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Effect of Low Temperature on Ternary Concrete Mixtures

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16. Abstract
Economic and environmental considerations have promoted the use of supplementary cementing materials (SCMs) such as slag cement (SC) and fly ash (FA). Ternary mixtures containing both slag cement and fly ash have gained popularity due to environmental issues and shortages in the supply of cement. However, in the 2003 AHTD Standard Specifications, ternary mixtures were prohibited for use in Portland Cement Concrete Pavement (PCCP). Previous research conducted by the University of Arkansas examined ternary mixtures containing SC and FA and cured at 70 F. The research program described in this thesis examined the behavior of ternary mixtures cured at lower temperatures. For this study, SC contents ranged from 0 to 40 percent, and the FA contents ranged from 0 to 60 percent. Six different mixtures containing Class C FA and Grade 100 SC were batched and tested at temperatures at and below 70 F. The curing temperatures for the study were 33, 40, 50, 60, and 70 F. The concrete properties measured were concrete temperature, slump, unit weight, air content, time of setting, and compressive strength.

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Slag cement, fly ash, ternary concrete mixtures, curing temperatures

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Abstract

Economic and environmental considerations have promoted the use of supplementary cementing materials (SCMs) such as slag cement (SC) and fly ash (FA). Ternary mixtures containing both slag cement and fly ash have gained popularity due to environmental issues and shortages in the supply of cement. However, in the 2003 AHTD Standard Specifications, ternary mixtures were prohibited for use in Portland Cement Concrete Pavement (PCCP). Previous research conducted by the University of Arkansas examined ternary mixtures containing SC and FA and cured at 70 F. The research program described in this thesis examined the behavior of ternary mixtures cured at lower temperatures. For this study, SC contents ranged from 0 to 40 percent, and the FA contents ranged from 0 to 60 percent. Six different mixtures containing Class C FA and Grade 100 SC were batched and tested at temperatures at and below 70 F. The curing temperatures for the study were 33, 40, 50, 60, and 70 F. The concrete properties measured were concrete temperature, slump, unit weight, air content, time of setting, and compressive strength. The results from the research show that mixtures containing 40 percent SCM can be used when cured at or above 40 F. Additionally, prediction equations based on concrete maturity were developed for the mixtures examined in this research program.

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Chapter 1

Introduction

1.1 Ternary Mixtures

Concrete durability and strength are major concerns in the design of modern concrete structures. Both properties can be improved through the use of supplementary cementing materials (SCMs) such as fly ash (FA), slag cement (SC), and silica fume (SF). Ternary concrete mixtures, or mixtures containing combinations of portland cement (PC) and two SCMs are gaining popularity due to the improved concrete properties and environmental concerns. By replacing a portion of the PC with SC and fly ash FA, improved fresh and hardened properties are achieved.

Ternary concrete mixtures are, for purposes of this research, those mixtures in which a portion of the PC is replaced with SC and FA. Partial replacement of PC with FA and SC in the proper proportions increases concrete durability and improves alkali-silica resistance, sulfate attack, and other environmentally-related problems (Wesche 1991). SC and FA are industrial byproducts that have cementitious properties in the proper environment. Both materials are less expensive than PC, and their use is beneficial to the environment. Often, these materials are simply placed in landfills. Partial replacement of PC with SC and FA can, however, have some detrimental effects on the concrete mixture. Some of these effects will be defined later.

1.2 Background

SC and FA are two industrial byproducts. These materials have the correct chemistry to exhibit cementitious properties. The use of modern FA in concrete dates back to 1914, but the first comprehensive study was done in 1937 by Davis et al of the University of California (Helmuth 1987). It wasn't until 1954 that the American Society for Testing and Materials (ASTM) adopted tentative specifications for FA (ASTM C350) and for portland-pozzolan cement (ASTM C340-54T); Great Britain didn't adopt specifications until 1965 (Helmuth 1987). According to Ostrowski (2002), approximately 30 percent of the FA produced in North America was used for construction related activities in 2002. Of that 30 percent, 10 percent was used in concrete. SC was established in 1911 as a suitable concrete admixture in the United States by Carnegie Steel. As of 2002, about 13 million tons of slag is used in North America annually (Ostrowski 2002).

FA is produced from the waste of coal-burning power plants. Depending on the type of coal burned in producing energy, the resulting FA is divided into two classes: Class C and Class F. The former is produced by burning sub-bituminous coal and lignite and is considered a high-calcium FA, and the latter is a result of burning bituminous coal and anthracite, considered a low-calcium FA (Wesche 1991). Class F FA exhibits only pozzolanic properties, while Class C FA also displays cementitious properties (Helmuth 1987). According to ASTM, pozzolans are silicious, or siliceous and aluminous materials, which alone possess no cementitious properties, but will react with calcium hydroxide (CH) to form compounds with cementitious properties (ASTM C 125).

SC is a byproduct of iron production, when fluxes, lime-based inorganic substances, and iron ore are combined and melted. The flux becomes rich in lime, silica, and alumina and, when cooled rapidly in water, forms glassy granules. These granules are then ground to the appropriate size for use in concrete (Mindess et al 2003). SC and FA both improve concrete properties by reacting with the products formed during the hydration of cement.

However, the addition of SC and FA to a concrete mixture does pose a few problems. For example, SC may increase set times of concrete, particularly at low temperatures (i.e. 70 F and below) (ACI 233 2003). Sivasundaram and Malhotra (1992) reported that concrete mixtures containing 50 to 75 percent SC (no slag grade was provided) have initial set times near those of mixtures containing PC only. Final set times, however, were affected more significantly by the use of high volumes of SC, with some set times extended as much as 4 hours when compared to mixtures containing only PC. These mixtures contained high range water reducers (HRWR) which may also affect setting time (Sivasundaram and Malhotra 1992).

In addition, SC affects the strength gain of concrete. Research conducted at National Taiwan University in Taipei, Taiwan, shows that concrete mixtures with SC develop compressive strengths slower than mixtures containing only PC. However, when cured properly, mixtures with 4.5 percent and 35 percent SC achieved higher compressive strength at 28 and 90 days than the PC-only mixtures studied (Chern and Chan 1989). Their study used Type I PC, but made no mention of SC grade.

1.3 Objectives and Testing Program

1.3.1 Time of Setting and Strength Gain

This project will examine the strength gain of ternary concrete mixtures cured at low temperatures. Time of setting of ternary mixtures will also be analyzed. Specifically, this project is intended to provide AHTD with allowable temperature limits and cement replacement rates for use with ternary concrete mixtures. Five ternary concrete mixtures and one control mixture containing only PC will be will be prepared and cured at five different temperatures. The testing matrix is shown in Table 1-1 below.

Table 1-1. Batching and Testing Matrix

Curing Temperature (F)	% SC / % Class C FA					
	20/20	40/20	40/40	20/40	20/60	0/0
33	X	X	X	X	X	X
40	X	X	X	X	X	X
50	X	X	X	X	X	X
60	X	X	X	X	X	X
70	X	X	X	X	X	X

The six mixtures were developed from prior research at the University of Arkansas (Becknell 2005). The ternary mixtures to be tested consist of a best performing mixture (20% SC and 20% FA), a worst performing mixture (20% SC and 60% FA), and three moderately performing mixtures (40% SC and 20% FA, 40% SC and 40% FA, and 20% SC and 40% FA).

Each of the five mixtures will be batched between 60 and 80 F, the range that most accurately represents field placement temperature. In extreme weather conditions (i.e. summer and winter), mixing water temperature is adjusted to ensure concrete is batched in the aforementioned range.

Upon completion of batching, fresh concrete properties for each mixture will be measured and recorded appropriately. These properties include slump, unit weight, air content, temperature, and time of setting, which is governed by ASTM C 403, the "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." In addition, strength specimens will be cast and immediately placed in a refrigeration unit maintained at a specific temperature, and will remain in the unit until the appointed time of testing. These specimens will be tested for compressive strength at 1, 3, 7, 28, and 90 days.

A portion of this research consists of a fresh concrete test not commonly performed, the time of setting of the concrete mixtures. This test is governed by ASTM C 403: "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance" (ASTM 2004). The test method is summarized in section 4.1 of the specification and reads as follows:

> *4.1 A mortar sample is obtained by sieving a representative sample of fresh concrete. The mortar is placed in a container and stored at a specified ambient temperature. At regular time intervals, the resistance of the mortar to penetration by standard needles is measured. From a plot of penetration resistance versus elapsed time, the times of initial and final setting are determined (ASTM 2004).*

The mortar discussed in ASTM C 403 is obtained by discarding all of the concrete mixture which is retained on a standard No. 4 (4.75 mm) sieve. The wet sieving procedure is controlled by ASTM C 172: "Standard Practice for Sampling Freshly Mixed Concrete" (ASTM 2004).

As will be illustrated in Chapter 2, many have conducted research studying the problems discussed herein. Particularly, research has shown that curing temperature, SC content, and FA content all tend to affect time of setting and strength gain of concrete individually. However, very little research has been conducted combining all three of these factors and their effects on time of setting and strength gain; this research program will study the effects of these factors.

1.3.2 Strength Prediction

In response to the need for further study of ternary mixtures containing SCMs and in particular the need for an accurate strength prediction method for these mixtures, this research also proposes to investigate strength gain of ternary concrete containing slag cement and fly ash cured at low temperatures, and to refine the application of the maturity method for the strength prediction of these concretes. Conclusions drawn from this study will support recommendations to the AHTD regarding updating current specifications to include this research. It is the hope of this investigator that changes to the current specifications would provide economic and environmental benefits to the construction industry and the citizens of Arkansas. A further benefit of this study is to provide AHTD with information that supplements ASTM C 1074 – 98, "Standard Practice for Estimating Concrete Strength by the Maturity Method" which would allow for an accurate, simplified maturity strength prediction method for ternary mixtures particularly involving cold weather concreting.

Chapter 2

Definitions and Background

2.1 Definitions

2.1.1 Slag Cement

Slag cement, formerly known as blast furnace slag, has been in use for more than two centuries. The Paris underground metro system was constructed in 1889 using slag cements (ACI 233 1995). SC is a byproduct of the production of iron. Fluxes, lime-based inorganic substances, and iron ore are combined and heated to a molten state. The flux becomes rich in lime, silica, and alumina and, when cooled rapidly in water, forms glassy granules. These granules are then ground to the appropriate size for use in concrete (Mindess et al 2003).

Slag is broken into grades based on its ability to increase the compressive strength of mortar cubes (ASTM C 989). There are three classifications, or grades, of SC: Grades 80, 100, and 120. In order to classify SCs, cubes are made with 50 percent slag and 50 percent PC, as well as a reference cube of 100 percent PC. If the 28-day compressive strength of the SC cubes is at least 75 percent of that of the reference cubes, the SC is classified as Grade 80. If the 28-day compressive strength of the SC cubes is at least 95 percent of that of the reference cubes, the SC is classified as Grade 100. Finally, Grade 120 SC means the SC cubes' 28-day compressive strength is at least 115 percent of the strength of the reference cubes. Typically, higher SC grades have higher fineness. In other words, Grade 120 contains much finer particles than Grade 100, and Grade 100 is finer than Grade 80. Finer SCs require more water. Thus, mixtures using Grade 120 will typically have a lower slump than those using lower grades (Hale 2000).

During the process of hydration, the reaction of portland cement (PC) and water, calcium silicate hydrate (C-S-H) is formed. This dense crystalline material is the primary contributor to strength in a concrete mixture. In addition to C-S-H, calcium hydroxide (CH), a much less dense material, is formed. The hydration reactions are illustrated below in Equations 2.1 and 2.2.

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \qquad (2.1)$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \qquad (2.2)$$

SCs contain amorphous silica (S), which reacts with the CH formed in Equations 2.1 and 2.2. This reaction forms more C-S-H, thereby increasing the density and the strength of the concrete (Hale 2000). This reaction is shown below in Equation 2.3.

$$CH + S + H_2O \rightarrow C_3S_2H_3 \qquad (2.3)$$

2.1.2 Fly Ash

FA has reportedly been in use as a supplementary cementing material (SCM) in the United States since 1914. Research on the use of FA in concrete began, however, in 1937, which was carried out at the University of California by R. E. Davis and his colleagues (Helmuth 1987). After much research and extensive testing, the United States Bureau of Reclamation decided in 1948 to use large quantities of FA in the construction of the Hungry Horse Dam, causing a major increase in the research and use of FA in concrete. The dam was the fourth largest dam in the world at the time, and was expected to use 132,277 tons of FA and 170,858 tons of PC (44 percent FA). The actual percentages of FA used were much less than expected, but this major project caused the use of FA in concrete to increase all over the United States, and worldwide (Helmuth 1987). The dam, located on the South Fork of the Flathead River near Kalispell, Montana, contains 3,086,200 cubic yards of concrete ("Hungry Horse Project Montana" 2005).

FA is a waste product from coal-burning power plants. It is the fine particulate matter removed from the stack gases of such plants (Wesche, 1991). Depending on the type of coal burned, the resulting FA is broken into two classes which are commonly used in concrete: Class C and Class F. Class C FA is produced in the burning of sub-bituminous coal and lignite and is considered a high-calcium FA. This class of FA displays both pozzolanic and cementitious properties (Helmuth 1987). Pozzolans are siliceous or siliceous and aluminous materials which alone possesses no cementitious properties. These materials will, however, react with CH to form compounds with cementitious properties (ASTM C 125). Class F FA is a result of burning bituminous coal and anthracite, and is considered a low-calcium FA (Wesche 1991). Class F FA exhibits only pozzolanic properties (Helmuth 1987).

FA affects cement hydration in a manner similar to that of SC. In fact, the equations are the same as those for SC, and are illustrated previously in Equations 2.1, 2.2, and 2.3. Hydration of PC results in, primarily, two products: calcium silicate hydrate (C-S-H) and calcium hydroxide (CH). FA contains amorphous silica, which reacts with the CH, which is less dense than C-S-H, and, thus, is not a primary contributor to the strength of the concrete. The reaction of silica with CH results in the formation of additional C-S-H, creating a denser, less permeable, and stronger concrete.

2.1.3 Time of Setting

When concrete is freshly mixed, numerous properties are measured. One of these is the time of setting, which is used to determine the amount of time required to reach initial and final set of a specific concrete mixture. Setting represents the transition of a concrete mixture from a liquid to a solid state. Generally, when concrete ceases to be a liquid and becomes firm and unworkable, it is said to have achieved initial set. Then, when it further becomes rigid, it has achieved final set (Pinto and Hover 1999). The standard method for determining set times is established by the American Society for Testing and Materials (ASTM). This method is titled "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance", designated as ASTM C 403. According to ASTM C 125, time of setting is defined as "the elapsed time from the addition of mixing water to a cementitious mixture until the mixture reaches a specified degree of rigidity as measured by a specific procedure" (1996). For ASTM C 403, the concrete mortar has reached initial set when the penetration resistance of the standard probes is 500 psi and final set is reached when the penetration resistance is 4000 psi (ASTM C 125 1996).

2.1.4 Strength Gain

Another concrete property that is directly related to set times is the rate of strength gain. Strength gain, in this sense, refers to the compressive strength of the hardening concrete. This property is measured according to the requirements set forth by ASTM C 39 – “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.” According to ASTM C 39, concrete compressive strength should be tested at 1, 3, 7, 28, and 90 days (1996).

2.2 Factors Affecting Time of Setting of Ternary Mixtures

2.2.1 Slag Cement

SC has many positive attributes. It is less energy-intensive to produce than PC, improves durability and workability, and decreases concrete permeability. SC, however, negatively affects the time of setting of concrete. According to ACI Committee 233, in concrete with 25 percent SC (or more), delays in setting times can be expected. The magnitude of these delays depends upon several factors, such as temperature of the concrete, quantity of SC, the water-to-cementitious materials ratio (w/cm), and the characteristics of the PC used in the mixture (ACI 233 2003). Hogan and Muesel (1981) discovered that mixtures containing 50 percent SC had both initial and final set time increases of 0.5 to 1 hour at 70 F. These mixtures showed little or no retardation when tested at 90 F. No mention of slag grade was made (Hogan and Muesel 1981).

2.2.2 Fly Ash

The addition of FA to concrete can also adversely affect the setting time of the mixture. Smith et al (1982) studied the effect on set times when portions of the cement were replaced with FA. The control mixture used in his research (100 percent ordinary PC) had an initial setting time of 7.9 hours at 53 F. The mixture with 40 percent FA had an initial setting time of 11.7 hours at 53 F. At 73 F, Smith's research indicated delayed setting times, with the control concrete reaching initial set in 4.5 hours, while the mixture with 40 percent FA reached initial set in 7.1 hours. At 53, 73, and 86 F, mixtures containing 60 percent FA reached initial set in 20.9, 10.2, 6.6 hours, respectively. Mixtures with 80 percent FA reached initial set in 30.9, 15.3 and 9.1 hours, respectively (Smith et al 1982). Diamond and Lopez-Flores (1981) conducted research comparing both high- and low-calcium FAs. Their research indicated that all FAs retarded both initial set and final set, but that final set was affected to a greater degree (1981).

2.2.3 Temperature

Temperature is also known to affect times of setting of concrete. Pinto and Hover (1999) examined the influence of temperature on setting times using the maturity approach and the Freiesleben-Hansen and Pederson maturity function. Concrete cured at 86 F reached initial set in approximately 2 hours, while that cured at 50 F did not reach initial set until after about 7 hours (Pinto and Hover 1999).

2.3 Factors Affecting Strength Gain of Ternary Mixtures

2.3.1 Slag Cement

In addition to increasing the setting times of concrete mixtures, the strength gain of concrete containing SC is also known to be reduced at early ages due to the slow hydration of SC (Miura and Iwaki 2000). Rivest et al (2004), however, found that concrete made with high volumes of SC have "adequate" early age strength, and superior strength at later ages. At one day of age, the slag concrete tested showed a compressive strength of 1,390 psi, while the control concrete, made with ordinary PC, displayed a compressive strength of 1,490 psi. After three days of curing, the slag concrete exhibited a compressive strength of 2,740 psi. Meanwhile, the control concrete reached a two day compressive strength of 2,280 psi (Rivest et al 2004). Note that in this study, three-day compressive strength of control concrete was compared to two day compressive strength of slag concrete. This may not be an accurate comparison.

2.3.2 Fly Ash

FA also affects strength gain. Ranganath et al (1995) determined that, at early ages, coarser FA causes concrete to have much lower compressive strength than control mixtures containing only PC, while concrete incorporating finer FA displays higher early strength. However, this study also reported that the 28-day strength of mixtures containing FA was affected very little as compared to the control mixtures (Ranganath 1995). Langley et al (1992) examined the effect of high volumes of FA (55 percent of total cementitious material) in large concrete blocks. They also discovered that at early ages, specifically at 3 and 7 days, concrete containing FA displayed lower compressive strengths than the control block containing only PC. At three and seven days of age, the site-cured test specimens of the control concrete (100 percent PC) had reached 3,860 psi and 4,960 psi, respectively. However, the site-cured specimens containing 55 percent FA attained a three-day compressive strength of 1,130 psi and a seven-day compressive strength of 3,130 psi (Langley et al 1992). Naik and Singh (1997) suggest that up to about 60 percent FA replacement, setting times are increased, but with more than 60 percent replacement, setting time will be decreased (Naik and Singh 1997).

2.4 Literature Review

2.4.1 Effect of Slag Cement on Time of Setting

According to ACI Committee 233 (2003), the use of SC in concrete will delay set times if the slag content is more than 25 percent (ACI 233 2003). Research conducted by Luther and Mikols (1993) demonstrated that over the slag fineness range of 400 to 1400 m^2/kg, all concrete mixtures containing 40 percent SC had approximately the same set times (Luther and Mikols 1993). Luther et al (1994) further showed that at 35 to 40 percent slag replacement, the set time was increased by approximately 1 hour at 70 F when compared to the control mixture of 100 percent PC (Luther et al 1994). Sivasundaram and Malhotra tested three series of mixtures. Each of these series had cement contents of 100, 125, and 150 kg/m^3. Sivasundaram and Malhotra (1992) determined that the initial set times of the SC concretes were very similar to the initial set times of the control concrete. However, the final set times were sometimes extended as long as 4 hours. Note that no slag grade was mentioned. It is also worth noting that Sivasundaram and Malhotra used “large dosages of superplasticizer” to provide the desired workability. Superplasticizers, also known as High Range Water Reducers (HRWR), are known to delay set times. Sivasundaram and Malhotra also incorporated very large quantities of SC (50 – 75 percent) into the mixtures (Sivasundaram and Malhotra 1992).

2.4.2 Effect of Fly Ash on Time of Setting

Many researchers have shown that FA, in general, has a tendency to retard the set times of concrete. Naik and Singh (1997) reported that it is generally accepted that Class F FA retards setting times. They conducted research on the effects of Class C FA on the setting times of concrete. In their research, Naik and Singh prepared thirty-four concrete mixtures, of which four were mixed without FA as control mixtures. FA from four different sources was used. One type was used to create mixtures with 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 percent FA. Once the mixtures were prepared, Naik and Singh proceeded to carry out the procedure shown in ASTM C 403, with some deviations to the specified test times. Their research results showed that, up to 60 percent FA replacement, the use of Class C FA retarded the set times of concrete mixtures. They also found that at 10 percent FA, the initial and final set times were affected very little (Naik and Singh 1997). In agreement with Naik and Singh, Wesche reported that the set times of concrete containing Class F FA are generally increased, but typically remain within the limits provided in standards (Wesche 1991). According to Smith (1982) times of setting of concrete containing Class C FA are increased at all temperatures beyond set times of control mixtures such that the maximum retardation occurred at a FA content of 80 percent. Smith discovered that, with the particular FA he studied, 100 percent FA mixtures reached final set in less than one hour when cured at or above 70 F. Smith attributed the faster set times of FA alone to the fact that the particular FA used in his study exhibited both cementitious and pozzolanic properties, and further explained that while the FA alone displayed rapid initial set, the ultimate strength was poor (Smith 1982).

Bouzoubaâ et al (1990) presented a review of FA cements including research conducted by Cheng and Osbæck. This source reports that Cheng and Osbæck measured the setting times of cement pastes using 10, 20, and 30 percent FA (no mention of FA classification). Vicat's procedure (ASTM C 191) was used to determine the setting time, and the research showed a decrease in setting time as fineness of the FA was increased (as FA becomes finer, setting times decrease), although no mention was made regarding the amount of decrease (Bouzoubaâ et al 1999).

2.4.3 Effect of Temperature on Time of Setting

Pinto and Hover (1999) studied the effects of curing temperature on the setting time of concrete mixtures. In their research, four batches of a mortar mixture were prepared using ordinary Type I PC and sand meeting ASTM C 33. Nine specimens were cast from each mixture, three of which were placed in an incubator at approximately 104 F (Sample 3), three placed in a refrigerator at approximately 50 F (Sample 1), and the remaining three cured at lab temperature (about 73.4 to 80.6 F, Sample 2). The specimens were tested in accordance with ASTM C 403, the "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." One batch consisted of samples with average temperatures of 50, 64.4, and 91.4 F. Sample 1, cured at 50 F, reached initial set in 7.1 hours. Sample two, cured at 64.4 F, reached initial set in 4.4 hours. The third sample, cured at 91.4 F reached initial set in 2.0 hours (Pinto and Hover 1999).

The effect of curing temperature on the time of setting varies when SCMs are present in the concrete mixtures. Eren, Brooks, and Celik (1995), studied these effects for concrete mixtures in which varying portions of the PC was replaced with either FA or SC. No mention was made as to types, classes, or grades of PC, FA, or SC. The specific mixtures studied consisted of a control mixture containing only PC, a mixture in which 30 percent of the PC had been replaced with FA, one with 50 percent FA, and two SC concrete mixtures with the same replacement rates as the FA mixtures. Each of these mixtures was cured at 43, 68, 95, 140, and 176 F. The ingredients used for batching were stored at these temperatures for 24 hours prior to batching. The times of initial and final setting were determined in accordance with ASTM C 403. Eren et al showed that increasing the FA content in a mixture led to increased times of setting at all curing temperatures. The researchers also claimed SC concrete showed faster setting times than FA mixtures at the same replacement rates and curing temperatures. Generally, the study showed that as curing temperature increased, the time of setting became less; however, the decrease in setting time depended on the type of concrete (ordinary PC, FA, or SC concrete) (Eren et al 1995).

2.4.4 Factors Affecting Strength Gain

2.4.4.1 Slag Cement and Environmental Effects

Hogan and Muesel (1981) found that the use of SC typically causes reduced early concrete strengths (1 to 3 days), but lead to higher ultimate strengths than concrete containing only PC (Hogan and Muesel 1981). ACI 233 further explains that Grade 100 SC generally results in lower early strengths and equal or greater later strengths. Grade 80 exhibits characteristics similar to those of Grade 100 (ACI 233 2003).

Strength gain is affected by SC content. Wimpenney et al (1989) studied the strength development of SC concretes at low curing temperatures. In their research, PC and SC (no slag grade given) were used. Mixtures were designed containing three cementitious materials contents (200, 300, and 400 kg/m^3). Five separate mixtures were created for each using two different types of SC with contents of 40 and 70 percent. The testing program was divided into two parts. Part 1 included casting specimens and curing them underwater at 68 and 104 F. In Part 2, additional specimens were cast and cured underwater at 41 F and in air at 50 F. This research showed that specimens consisting only of ordinary PC and cured at 50 F will achieve 50 percent of their projected 28-day strength at 3 days. Meanwhile, at 3 days, the mixtures containing 40 and 70 percent SC only attained one-third and one-fifth of their respective 28-day strengths. Further, at one day of age, all mixtures cured at 41 F attained approximately one-third to one-half of the compressive strengths attained at 50 F (Wimpenny et al 1989).

Sivasundaram and Malhotra (1992) investigated concrete mixtures containing high volumes of SC. The tests consisted of three mixtures with the following slag contents: 60, 70, and 75 percent in Series 1; 50, 60, and 70 percent in Series 2; 50, 60, and 65 percent in Series 3. In addition, three control mixtures were prepared containing only PC. The research results showed that compressive strengths of all the high-volume slag concretes were comparable to control mixtures after 7 days (Sivasundaram and Malhotra 1992). As mentioned previously, the samples tested contained very high volumes of SC, as well as large doses of HRWR. No slag grade was provided.

Chern and Chan (1989) also studied the effects of SC on concrete. Their program consisted of concrete containing Type I PC and SC (no slag grade given) at replacements of 4.5, 35, and 68 percent. No chemical admixtures were used. Specimens were cured in a fog room at 73.4 F, as per ASTM C 512 – 87. Chern and Chan found that at early ages (prior to 7 days), compressive strength of slag concrete was somewhat lower than that of the control mixture; however, at later ages, such as 28 and 90 days, the slag concretes displayed higher compressive strength than the control concrete. At 28 days, the mixtures containing 4.5 and 35 percent SC had compressive strengths of approximately 4800 psi, while the control mixture reached only 4300 psi. The mixture incorporating 68 percent SC reached only 3900 psi. At 90 days, the mixtures with 4.5 and 35 percent SC attained compressive strength of about 5100 psi, while the control mixture achieved only 4700 psi. The 68 percent slag mixture reached only 4100 psi (Chern and Chan 1989).

The effect of SC on strength development is amplified by low temperatures. Miura and Iwaki (2000) examined this concept, conducting research including concrete made with SC of three different specific surface areas (404, 591, and 789 m^2/kg) and PC (no type given). The mixtures used cement replacements of 50, 60, 70, and 80 percent SC. Once mixed, the concrete was cured at 41 and 68 F, representing the average daily temperature in cold regions and the standard curing temperature, respectively. Miura and

Iwaki also subjected the various mixtures to different curing methods, including water curing, sealed curing, and air curing. They determined that, at 7 days, the compressive strength did not vary with respect to curing method. However, at later ages SC concrete cured at low temperatures displayed much lower strengths when air cured than with other curing methods. They also found that at later ages, concrete with cement replacements of 50 percent SC having a surface area of 789 m^2/kg displayed "adequate strength", even at low temperatures. Specifically, at 56 and 91 days of age, the compressive strength of the SC mixtures exceeded the strength of the mixtures containing only PC (Miura and Iwaki 2000).

Uomoto and Kobayashi (1989) studied the effect of curing temperature and humidity on strength gain of SC concrete. The samples tested consisted of ordinary PC (no type given) and SC (fineness of 350 m^2/kg) with replacements of 30, 50, and 70 percent. A 100 percent PC control mixture was also prepared. These mixtures were subjected to curing temperatures of 50, 68, 86, and 104 F. As expected, they discovered that at lower temperatures, slag concretes display low early-age compressive strengths. They did, however, come to another somewhat surprising conclusion. According to their research, Uomoto and Kobayashi reported that slag concretes at low temperatures displayed higher rates of strength development than ordinary PC concretes (Uomoto and Kobayashi 1989). Chern and Chan (1989) conducted similar research, with a program consisting of Type I PC and SC (no grade given) contents of 4.5, 35, and 68 percent. Specimens were cured at 50 percent relative humidity (RH) and 73 F, 95 percent RH and 95 F, and 100 percent RH and 73 F. Their research concluded that concretes containing 4.5 and 35 percent SC displayed reduced strength at early ages, but the compressive strength increased at later ages. Also, at 68 percent SC, reduced strength was observed at all ages (1, 4, 7, 10, 14, 28, 90, 180, and 365 days). Chern and Chan also found that mixtures cured at 50 percent RH resulted in lower strengths than those cured at 95 percent RH. According to Chern and Chan, this occurred because the concrete became prematurely dry at 50 percent RH, preventing the cement from receiving all the moisture it needs for hydration (Chern and Chan 1989). With respect to curing temperature, Chern and Chan found results similar to other authors mentioned herein, in that lower strengths were observed at early ages.

Lane and Ozyildirim (1999) examined the effects of pozzolans and SC on concrete properties. The research program studied 19 mixtures. These mixtures consisted of binary (PC + FA, PC + SC, PC + SF) and ternary (PC + SC + SF, PC + FA + SF) mixtures as well as a control mixture containing only PC. The study examined the compressive and flexural strength, drying shrinkage, and electrical transport of the concrete mixtures. The mixtures studied met requirements set forth by the Virginia Department of Transportation with a minimum 28 day compressive strength of 4350 psi, 635 pounds of cementitious materials per cubic yard, w/cm was 0.45, 6.5 +/- 1.5 % air and 1870 pounds of coarse aggregate per cubic yard. The FA used was Class F; the SC used was Grade 120. The silica fume (SF) was in a dry-densified form. No mention of PC type was given. The compressive strength specimens, cast in 4 in by 8 in cylindrical molds, were moist cured at 73 F until tested (3, 7, 28, 56, and 365 days). The researchers reported that increasing the quantity of SC or FA led to decreased compressive strength at early ages (through 56 days) when compared to the control mixture. Once the samples reached 365 days of age, this decrease in compressive strength was not significant. All mixtures exceeded the design compressive strength of 4350 psi at one year of age. Lane and Ozyildirim also claim that those binary mixtures containing SC did not experience as pronounced a decrease in compressive strength between 7 and 28 days of age as the FA mixtures. Only one of the nineteen mixtures tested failed to meet the 28 day compressive strength requirement when the specimens were actually 28 days of age. The researchers attribute this failure to the excessive slump of the mixture. They point out, however, that if the w/cm were lowered, the slump would also be lowered and the compressive strength would improve. The ternary mixtures tested in the study contained small amounts of SF (2.5 to 5 percent) and either SC or FA. These mixtures exhibited higher early strength when compared with high-replacement binary mixtures, and maintained the high durability that is characteristic of high-replacement concrete (Lane and Ozyildirim 1999).

2.4.4.2 Fly Ash Effects

The use of FA in concrete also affects its strength development. Langley et al (1992) studied strength development in concrete blocks containing high volumes of Class F FA. In their research program, Langley et al used concrete containing Type I PC and Class F FA. Test specimens were large blocks (10 ft by 10 ft by 10 ft). One block was cast with five batches of control concrete (containing only PC). Two blocks were cast with mixtures comprised of 55 percent Class F FA. Test cylinders were cast using 6 x 12 inch cylindrical molds. Some of these were cured at the site under the same conditions as the concrete blocks; others were cured under lab conditions. At 3, 7, 28, 91, 365, and 730 days, three specimens were tested from each curing condition. Langley et al determined that at 365 and 730 days, the high FA specimens displayed higher compressive strengths than the control concrete. At 365 days, the compressive strength of the ordinary PC specimens was 6860 psi, while that of the high FA specimens was 7350 psi. At 730 days, the compressive strengths of the control mixture and high FA mixture were 7440 psi and 8240 psi, respectively. Compressive strengths of laboratory-cured cylinders containing high volumes of FA were also higher at 91 days than the control concrete. At nearly all ages, the researchers found that laboratory-cured specimens attained higher strength than the field-cured specimens. The ordinary PC mixture at this age reached a compressive strength of 7250 psi, while the high FA mixture reached 8660 psi. The exception was the high-volume FA concrete at 28 days. Langley et al concluded that high-volume FA concrete can be produced that is comparable in strength to conventional concrete at 91 days of age, and this comparable strength may even be attainable at 28 days. Under lab conditions, high FA mixtures can reach very high strength even sooner than 28 days (Langley et al 1992).

The type of FA used in a mixture influences the strength gain of that mixture. Folliard, Du, and Trejo (2003) studied the ways in which curing conditions affect the strength development of Controlled Low-Strength Material (CLSM). The researchers studied six CLSM mixtures with varying cement contents. Five of the mixtures also contained varying quantities of either Class C or Class F FA. One mixture tested contained only PC and was air-entrained. No mention was made about the type of cement used. The mixture proportions for these mixtures are shown below in Table 2-1.

Table 2-1: Mixture Proportions of CLSM Mixtures*

Mixture	Cement Content kg/m^3	Fly Ash Type	FA Content kg/m^3	Concrete Sand kg/m^3	Water kg/m^3
60-F1200	60	Class F	1200	None	492
15-F240	15	Class F	240	1500	197
15-C240	15	Class C	240	1500	175
30-F180	30	Class F	180	1500	188
30-C180	30	Class C	180	1500	181
60-AIR#	60	None	0	1500	123

* - from Folliard et al 2003

\# - mixture contained air-entraining admixture

Folliard et al prepared 3 inch by 6 inch cylindrical specimens for conducting compressive strength tests. Three curing temperatures were employed in the study (50, 70, and 100 F) as well as two moisture conditions ("wet" and "dry"). The "wet" condition was defined as specimens permitted to remain in the capped cylindrical molds until used for compressive strength testing. "Dry" conditions were obtained by removing the specimens from the molds after three days of curing. These cylinders were replaced into the appropriate curing chamber in open air until used for compressive strength tests. Compressive strength tests were performed on the mixtures at 7, 28 and 91 days of age.

The study showed that mixtures containing Class C FA reached higher strengths in all curing conditions and at all ages than mixtures using Class F FA. The researchers report that the strength of mixture 15-C240 cured in wet conditions for 91 days reached between 2.7 and 11.7 times the strength of mixture 15-F240 exposed to the same curing conditions. The only difference in the mixtures was the class of FA. Researchers report that specimens dry cured at low temperatures (50 and 70 F) nearly always displayed lower compressive strengths at 91 days than at 28 days. For example, mixture 60-F1200 lost about 88 percent of its evaporable moisture with a 50 percent loss in compressive strength from 28 to 91 days when dry cured at 50 F. Folliard et al attributed this loss of compressive strength to the development of microcracks during the drying process. This trend did not apply when specimens were cured at 100 F (Folliard et al 2003).

The fineness of FA also affects the strength gain of concrete. Popovics (1993) studied the fineness effect on compressive strength of mortars. His testing program consisted of more than 60 different concrete mixtures consisting of Types I and III PC, Classes C and F FA, SF, superplasticizer, and set accelerator. Popovics tested 11 different mixtures for compressive strength according to ASTM C 109 and C 597 ("Standard Test Method for Pulse Velocity Through Concrete"). As expected, the replacement of 30 percent of the Type I cement with Class F FA resulted in reduced mortar strength, especially at early ages. This also occurred when Type III cement or Class C FA was used. Popovics then prepared additional mixtures containing Types I and III cements, this time using ground Class F FA. The particle size distributions of materials used by Popovics are shown below in Table 2-2.

