time

5.3 Results of Splitting Tensile Strength Tests

The average splitting tensile strengths at various curing times of the ten concrete mixes evaluated are displayed in Table 5-2. The individual splitting tensile strength values are shown in Table A-2 in Appendix A.

Figure 5-4 shows the splitting tensile strength development with time for the four concrete mixes containing 20 % fly ash. It can be seen that these fly ash mixes continue to grow in splitting tensile strength up to 91 days. Mix 1, with a w/c ratio of 0.24, has a splitting tensile strength of 960 psi at 91 days. The other three fly ash mixes with a W/C of 0.37 to 0.41 have a splitting tensile strength of 730 to 840 psi at 91 days. Figure 5-5 shows the splitting tensile strength development with time for the four concrete mixes containing slag as additives. It can be seen that strength development slows down considerably after 28 days. The two mixes containing 50% slag and with a W/C of 0.33 and 0.36 (Mix 4 & Mix 7) have a splitting tensile strength of 750 to 800 psi at 91 days. The two mixes with a W/C of 0.41 and 0.44 (Mix 8 and Mix 9) have a splitting tensile strength of 640 to 680 psi at 91 days.

Figure 5-6 shows the splitting tensile strength development with time for the two mixes using the lightweight aggregate Stalite. In comparison with the plots on Figures 5-4 and 5-5, it can be seen that the lightweight concretes have a relatively lower splitting tensile strength as compared with the normal-weight concretes with similar w/c and mineral additives. Mix 2, with a lightweight aggregate, W/C of 0.36 and 20% fly ash, has a splitting tensile strength of around 590 psi at 91 days. Mix 6, with a lightweight aggregate, W/C of 0.39 and 60% slag has a splitting tensile strength of around 610 psi at 91 days.

Table 5-2. Splitting tensile strengths of the ten concrete mixtures evaluated (psi)

Mix Number	Age of Testing (days)					
	3	7	14	28	56	91
mix-1	N/A	659	786	829	919	960
mix-2	395	480	493	518	531	588
mix-3	438	498	615	678	723	735
mix-4	464	619	648	689	736	746
mix-5	515	519	618	634	714	761
mix-6	250	349	469	500	555	612
mix-7	593	689	696	697	719	802
mix-8	296	469	570	591	653	681
mix-9	352	527	596	598	638	644
mix-10	426	533	570	676	736	842

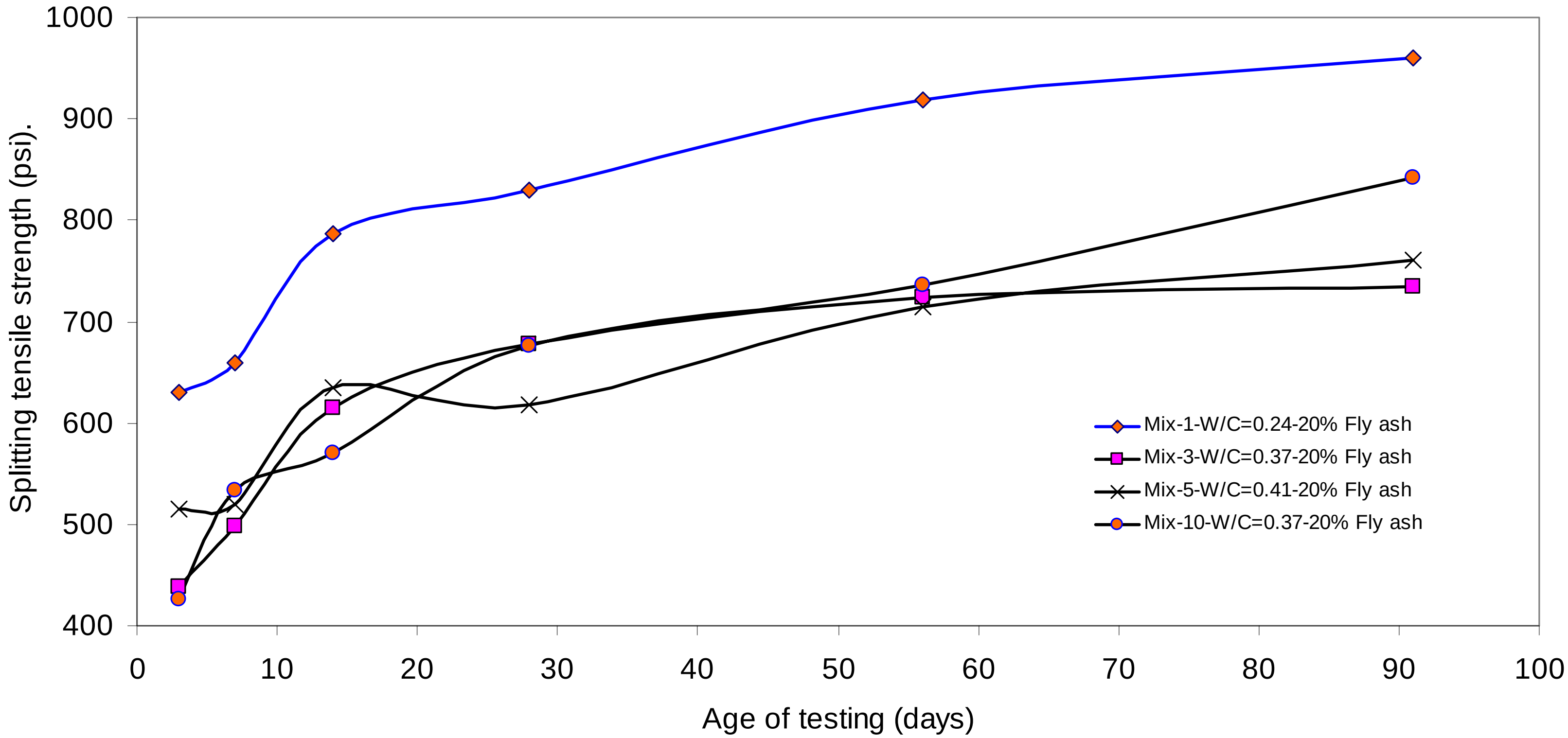


Figure 5-4. Splitting tensile strength of normal weight concretes with fly ash as mineral additive

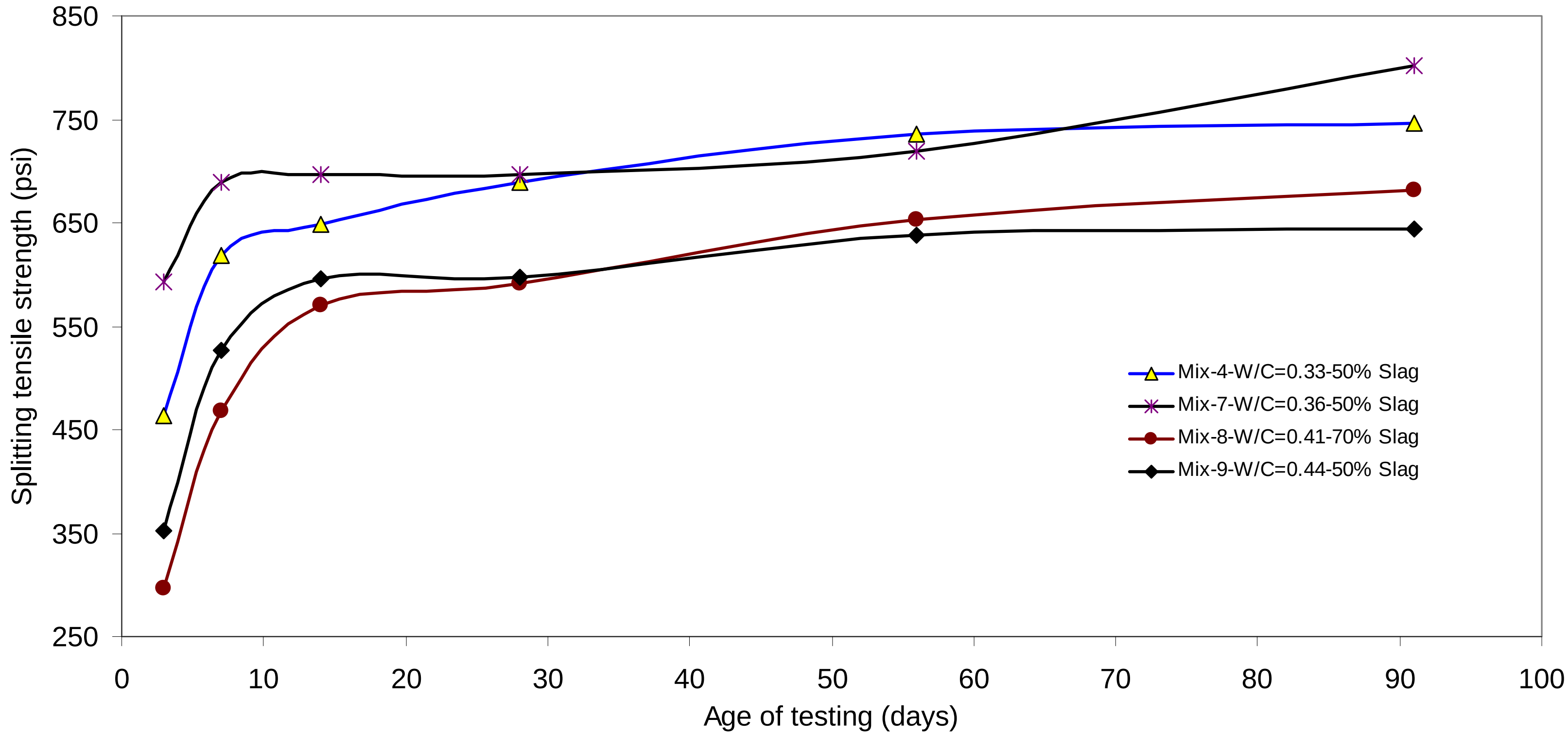


Figure 5-5. Splitting tensile strength of normal weight concretes with slag as mineral additive

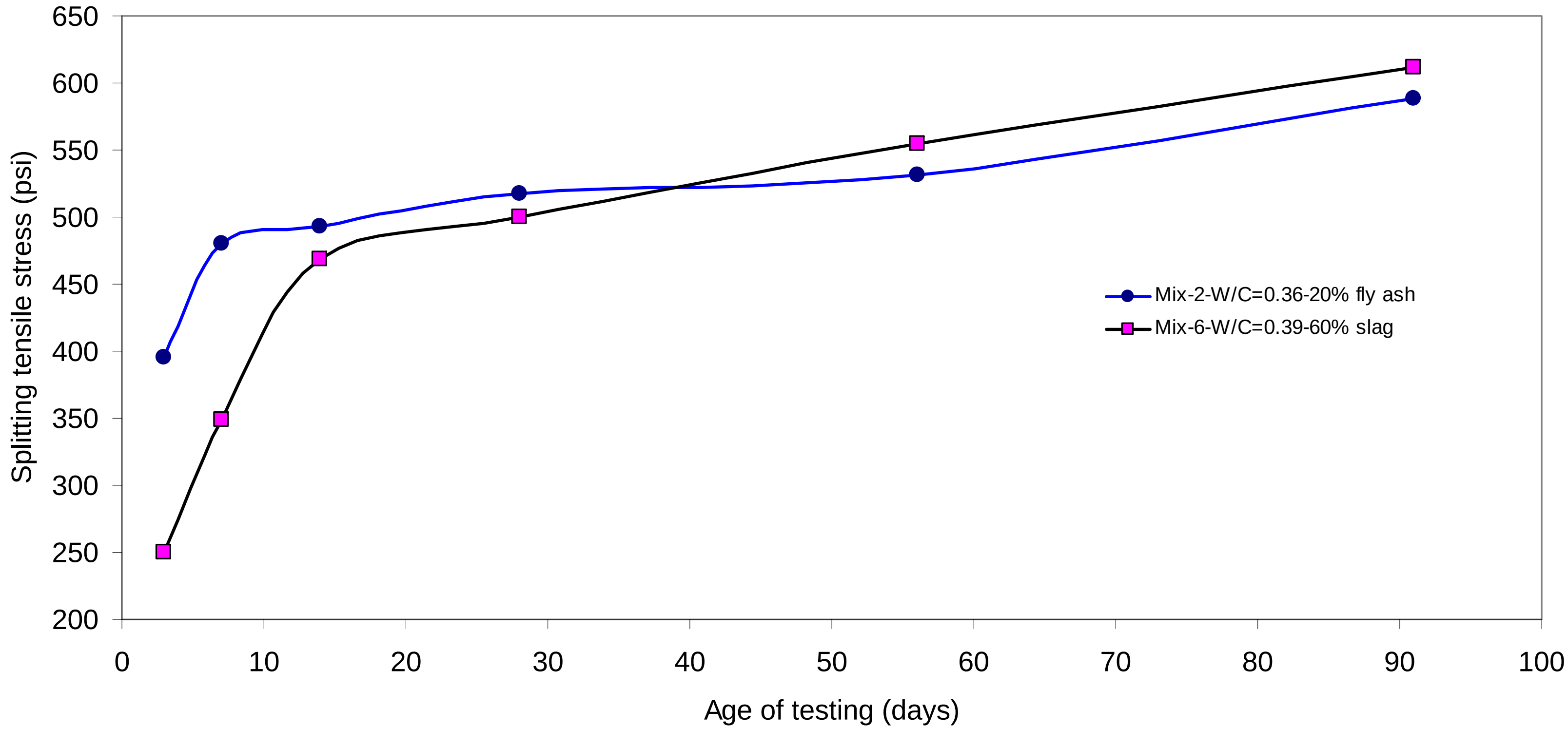


Figure 5-6. Development of splitting tensile strength of lightweight aggregate concrete with time

5.4 Results of Elastic Modulus Tests

The average elastic modulus values at various curing times of the ten concrete mixes evaluated are displayed in Table 5-3. The individual elastic modulus values are shown in Table A-3 in Appendix A.

Figure 5-7 shows the elastic modulus development with time for the four concrete mixes containing 20 % fly ash. It can be seen that these fly ash mixes continue to grow in elastic modulus up to 91 days. Mix 1, with a W/C of 0.24, has an elastic modulus of 6.3×10^6 psi at 91 days. The other three fly ash mixes with a W/C of 0.37 to 0.41 have an elastic modulus 5.0 to 5.5×10^6 psi at 91 days.

Figure 5-8 shows the elastic modulus development with time for the four concrete mixes containing slag as additives. It can be seen that the increase in elastic modulus slows down considerably after 28 days. The two mixes containing 50 % slag and with a W/C of 0.33 and 0.36 (Mix 4 & Mix 7) have an elastic modulus of 5.6 to 5.8×10^6 psi at 91 days. The two mixes with a W/C of 0.41 and 0.44 (Mix 8 and Mix 9) have an elastic modulus of 4.9 to 5.2×10^6 psi at 91 days.

Figure 5-9 shows the elastic modulus development with time for the two mixes using the lightweight aggregate Stalite. In comparison with the normal-weight concretes, the lightweight concretes have a substantially lower elastic modulus. Mix 2, with a lightweight aggregate, W/C of 0.36 and 20% fly ash, has an elastic modulus of 3.5×10^6 psi at 91 days. Mix 6, with lightweight aggregate, W/C of 0.39 and 60% slag has an elastic modulus of 3.3×10^6 psi at 91 days.

Table 5-3. Elastic moduli of the ten concrete mixtures evaluated ($\times 10^6$psi)

Mix Number	Age of Testing (days)					
	3	7	14	28	56	91
mix-1	N/A	5.38	5.52	5.70	5.94	6.29
mix-2	2.71	2.96	3.15	3.28	3.46	3.52
mix-3	3.99	4.26	4.51	4.65	4.78	4.98
mix-4	4.38	5.04	5.35	5.42	5.61	5.62
mix-5	4.19	4.53	4.87	5.02	5.18	5.51
mix-6	2.03	2.29	2.65	2.94	3.20	3.33
mix-7	4.66	5.20	5.53	5.64	5.73	5.83
mix-8	3.36	4.27	4.60	4.73	4.83	4.87
mix-9	3.52	4.41	4.80	4.80	5.19	5.22
mix-10	4.10	4.45	4.68	5.01	5.43	5.45

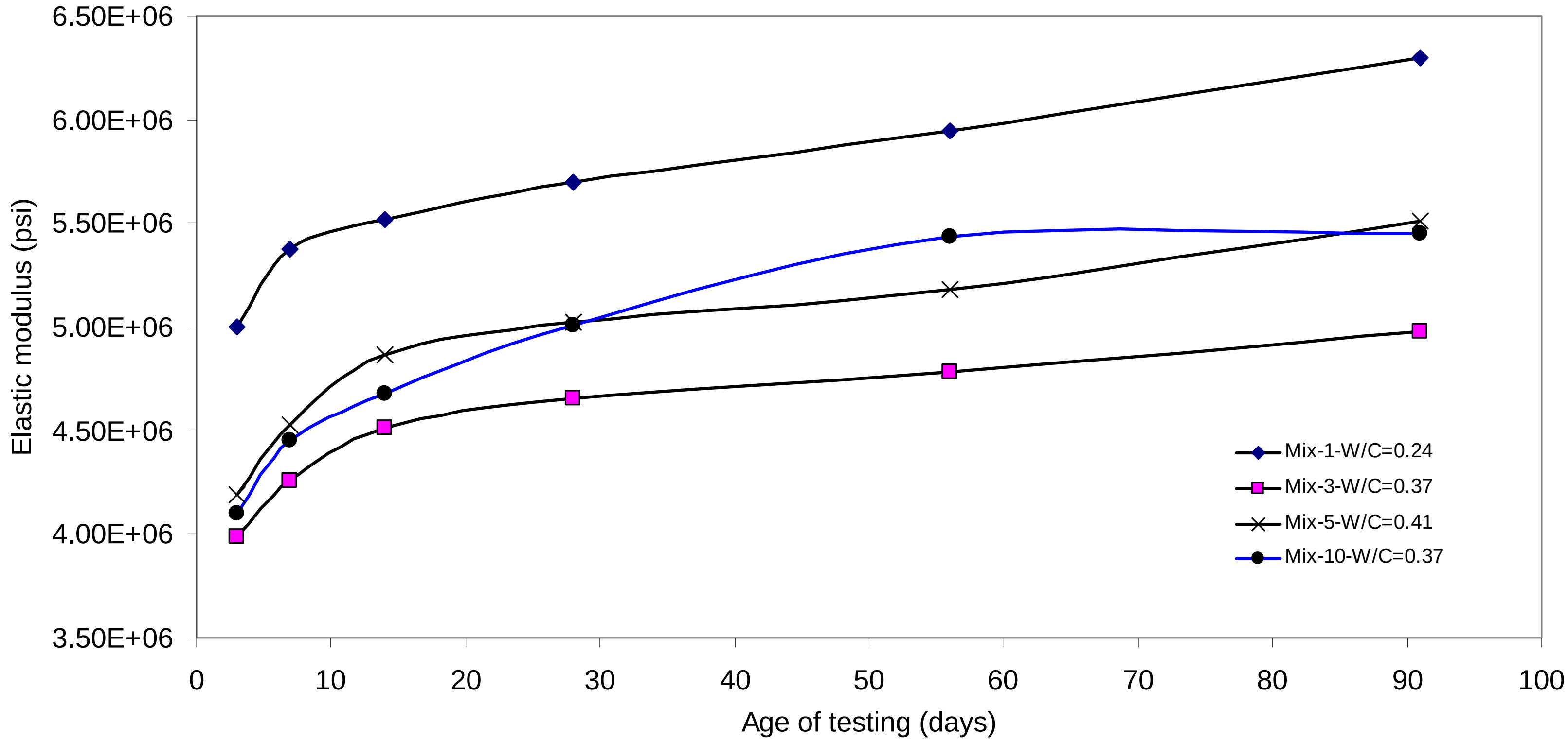


Figure 5-7. Elastic modulus of the normal weight concrete with fly ash as mineral additive

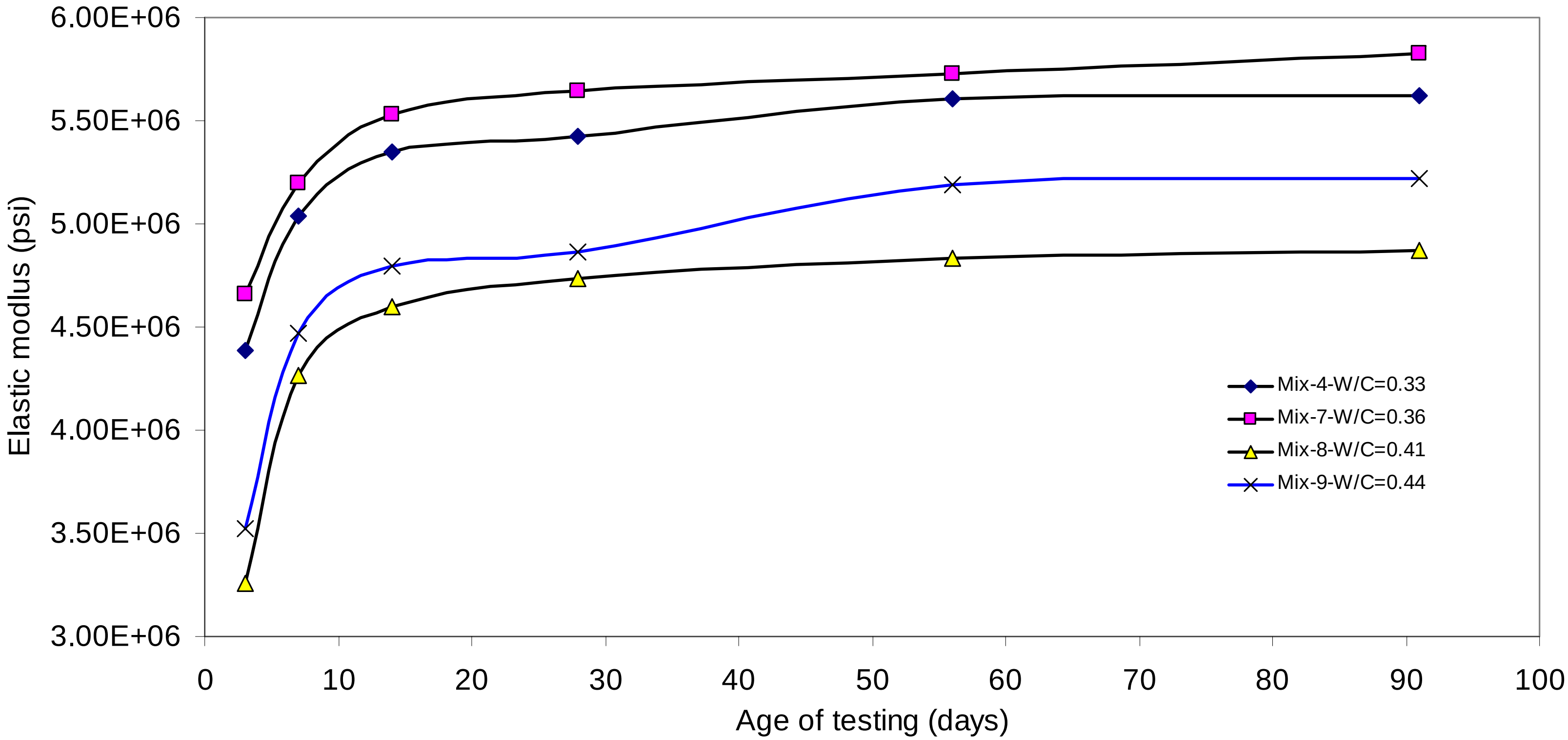


Figure 5-8. Elastic modulus of normal weight concrete with slag as mineral additive

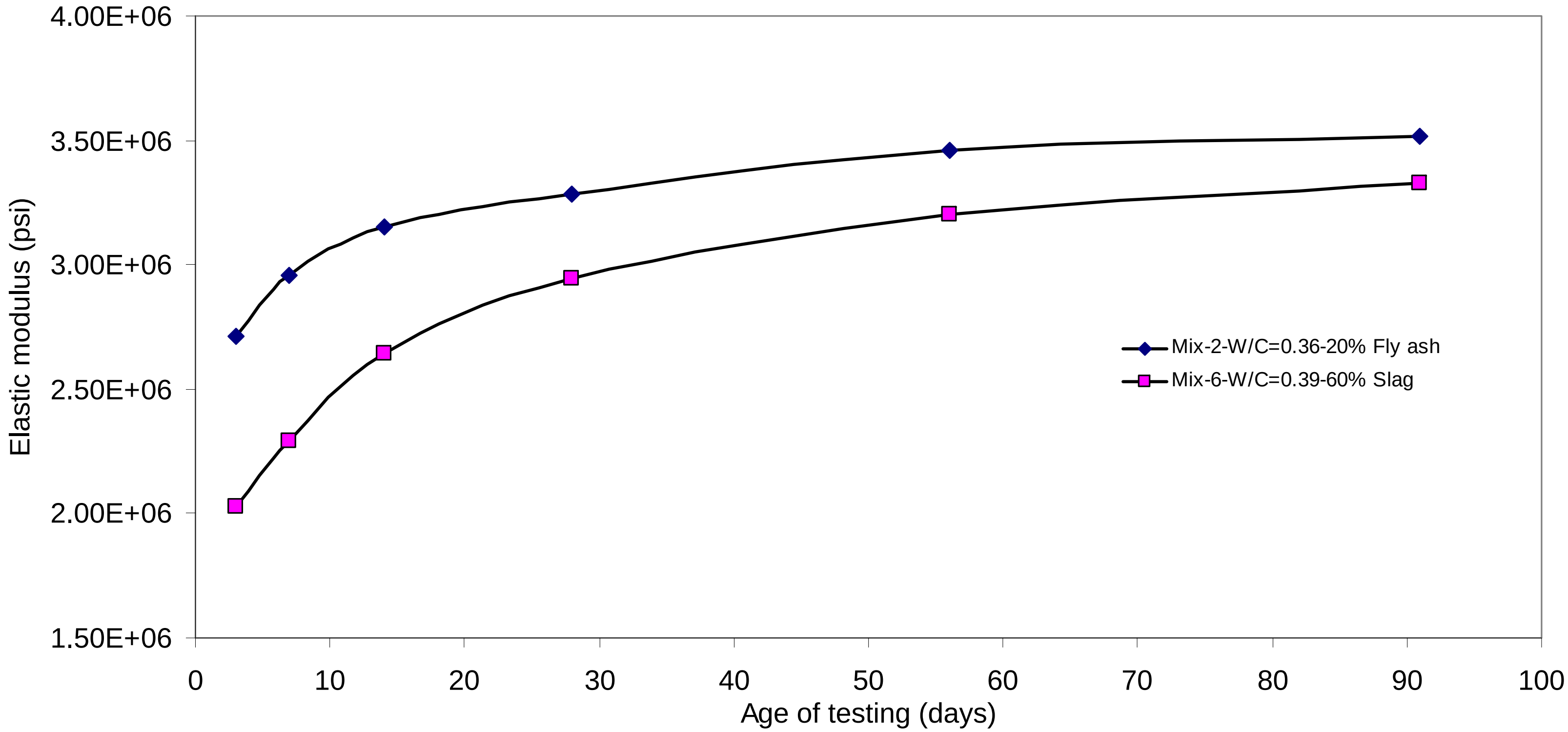


Figure 5-9. Development of elastic modulus of lightweight aggregate concrete with time

5.5 Relationship between Compressive Strength and Splitting Tensile Strength

The compressive strengths of the normal-weight concretes evaluated in this study (as tabulated in Table A-1) were plotted against the corresponding splitting tensile strengths (as tabulated in Table A-2) for all curing conditions in Figure 5-10. Regression analyses to establish empirical relationship between compressive strength and splitting tensile strengths were performed using the following equations:

$$f_{ct} = A \cdot \sqrt{f_c^{'}} \qquad \text{[Equation 5.1]}$$

$$f_{ct} = \left(f_c^{'}\right)^B \qquad \text{[Equation 5.2]}$$

where f_{ct} = splitting tensile strength (psi)

$f_c^{'}$ = compressive strength (psi)

A, B = coefficients

The ACI Code 318 uses Equation 5.1 for estimation of splitting tensile strength of lightweight concrete, where the coefficient A is equal to 6.7 [ACI, 1983]. The investigation by Carino and Lew [Carino et al, 1982] determined that the coefficient A was approximately 6.49. They suggested that Equation 5.2 was better than Equation 5.1 in the estimation of splitting tensile strength from compressive strength. The coefficient B was determined to be 0.73 in their investigation.

The results of the regression analyses are summarized in Table 5-4. The coefficient A (7.08) is slightly higher than both the values suggested by ACI (6.7) and the value by Carino and Lew (6.49). The coefficient B (0.72) is about the same as that suggested by Carino and Lew (0.73). These two developed regression equations are also plotted on Figure 5-10.

Table 5-4. Regression coefficients for equation relating compressive strength to splitting tensile strength

Equation	Curing condition	Coefficient A or B	Standard Error
ACI Code $f_{ct} = A \cdot \sqrt{f_c^{'}}$ $A = 6.7$	Moist curing	7.08	0.76
Carino and Lew model $f_{ct} = \left(f_c^{'}\right)^B$ $B = 0.73$	Moist curing	0.72	0.015

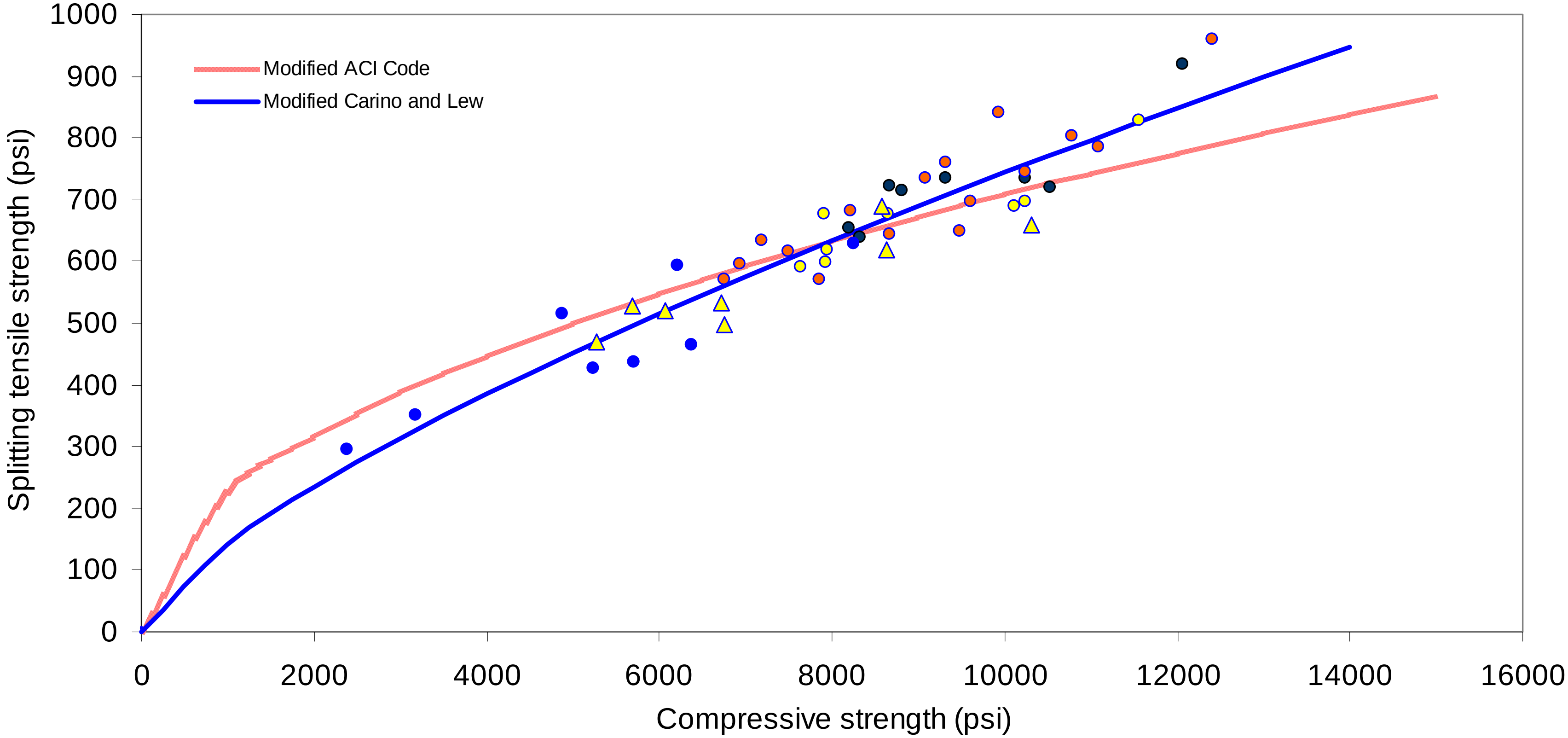


Figure 5-10. Relationship of compressive to splitting tensile strength for all curing conditions

5.6 Relationship between Compressive Strength and Elastic Modulus

Regression analyses were performed to establish empirical relationships between the compressive strength and elastic modulus of the normal-weight concretes evaluated in this study using an equation of the following form:

$$E = A \cdot w^{1.5} \cdot \sqrt{f_c'} \qquad \text{[Equation 5.3]}$$

where E = elastic modulus (psi)

f_c' = compressive strength (psi)

w = density of concrete (pci)

A = coefficient

ACI Code 318 [ACI, 1983] suggested a value of 33 for coefficient A to be used for the above equation.