Table 2-2: Particle Size Distributions of Popovics' Cements and Fly Ashes *

	Total Percentage Smaller Than d							
d Size (mm)	PC Type I		PC Type III		Fly Ash Class F		Fly Ash, Ground Class F	
125	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
88	100.0	100.0	100.0	100.0	97.4	96.5	100.0	100.0
62	96.8	96.4	100.0	99.7	89.9	89.4	100.0	100.0
44	87.1	87.3	97.2	97.8	76.6	76.5	100.0	100.0
31	74.7	72.0	87.9	89.4	61.9	60.9	100.0	100.0
22	61.4	56.5	75.7	76.6	47.4	46.5	100.0	100.0
16	46.5	42.6	60.8	62.9	34.1	34.0	95.9	95.4
11	31.7	28.6	44.8	47.3	23.8	24.3	82.7	81.1
7.8	21.2	18.4	30.0	30.2	15.8	15.3	65.8	63.9
5.5	11.2	10.4	16.8	16.5	8.9	9.7	48.5	46.0
3.9	5.3	5.1	8.3	8.4	4.8	5.3	34.3	32.6
2.8	2.5	2.1	3.6	3.6	2.8	2.1	23.2	22.5
1.7	-	-	-	-	-	-	14.6	13.7
1.0	-	-	-	-	-	-	7.4	7.0
0.66	-	-	-	-	-	-	2.9	2.7

* - From Popovics 1993

The use of this ground FA resulted in an increase in 1 day compressive strength, and an even more distinct increase at later ages with both types of cement. Popovics reported that concrete using Type I cement and ground FA displayed higher compressive strengths at 7 days and later than concrete using Type III cement and the same FA before grinding (Popovics 1993).

Yuan and Cook (1983) also examined concrete containing Type I PC and Class C FA. In studying strength, the w/cm was held constant at 0.45. The mixtures tested contained 0, 20, 30, and 50 percent FA. As expected, Yuan and Cook's study illustrated a decrease in strength development. Specifically, from 7 to 28 days, Yuan and Cook report a slightly higher strength gain with FA concrete than with the control mixtures; this gain continues after 28 days, but is somewhat slower (Yuan and Cook 1983).

Ronne (1989) examined the effect of curing conditions on the strength development of concrete using FA and SF. A blended cement containing 25 percent FA was used (no cement type or FA class given), as well as condensed SF. A plasticizer was also added. Two different mixtures were used: one with SF and one without. The compressive strength tests were performed on 4 inch x 4 inch x 4 inch cubes and subjected to six different curing methods. One of the curing methods employed was submersion in water at 68 F. Another method included air-curing the samples at 68 F and 50 percent RH. Some samples were submerged in water at 68 F for 3 days, then air-cured at 68 F and 50 percent RH while more were cured at 68 F and 50 percent RH in the mold. Some samples were submerged in 68 F water for 28 days, demolded, and submerged in 158 F water until tested, with the remainder cured in air at 68 F and 50 percent RH in molds for 28 days, then demolded and air-cured at 158 F until testing. Ronne's research showed that concrete cured in water at 68 F showed increasing strengths at all ages. Concrete exposed to only 50 percent RH showed lower 28-day strengths than that moist cured (control). Concrete cured in water for three days then air cured showed higher initial strength, but showed lower strength at later ages (Ronne 1989). In general, there were no unexpected results in Ronne's study.

Thomas, Matthews, and Haynes (1989) studied the effect of curing on the strength and permeability of concrete containing FA and PC. Six mixtures were prepared (no mention was made of FA class or cement type). The test specimens were cast and left in their molds in damp conditions at 68 F for 1 day. Next, the specimens were subjected to one of five curing methods: (i) air-cured for 1 day; (ii) left in the damp condition for 1 additional day, then air cured; (iii) left in the damp condition for 2 additional days, then air-cured; (iv) left in the damp condition for 6 additional days, then air-cured; (v) submerged in water until test. Their results showed that specimens subjected to air-curing immediately after casting exhibited lower strength gain than specimens completely submerged in water until testing (control). According to Thomas et al strength development rates increase as the initial damp curing time increases (Thomas et al 1989).

2.4.5 Maturity Method

The maturity method is an in-place technique to predict the compressive strength of concrete. ASTM C 1074 provides a standard practice for the method. The method is an alternative to the traditional practice of strength testing field cured cylinders at specified ages then using the strength data as a strength development indicator for the in-place concrete. A background on the historical and theoretical development for the method will follow including recent technological advances in the development of instrumentation.

2.4.5.1 The Maturity Concept

ASTM C 1074 Standard Practice for Estimating Concrete Strength by the Maturity Method defines maturity as "the extent of the development of a property of a cementitious mixture." Typically, maturity refers to the development of compressive strength of concrete as a function of time and temperature. The concept is that the strength of hardening concrete can be predicted based on the temperature and time history (Carino et. al. 1983). The fundamental implication of the maturity concept is that concrete of the same mix design and maturity will have approximately equal strength

(Carino et al. 1983, Oluokun 1990). This concept stretches back some fifty years in the peer-reviewed literature. Saul (1951) reported that concretes of equal maturity and mix design will have approximately the same strength even though their age and temperature histories may differ.

2.4.5.2 The Maturity Method

Concrete maturity is reported by the maturity index which represents the maturity calculated from the time and temperature history. The index is determined from a maturity function—the function is an equation that factors in the temperature and time history during the curing period and translates that data into an index. Two maturity indexes are accepted for reporting maturity: temperature-time and equivalent age. These indexes are determined from maturity functions which calculate the index from the temperature and time history of hardening concrete (ASTM C 1074 – 98). The typical units of the time-temperature index are °C-days or °C-hours. Typical units for the equivalent age maturity index are hours.

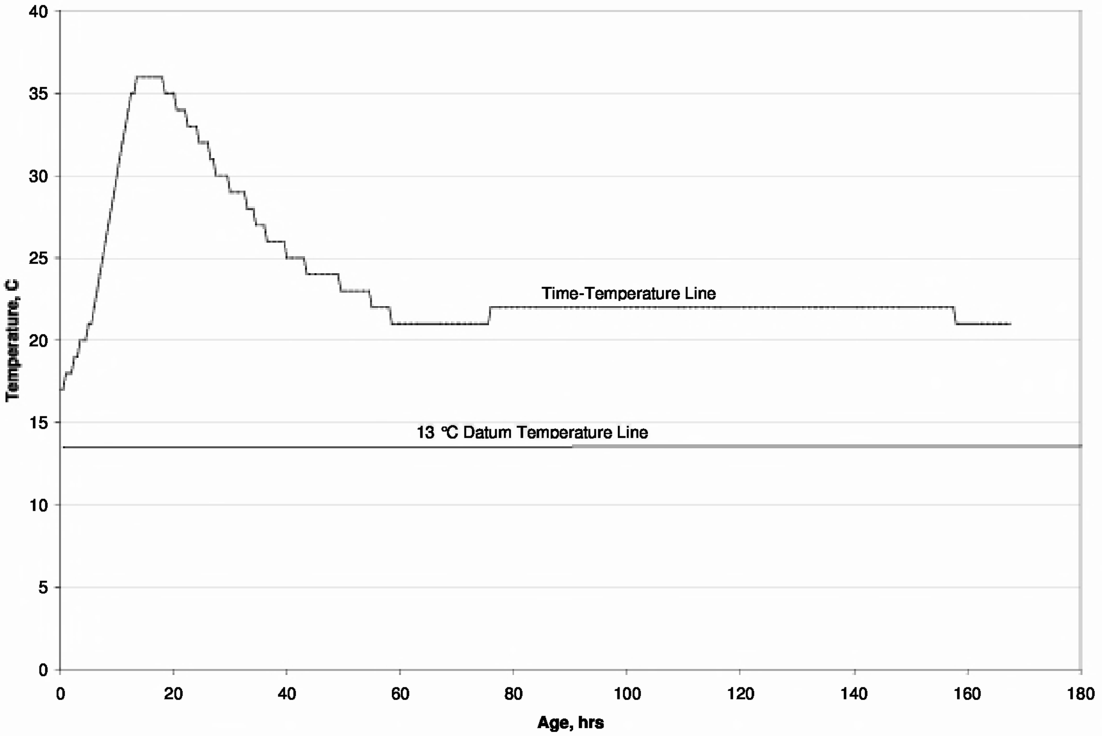


Figure 2-1. Time-temperature curve showing graphical representation of the maturity index calculated from the temperature-time maturity function. The curve was generated from a control mixture cured at 70 °F.

The first maturity function calculates the temperature-time maturity index:

$$M(t) = \sum (T_a - T_0)\Delta t \qquad (1)$$

M(t) = temperature-time maturity index in degree-days or degree-hours

Δt = time interval in days or hours

T_a = average temperature of the concrete during Δt in °Celsius

T_o = datum temperature, °Celsius

The temperature-time maturity function also known as the Nurse-Saul equation is the simplest and most commonly used index function. It is the sum of the difference between the average temperature during a time increment and the datum temperature multiplied by the time increment. The datum temperature represents the temperature below which concrete strength development ceases. The datum temperature is unique to a particular concrete mixture. Note that the SI system rather than the U.S. customary system is used to express units.

This function demonstrates that the maturity index expressed as the temperature-time factor is simply the area between the curve of time versus temperature and bounded by the line represented by the datum temperature (Volz et al. 1981). The datum temperature represents the baseline above which the area under the strength-maturity curve is calculated. Figure 2-1 is a hypothetical time-temperature curve using a datum temperature of 13°C. This figure provides a graphical representation of maturity. Maturity is the area bounded by the time-temperature line above and the 13 °C datum temperature line below.

The second maturity function determines the equivalent age maturity index:

$$T_e = \sum e^{-\left(\frac{E}{R}\right)\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \Delta t \qquad (2)$$

T_s = specified temperature in Kelvin (typically 293 K)

T_e = equivalent age at T_s in days or hours

T_a = average temperature of concrete during Δt in Kelvin

E = activation energy in J/mol

R = ideal gas constant, 8.3144 J/K*mol

Equivalent age index is the days or hours at a specified temperature which produces a maturity equivalent to that of a maturity produced by a curing regimen at different temperatures from the specified temperature (ASTM C 1074 – 98). Activation energy is a constant which represents the temperature sensitivity of a concrete mixture. The activation energy constant is unique to a particular concrete mixture.

ASTM C 1074 covers these equations in detail, and provides the procedures to determine the datum temperature (T_o) for the temperature-time factor and the activation energy for determining equivalent age. This specification also gives precise instructions as to the development of the strength-maturity relationship. A summary of this procedure is provided below.

Strength prediction by the maturity method requires development of a unique maturity curve for a particular mixture. The maturity curve is a plot of compressive strength compared to the maturity index. This maturity curve, the strength-maturity relationship, is determined by casting a number of cylinders from one or more batches of the same mixture. During the curing period, the temperature and time history of the cylinders is recorded, and strength tests at different, specified ages are performed on the concrete cylinders. The maturity index at each test age is determined, and then, once all the cylinders have been tested, the strength-maturity relationship can then be plotted on a graph.

This strength-maturity curve may then be used to predict the strength development of in-place concrete of the same mixture constructed in the field. During field construction when concrete is placed, sensors are positioned strategically in the formwork to best represent and measure the temperature of the mass in-place concrete. The maturity index of the in-place concrete is determined based on temperature and time measurements using a maturity function, and then strength is predicted by going to the maturity curve and reading off the expected strength (Carino et al. 1983).

The maturity-strength curve is unique to a particular mix design and curing regimen, and early age temperature. As will be noted later, temperature conditions during curing at early ages will significantly impact subsequent strength development. These early ages are typically considered to be the first 72 hours after casting, but there is a "critical age" corresponding to the first 6 hours where temperature effects are most significant. In order to insure that an accurate strength-maturity curve is developed, the concrete samples used to develop the curve should be cured under early age temperature conditions that represent those conditions expected in the field (Carino et. al. 1983).

The use of maturity meters (versus using thermocouples and directly measuring temperature) increases the accuracy of the strength-maturity curve and reduces the amount of labor required to develop the relationship. Unless maturity is determined by taking temperature readings in very small time increments, the concrete maturity will be underestimated and in turn the strength development will be underestimated (Hulshizer 2001). The maturity meter is used to read data recorded by sensors installed during initial concrete placement, and the meter converts that recorded data into an index. The maturity meter allows for continuous instantaneous monitoring as well as recording of the concrete's temperature-time history and automates maturity index calculation insuring an accurate determination of maturity.

2.4.5.3 The Nurse-Saul Equation

Nurse (1949) indicated the importance of temperature on concrete strength development. This early work compared strength development for steam cured concrete against a temperature-time factor. Saul (1951) proposed the maturity concept as a means to characterize strength development based on temperature and time effects on hardening concrete. Saul (1951) defined maturity as the age of the concrete multiplied by the average temperature above freezing at which the concrete is maintained. The result of this early work is the Nurse-Saul Equation reported in Volz, et. al (1981):

$$M = \sum (T - T_0)\Delta t \tag{3}$$

Note that this equation is almost identical to equation (1), the temperature-time function identified in ASTM C 1074 – 98. Here T is the temperature of the concrete during the time interval Δt. This Nurse-Saul equation is the original maturity function that has become known as the time-temperature function.

Heavily debated in the early literature was the appropriate value for the datum temperature, T_o. Plowman (1956) described datum temperature as "the curing temperature at which the strength of concrete remains constant irrespective of age." Although Saul (1951) did not formally state the temperature-time function in his paper, the context of the literature suggests that the researcher calculated maturity using this function and a datum temperature of 32 °F. Plowman (1956) concluded based on research that a datum temperature of 11 °F should be used. Plowman also stated that Saul used a datum temperature of 14 °F. Volz et al. (1981) recommended using a datum in the range of 10 to 14 °F and used a datum of 14 °F for their work. Carino et. al. (1983) used a datum temperature of 10 °F. Plowman (1956) stated that the need for a datum temperature below freezing became apparent when data from different curing temperatures did not agree—the datum temperature of 11 °F was determined from iteratively trying different datum temperatures until agreement occurred amongst the data. Plowman further concluded that the datum temperature needed to be carefully chosen, because the datum temperature affects the calculated maturity. Two degree difference in temperature is equivalent to a 10% increase in maturity for concrete cured above the freezing point of water. Work by Carino (1984) further supports the conclusion that the accuracy of maturity method using the time-temperature function is greatly improved by using the appropriate datum temperature.

Carino (1984) defined the datum temperature as the temperature below which no further strength gain will occur. This definition explains the variation in datum temperatures used by different researchers, and it supports the need to experimentally determine a datum temperature for each mix design prior to predicting compressive strength for in-place concrete during construction as required by ASTM C 1074-98. Given the wide variety of portland cements, admixtures, and SCMs that are used for producing concrete, it is no doubt that the lowest temperatures at which the hydration reaction will occur vary for different mixtures, and hence the datum temperature will vary depending on the properties of the constituent materials.

2.4.5.4 Limitations of the Time-Temperature Function

Carino (1984) critically examined the theoretical basis of the time-temperature function and found that the fundamental assumption is that the rate of strength development is a linear function of temperature. The strength gain of concrete is the result of the hydration reaction, and, therefore, the equations that predict the rate of strength gain should resemble equations that describe rates of chemical reactions. Central to Carino's research is the application of a rate constant to the maturity function and the understanding that the rate constant is a function of temperature. Carino and Tank (1991) state that accurate estimation of in-place strength development and the proper selection of a suitable maturity function requires choosing the proper rate constant.

The rate constant, k, is a function of temperature and represents the initial slope of the curve for the relationship between relative strength (relative strength is the compressive strength at time t divided by the limiting strength at infinite age) and time (Carino and Tank 1991). Carino (1982) determined that the linear rate constant time-temperature function was a good representation for maturity under isothermal or constant curing temperatures, but that under variable temperature conditions a nonlinear rate constant needed to be present. Chengju (1989) stated that cement hydration involves a series of chemical reactions that behave nonlinearly under rising temperature conditions. Hansen and Pederson (1977) are credited for having first proposed a maturity function based on the Arrhenius equation to represent the effect of a nonlinear rate constant on maturity. The Arrhenius equation comes from Svante Arrhenius, a Swedish chemist, who proposed in the late 1880's that there exists a mathematical relationship that connects activation energy, temperature, and a rate constant (Moeller et. al. 1989). The Arrhenius equation is accepted to be:

$$k(T) = A^{-(E/RT)} \quad (4)$$

k = rate constant (1/s)

A = constant

E = activation energy (kJ/(mol*K)

T = temperature (K)

R = ideal gas constant (kJ/(mol*K)

The maturity function introduced by Hansen and Pederson (1977) utilizing the Arrhenius rate constant is the equivalent age function. This function determines a maturity index based on a temperature dependent rate constant that may then better predict the strength gain of concrete particularly under varying temperature conditions.

Figure 2-2 adapted from Carino (1982) illustrates that the nonlinear rate constant is a better fit to the experimental data then the linear rate constant. Carino (1984) concluded that the Arrhenius equation describes more accurately the relationship between time and temperature. The equivalent age maturity function indicated in Equation 2 results from the use of the nonlinear rate constant derived from the Arrhenius equation.

Carino and Tank (1991) proposed a simpler nonlinear rate constant function but with similar performance to the Arrhenius equation:

$$k(T) = Ae^{(\beta T)} \quad (5)$$

A = constant (day^{-1})

β = temperature sensitivity factor (1/ °C)

T = curing temperature (°C)

The constants A and β are obtained from linear regression analysis of the logarithm of the rate constant and curing temperature relationship. The development of the nonlinear rate constant function becomes significant for deriving equations that are capable of accurately predicting strength based on maturity.

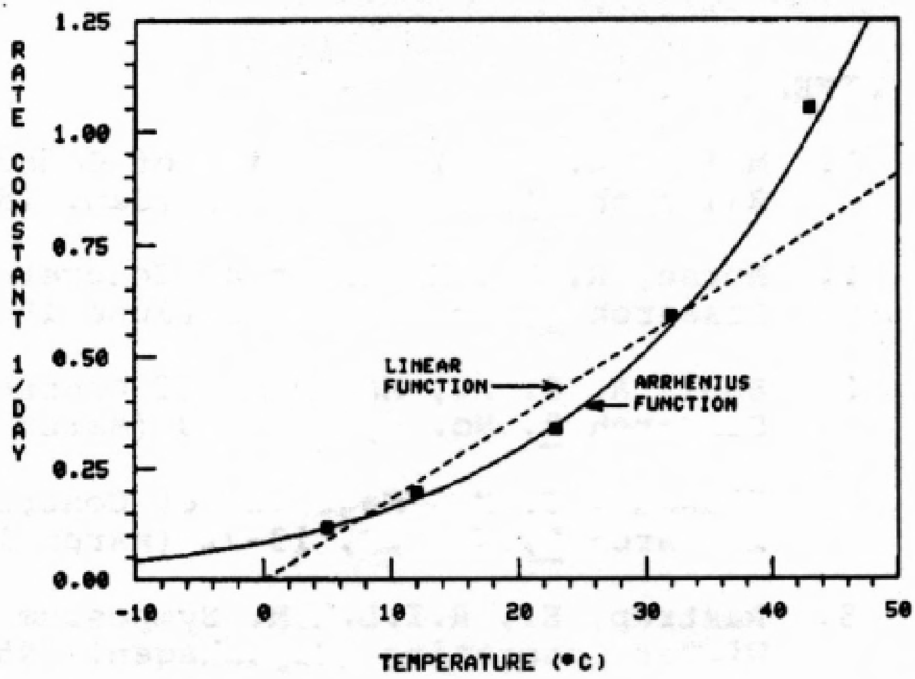


Figure 2-2. Variation of the rate constant, k, with curing temperature. From Carino 1982.

2.4.5.5 Developed Maturity Equations

Plowman (1956) developed a maturity equation which can predict strength based on maturity. The equation requires determining two regression constants through statistical analysis of compression test data and the temperature-time history of the initial concrete samples taken before any field (in-place) concrete studies begin.

$$S = \alpha + \beta \log_{10} M \qquad (6)$$

α and β = constants

S = strength

M = maturity (°F-hr)

Later work demonstrated the limitations of Plowman's equation. The most notable deficiency in this early equation is the prediction of infinite strength as maturity approaches infinity (Carino et. al. 1983). Plowman indicated that the equation would only apply to curing temperatures below 100 °F (Plowman 1956). Oluokun (1990) identified another shortcoming of Plowman's equation—the function was developed based on testing of Type I cement. Today, the range of available cements, admixtures, and SCMs necessitates development of functions that predict concrete development based on maturity where these different materials are used. Another deficiency identified by Oluokun (1990) is that Plowman's equation is unreliable for strength prediction at early ages (less than 3 days).

Later studies examined the limitations of early work involved with the maturity method—alternative equations were proposed which overcame many of the method's deficiencies. Kee (1971) developed an equation showing a hyperbolic representation of the strength-maturity relationship. Carino et. al. (1983) confirmed that Kee's hyperbolic strength-maturity equation is an accurate representation of strength versus maturity data, and that the hyperbolic strength-maturity equation will accurately predict strengths at early ages and under varying early age temperature conditions. Kee's equation according to Carino et al (1983) is:

$$S = \frac{M}{\frac{1}{A} + \frac{M}{Su}} \tag{7}$$

S = compressive strength

S_u = limiting compressive strength at infinite age

M = maturity

A = initial slope of the strength-maturity curve

Oluokun (1990) also developed an equation to accurately predict strengths given maturity for early age concretes. Oluokun's equation should only be used for ages up to 28 days, but for the recommended age range, the equation is more accurate. The greatest improvement is for early ages up to 1 day. The equation is as follows:

$$f_{cx} = f'c(1-e^{-\gamma m}) \tag{8}$$

f_{cx} = strength at maturity M

m = maturity M divided by 10,000

f'c = 28 day compressive strength

γ = constant

Carino and Tank (1991) showed that because curing temperature affects the ultimate or limiting strength of a concrete mixture, there is a not a unique strength versus equivalent age relationship for a concrete mixture—instead, there is a unique relative strength/equivalent age relation. So that for any given maturity numerical index the relative strength gain of a concrete could be then predicted. If the limiting strength of a particular concrete is known, then the compressive strength could be determined. The investigators proposed the "rate constant model" to predict the relative strength of in-place concrete from its equivalent age. The equation utilizes the simplified exponential rate constant shown in (5).

$$\frac{S}{S_u} = \frac{k_r(t_e - t_{or})}{1 + k_r(t_e - t_{or})} \tag{9}$$

S = compressive strength

S_u = limiting compressive strength at infinite age

k_r = rate constant at a reference temperature

t_{or} = age at reference temperature where strength development begins

t_e = equivalent age

Relative strength/equivalent age relationships for a wide range of mixtures utilizing Type I, II, and III portland cement with w/cm ranging from .45 to .60 and curing temperatures of 50, 73, and 104 °F (10, 23, and 40 °C) as well as mixture designs with additions of fly ash and slag cement were compared with a relative strength/equivalent age relationship determined from the rate constant model and the data was modeled accurately (Carino and Tank 1992).

2.5 Summary

A great deal of research has been conducted on the factors that affect setting times and concrete strength gain. It has been widely accepted that the substitution of either SC or FA in concrete tends, typically, to delay the setting times of concrete. These substitutions are also known to reduce the rates of strength development, resulting in lower strength at early ages. Curing temperature has also been found to affect these properties of concrete. Curing concrete at relatively low temperatures (32 F to about 68 F) will typically cause longer setting times, as well as prolong the strength gain of the concrete.

However, very little research has been conducted incorporating all three of the aforementioned factors: SC, FA, and low temperatures. In order to establish any specifications for the use of ternary concrete mixtures in low temperatures, the behavior of such mixtures should be examined under these conditions. This research program will study ternary mixtures incorporating different quantities of SC and FA at a wide range of temperatures to understand the behavior of such mixtures.

Chapter 3

Research Program and Experimental Procedures

3.1 Introduction

The objective of the research program was to examine the time of setting and strength gain characteristics of ternary concrete mixtures cured at varying temperatures. Specifically, these mixtures were cured lower than 70 F, with 70 F being the control temperature. Standard fresh and hardened concrete properties were measured for each batch.

3.2 AHTD Specifications for Portland Cement Concrete Pavements

Any mixture classified as "Portland Cement Concrete Pavement" must adhere to the requirements established by AHTD in Division 500, Section 501 of the Standard Specifications. A minimum of 564 pounds of cement must be used in each cubic yard of concrete produced, and the mixture's water-to-cementitious materials ratio (w/cm) cannot exceed 0.45, including the moisture contained in the aggregate. Also, an air content range of 4 to 8 percent is specified, though no air-entraining admixtures (AEA) were used in the study. The addition of AEAs will decrease strength and affect workability. To eliminate the differences caused by the AEA, the mixtures examined in this study contained only entrapped air. AHTD allows the use of fly ash (FA) at a rate of 1 pound of FA for each pound of PC replaced. However, this replacement is limited to 20 percent (by mass) of the total cement content. Both classes of FA (Class C and Class F) are acceptable, but cannot be mixed. Similarly, slag cement (SC) may be substituted at a rate of 1 pound of SC per pound of PC replaced, up to 25 percent of the total cement content. SC used must be Grade 100 or higher. Neither FA nor SC may be used as a replacement for Type III or blended cements. Currently, AHTD's Standard Specifications do not permit the use of ternary concrete mixtures (AHTD 2003).

In addition to specifying concrete material quantities, AHTD also requires pavement concrete mixtures to exhibit various properties. As mentioned previously, air content and w/cm are specified. AHTD also requires a minimum 28-day compressive strength of 4000 psi. The concrete should have a "uniform consistency", and a slump of 2 inches or less (AHTD 2003).

3.3 Materials

3.3.1 Aggregates

Fine aggregate used in this study was river sand obtained from Arkhola in Van Buren, AR. The coarse aggregate used at the beginning of the study (CA 1) was crushed limestone from McClinton-Anchor in Springdale, AR. After batches A-1, A-2, B-1, B-2, C-1, C-2, D-1, and D-2 were completed, a new shipment of coarse aggregate was obtained from Arkhola, also in Springdale, AR. This aggregate (CA 2) displayed properties similar to CA 1. Aggregate properties will be discussed below in more detail. All aggregates used in this study complied with AHTD Standard Specifications Section 501.02. According to this section, fine aggregates used in Portland Cement Concrete Pavement (PCCP) should consist of clean, hard, and durable particles. Fine aggregates should meet AHTD requirements for deleterious substances and gradations. Coarse aggregates used in rigid pavements should meet the same requirements as those for fine aggregates. In addition, coarse aggregate should adhere to the guidelines for soundness and abrasion, as specified in the Standard Specifications (AHTD 2003). Table 3-1 shows the absorption, specific gravity, dry rodded unit weight and MSA of the aggregates used for this study.

Table 3-1: Fine and Coarse Aggregate Properties

	Fine Aggregate	Coarse Aggregate	
	River Sand	CA 1	CA2
Absorption (SSD)	0.48	0.38	1.10
Specific Gravity	2.60	2.68	2.66
Dry Rodded Unit Weight (lb/ft^3)	-	110.9	94.4
MSA (in)	-	1.5	1.5

The fine aggregate properties in Table 3-1 were determined by Arkhola, the properties of CA 1 were determined by McClinton-Anchor, and the properties of CA 2 were determined by Arkhola. Listed in Table 3-2 are the gradations of the coarse aggregates used in the study, along with allowable gradation limits, as specified by AHTD. Table 3-3 shows the gradation and AHTD limits for the fine aggregate used in the study. Both gradations were determined according to ASTM C 136.

Table 3-2: Coarse Aggregate Sieve Analysis

Sieve	CA 1 % Passing	CA 2 % Passing	AHTD Standard Gradation % Passing	AASHTO M43 #57 % Passing
1-1/2”	100	100	100	100
1”	100	100	60-100	95-100
3/4"	74	72	35-75	-
1/2"	35	38	-	25-60
3/8"	14	23	10-30	-
# 4	2	2	0-5	0-10
# 8	1	2	-	0-5
# 200	-	1.5	-	-

Table 3-3: Fine Aggregate Sieve Analysis		
Sieve	Fine Aggregate % Passing	AHTD Specifications % Passing
3/8"	100	100
# 4	98	95-100
# 8	92	70-95
# 16	80	45-85
# 30	58	20-65
# 50	18	5-30
# 100	2	0-5

3.3.2 Cementitious Materials

Portland cement and supplementary cementing materials (SCMs) used in this study conformed to AHTD specifications, as well as ASTM C 150 for PC, ASTM C 618 for FA, and ASTM C 989 for SC. The PC used was Lafarge Type I cement from Tulsa, OK. SC used was Grade 100 from Holcim, Inc. in Birmingham, AL. FA used was a Class C fly ash from Headwaters Resources in Redfield, AR.

3.4 Strength Gain Study

The major task in the research program was the examination of the strength gain of ternary concrete mixtures. Specifically, the study examined the effect of low curing temperatures (33, 40, 50, 60, and 70 F) on the rate of strength gain. Included in the study are six mixtures.

All the mixtures tested contained the same quantity of coarse aggregate, w/cm, and total cement content. The only variations in the mixtures were the quantities of SCMs, curing temperatures, and sand content. The proportions for the mixtures studied in the research program are shown in Table 3-4.

Table 3-4: Mixture Proportions

Mixture ID	w/cm	Cement (lb/yd^3)	Slag Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Coarse Agg. (lb/yd^3)	Fine Agg. (lb/yd^3)	Water (lb/yd^3)
0/0	0.45	650	0	0	1900	1164	293
20/20	0.45	390	130	130	1900	1135	293
40/20	0.45	260	260	130	1900	1114	293
40/40	0.45	130	260	260	1900	1093	293
20/40	0.45	260	130	260	1900	1113	293
20/60	0.45	130	130	390	1900	1092	293

The mixtures tested included a control mixture containing only PC, a low replacement mixture (20 percent SC, 20 percent FA), two high replacement mixtures (40 percent SC, 40 percent FA and 20 percent SC, 60 percent FA), and two moderate replacement mixtures. Each mixture will be referred to herein as %SC/%FA (Curing Temperature). For example, when Mixture 2 was cured at 70 F the batch will be identified by the name "20/20 (70)."

As Table 3-4 illustrates, the only variable between mixtures was the content of SCMs and the sand content. Mixture 0/0, the control mixture to which all other mixtures were compared, contained only PC. In Mixture 20/20, 20 percent of the PC was replaced with SC and 20 percent with FA. In Mixture 40/20, 40 percent of the PC was replaced with SC, while 20 percent was replaced with FA. Mixture 40/40 consisted of 40 percent SC, 40 percent FA, and 20 percent PC. Mixtures 20/40 and 20/60 contained 20 percent SC, 40 and 60 percent FA (respectively), and 40 and 20 percent PC (respectively). Each of these mixtures was batched five times – once for each curing temperature (70, 60, 50, 40, 33 F).

3.5 Experimental Procedures

3.5.1 Mixtures and Batching

The six mixtures tested in the study were developed by research conducted at the University of Arkansas (Becknell 2005). The w/cm of these mixtures was 0.45 and the mixtures were designed based on the requirements set forth by AHTD specifications. No air-entraining admixtures (AEAs) were employed, resulting in air contents lower than those required by AHTD. However, the air content could be increased to within the acceptable range with the addition of AEAs to the mixtures. SC and FA were substituted into the mixtures at a rate of one pound of SC or FA added for each pound of PC removed. The mixture proportions of the mixtures are illustrated in Table 3-4.

Aggregate used in the mixtures was conveyed to the lab in wheelbarrows and shoveled into five gallon buckets. Each bucket was weighed and adjusted to 50 pounds. Lids were immediately placed on these buckets to prevent moisture loss. Before the batching was carried out, moisture contents were determined for the coarse and fine aggregates. This was completed by obtaining representative samples of aggregates from the wheelbarrows during the aggregate preparations one day prior to batching. These samples were weighed and oven dried to a constant mass (ASTM C 566). The mixture proportions were then adjusted for the moisture contained in the aggregates.

All batches were mixed according to ASTM C 192, the “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory”. Mixing was carried out in a rotating drum mixer with a capacity of nine cubic feet. Mixtures were typically 6.5 cubic feet. The mixing procedure consisted of adding all of the coarse aggregate and half the mixing water. The mixer was then started and the fine aggregate was added, followed by the cementitious materials and the remainder of the mixing water.

Batching began during February, and continued into September, which presented a dramatic change in ambient temperatures. To ensure a more consistent fresh concrete temperature, mixtures prepared during the warmer months were batched with chilled mixing water. One day prior to batching, when preparing aggregates, an adequate amount of water (around 60 pounds) was placed in the 33 F curing chamber and left overnight. Also, aggregates were placed on a cart and stored overnight in an air-conditioned area to avoid batching with hot aggregates.

3.5.2 Curing

Immediately after batching and casting, compressive strength and time of setting specimens were placed in chambers adjusted to the appropriate temperature. All specimens except those cured at 33 F were moist cured. “Moist” conditions were achieved by covering the specimens with wet burlap and plastic sheeting. Specimens were maintained in moist conditions at the appropriate temperatures until testing. Mixtures cured at 33 F were excluded from moist curing due to the near-freezing conditions in the chamber.

Since the study examined the effects of low temperatures on the mixtures, five chambers were required for curing the test specimens. Those batches cured at 70 F were placed in an environmental chamber which was already in place in the laboratory. To cure mixtures at 40, 50, and 60 F, three chambers were constructed by the research team. These chambers can be seen in Figures 3-1 and 3-2.

Figure 3-1: The Curing Chambers (before insulating the A/C unit)

Figure 3-2: Inside a Curing Chamber

These chambers, made of wood, were placed adjacent to one another, with wooden "ducts" connecting them. These chambers were approximately 4 feet wide by 4 feet long by 2 feet deep. They were insulated by 0.75 inch Styrofoam® sheets. An air-conditioning (A/C) unit, which was re-wired to allow the fan and compressor to be controlled separately, was installed in the 40 F chamber, which was the first in the series. Inside each chamber, a small 1,500 watt ceramic heater was placed. These heaters were also reconfigured to allow the heating elements and fans to work independently. These heaters were used to raise the temperatures in each chamber to 10 F above that of the previous chamber. For example, the A/C unit brought the air below 40 F, and the heater in the first chamber maintained the temperature at 40 F. Then, the heater in the second chamber raised the temperature to 50 F, and the heater in the third chamber raised the temperature to 60 F. At the end of the system (outside the 60 F chamber) a flexible

HVAC duct was installed to route the air leaving the system into a small insulated box containing the A/C unit, allowing the unit to cool the 60 F air instead of room temperature air to 40 F.

During the summer months, the researchers discovered that the A/C unit could not achieve the 40 F temperatures desired. The A/C unit was installed just outside the system, with a wooden duct connecting the unit to the 40 F chamber. To aid the unit in cooling warm summer air to 40 F, a small box made of the same insulating material used inside the chambers was placed around the unit (see Figure 3-3). A flexible HVAC duct was then routed to this box from the end of the system (the 60 F chamber), as discussed above.

Figure 3-3: Insulated Box Surrounding the A/C Unit

Figure 3-4: Intervalometer

As stated previously, the unit was reconfigured to permit individual control of the fan and the compressor. The fan remained in the "ON" position at all times, forcing a constant air flow through the system. The compressor was controlled by an intervalometer, or a timer (Figure 3-4). This device kept the compressor on as long as possible to ensure adequate and consistent low temperatures, but turned it off soon enough and long enough to ensure that ice did not form on the condenser. The settings of the intervalometer were changed as necessary to accommodate changes in weather conditions.

Small heaters were installed inside each of the three curing chambers to increase the temperature from that coming from the A/C unit or the previous chamber to the desired temperature. These heaters were reconfigured in a manner similar to that of the

A/C unit. The fans in the heaters remained on at all times to distribute air inside each chamber and ensure uniform temperatures within them. The heating elements were controlled by temperature controllers manufactured by Cole-Parmer® which were set at the desired temperatures for each chamber. To check the consistency of the chamber temperatures, a bottle of tap water was placed in each chamber and a digital cooking thermometer was inserted into each bottle. These thermometers were monitored to ensure that each chamber was maintained at the appropriate temperature.

Figure 3-5: Temperature Controller

In order to cure samples at 33 F, a different apparatus was needed, especially in the summer months. To accommodate such a low temperature, a large chest freezer was equipped with a heater and temperature controller similar to those used in the other curing chambers. This freezer is shown in Figures 3-6 and 3-7.

Figure 3-6: Chamber for 33 F Curing (Inside)

Figure 3-7: Chamber for 33 F Curing (Outside)

3.5.3 Fresh Concrete Tests

Several fresh concrete tests were performed on each batch. These tests included temperature (ASTM C 1064), slump (ASTM C 143), unit weight and relative yield (ASTM C 138), and air content (ASTM C 231). Relative yield is defined in ASTM C 138 as the ratio of the actual volume (yield) of concrete after batching to the design volume (design yield). Each of these tests was performed at the time of batching.

3.5.4 Time of Setting Tests

The times of initial and final setting (ASTM C 403) were measured for each batch tested in the research program. Each time of setting was based on the average of at least three specimens. When possible, four specimens were cast and tested. However, on some occasions there was not enough material to cast a fourth. The specification required only three specimens. To determine time of setting, a needle of known cross-sectional area was pushed one inch into the specimen in ten seconds. The penetration resistance (pounds) required for this act was recorded and divided by the area of the needle used. As the setting process proceeded, the area of the needle decreased from 1 in^2 to 0.025 in^2. A minimum of six readings were taken for each of the samples tested. These points were plotted and a trendline was fit to the data using a spreadsheet. The equation for the trendline was used to calculate the times of initial and final setting. The time of initial setting is defined as the time required to achieve penetration resistance of 500 psi. The time of final setting is defined as the time required to attain penetration resistance of 4000 psi.

3.5.5 Compressive Strength Tests

Compressive strength (ASTM C 39) was measured for each of the mixtures at each of the temperatures. These tests were conducted when samples reached 1, 3, 7, 28, and 90 days of age. Three cylinders were tested at each age. The compressive strength was measured using a 400 kip capacity testing machine. Sample ends were placed on neoprene pads (70 durometer hardness). These pads were seated in steal rings.

3.6 Maturity Testing

The final objectives of the research program were to perform a strength gain study, a maturity testing program, and an activation energy/datum temperature study in order to develop strength estimation methods for ternary concrete mixtures cured at low temperatures. The strength gain study involved batching the same ternary concrete mixtures as previously discussed and measuring compressive strength at specified ages. Three concrete slabs measuring 20”x8”x8” were cast from each mixture and cured at temperatures ranging from 33 to70°F in order to simulate a range of low temperature conditions. The slabs contained a maturity logger which measured the temperature-time history of the hardening concrete. Maturity index calculations were performed using the temperature-time data, and, subsequently, strength-maturity relationships were developed from the compressive strength data derived from the slab testing.

After the maturity study had begun, it became obvious that more appropriate values for activation energy and datum temperature be used for the time-temperature and equivalent age maturity functions (Equations 1 and 2). Activation energy and datum temperature for ternary mixtures are not available in the peer-reviewed literature. Schindler (2004) provides an activation energy model applicable to ternary concrete mixtures provided the chemical composition of all the cementitious materials is known. Preliminary attempts to determine these values accurately from the results of the strength and maturity studies were ineffective. Based on these shortcomings, an activation energy and datum temperature study was undertaken to experimentally derive these values.

This final study required casting and curing 2 in. mortar cubes representative of the same mixtures used in the strength and maturity studies. The cubes were cured in water baths at 40, 70, and 100 °F. Rate constants for each mixture at the three different curing temperatures were determined by regression analysis from mortar cube compressive strength test results. As will be discussed in more detail in the following sections, the activation energy and datum temperature was derived from an analysis of the rate constants.

3.6.1 Maturity Study

The maturity study involved casting concrete slabs from identical mixtures as the strength study. These mixtures are shown in Table 3-4 of Section 3.4. These slabs were intended to better represent field conditions for in-place concrete than traditional 4"x8" cylinders. The purpose of this study was to develop strength versus maturity index relationships which could be used for measuring strength gain for similar concrete mixtures in the field. The activation energy and datum temperature study was completed to experimentally derive these values for ternary concrete which allowed for accurate calculation of maturity indices. This last study involved casting and curing mortar cubes and then measuring compressive strength of the cubes at specified ages. A regression analysis was subsequently conducted to determine the rate constants for strength gain. The rate constant temperature relationships were further analyzed in order to determine activation energy and datum temperatures for each mixture.

3.6.1.1 Batching and Test Specimens

The batching and specimen preparation process followed ASTM C 192 "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." Batches were mixed in a stationary revolving drum mixer, and immediately after mixing fresh concrete tests were performed and the sample specimens were prepared (Figure 3-8). For the strength study, standard 4"x8" cylinders were cast. For the maturity study, 20"x8"x8" slab forms were cast (Figure 3-9). These slab forms were specifically constructed for this project. Each of the slabs contained (3) 4"x8" waxed cardboard cylinder molds and a maturity logger.

Figure 3-8. Stationary Drum Mixer.

Figure 3-9. Experimental Slab Forms.

3.6.1.2 Maturity Loggers

The maturity loggers, manufactured by Engius, are one part of the Intellirock II maturity and temperature measurement system. The logger after placement in the fresh concrete records temperature and automatically calculates maturity based on user-defined parameter inputs at 15 minute intervals. The loggers available from Engius include the Nurse-Saul and Arrhenius models. The former model uses the time-temperature maturity function while the latter uses the equivalent age maturity function. The latter model was chosen by the investigators due to the preferred use of the equivalent age function in recent peer-reviewed literature.

Figure 3-10. Maturity Meter and Loggers.

The second part of the Intellirock II system is a reader which sends commands to the logger and acts as a shuttle for data transfer. The reader is commonly referred to as a maturity meter, because of the reader's most common function, connecting with in-place loggers and displaying maturity information for hardening concrete. Figure 3-10 is a photograph of the maturity meter used in this research program and three loggers. The Intellirock II system includes Windows® based software that allows for transferring the results to a spreadsheet program for further manipulation.

The cylinders contained within the slab forms were prepared identically to that of the strength study cylinders following ASTM C 192. After the cardboard cylinder molds had been cast, the slabs were filled with concrete in two lifts. After each lift, the area around the cardboard molds was rodded approximately 80 times, and a trowel was used to spade along the sides and ends of the forms. The slab forms were then tapped sharply with a rubber mallet 10-12 times per side. The maturity logger was inserted into the fresh concrete after the first layer and was placed between two of the three cylinders. After the second concrete layer was placed and rodded in the slab form, the maturity loggers were started and the slabs were striked flat with a trowel.

During the start procedure for the maturity loggers, the investigators entered the user-defined parameter inputs: batch identification, activation energy, and the reference temperature. The initial activation energy used was 41500 J/mol following the recommendation of ASTM C 1074 which identifies a typical range for Type I cement between 40,000 and 45,000 J/mol. The activation energy was later changed based on experimentally derived values from the final study, and the maturity indices were recalculated. For this reason, the initial maturity indices calculated by the logger were not reported. A reference temperature of 23°C was used based also on ASTM C 1074.

3.6.1.3 Curing

After specimen preparation, samples were transferred to the environmental chambers. The air-temperature of the chambers was maintained at 33, 40, 50, 60, and 70°F. The 33, 40, 50, and 60°F chambers were specifically constructed for this project. Due to their temporary nature and cost considerations, these were built relatively small (40, 50, and 60°F chambers were 2ftx4ftx4ft). The curing chambers were described in greater detail in section 3.5.2.

3.6.2 Activation Energy and Datum Temperature Study

This study was undertaken to more accurately determine the activation energy and datum temperature used for the equivalent age and temperature-time maturity functions. These parameters were derived experimentally for the different curing temperatures and mixtures following a mortar cube procedure presented in ASTM C 1074.

3.6.2.1 Mortar Cube Mixture Proportion and Batching

The proportion of cementitious materials and w/cm for the mortar mixtures followed the strength and maturity study concrete mixtures. The proportion of fine aggregate for the mortar mixtures were selected based on a ratio of fine aggregate-to-cement that was identical to the coarse aggregate-to-cement ratio for the corresponding concrete mixture following the recommendation of ASTM C 1074. The material from the fine aggregate stockpile was sieved through a No. 4 screen to remove coarse aggregate particles. A total of six different mortar mixtures were examined, and these mixtures were numbered the same as the corresponding concrete mixtures based on the amount of PC replacement (See Table 3-8). Since the mortar mixture numbers were the same as the mixture numbers used in the strength and maturity studies, the "M" designation was added to indicate that these mixtures are the mortar mixtures.

Note that in Table 3-5 the total weight of cementitious material is constant for all mixtures. The total weight of cementitious material is the sum of the weights of the portland cement, fly ash, and slag cement. Replacement of PC by either SC or FA is done by weight, and an equal weight of SC or FA is substituted for the weight lost due to the PC replacement. Therefore, the different replacement rates across the range of mixtures cause the weight of the different constituent cementitious materials to change, but the total cementitious material weight does not change. The sum of the weights for PC, SC, and FA for all of the mixtures are the same even though the individual weight of each material may vary from mixture to mixture.

Temperature control of the fresh mortar was performed in order to produce a fresh mortar temperature that was as close to the target curing temperature as possible. The three targeted mortar temperatures were 40, 70, and 100°F. The optimum conditions for experimental determination of activation energy and datum temperature occur when the internal temperature of the mortar cubes reach equilibrium with the water baths as quickly as possible. This minimizes differences in the strength development between the batches which may otherwise have been attributed to early age temperatures that are significantly different from the target curing temperatures. Further, equations used for determining activation energy and datum temperature were developed for isothermal curing conditions.

The primary method used to control the fresh mortar temperature was storing the aggregate and mixing water in the curing chamber prior to mixing for at least 24 hr. In the case of the 100°F curing condition, hot tap water was used for the mixing water. The aggregate and mixing water was not stored in the 100°F chamber. This became necessary due to several failures of the 100 °F curing chamber's heating system. The thermal overload safety switch was opening which was caused by insufficient air movement through and around the heater. This shut down the heating system. Storage of the aggregate and mixing water in the chamber was no longer possible in order to provide a clear zone of approximately 1 ft radius around the heater. The investigator then began using the heated tap water for the mixing water as an alternative to the previous method.

Table 3-5. Mortar Mixture Proportions (yd^3)

Mortar Mixture Number	Total Cementitious Material (lb)	PC (lb)	SC (lb)	FA (lb)	Fine Aggregate (lb)	Water (lb)
M 0/0	650	650	0	0	1900	293
M 20/20	650	390	130	130	1900	293
M 40/20	650	260	260	130	1900	293
M 40/40	650	130	260	260	1900	293
M 20/40	650	260	130	260	1900	293
M 20/60	650	130	130	390	1900	293

Figure 3-11. Paddle Mixer.

Figure 3-12. Flow Test Measurement.

Two inch mortar cubes were cast in polyethylene cube molds. The mortar was mixed in a paddle mixer following ASTM C 305 (Figure 3-11). Immediately after mixing, the flow for the mortar was measured according to ASTM C 1437 (Figure 3-12). Following the flow test and prior to casting, the fresh mortar temperature was measured and recorded. The mortar was then placed in the cube molds in two layers, tamped after each layer, and the excess was struck off following the specimen preparation procedures in ASTM C 109 (Figure 3-13). Two of the cubes contained thermocouples for temperature measurement during the curing process.

Figure 3-13. Mortar Cube Casting.

3.6.2.2 Mortar Cube Curing

After casting, the cube molds were carefully submerged in water baths maintained at 40, 70, and 100°F (Figure 3-14). The environmental chambers from the strength and maturity studies were utilized for the mortar cubes. In order to facilitate the submerged curing, plastic storage bins were filled with water and placed in the chambers and the water temperature was allowed to reach equilibrium with the air temperature. The 100°F curing condition was provided by increasing the set point of the previously used 60°F chamber from the strength and maturity studies. All of the cubes were kept in the curing water baths until time of testing. The different water bath temperatures were chosen in order to cover the range of temperatures which concrete is likely to experience in the field as well as to better understand rate constant behavior over a wide range of temperatures (ASTM C 1074).

Recording the internal temperature of the mortar cubes was achieved through the use of a data logger (Measurement Computing Model USB-5201) and thermocouples following a modified procedure adapted from Tank (1988). Two mortar cubes from each batch were instrumented with thermocouples. After the cubes were submerged in the water baths, the thermocouples were connected to the data logger. The data logger's eight input channels allowed for simultaneous monitoring of up to four different batches. Temperature was recorded every minute up to the time of the third test. The curing temperature used in the data analysis was the average temperature that occurred during the time between initial submergence and the third test age. The monitoring period was selected based on previous research in the literature (Tank 1988) and based on the need to free up the data logger for subsequent mortar batches.

Typically, the mortar cubes were demolded following the first compression test. Mixtures 40/40 and 20/60 were demolded following the second test, because of the risk of damage to the cubes during early ages due to handling. The cubes maintained at 100°F were demolded within 24 hrs. except for Mixtures 40/40 and 20/60 which were demolded within 48 hrs.

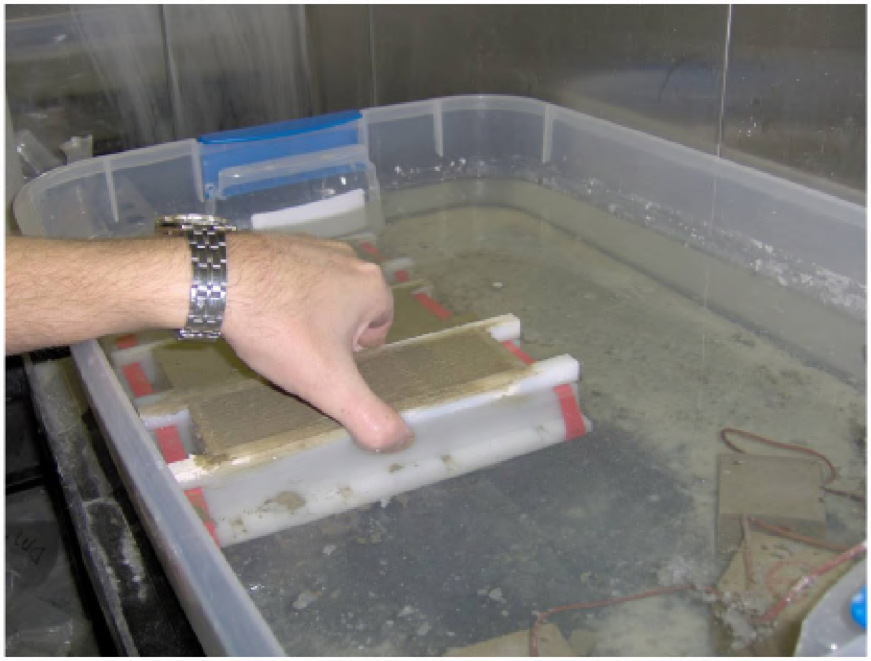


Figure 3-14. Placement of Mortar Cube Molds in Water Bath

3.6.2.3 Compression Testing of Mortar Cubes

The mortar cubes were tested in compression following ASTM C 109. The initial test ages were selected based on the investigator's experience with the different mixtures gained from the strength and maturity studies and from time of setting results for these same mixtures reported in Wilhite (2007). In an attempt to replicate the experimental procedures used in previous work by Carino (1982) and by Tank (1988), seven different test ages were selected. Following the initial test, subsequent tests were conducted at ages approximately double that of the previous tests.

3.6.2.4 Data Analysis

A statistical analysis program, SAS, was initially used to perform a multiple factor analysis of variance in order to determine if significant statistical differences exist between the compression tests versus age data of the maturity study slab cylinders compared with the data of the strength study cylinders for all different mixtures and curing temperatures. This method of analysis was abandoned after results demonstrated that the data was not normally distributed and that a constant variance did not exist. A larger sample size at each test age ($n \geq 30$) would be required to make use of this method of analysis. The investigator chose instead to compare 90% confidence intervals for the slab and cylinder data.

As part of the activation energy and datum temperature study, a regression analysis procedure was applied to the results of the mortar cube compression tests using a computer program, Kaleidagraph. This regression procedure produced equations based on the mortar cube strength and age data. The goodness-of-fit for these models were compared based on statistical analysis.

3.6.2.5 Activation Energy and Datum Temperature Determination

The accuracy of the activation energy used for calculating the equivalent age maturity function is important in order to improve the results of the maturity method. Activation energy was determined following a procedure provided in ASTM C 1074. A software program, Kaleidagraph, was used to perform a generalized curve fit of the mortar cube compression test results to the hyperbolic equation for isothermal curing conditions presented by Carino (1984):

$$\frac{S}{S_u} = \frac{k_T(t - t_0)}{1 + k_T(t - t_0)} \qquad (12)$$

S = average mortar cube compressive strength at the test age (psi)

S_u = ultimate or limiting strength (psi)

k_T = rate constant (1/day)

t = test age (day)

t_o = dormant period where strength development is believed not to occur (day)

A strength versus age plot was first created in Kaleidagraph for the mixture and curing temperature. The program then performed a generalized curve fit to the data based on the hyperbolic equation. The investigator is required to enter initial guesses for ultimate strength, S_u, rate constant, k_T, and, dormant period, t_o. Further, the allowable error must also be entered. The initial inputs used were 9000 (psi), 1 (1/day), and 0.001 (day) for S_u, k_T, and t_o respectively. These are only the initial guesses that the program uses in order to begin the iteration, and have no affect on the results. The allowable error chosen was 0.1%. The program performs a regression analysis to determine the best-fit for each of the three unknown parameters. The results of the regression provide the parameter value, parameter standard error, Chi-square value, and the correlation coefficient, R.

This curve-fitting process was performed for each mixture at each of the three curing temperatures. The rate constants, k_T, for each curing temperature were used to calculate the activation energy. The natural logarithm of the rate constant was plotted against the inverse of the curing temperature. The curing temperature must be converted to the Kelvin scale. A linear trend line was then fit to the plot. The negative of the slope of the line is the activation energy in units of J/mol divided by the ideal gas constant, 8.3144 J/(K-mol).

The datum temperature required for the time-temperature maturity function was also determined using the rate constants derived from the regression analysis. In this case, for each mixture the three rate constants from the three curing temperatures were plotted as a function of temperature and a linear trend line was fit to the data. The datum temperature is the intercept with the x-axis. In this case, the Celsius scale is used for temperature.

Chapter 4

Strength Gain Study

Results and Discussion

4.1 General

This chapter is a presentation of the results and observations of the experimental program, the statistical analyses conducted on the results, and a thorough discussion thereof. Data are presented for the strength gain study. The fresh concrete results are presented first, followed by time of setting results. Finally, the results of compressive strength tests are included. Throughout the chapter, mixtures and specific batches are designated using the identification system presented in Chapter 3. For example, the control mixture (Mixture 0/0) is referred to as Batch 0/0 (70) when cured at 70 F. The statistical analyses conducted on the data were discussed briefly in Section 3.6.

4.2 Results of the Strength Gain Study

The experimental program examined the effects of low curing temperatures on the strength gain characteristics of six ternary concrete mixtures. Specifically, the study investigated whether curing temperature affected strength gain of ternary mixtures as significantly as it affected the control mixture. The study examined the time of setting of the ternary mixtures when compared to the control mixture. Also examined was the interaction between portland cement (PC) replacement rates and the curing temperature. The mixtures tested were designed and specimens prepared as outlined in Chapter 3.

4.2.1 Fresh Concrete Properties

The fresh concrete tests performed on the concrete mixtures included concrete temperature, slump, unit weight, relative yield, and air content. Results of these tests are presented in Table 4-1 as an average of all five curing temperatures for each mixture. The values included in the average are based on the statistical analysis described in Chapter 3. The individual values of fresh concrete properties for each batch are included in Appendix A. These tables in Appendix A also include the standard deviations and coefficients of variation (COVs) for the averages shown in Table 4-1.

Table 4-1: Fresh Concrete Properties

Mixture	**Concrete Temperature (F)**	**Slump (in)**	**Unit Weight (lb/ft^3)**	**Relative Yield**	**Air Content (%)**
0/0	68	4.25	150.5	0.9812	1.4
20/20	63	5.25	150.1	0.9753	1.1
40/20	72	4.50	148.9	0.9817	1.1
40/40	71	5.75	148.1	0.9799	0.9
20/40	66	8.00	149.0	0.9789	0.8
20/60	66	8.25	148.5	0.9763	0.6

4.2.1.1 Fresh Concrete Temperature

To ensure quality control, concrete temperature was observed and recorded for each batch that was prepared. The study was intended to model the properties of concrete prepared for field use. Thus, the concrete was batched to exhibit a fresh temperature ranging from 60 to 80 F. While two of the individual batches were slightly outside this window (0/0 (40): 58 F and 20/20 (60): 55 F), the average temperatures for each mixture were well within the specified range. The temperatures reported are a function of the temperature of materials prior to batching and ambient temperatures during mixing. During the summer months, materials were stored in an air-conditioned room and mixing water was chilled to ensure concrete temperatures within the desired range.

4.2.1.2 Slump

Average slumps for each mixture are listed in Table 4-1. The slumps of each individual batch may be seen in Appendix A. In general, slump tended to increase with increasing fly ash (FA) content. Increasing slag cement (SC) content caused a slight decrease in the average slump between Mixture 20/20 (5.25 in.) and Mixture 40/20 (4.50 in.); however, FA contents which were equal to or greater than the SC content offset the detrimental effects of SC. Mixture 20/20 and Mixture 40/40 contained equal replacements of SC and FA, and the average slumps were greater than those of the control mixture, though the difference was not significant in either case. These mixtures (Mixtures 20/20 and 40/40) displayed similar slumps (5.25 and 5.75, respectively). Also, these mixtures displayed slumps slightly higher than that of the control mixture. Mixture 40/20 displayed an average slump somewhat lower than Mixtures 20/20 and 40/20, but very similar to that of the control mixture. The lower slump values for mixtures containing more SC than FA can be attributed to the shape of the SC particles, which are more angular than FA and smaller than PC particles. SC had little effect on slump when compared to the control mixture. Mixtures 0/0, 20/20, 40/20, and 40/40 displayed equivalent slumps when analyzed with a 90 percent confidence interval. These confidence intervals can be seen in Figure 4-1.

Mixtures 20/40 and 20/60 contained higher quantities of FA than SC. FA consists of small, spherical particles which lubricate the mixture and increase workability. Thus, mixtures containing high FA replacements display increased slumps when compared to those with less FA. These two mixtures displayed slumps significantly higher than those of the other four mixtures, based upon 90 percent confidence intervals. The average increase in slump for Mixtures 20/40 and 20/60 when compared to the control mixture is about 4 in.

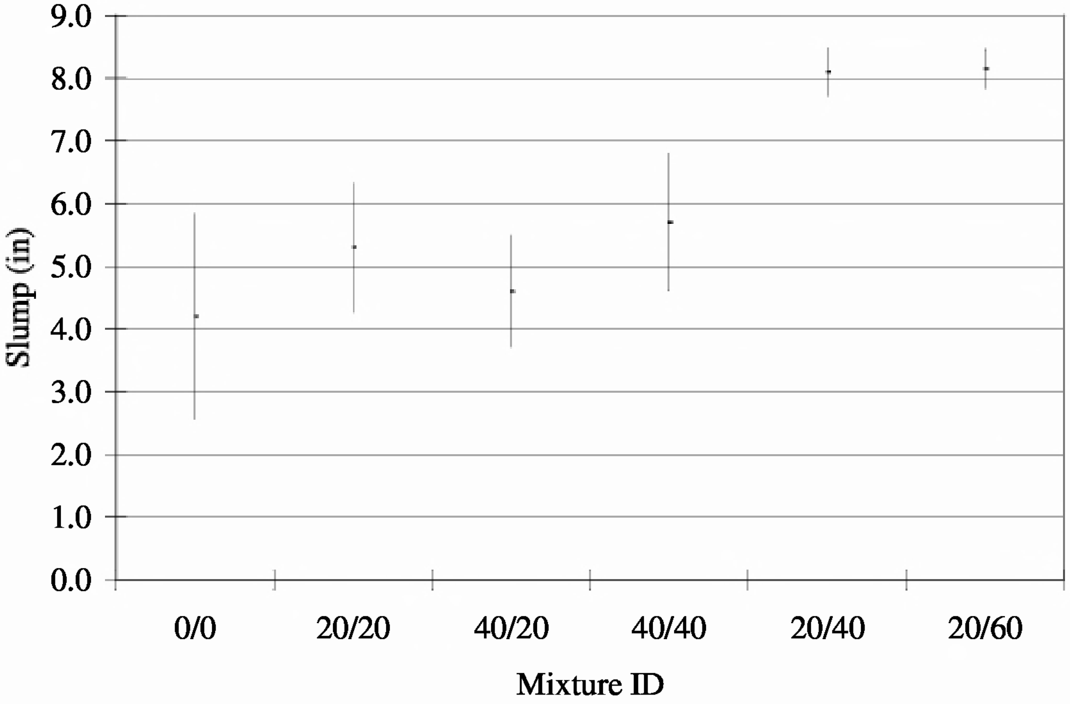


Figure 4-1: 90 % Confidence Interval for Average Slumps

In addition to comparing average slumps for each mixture, the individual slumps for each curing temperature were compared. Mixtures 0/0, 20/20, 40/20, and 40/40 displayed highly variable slumps, based on an analysis of the COV, with a COV greater than 15 percent representing "significant variability". The highest COV was 53 % (Mixture 0/0), with slumps ranging from 1.25 to 7.25 in. Upon examination, the batch with a 1.25 in slump had a fresh temperature of 80 F, while the batch with a 7.25 in slump was batched at 66 F. Throughout the testing program, batches tested at higher concrete temperatures generally displayed lower slumps than otherwise identical batches tested at lower concrete temperatures. Mixtures 20/40 and 20/60 had a COV of 6.4 and

5.1 %, respectively, for slump. The fresh concrete temperatures for these mixtures were maintained at a more consistent level by using chilled mixing water and storing the materials in a room in which temperature could be regulated.

4.2.1.3 Unit Weight

The average unit weights for the mixtures tested are listed in Table 4-1. Individual values are tabulated in Appendix A. Average unit weights ranged from 148.1 lb/ft^3 to 150.1 lb/ft^3. The highest unit weight (150.5 lb/ft^3) was that of Mixture 0/0, followed by Mixture 20/20 (150.1 lb/ft^3). These mixtures are not statistically different, based on the 90 percent confidence intervals, included in Figure 4-2. The remaining mixtures (40/20, 40/40, and 20/40) are not statistically different from each other, but are significantly different from Mixtures 0/0 and 20/20. Mixtures 40/20 and 20/40 contain equal replacements of SCMs, but the average unit weight of Mixture 20/40 is slightly larger than that of Mixture 40/20. The cause of this increase is the higher percentage of FA in Mixture 20/40 than in Mixture 40/20. The specific gravity of FA is 2.6, while that of SC is 2.9, accounting for the variations in the unit weights. A similar trend exists between Mixture 40/40 and Mixture 20/60. The cause of this trend is the same as for Mixtures 40/20 and 20/40. The average unit weights of the mixtures in the study did not vary more than 1.6 percent from lowest to highest.

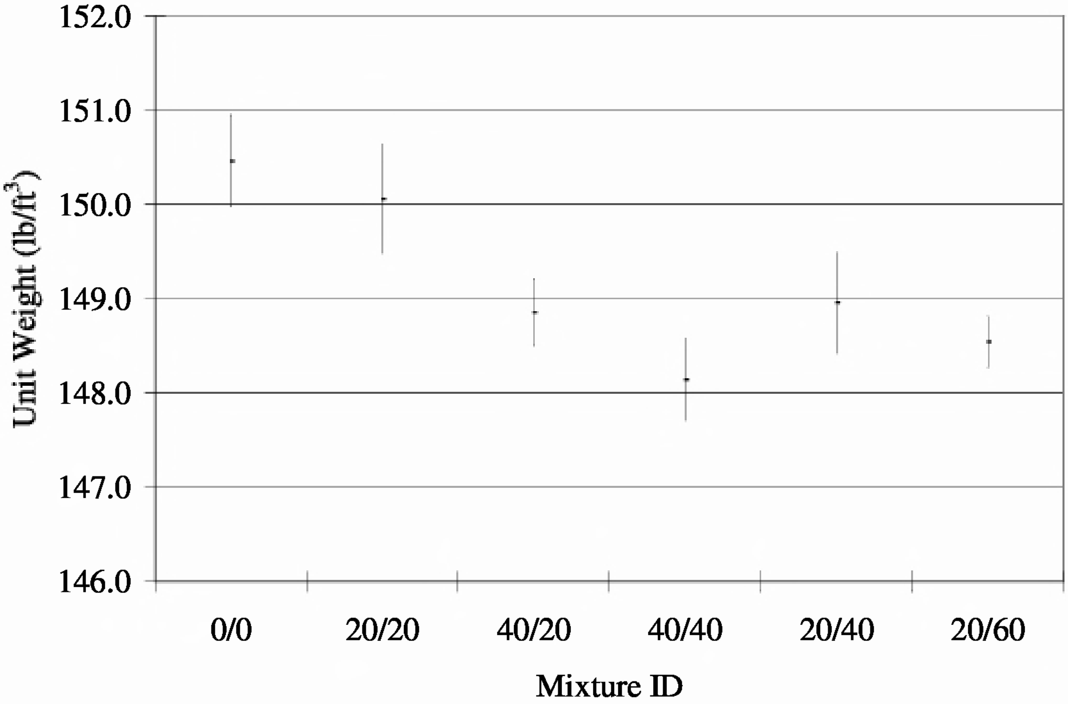


Figure 4-2: 90 % Confidence Intervals for Average Unit Weights

The unit weights of the individual batches of each mixture were compared for uniformity, as well. To perform the analysis, COV was computed including five replicates of unit weight for each mixture (one for each curing temperature the mixtures were subjected to). The COV for each of the six mixtures was less than one percent, indicating that no practical variability existed between each the individual batches.

4.2.1.4 Relative Yield

From the unit weights determined, relative yields were calculated for each mixture. The averages of these values are listed in Table 4-1. The 90 percent confidence intervals are included in Figure 4-3. The relative yields ranged from 0.9753 to 0.9817, meaning that all mixtures tested were within about 98 percent of the design batch volume. Mixture 20/20 was farthest from the design volume, with a relative yield of

0.9753, or 97.5 percent. The mixture closest to the design volume was Mixture 40/20. However, as illustrated by Figure 4-3, none of the ternary mixtures displayed relative yields significantly different from the control mixture. Also, the variation between individual batches of each mixture was analyzed by calculating the COV. The COV in all cases was less than one percent. As 15 percent was the accepted level of variability, the relative yields are considered constant.

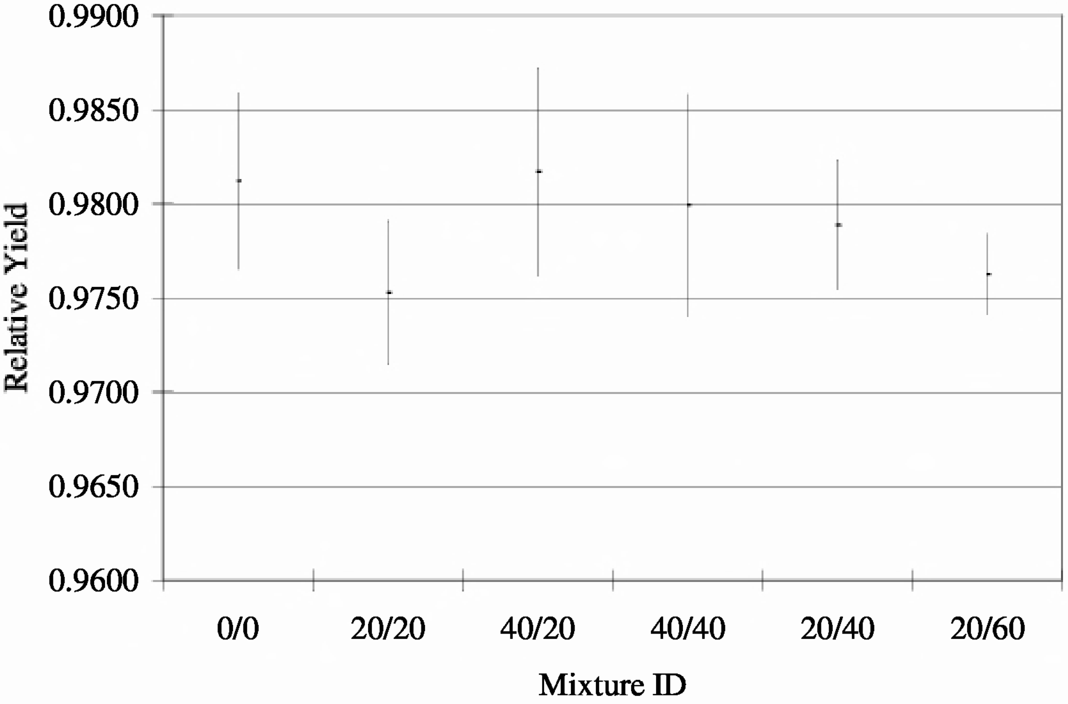


Figure 4-3: 90 % Confidence Intervals for Average Relative Yields

4.2.1.5 Air Content

Air contents were also measured and recorded for each of the 30 batches studied (six mixtures at five curing temperatures). The five replicates for each mixture were averaged to compare the mixtures. These averages are tabulated in Table 4-1. The mixtures tested in the research program contained no air-entraining admixture (AEA). The air contents reported in Table 4-1 are typical of the commonly accepted range of 0.5 to 3.0 percent of air entrapped in mixtures without AEAs (Mindess 2003).The average air contents ranged from 0.6 percent to 1.4 percent. Four of the six mixtures contained between 0.8 and 1.1 percent air. Mixture 0/0, the control mixture, had an air content of 1.4 percent, which was statistically higher than all other mixtures. Mixture 20/60, which contained 20 percent SC and 60 percent FA, achieved the lowest air content (0.6 percent) of the mixtures tested, according to an analysis of the 90 percent confidence interval (Figure 4-4). Upon inspection of the 90 percent confidence intervals, the control mixture displayed significantly higher air content than other mixtures. The addition of SCMs (SC and FA) to the mixture resulted in somewhat less air becoming entrapped in the mixture. Increasing the content of SC caused no practical change in the air content. Increasing the FA caused a significant decrease in the entrapped air, which corresponds with the increased slump/workability displayed by the mixtures containing high FA replacement rates. Mixture 40/40, which contained 40 percent SC and 40 percent FA, was not statistically different from Mixtures 40/20 and 20/40 in terms of air content.

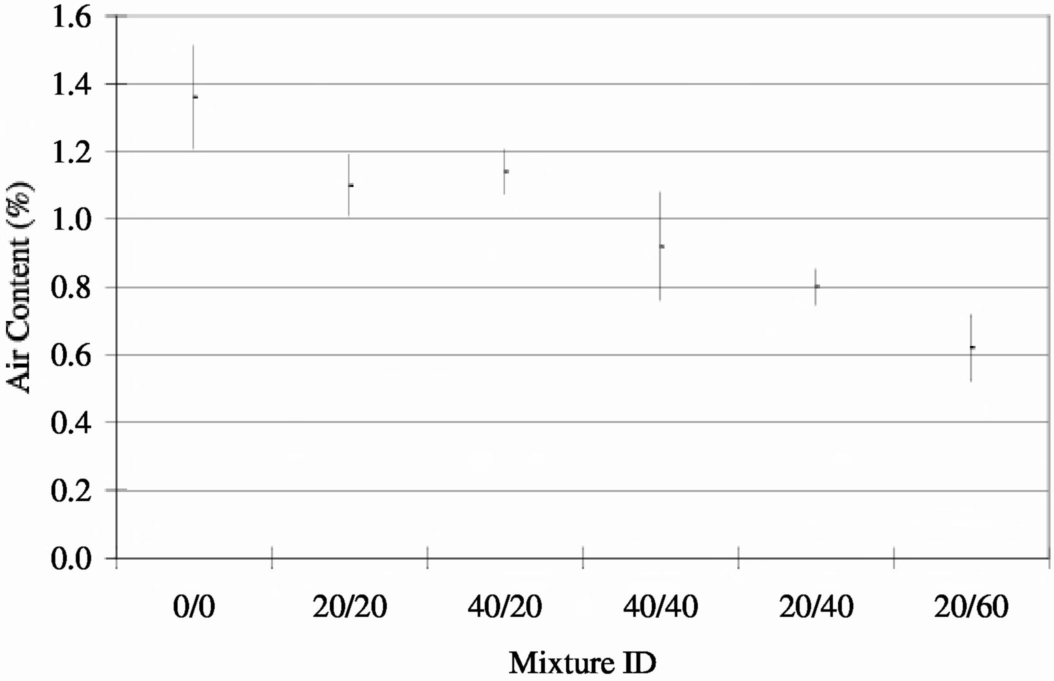


Figure 4-4: 90 % Confidence Intervals for Average Air Contents

Like the other fresh concrete properties, the air contents of the individual batches were also compared for consistency. Using the COV, there is no significant variability in the average air contents of Mixtures 0/0, 20/20, 40/20, and 20/40, indicating that the air contents of identical batches were equivalent. Significant levels of variability are defined in Section 3.6. The COV for Mixture 20/60 was 21, which is slightly higher than the typically accepted value of 15. Upon inspection of the data, no clear explanation for this variability is noticed. Mixture 40/40 displayed a COV of 24, again signifying a more-than-acceptable level of variation. Since the air contents were lower for these mixtures, it is expected that the COV would be slightly higher. Also, the wide variation in ambient temperatures on the batch days of these two mixtures may have led to the higher level of variability in air contents.