Table 5-5 summarizes the results of the regression analysis. It can be seen that the determined values for coefficient A for the various combinations of conditions are fairly close to the ACI suggested value of 33. The different curing times appear to have no significant effect on the coefficient of the regression equations. The regression equations for the fly ash concretes are also fairly close to those for the slag concretes. Figure 5-11 shows the plot of compressive strength versus elastic modulus of the concrete at 28 days, while Figure 5-12 shows a similar plot for the curing time of 91 days. Figure 5-13 shows the plot of compressive strength versus elastic modulus of concrete for all curing conditions.

Table 5-5. Regression coefficients for equations relating compressive strength to modulus of elasticity

Equation	Curing Condition	additives	Coefficient A	Standard Error
$E = A \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$ $A = 33.00$ Given by ACI 318-95	28-d moist curing	Fly ash	31.61	1.81
		Slag	32.80	0.72
		Combined	32.21	1.35
	91-d moist curing	Fly ash	32.35	0.98
		Slag	33.31	0.54
		Combined	32.83	0.77
	All curing conditions	Fly ash	32.17	1.55
		Slag	33.54	2.29
		Combined	33.02	1.93

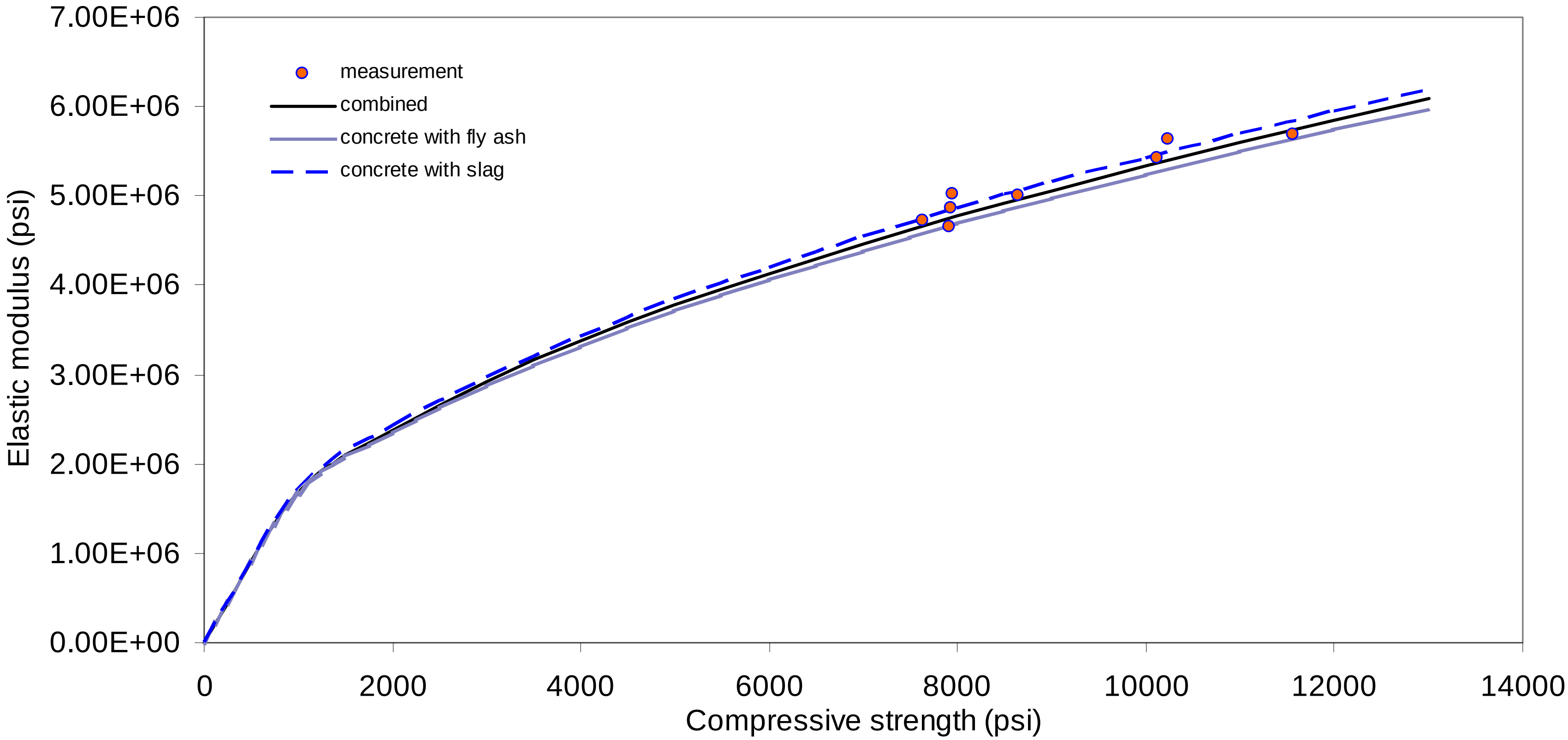


Figure 5-11. Relation between elastic modulus and compressive strength at the age of 28 days

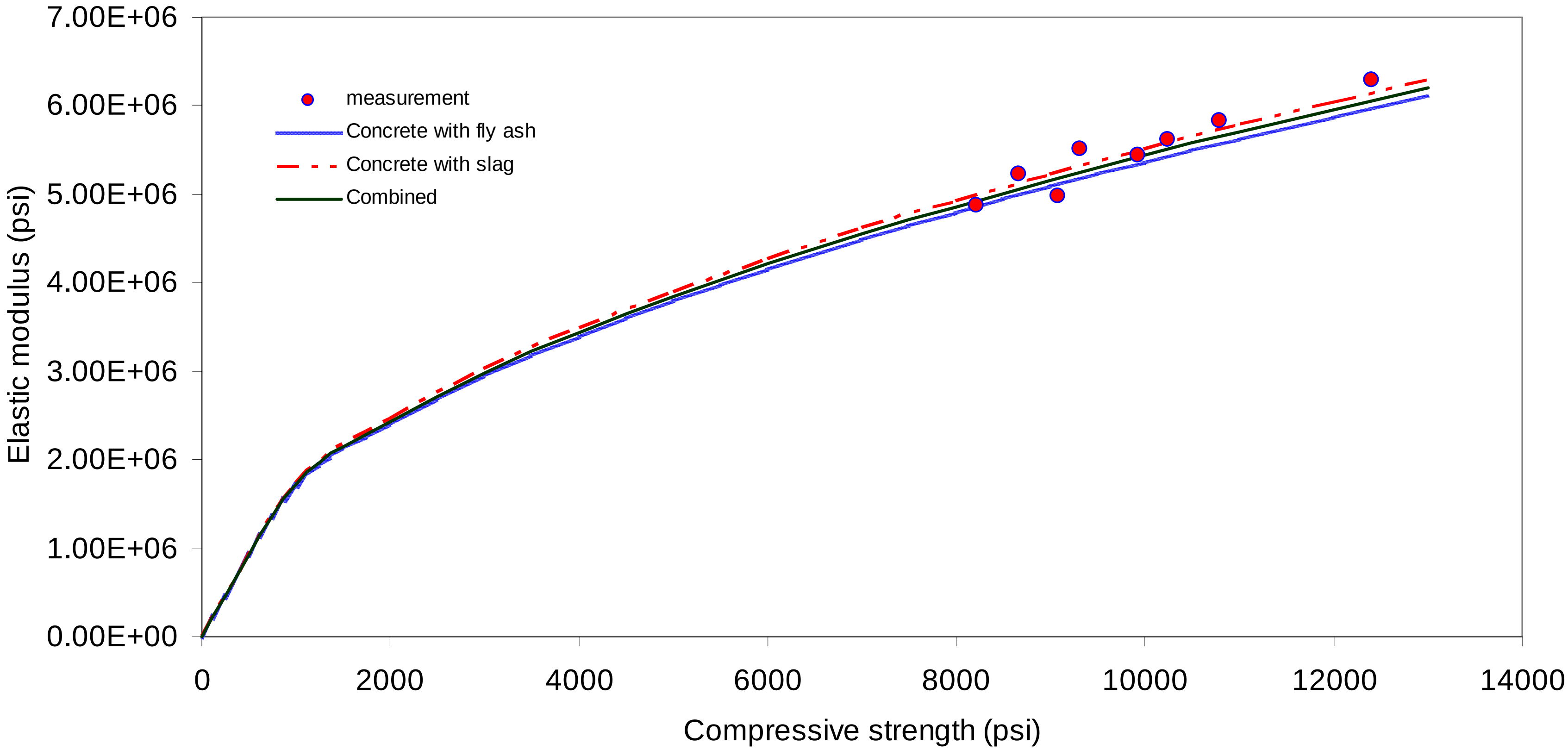


Figure 5-12. Relationship between compressive strength and elastic modulus at 91 days

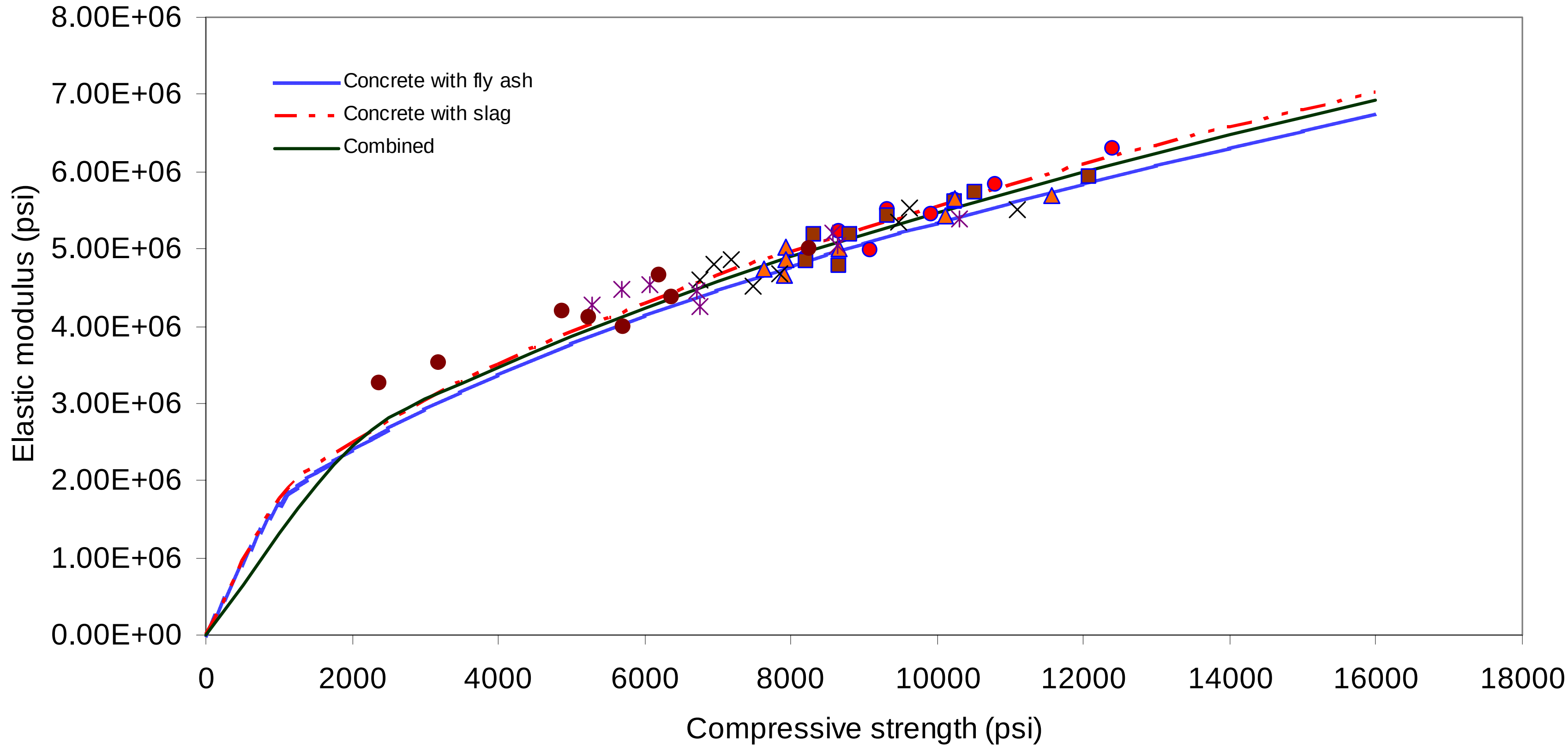


Figure 5-13. Relationship of compressive strength to elastic modulus for all curing conditions

Chapter 6

RESULTS OF SHRINKAGE AND CREEP TESTS

6.1 Introduction

The test procedures and methods of computation for the shrinkage and creep strains and parameters have been presented in Chapter 4. This chapter presents the results of shrinkage measurements and creep tests on the ten concrete mixes evaluated in this study.

6.2 Results of Shrinkage Measurement

Table 6-1 presents the measured shrinkage strains at the various ages for the ten concrete mixes evaluated in this study. One group of concrete specimens were moist-cured for 7 days and then air-dried in the laboratory for the rest of the time. Another group of specimens were moist-cured for 14 days and then air-dried for the rest of the time.

Figures 6-1 and 6-2 show the plots of shrinkage strains with time for the concretes using 20 % fly ash, with moist curing times of 7 and 14 days, respectively. It can be observed that the fly ash concretes with 14-day moist curing have lower shrinkage strains than those with 7-day moist curing. For example, for Mix 3, which has a w/c of 37 and 20 % fly ash, the shrinkage strain at 91 days is 0.00028 for the 14-day moist cured concrete and 0.00037 for the 7-day moist cured concrete. The shrinkage strains can also be noted to generally increase as the w/c increases.

Figures 6-3 and 6-4 present the plots of shrinkage strains with time for the concretes using 50 to 70 % slag, with moist curing times of 7 and 14 days, respectively. Unlike the fly ash concretes, the slag concretes with 14-day moist curing do not have significantly lower shrinkage strains than those with 7-day moist curing. When compared with Figures 6-1 and 6-2, it can be noted that the slag concretes have substantially lower shrinkage than the fly ash concretes of comparable w/c. For example, Mix 8, which has 70% slag and a w/c of 0.41, has a shrinkage strain of 0.00020 at 91 days for the 14-day moist cured specimens, while Mix 5, which has 20 % fly ash and a w/c of 0.41, has a shrinkage strain of 0.00032 at the same curing condition.

Figures 6-5 and 6-6 present the plots of shrinkage strains with time for the two lightweight concretes with 7-day and 14-day moist curing, respectively. Mix 2, a lightweight concrete using 20 % fly ash, appears to have similar shrinkage as Mix 6, a lightweight concrete using 60 % slag. The longer moist curing period is also seen to reduce the shrinkage of the lightweight concretes. When compared with the normal-weight concretes, these two lightweight concretes appear to have relatively higher shrinkage. For example, Mix 2, which has a lightweight aggregate, 20% fly ash and a w/c of 0.36, has a shrinkage strain of 0.00037 at 91 days for the 14-day moist cured specimens, while Mix 3, which has a normal-weight aggregate, 20% fly ash and a w/c of 0.37, has a shrinkage strain of 0.00028 at the same curing condition.

Table 6-1. Shrinkage strains of the ten concrete mixtures evaluated

Mix Number	Curing condition	Age of testing (days)					
		3	7	14	28	56	91
Mix-1	7-day moist cure	-0.000070	-0.000007	0.000050	0.000100	0.000167	0.000202
	14-day moist cure	-0.000031	0.000007	0.000041	0.000079	0.000146	0.000191
Mix-2	7-day moist cure	-0.000087	-0.000103	0.000046	0.000191	0.000363	0.000469
	14-day moist cure	-0.000062	-0.000063	-0.000022	0.000207	0.000343	0.000367
Mix-3	7-day moist cure	-0.000027	-0.000039	0.000142	0.000211	0.000301	0.000371
	14-day moist cure	-0.000038	-0.000061	-0.00003	0.000127	0.000219	0.000279
Mix-4	7-day moist cure	-0.000037	-0.000043	0.000052	0.000120	0.000206	0.000236
	14-day moist cure	-0.000089	-0.000099	-0.000027	0.000030	0.000099	0.000141
Mix-5	7-day moist cure	0.000052	0.000103	0.000157	0.000241	0.000316	0.000334
	14-day moist cure	0.000041	0.000066	0.000127	0.000207	0.000264	0.000318
Mix-6	7-day moist cure	0.000189	0.000211	0.000253	0.000331	0.000427	0.000459
	14-day moist cure	0.000105	0.000129	0.000158	0.000214	0.000309	0.000364
Mix-7	7-day moist cure	0.000035	0.000068	0.000112	0.000190	0.000235	0.000262
	14-day moist cure	0.000033	0.000051	0.000071	0.000110	0.000137	0.000169
Mix-8	7-day moist cure	0.000044	0.000072	0.000111	0.000148	0.000191	0.000218
	14-day moist cure	0.000076	0.000089	0.000106	0.000141	0.000174	0.000199
Mix-9	7-day moist cure	0.000062	0.000094	0.000108	0.000142	0.000190	0.000226
	14-day moist cure	0.000083	0.000108	0.000129	0.000158	0.000183	0.000207
Mix-10	7-day moist cure	N/A	N/A	N/A	N/A	N/A	N/A
	14-day moist cure	0.000063	0.000082	0.000112	0.000151	0.000202	0.000260

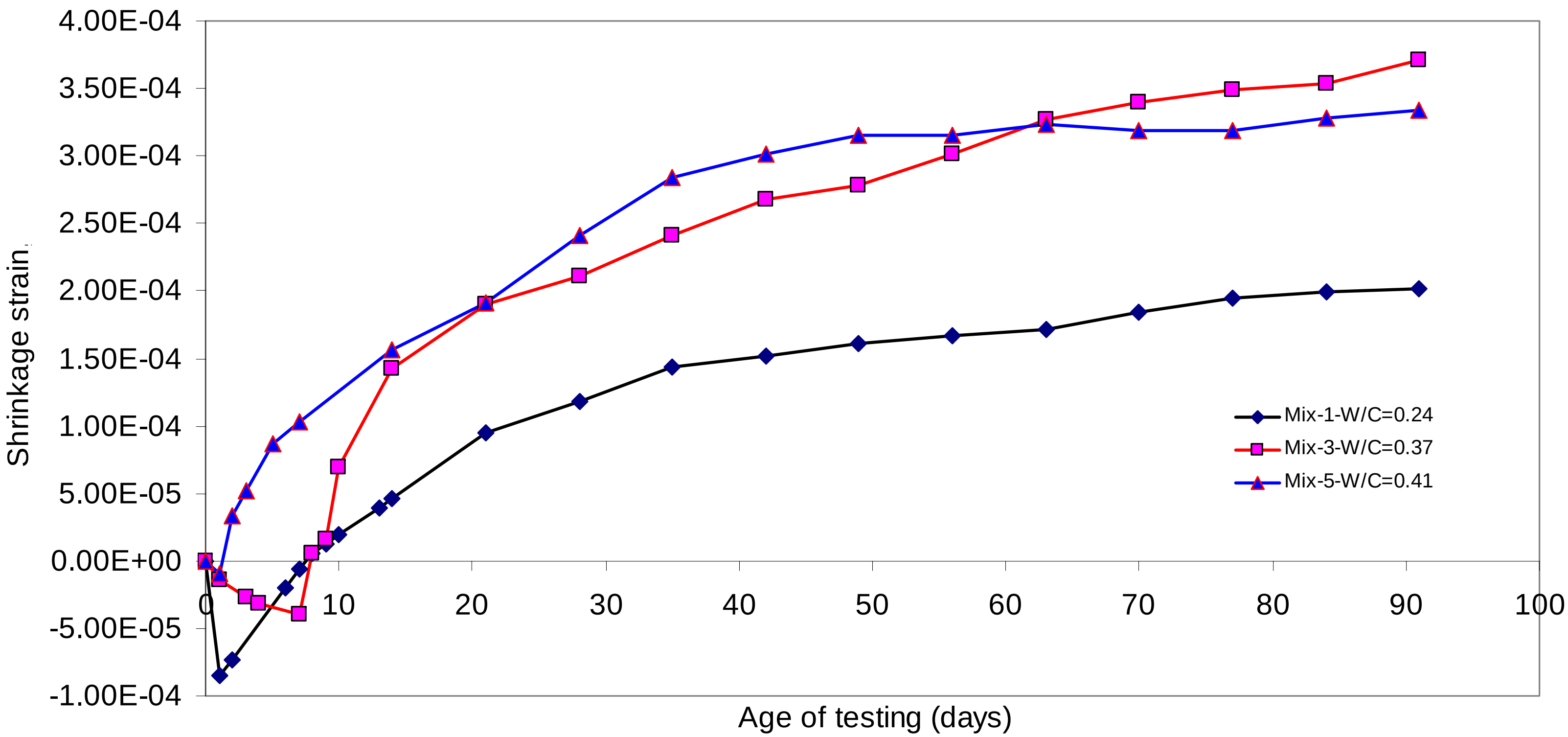


Figure 6-1. Development of shrinkage strain of concretes with 20% fly ash (7-day moist curing)

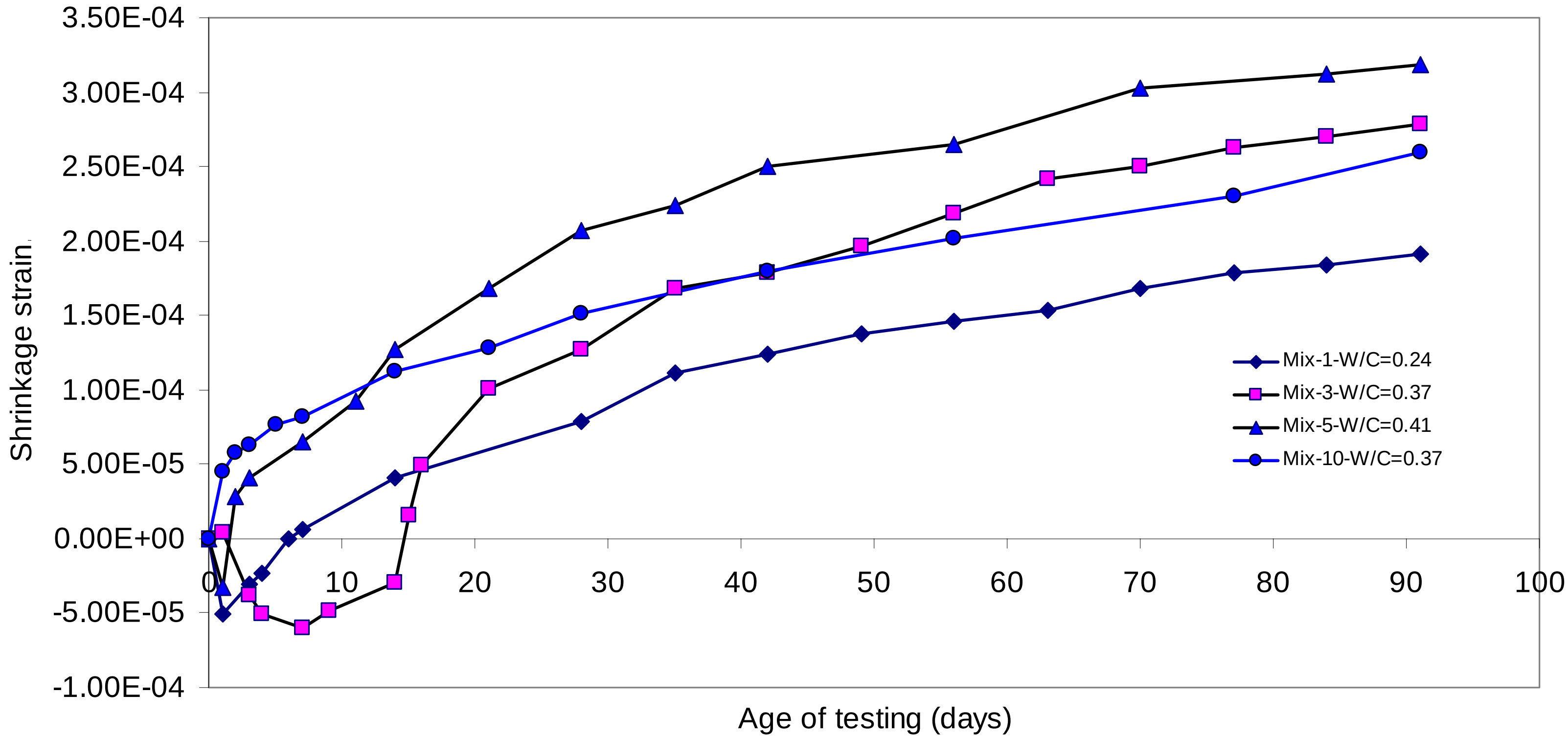


Figure 6-2. Development of shrinkage strain of concrete with 20% fly ash (14-day moist curing)

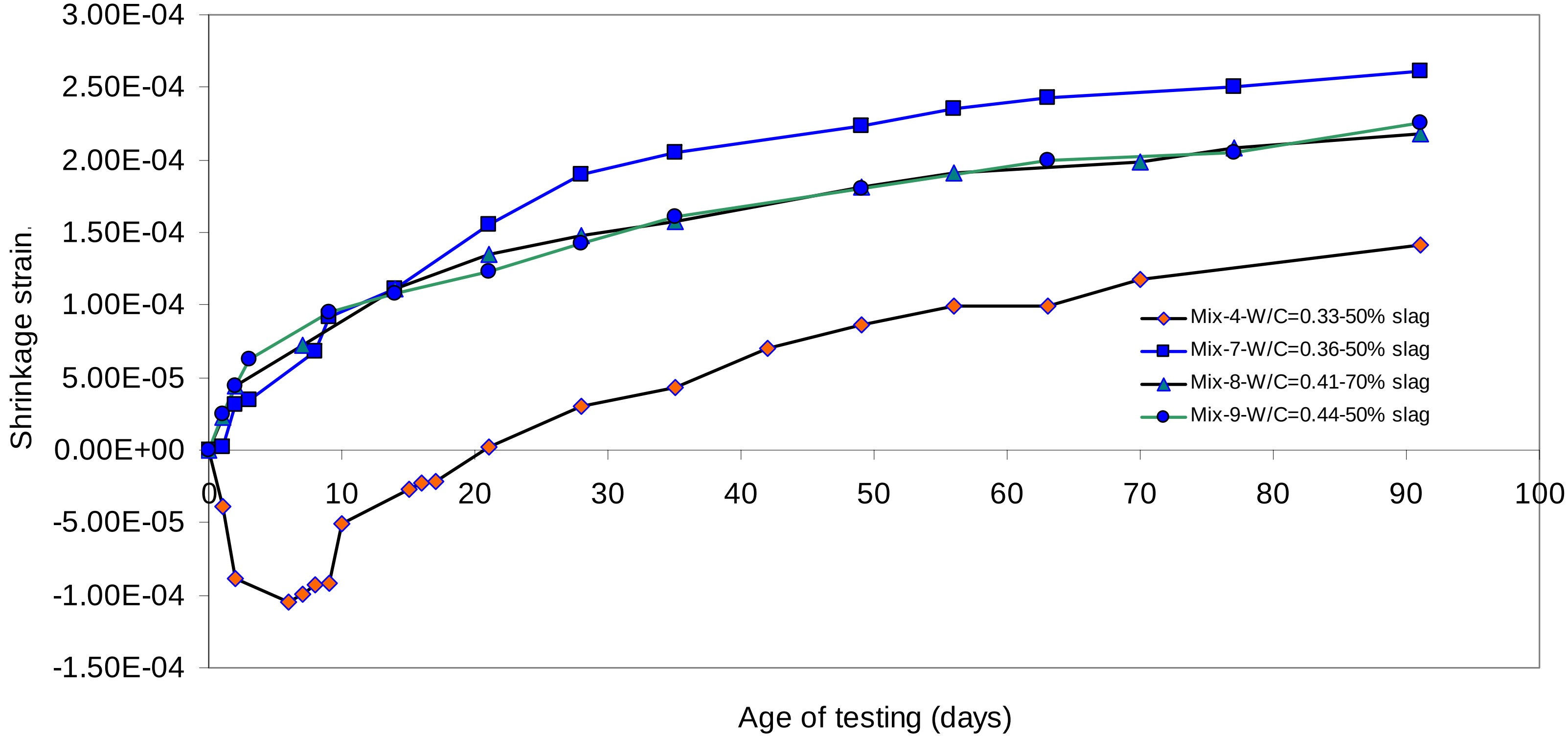


Figure 6-3. Development of shrinkage strain of concrete with slag (7-day moist curing)

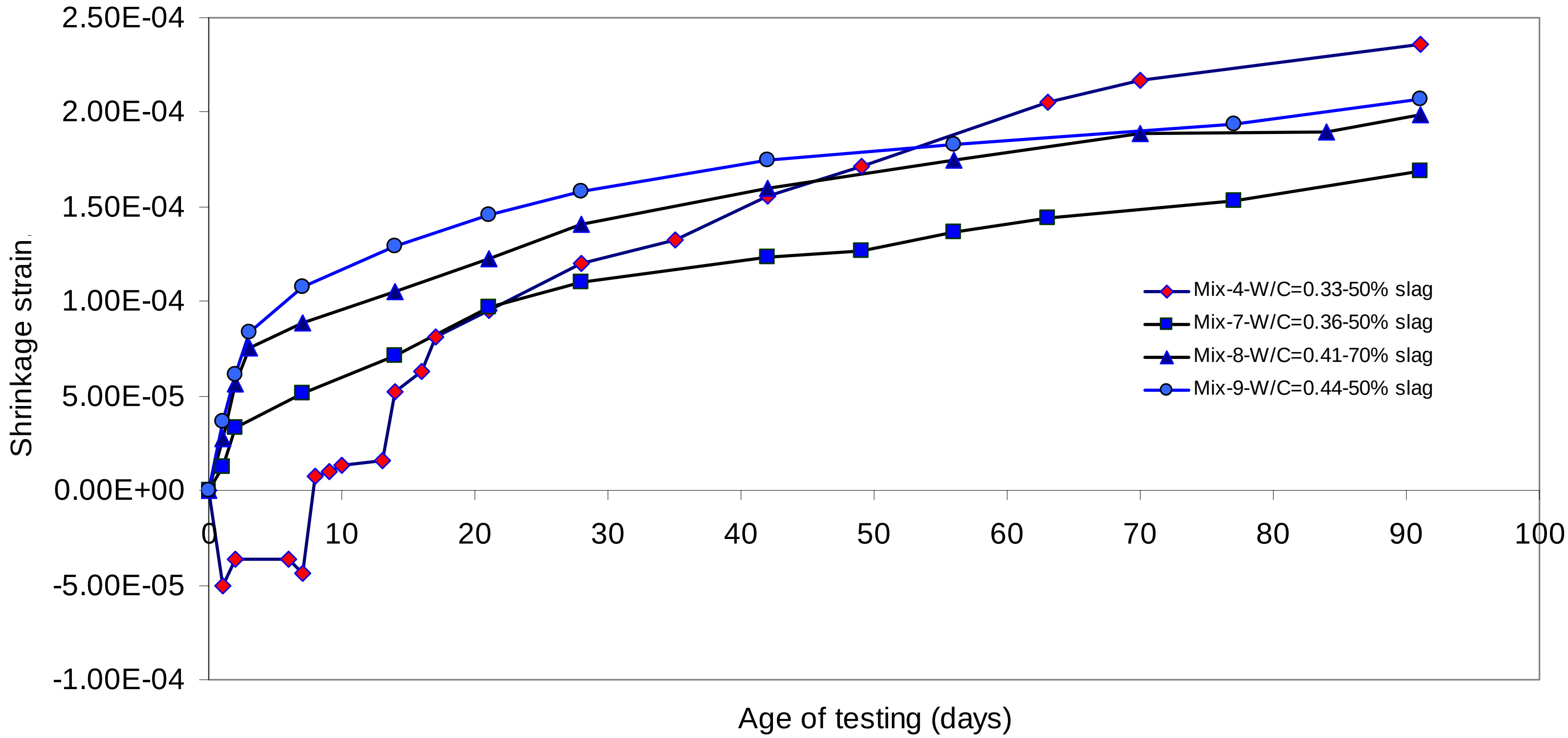


Figure 6-4. Development of shrinkage strain of concrete with slag (14-day moist curing)