4.2.2 Time of Setting

Times of initial and final setting were determined for each of the 30 batches to examine the effect of curing temperature and SCM content on setting times. These times were determined using the method prescribed in ASTM C 403. The setting times for each of the batches tested are shown in Table 4-2. The times listed in this table are the averages of four individual test specimens for each batch. Results are also shown in the form of bar charts in Figures 4-5 through 4-10. Figures 4-11 and 4-12 illustrate the effect of curing temperature on the elapsed time between initial and final set. Figure 4-11 includes all mixtures with less than 80 percent total replacement and comparisons to the control mixture. Figure 4-12 includes those mixtures with 80 percent total replacement (Mixtures 40/40 and 20/60) and comparisons to the control mixture (Mixture 0/0). The results of the time of setting tests are presented and discussed below.

As discussed in Chapter 3, the time of setting data was analyzed using a two-factor Analysis of Variance (ANOVA). The analysis was conducting using SAS Version 9.1. The two factors considered were the mixture number and the curing temperature. The ANOVAs were first conducted for the data as collected. However, the ANOVA assumes that the error terms are normally and independently distributed with a constant variance. These assumptions were proven false when the data was analyzed, so a rank transformation was used. The assumptions were still false when the data was ranked. Thus, the results of the time of setting tests were finally examined using 90 percent confidence intervals.

Table 4-2: Times of Setting

Mixture	Curing Temperature (F)	Initial (hr)	Final (hr)	Time Elapsed (hr)
0/0	70	4.78	6.05	1.27
	60	6.67	8.73	2.06
	50	6.14	8.37	2.23
	40	7.17	10.07	2.90
	33	7.64	12.18	4.54
20/20	70	8.00	10.33	2.33
	60	12.02	15.41	3.39
	50	12.23	16.45	4.22
	40	9.73	13.85	4.12
	33	8.27	12.28	4.01
40/20	70	9.12	11.81	2.69
	60	10.05	13.42	3.37
	50	9.13	12.98	3.85
	40	10.67	13.60	2.93
	33	24.72	36.23	11.51
40/40	70	11.86	39.29	27.43
	60	24.21	79.54	55.33
	50	37.45	175.35	137.90
	40	57.72	192.24	134.52
	33	57.02	159.03	102.01
20/40	70	11.41	14.27	2.86
	60	9.81	12.33	2.52
	50	14.25	18.81	4.56
	40	16.34	22.50	6.16
	33	32.74	46.58	13.84
20/60	70	11.00	260.00	249.00
	60	9.70	282.40	272.70
	50	14.80	314.30	299.50
	40	21.15	869.20	848.05
	33	21.61	163.36	141.75

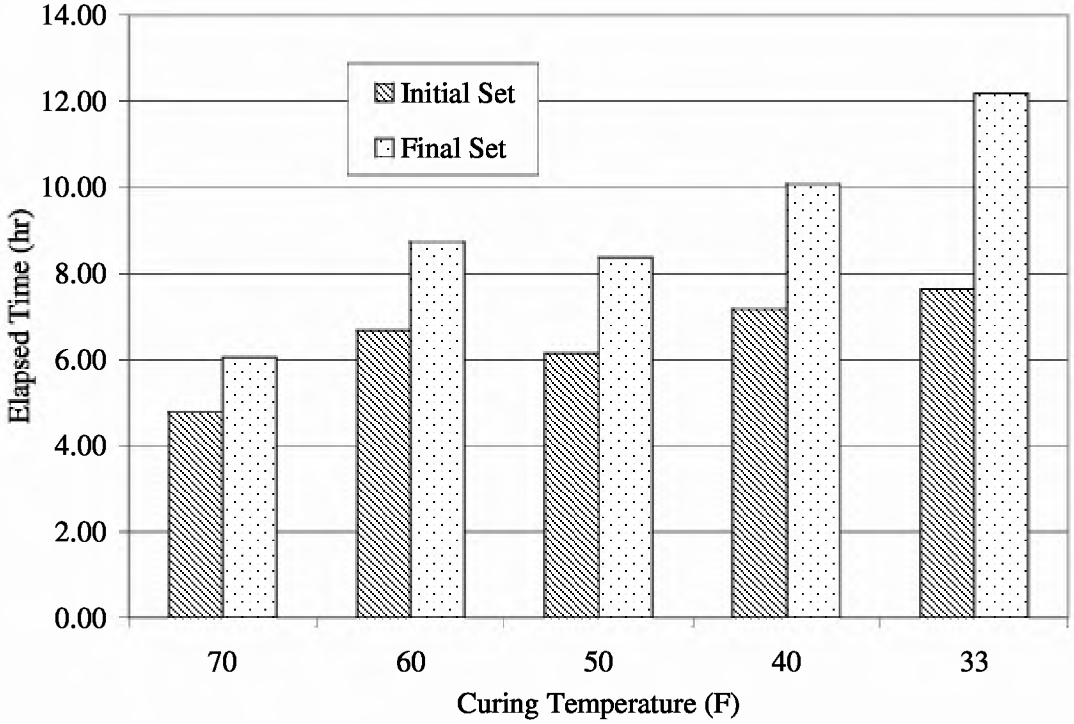


Figure 4-5: Times of Setting for Mixture 0/0

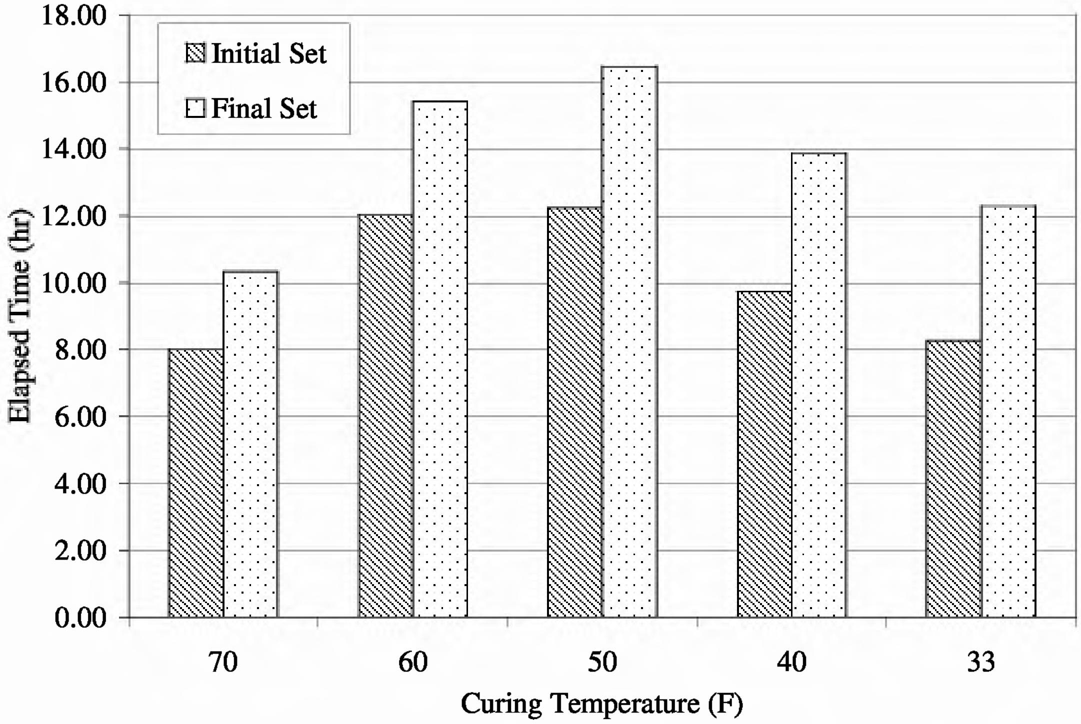


Figure 4-6: Times of Setting for Mixture 20/20

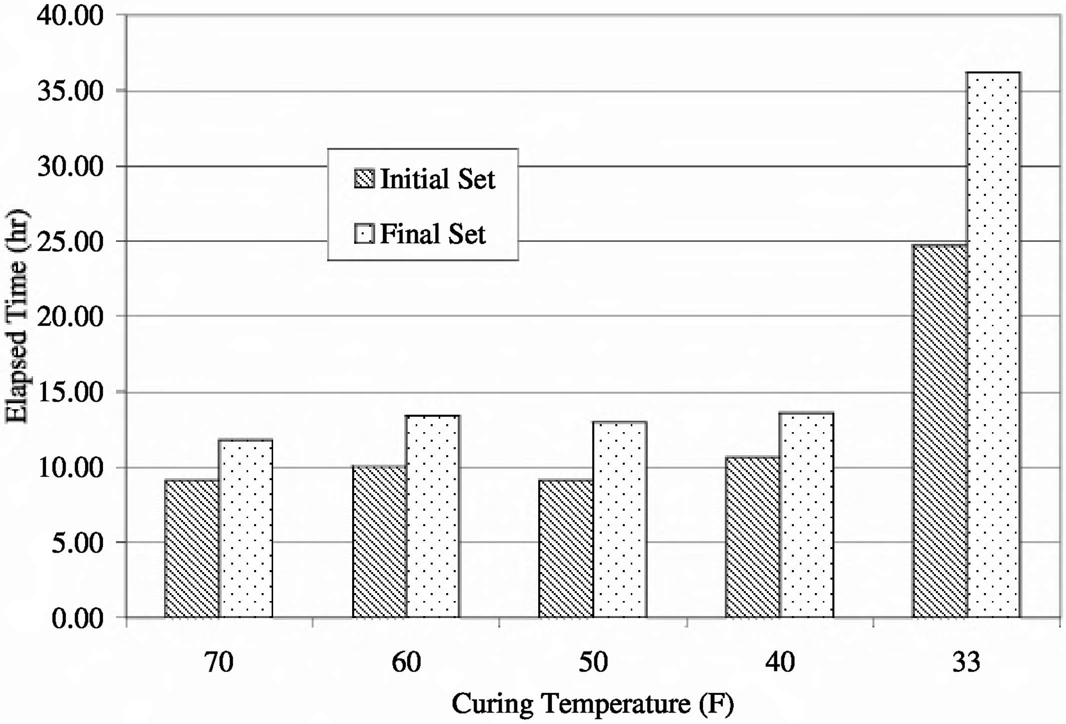


Figure 4-7: Times of Setting for Mixture 40/20

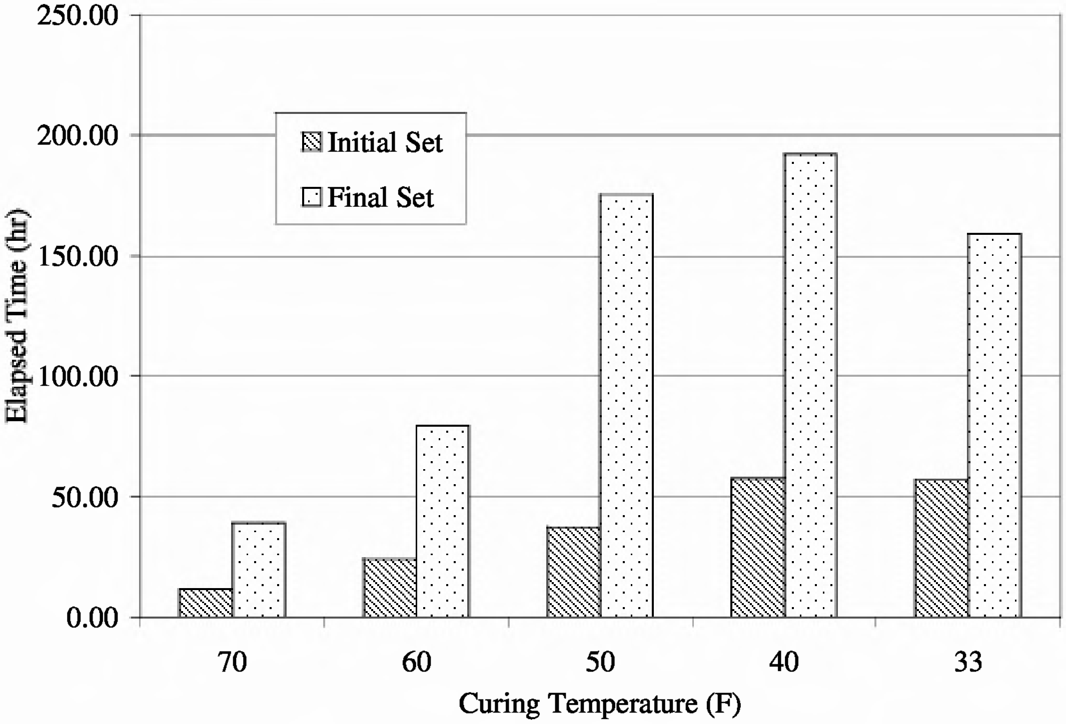


Figure 4-8: Times of Setting for Mixture 40/40

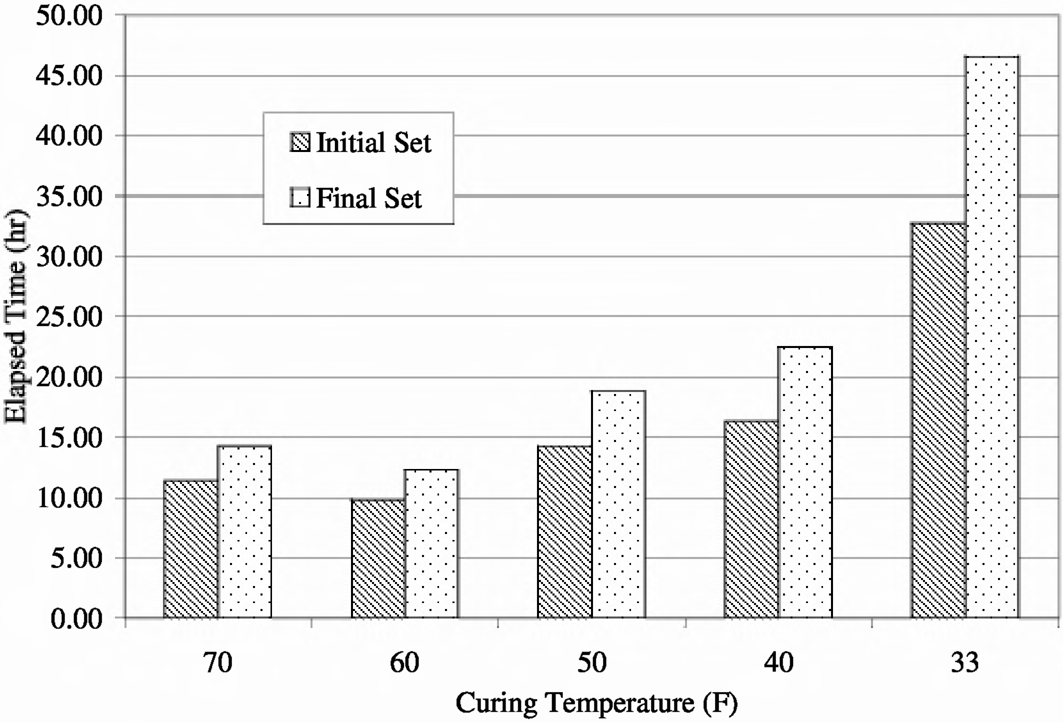


Figure 4-9: Times of Setting for Mixture 20/40

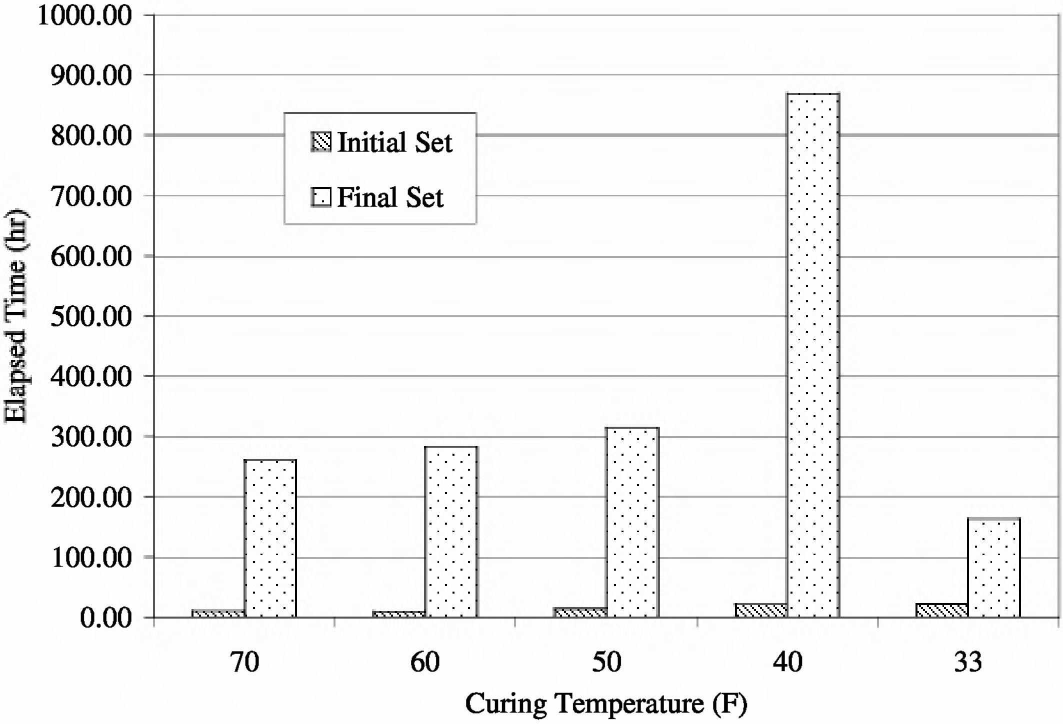


Figure 4-10: Times of Setting for Mixture 20/60

4.2.2.1 Times of Initial Setting

The times of initial setting for the mixtures tested displayed various trends depending on the replacement rates and the curing temperatures, and these trends can be seen in Figures 4-5 through 4-10. Generally, times of final setting increased as curing temperature decreased. Also, the intervals between initial and final setting typically increased as curing temperature decreased. Times of final setting and the interval between initial and final setting both increased as replacement rates increased.

The setting times of Mixture 0/0 increased as curing temperature decreased. The initial setting times of all batches of Mixture 0/0 were statistically different except those cured at 40 and 33 F (Mixtures 0/0 (40) and 0/0 (33)). Batches 0/0 (40) (7.17 hours) and 0/0 (33) (7.64 hours) were not statistically different, according to the 90 percent confidence intervals. Mixtures 40/20, 40/40, 20/40, and 20/60 followed the same general trend of increasing initial setting times as the curing temperature decreased, although a few anomalies were present. Mixtures 20/40 and 20/60, when cured at 60 F, displayed a statistically significant decrease in time of initial setting. Batches 20/40 (60) and 20/60 (60) displayed lower slumps than other batches of their respective mixtures, indicating a somewhat drier mixture. It should be noted that the COV analysis of Mixtures 20/40 and 20/60 reveal that these decreased slumps are statistically significant.

Mixture 40/40, in which 80 percent of the PC was replaced, time of setting increased significantly with respect to the other mixtures. Times of initial setting for Mixture 40/40 ranged from 11.57 to 57.72 hours, increasing as curing temperature decreased. Mixture 20/60, also with 80 percent PC replacement, did not exhibit such a drastic increase in setting time with decreasing curing temperature, although an increase did occur. In fact, the setting times of all batches of this mixture were statistically similar to that of Batch 20/60 (40). Mixture 6 contained a higher volume of Class C FA, which exhibits some cementitious properties. Thus, the early hydration reaction of Mixture 20/60 occurred more quickly than in the mixtures containing higher volumes of SC.

Mixture 20/20 did not follow the trend of increasing setting times as curing temperature decreased, with it longest initial setting time (12.23 hours) belonging to the batch cured at 50 F. Batch 20/20 (40) reached initial set approximately 2.5 hours faster than Batch 20/20 (50). Batch 20/20 (33) reached initial set about 1.5 hours faster than Batch 20/20 (40). Furthermore, the setting time of Batch 20/20 (33) was not statistically longer than that of the same mixture cured at 70 F (Batch 20/20 (70)). All other batches of Mixture 20/20 (60F, 50 F, and 40 F) displayed statistically longer setting times than Batches 20/20 (33) and 20/20 (70). Batches 20/20 (40) and 20/20 (33) were somewhat stiffer than other batches of Mixture 20/20, with significantly different slumps than the other batches. Also, on the day Batch 20/20 (50) was mixed, the ambient temperature was about 49 F, but the ambient temperature when Batches 20/20 (40) and 20/20 (33) were prepared exceeded 70 F. The concrete temperatures of these batches (20/20 (50), 20/20 (40), and 20/20 (33)) were 64, 65, and 68 F, respectively. The elevated ambient temperatures for Batches 20/20 (40) and 20/20 33) most likely sped the hydration reaction, causing a decreased setting time.

4.2.2.2 Times of Final Setting

The times of final setting of the mixtures followed the same general trends as the initial setting, with an exception. These trends may also be viewed in the bar charts which are included as Figures 4-5 through 4-10. Mixture 0/0 experienced statistically significant increases in setting time as curing temperatures decreased, with times ranging from 6.05 to 12.18 hours. Times of final setting for this mixture increased as curing temperature decreased. Mixture 20/20 followed the same trend for final set as for initial set with the batches cured at 40 and 33 F exhibiting decreased set times with respect to warmer batches of the same mixture. Batch 20/20 (33) was again statistically similar to the 70 F batch (Batch 20/20 (70)). The decreased setting times of Batches 20/20 (40) and 20/20 (33) may again be attributed to the early stiffness of the batches and elevated ambient temperatures when the batching was carried out.

Mixtures 40/20 and 20/40 also followed the same general trends for final set as for initial set, with the time of final setting generally increasing as curing temperature decreased. The setting times of Mixture 40/20 increased significantly as curing temperature decreased. However, when the mixture was cured at 70, 60, 50, and 40 F, the differences in curing temperature were of no concern, ranging from 11.81 to 13.6 hours. The 33 F batch of Mixture 40/20 displayed a considerably longer setting time (36.23 hours). Setting times for all batches of Mixture 20/40 were statistically different. Batch 20/40 (60) displayed decreased setting time (9.81 hours) when compared to the same mixture cured at 70 F (11.41 hours) and 50 F (14.25 hours). The ambient temperature on the day 20/40 (60) was prepared was nearly 90 F, while the temperature when Batch 20/40 (70) was prepared was only about 80 F. While the fresh concrete temperature was similar for Batches 20/40 (70) and 20/40 (60) (62 and 67 F, respectively), the elevated ambient temperature for Batch 20/40 (60) rapidly increased the concrete temperature and allowed the hydration reaction to occur faster. The final setting time of Mixture 40/40 also followed a trend much like that of the initial setting, with times of final setting ranging from 39.29 to 159.03 hours.

Mixture 20/60, however, displayed somewhat different trends for final setting than for initial setting. This mixture took longer to reach final set than any other mixture. As discussed previously, the mixture's time of initial setting was comparable to that of other mixtures due to the content of cementitious Class C FA. The pozzolanic reaction which occurs in mixtures containing SC and/or FA proceeds slowly (Mindess et al 2003). With a high content of SCMs (80 percent of the cementitious materials) the pozzolanic reaction of this mixture was most likely slowed much more than with mixtures containing a lower replacement rate. This dormant phase in the setting process can be seen in the plots included in the appendices.

Mixture 20/60 was the worst performing mixture with respect to the time required to reach final setting. An anomaly was present in both Mixture 40/40 and Mixture 20/60; the time of setting decreased for the batches cured at 33 F when compared to the same mixtures cured at 40 F. In fact, both of these mixtures reached final set after about 160 hours had elapsed. In the case of Mixture 40/40, the setting time of the 33 F batch was statistically similar to that of the same mixture cured at 50 F. This phenomenon was more severe for Mixture 20/60. When this mixture was cured at 33 F, the setting time was statistically lower than the setting times of Mixture 6 at all other curing temperatures. The chamber used to achieve 33 F was very difficult to maintain, and very often fell below 33 F. The mixtures with the longest times of final setting, Mixtures 40/40 and 20/60, most likely fell below 33 F by the time several days had passed and final set was achieved, though temperatures were not logged to verify this hypothesis. Thus, the mixtures were frozen and appeared to have achieved final set when in fact hydration was still taking place, albeit very slowly. Time of setting is determined by measuring the pressure required for a standard probe to penetrate one inch and recording the elapsed time from first contact of cement and water, and a frozen concrete mixture will require more pressure to penetrate.

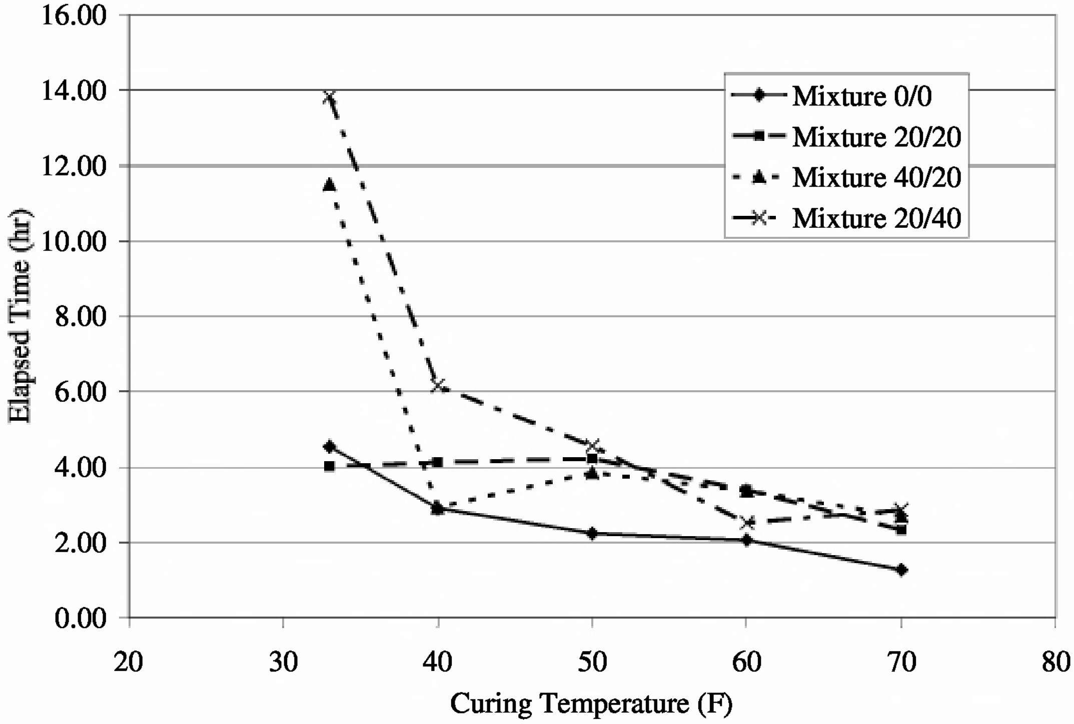


Figure 4-11: Time Between Initial and Final Set for Low-Replacement Mixtures

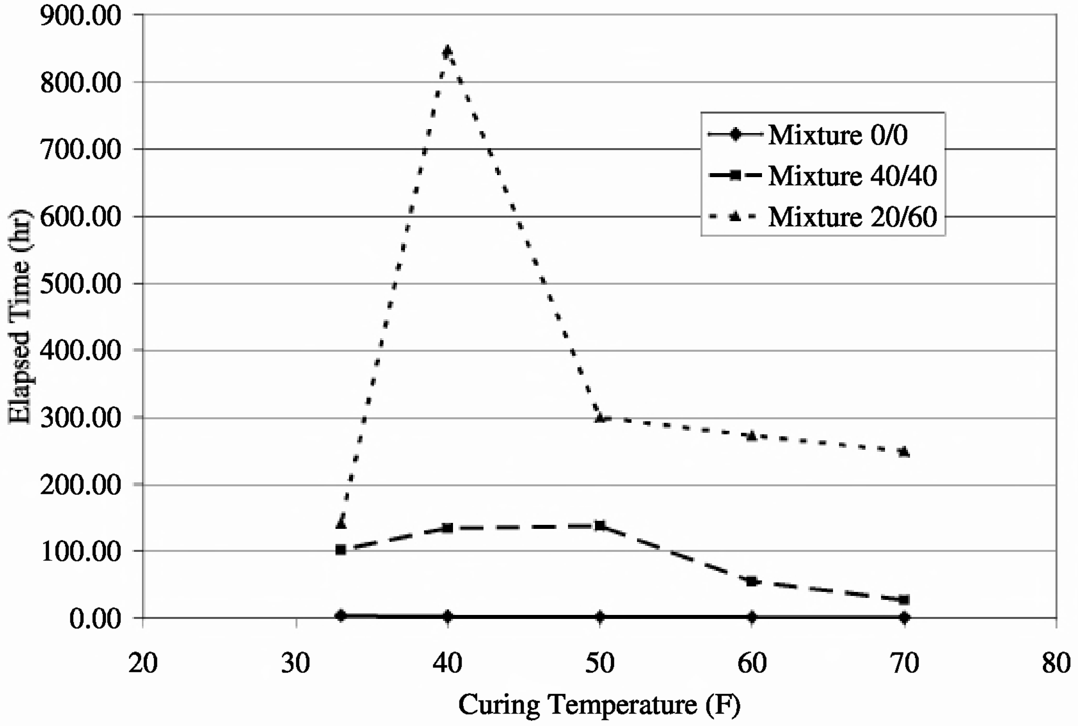


Figure 4-12: Time Between Initial and Final Set for High-Replacement Mixtures

4.2.2.3 Interval Between Initial and Final Setting

The relative times of setting were determined for each of the mixtures. Specifically, this time is the interval between initial and final setting of a mixture. These times are plotted as a function of curing temperature above in Figures 4-10 and 4-11. When cured at or above 50 F, Mixture 20/20 and Mixture 40/20 exhibit a trend similar to that of the control mixture. The interval between initial and final set for Mixtures 0/0, 20/20, and 40/20 increases 1.8, 1.8, and 1.4 times as temperature decreases from 70 to 50 F. Mixture 20/20 also behaves similarly to the control mixture at lower curing temperatures. When cured at 33 and 40 F, Mixtures 40/20 and 20/40 perform similarly, with the elapsed time increasing as curing temperature decreased, especially when the temperature decreased from 40 to 33 F.

Mixture 40/40 and Mixture 20/60 behave differently from all other mixtures. Generally the interval between initial and final set of these mixtures was more affected by curing temperature than the other mixtures tested. For Mixture 40/40, this time increased more than five times as temperature decreased from 70 to 50 F. The interval decreased slightly (from 138 to 135 hours) as curing temperature dropped from 50 to 40 F. The interval decreased more sharply (from 135 to 102 hours) as the temperature decreased to 33 F. As illustrated in Figure 4-11, the slope of the line for Mixture 40/40 was much steeper than that of the control mixture (0/0). The same was true for Mixture 20/60, especially when this mixture was cured between 33 and 50 F. As temperature rose from 50 to 70 F, the time between initial and final set for Mixture 20/60 remained more constant than the same mixture at lower curing temperatures, but was more variable than that of Mixtures 0/0, 20/20, and 40/20, increasing from 249 hours to 299.5 hours as the temperature increased from 50 to 70 F.

4.2.3 Concrete Compressive Strength Determination

The compressive strength of the concrete mixtures was tested at 1, 3, 7, 28, and 90 days of age, as described in Chapter 3. Average compressive strengths at each of these ages are included in Table 4-3. Each value reported in Table 4-3 was the average of three compressive strength tests. The compressive strength gain curves of the six mixtures tested are shown in Figures 4-13 through 4-18, with all five curing temperatures reported on each plot. Also shown below (Figures 4-19 through 4-23) are strength gain curves for the five curing temperatures, with all mixtures on each plot.

Table 4-3: Average Compressive Strength of Mixtures Studied

Mixture	Curing Temperature (F)	Concrete Compressive Strength (psi)				
		1 day	3 days	7 days	28 days	90 days
0/0	**70**	3190	5210	5730	6890	7720
	60	1620	3670	5180	6640	7270
	50	1650	4710	5450	6580	8120
	40	660	3710	5210	6780	7850
	33	610	2750	4380	5470	6720
20/20	**70**	1300	3440	5200	7170	8720
	60	610	3270	5490	6960	8280
	50	270	2430	4420	7280	8650
	40	300	2190	4040	6840	9040
	33	200	880	2110	4270	6830
40/20	**70**	620	2660	4430	7760	8460
	60	450	2160	3870	6860	8230
	50	340	1490	3090	6570	9020
	40	150	960	2300	5860	8530
	33	60	330	280	300	3480
40/40	**70**	50	190	1160	4270	5650
	60	60	130	1020	3770	6650
	50	60	70	310	3090	4770
	40	50	70	110	1770	4100
	33	50	70	310	400	530
20/40	**70**	260	2020	3740	6280	7730
	60	200	1570	3670	5870	8030
	50	120	700	2620	5890	8080
	40	90	650	2250	5400	6430
	33	20	260	490	420	1330
20/60	**70**	60	70	80	2480	6320
	60	80	80	80	1560	3290
	50	40	60	60	1460	3380
	40	60	60	90	580	2890
	33	60	410	230	490	260

* : Test actually performed at six days due to inclement weather.

\+ : Test actually performed at two days because concrete was too green to de-mold at one day.

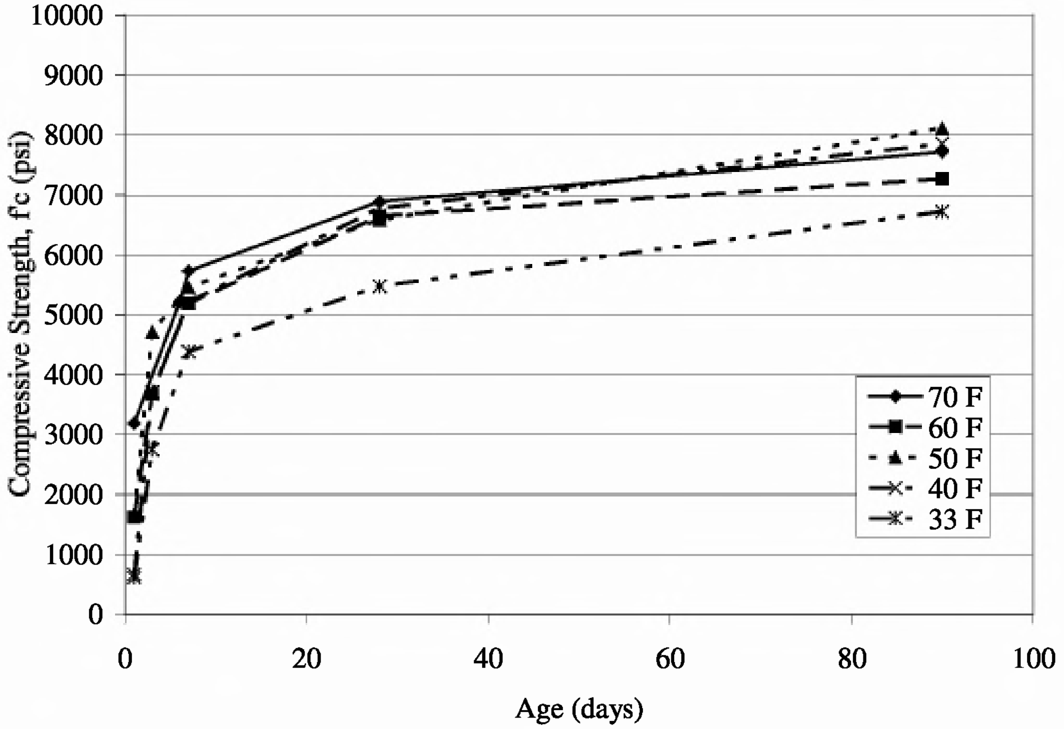


Figure 4-13: Strength Gain Curve for Mixture 0/0 at All Curing Temperatures

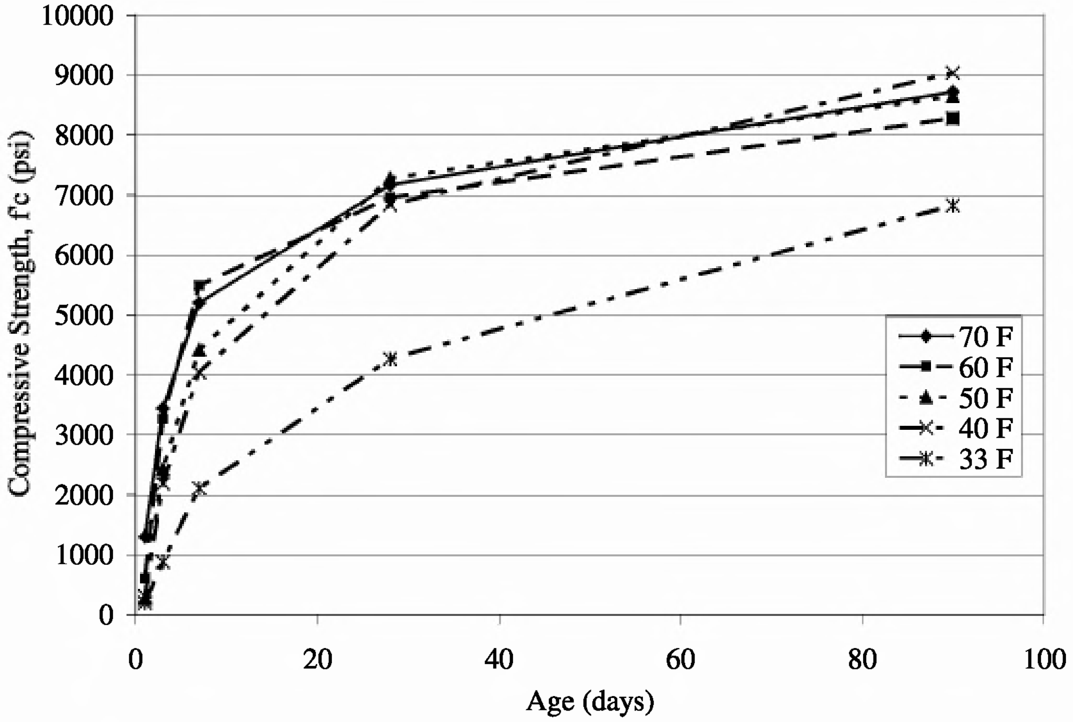


Figure 4-14: Strength Gain Curve for Mixture 20/20 at All Curing Temperatures

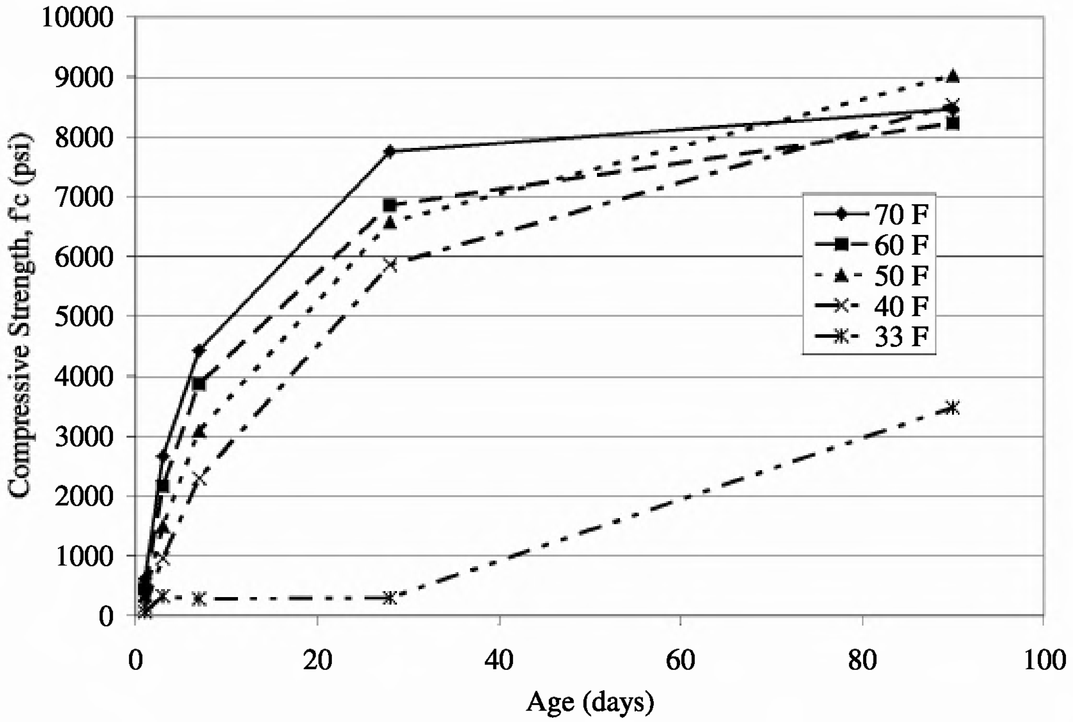


Figure 4-15: Strength Gain Curve for Mixture 40/20 at All Curing Temperatures

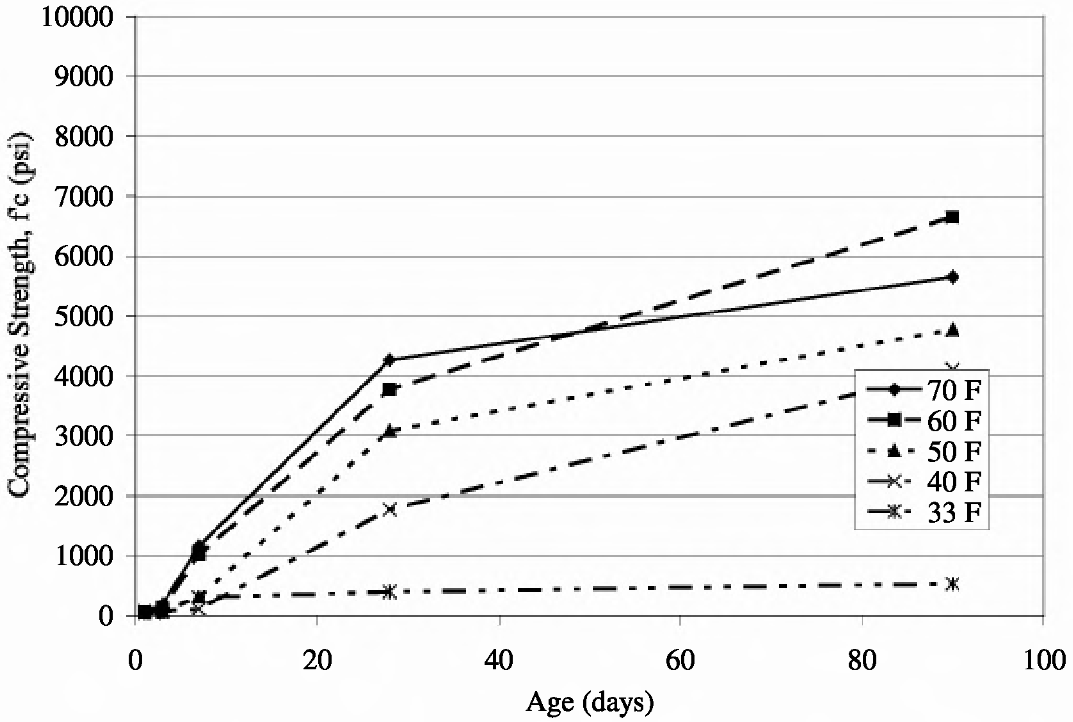


Figure 4-16: Strength Gain Curve for Mixture 40/40 at All Curing Temperatures

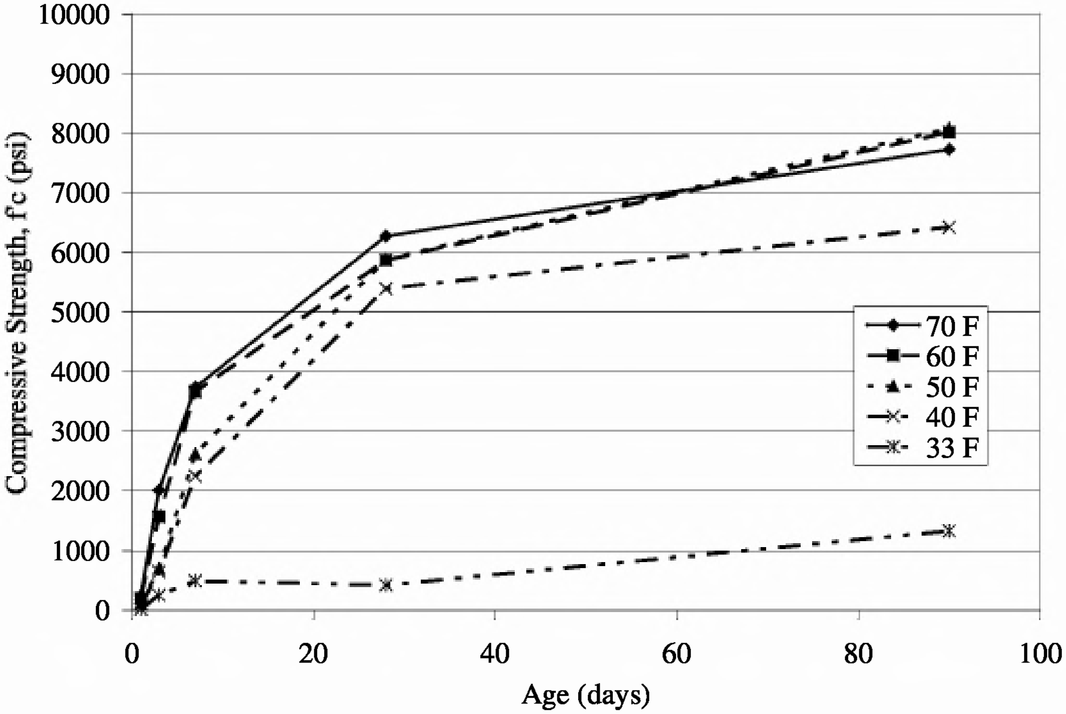


Figure 4-17: Strength Gain Curve for Mixture 20/40 at All Curing Temperatures

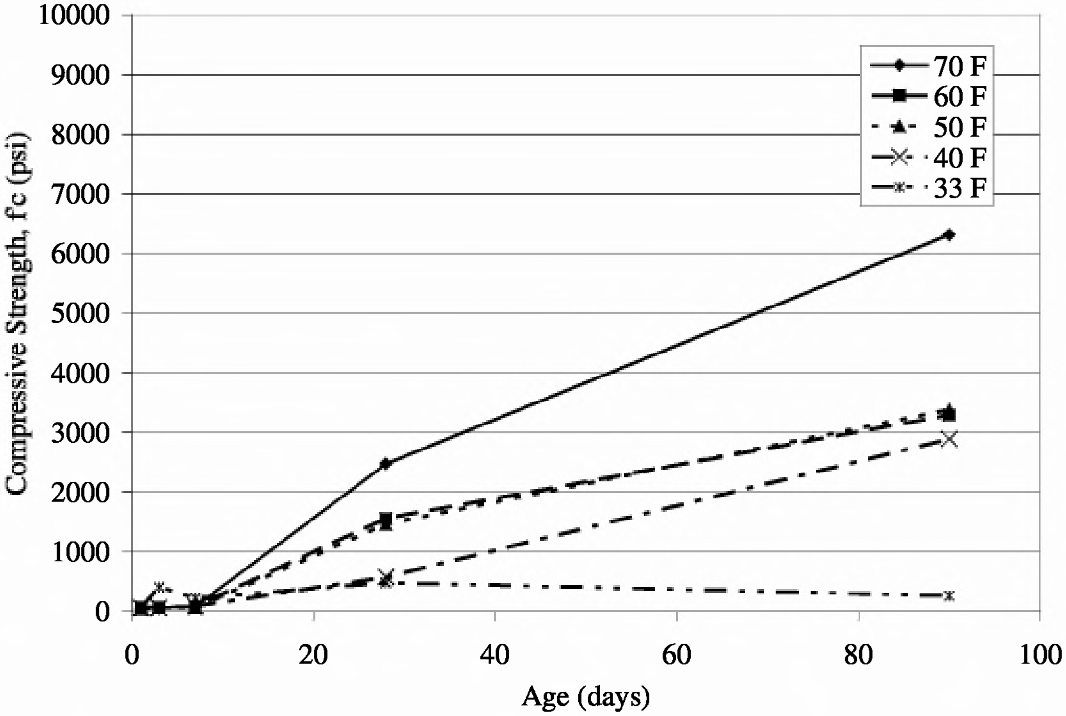


Figure 4-18: Strength Gain Curve for Mixture 20/60 at All Curing Temperatures

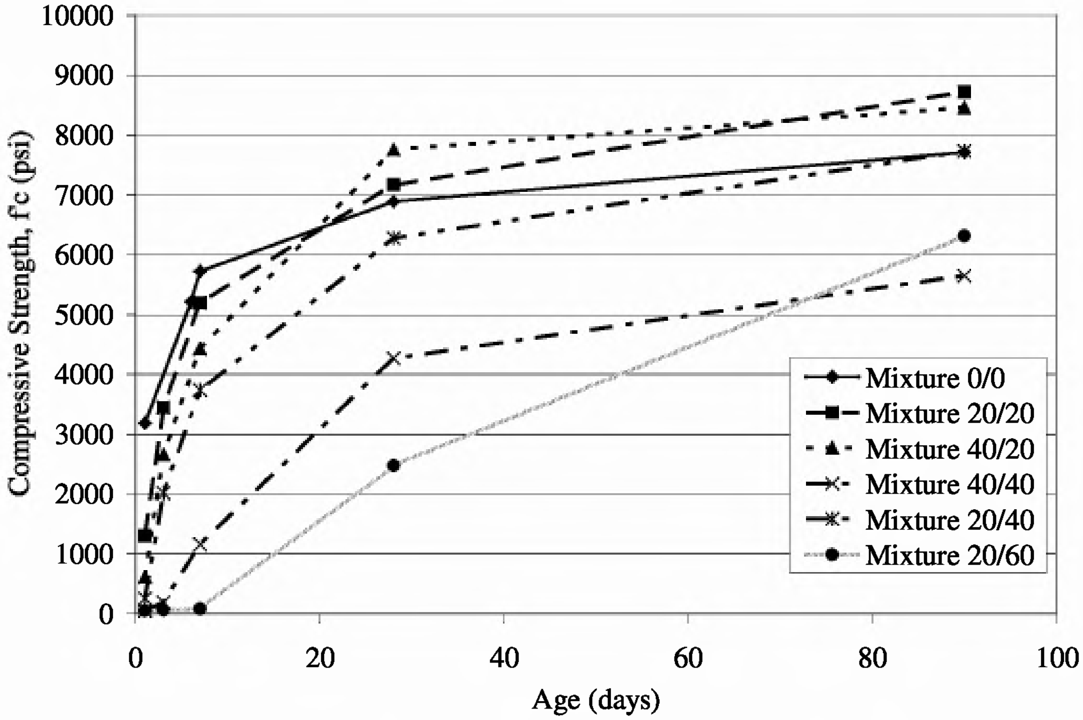


Figure 4-19: Strength Gain Curve for All Mixtures Cured at 70 F

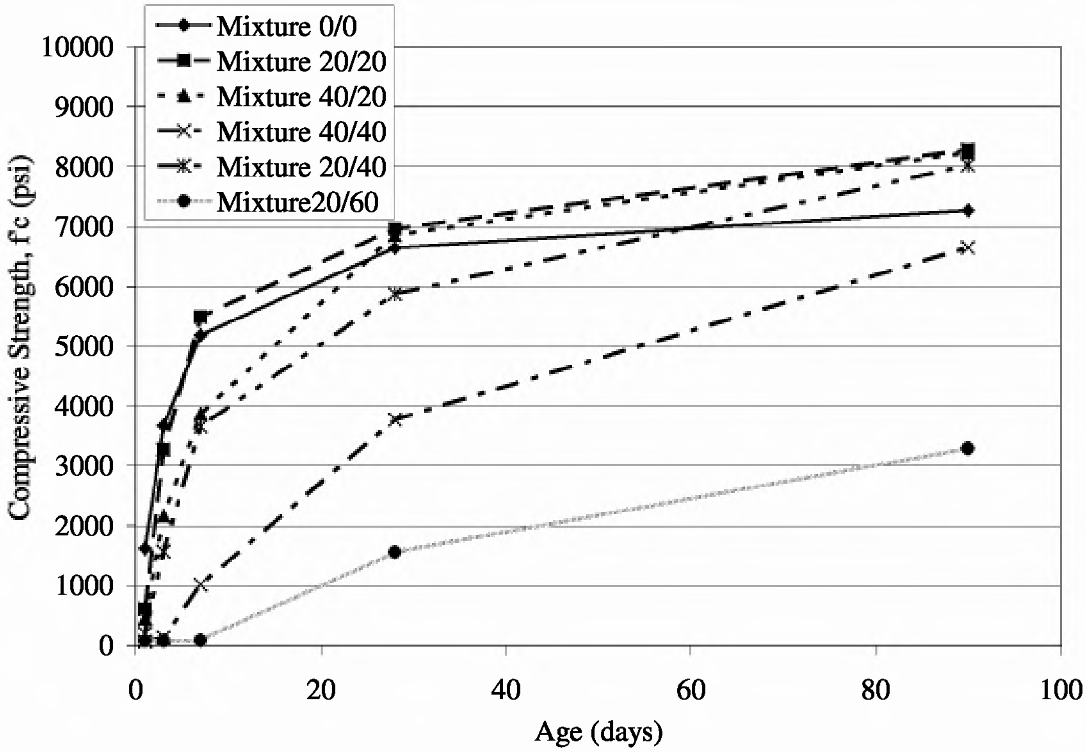


Figure 4-20: Strength Gain Curve for All Mixtures Cured at 60 F

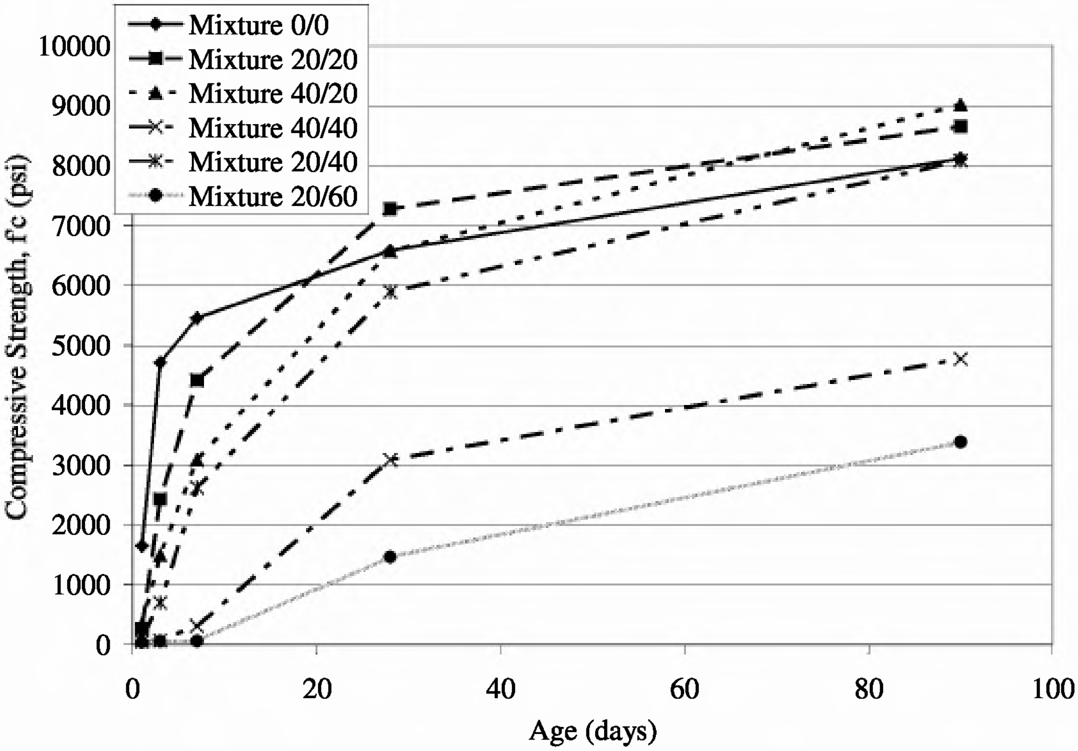


Figure 4-21: Strength Gain Curve for All Mixtures Cured at 50 F

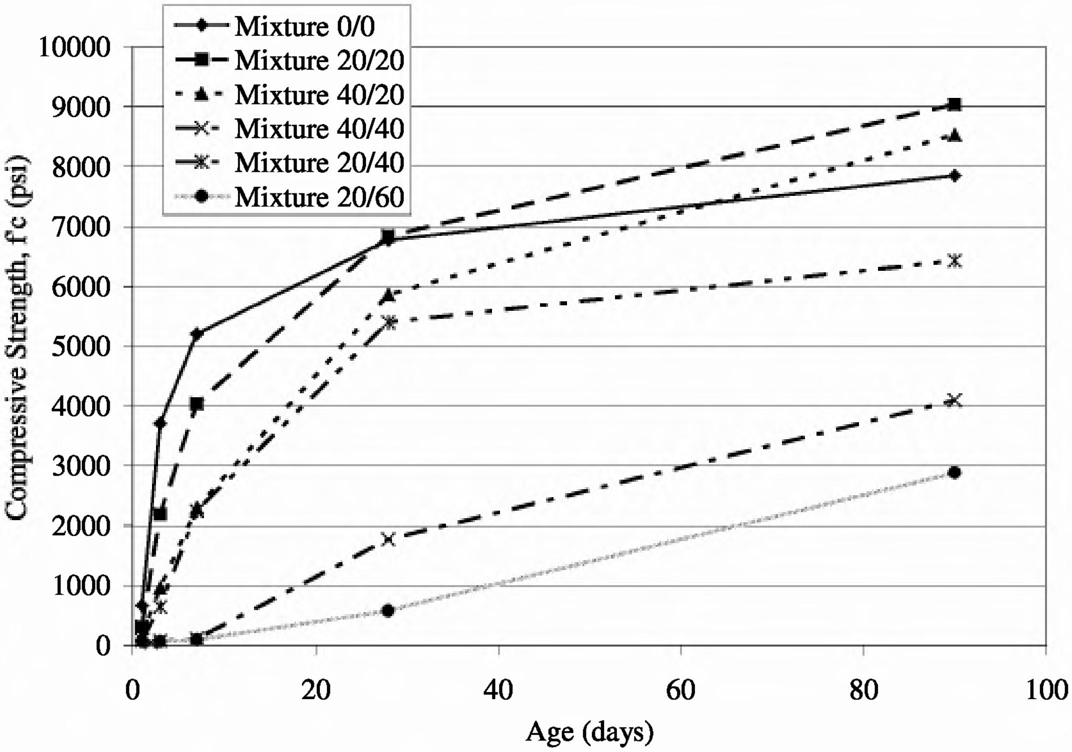


Figure 4-22: Strength Gain Curve for All Mixtures Cured at 40 F

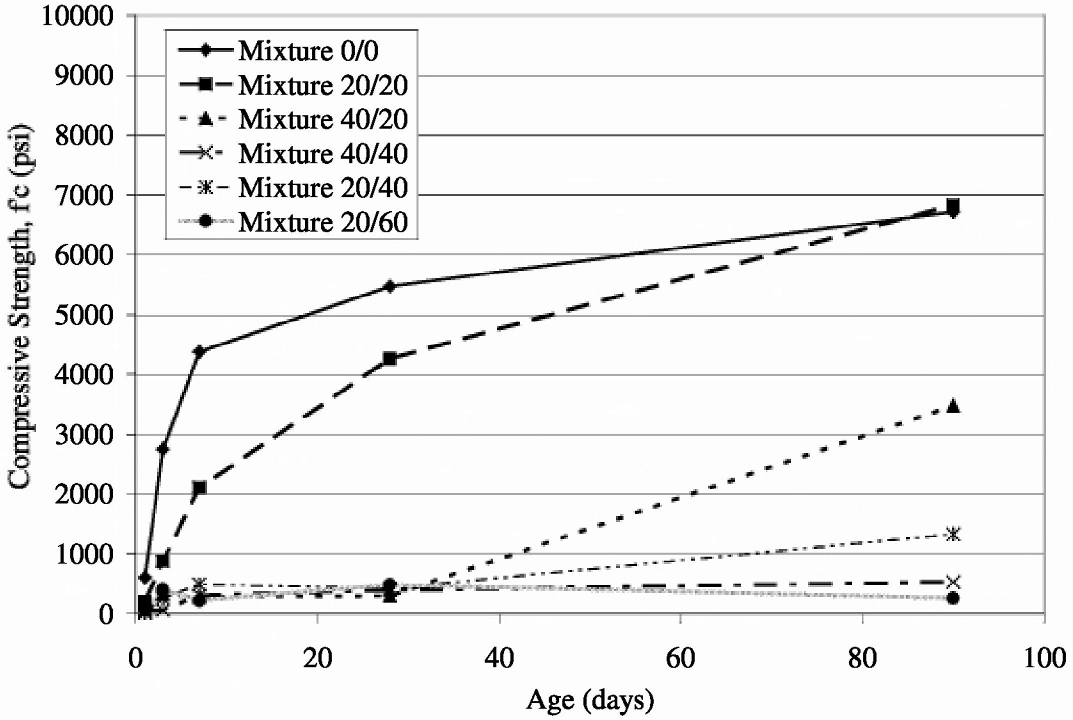


Figure 4-23: Strength Gain Curve for All Mixtures Cured at 33 F

The data included in Table 4-3 were analyzed at each age using 90 percent confidence intervals, which are included in the following sections. Also, two-factor analyses of variance (ANOVAs) were performed for 28- and 90-day strengths. However, due to the time intensive nature of the study, not enough data points were collected to assume normal distribution of the data. Thus, these ANOVAs were not used in this discussion.

All mixtures displayed lower compressive strength when cured at 33 F, as compared to the same mixture cured above 33 F, an effect that is not surprising since heat is required for cement hydration and pozzolanic reactions to occur. In general, this effect becomes more significant as SCM content, or replacement rate, increases. This trend was observed in all mixtures except Mixture 20/60, which performed poorly at all curing temperatures. The lower compressive strengths may also be attributed to the difficulty of maintaining an environmental chamber at 33 F. As mentioned previously, the chamber temperature most likely fell below freezing at times during the study; however, this claim cannot be proven since ambient temperatures in the chambers were not logged or recorded.

4.2.3.1 One-Day Compressive Strength

Compressive strength was first measured at one day of age to determine the early effects of PC replacement by SCMs. Again, the reported compressive strength was the average strength of three samples. For the one-day results, 90 percent confidence intervals were used for analysis, as well as the strength gain curves presented previously. The 90 percent confidence intervals are shown in Figure 4-24.

The one-day compressive strength decreased as the curing temperatures decreased. The curing temperature affected the strength of low replacement mixtures (less than or equal to 60 percent total SCMs) more than the mixtures with 80 percent total replacement, due to the longer setting times of these high replacement mixtures. In general, the strength of all mixtures was significantly different from the control at like temperatures. The strengths decreased as the total cement replacement increased. The control mixture and the mixture with 40 percent total replacement attained a minimum of 1300 psi when cured at 70 F. Replacement by FA tended to have more adverse effects on the one-day compressive strength than replacement by SC, especially at high replacement rates, though increasing rates of SC resulted in somewhat lower compressive strengths.

Mixtures containing more than 20 percent FA performed poorly at one day of age, not exceeding 300 psi.

Compressive strength of four of the mixtures tested (Mixtures 0/0, 20/20, 40/20, and 20/40) decreased as curing temperatures decreased. These mixtures displayed significantly higher one-day compressive strength when cured at 70 F than the same mixtures cured at temperatures less than 70 F. Mixture 0/0, when cured at 70 F, displayed a one-day compressive strength at least 50 percent larger than that of all other batches tested. In general, the one-day compressive strength of the mixtures decreased as curing temperature decreased. Although the 90 percent confidence interval displays a significant difference, the strengths of Mixtures 40/40 and 20/60 were not affected in a substantial manner by varying curing temperatures, and ranged from 50 to 80 psi. The mixtures performed so poorly at one day of age that the differences in the strengths are irrelevant. These poor strengths were due to the high replacement rates of these mixtures. These mixtures also experienced corresponding delays in setting. When cured at 70 F, Mixture 40/40 did not reach final set, the point at which concrete begins gaining "strength", until 39.4 hours, or at about 1.5 days after batching. Mixture 20/60, when cured at the same temperature reached final set in 260 hours, or almost 11 days. Since 70 F was the warmest temperature used in the study, and thus the "best case", Mixtures 40/40 and 20/60 required even longer periods to reach final set when subjected to reduced curing temperatures. These mixtures did not begin to gain substantial compressive strength until final set was reached.

Mixture 20/40, with 20 percent SC and 60 percent FA, suffered the most from decreasing curing temperature at one day of age, although Mixtures 0/0, 20/20, and 40/20 were also severely affected by decreasing temperature. When cured at 33 F, this mixture's compressive strength was less than ten percent of the one-day compressive strength of the same mixture cured at 70 F. The 33 F strengths of Mixtures 0/0, 20/20, and 40/20 were 20, 15, and nine percent of the 70 F strengths, respectively. Mixture 20/40 experienced delays in setting times, with final setting times about 25 percent longer than those of Mixture 40/20, a similar mixture with 60 percent replacement. These longer setting times tend to correspond to the low early-age strengths attained by Mixture 20/40. A possible explanation might be the high FA content (40 percent). Mixtures with such high volumes of FA tended to gain strength more slowly at early ages than other mixtures.

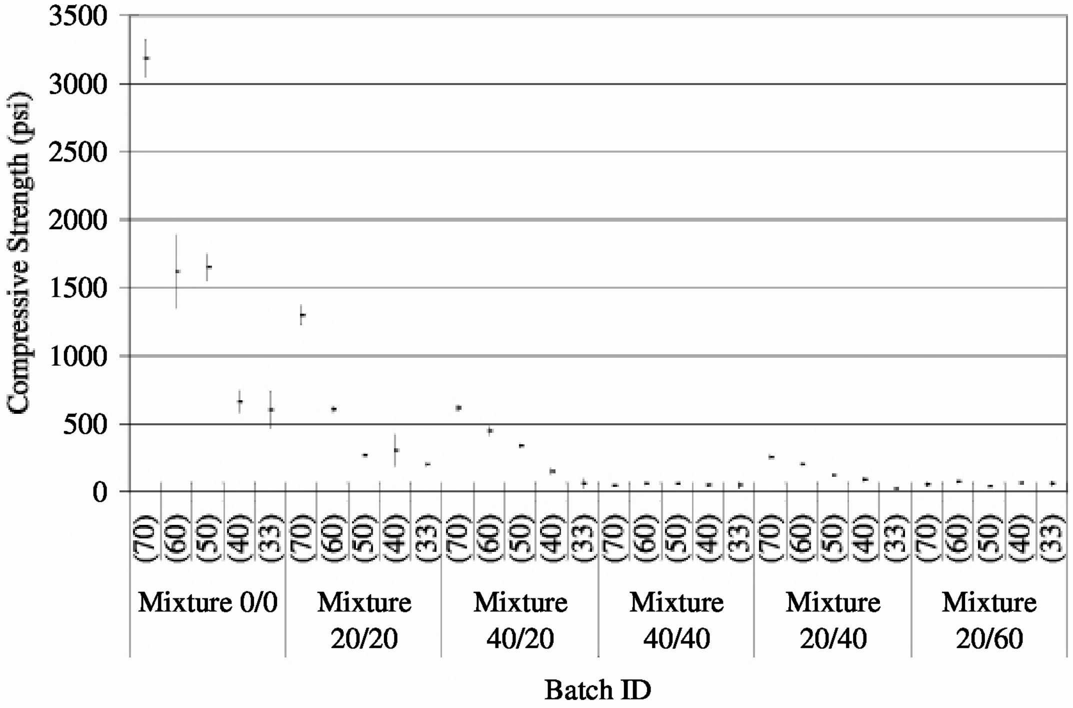


Figure 4-24: 90 % Confidence Intervals for One-Day Compressive Strength

4.2.3.2 Three-Day Compressive Strength

The compressive strengths of the concrete mixtures were also measured when specimens reached an age of three days. The 90 percent confidence intervals for the three day compressive strengths are shown in Figure 4-25. Due to severe weather and travel conditions, the three-day strength of Mixture 0/0 (70) could not be measured until the specimens were six days of age. Thus, this particular batch was not considered in the three-day analysis. Of the remaining batches, the 50 F batch of Mixture 0/0 attained the highest compressive strength. Generally, the three-day compressive strength decreased as the curing temperatures decreased. The strengths of mixtures with higher SCM contents were widely variable as temperature decreased. Mixtures with lower replacement rates were not so widely affected by curing temperature. In general, the strength of all mixtures was significantly different from the control at like temperatures. The strengths decreased as the total cement replacement increased. The decrease in compressive strength was proportional to the increase in replacement rate up to 60 percent total replacement. Mixtures with 80 percent total replacement were not affected by decreasing curing temperatures, as these mixtures performed poorly at all temperatures. The strongest batch at this replacement attained less than 200 psi.

In the cases of Mixtures 0/0, 20/20, 40/20, and 20/40, the batches cured at 70 F attained higher three-day compressive strengths than those mixtures cured at lower temperatures. For all mixtures, the batches cured at 33 F gained the least compressive strength. Mixtures 40/20 and 20/40 suffered more than Mixtures 0/0 and 20/20 when cured at 33 F. These 33 F batches of Mixtures 40/20 and 20/40 each attained only about 12 percent of the compressive strength reached by the same mixtures at 70 F, while

Mixtures 0/0 and 20/20 at 33 F reached about 50 and 25 percent of the 70 F compressive strength, respectively.

In most cases, compressive strength decreased as curing temperature decreased. An exception, however, is in the case of Mixture 0/0 when cured at 50 F. Batch 0/0 (50) attained a significantly higher compressive strength (4710 psi) than when the same mixture was cured at 60 F (3670 psi). In addition, the strength of the batch cured at 40 F (3710 psi) was not significantly different from the 60 F batch. The 50 and 40 F batches had slumps much lower than that of the 60 F batch. The concrete temperatures of Batches 0/0 (60), 0/0 (50), and 0/0 (40) were 68, 65, and 58 F, respectively. Ambient weather conditions were not recorded when Batch 0/0 (60) was prepared. No logical explanation for this phenomenon was discovered.

Mixtures 40/40 and 20/60 were practically unaffected by decreases in curing temperatures. While the 90 percent confidence interval showed a statistical difference between some of the different batches of these two mixtures, the compressive strength at three days remained so low that the difference was irrelevant. Mixture 40/40 displayed almost a constant strength at three days of age regardless of curing temperature, ranging from 50 to 60 psi. The compressive strength of Mixture 20/60 was only slightly more variable than Mixture 40/40, ranging from 60 to 80 psi for all batches except 33 F. When cured at 33 F, Mixture 20/60 attained strength of 410 psi. In this case, water in the mixture was probably frozen, leading to an increased compressive strength.