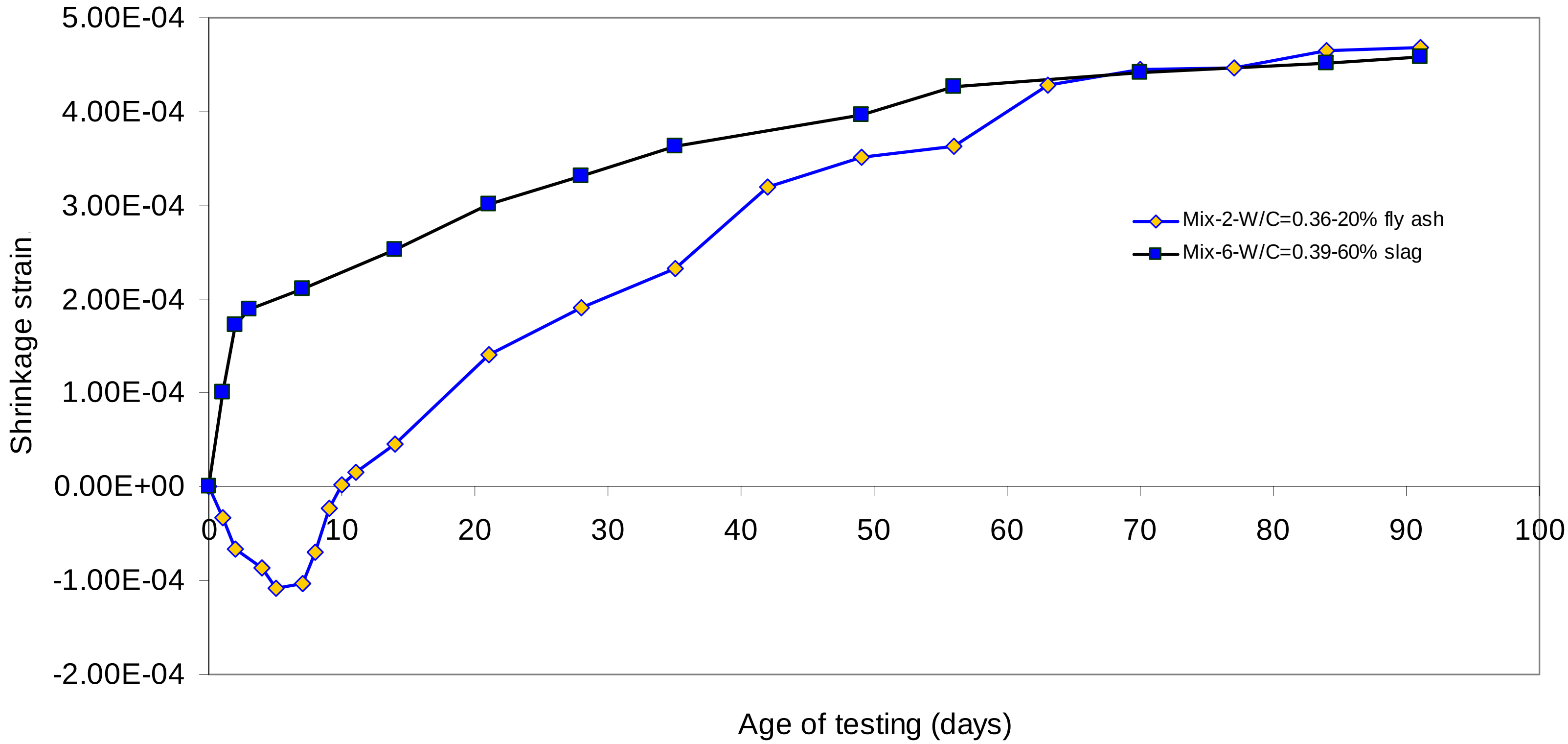


Figure 6-5. Development of shrinkage strain of lightweight concrete (7-day moist curing)

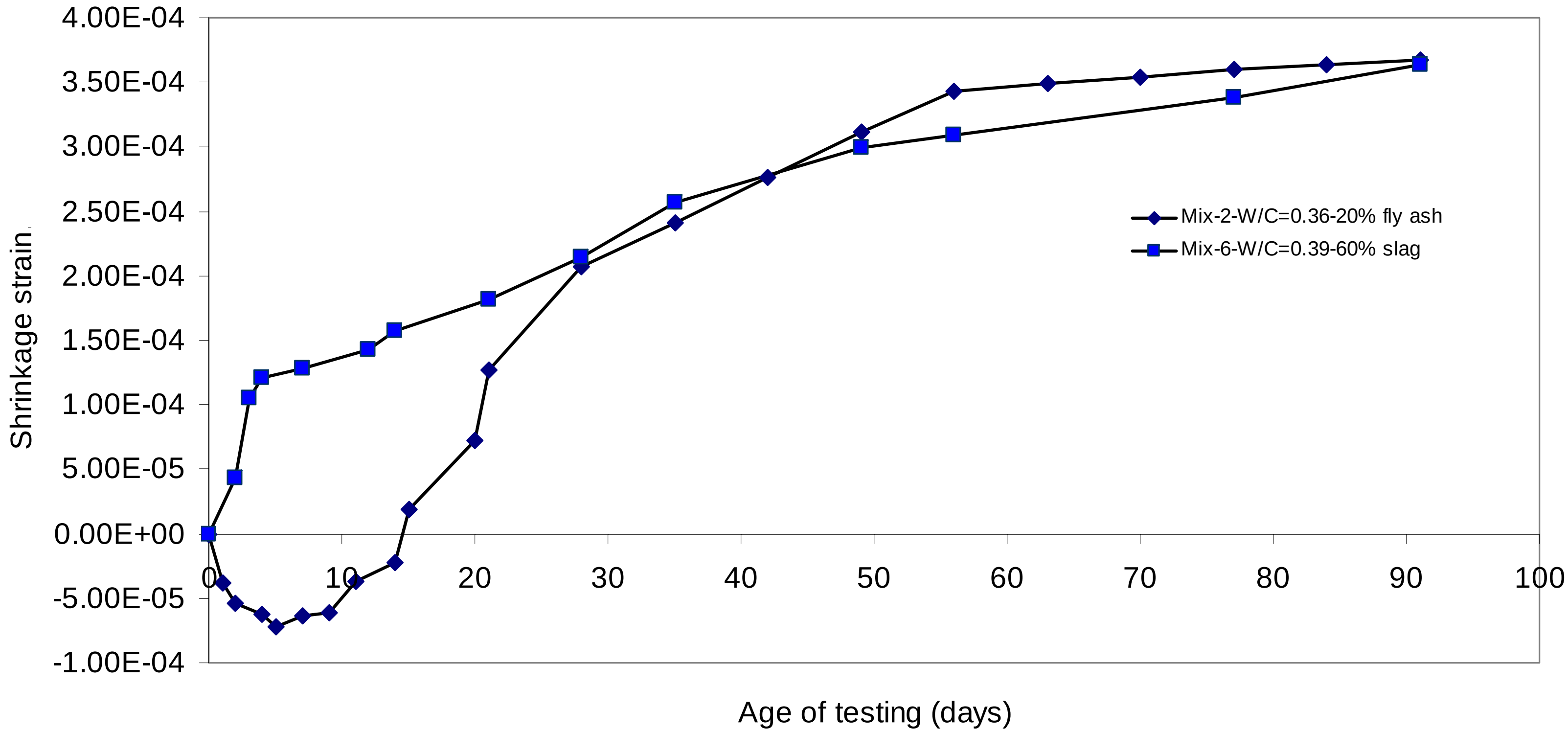


Figure 6-6. Development of shrinkage strains of lightweight concete (14-day moist curing)

6.3 Results of Creep Tests

Table 6-2 presents the measured and calculated results from the creep tests on the ten concrete mixes evaluated in this study. The results presented include the total strain, shrinkage strain, creep strain, elastic strain and creep coefficient at various loading ages. And the development of creep strain with time for each of ten mixtures is presented in Appendix B.

The shrinkage strain is the additional shrinkage strain experienced by a test specimen after it has been loaded in the creep frame. It is obtained by subtracting the measured shrinkage strain at the start of the creep test from the total measured shrinkage strain at the specified age. The creep strain is obtained by subtracting the shrinkage strain from the total strain measured from the test specimen. The elastic strain is obtained by dividing the applied stress by the elastic modulus of the concrete at that time. The creep coefficient is the ratio of the creep strain to the elastic strain.

The concrete creep test specimens from each concrete mix were loaded at two different curing times (14 and 28 days) and at two load levels (40 and 50% of ultimate strength). Figures 6-7 through 6-10 show the plots of creep coefficient versus loading time for the concretes with 20 % fly ash for the four combinations of curing times and load levels. Figures 6-11 through 6-14 show similar plots of creep coefficient for the concretes with 50 or 70 % slag. Figures 6-15 through 6-18 show similar plots for the lightweight concretes. The following observations can be made from these data:

(1) The creep coefficient is generally lower for a concrete with a lower w/c.

(2) The creep coefficient of a concrete with slag is generally lower than that for a concrete with fly ash, for comparable w/c.

(3) The creep coefficients of lightweight concretes are substantially lower than those of normal-weight concretes.

(4) The creep coefficient does not vary linearly with load level. As the load increases from 40% to 50% of ultimate load, the creep coefficient increases more than proportionally. For example, for Mix 8 (with 70 % slag and w/c of 0.41) loaded at 14 days, the creep coefficient was 1.374 at 40 % load level, while it was 2.242 at 50 % load level. The creep coefficient increased by 63 % while the applied load increased by 10 %.

(5) With the exception of Mix 1 with a low w/c of 0.24, the creep coefficients of the other nine concrete mixes appeared to continue to increase significantly beyond 91 days.

(6) Three of the ten concrete mixes (Mixes 8, 9 and 10) had creep coefficients exceeding the value of 2.0 at 91 days. At least two other concrete mixes (Mixes 3 and 5) had predicted creep coefficients exceeding 2.0 at one year.

Table 6-2. Measured and calculated results from creep tests

No. of Mix	Curing condition	Load level	strain	Age of testing (days)					
				3	7	14	28	56	91
Mix-1	7-day moist cure	40%	Total	0.000242	0.000352	0.000464	0.000571	0.000703	0.000777
			Shrinkage	0.000036	0.000053	0.000102	0.000150	0.000178	0.000210
			Creep	0.000206	0.000299	0.000362	0.000421	0.000523	0.000567
			Elastic	0.000804	0.000804	0.000804	0.000804	0.000804	0.000804
			Creep coefficient	0.256	0.372	0.450	0.524	0.653	0.705
		50%	Total	0.000224	0.000308	0.000467	0.000598	0.000738	0.000809
			Shrinkage	0.000026	0.000053	0.000102	0.000150	0.000178	0.000210
			Creep	0.000198	0.000256	0.000365	0.000448	0.000560	0.000599
			Elastic	0.000804	0.000804	0.000804	0.000804	0.000804	0.000804
			Creep coefficient	0.246	0.318	0.454	0.558	0.696	0.745
	14-day moist cure	40%	Total	0.000165	0.000212	0.000294	0.000397	0.000527	0.000591
			Shrinkage	0.000036	0.000038	0.000070	0.000097	0.000137	0.000154
			Creep	0.000129	0.000174	0.000224	0.000300	0.000390	0.000437
			Elastic	0.000811	0.000811	0.000811	0.000811	0.000811	0.000811
			Creep coefficient	0.16	0.21	0.28	0.37	0.48	0.54
		50%	Total	N/A	N/A	N/A	N/A	N/A	N/A
			Shrinkage	N/A	N/A	N/A	N/A	N/A	N/A
			Creep	N/A	N/A	N/A	N/A	N/A	N/A
			Elastic	N/A	N/A	N/A	N/A	N/A	N/A
			Creep coefficient	N/A	N/A	N/A	N/A	N/A	N/A

Continued

Mix-2	7-day moist cure	40%	Total	0.000336	0.000451	0.000614	0.000803	0.000988	0.001062
			Shrinkage	0.000060	0.000094	0.000144	0.000273	0.000407	0.000423
			Creep	0.000276	0.000357	0.000470	0.000530	0.000581	0.000639
			Elastic	0.000761	0.000761	0.000761	0.000761	0.000761	0.000761
			Creep coefficient	0.362	0.469	0.618	0.697	0.763	0.839
		50%	Total	0.000326	0.000464	0.000630	0.000845	0.001058	0.001154
			Shrinkage	0.000060	0.000094	0.000134	0.000273	0.000407	0.000423
			Creep	0.000266	0.000372	0.000496	0.000572	0.000651	0.000731
			Elastic	0.000761	0.000761	0.000761	0.000761	0.000761	0.000761
			Creep coefficient	0.349	0.489	0.652	0.751	0.855	0.960
	14-day moist cure	40%	Total	0.000250	0.000355	0.000496	0.000633	0.000793	0.000898
			Shrinkage	0.000056	0.000085	0.000123	0.000184	0.000228	0.000243
			Creep	0.000194	0.00027	0.000373	0.000449	0.000565	0.000655
			Elastic	0.000833	0.000833	0.000833	0.000833	0.000833	0.000833
			Creep coefficient	0.233	0.324	0.448	0.539	0.679	0.788
		50%	Total	0.000330	0.000479	0.000652	0.000798	0.001008	0.001126
			Shrinkage	0.000056	0.000085	0.000123	0.000184	0.000228	0.000243
			Creep	0.000274	0.000394	0.000529	0.000614	0.000780	0.000883
			Elastic	0.000833	0.000833	0.000833	0.000833	0.000833	0.000833
			Creep coefficient	0.329	0.473	0.635	0.738	0.937	1.061

Continued

Mix-3	7-day moist cure	40%	Total	0.000271	0.000488	0.000560	0.000800	0.001000	0.001111
			Shrinkage	0.000038	0.000042	0.000048	0.000100	0.000184	0.000232
			Creep	0.000233	0.000446	0.000512	0.000700	0.000816	0.000879
			Elastic	0.000640	0.000640	0.000640	0.000640	0.000640	0.000640
			Creep coefficient	0.364	0.697	0.800	1.094	1.275	1.374
		50%	Total	0.000352	0.000645	0.000767	0.001043	0.001328	0.001441
			Shrinkage	0.000038	0.000042	0.000048	0.000100	0.000184	0.000232
			Creep	0.000314	0.000603	0.000719	0.000943	0.001144	0.001209
			Elastic	0.000640	0.000640	0.000640	0.000640	0.000640	0.000640
			Creep coefficient	0.491	0.942	1.123	1.474	1.787	1.889
	14-day moist cure	40%	Total	0.000367	0.000495	0.000565	0.000697	0.000845	0.001019
			Shrinkage	0.000092	0.000021	0.000032	0.000072	0.000123	0.000138
			Creep	0.000275	0.000474	0.000533	0.000625	0.000722	0.000881
			Elastic	0.000680	0.000680	0.000680	0.000680	0.000680	0.000680
			Creep coefficient	0.405	0.697	0.784	0.919	1.0618	1.296
		50%	Total	0.000462	0.000643	0.000782	0.000958	0.001161	0.001351
			Shrinkage	0.000092	0.000021	0.000032	0.000072	0.000123	0.000138
			Creep	0.000370	0.000622	0.000750	0.000886	0.001038	0.001213
			Elastic	0.000680	0.000680	0.000680	0.000680	0.000680	0.000680
			Creep coefficient	0.544	0.915	1.103	1.303	1.527	1.784

Continued

Mix-4	7-day moist cure	40%	Total	0.000213	0.000282	0.000361	0.000488	0.000684	0.000830
			Shrinkage	0.000079	0.000084	0.000131	0.00017	0.000228	0.000274
			Creep	0.000136	0.000198	0.00023	0.000318	0.000456	0.000556
			Elastic	0.000710	0.000710	0.000710	0.000710	0.000710	0.000710
			Creep coefficient	0.1912	0.280	0.325	0.448	0.645	0.784
		50%	Total	0.000253	0.000371	0.000501	0.000677	0.000924	0.001046
			Shrinkage	0.000079	0.000084	0.000131	0.000170	0.000228	0.000274
			Creep	0.000176	0.000287	0.00037	0.000507	0.000696	0.000772
			Elastic	0.000710	0.000710	0.000710	0.000710	0.000710	0.000710
			Creep coefficient	0.248	0.405	0.522	0.715	0.982	1.088
	14-day moist cure	40%	Total	0.000162	0.000204	0.000288	0.000436	0.000666	0.000796
			Shrinkage	0.00007	0.000084	0.000109	0.000144	0.000210	0.000230
			Creep	0.000092	0.000120	0.000179	0.000292	0.000456	0.000566
			Elastic	0.000763	0.000763	0.000763	0.000763	0.000763	0.000763
			Creep coefficient	0.121	0.157	0.235	0.383	0.598	0.742
		50%	Total	0.000217	0.000249	0.000348	0.000489	0.000720	0.000836
			Shrinkage	0.000070	0.000084	0.000109	0.000144	0.000210	0.000230
			Creep	0.000147	0.000165	0.000239	0.000345	0.000510	0.000606
			Elastic	0.000763	0.000763	0.000763	0.000763	0.000763	0.000763
			Creep coefficient	0.192	0.216	0.313	0.452	0.668	0.794

Continued

Mix-5	7-day moist cure	40%	Total	0.000302	0.000456	0.000570	0.000901	0.001106	0.001236
			Shrinkage	0.000061	0.000113	0.000167	0.000251	0.000326	0.000364
			Creep	0.000241	0.000342	0.000403	0.000650	0.000780	0.000872
			Elastic	0.000590	0.000590	0.000590	0.000590	0.000590	0.000590
			Creep coefficient	0.409	0.580	0.683	1.101	1.320	1.476
		50%	Total	0.000466	0.000626	0.000792	0.001040	0.001329	0.001469
			Shrinkage	0.000061	0.000113	0.000167	0.000251	0.000326	0.000364
			Creep	0.000405	0.000512	0.000626	0.000789	0.001003	0.001105
			Elastic	0.000590	0.000590	0.000590	0.000590	0.000590	0.000590
			Creep coefficient	0.685	0.867	1.059	1.336	1.698	1.871
	14-day moist cure	40%	Total	0.000321	0.000424	N/A	0.000713	0.000910	0.001093
			Shrinkage	0.000036	0.000041	N/A	0.000123	0.000176	0.000196
			Creep	0.000285	0.000383	N/A	0.000590	0.000734	0.000897
			Elastic	0.000632	0.000632	N/A	0.000632	0.000632	0.000632
			Creep coefficient	0.451	0.606	N/A	0.934	1.161	1.419
		50%	Total	0.000571	0.00077	N/A	0.001041	0.001221	0.00133
			Shrinkage	0.000036	0.000041	N/A	0.000123	0.000176	0.000196
			Creep	0.000535	0.000729	N/A	0.000918	0.001045	0.001134
			Elastic	0.000632	0.000632	N/A	0.000632	0.000632	0.000632
			Creep coefficient	0.847	1.153	N/A	1.453	1.653	1.794

Continued

Mix-6	7-day moist cure	40%	Total	0.000229	0.000400	0.000521	0.000686	N/A	0.000997
			Shrinkage	0.000172	0.000211	0.000253	0.000331	N/A	0.000459
			Creep	5.69E-05	0.000189	0.000268	0.000355	N/A	0.000538
			Elastic	0.000751	0.000751	0.000751	0.000751	N/A	0.000751
			Creep coefficient	0.076	0.252	0.357	0.473	N/A	0.717
		50%	Total	0.000421	0.000609	0.000768	0.000942	N/A	0.001277
			Shrinkage	0.000172	0.000211	0.000253	0.000331	N/A	0.000459
			Creep	0.000249	0.000398	0.000515	0.000611	N/A	0.000818
			Elastic	0.000751	0.000751	0.000751	0.000751	N/A	0.000751
			Creep coefficient	0.332	0.531	0.686	0.815	N/A	1.090
	14-day moist cure	40%	Total	0.000293	0.000360	0.000506	0.000649	0.000883	0.001028
			Shrinkage	0.000105	0.000129	0.000158	0.000214	0.000318	0.000364
			Creep	0.000188	0.000231	0.000348	0.000435	0.000565	0.000664
			Elastic	0.000802	0.000802	0.000802	0.000802	0.000802	0.000802
			Creep coefficient	0.235	0.289	0.434	0.544	0.707	0.830
		50%	Total	0.000297	0.000356	0.000442	0.000558	0.000773	0.000931
			Shrinkage	0.000105	0.000129	0.000158	0.000214	0.000318	0.000364
			Creep	0.000192	0.000227	0.000284	0.000344	0.000455	0.000567
			Elastic	0.000802	0.000802	0.000802	0.000802	0.000802	0.000802
			Creep coefficient	0.240	0.283	0.355	0.430	0.569	0.709

Continued

Mix-7	7-day moist cure	40%	Total	0.000159	0.000283	0.000328	0.000419	0.000554	0.000664
			Shrinkage	0.000032	0.000058	0.000075	0.000135	0.000187	0.000202
			Creep	0.000127	0.000225	0.000253	0.000284	0.000367	0.000462
			Elastic	0.000681	0.000681	0.000681	0.000681	0.000681	0.000681
			Creep coefficient	0.187	0.331	0.372	0.417	0.540	0.680
		50%	Total	0.000203	0.000351	0.000449	0.000559	0.000661	0.000767
			Shrinkage	0.000032	0.000052	0.000095	0.000145	0.000187	0.000202
			Creep	0.000171	0.000299	0.000354	0.000414	0.000474	0.000565
			Elastic	0.000681	0.000681	0.000681	0.000681	0.000681	0.000681
			Creep coefficient	0.252	0.440	0.520	0.609	0.697	0.830
	14-day moist cure	40%	Total	0.000163	0.000252	0.000301	0.000368	0.000460	0.000617
			Shrinkage	0.000010	0.000026	0.000039	0.000052	0.000073	0.000103
			Creep	0.000154	0.000226	0.000262	0.000316	0.000387	0.000514
			Elastic	0.000720	0.000720	0.000720	0.000720	0.000720	0.000720
			Creep coefficient	0.214	0.314	0.364	0.438	0.537	0.713
		50%	Total	0.000236	0.000330	0.000450	0.000546	0.000662	0.000836
			Shrinkage	0.000010	0.000026	0.000039	0.000052	0.000073	0.000103
			Creep	0.000226	0.000304	0.000411	0.000493	0.000589	0.000733
			Elastic	0.000720	0.000720	0.000720	0.000720	0.000720	0.000720
			Creep coefficient	0.314	0.422	0.571	0.685	0.818	1.017

Continued

Mix-8	7-day moist cure	40%	Total	0.000344	0.000391	0.000444	0.000511	0.000616	0.000756
			Shrinkage	0.000060	0.000072	0.000110	0.000148	0.000191	0.000218
			Creep	0.000284	0.000319	0.000334	0.000363	0.000425	0.000538
			Elastic	0.000413	0.000413	0.000413	0.000413	0.000413	0.000413
			Creep coefficient	0.626	0.711	0.808	0.929	1.119	1.374
		50%	Total	0.000493	0.000573	0.000661	0.000779	0.001031	0.001233
			Shrinkage	0.000060	0.000072	0.000110	0.000148	0.000191	0.000218
			Creep	0.000433	0.000501	0.000551	0.000631	0.000840	0.001015
			Elastic	0.000413	0.000413	0.000413	0.000413	0.000413	0.000413
			Creep coefficient	0.896	1.042	1.203	1.416	1.875	2.242
	14-day moist cure	40%	Total	0.000183	0.000281	0.000323	0.000427	0.000580	0.000776
			Shrinkage	0.000066	0.000089	0.000106	0.000141	0.000174	0.000199
			Creep	0.000117	0.000192	0.000217	0.000286	0.000406	0.000577
			Elastic	0.000422	0.000422	0.000422	0.000422	0.000422	0.000422
			Creep coefficient	0.291	0.446	0.513	0.677	0.921	1.231
		50%	Total	0.000257	0.000314	0.000430	0.000557	0.000743	0.000989
			Shrinkage	0.000066	0.000089	0.000106	0.000141	0.000174	0.000199
			Creep	0.000191	0.000225	0.000324	0.000416	0.000569	0.000790
			Elastic	0.000422	0.000422	0.000422	0.000422	0.000422	0.000422
			Creep coefficient	0.407	0.499	0.683	0.884	1.180	1.570

Continued

Mix-9	7-day moist cure	40%	Total	0.000217	0.000331	0.000443	0.000569	0.000820	0.001046
			Shrinkage	0.000023	0.000030	0.000036	0.000073	0.000118	0.000167
			Creep	0.000194	0.000301	0.000407	0.000496	0.000702	0.000879
			Elastic	0.000550	0.000550	0.000550	0.000550	0.000550	0.000550
			Creep coefficient	0.352	0.547	0.741	0.902	1.2762	1.597
		50%	Total	0.000443	0.000539	0.000647	0.000834	0.001133	0.001349
			Shrinkage	0.000023	0.000030	0.000036	0.000073	0.000118	0.000167
			Creep	0.000420	0.000509	0.000611	0.000761	0.001015	0.001182
			Elastic	0.000550	0.000550	0.000550	0.000550	0.000550	0.000550
			Creep coefficient	0.764	0.925	1.110	1.384	1.846	2.149
	14-day moist cure	40%	Total	0.000243	0.000312	0.000402	0.000579	0.000867	0.001059
			Shrinkage	0.000009	0.000011	0.000017	0.000026	0.000043	0.000063
			Creep	0.000235	0.000301	0.000385	0.000553	0.000824	0.000996
			Elastic	0.000640	0.000640	0.000640	0.000640	0.000640	0.000640
			Creep coefficient	0.367	0.471	0.602	0.864	1.287	1.556
		50%	Total	0.000369	0.000453	0.000557	0.000726	0.001128	0.001336
			Shrinkage	0.000009	0.000011	0.000017	0.000026	0.000043	0.000063
			Creep	0.000360	0.000442	0.000540	0.000700	0.001085	0.001273
			Elastic	0.000640	0.000640	0.000640	0.000640	0.000640	0.000640
			Creep coefficient	0.563	0.691	0.843	1.093	1.695	1.988

Continued

Mix-10	7-day moist cure	40%	Total	0.000568	0.000709	0.000837	0.001171	0.001359	0.001531
			Shrinkage	0.000073	0.000102	0.000122	0.000168	0.000202	0.000250
			Creep	0.000495	0.000607	0.000715	0.001003	0.001157	0.001281
			Elastic	0.000670	0.000670	0.000670	0.000670	0.000670	0.000670
			Creep coefficient	0.738	0.906	1.0667	1.497	1.727	1.912
		50%	Total	0.000900	0.001158	0.001306	0.001674	0.001853	0.001942
			Shrinkage	0.000073	0.000102	0.000122	0.000170	0.000202	0.000250
			Creep	0.000827	0.001056	0.001184	0.001504	0.001651	0.001692
			Elastic	0.000670	0.000670	0.000670	0.000670	0.000670	0.000670
			Creep coefficient	1.234	1.576	1.767	2.245	2.465	2.526
	14-day moist cure	40%	Total	0.000843	0.001000	0.001211	0.001274	0.001484	0.001637
			Shrinkage	0.000062	0.000102	0.000128	0.000151	0.00021	0.00026
			Creep	0.000781	0.000898	0.001083	0.001123	0.001274	0.001377
			Elastic	0.000680	0.000680	0.000680	0.000680	0.000680	0.000680
			Creep coefficient	1.149	1.321	1.593	1.652	1.874	2.025
		50%	Total	0.000910	0.001196	0.001526	0.001782	0.001933	0.002213
			Shrinkage	0.000062	0.000102	0.000128	0.000151	0.000202	0.00026
			Creep	0.000848	0.001094	0.001398	0.001631	0.001731	0.001953
			Elastic	0.000680	0.000680	0.000680	0.000680	0.000680	0.000680
			Creep coefficient	1.247	1.608	2.055	2.399	2.546	2.873

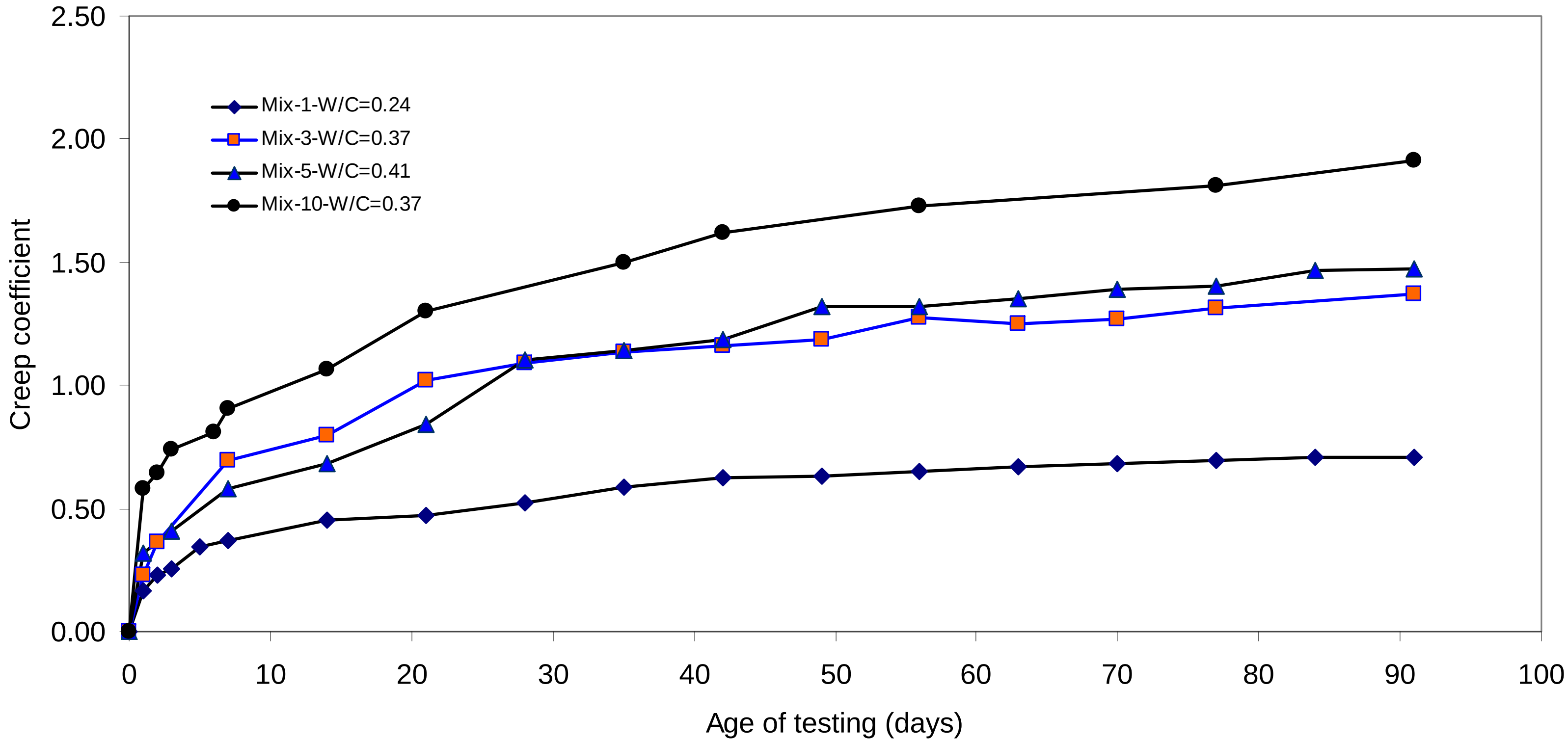


Figure 6-7. Creep coefficient of concrete with 20% fly ash (7-day moist curing, 40% load level)