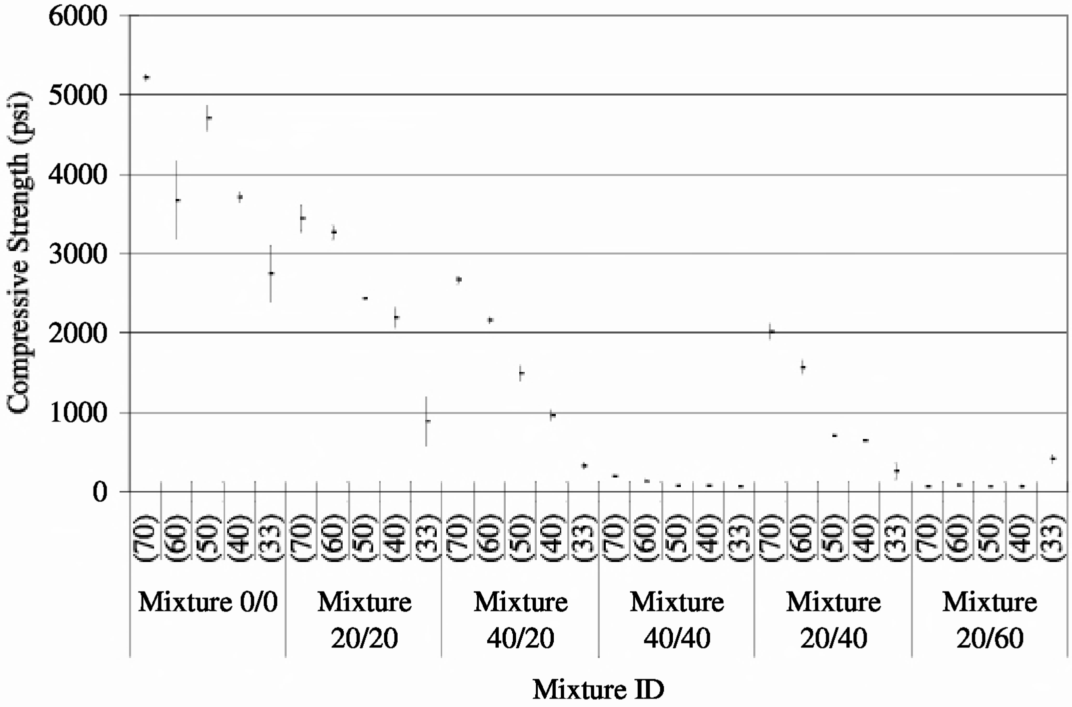


Figure 4-25: 90 % Confidence Intervals for Three-Day Compressive Strength

The low strengths of Mixtures 40/40 and 20/60 correspond to long setting times observed for these mixtures. No batch of Mixture 40/40 had reached final set prior to reaching an age of three days, and none of the batches of Mixture 20/60 reached final set before seven days.

4.2.3.3 Seven-Day Compressive Strength

The compressive strength of the mixtures considered in the research program was again tested at seven days of age. The 90 percent confidence intervals are shown in Figure 4-26. The compressive strength at seven days tended to decrease with decreasing temperatures for the mixtures containing SCMs. Mixtures containing low replacement rates were again less affected than those with moderate replacements (60 percent). Mixtures with the highest replacements (80 percent) tended to, again, remain unaffected by curing temperature. This effect was independent of the amount of FA or SC in the mixture.

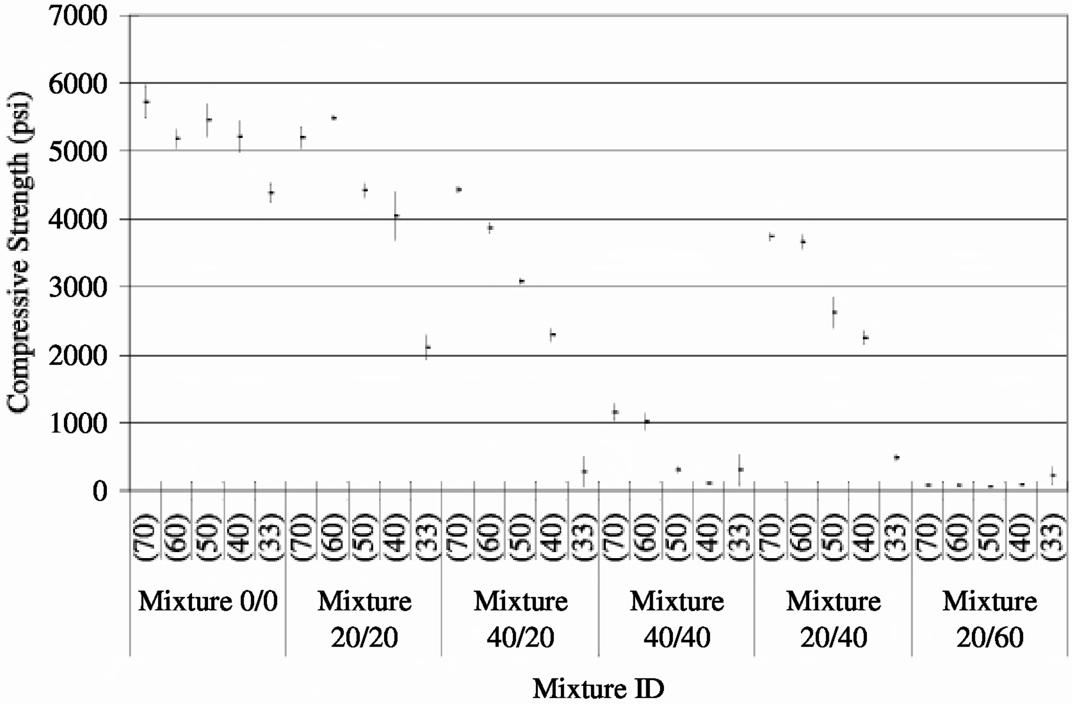


Figure 4-26: 90 % Confidence Intervals for Seven-Day Compressive Strength

At seven days of age, the 70 F batch of Mixture 0/0 attained the highest compressive strength of all the batches with 5730 psi. Statistically, little difference existed between the various batches of Mixture 0/0. As shown in Figure 4-23, Mixtures 0/0 (70) and 0/0 (50) were not statistically different, with respective compressive strengths of 5730 and 5450 psi. Batch 0/0 (50) was also similar to Batches 0/0 (60) and 0/0 (40), with strengths of 5180 and 5210 psi. Batch 0/0 (33, with a strength of 4380 psi, was significantly different from all other batches of Mixture 0/0.

At the two warmest curing temperatures, Mixture 20/20 performed similarly to Mixture 0/0 at seven days of age. According to the 90 percent confidence intervals, Batches 20/20 (70) and 20/20 (60) are not significantly different from Batches 0/0 (60) and 0/0 (50). These two low-replacement batches (Batches 20/20 (70) and 20/20 (60)) attained seven-day compressive strengths of 5200 and 5490 psi, exceeding the required 28-day strength of 4000 psi, as described in Chapter 3. Even when cured at 40 and 50 F, the compressive strength of Mixture 20/20 still exceeded 4000 psi at seven days. When cured at 33 F, however, Mixture 20/20 experienced a sharp decrease in compressive strength, reaching only 2110 psi when tested at seven days.

Mixture 40/20 displayed significantly lower seven-day strengths when compared to Mixtures 0/0 and 20/0, except when cured at 70 and 60 F, as illustrated in Figure 4-26. When cured at 33 F, Mixture 40/20 attained less than 10 percent of the compressive strength attained by Mixture 0/0 and about 13 percent of that attained by Mixture 20/20. Batches 40/20 (70) and 40/20 (60) (4430 and 3870 psi, respectively) are not significantly different from Batch 20/20 (40). Examining the strength gain curves for Mixture 40/20 reveals that compressive strength decreases nearly proportionately to the decrease in curing temperature (an approximate strength decrease of 20 to 25 percent for each 10-degree drop in curing temperature). The 33 F batch (280 psi) only achieved 12 percent of the strength of the same mixture cured at 40 F. The increasing PC replacement rate (from 40 percent for Mixture 20/20 to 60 percent for Mixture 40/20) most likely led to the decreases in compressive strength, as the pozzolanic reactions occur more slowly than cementitious reactions.

Mixture 20/40 achieved compressive strength similar to that of Mixture 40/20. Batches 20/40 (70) and 20/40 (60) (3740 and 3670 psi, respectively) were statistically similar to Batch 40/20 (60). At seven days of age, these particular batches nearly attained the required 28-day strength of 4000 psi as discussed in Chapter 3. The 50 and 40 F batches of Mixture 20/40 performed reasonably well, each exceeding 2000 psi.

Mixture 40/40 performed very poorly at all temperatures when compared to the compressive strength of Mixtures 0/0, 20/20, and 40/20. This mixture attained only 1160 psi when cured at 70 F. The batch cured at 60 F was not statistically different from the 70 F batch, but the strength decreased sharply as the curing temperatures fell below 60 F. At all temperatures except 33 F, Mixture 20/60 had strengths ranging from 60 to 90 psi and performed similarly to the colder curing temperatures of Mixture 40/40 (40 and 33 F). When cured at 33 F, Mixture 20/60 displayed an increase in strength (230 psi) as compared to the 40 F batch (90 psi). As discussed previously, the chamber used for 33 F curing was difficult to maintain, and at times fell below 33 F. Thus, the concrete in this chamber tended to show higher values of compressive strength due to freezing. This effect was also present in Mixture 40/40, though less prominent. The other mixtures tested did not exhibit this property, as these mixtures were less sensitive to extremely low curing temperatures.

The low strengths of Mixtures 40/40 and 20/60 correspond to their long setting times. As mentioned previously, Mixture 40/40 attained compressive strengths exceeding 1000 psi when cured at 70 and 60 F. These batches were also the only batches of Mixture 40/40 to achieve final set prior to reaching seven days of age. Regardless of the temperature, Mixture 20/60 did not reach final set before seven days. In fact, the 50 F batch of Mixture 20/60 did not set until 13 days and the 40 F batches did not set until the specimens reached 36 days of age.

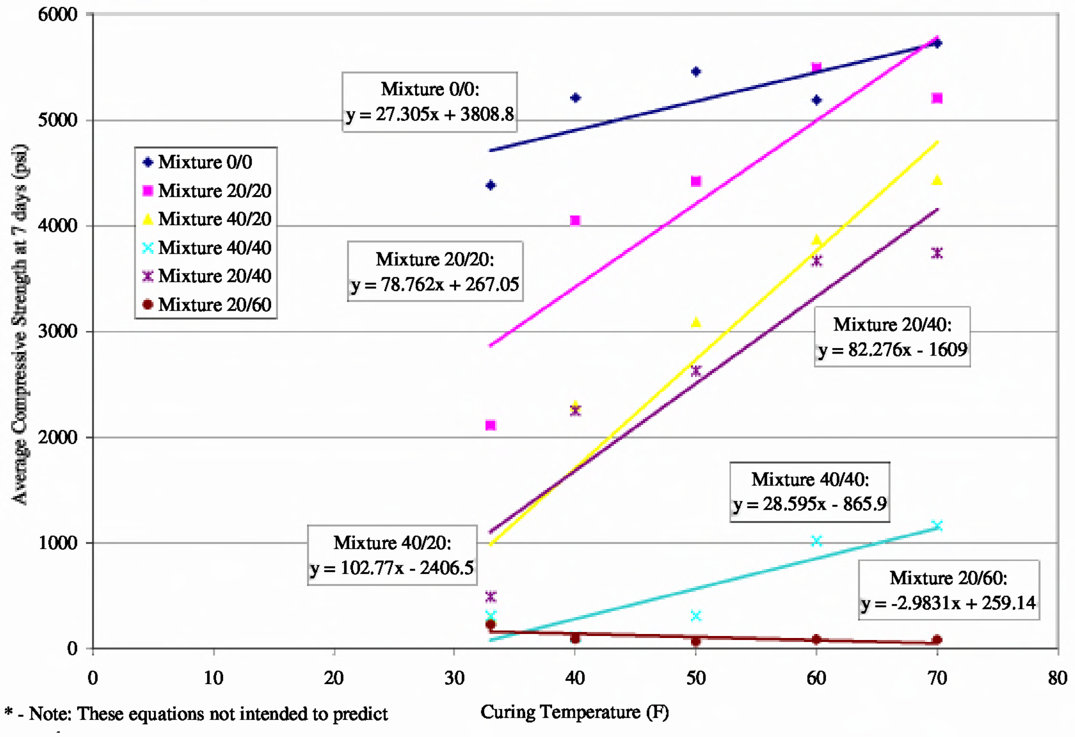


Figure 4-27: Effect of Curing Temperature on Seven-Day Strength

Figure 4-27 shows the average seven-day strengths of each of the six mixtures, with all curing temperatures included. A trendline was fit to each of the mixtures to demonstrate the loss of compressive strength as curing temperature decreased. The equations for these trendlines were not intended to estimate strength as a function of curing temperature, but rather to determine the slopes of the trendlines as a measure of the effect of curing temperature on the compressive strength. According to the slopes of these lines, the control mixture (Mixture 0/0) was minimally affected by decreasing curing temperature, increasing about 270 psi for each 10 F increase in curing temperature. Mixture 40/40 was also minimally affected, with strength increasing almost 300 psi per 10 F increase in curing temperature. The least affected was Mixture 20/60, the trendline for which actually showed decreasing strength as curing temperature increased. When cured at 33 F, Mixture 20/60 displayed a significantly higher compressive strength than like mixtures cured at higher temperatures. This was likely due to the frozen concrete, as discussed previously. The strength in this case was only 230 psi. The mixture most affected by the curing temperature was Mixture 40/20, which gained over 1000 psi for each 10 F increase in curing temperature. Mixtures 20/20 and 20/40 were only slightly less affected by temperature, each with strengths increasing about 800 psi per 10 F increase.

4.2.3.4 28-Day Compressive Strength

Compressive strength was evaluated at 28 days of age as well. The strengths of Mixture 0/0 and the lowest replacement mixture (Mixture 20/20) were unaffected by curing temperature when cured above 33 F. Other mixtures (60 percent total replacement) were only slightly affected by curing temperature. Strength decreased somewhat as replacement increased, but the difference was minor until the replacement exceeded 60 percent. Mixtures with 80 percent replacement displayed compressive strengths significantly lower than those of other mixtures. Increased FA content tended to result in lower compressive strengths. Two of the mixtures contained 60 percent replacement (Mixtures 40/20 and 20/40). Mixture 20/40 displayed slightly lower compressive strength than Mixture 40/20. A similar trend was observed between Mixtures 40/40 and 20/60, which each contained 80 percent replacement. Mixture 20/60, with a higher FA content than Mixture 40/40, displayed lower strength at all temperatures than Mixture 40/40.

In general, the control mixture and low-replacement mixtures (60 percent and less) performed well, except when cured at 33 F. These mixtures – specifically, Mixtures 0/0, 20/20, 40/20, and 20/40 – consistently exceeded the AHTD minimum 28-day compressive strength of 4000 psi. However, these mixtures did not perform as well when subjected to a curing temperature of 33 F. At 33 F, Mixtures 0/0 and 20/20 still exceeded 4000 psi, but Mixtures 40/20 and 20/40 fell well below this mark. The strength of Mixtures 40/40 and 20/60, with 80 percent of the PC replaced, decreased drastically as curing temperatures decreased. In general these mixtures failed to attain 4000 psi, except Mixture 4 when cured at 70 and 60 F. Mixture 40/40 contained an equal weight of SC and FA (40 percent each). At higher temperatures, mixtures with higher SC contents gained more strength than mixtures with high FA replacement, as discussed in Chapter 2. Mixture 40/40, with less FA than Mixture 20/60, performed somewhat better than Mixture 20/60, which contained 60 percent FA and only 20 percent SC. The results of these data were analyzed using 90 percent confidence intervals, which are shown in Figure 4-28.

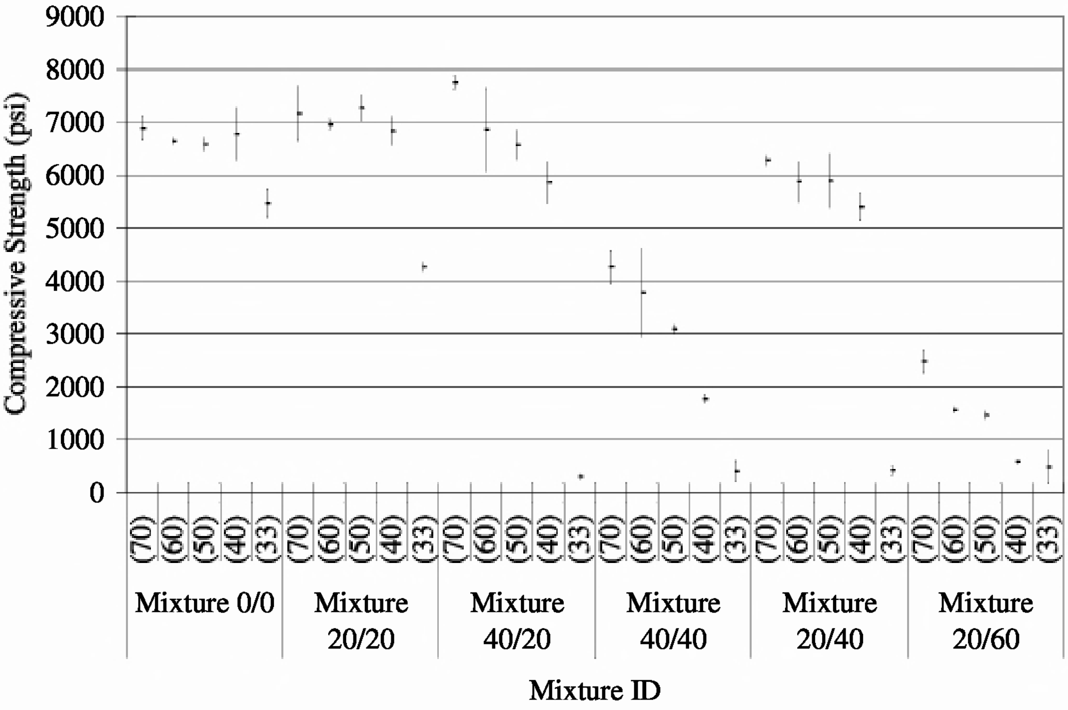


Figure 4-28: 90 % Confidence Intervals for 28-Day Compressive Strength

All batches of Mixture 0/0 (control) except that cured at 33 F were statistically similar to the 70 F batch, which is considered the control batch for the study. The average 28-day compressive strength of this batch (0/0 (70)) was 6890 psi – well above the minimum of 4000 psi required (AHTD 2003). In all cases except Mixture 20/60, batches cured at 33 F displayed significantly less compressive strength than like mixtures cured at higher temperatures. In the case of Mixture 20/60, the 40 F batch was not significantly different from the 33 F batch, which attained strengths of 580 and 490 psi, respectively. Mixture 20/20 had higher average compressive strengths than Mixture 0/0 at the 70, 60, and 50 F curing temperatures, though the difference is not significant. When cured at 70 F, Mixture 20/20 reached 28-day strength of 7170 psi. Mixture 20/20 is also similar to Mixture 0/0 when cured at 40 F, according to the 90 percent confidence interval shown above. While the 33 F batch of Mixture 20/20 only attained 62 percent of the strength of the same mixture cured at 40 F, this batch still displayed an average 28-day compressive strength greater than 4000 psi.

When cured at 70 F, Mixture 340/20 displayed the highest 28-day compressive strength of all the batches tested with 7760 psi. However, compressive strength of this mixture decreased more rapidly as curing temperature decreased. Thus, Mixture 40/20 was less consistent than Mixtures 0/0 or 20/20. The same mixture cured at 60 F was not statistically different, and there was no significant difference between batches cured at 60, 50, and 40 F, although average compressive strength tended to decrease as curing temperature decreased. Batches 40/20 (70), 40/20 (60), 40/20 (50), and 40/20 (40) displayed respective compressive strengths of 7760, 6860, 6570, 5860 psi, certainly exceeding the required 28-day strength of 4000 psi. When Mixture 40/20 was cured at 33 F, however, the compressive strength (300 psi) was severely decreased, only attaining five percent of the strength of the same mixture cured at 40 F (5860 psi). It should be noted that in all cases except the 33 F batch, this mixture gained significant strength between seven and 28 days. The batch cured at 33 F gained only an average of 20 psi.

Mixture 40/40 displayed markedly lower 28-day compressive strength than the mixtures discussed previously, with the 70 F batch achieving only 4270 psi – barely exceeding the minimum 28-day strength of 4000 psi discussed in Chapter 3. This batch showed no significant difference from the 33 F batch of Mixture 20/20. According to the 90 percent confidence interval, the strength of the batch cured at 60 F (3770 psi) was similar to Batch 40/40 (70) and to 40/40 (50) (3090 psi), though 40/40 (70) and 40/40 (50) were not similar to each other. When cured at temperatures colder than 50 F, the 28-

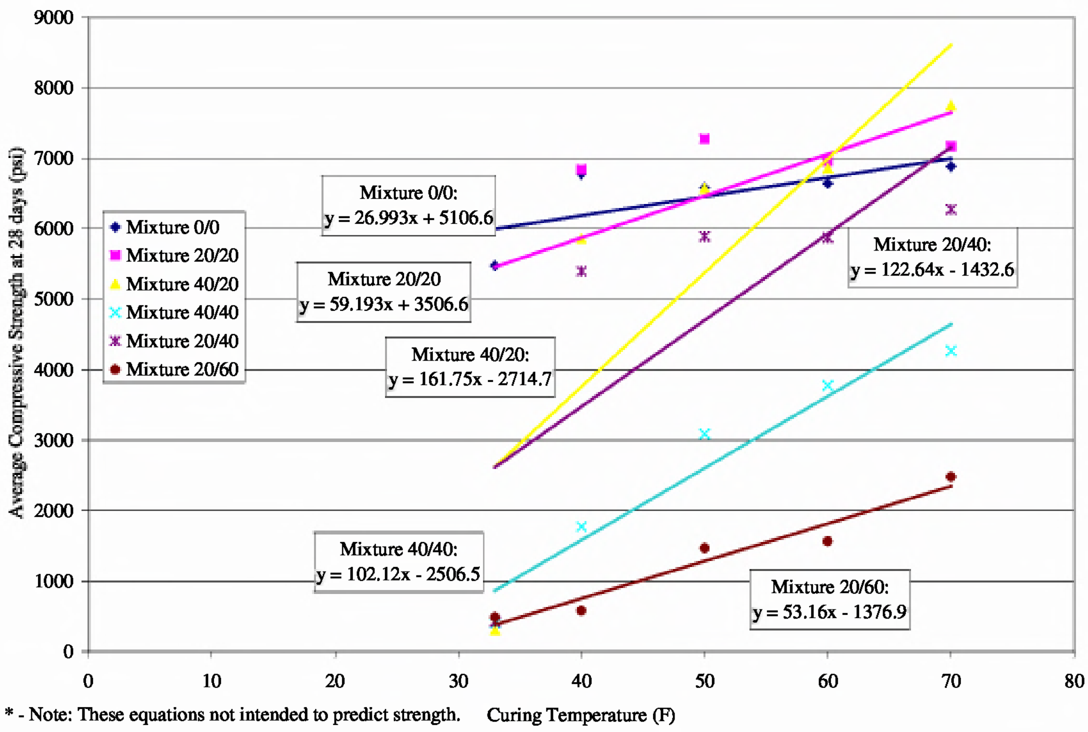
day compressive strength of Mixture 40/40 decreased drastically. Batch 40/40 (40) (1770 psi) achieved only 57 percent of the strength of Batch 40/40 (50), and Batch 40/40 (33) (400 psi) reached only 23 percent of the strength of Batch 40/40 (40).

Mixture 20/40 exhibited compressive strength similar to that of the cooler batches of Mixture 40/20. This trend was not surprising in that 60 percent of the PC was replaced in each of the two mixtures. In Mixture 40/20, a larger percentage of this was SC, while in Mixture 20/40 the majority of the replacement material was FA. The high-SC mixture attained higher compressive strengths at warmer temperatures, but the high-FA mixture exhibited a more consistent strength. The average 28-day strengths of Mixture 20/40 decreased less than those of Mixture 40/20 as curing temperature decreased. Mixture 20/40 reached its highest strength, 6280 psi, when cured at 70 F. The 60 and 50 F batches of Mixture 20/40, with respective 28-day strengths of 5870 and 5890 psi, were not statistically different from Batch 20/40 (70). The compressive strength of Batch 20/40 (40), 5400 psi, was similar to those of Batches 20/40 (60) and 20/40 (50), according to the 90 percent confidence intervals. When cured at 70, 60, 50, and 40 F, Mixture 20/40 exceeded the minimum average 28-day compressive strength of 4000 psi required by AHTD (2003).

Mixture 20/60 was the worst performing mixture examined in the study. This mixture attained peak 28-day compressive strength of 2480 psi when cured at 70 F. A sharp decrease in strength occurred when the curing temperature was reduced to 60 F. Batch 20/60 (60) reached only 1560 psi, 63 percent of the strength reached by the 70 F batch. From the 90 percent confidence intervals, no significant difference was detected between the strengths of Batches 20/60 (50) (1460 psi) and 20/60 (60). Strength decreased again when curing temperature decreased to 40 F, falling to only 580 psi. Batch 20/60 (40) did not reach final set until the samples reached about 36 days of age, explaining the sharp decrease in compressive strength for Mixture 20/60 when curing temperature was decreased from 50 to 40 F. The 50 F batch reached final set in about 13 days. Batch 20/60 (33), reaching 490 psi, was not significantly different from the 40 F batch (20/60 (40)). This is a surprising result, as Batch 20/60 (33) reached final set in 163.36 hours, or about 7 days, which was about 29 days sooner than Batch D-6. As discussed previously, the chamber used for curing specimens at 33 F was difficult to maintain, and most likely caused the concrete to freeze before the setting actually occurred. This phenomenon would result in shorter-than-expected setting times.

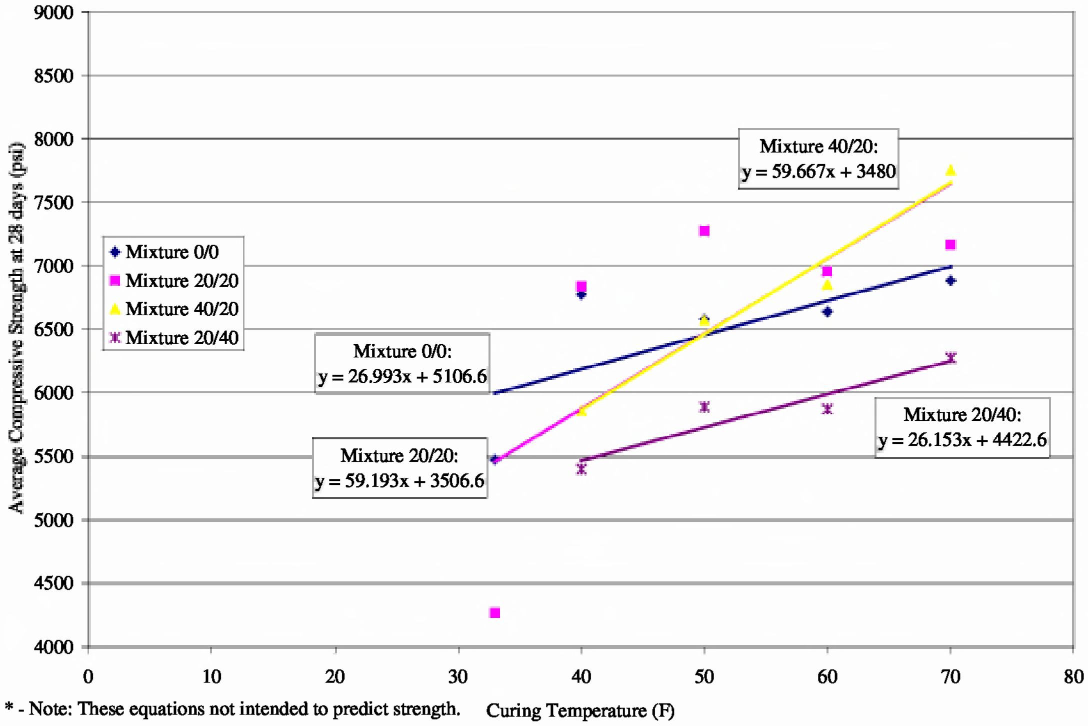
Figure 4-29 shows the sensitivity of the 28-day compressive strength of each mixture to changing curing temperatures. Again, the equations of the trendlines in this plot were not intended to predict the 28-day strength of mixtures based on curing temperature, but rather to determine the slope of the linear trendline for each of the particular mixtures. The compressive strength of the control mixture was least affected by decreasing curing temperatures, with about a 270 psi increase in strength for each 10 F increase in temperature. Mixtures 20/20 was slightly more sensitive to curing temperature than the control, with strength increasing almost 600 psi per 10 F increase in curing temperature. Mixture 20/60 was minimally affected by curing temperature at 28 days of age. The compressive strength of this mixture gained about 500 psi for each 10 F temperature increase. The mixture most severely affected by varying curing temperatures was Mixture 40/20. The compressive strength of this mixture increased more than 1500 psi per 10 F increase in temperature. Mixtures 40/40 and 20/40 were slightly less affected by curing temperature, with increases in strength of about 1000 and 1200 psi, respectively, for each 10 F curing temperature increase.

The average strengths of Mixtures 40/20 and 20/ were also plotted without the 33 F data. On this plot (Figure 4-30) Mixtures 0/0 and 20/20 were plotted with all data. This plot showed that the trendline for Mixtures 20/20 and 40/20 had the same slopes (strengths increased about 600 psi for each 10 F temperature increase), indicating that above 33 F, Mixture 40/20 is no more sensitive to decreasing curing temperature than Mixture 20/20. Mixture 20/40, without 33 F data, had a trendline with the same slope as Mixture 0/0 (strength increasing less than 300 psi per 10 F temperature increase).



* - Note: These equations not intended to predict strength.

Figure 4-29: Effect of Curing Temperature on 28-Day Strength



* - Note: These equations not intended to predict strength.

Figure 4-30: Effect of Curing Temperatures Above 33 F on 28-Day Strength of Mixtures 40/20 and 20/40

4.2.3.5 90-Day Compressive Strength

The final age for compressive strength tests was 90 days of age. The results of the 90-day tests were again analyzed using 90 percent confidence intervals. These confidence intervals may be seen in Figure 4-31. In general, mixtures in which 60 percent of the PC or less was replaced with SC or FA and cured at or above 50 F performed the best, attaining higher average 90-day compressive strengths than the control mixture. Mixtures containing 80 percent SCMs (Mixtures 40/40 and 20/60) displayed significantly less compressive strength than other mixtures.

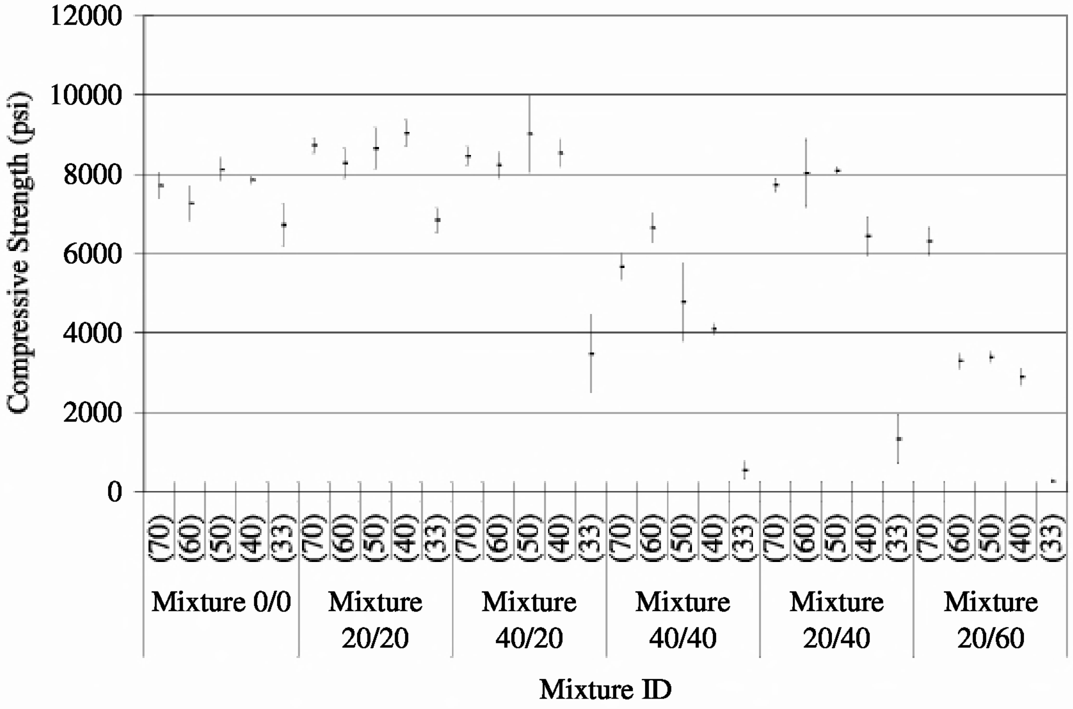


Figure 4-31: 90 % Confidence Intervals for 90-Day Compressive Strength

Mixture 0/0 attained between 6720 and 8120 psi, with the lowest strength being the batch cured at 33 F. The highest strength achieved by Mixture 0/0 occurred in the batch cured at 50 F. This trend is not surprising, as concrete tends to reach higher late-age compressive strength when cured at lower temperatures (Mindess 2003). According to the 90 percent confidence interval, Batches 0/0 (60), 0/0 (50), and 0/0 (40) are statistically similar to Batch 0/0 (70). There is no significant difference between the 33 F batch of Mixture 0/0 and the 60 F batch. All batches performed satisfactorily, attaining strength of 6720 psi when cured at 33 F, and exceeding 7000 psi at all other temperatures.

Mixture 20/20, when cured above 33 F, achieved higher compressive strength than any batch of Mixture 0/0, although this difference is not statistically significant in all cases. For example, the strengths of the 60 and 50 F batches of Mixture 20/20 (8280 and

8650 psi) are not significantly different from the 50 F batch of Mixture 0/0 (8120 psi), according to the 90 percent confidence intervals. The batches of Mixture 20/20 cured above 33 F exceeded 8000 psi at 90 days in all cases, and there is no significant difference in these batches. The batch cured at 40 F attained an average strength of 9040 psi, which is statistically greater than the strength of the same mixture cured at 60 F, but not statistically different from those batches cured at 70 and 50 F. This increased strength for a low-temperature batch may be attributed to a late-age strength increase for mixtures cured at low temperatures (Mindess 2003). The 33 F batch of Mixture 20/20 displayed significantly lower strength at 90 days, 6830 psi, than the other batches of this mixture. This strength is statistically the same as the strength of Mixture 0/0 when cured at the same temperature.

When cured at or above 40 F, Mixture 40/20 attained strength statistically equivalent to those batches of Mixture 20/20 cured at the same temperatures. Batches 40/20 (70), 40/20 (60), 40/20 (50), and 40/20 (40) reached compressive strengths ranging from 8230 to 9020 psi. The highest value, 9020 psi, was obtained by Batch 40/20 (50), which was cured at 50 F. This trend is similar to the one discussed previously for Mixture 0/0, and is attributed to a known late-age strength increase as curing temperature decreases (Mindess 2002). Statistically, however, the differences in the strengths of the four warmest batches of Mixture 40/20 were not significant. These four batches also were not significantly different from the strengths of Mixture 20/20 when cured at the same range of temperatures. The 90-day compressive strengths of Mixture 40/20 when cured at 70, 60, 50, and 40 F were significantly greater than the strengths of the Mixture 0/0 batches cured at 70, 60, and 40 F, with the exception of the 50 F batch of Mixture 0/0, which attained over 8000 psi. When cured at 33 F, the compressive strength of Mixture 40/20 decreased dramatically as compared to the 33 F compressive strengths of Mixtures 0/0 and 20/20. Mixture 40/20 contained a high volume of SCMs, and mixtures containing such volumes of SCMs tend to be more sensitive to low curing temperatures than ordinary PC concrete.

Mixture 40/40 exceeded 4000 psi at 90 days of age when cured at or above 40 F. However, the mixture was inconsistent and sporadic, with compressive strengths ranging from 4100 to 6650 psi. The greatest strength attained by this mixture occurred when cured at 60 F. None of the other batches of Mixture 40/40 reached strengths statistically similar to this batch. Batches not significantly different from Batch 40/40 (60) include 0/0 (60), 0/0 (33), and 20/20 (33). The strengths of Batches 40/40 (70) (5650 psi) and 40/40 (60) (4770 psi) are not significantly different. There is also no significant difference between the strengths of Batch 40/40 (50) and 40/40 (40) (4100 psi). When cured at 33 F, Mixture 40/40 performed worse than other mixtures due to the higher replacement rate (80 percent). This batch attained an average 90-day compressive strength of only 530 psi, about 13 percent of the strength achieved by the same mixture cured at 40 F.