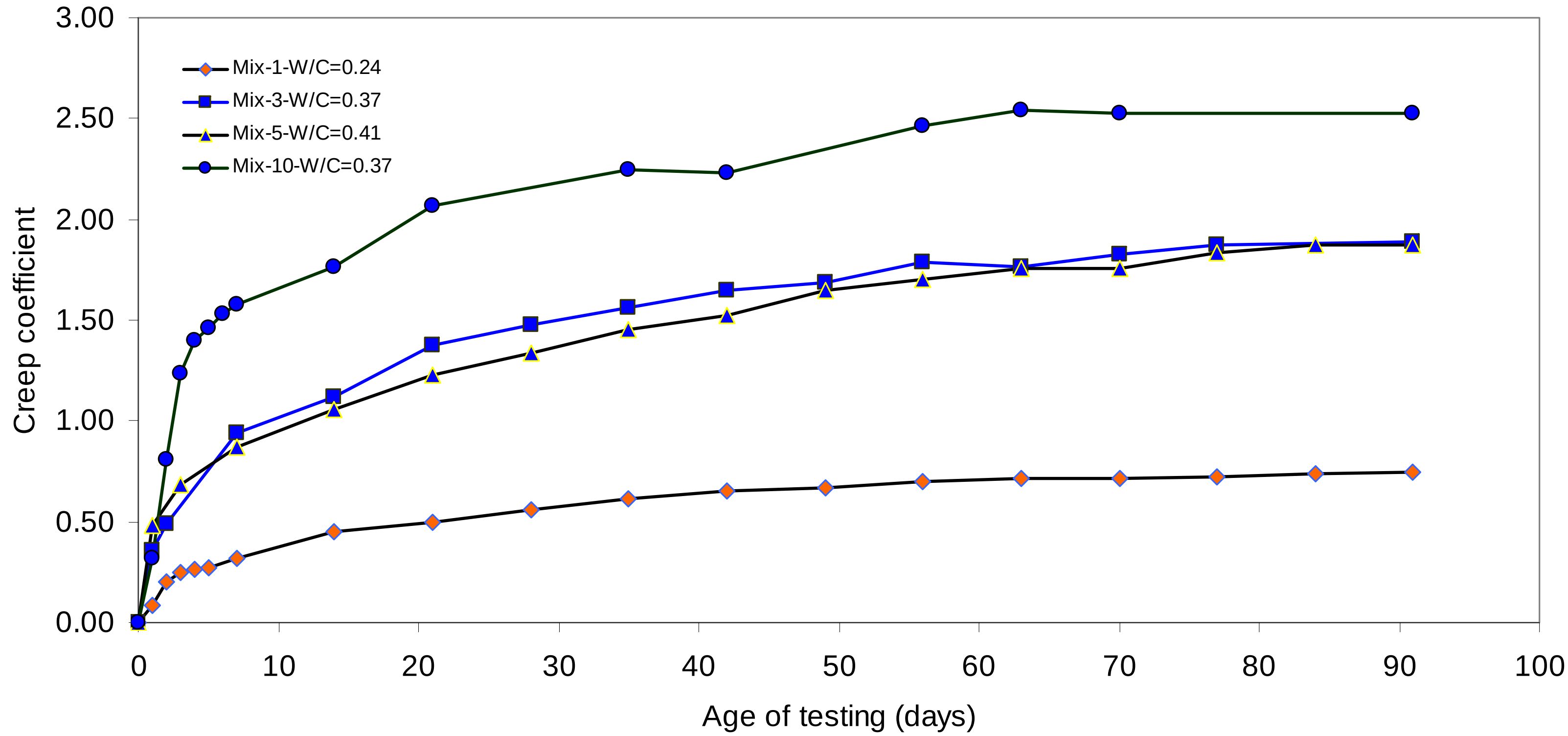


Figure 6-8. Creep coefficient of concrete with 20% fly ash (7-day moist curing, 50% load level)

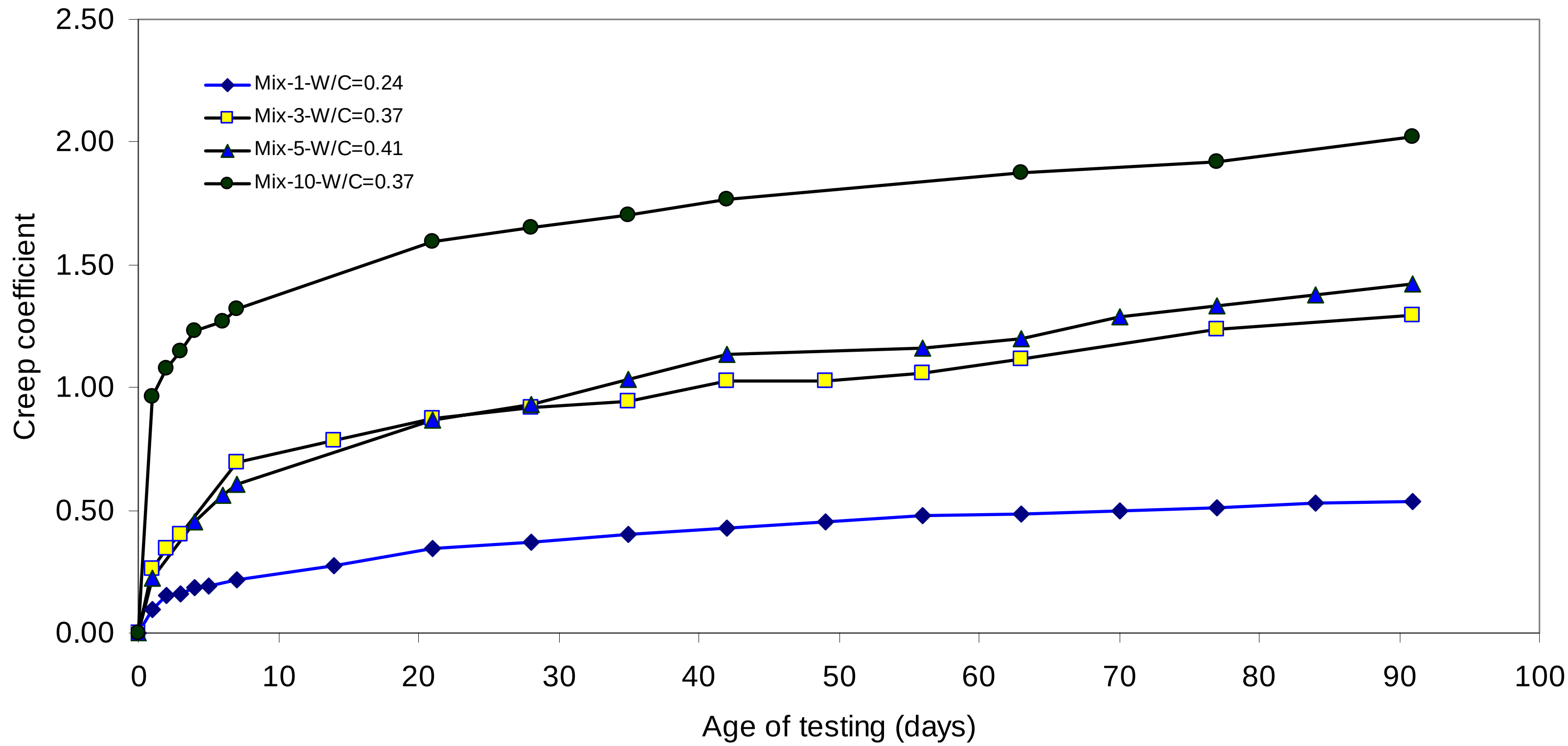


Figure 6-9. Creep coefficient of concrete with 20% fly ash (14-day moist curing, 40% load level)

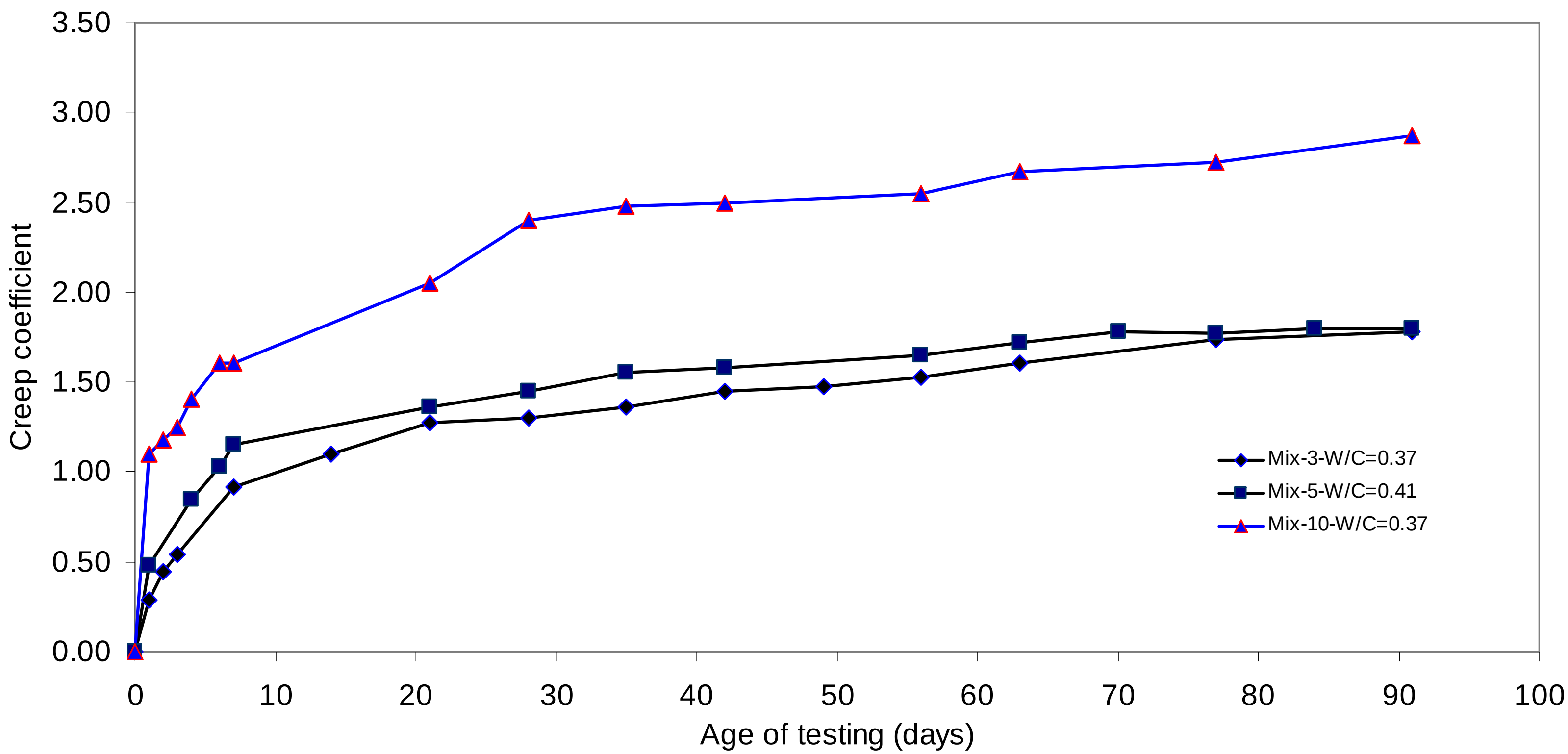


Figure 6-10. Creep coefficient of concrete with fly ash (14-day moist curing, 50% load level)

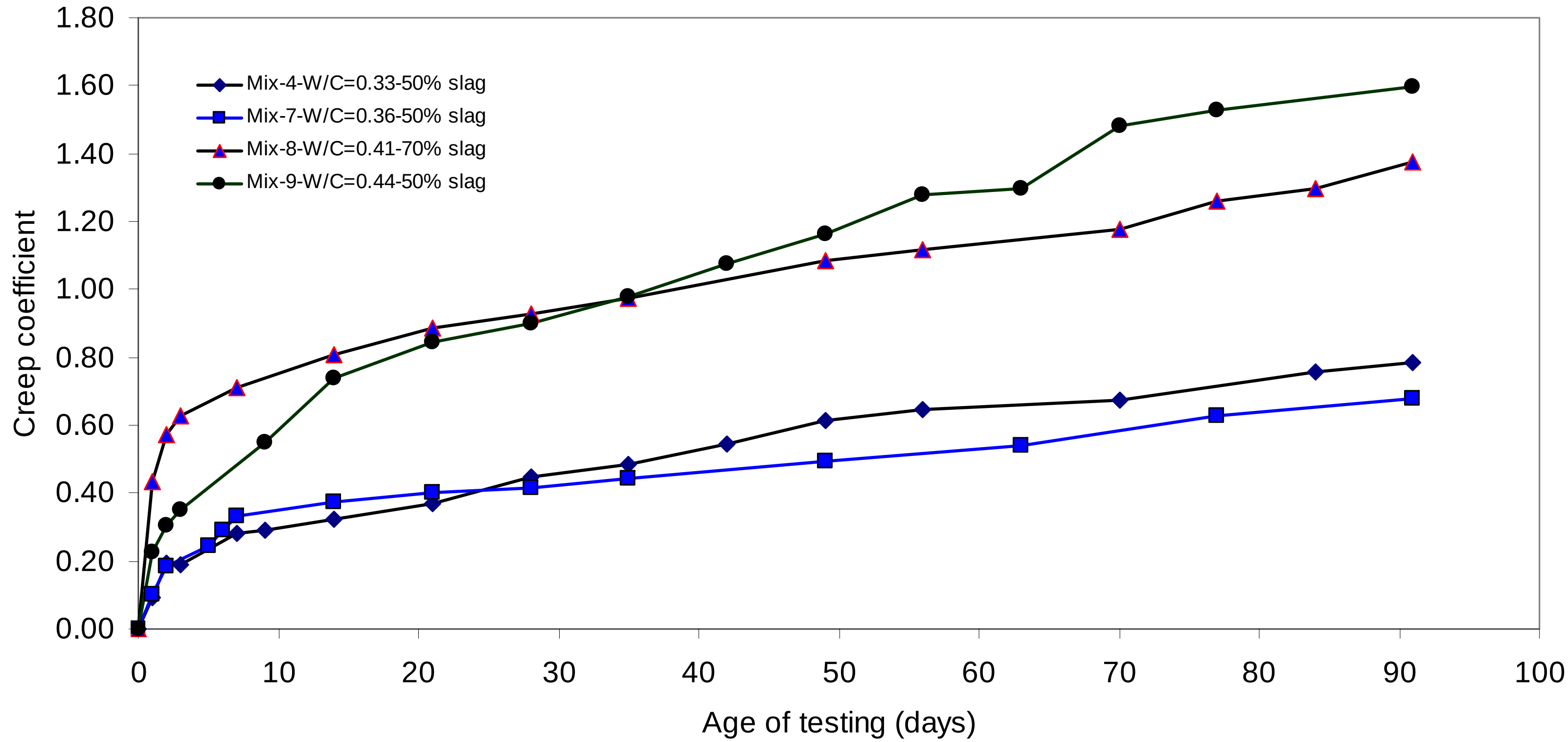


Figure 6-11. Creep coefficient of concretes with slag (7-day moist curing, 40% load level)

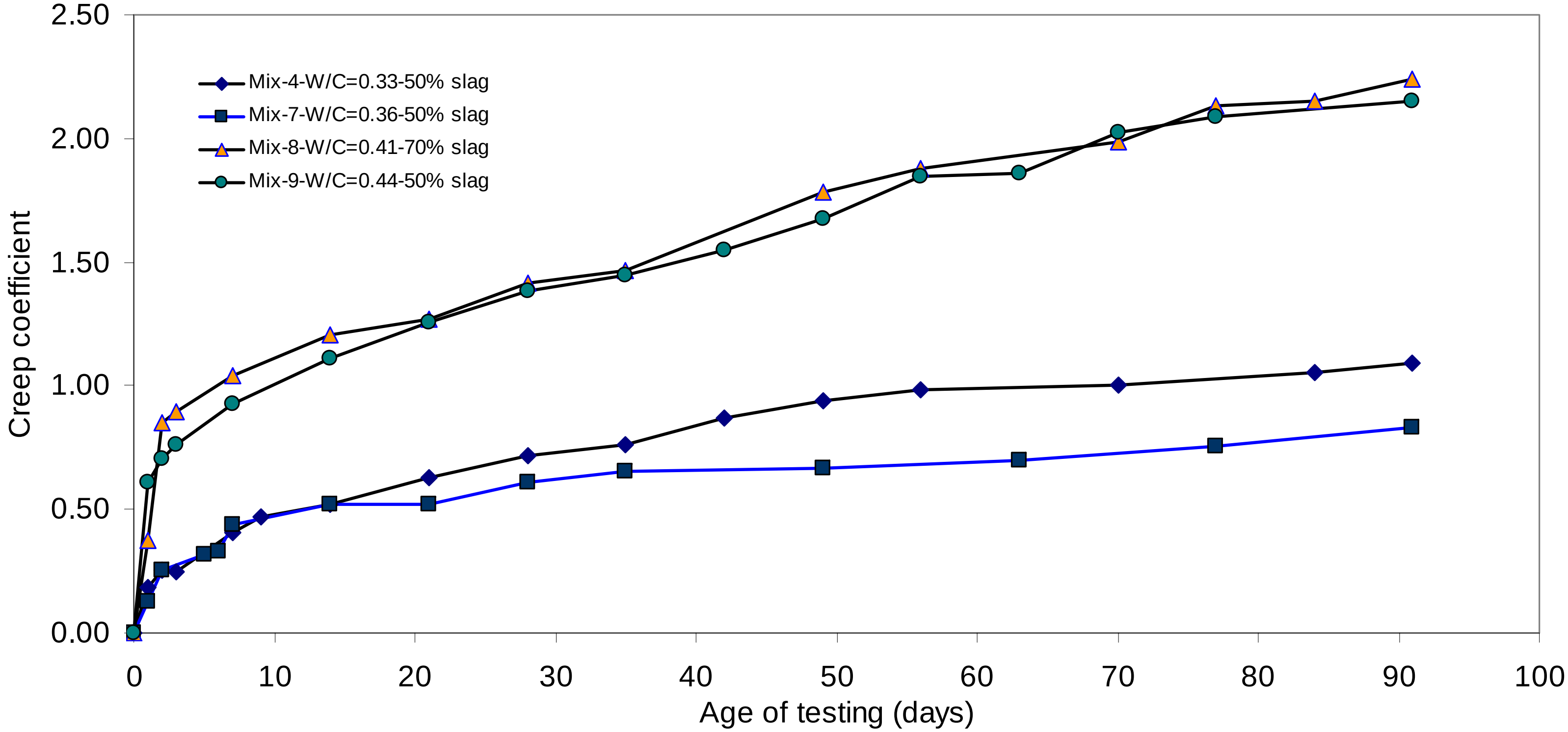


Figure 6-12. Creep coefficient of concrete with slag (7-day moist curing, 50% load level)

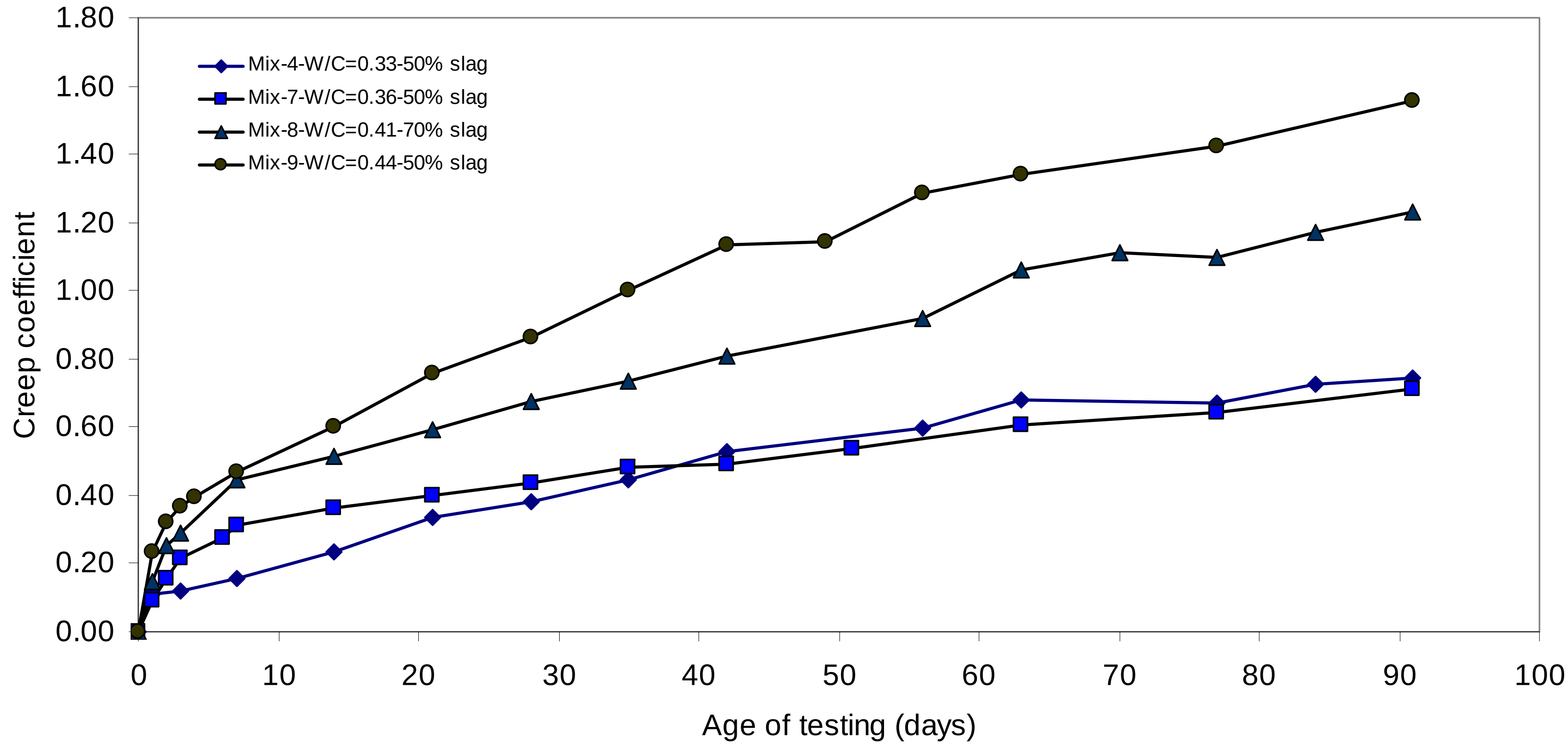


Figure 6-13. Creep coefficient of concrete with slag (14-day moist curing, 40% load level)

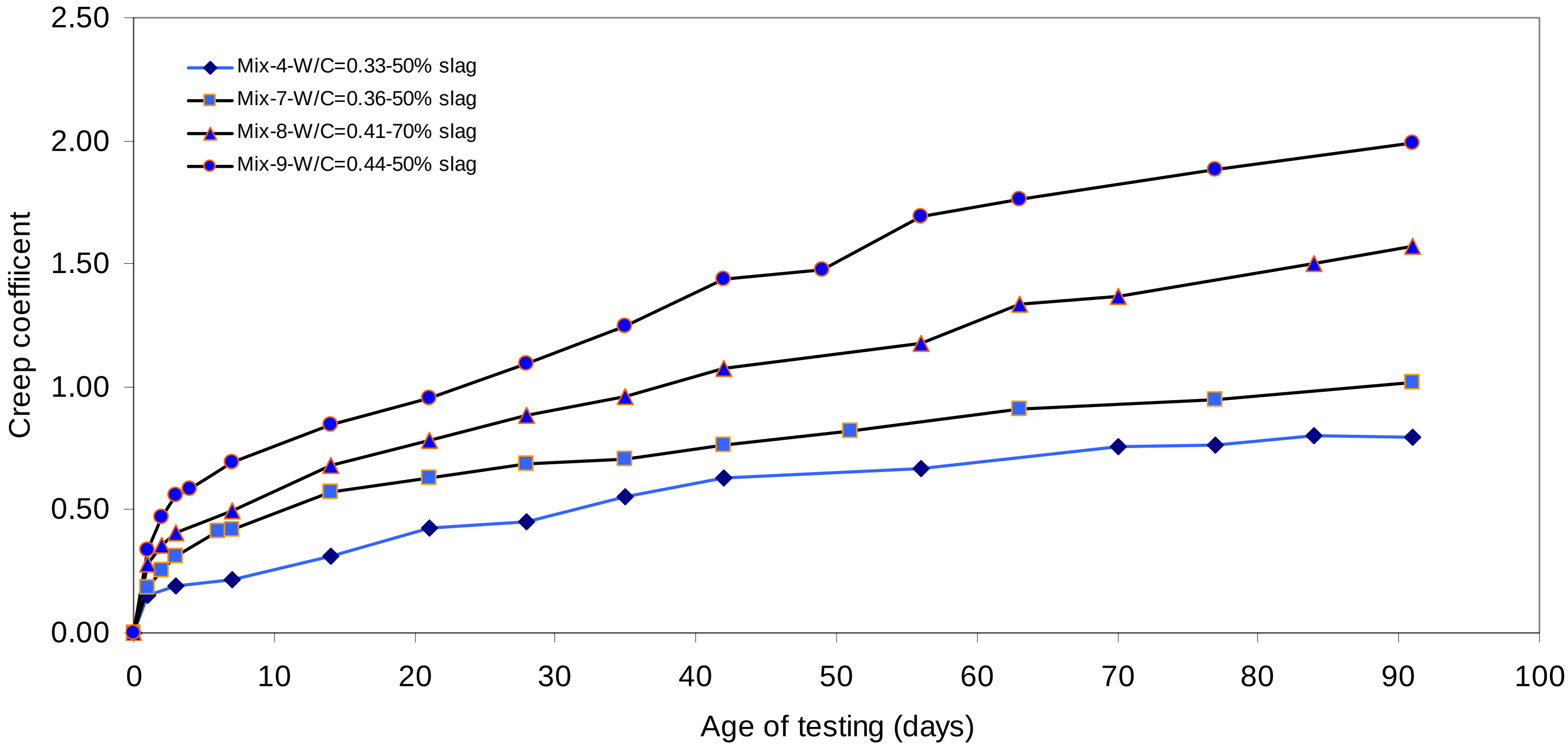


Figure 6-14. Creep coefficient of concrete with slag (14-day moist curing, 50% load level)

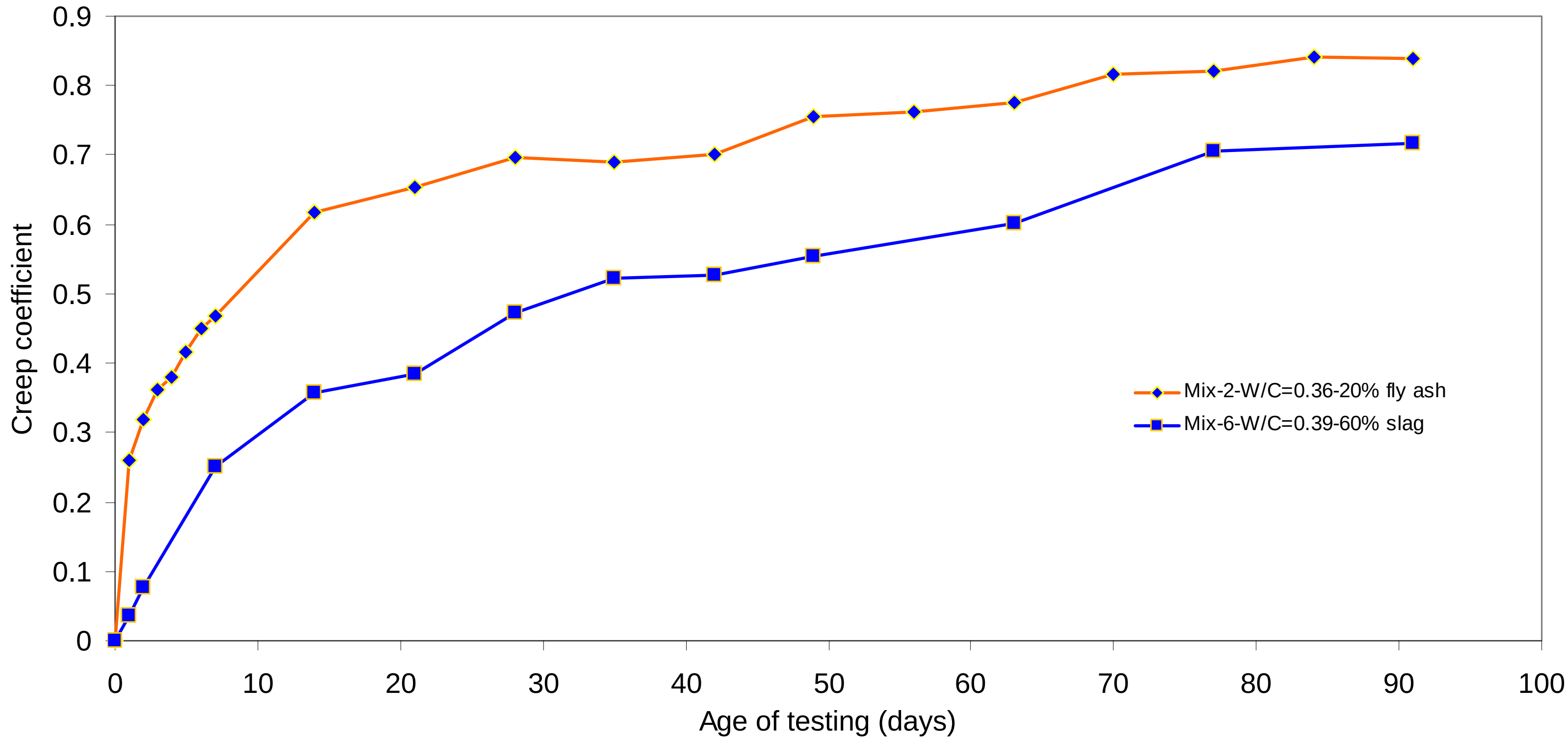


Figure 6-15. Creep coefficient of lightweight concretes (7-day moist curing, 40% load level)

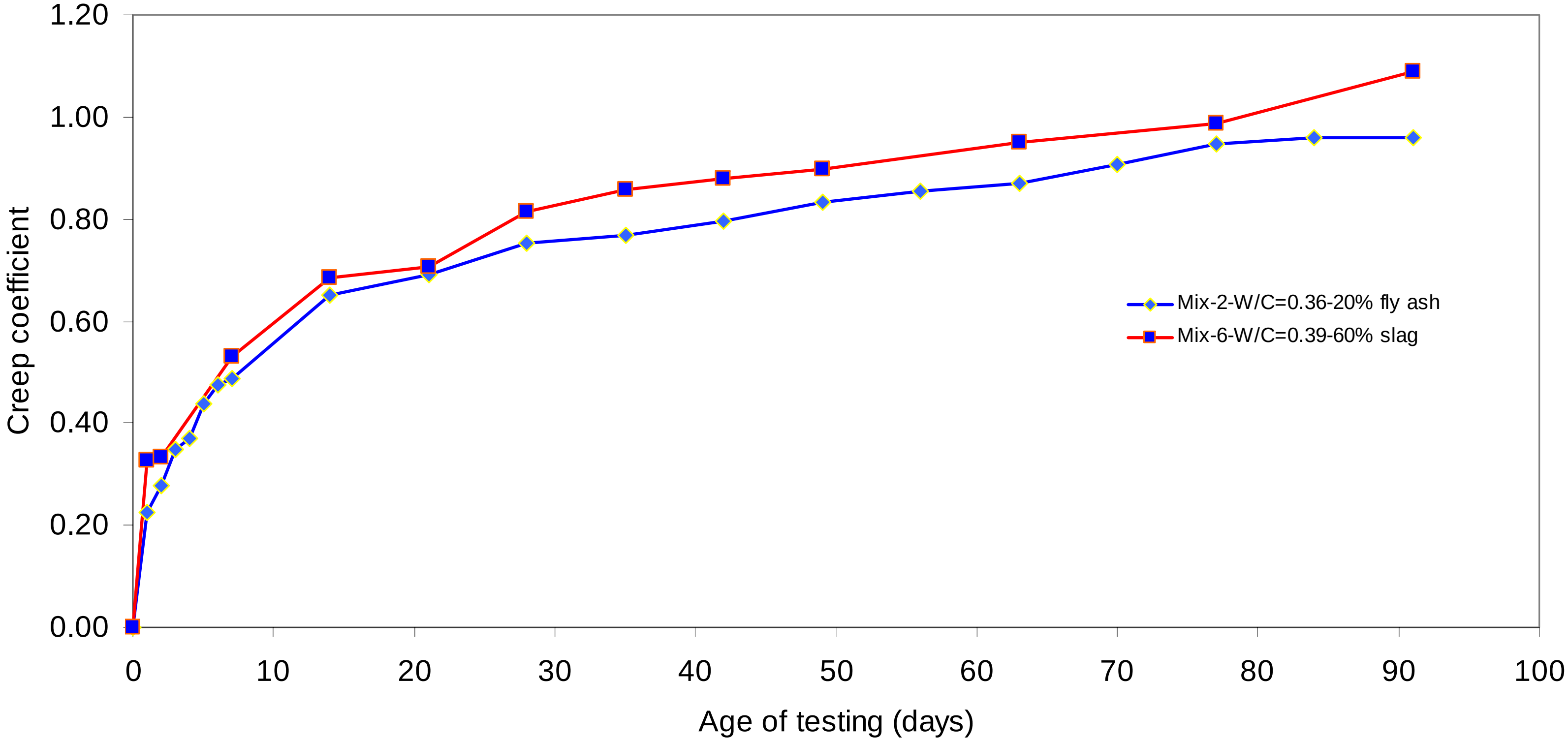


Figure 6-16. Creep coefficient of lightweight concretes (7-day moist curing, 50% load level)

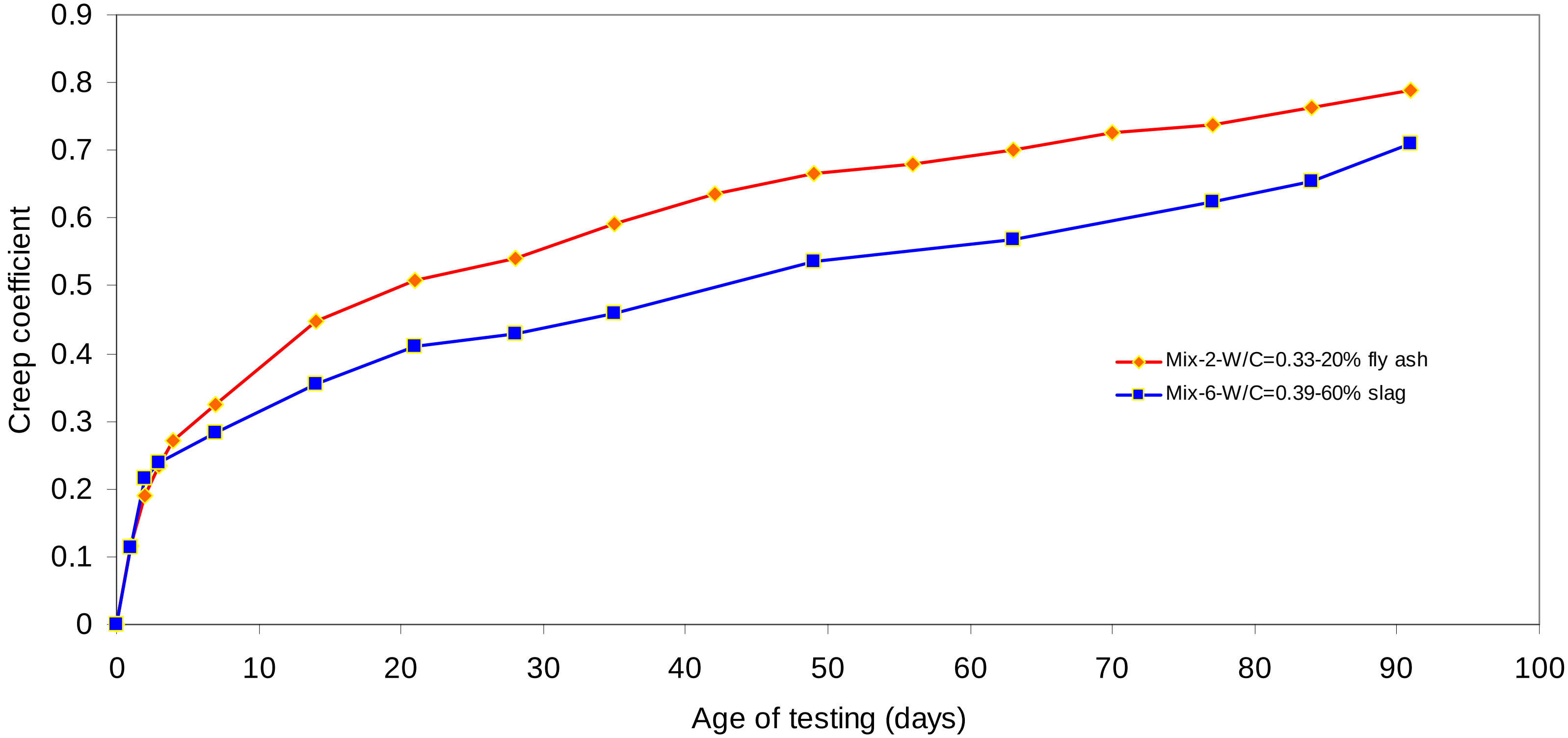


Figure 6-17. Creep coefficient of lightweight concete (14-day moist curing, 40% load level)

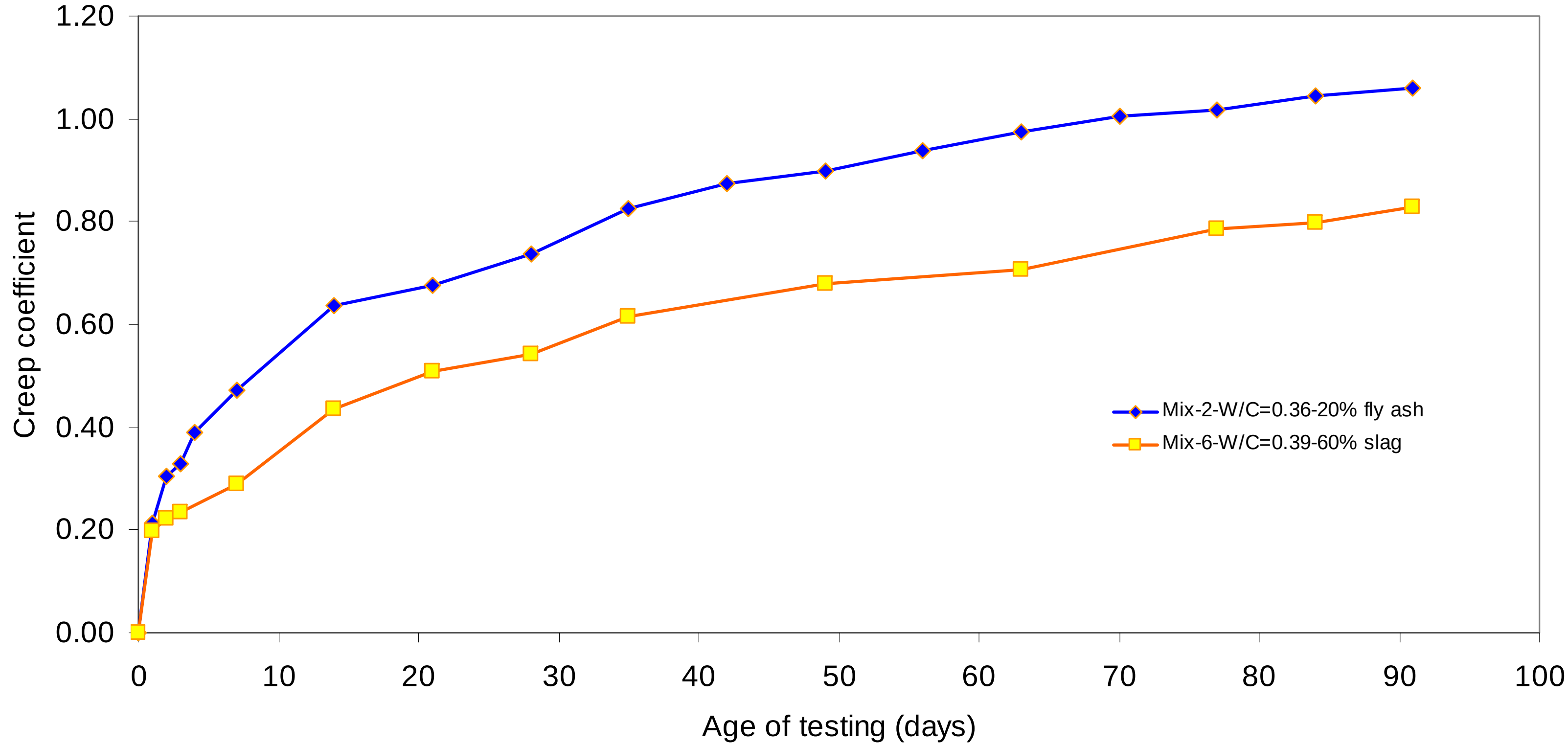


Figure 6-18. Creep coefficient of lightweight concetes (14-day moist curing, 50% load level)

Chapter 7

SUMMARY AND RECOMMENDATIONS

7.1 Design and Construction of Creep Apparatuses

The creep test apparatus was designed, and twelve creep test apparatuses were constructed and set up in the laboratory for use in performing the creep tests in this study. In each test frame, three $6'' \times 12''$ cylindrical specimens can be placed on top of one another and cemented together by an epoxy and tested under the same load. The maximum capacity of each creep apparatus is 1.92×10^5 lbf. The maximum stress that can be applied to the $6'' \times 12''$ cylindrical concrete specimens in the creep frame is 6795 psi. Three pairs of gage points with a gage distance of 10 inches are to be placed in each test concrete specimen. A mechanical strain gage (formerly known as Whittemore gage) is to be used to measure the change in distance between the gage points, which is the creep of the concrete specimen during the creep test.

The creep test apparatus was evaluated to be working satisfactorily. An effective procedure for the creep test using this apparatus was developed and documented.

7.2 Findings from the Research Testing Program

Ten typical Florida concrete mixes were evaluated in the research testing program for their compressive strength, splitting tensile strength, elastic modulus, shrinkage and creep characteristics. Eight of the ten concrete mixes used a Miami Oolite as the coarse aggregate, while two concrete mixes used a lightweight aggregate Stalite. Four normal-weight concretes and one lightweight concrete used 20 % fly ash, while the other four normal-weight concretes and one lightweight concrete used 50 to 70 % slag. Tests were run on the concrete specimens up to an age of 91 days.

Major findings from the tests on these ten concrete mixes are summarized as follows:

❖ **On Strength and Elastic Modulus**

1. The compressive strength, splitting tensile strength and elastic modulus of the normal-weight concretes with 20 % fly ash continue to increase significantly beyond 28 days, while those of the normal-weight concretes with 50 to 70 % slag level off considerably beyond 28 days.
2. The lightweight concretes have considerably lower compressive strength, splitting tensile strength and elastic modulus than those of the normal-weight concretes with similar w/c and mineral additive.
3. The empirical relationships between compressive strength (f_c') in psi and splitting tensile strength (f_{ct}) in psi for the normal-weight concretes evaluated in this study are as follows:

$$f_{ct} = 7.08 \cdot \sqrt{f_c'} \qquad \text{[Equation 7.1]}$$

$$f_{ct} = \left(f_c'\right)^{0.72} \qquad \text{[Equation 7.2]}$$

Equation 7.2 was found to fit the data slightly better than Equation 7.1.

4. The empirical relationships between compressive strength ($f_c^{'}$) in psi, density (w) in pci, and elastic modulus (E) in psi for the normal-weight concretes evaluated in this study are as follows:

For 28-day curing, $E = 32.2 \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$ [Equation 7.3]

For 91-day curing, $E = 32.8 \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$ [Equation 7.4]

For all curing conditions, $E = 33.0 \cdot w^{1.5} \cdot \sqrt{f_c^{'}}$ [Equation 7.5]

❖ On Drying Shrinkage

5. For the normal-weight concretes containing 20 % fly ash, the drying shrinkage decreases as w/c decreases, and as the moist curing time increases from 7 days to 14 days.
6. For the normal-weight concretes containing 50 to 70 % slag, the drying shrinkage does not change significantly as the moist curing time increases from 7 days to 14 days.
7. The normal-weight concretes containing 20 % fly ash have a significantly higher drying shrinkage than the concretes containing 50 to 70 % slag of comparable w/c.
8. For the two lightweight concretes evaluated, the drying shrinkage decreases significantly as the moist curing time increases from 7 days to 14 days.
9. The lightweight concretes have a significantly higher drying shrinkage than the normal-weight concretes.

❖ **On Creep Characteristics**

10. The creep coefficient is generally lower for a concrete with a lower w/c.
11. The creep coefficient of a concrete with slag is generally lower than that for a concrete with fly ash, for comparable w/c.
12. The creep coefficients of lightweight concretes are substantially lower than those of normal-weight concretes.
13. The creep coefficient does not vary linearly with load level. As the load increases from 40 to 50 % of ultimate load, the creep coefficient increases more than proportionally.
14. With the exception of Mix 1 with a low w/c of 0.24, the creep coefficients of the other nine concrete mixes appeared to continue to increase significantly beyond 91 days.
15. Three of the ten concrete mixes evaluated had creep coefficients exceeding the value of 2.0 at 91 days. At least two other concrete mixes had predicted creep coefficients exceeding 2.0 at one year.

7.3 Recommendations

While this study has generated valuable data and determined general trends on the compressive strength, splitting tensile strength, elastic modulus, drying shrinkage strains and creep coefficient of typical Florida structural concretes made with normal weight and lightweight aggregates, it must be noted that this study was limited in scope due to the constraint of time and budget. Due to the time constraint, no replicate batch of the concrete mixes in the testing program was tested. There is a need to test the replicates of these concrete mixes to establish reliability of the findings and to evaluate the variability of the test results. The creep tests in this study were run only up to 91 days. However, the creep test results from this study indicate that most of concretes still continued to creep considerably at 91 days. There is a need to extend the creep tests beyond 91 days, and preferably to one year, so that the ultimate creep coefficient can be determined more reliably.

Due to the limited scope of this study as described above, the concrete properties as determined from this study should not be recommended for use in structural designs yet at this point. It is recommended that further testing be conducted in the following areas:

- Replicate batches of the ten concrete mixes evaluated in this study should be tested to establish reliability of the findings and to evaluate the variability of the test results.
- The creep tests should be run up to one year, instead of 91 days.
- Structural concretes using other Florida coarse aggregates should also be evaluated.
- The effects of the type and amount of mineral admixtures (fly ash, slag and silica fume), and other admixtures should be evaluated.

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Appendix A

Table A-1. Results of compressive strength tests (psi)

No. of mix	Age of Testing (days)																	
	3			7			14			28			56			91		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
mix-1	N/A	N/A	N/A	10274	10345	10342	11042	11484	10734	11480	11630	11580	12200	12040	11970	11700	12600	12900
mix-2	3620	3910	3620	5130	4770	5000	5810	6080	6040	6030	6700	6870	7160	7360	7510	8320	7880	8100
mix-3	5630	5710	5760	6620	6880	6740	7570	7470	7430	7870	7990	7890	8590	8590	8810	9110	8900	9110
mix-4	6260	6330	6530	8410	8630	8870	9360	9550	9510	10290	10300	10160	10070	9980	10300	10260	10480	10000
mix-5	4770	4920	4950	6230	5950	6050	7140	7340	7070	7560	8140	8120	8990	8820	8620	9460	9030	9440
mix-6	1980	1830	1970	3530	3520	3580	5020	5020	5150	6070	5910	6570	7010	7120	7070	7350	7410	7180
mix-7	6120	6380	6110	8530	8570	8640	9490	9260	10090	10200	10150	10350	10750	10460	10370	10720	10920	10720
mix-8	2320	2410	2410	5200	5340	5290	6270	7090	6880	7410	7830	6760	8250	8180	8180	8030	8280	8320
mix-9	3220	3100	3210	5640	5610	5830	7040	6750	7030	7940	8010	7840	8620	8260	8070	8960	8460	8570
mix-10	5230	5200	5300	6770	6560	6810	7970	7780	7810	8730	8580	8640	9390	9260	9300	9560	10060	10150

Table A-2. Results of splitting tensile strength tests (psi)

Mix Number	Age of Testing (days)																	
	3			7			14			28			56			91		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
mix-1	N/A	N/A	N/A	708	610	N/A	761	809	N/A	824	826	N/A	878	960	N/A	1024	943	913
mix-2	295	398	392	470	421	490	643	493	616	542	469	544	573	492	529	594	551	675
mix-3	451	428	434	479	529	486	700	585	562	685	669	680	809	709	652	727	817	660
mix-4	426	553	468	573	618	754	656	618	585	819	645	774	648	695	737	633	755	681
mix-5	549	450	547	507	575	475	656	590	650	595	658	602	763	662	718	709	775	799
mix-6	259	223	267	346	341	361	451	488	468	472	475	553	602	564	600	614	601	623
mix-7	601	560	617	625	704	736	626	772	690	770	705	616	663	697	786	755	798	854
mix-8	310	317	262	500	432	474	559	486	664	688	525	660	612	701	646	735	634	675
mix-9	347	306	463	520	536	524	599	589	600	560	594	640	587	619	709	619	660	652
mix-10	358	410	512	527	516	556	660	502	548	658	728	640	698	721	789	857	836	832

Table A-3. Results of elastic modulus tests (×10^6psi)

Mix Number	Age of Testing (days)											
	3		7		14		28		56		91	
	1	2	1	2	1	2	1	2	1	2	1	2
mix-1	N/A	N/A	5.43	5.32	5.52	5.52	5.68	5.71	5.94	5.94	6.31	6.27
mix-2	2.75	2.67	2.99	2.92	3.12	3.18	3.32	3.25	3.46	3.46	3.53	3.50
mix-3	3.99	3.98	4.23	4.28	4.59	4.44	4.70	4.61	4.77	4.80	4.91	5.05
mix-4	4.40	4.37	4.96	5.12	5.37	5.32	5.43	5.42	5.68	5.53	5.66	5.59
mix-5	4.16	4.21	4.55	4.51	4.88	4.86	5.02	5.02	5.17	5.19	5.46	5.56
mix-6	2.01	2.05	2.28	2.30	2.58	2.72	2.91	2.98	3.19	3.22	3.28	3.38
mix-7	4.86	4.46	5.15	5.25	5.46	5.60	5.56	5.72	5.77	5.69	5.81	5.85
mix-8	3.24	3.28	4.35	4.18	4.67	4.52	4.75	4.71	4.72	4.94	4.86	4.89
mix-9	3.54	3.51	4.57	4.36	4.89	4.71	4.85	4.86	5.11	5.27	5.10	5.34
mix-10	3.99	4.22	4.47	4.43	4.68	N/A	5.02	5.00	5.34	5.53	5.45	5.45

Appendix B Plots of Shrinkage Strain, Creep Strain and Creep Coefficient

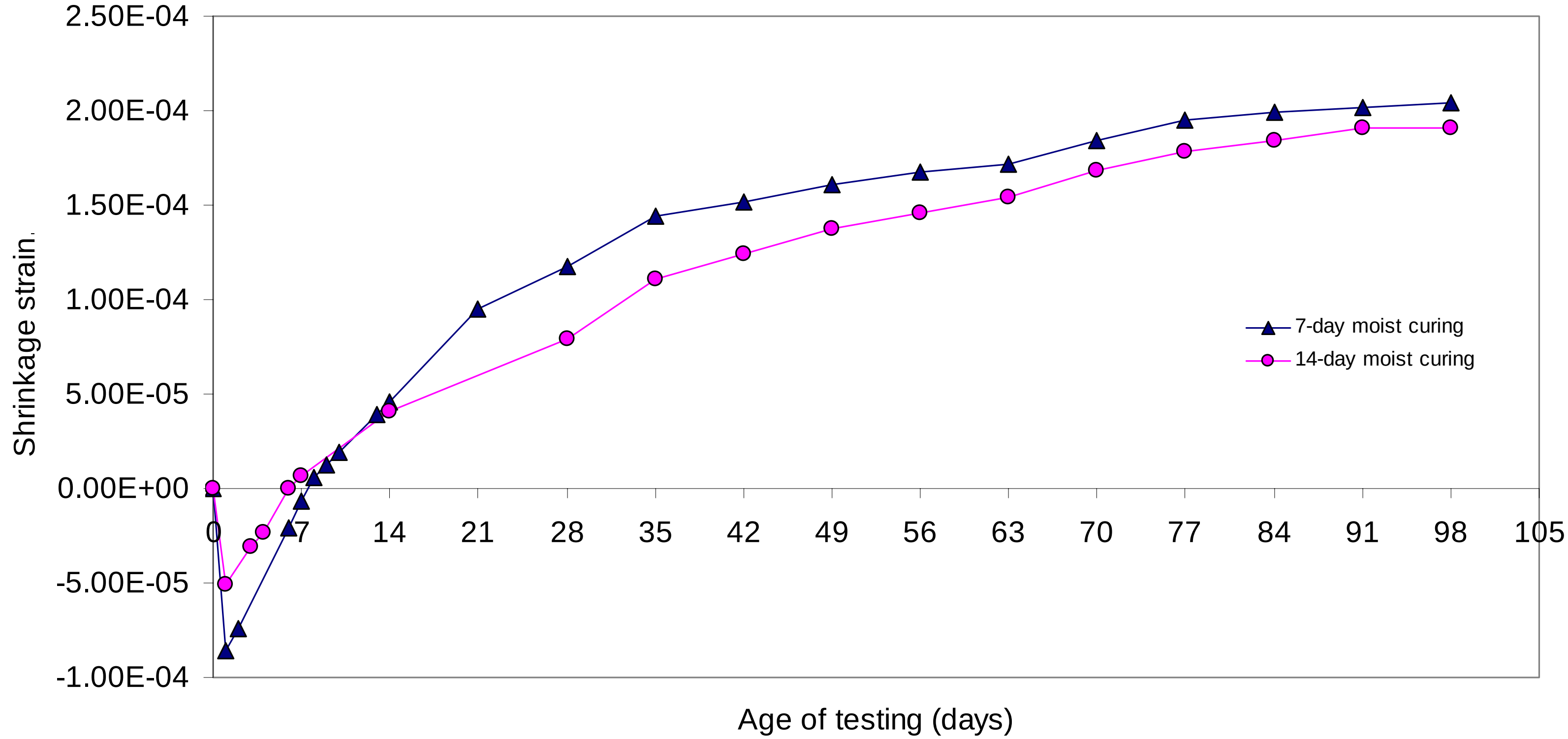

Figure B-1. Development of shrinkage strain of Mix-1 with time

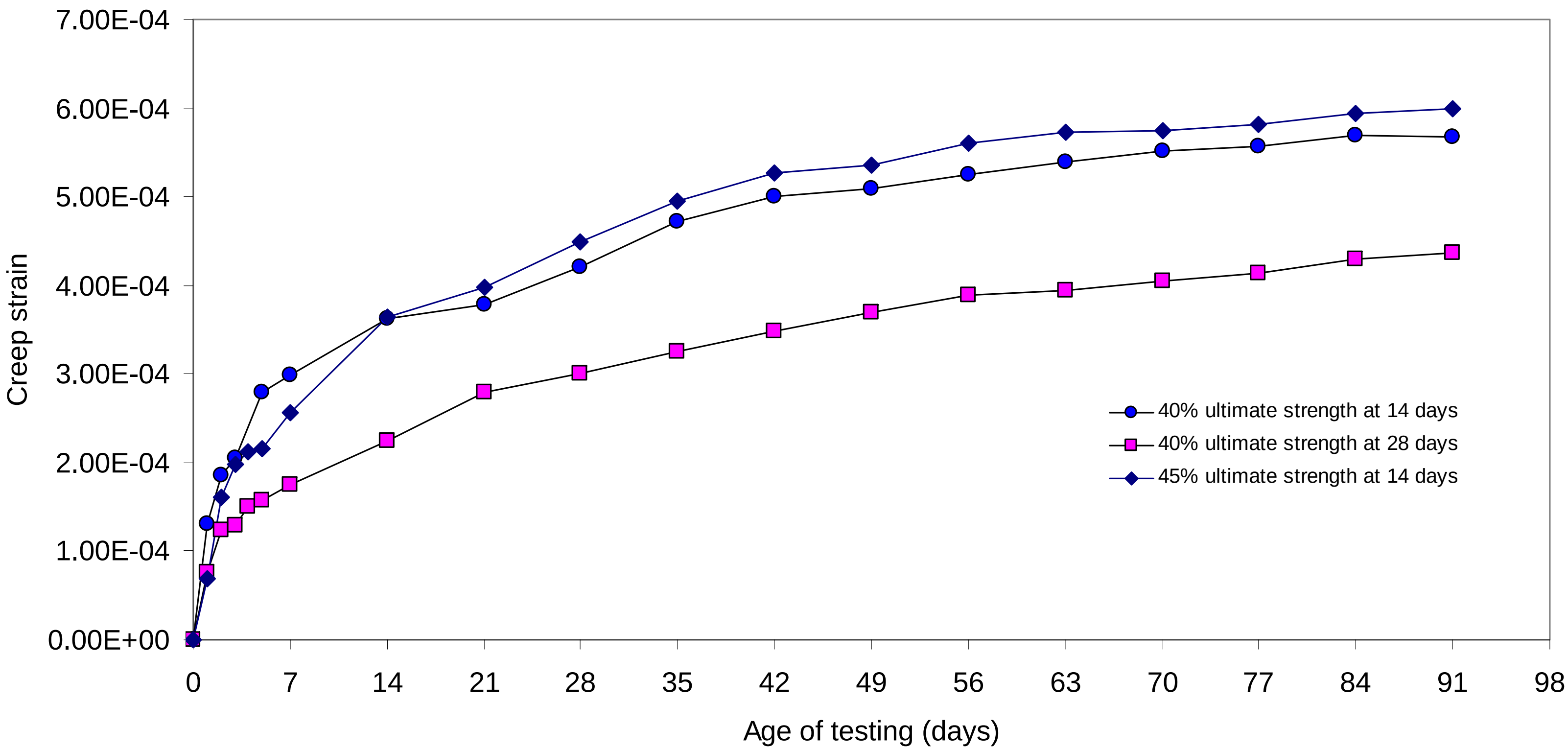

Figure B-2. Comprison of creep strains of Mix-1 at different curing ages

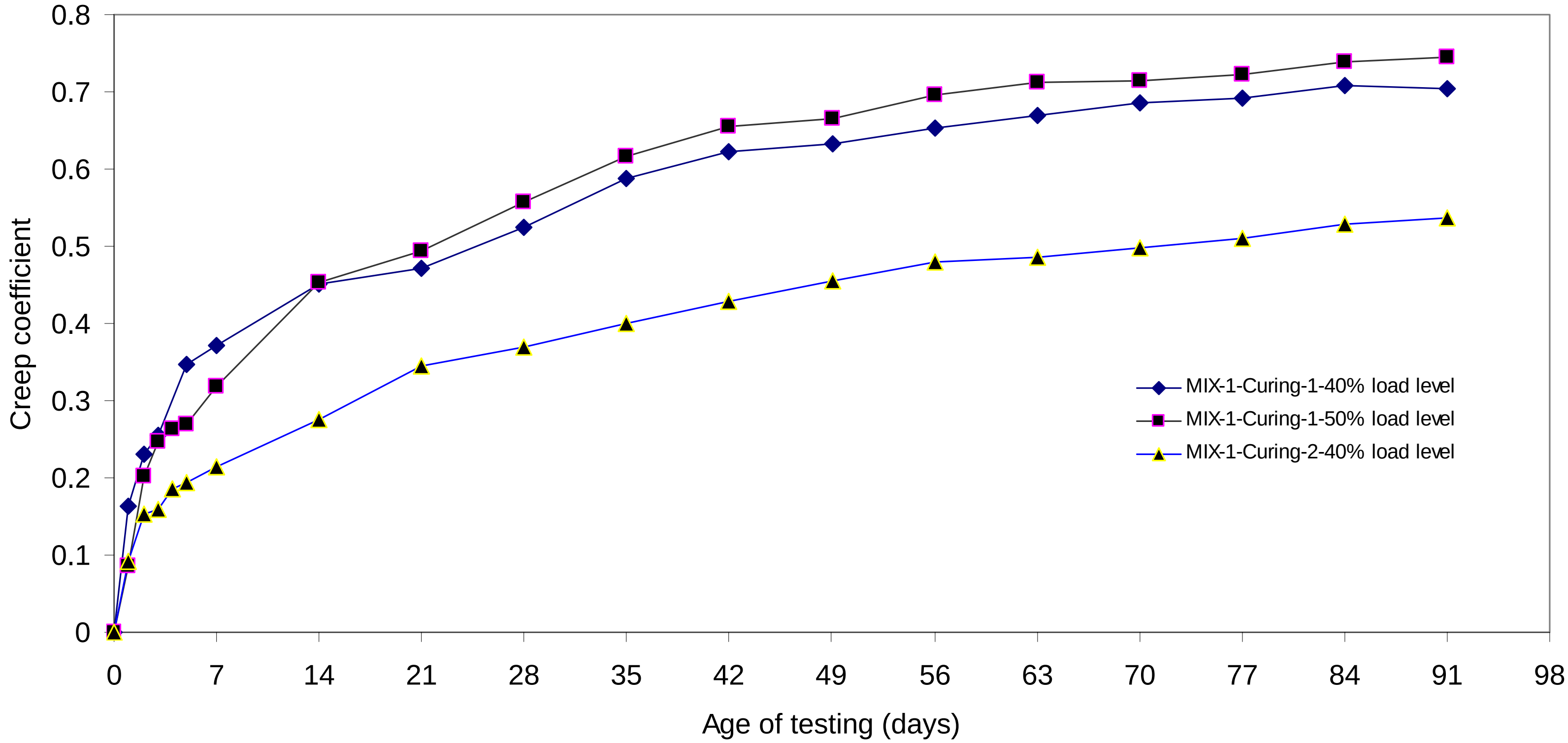

Figure B-3. Development of creep coefficient of Mix-1 with time

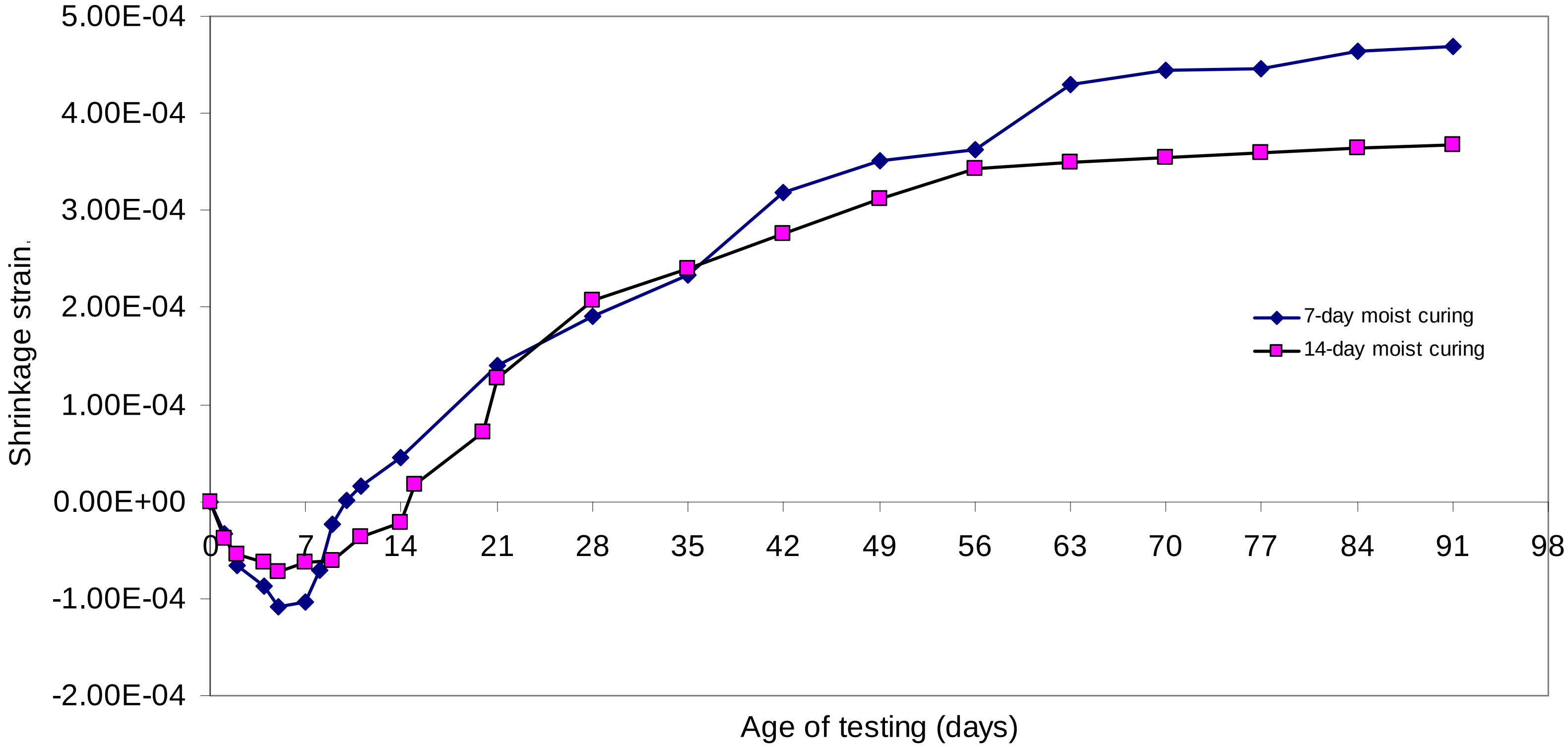

Figure B-4. Comparison of shrinkage strains of Mix-2 with different curing conditions