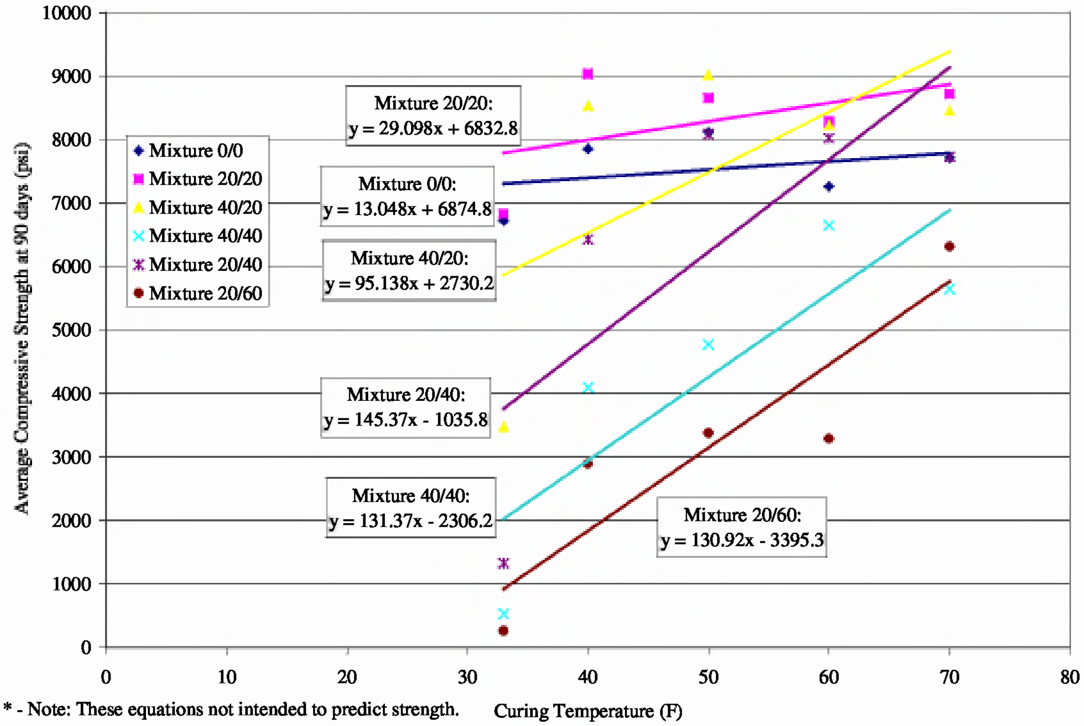
Mixture 20/40 performed similarly to the control mixture when cured at or above 50 F. This mixture performed best when cured at 50 F, attaining compressive strength of 8080 psi. When cured at 60 F, the strength was only slightly less at 8030 psi. Neither the 70 F (7730 psi) nor the 50 F batch were significantly different from Batch 20/40 (60). Mixture 20/40 displayed a severe decrease in strength as curing temperature decreased below 50 F, however. When cured at 40 F, the compressive strength of this mixture

(6430 psi) was 20 percent lower than that of the same mixture cured at 50 F. All these values exceed the AHTD minimum 28-day compressive strength of 4000 psi. The strength decreased to only 1330 psi (less than 20 percent of the strength of the 50 F batch) when Mixture 20/40 was subjected to a curing temperature of 33 F. This strength was statistically similar only to Mixture 40/40 when cured at 33 F.

Mixture 20/60, like Mixture 40/40, attained lower strengths than mixtures with lower replacement rates, and was somewhat inconsistent, although Mixture 20/60 was more consistent than Mixture 40/40. When cured at 70 F, the 90-day strength of the mixture exceeded the AHTD minimum of 4000 psi, attaining 6320 psi, though the same mixture under the same conditions attained less than 2500 psi at 28 days of age. The compressive strength decreased severely, however, when Mixture 20/60 was cured at 60 F. This batch attained only 3290 psi, about 50 percent of the strength of the same mixture cured at 70 F. Batch 20/60 (50) was not significantly different from the 20/60 (60), attaining 3380 psi. The strength of the 20/60 (40) was significantly lower than both Batches 20/60 (60) and 20/60 (33), attaining 2890 psi. Another severe strength decrease occurred when the curing temperature of Mixture 20/60 decreased from 40 F to 33 F. 20/60 (33) attained only 260 psi, barely higher than the strength of the same batch at one day of age, and less than five percent of the 90-day strength of the same mixture cured at 70 F.

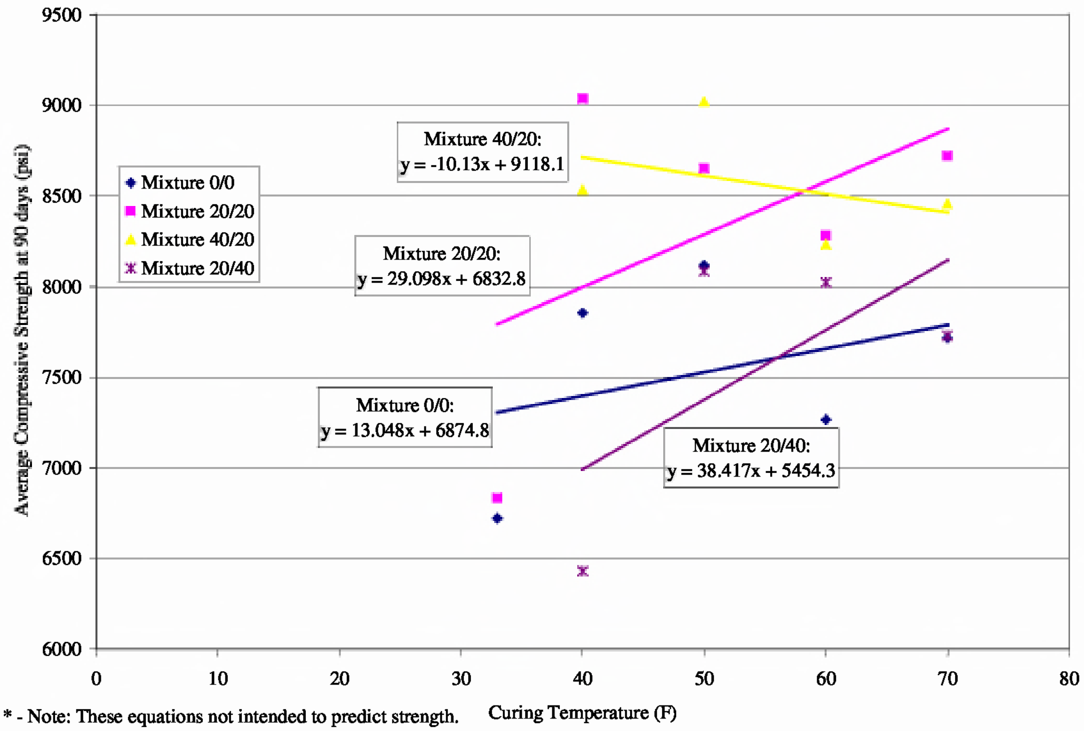
Figure 4-32 illustrates the effect of varying curing temperature on the average 90 day compressive strength. As mentioned previously regarding similar figures, the equations for the trendlines on this plot were not intended to predict 90-day compressive strength of the mixtures studied. These equations were simply used to measure the slope of the linear trendline for each of the six mixtures to illustrate the effect of the decreasing curing temperatures. As shown in the figure, Mixture 0/0 was least affected by temperature, with strength increasing about 130 psi for each 10 F increase in temperature. Mixture 20/20 was only slightly more affected by varying curing temperatures, increasing about 300 psi for each 10 F increase in temperature. The figure shows that the linear trendlines fit to the ternary mixtures (except Mixture 20/20) are much more affected by differences in curing temperatures than the control mixture.

Figure 4-32 further shows that the ternary mixtures, excepting Mixtures 20/20 and 40/20, are affected similarly, with the trendlines having nearly the same slope, indicating an increase in strength of about 1400 psi for each 10 F increase in curing temperature. Upon closer inspection, however, it can be seen that at warmer curing temperatures (40 F and warmer), Mixtures 40/20 and 20/40 are affected much less severely. In the case of these two mixtures, if 33 F batches were discarded, the slopes of their trendlines would most likely approach the trendline for Mixtures 0/0 and 20/20. The results of this hypothesis are included as Figure 4-33. Mixtures 0/0 and 20/20 were plotted with all data (including 33 F), while 33 F data for Mixtures 40/20 and 20/40 were discarded. Indeed, Mixture 20/40 displays a slope similar to that of Mixtures 0/0 and 20/20, displaying an increase of strength of about 400 psi for each 10 F increase in strength, a sensitivity much closer to the control than when the 33 F batch was considered. Mixture 40/20 actually showed a decrease in strength of about 100 psi per 10 F temperature increase. When 33 F was not considered, Mixture 40/20 was actually the least affected by varying curing temperature.



* - Note: These equations not intended to predict strength.

Figure 4-32: Effect of Curing Temperature on 90-Day Strength



* - Note: These equations not intended to predict strength.

Figure 4-33: Effect of Curing Temperatures Above 33 F on 90-Day Strength of Mixtures 40/20 and 20/40

Chapter 5

Maturity Study

Results and Discussion

5.1 General

This chapter presents the results and a thorough discussion of the experimental program. The scope of the work included casting 90 experimental slabs from 30 separate concrete batches and casting 540 mortar cubes from 18 separate mortar batches. Data analysis included reduction of 90 logger output files, development of strength-age and strength-maturity relationships, comparison of confidence intervals, and regression procedures in order to develop suitable datum temperature and activation energy parameters as well as to derive predictive models for estimating compressive strength. The results are intended to provide a background for estimating compressive strength of ternary concrete mixtures used in cold weather conditions in the field.

The research program was composed of three studies: the activation energy/datum temperature study, the strength study, and the maturity study. Activation energy is a numerical value which describes the temperature sensitivity of a concrete mixture (Schindler 2004). Activation energy is a constant in the equation for the equivalent age maturity index. The datum temperature is the temperature below which strength development for a particular concrete mixture no longer occurs. Datum temperature is also a constant, and it is required for the time-temperature maturity index equation. These two constants were experimentally derived based on analysis of mortar cube compressive strength and age data. The strength study examined strength development behavior of concrete containing fly ash and slag cement cured at low temperatures. The study involved casting cylinders and curing them under constant temperature conditions. The cylinders were subsequently compression tested at specified ages. The purpose of the strength study was to support the results of the maturity study. The maturity study focused on the development of empirical relationships between maturity indices and compressive strength for ternary concrete mixtures. This was achieved by casting experimental slabs and recording the time and temperature history with a maturity meter. The slabs were cured and compression tested similarly to the strength study cylinders. Both the time-temperature and equivalent age maturity indices were calculated using the temperature-time history and the constants derived in the activation energy/datum temperature study. The relationship between the compressive strength and the maturity index for the different concrete mixtures was examined in order to provide a basis for estimating ternary concrete compressive strength using similar concrete mixtures cured at low temperatures.

The concrete mixtures from the strength and maturity studies are identified by the percentage replacement rates by weight for slag cement (SC) and then fly ash (FA). For example, Mixture 20/20 represents 20% SC replacement and 20% FA. The control mixture is identified as 0/0 with no SC or FA replacement. Batches are identified by the mixture identification followed by the target curing temperature in parentheses. For example, Batch 40/40 (40) is the specific batch representing a mixture with 40% SC replacement and 40% FA replacement which had a target curing temperature of 40°F. The mortar mixtures and batches for the activation energy and datum temperature study follow the same identification scheme used for concrete with the exception that the letter

"M" is placed in front of the identification to indicate a mortar mixture or a specific mortar batch.

5.2 Results of the Activation Energy and Datum Temperature Study

Six different mortar mixtures were examined with the same proportion of cementitious materials and w/cm as the concrete mixtures used for the strength and maturity studies. The proportion of fine aggregate for the mortar mixtures were selected based on a ratio of fine aggregate-to-cement that was the same as the coarse aggregate-to-cement ratio for the corresponding concrete mixture.

First, the fresh mortar properties, temperature and flow, will be presented followed by compressive strength. Second, the results of the generalized curve fitting of the compressive strength and age data to the hyperbolic equation (Equation 12) will be presented. Finally, the datum temperature and activation energy results from regression analysis of the rate constant and temperature relationship will be discussed. These rate constants for all six mixtures and each curing temperature were obtained from the generalized curve fitting procedure.

5.2.1 Fresh Mortar Properties

The fresh mortar properties examined were temperature and flow. The results of these tests are listed in Table 5-1. Fresh mortar properties were measured to ensure quality control and to quantify the effects of the different SCM replacement rates on flow. Further, the effectiveness of attaining the targeted fresh mortar could be evaluated by measuring the mortar temperature immediately after mixing and the flow test.

Table 5-1: Results of Fresh Mortar Properties

Batch	Fresh Temperature, °F	Flow (mm)
M 0/0 (40)	51	187
M 0/0 (70)	65	218
M 0/0 (100)	78	208
M 20/20 (40)	51	219
M 20/20 (70)	62	236
M 20/20 (100)	NA	225
M 40/20 (40)	48	229
M 40/20 (70)	73	227
M 40/20 (100)	76	204
M 40/40 (40)	52	244
M 40/40 (70)	61	232
M 40/40 (100)	NA	226
M 20/40 (40)	55	243
M 20/40 (70)	68	241
M 20/40 (100)	73	222
M 20/60 (40)	56	250
M 20/60 (70)	63	>300*
M 20/60 (100)	73	242

*Maximum flow that can be measured is 300mm.

5.2.1.1 Fresh Mortar Temperature

The results of the fresh mortar temperature measurements are shown in Table 5-2, Table 5-3, and Table 5-4. The average, standard deviation, and coefficient of variation for all batches with the same target curing temperature are listed as well as the difference for each batch from the target curing temperature. Further, the average difference of the fresh mortar temperature from the target curing temperature is shown.

Table 5-2: Fresh Mortar Temperature, 40°F Target Batches

Batch ID	Fresh Temperature, °F	Difference |(x-40)|, °F
M 0/0 (40)	51	11
M 20/20 (40)	51	11
M 40/20 (40)	48	8
M 40/40 (40)	52	12
M 20/40 (40)	55	15
M 20/60 (40)	56	16
Average	52	12
Std. Deviation	3	
COV (%)	5	

Table 5-3: Fresh Mortar Temperature, 70°F Target Batches

Batch ID	Fresh Temperature, °F	Difference |(x-70)|, °F
M 0/0 (70)	65	5
M 20/20 (70)	62	8
M 40/20 (70)	73	3
M 40/40 (70)	61	9
M 20/40 (70)	68	2
M 20/60 (70)	63	7
Average	65	6
Std. Deviation	4	
COV (%)	6	

The effectiveness of attaining the targeted fresh mortar temperature varied based on the targeted curing temperature. The 70°F series were the most successful with an average difference in temperature between the fresh mortar and the targeted curing temperature of 6°F. The aggregate and mixing water were stored in the curing chamber, and the cementitious materials were kept in the laboratory which maintained an ambient temperature near that of the target curing temperature. The 40°F series had a 12°F average difference of temperature. Even though the aggregate and mixing water were kept in the curing chamber for 24 hrs. prior to mixing, the cementitious materials were maintained in the laboratory at room temperature which accounts for the 12°F difference between the actual and targeted temperatures. Least successful was the 100°F series with an average difference of 25°F. In the case of the 100°F batches, the aggregate and cementitious materials were maintained at room temperature while only the mixing water was heated prior to mixing of the materials.

Table 5-4: Fresh Mortar Temperature, 100°F Target

Batch ID	Fresh Temperature, °F	Difference |(x-100)|, °F
M 0/0 (100)	78	22
M 20/20 (100)	NA*	NA
M 40/20 (100)	76	24
M 40/40 (100)	NA*	NA
M 20/40 (100)	73	27
M 20/60 (100)	73	27
Average	75	25
Std. Deviation	2	
COV (%)	3	

*Fresh mortar temperature not recorded.

Analysis of the coefficient of variation (COV) for the three batch series indicates that the variation between the individual batches at the same target curing temperature was from 3 to 6%. Although the average differences between the fresh mortar temperatures and the target were in some cases large (25°F for the 100°F batch series), the difference was approximately the same for all the batches in the series. The final results of the experiment were not impacted by the differences in temperature between the actual fresh mortar temperature and the targeted curing temperature. All of the batches for a particular temperature series had approximately the same fresh mortar temperature. Therefore, the initial conditions were the same for all in the series.

5.2.1.2 Flow

The results of the individual flow tests are shown in Table 5-1. The average flow, standard deviation, and coefficient of variation for each mixture are indicated in Table 5-5. These are the average flows for the three batches of the same mixture corresponding to the three curing temperatures (40, 70, and 100°F). Increases in workability were observed with increasing SCM content. This increase in workability was particularly evident between the control mixture and all of the ternary mixtures. The workability increase was most evident for the mixtures containing high amounts of FA. The observed increases in workability were supported by comparing the average results of the flow tests for each mixture with the averages for all the other mixtures. The mixture with the lowest flow reported was the control mixture at 204 mm. The 20% SC/60% FA mixture had the highest average flow, 264 mm. The batch M 20/60 (70) was suspect with a flow greater than 300 mm. The size of the flow table only allows for flow measurement up to 300 mm. Note that 300 mm was used to calculate the mean, std. deviation, and COV for the series.

Table 5-5: Flow

Mixture ID	Average Flow (mm)	Std. Deviation (mm)	COV (%)
M 0/0	204	13	6
M 20/20	227	7	3
M 40/20	220	11	5
M 40/40	234	7	3
M 20/40	235	9	4
M 20/60	264*	26*	10*

*Flow for Batch M 20/60 (70) exceeded the 300mm measuring capacity of the table.

5.2.2 Mortar Compressive Strength Determination

Following the casting of the 2 in. mortar cubes, the cubes remained in the water baths until time of testing. The cubes were tested in compression at specified ages following a strategy discussed in Section 3.6.2.3. The individual batches are grouped together by mixture identification to simplify presentation.

A discussion of the strength development of the mortar mixtures is not provided. It is not the intent of the study to correlate mortar strength to concrete strength. The strength gain of the concrete mixtures will be discussed later. The goal of the mortar compression testing was to utilize the results to perform an analysis of rate constant-temperature behavior for the mortar mixtures. The outcome of that analysis is to determine datum temperature and activation energy. The derived datum temperature and activation energy will be correlated to the corresponding concrete mixtures used in the maturity study.

5.2.3 Results of the Generalized Curve Fitting to the Hyperbolic Equation

The strength and age data generated from the mortar cube compressive tests was entered into the computer program, Kaleidagraph. Note that eighteen different curve fits were performed by the program for each set of strength and age data. A set of data is defined as the strength and age data for a particular batch. In order to perform a generalized curve fit, Kaleidagraph requires that the user also specifies an equation. The computer program was instructed to fit the data to the hyperbolic equation presented by Carino (1984):

$$\frac{S}{S_u} = \frac{k_T(t-t_0)}{1+k_T(t-t_0)} \qquad (12)$$

S = average mortar cube compressive strength at the test age (psi)

S_u = ultimate or limiting strength (psi)

k_T = rate constant (1/day)

t = test age (day)

t_o = dormant period where strength development does not to occur (day)

The program determined the best-fit values for unknown variables, S_u, k_T, and t_o, that provide the least amount of error. The strength and age data entered into the program corresponded to the known variables S and t. Because the program generates numerical results for multiple unknown variables that belong to a particular nonlinear function, the generalized curve fit performed by Kaleidagraph is also referred to as a nonlinear regression procedure in this discussion.

The parameters determined by the curve fit, S_u, k_T, and t_o, as well as the standard errors for each are shown. Table 5-6 provides a summary of S_u, k_T, and t_o results. Also, the initial values as entered for the iterations are also shown. The number of data points (age and corresponding average strength), N, that were used for the analysis are listed. Kaliedagraph also determined the chi square value and the correlation coefficient, R^2, associated with the generalized curve fit regression. The set of regression results for each batch includes: S_u, k_T, t_o, chi-square, R^2, and the three parameter errors.

Table 5-6: Summary of S_u, t_0, and k_T Results

	Ultimate Strength (psi)			Dormant Period (day)			Rate Constant (1/day)		
Mixture	$S_{u40°F}$	$S_{u70°F}$	$S_{u100°F}$	$t_{040°F}$	$t_{070°F}$	$t_{0100°F}$	$k_{T40°F}$	$k_{T70°F}$	$k_{T100°F}$
0/0	8430	7210	5770	-0.19	0.21	-0.01	0.083	0.296	1.202
20/20	7150	7880	7670	0.56	0.15	0.15	0.089	0.138	0.334
40/20	6020	15820	10760	0.03	-2.62	0.12	0.037	0.013	0.133
40/40	2090	7180	7770	7.92	2.71	1.94	0.047	0.012	0.127
20/40	4880	4980	8460	1.90	0.83	0.47	0.067	0.155	0.137
20/60	3440	4950	6340	14.76	7.36	2.54	0.014	0.016	0.121

The rate constant, k_T, is the only result that is used for determining activation energy and datum temperature. An analysis of the interaction between the rate constant and temperature is required to determine activation energy and datum temperature. This analysis will be the subject of the following two sections. The other parameters determined by the regression, S_u and t_o, are discussed only to support conclusions regarding the accuracy of the rate constant results. The intent of this discussion is not to evaluate the performance of the mortar or associated concrete mixtures in terms of the ultimate strength results or dormant period results. The chi-square and R^2 values are also discussed in order to evaluate the regression results and thereby further support conclusions regarding the accuracy of the rate constant results.

A comparison of the ultimate strengths generated by the generalized curve fit for all of the mortar batches is shown in Figure 5-1. The results are also listed in Table 5-6.

The mortar mixtures with the highest ultimate strengths determined by the generalized curve fit were M 0/0, M 20/20, and M 40/20. The ultimate strengths for these mixtures were above 5000 psi for all curing temperatures. Batch M 20/40 (100) also performed well with a result of 8460 psi. The ultimate strength reported for Mixture 40/20 at the 100°F curing was 10760 psi with an error of 680 psi. The ultimate strength at the 70°F curing temperature for Mixture M 40/20 was 15820 psi which was the greatest of all mixtures, but there was an associated error of 7380 psi. This error was as large as the ultimate strength expected for the batch based on the results of the strength study. Given the high range of error for batch 40/20 (70), that value should be disregarded. Batch 40/40 (70) also demonstrated a high amount of error, and, therefore this ultimate strength is highly suspect as well. The mixtures with total PC replacement of 80% and above, Mixture 40/40 and Mixture 20/60, developed the lowest ultimate strengths of all the batches tested. This trend is in agreement with the strength performance of the concrete (See Section 5.3.2).

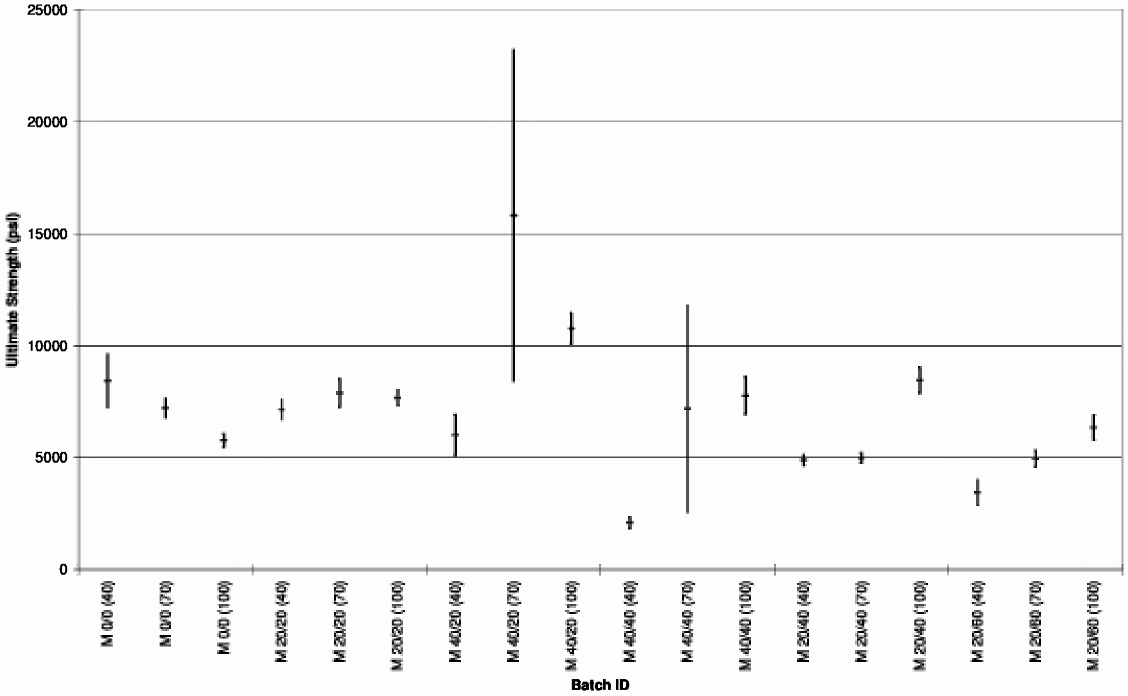


Figure 5-1. Ultimate Strength Results for All Mortar Batches.

The dormant period, t_o, indicates the period of time in which strength development is not occurring and is analogous to time of setting. Figure 5-2 graphically illustrates the different dormant period results for all of the batches examined in the study. Table 5-6 also lists all of the t_0 results. Most notable are the 80% total portland cement replacement Mixtures, 40/40 and 20/60. At the 40°F target curing temperature, the resulting t_o for Mixture 40/40 was 7.9 days, and 14.8 days for Mixture 20/60. These results are supported by the results of the concrete strength study (Section 5.3.2) and by the results of the mortar cube strength tests. Note that Batch M 20/60 (40) only developed an average strength of 90 psi at 17 days.

Analysis of the ultimate strength parameter for Batches M 40/20 (70) and Batch M 40/40 (70) suggested poor regression results for those batches; this conclusion was further supported by the dormant period parameter. For Batch M 40/20 (70), the dormant period was -2.6 days. This result shows that the batch began to gain strength 2.6 days before mixing. A negative value of this magnitude for t_0 is not supportable. The error associated with the dormant period parameter for Batch M 40/40 (70) further supports a conclusion of a poor regression for this batch. M 40/40 (70) demonstrated the highest t_0 error of any of the batches examined in this study. According to this value, the actual dormant period lies between -1.1 and 3.8 days. The t_0 error for Batch M 40/20 (70) was the second highest, and this further confirms that a problem exists with this particular regression.

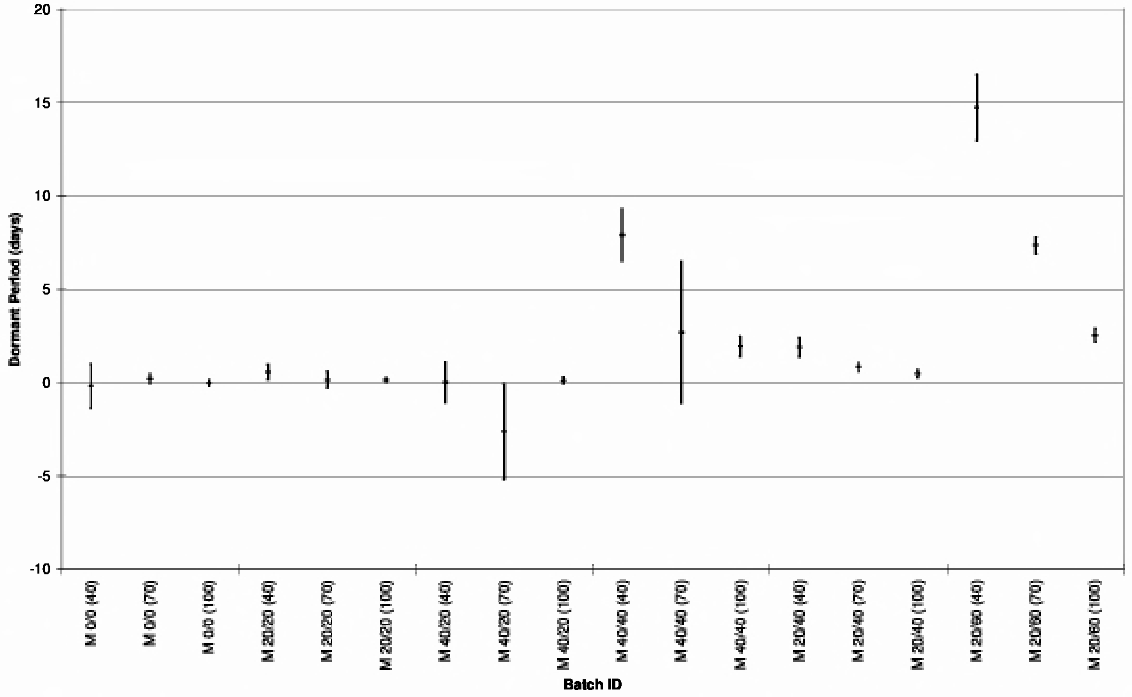


Figure 5-2. Dormant Period Results for all Mortar Mixtures.

In addition to evaluating the regression by identifying individual results with high amounts of error or by improbable results not supported by other data, the individual regression results may be further evaluated by two different parameters, the correlation coefficient, R^2, and chi-square, both of which are provided in the results from Kaleidagraph. R^2 is typically used as a measure of goodness-of-fit for a model to the data, and the range of possible values is from zero to one. Models with R^2 values close to one are considered to provide a good fit to the data. A comparison of R^2 for all batches is shown in Figure 5-3. The lowest R^2 values occurred for batches: M 0/0 (40), M 40/20 (70), and M 40/40 (70). Note that these same batches also had the highest error associated with the parameters S_u and t_0.

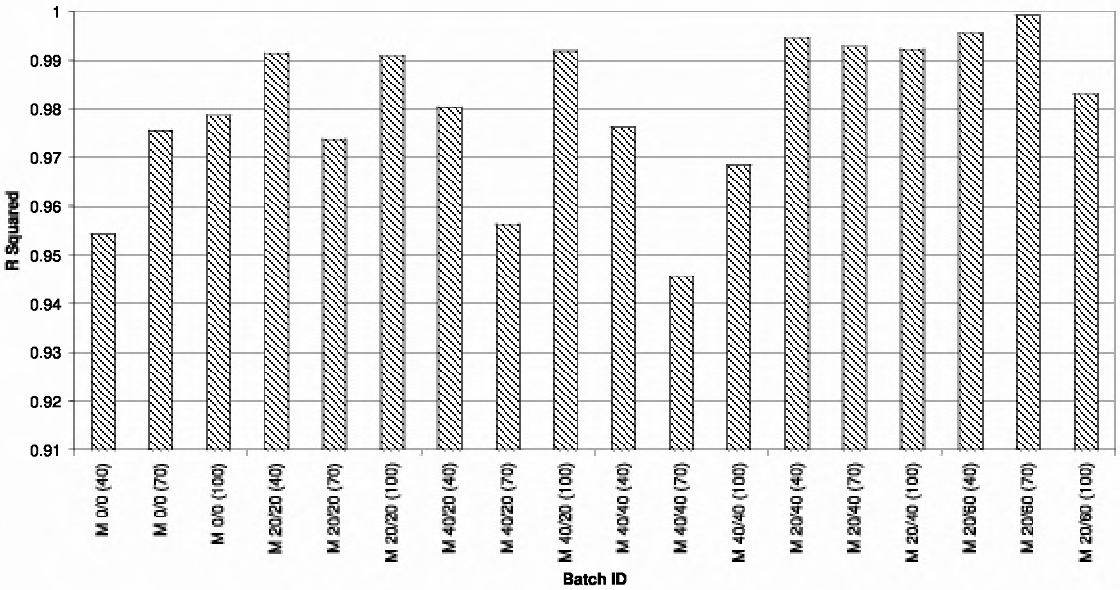


Figure 5-3. Comparison of correlation coefficient, R^2.

Chi square is another measure of goodness of fit of a model—it is an indicator of the difference between an actual distribution of values and a theoretical distribution. It is the sum of the squared differences between the data and the calculated curve.

In this case, lower values indicate a good fit of the data to the model. Figure 5-4 is a comparison of different chi square results from the regression. The batches with the highest chi square were: M 40/20 (70), M 0/0 (40), and M 20/20 (70). This measure of goodness-of-fit is sensitive however to the number of data points used in the regression As the number of data points used in the analysis increases the chi-square value may increase as the accumulated error from the individual data points increases even though the additional data points may cause the calculated curve to better approximate actual strength development. In the case of M 40/20 (70), the high chi square value further supports the poor regression conclusion.

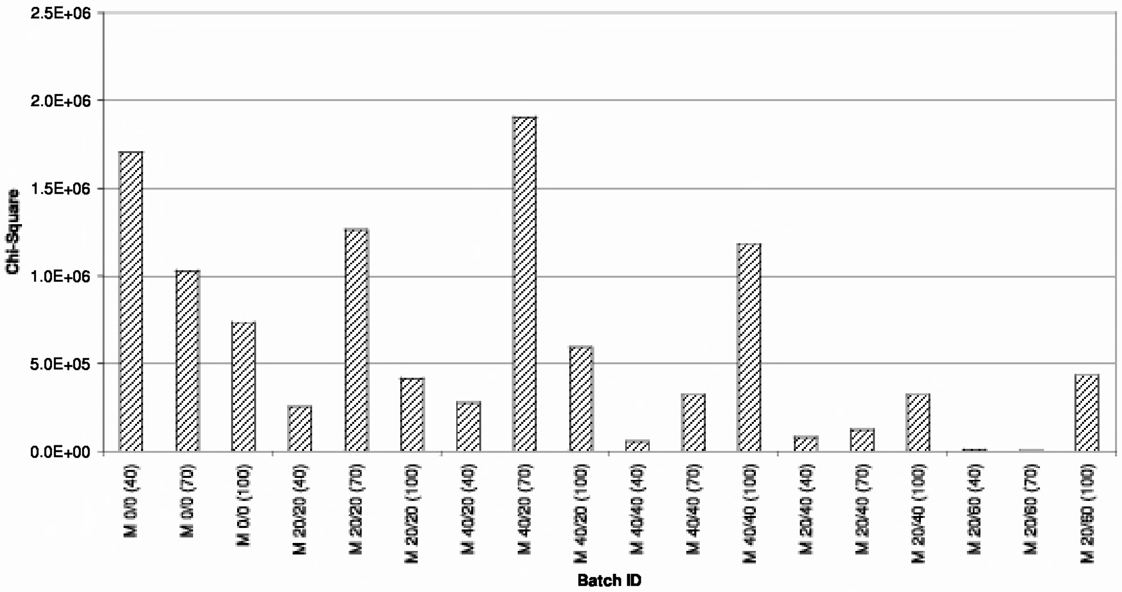


Figure 5-4. Comparison of Chi Square Results for Generalized Curve Fit Procedure.

The last parameter determined by the regression procedure discussed herein is the rate constant, k_T, which is the initial slope of the hyperbolic curve. The k_T results for the all of the batches are shown in the summary table (Table 5-6). Figure 5-5 is a graphical comparison of all the k_T results. The rate constants for each mixture are temperature dependent, and the relationship between the rate constants and temperature is the subject of the following two sections. Recall that the rate constant is the initial slope of the curve for the compressive strength versus age plot. The rate constant is also the only parameter that is determined by the program which is necessary for the determination of activation energy and datum temperature.

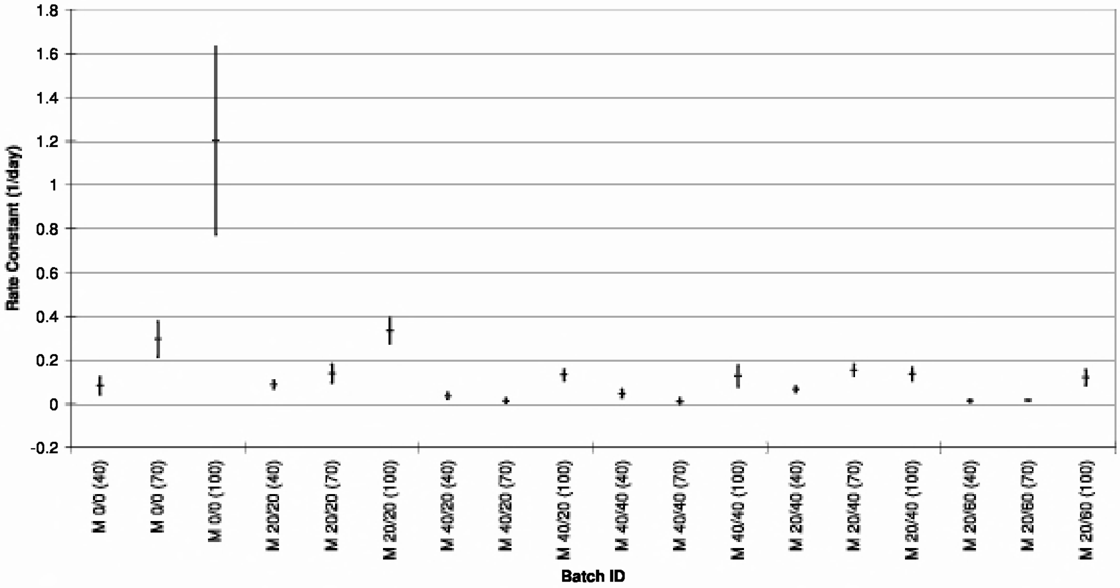


Figure 5-5. Rate Constant Results for all Mortar Mixtures.