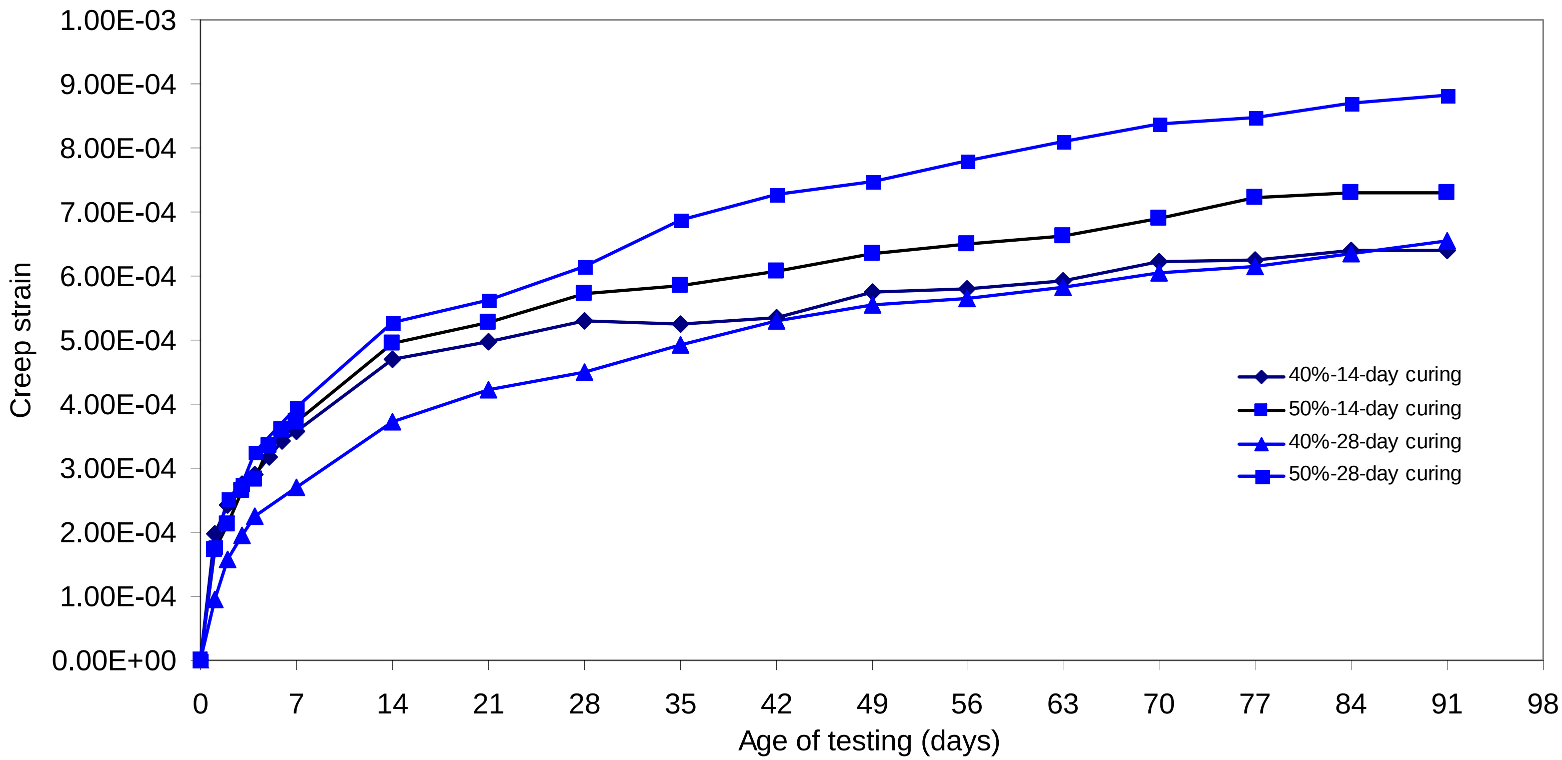

Figure B-5. Comparison among creep strains of Mix-2 at different curing age

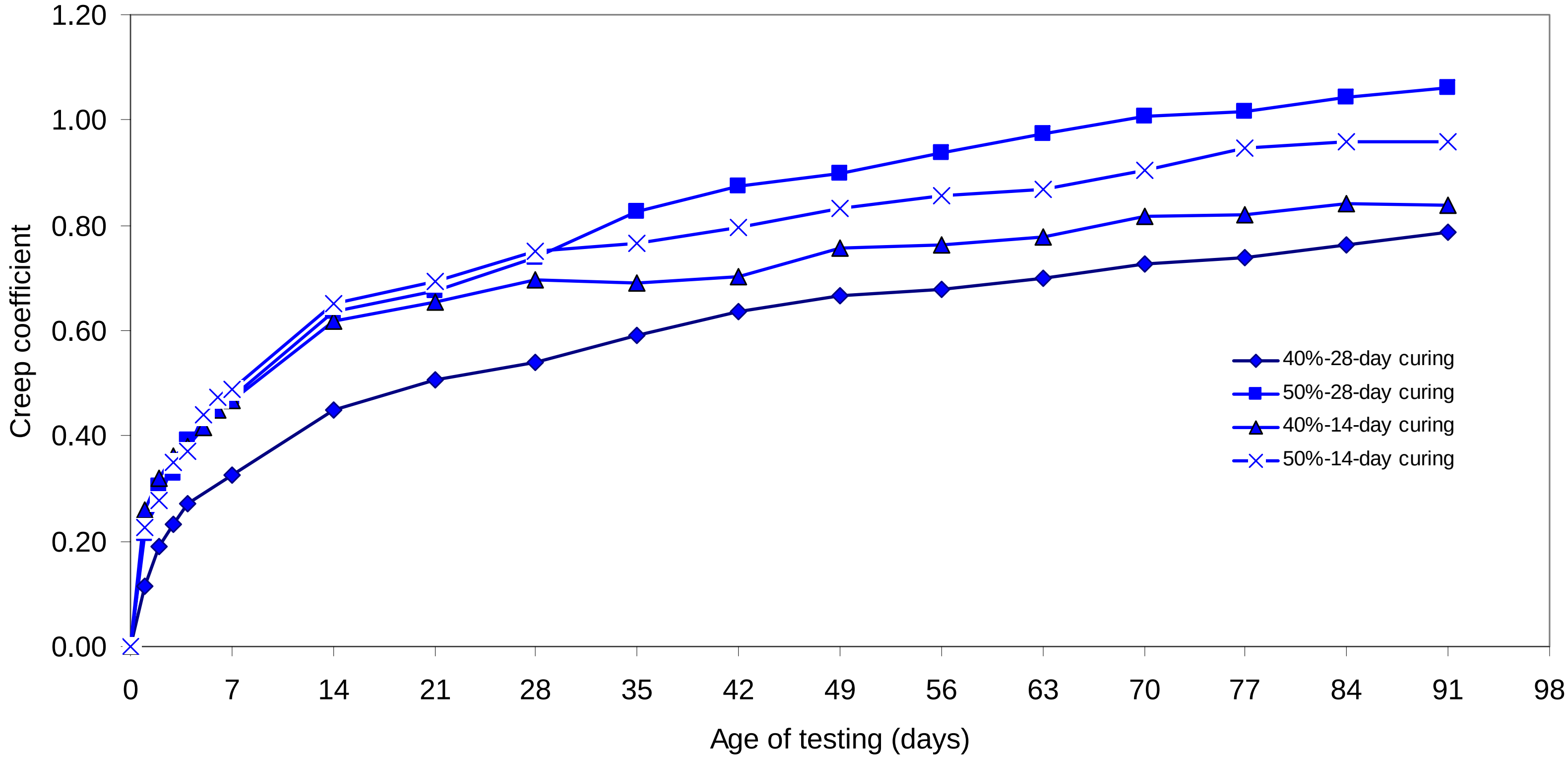

Figure B-6. Development of creep coefficient of Mix-2 with time

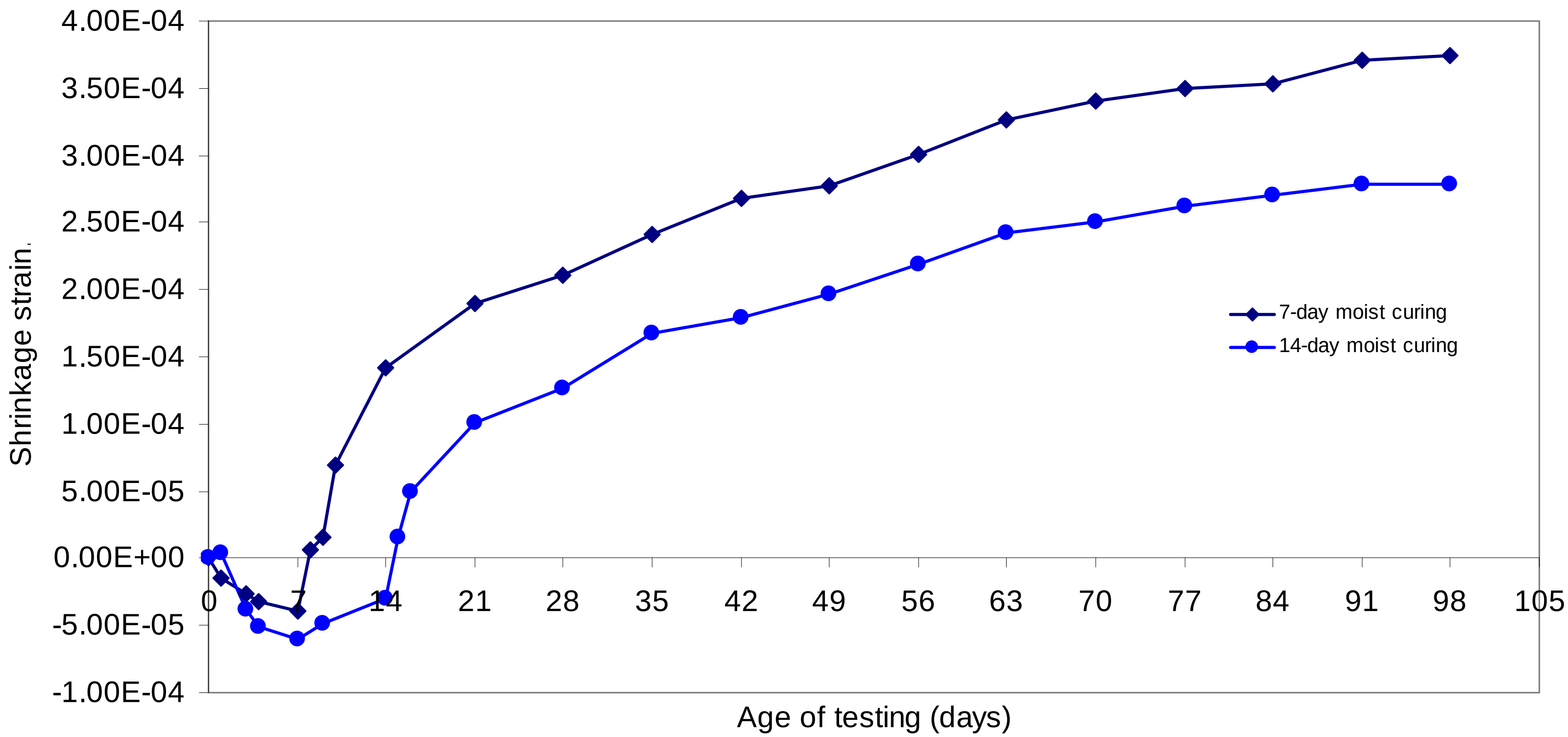

Figure B-7. Comparison of shrinkage strains of Mix-3 under the different curing conditions

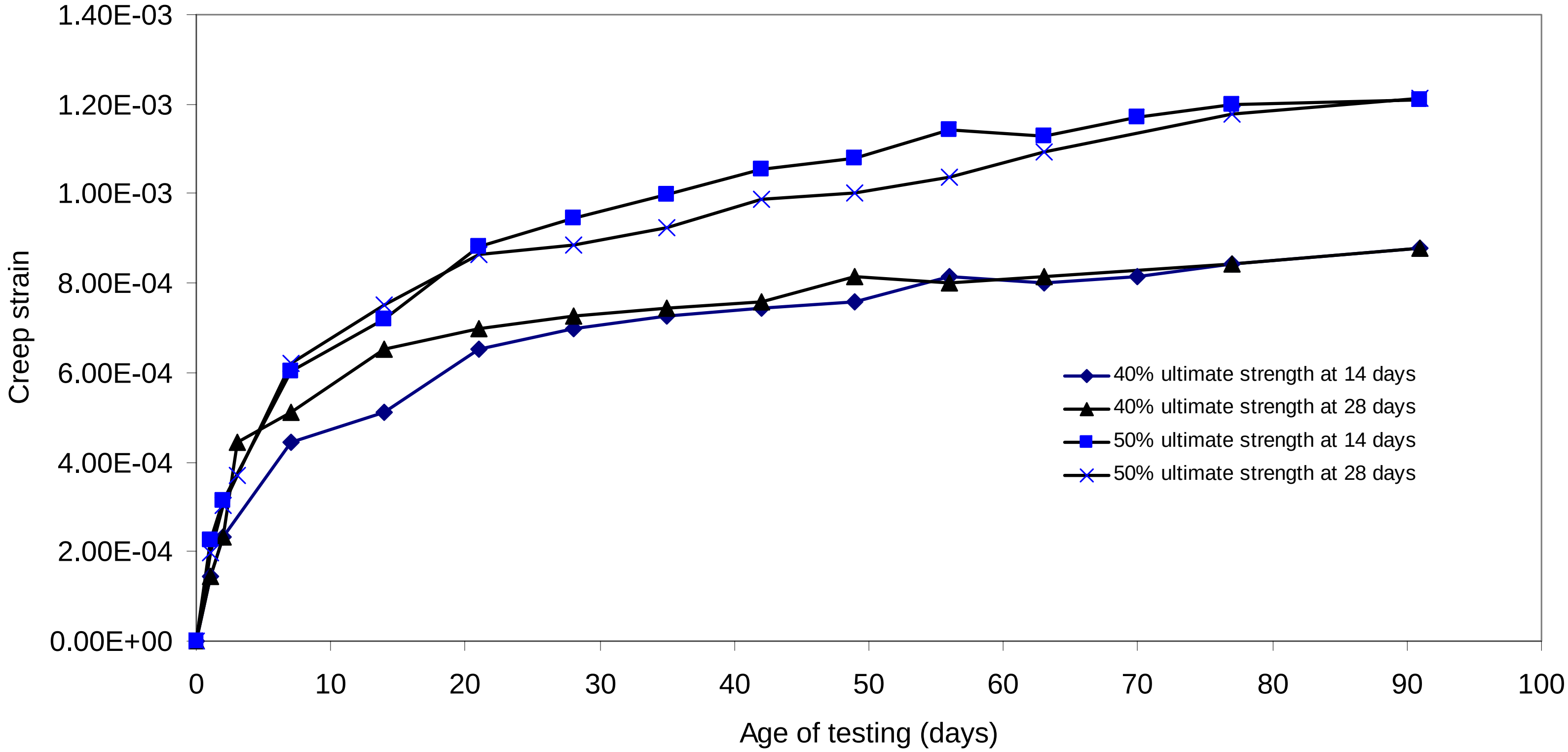

Figure B-8. Comparison of creep strains of Mix-3 at various ages

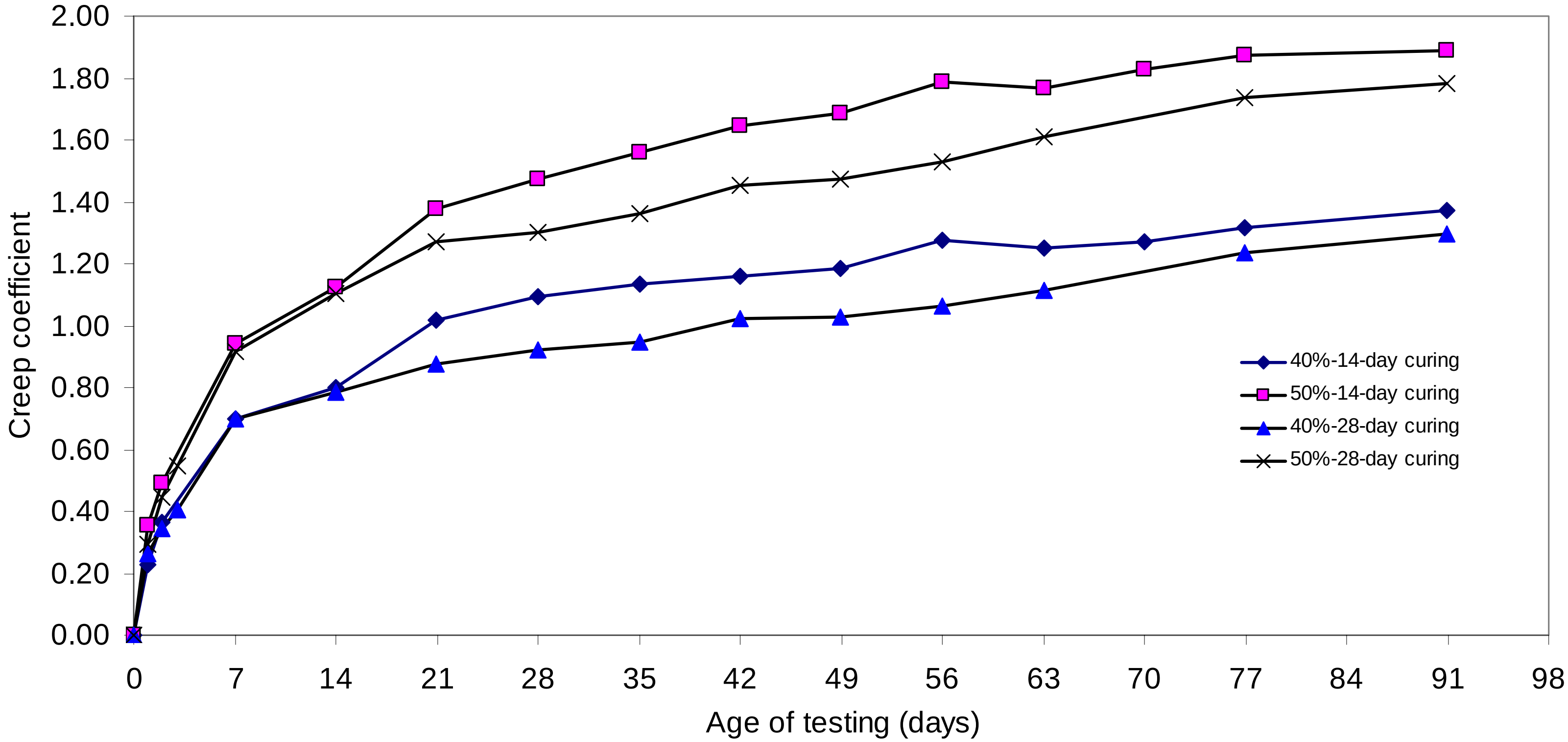

Figure B-9. Development of creep coefficient of Mix-3 with time

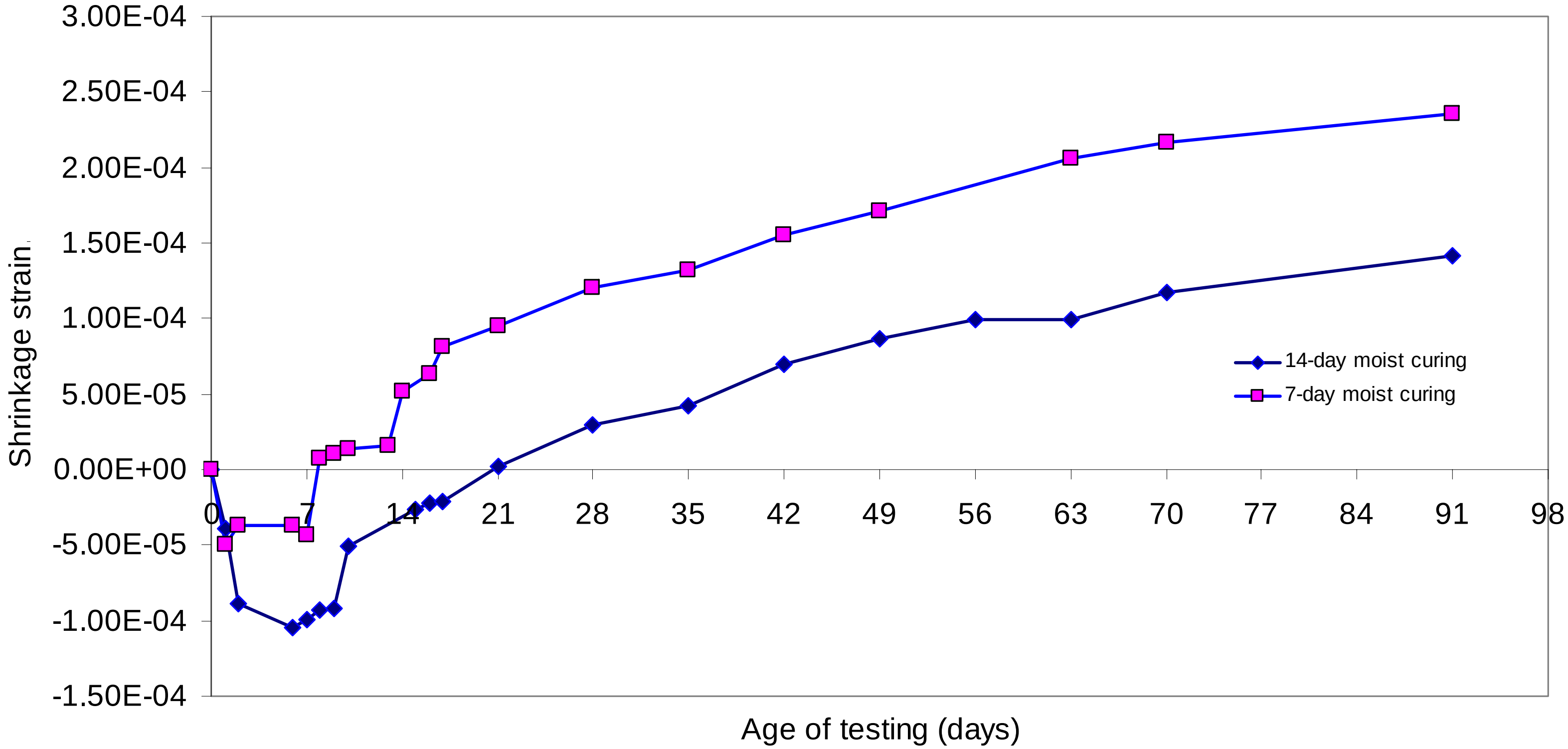

Figure B-10. Comparison of shrinkage strains of Mix-4 under the different curing conditions

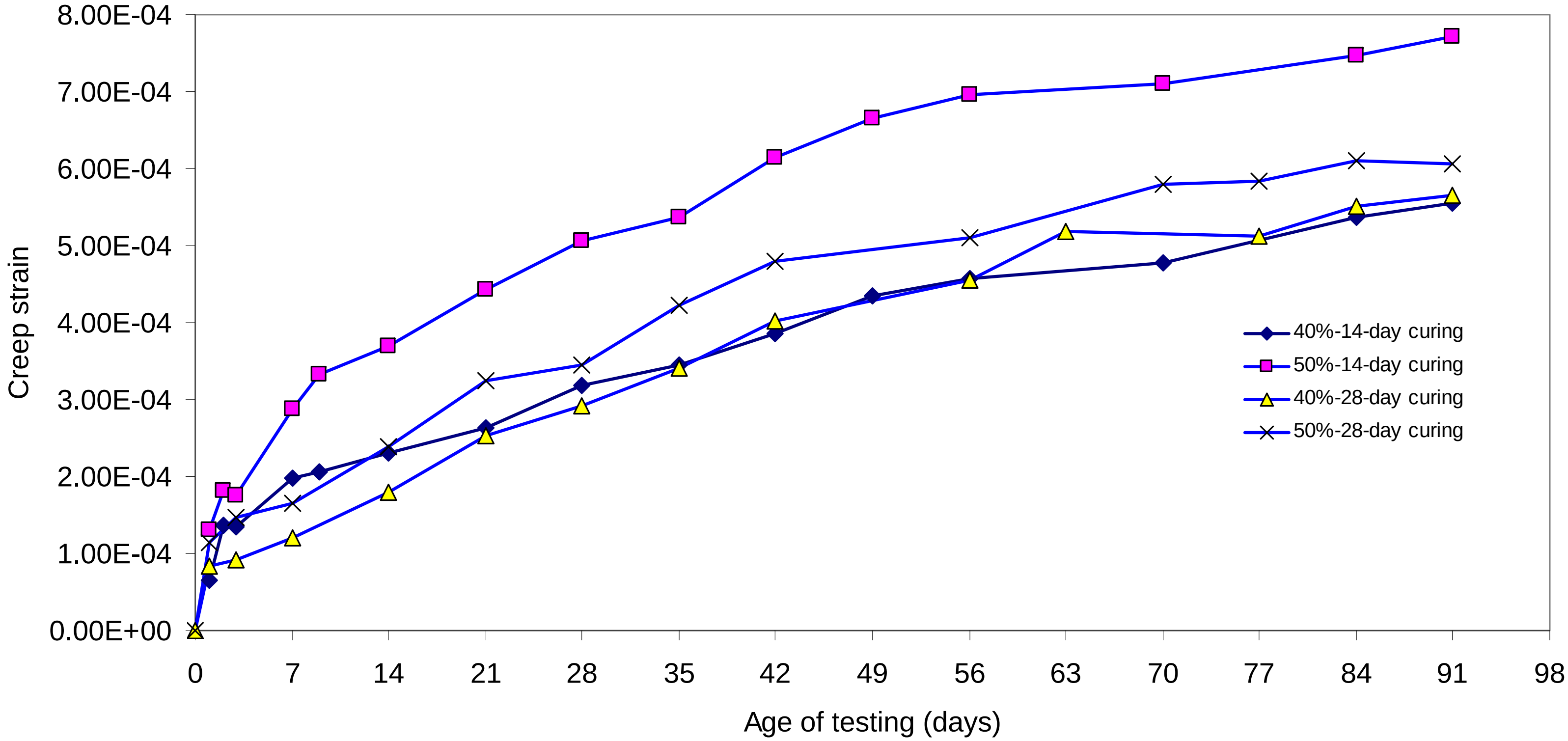

Figure B-11. Comparison of Creep Strains of Mix-4 with different curing and loading conditions

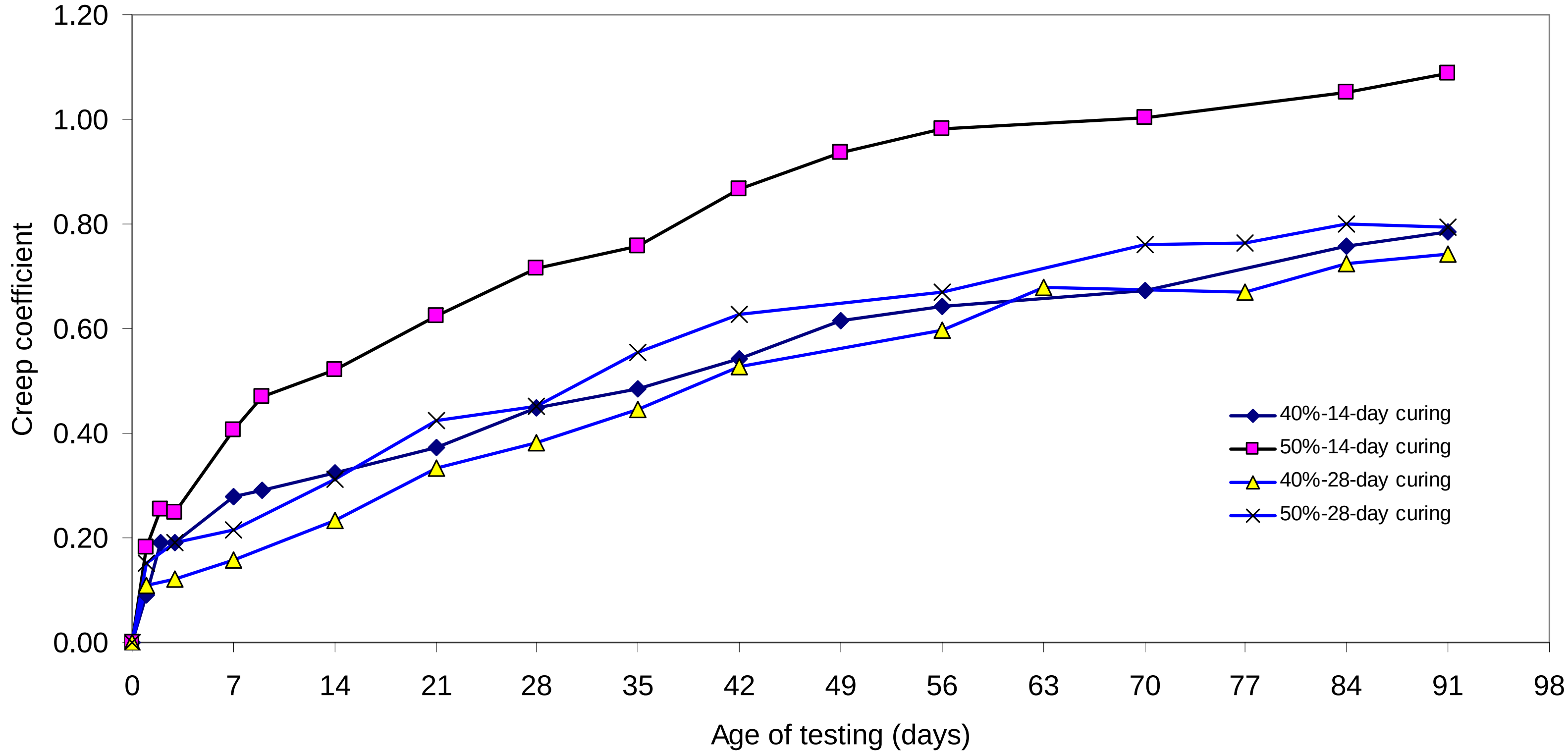

Figure B-12. Development of creep coefficient of Mix-4 with time

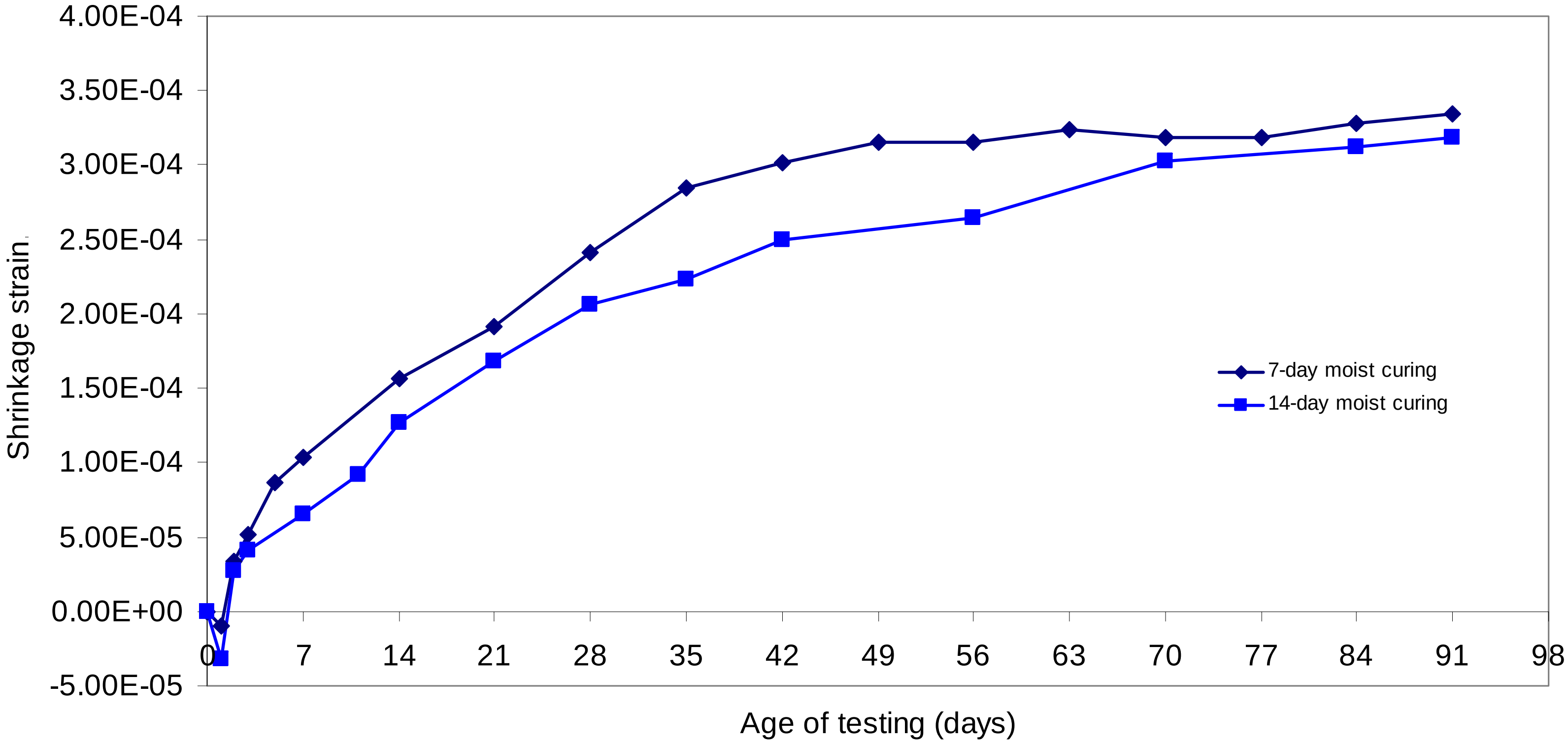

Figure B-13. Comparison of shrinkage strains of Mix-5 under the different curing conditions

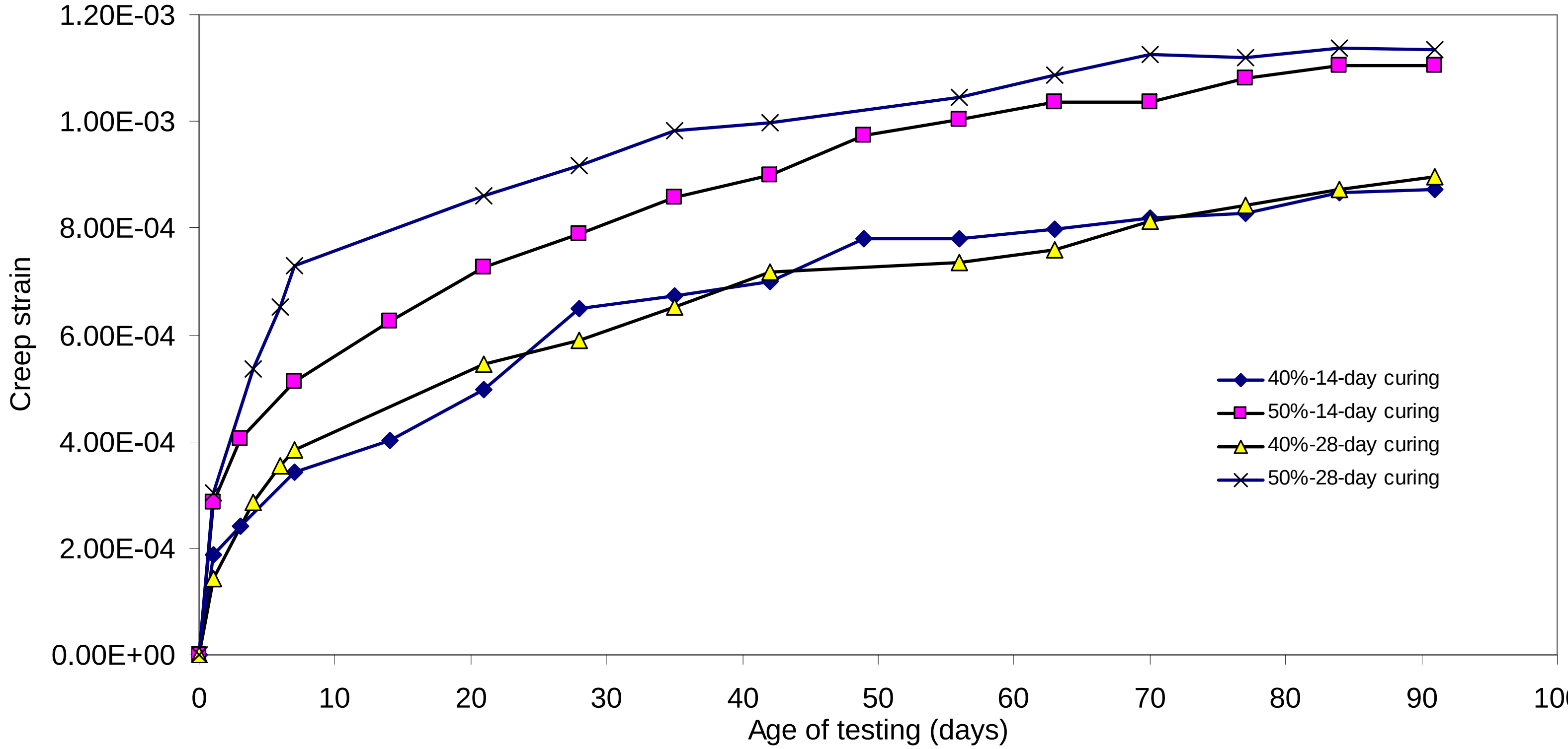

Figure B-14. Comparison of creep strain of Mix-5 under different curing and loading conditions

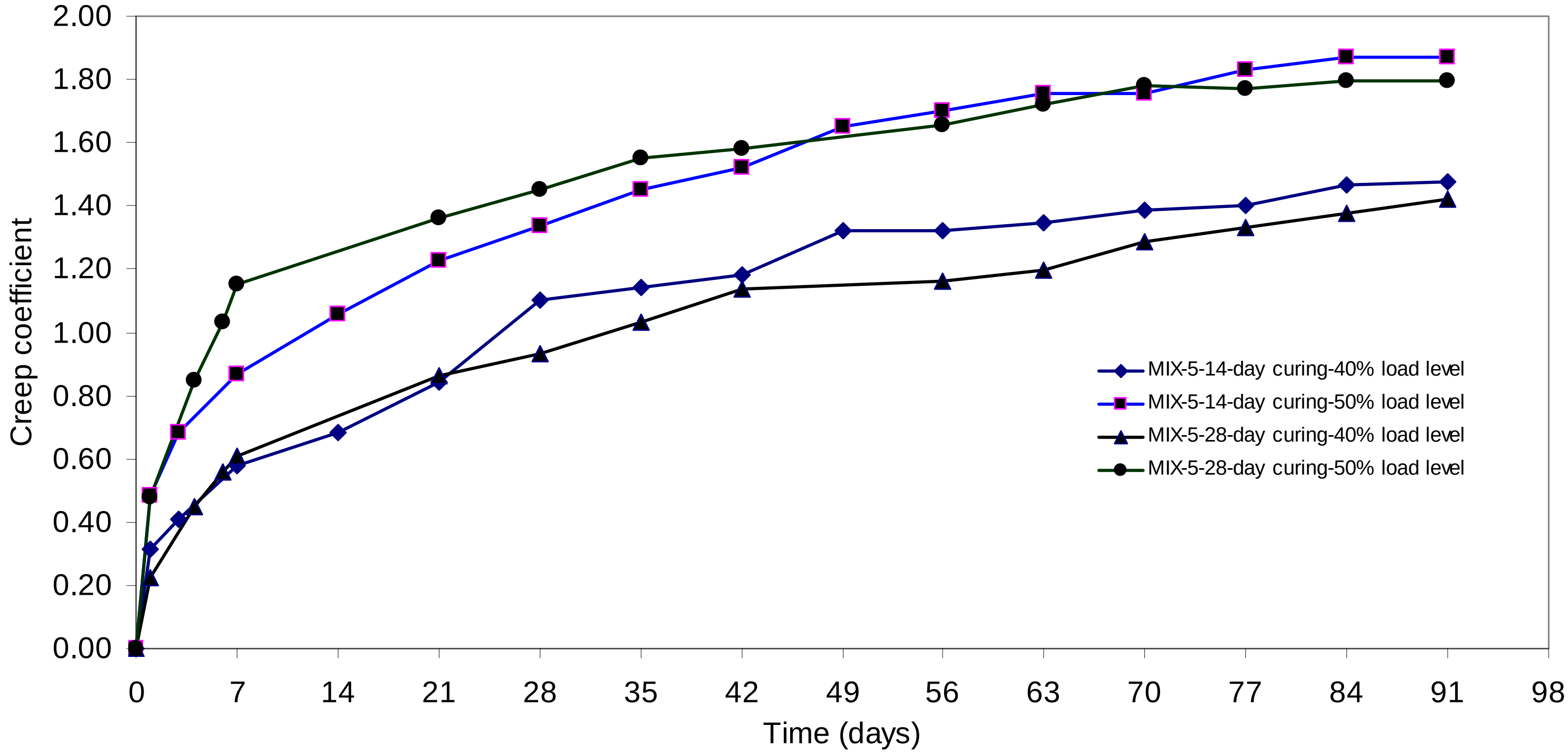

Figure B-15. Development of creep coefficient of Mix-5 with time

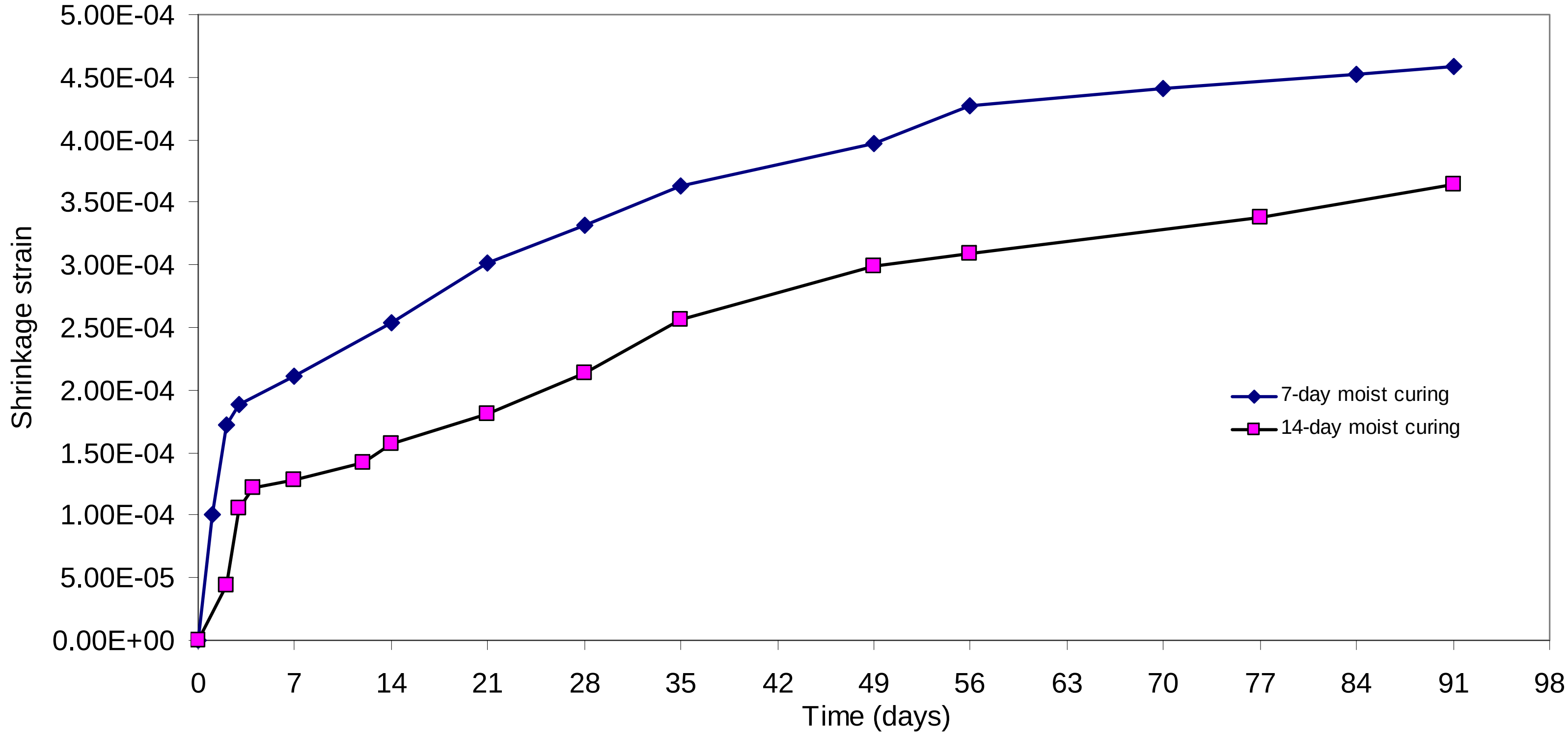

Figure B-16. Comparison of shrinkage strains of Mix-6 under the different curing conditions

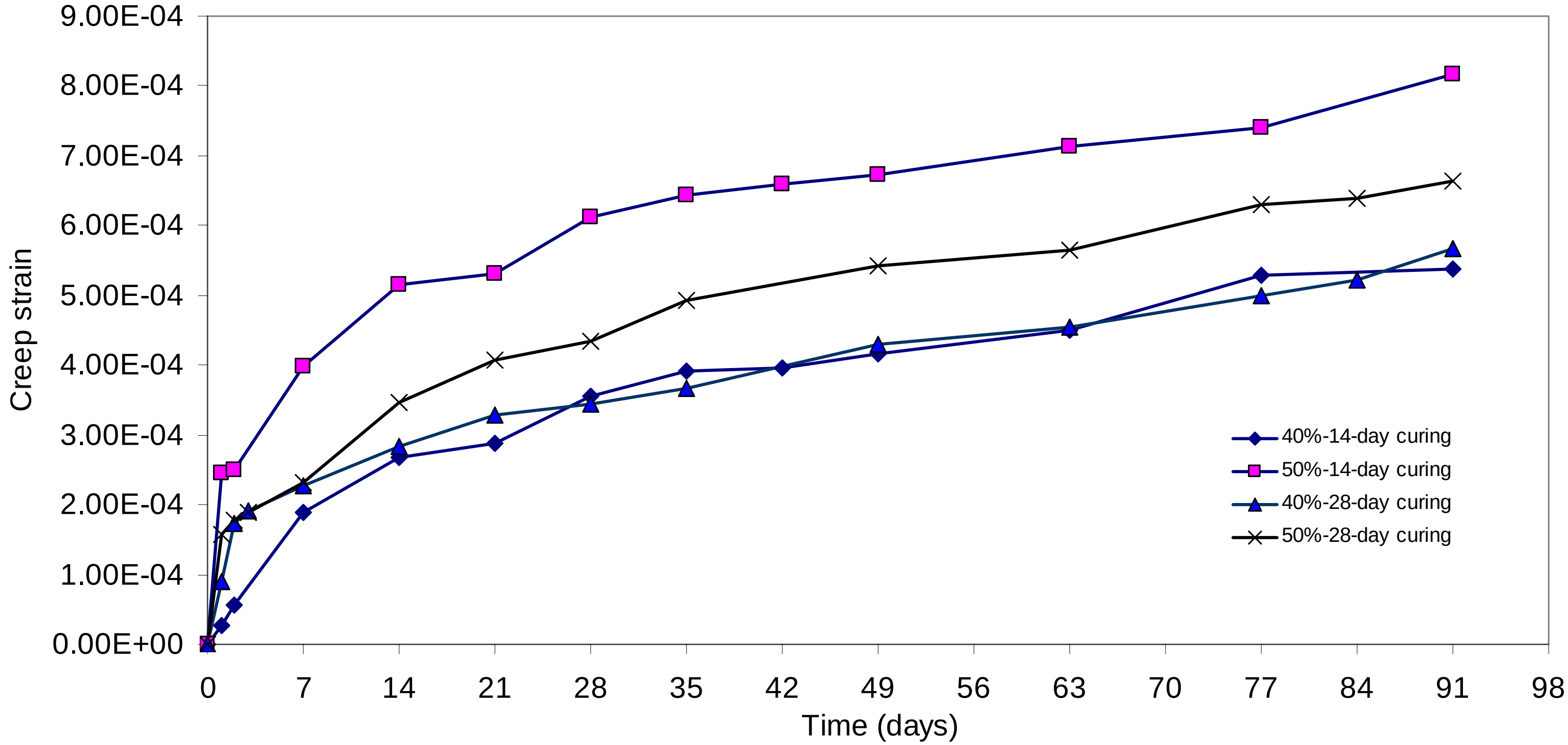

Figure B-17. Comparison of creep strain of Mix-6 under different curing and loading conditions

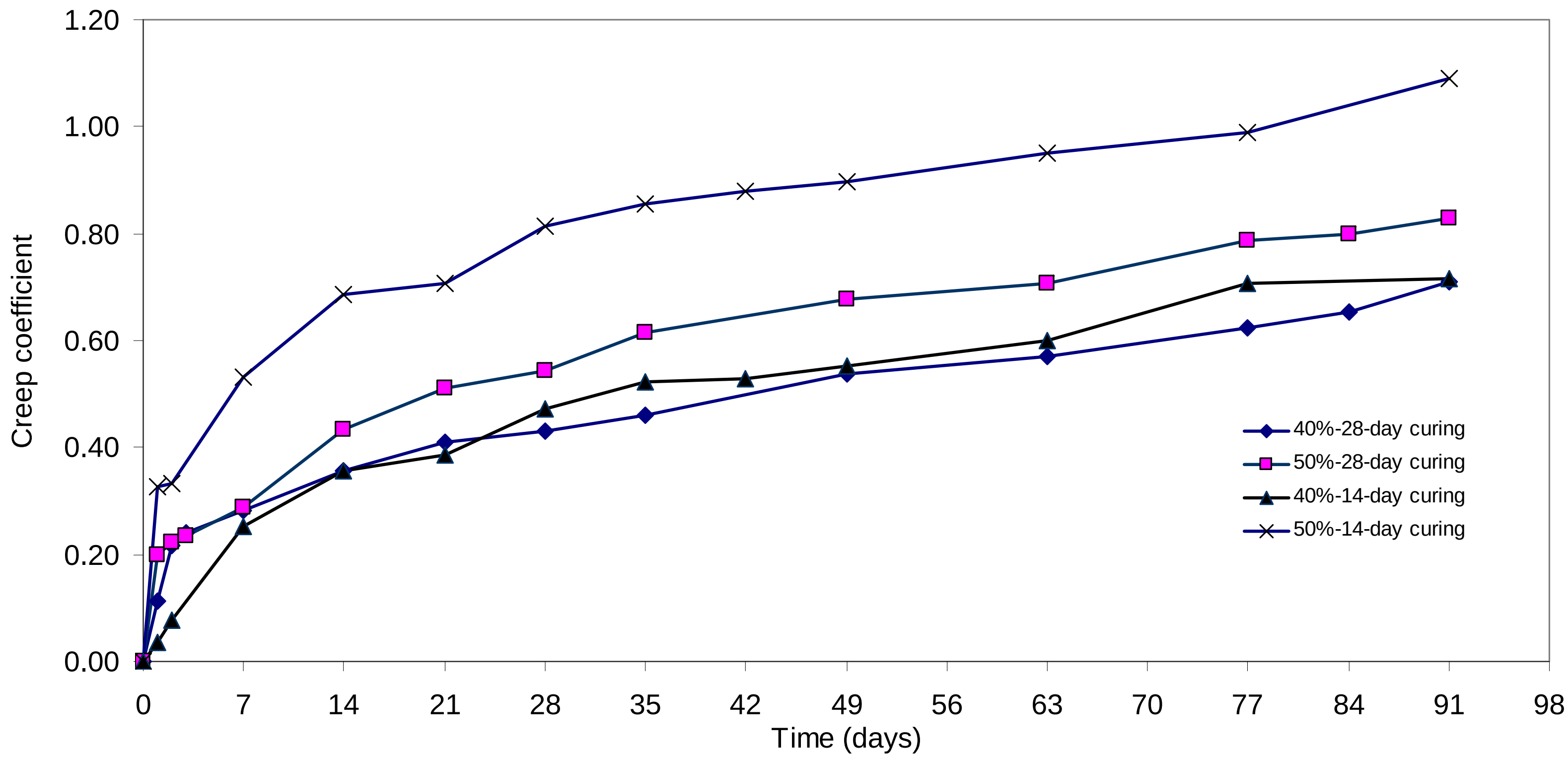

Figure B-18. Development of creep coefficient of Mix-6 with time

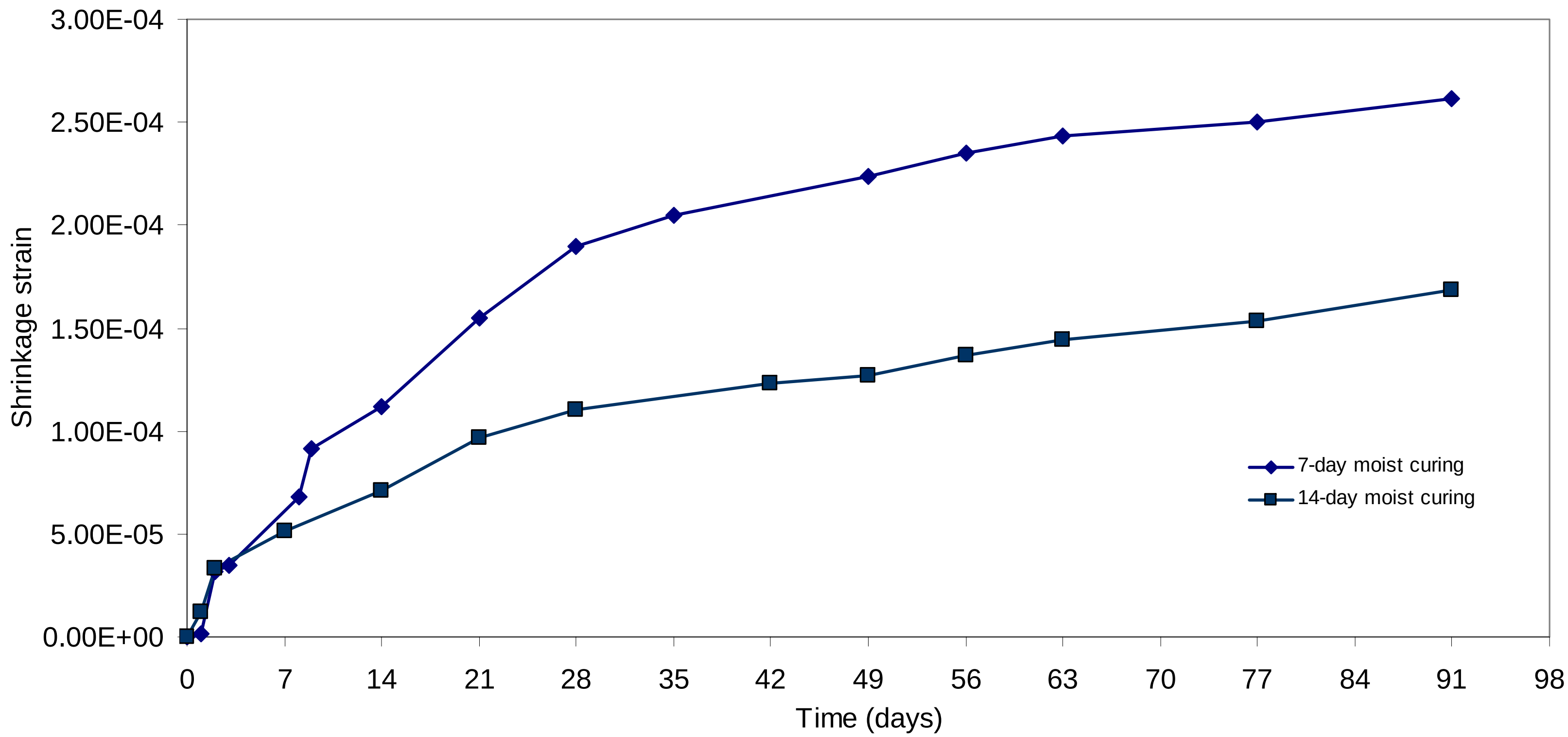

Figure B-19. Comparison of shrinkage strains of Mix-7 under the different curing conditions

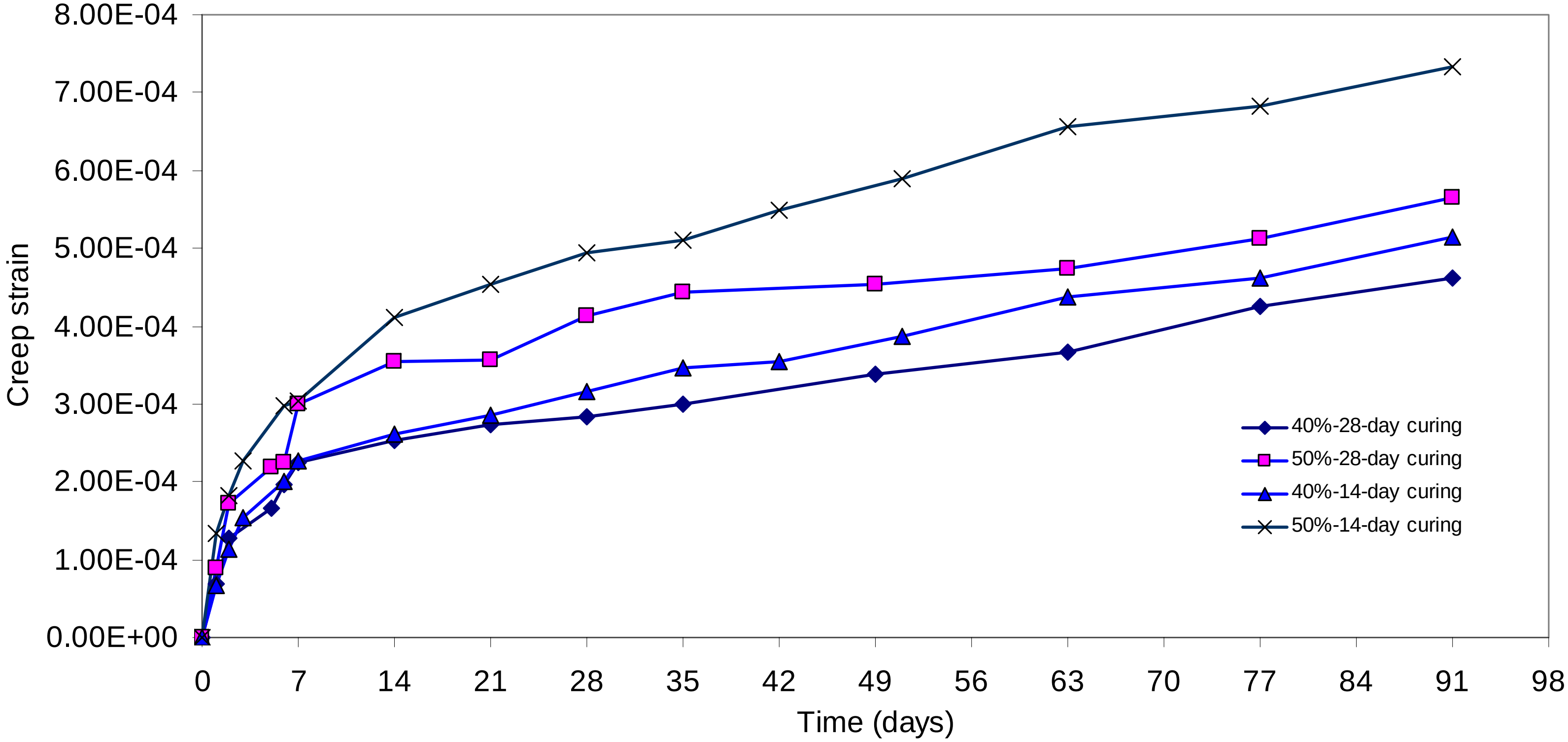

Figure B-20. Comparison of creep strains of Mix-7 under different curing and loading conditions

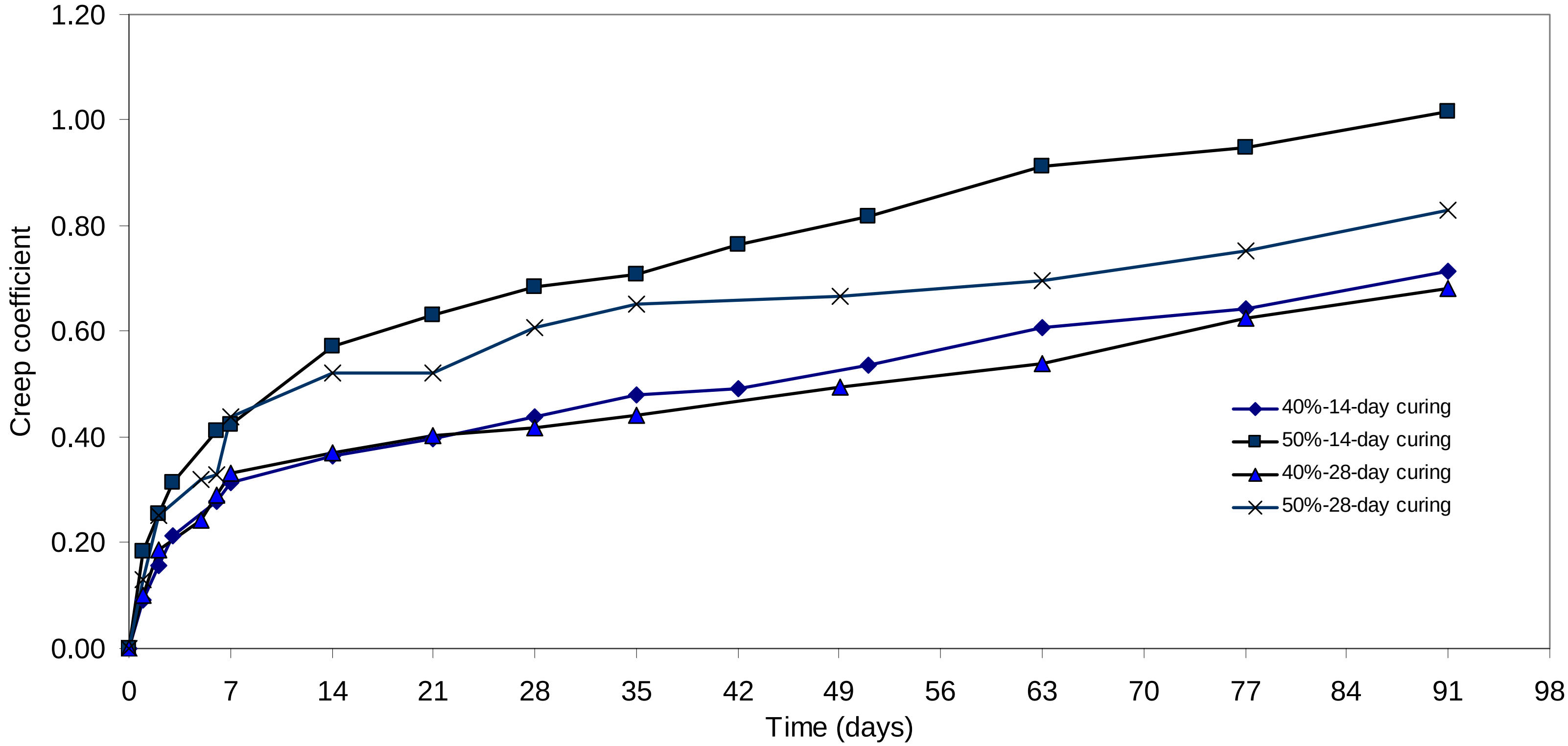

Figure B-21. Development of creep coefficient of Mix-7 with time

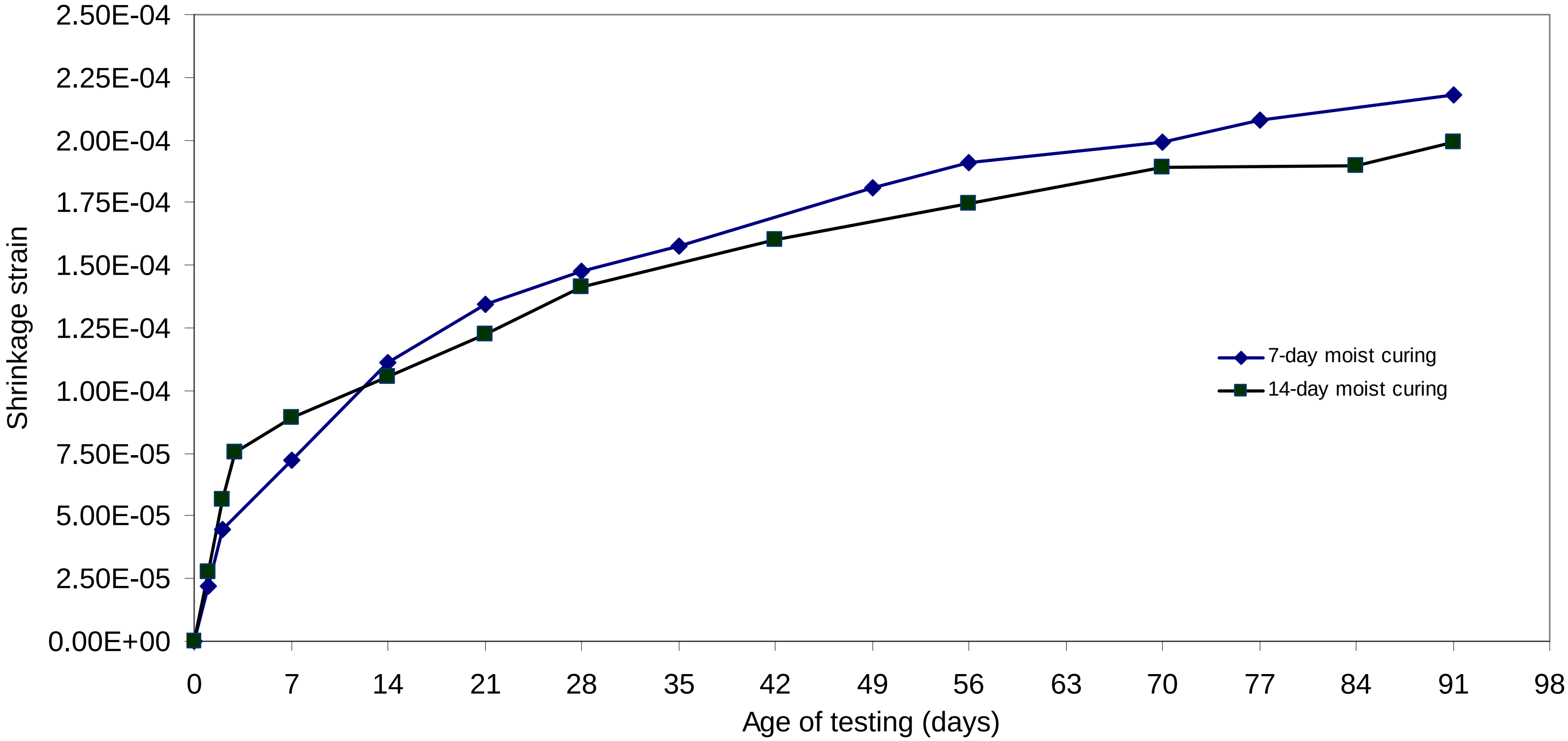

Figure B-22. Comparison between shrinkage strains of Mix-8 under different curing conditions

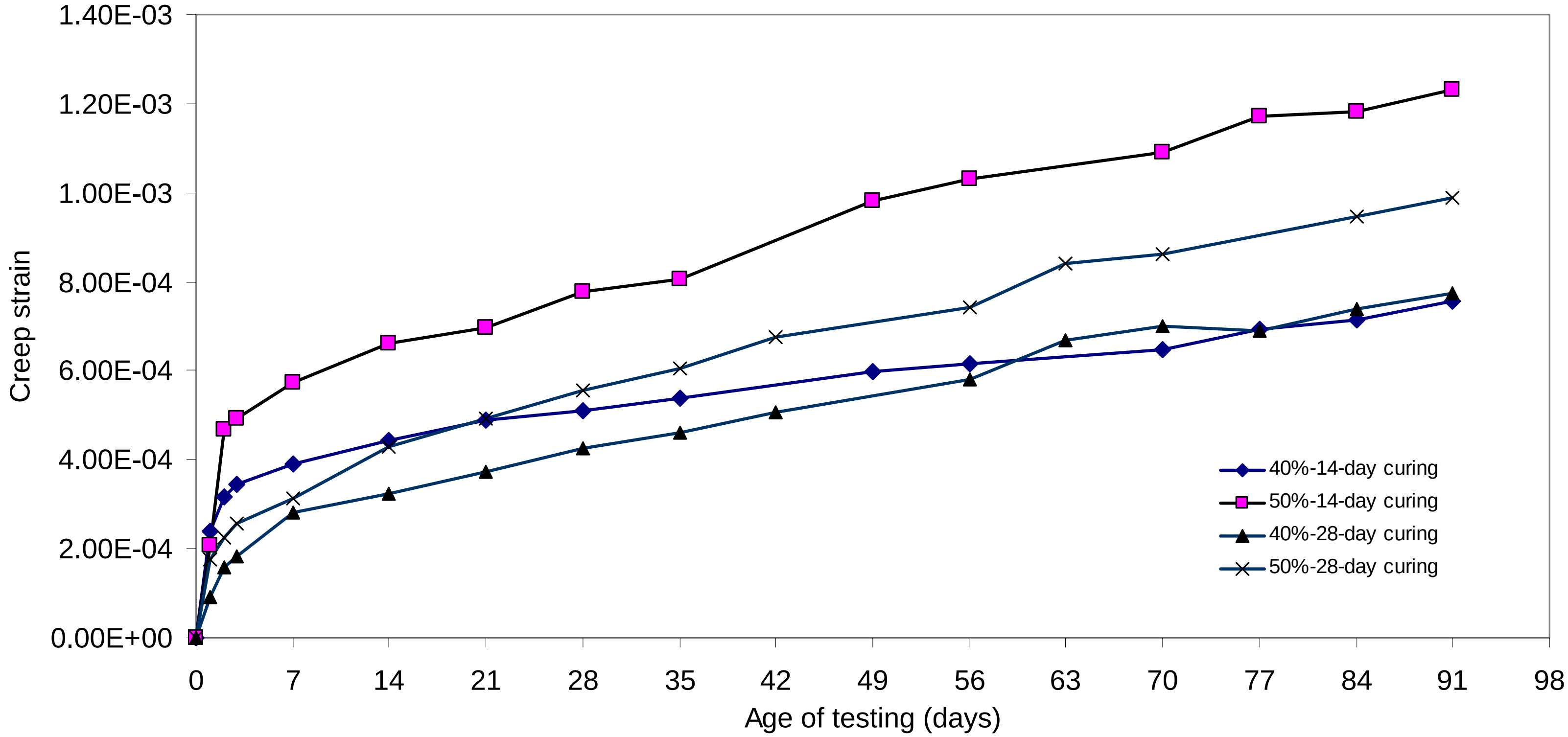

Figure B-23. Comparison of creep strains of Mix-8 under different curing and loading conditions

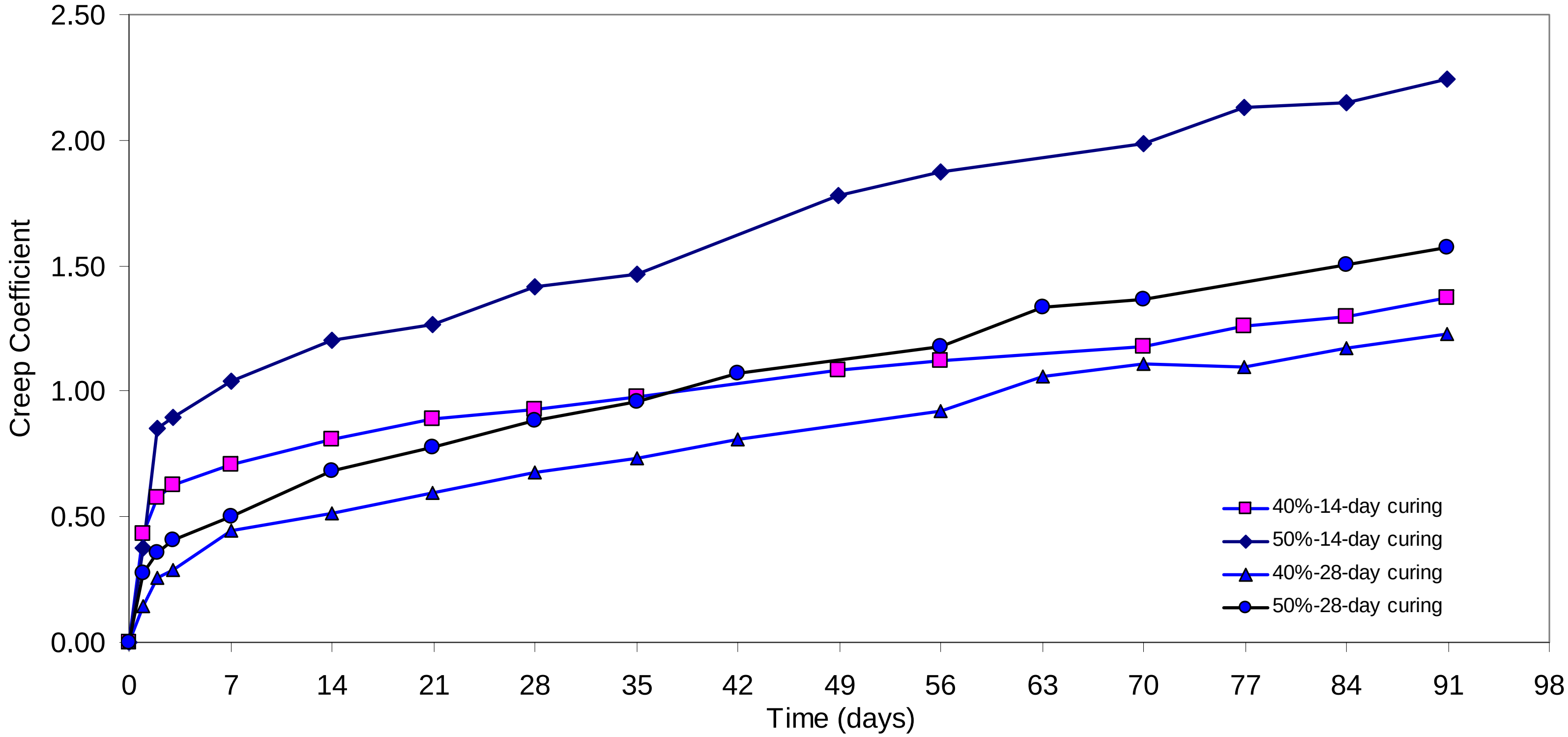

Figure B-24. Development of creep coefficient of Mix-8 with time

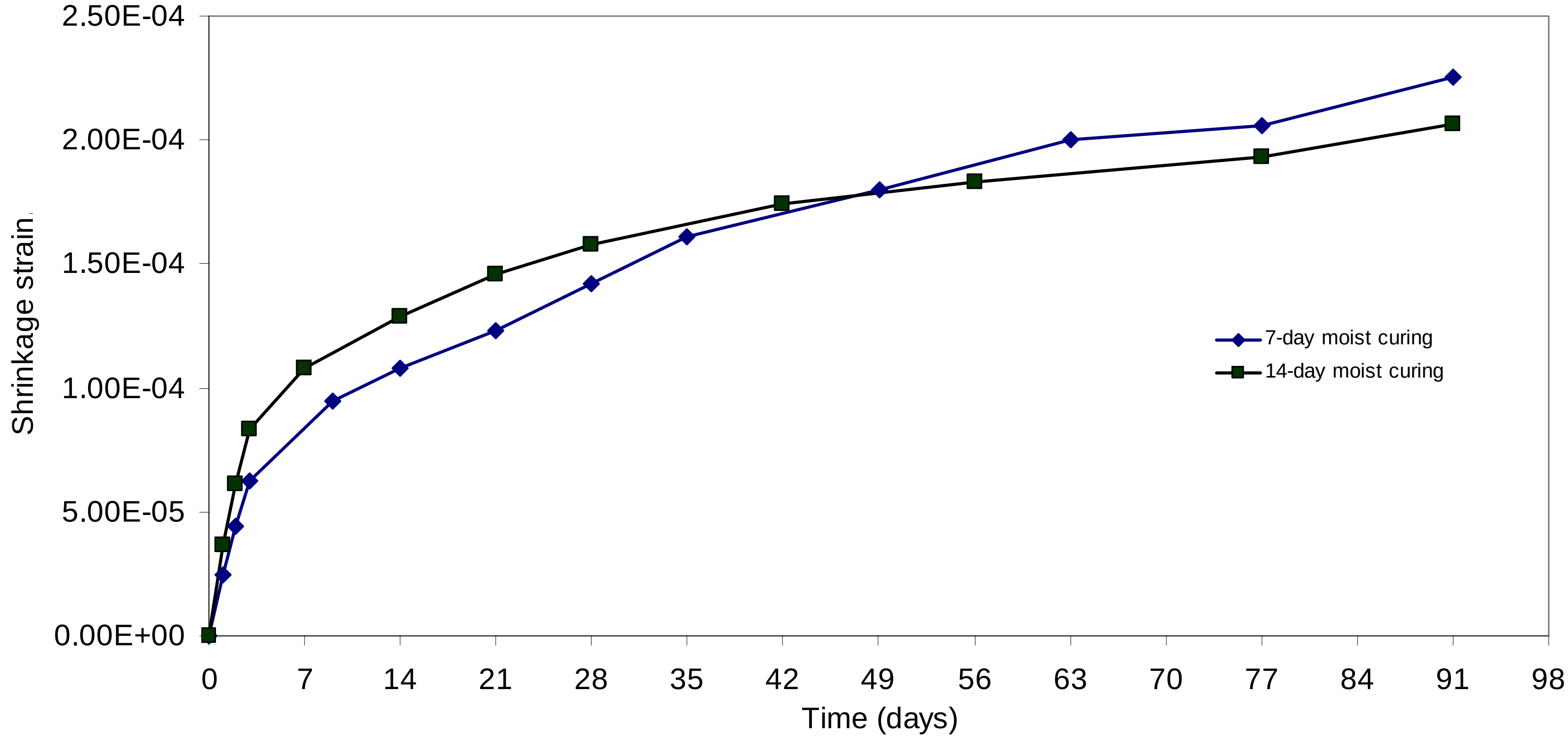

Figure B-25. Comparison of shrinkage strains of Mix-9 under different curing conditions

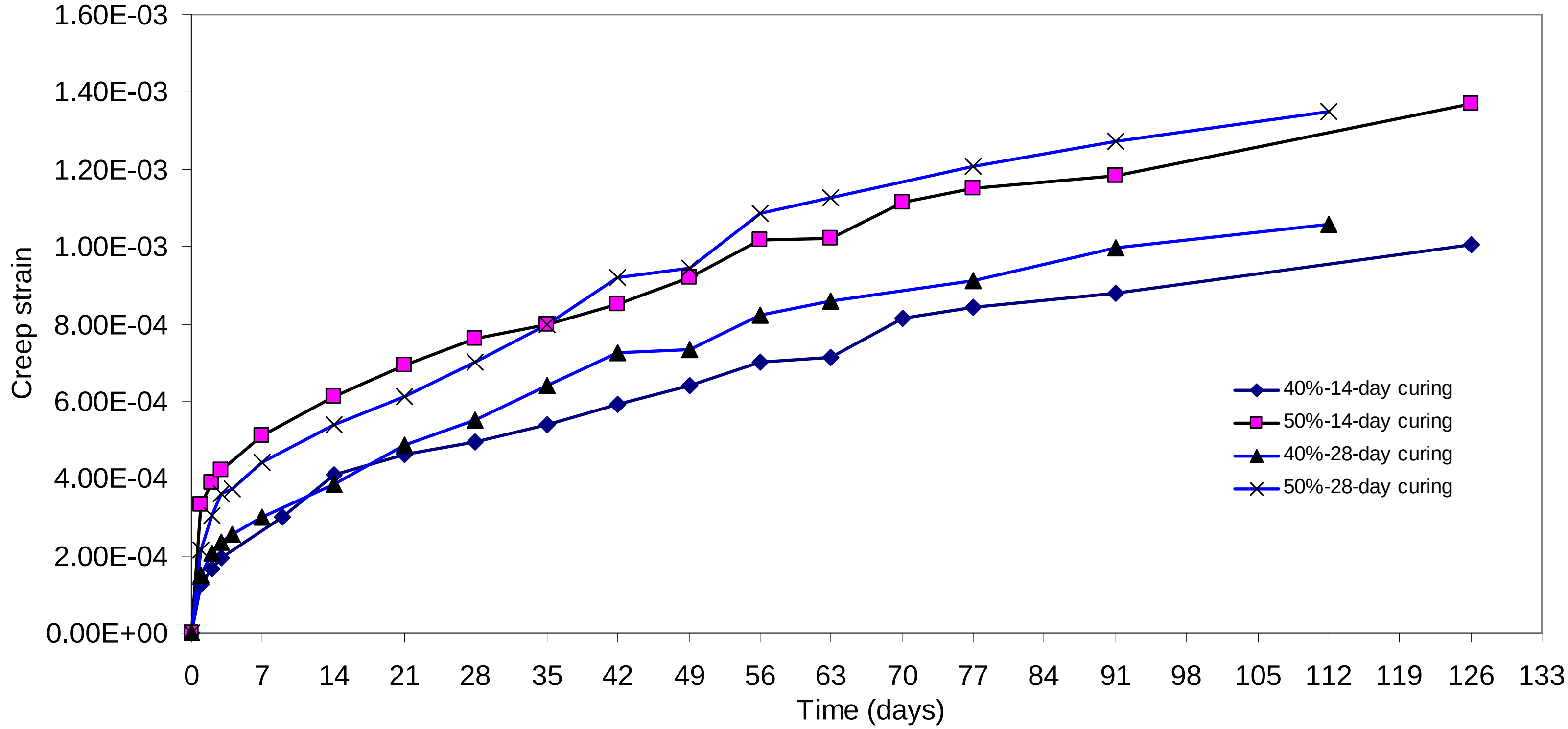

Figure B-26. Comparison of creep strains of Mix-9 under different curing and loading conditions

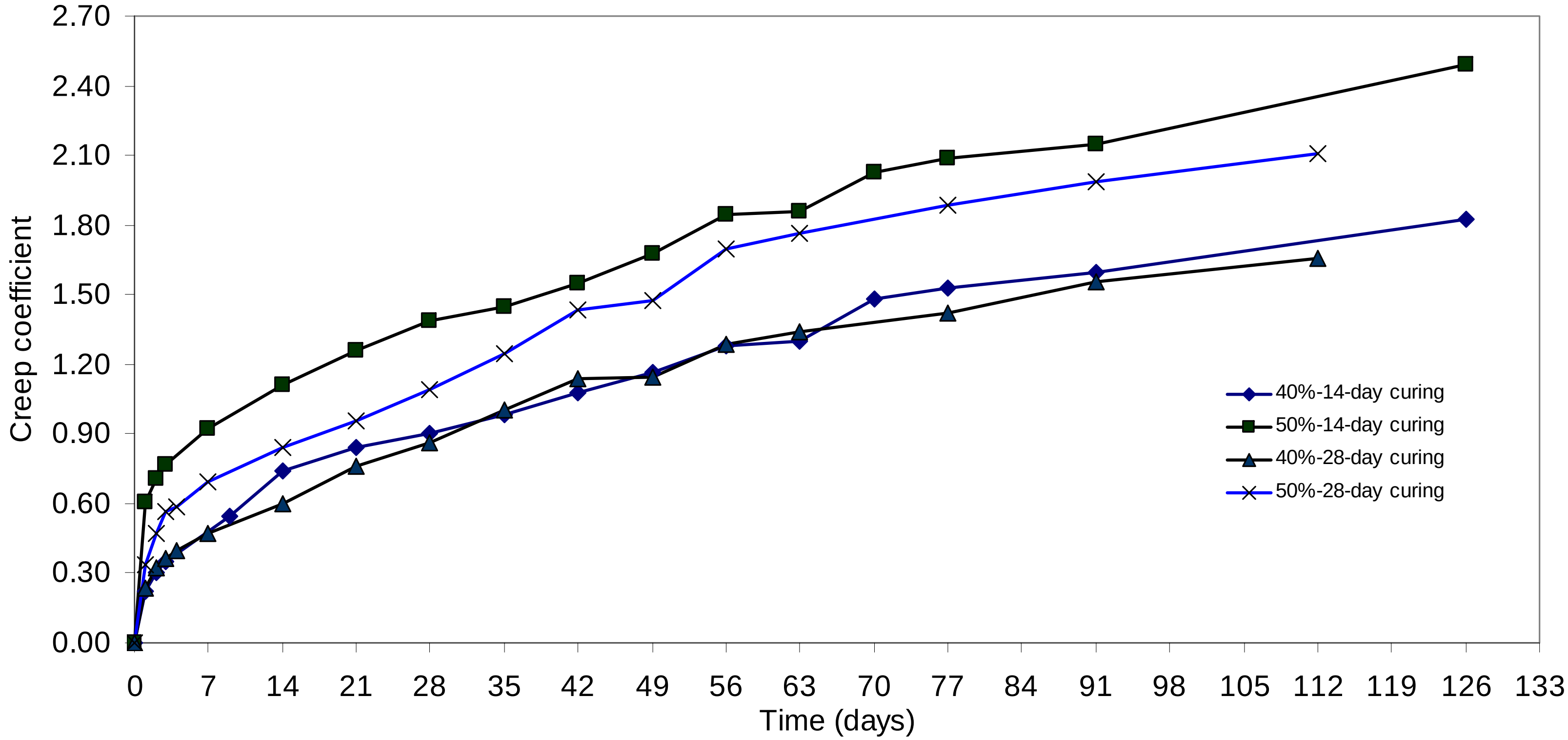

Figure B-27. Development of creep coefficient of Mix-9 with time

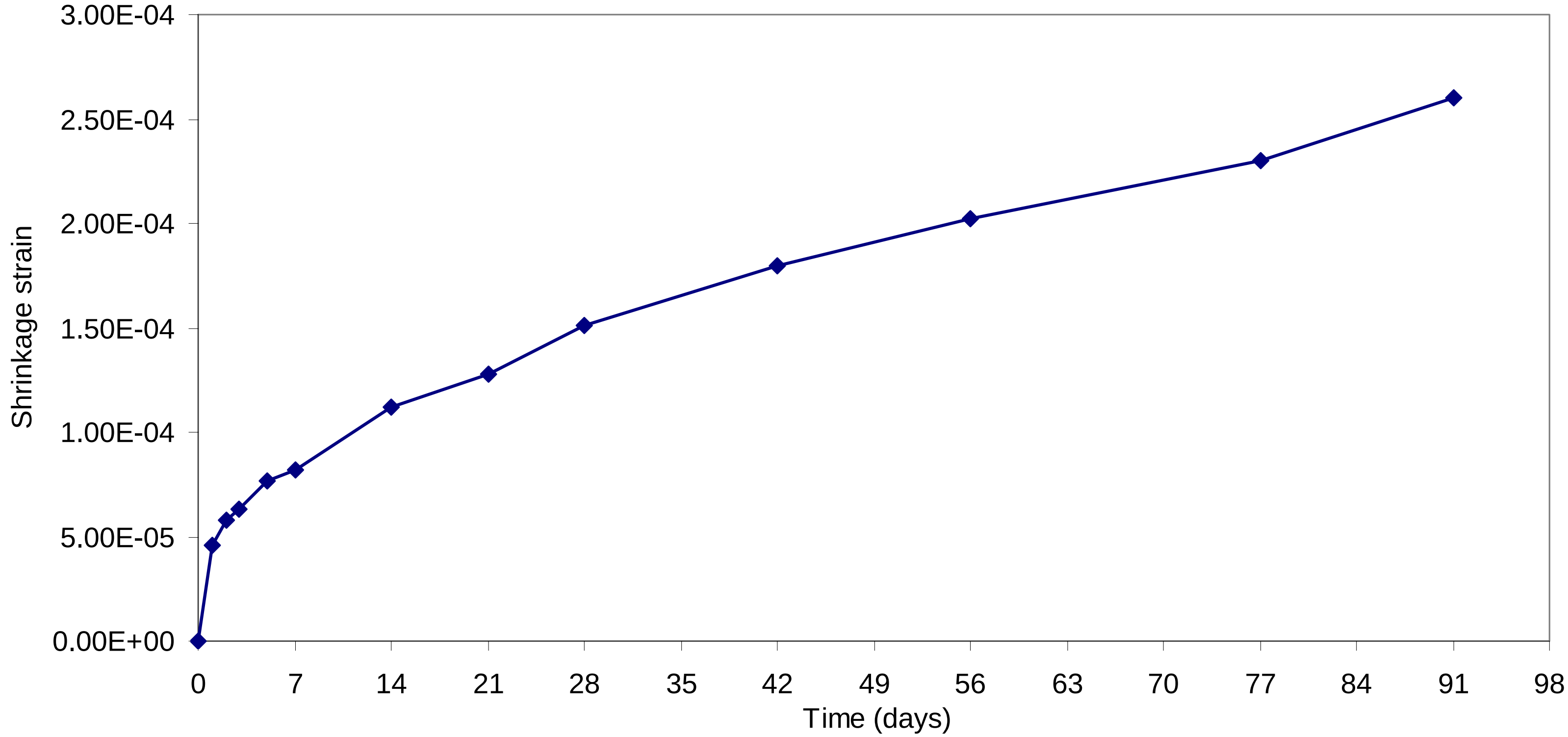

Figure B-28. Development of shrinkage strain of Mix-10 with time

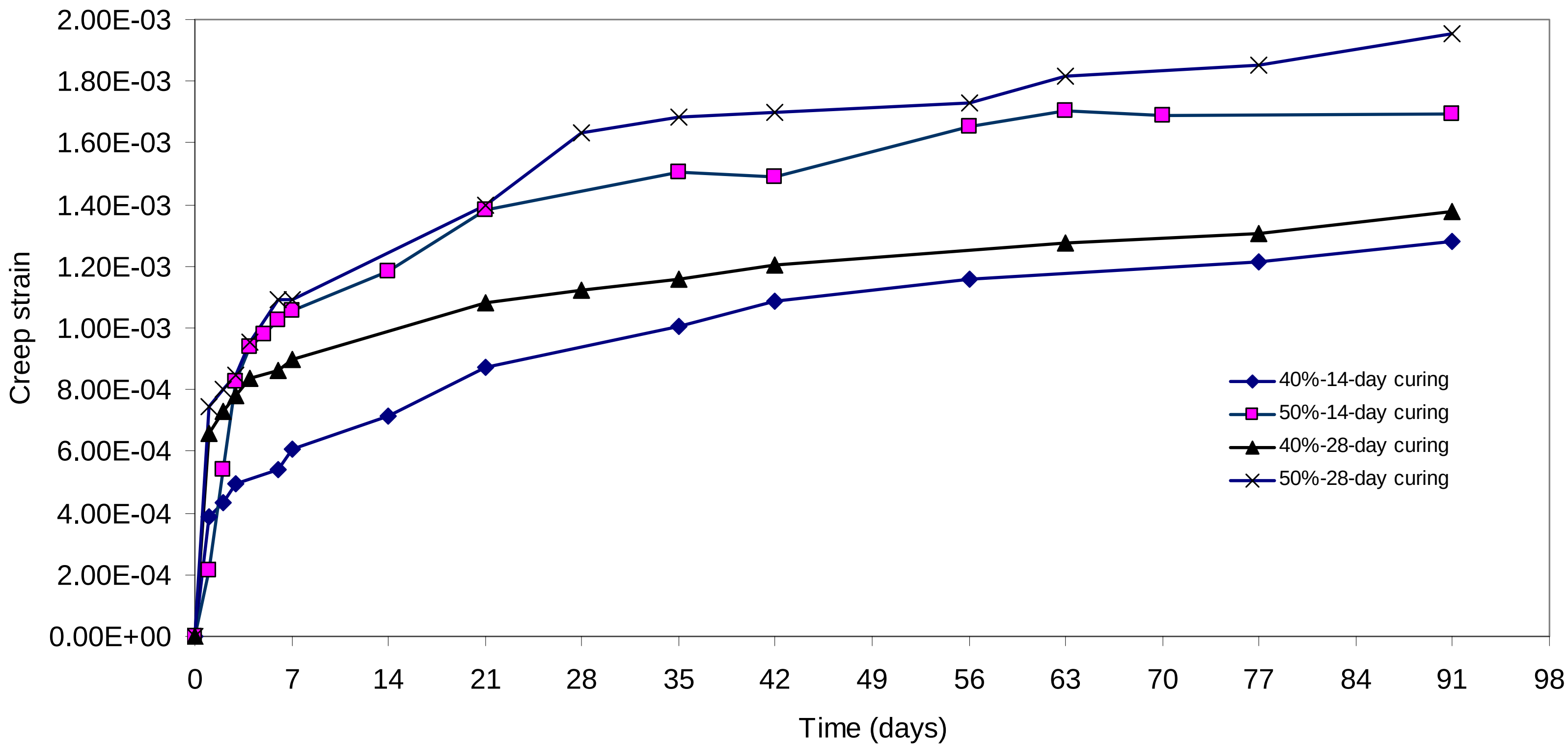

Figure B-29. Creep strains of Mix-10 under different curing and loading conditions

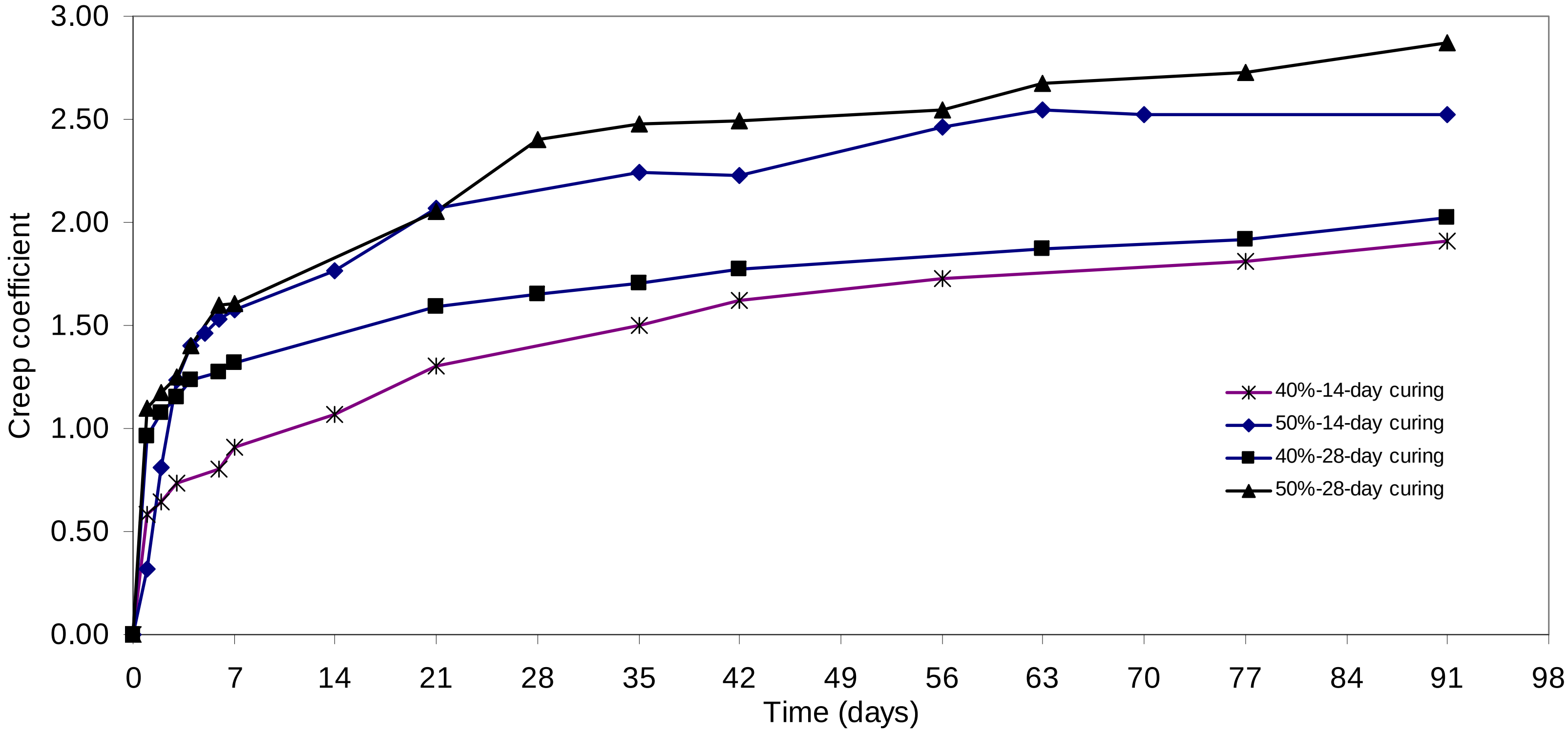

Figure B-30. Development of creep coefficient of Mix-10 with time