Examination of the rate constant behavior for the six mixtures and three curing temperatures indicated a trend of increased rate constant magnitude with increased curing temperature and decreased rate constant magnitude with increased SCM content. For each mixture, the magnitude of the rate constant increased as the curing temperature increased from 40°F to 100°F. The rate constant results are shown graphically in Figure 5-5. The six different mixtures are each separated by gridlines to assist in differentiating between the mixtures. For each mixture, three batches are shown representing the results of the three different curing temperatures. The highest rate constants for each mixture occurred for the batches cured at 100°F. The lowest rate constants for each mixture occurred when cured at 40°F. The two exceptions are that the rate constants results for the Batches M 40/20 (70) and M 40/40 (70) were lower than the rate constants for the batches of the same mixtures cured at 40°F. These two batches had been identified earlier in this discussion as having poor generalized curve fit results, and therefore any conclusions formulated based on rate constant behavior should be supported by Batches M 40/20 (70) and M 40/40 (70). The mixtures which resulted in the highest rate constants were Mixture 0/0 and Mixture 20/20. These mixtures had either no SCM content or the lowest SCM content when compared to all the other mixtures. Rate constant results for Mixtures 20/60 and 40/40 were the smallest when compared to all the other mixtures, and these two mixtures contained the highest amount of SCM's.

Table 5-7. Summary of Δk_T

Mixture ID	**Δk_T ($k_{100°F}$-$k_{40°F}$)**
0/0	1.12
20/20	0.25
40/20	0.10
40/40	0.08
20/40	0.07
20/60	0.11

The control mixture developed large k_T increases with increasing temperature. The magnitude of k_T for the control mixture increased from 0.08 at 40°C to 0.3 at 70°C. The largest increase was from 70°F to 100°F, the final k_T value was 1.20 for the control at 100°F. The change in k_T for an individual mixture, Δk_T, determined by subtracting the rate constant result for the batch cured at 40°F, $k_{40°F}$, from the result for the batch cured at 100, $k_{100°F}$, was examined in order to quantify the temperature sensitivity of the rate constant for a particular mixture and allow for comparison between the different mixtures. Table 5-7 contains the Δ k_T results for all of the mixtures. The Δ k_T for Mixture 0/0 was 1.12. Batch M 0/0 (100) generated the maximum k_T for all batches in this study. There is also a high amount of error which places the true k_T value for this batch in the range of 0.78 to 1.63. There are similar findings in the literature; Tank (1988) reported a k_T of 2.61 with an error of ±0.79 for a Type I cement (w/cm of 0.45) mortar mixture cured at 108°F.

Rate constant values for the ternary mortar mixtures behaved differently than the control—these values were fairly uniform with only small increases for higher temperature curing conditions. The rate constant, k_T, and associated error as determined by the regression equation are indicated for all of the batches in Figure 5-5. Note that the highest k_T for any of the ternary mixtures was 0.33 for batch M 20/20 (100). The k_T for M 20/20 (40) was 0.09. The change in k_T, Δ k_T, over the range of curing conditions between 40°F and 100°F for this mixture was only 0.25. The Δ k_T for M 20/20 was the largest of all ternary mixtures. This was attributed to M 20/20 having the least total PC replacement at 40% compared to 60% and 80% for the remaining ternary mixtures, and therefore this mixture is the most similar to the control in terms of the composition of cementitious materials. For a summary of Δ k_T for the other ternary mixtures refer to Table 5-7.

The curve fit performed by the program, Kaleidagraph, produced numerical values for S_u, k_T, and t_o, for each set of strength and age data. Only k_T is necessary for determining the constants, activation energy and datum temperature. These constants are contained in the maturity index functions, and therefore are required for the index calculations. The preceding discussion identified two rate constant results, k_T for M 40/20 (70) and k_T for M 40/40 (70), that are the least accurate. In the following two sections, the three rate constant results for each mixture which represent three different curing temperatures were used to perform an analysis of the interaction between the rate constant and temperature.

5.2.4 Datum Temperature Results for the Time-Temperature Maturity Function

The datum temperature is the temperature below which concrete strength development no longer occurs, and it is a constant in the time-temperature maturity index function. The datum temperature was obtained by plotting for each mortar mixture the rate constants (Figure 5-5) obtained from the curve fitting procedure against the actual curing temperatures. The y-axis represents the rate constant in units of 1/day, and the x-axis represents the average internal mortar cube temperature from submersion in the water bath until the third test age. In order to improve the accuracy of the analysis, the average internal mortar cube temperature during the early period of strength development was used as opposed to the target curing temperature for the study. For example, for Batch 0/0 (100), a temperature of 105.2°F was used in the analysis instead of the targeted value of 100°F. For ease of readability and comparability of results the investigator chose to refer to the target curing temperatures in this discussion. These average internal temperatures for the batches used for developing these relationships are shown in Table 5-8. To find the datum temperature, a linear trend line that best fit the data was obtained, and the equation for that line was determined. The datum temperature is the value for the curing temperature when the rate constant equals zero. In this case, the y variable is set to zero, and the equation for the linear trend line is solved for the x variable. The datum temperature can also be determined by extending the linear trend line to the temperature axis. The intersection of the linear trend line with the x-axis is the datum temperature. A summary table, Table 5-9, lists the results of the datum temperature, T_0, determinations for all mixtures.

Following ASTM C 1074 method of reporting maturity, the Celsius temperature scale was used in these plots. Although datum temperatures are typically reported in SI units, the datum temperature results in the tables are presented in both U.S. customary units and SI units to assist the reader. The maturity meter used in this research program requires the datum temperature input to be in metric units, and the resulting output for the maturity index calculated from the time-temperature function is in units of °C-hrs.

Each of the plots illustrates the rate constant-temperature relationship for the various mixtures. Both linear and exponential best-fit trend lines were generated in order to identify whether the relationship between the rate constant and temperature was better described by a linear or non-linear model. The equations and R^2 for the respective trend lines are also shown in each figure.

Table 5-8. Summary of Average Internal Mortar Cube Temperature		
Batch ID	**°F**	**°C**
M 0/0 (40)	45.8	7.7
M 0/0 (70)	66.9	19.4
M 0/0 (100)	105.2	40.7
M 20/20 (40)	44.9	7.2
M 20/20 (70)	66.8	19.4
M 20/20 (100)	99.5	37.5
M 40/20 (40)	43.6	6.5
M 40/20 (70)	64.9	18.3
M 40/20 (100)	96.6	35.9
M 40/40 (40)	43.4	6.3
M 40/40 (70)	65.1	18.4
M 40/40 (100)	99.4	37.4
M 20/40 (40)	43.1	6.2
M 20/40 (70)	65.4	18.5
M 20/40 (100)	96.2	35.7
M 20/60 (40)	44.7	7.0
M 20/60 (70)	65.4	18.6
M 20/60 (100)	98.9	37.2

Table 5-9: Summary of Datum Temperatures		
Mixture ID	**T_0 (°F)**	**T_0 (°C)**
0/0	45.5	7.5
20/20	29.9	-1.2
40/20	37.3	2.9
40/40	30.8	-0.7
20/40	-30.1	-34.5
20/60	45.4	7.4

A high amount of variability exists for the results of the datum temperature. The lowest datum temperature reported was -30.1°F for Mixture 20/40. The highest datum temperature reported was 45.48°F for the control mixture. Because the range of k_T values for the ternary mixtures as described by Δ k_T was small, differences in k_T as small as 0.01 have a large impact on the slope of the linear trend line.

Based on the R-squared results for the linear and exponential models, the exponential model is a better fit to the data. The exceptions to this rule are Mixtures 40/20 and 40/40 where the R^2 for the linear equation exceeded the exponential. Recall that in the results of the regression procedure to determine k_T, there were problems with batches M 40/20 (70) and M 40/40 (70). In both cases the $k_{70°F}$ was less than the $k_{40°F}$. This result is contrary to the strength gain behavior of the mortar mixtures shown by the compressive strength data. If the $k_{70°F}$ values exceeded $k_{40°F}$, it is likely that the fit of the exponential trend lines would have been improved for these two mixtures.

Earlier in this discussion, datum temperature had been defined as the temperature below which strength development ceases for a particular mixture. Accuracy is of particular importance when the behavior of concrete cured at low temperatures is considered. It was shown that the exponential model was a better fit to the data. This supports the conclusion that there is nonlinear behavior between the rate constant and temperature. Therefore, the use of a linear trend line does not give an accurate indication of the temperature where strength development ceases. As will be noted later in Section 5.3.4, a number of problems resulted from the use of the datum temperatures derived from this study using a linear relationship between rate constant and temperature. Ultimately, the investigator chose to use an arbitrary value for datum temperature in order to achieve acceptable results for the maturity index derived from the time-temperature function.

5.2.5 Activation Energy Results for the Equivalent Age Maturity Function

Schindler (2004) defined activation energy as a measure of the temperature sensitivity of a concrete mixture. It is a constant in the equation for the equivalent age maturity index function. The activation energy is determined following a procedure suggested by ASTM C 1074 C. A plot of the natural log of the rate constant versus the inverse of the temperature of the mortar (absolute temperature) is generated. Through the use of a spreadsheet program, a linear trend line is fit to the data, and the equation of the line is determined. The slope of the line is a negative number which when multiplied by negative one represents the value Q. Q is the activation energy, E, divided by the ideal gas constant, R. Table 5-10 summarizes the results for Q and activation energy, E.

Table 5-10: Summary of Activation Energy Results

Mixture ID	Q	E (kJ/mol)
0/0	7026	58.4
20/20	3844	32.0
40/20	4206	35.0
40/40	3358	27.9
20/40	1985	16.5
20/60	6525	54.3

The mixtures containing FA and SC are characterized by a reduction in activation energy when compared to the control. The activation energy for Mixture 0/0 was 58.4

kJ/mol while the SCM mixtures ranged from 16.5 to 32.0 kJ/mol. The exception was mixture 20/60 with an activation energy, 54.3 kJ/mol, only slightly less than the control.

Activation energy describes the sensitivity of the different concrete mixtures to temperature. When comparing different mixtures, the mixture with the highest activation energy will be the most sensitive to temperature. Conversely, the mixture with the lowest activation energy will be the least sensitive. Sensitivity in this case refers to the rate of change of the rate constant with temperature, and a mixture with high temperature sensitivity will exhibit a much larger rate of change of the rate constant with increased temperature than a mixture with lower temperature sensitivity.

Activation energies reported in the literature provide support for results of this research program. The activation energy for the control was 58 kJ/mol which is higher than the ASTM C 1074 recommendation of between 40 and 45 kJ/mol for Type I cement concrete without admixtures or additions. It is also higher than the 41 kJ/mol for a Type I cement concrete reported by Carino (1984). Research by Tank (1988) indicated a 61 kJ/mol activation energy for a Type I cement concrete without admixtures which is slightly higher than the control mixture result. Tank (1988) also reported 30 kJ/mol for Type I cement concrete with 20% FA, and 46 kJ/mol for Type I cement concrete mixtures with 50% SC. The trend of decreased activation energy for concrete containing SCM's demonstrated in this study was also shown in the work of Tank (1988).

5.3 Results of the Maturity and Strength Studies

The focus of the maturity study was to examine the empirical relationship between maturity and compressive strength for ternary concrete containing various amounts of portland cement (PC) replacement with fly ash (FA) and slag cement (SC) cured at low temperatures. Where the datum temperature and activation energy study determined the constants necessary for the maturity index functions, this study compares the maturity index with compressive strength. The maturity index and compressive strength relationships may be used to measure strength development for hardening concrete of similar mixture proportions and curing conditions in the field.

The focus of the strength study was to examine the strength gain of ternary concrete utilizing traditional 4 in. by 8 in. cylinders for correlation with the experimental slabs used in the maturity study to develop the strength and maturity relationships. The experimental slabs were intended to better simulate field concrete, and the strength study results were compared with the slabs' compressive strength data so that conclusions might be drawn as to whether the slabs tended to give similar results as the traditional 4 in. by 8 in. cylinder.

This research program occurred simultaneously with another, Wilhite (2007), and both programs cast samples out of the same concrete batches. The latter program provides a detailed description of fresh concrete properties including time of setting for all of the mixtures examined in this study. Furthermore, Wilhite (2007) discusses in great detail strength development for these same mixtures cured at low temperatures. Some of the data has been again presented here in order to provide the necessary background for this study.

5.3.1 Fresh Concrete Properties

Wilhite (2007) provides a detailed discussion of the fresh concrete properties including time of setting for all of the batches which were shared by the two research programs. A summary table of fresh concrete properties has been reproduced here (Table 5-11).

The fresh concrete properties measured included temperature, slump, unit weight, and air content. The investigators attempted to keep fresh concrete temperatures between 60°F and 80°F in order to maintain consistency between batches. This was accomplished by storing aggregates in the laboratory for at least 24 hr prior to batching. During periods of hot weather, the mixing water was chilled to near freezing. This range of fresh concrete temperatures was met for the majority of the batches except for batch 0/0 (40) and 20/20 (60) which were 58°F and 55°F respectively. Slumps were also measured at time of batching. Increasing fly ash content increased slump. The replacement of portland cement with slag cement tended to decrease slump, but this was offset by the simultaneous use of fly ash.

Average air contents for the different mixtures ranged from 1.4% to 0.6%. These air contents are due to entrapped air, because no air-entraining admixtures were used. Increased portland cement replacement with SCM's caused a decrease in the amount of air content—this trend was particularly evident for the mixtures with the highest fly ash content. The highest average air content was 1.4% for the control mixture with no portland cement replacement. Likewise, the mixture which exhibited the lowest average air content was Mixture 20/60 with 60% PC replacement by FA.

There were only small variations in average unit weight among the different mixtures. Average unit weights varied from a high of 150.5 lb/ft^3 for the control mixture to a low of 148.1 lb/ft^3 for Mixture 40/40. PC replacement with the SCM's utilized in this study tended to slightly decrease unit weight. The mixtures with the highest PC replacement rates exhibited the largest reduction in unit weight, a reduction ranging from 2.0 to 2.4 lb/ft^3 as compared to the control mixture.

Table 5-11: Average Fresh Concrete Properties

Mixture	Concrete Temperature (F)	Slump (in)	Unit Weight (lb/ft^3)	Air Content (%)
0/0	68	4.25	150.5	1.4
20/20	63	5.25	150.1	1.1
40/20	72	4.5	148.9	1.1
40/40	71	5.75	148.1	0.9
20/40	66	8	149	0.8
20/60	66	8.25	148.5	0.6

5.3.2 Concrete Compressive Strength Determination

The maturity study examined the maturity and compressive strength relationships for ternary concrete mixtures. In this study, 20"x8"x8" slabs were cast containing (3) 4"x8" cylindrical, cardboard push-out molds. The slabs allowed for the use of one logger to measure the time-temperature history of three samples. The slabs were intended to better simulate a more typical mass of concrete found in field construction than a 4"x8" cylinder sample alone. Traditional 4"x8" cylinders were cast simultaneously with the slabs as part of the Wilhite (2007) research program.

Although Wilhite (2007) provides a detailed discussion of the strength development, a brief discussion of strength gain results for the experimental slabs will be presented here in order to provide a background upon which to build the maturity results. Figures 5-6 to 5-16 show the slab strength gain curves. Figures 5-6 to 5-11 are strength gain curves for each mixture at all curing temperatures. Figures 5-12 to 5-16 are the strength gain curves for all mixtures at each of the curing temperatures.

The results of the compression tests for the cylinders obtained from the slabs as part of the maturity study indicated a general trend toward decreased strength with decreased curing temperature. Typically, decreased curing temperature caused a corresponding compressive strength decrease, and the order of strengths for a particular mixture from highest to lowest followed the order of curing temperatures with the highest strengths occurring at 70°F and the lowest at 33°F. This trend was most noticeable for the SCM mixtures. The control mixture followed this trend to some degree as well, except that the 40°F and 50°F batches exceeded the 60°F batch at the 7 and 28 day test ages. The 70°F batch however developed the highest strength when compared to all the other curing temperatures for Mixture 0/0.

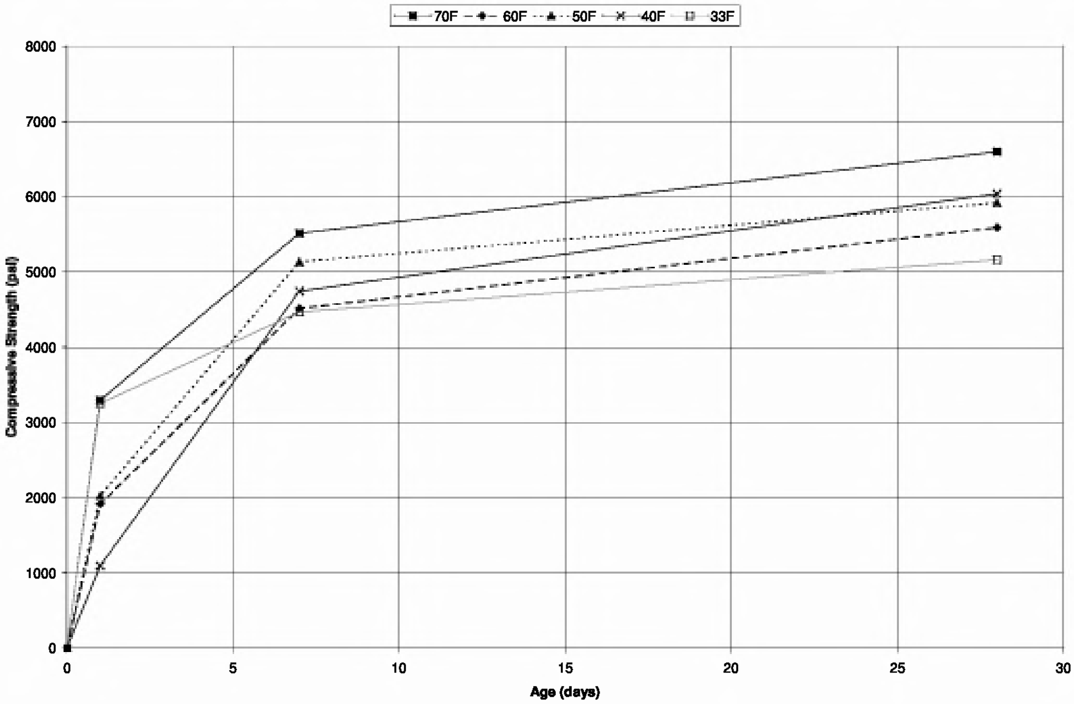


Figure 5-6. Slab Strength Gain Curve for Mixture 0/0.

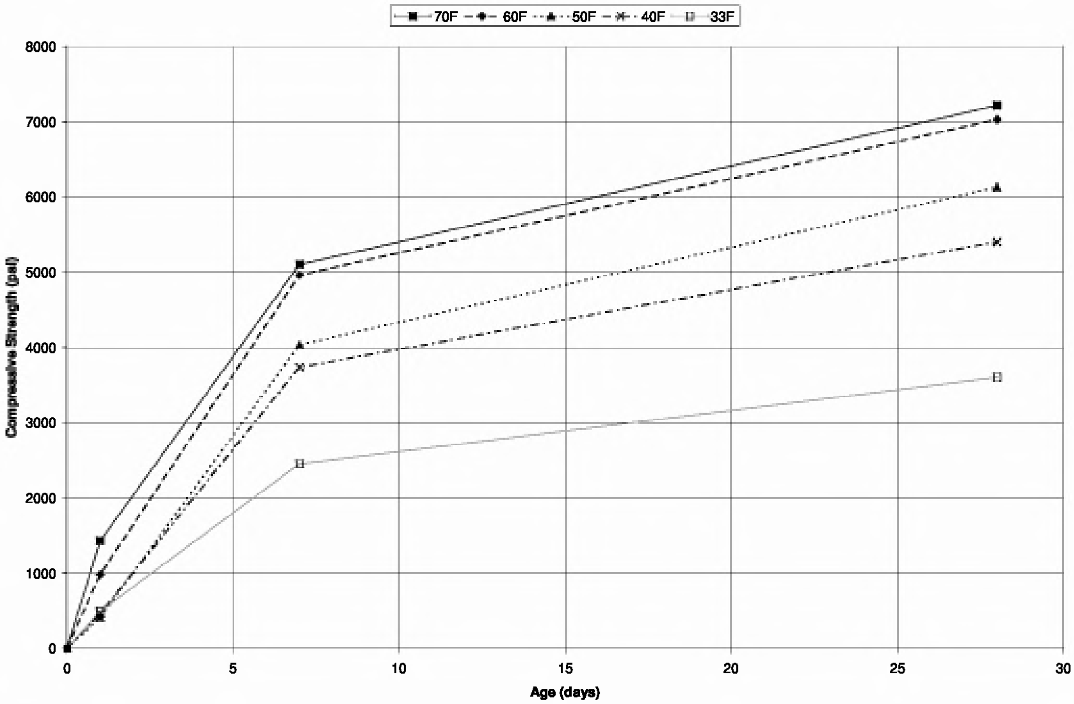


Figure 5-7. Slab Strength Gain Curve for Mixture 20/20.

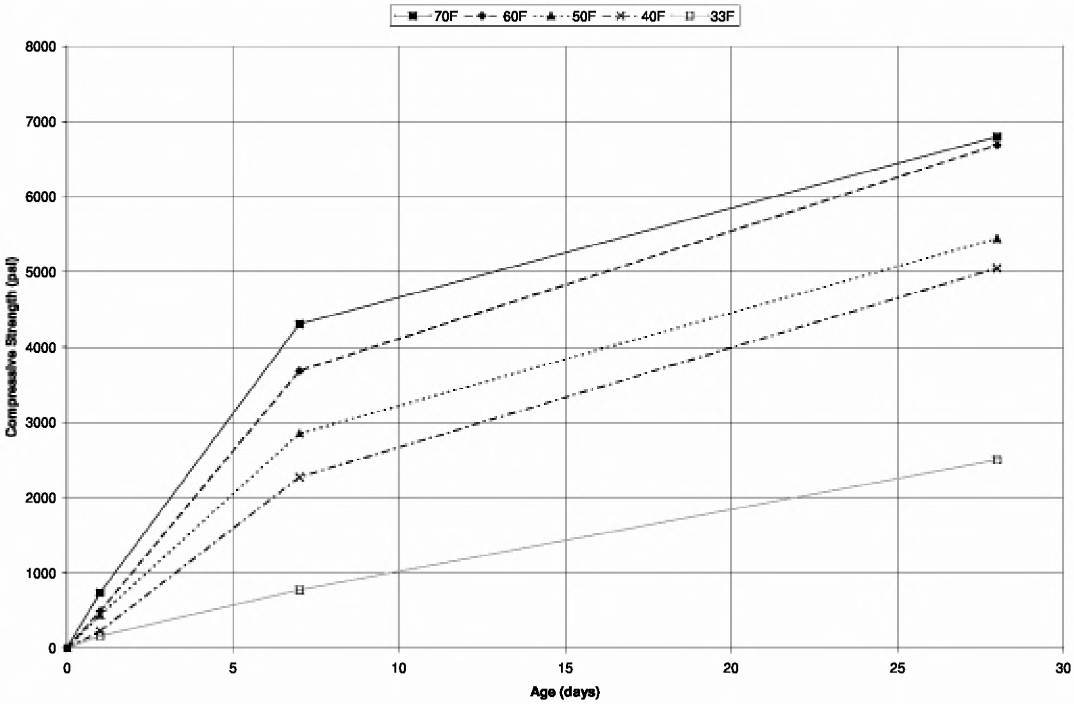


Figure 5-8. Slab Strength Gain Curve for Mixture 40/20.

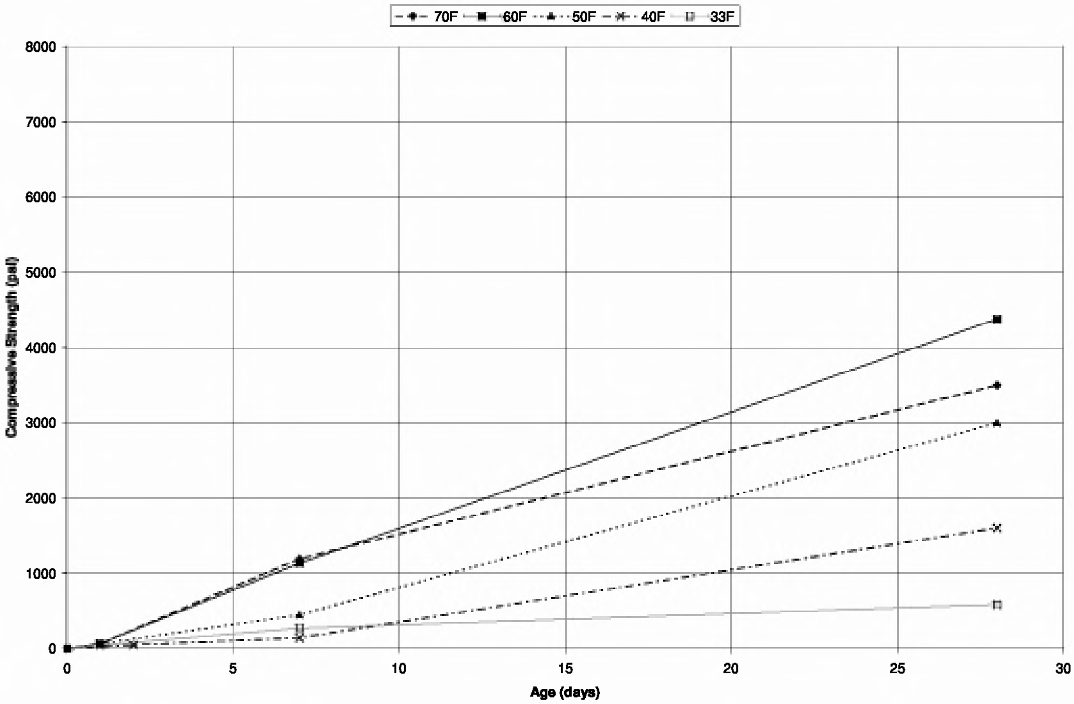


Figure 5-9. Slab Strength Gain Curve for Mixture 40/40.

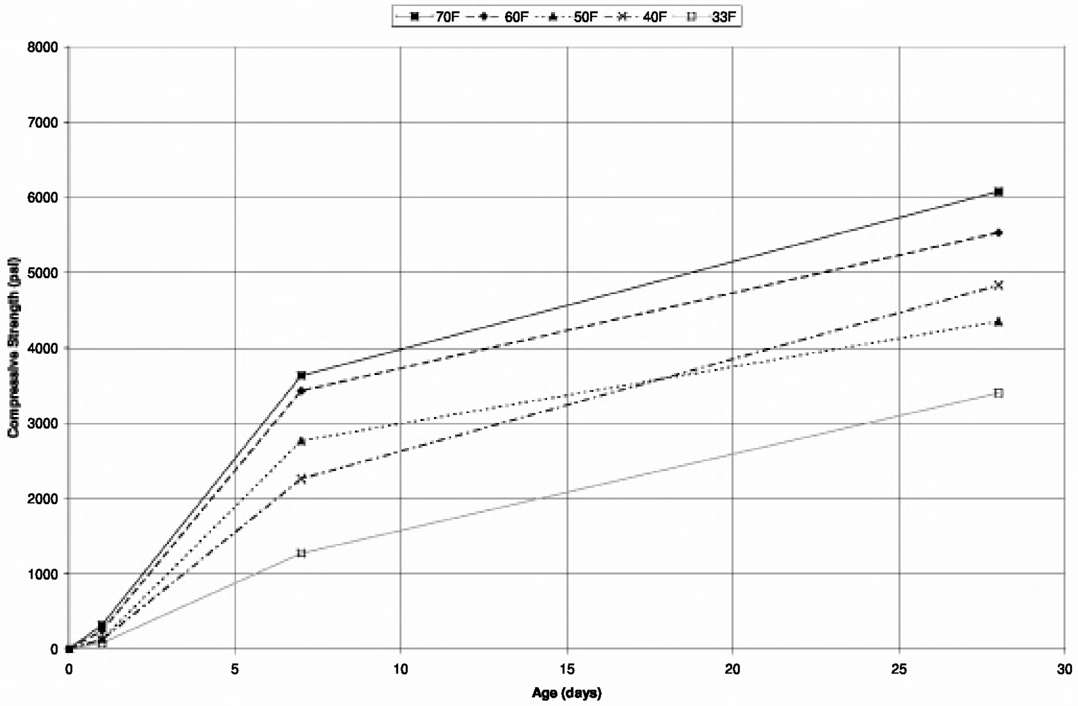


Figure 5-10. Slab Strength Gain Curve for Mixture 20/40.

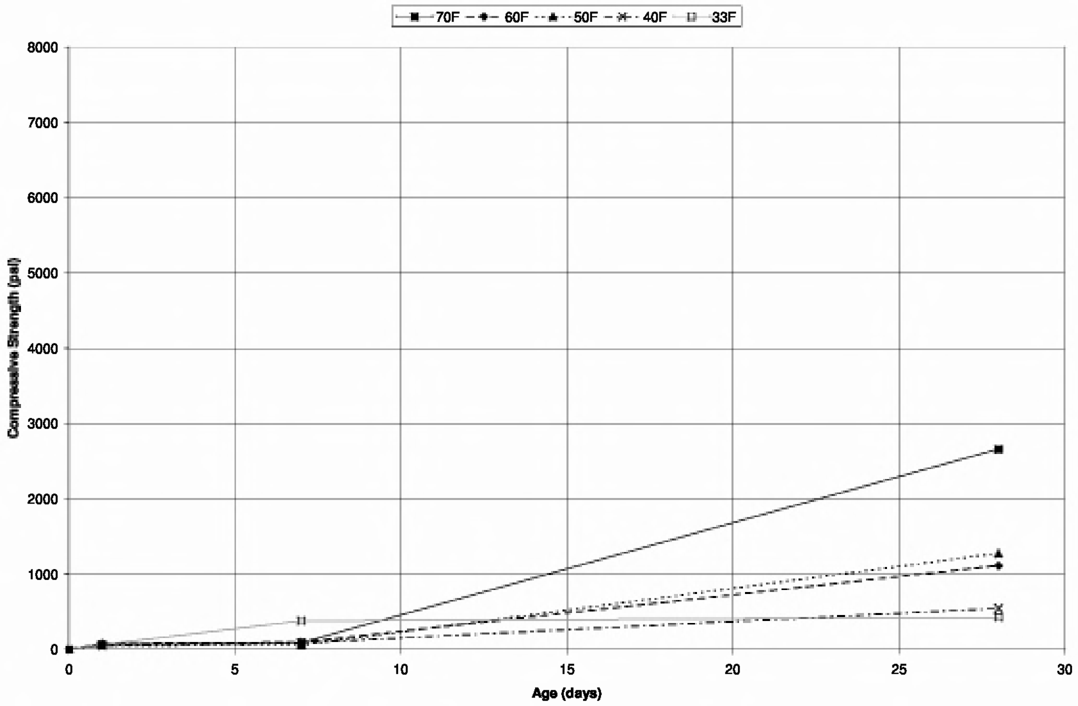


Figure 5-11. Slab Strength Gain Curve for Mixture 20/60.

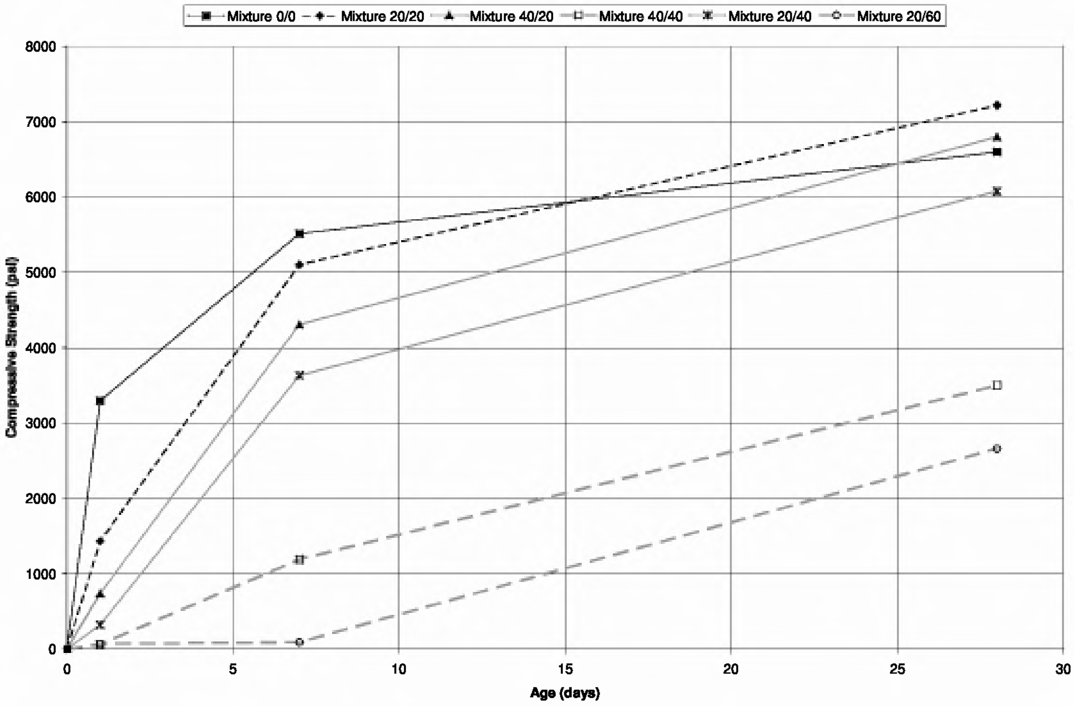


Figure 5-12. Slab Strength Gain Curve for All Mixtures Cured at 70°F.

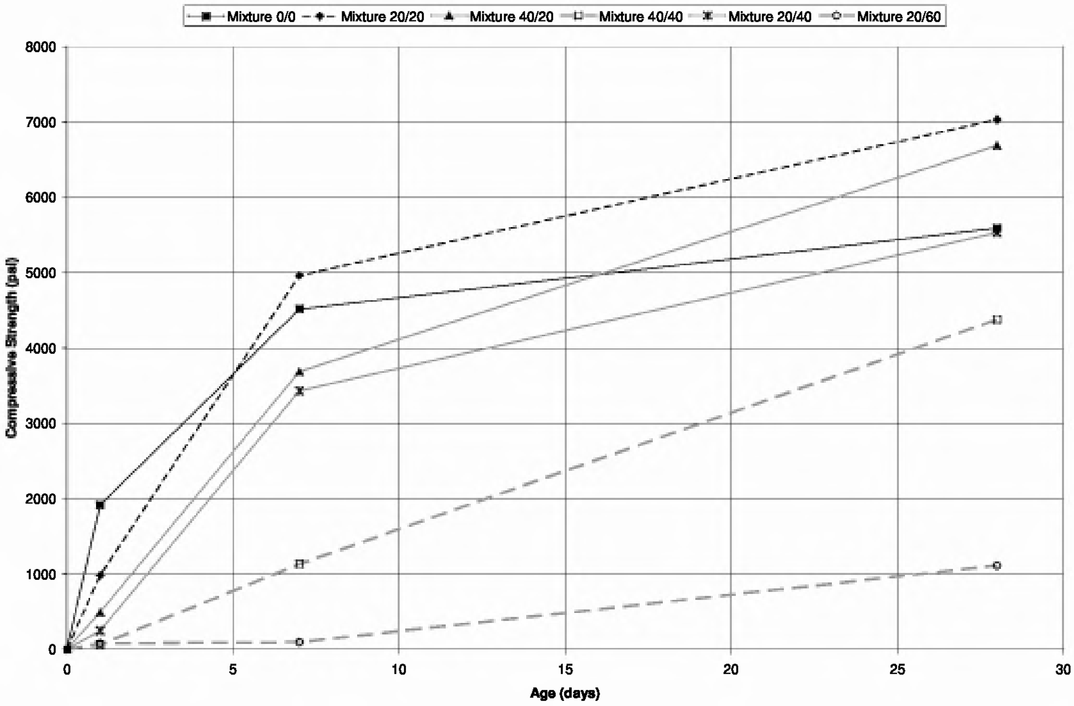


Figure 5-13. Slab Strength Gain Curve for All Mixtures Cured at 60°F.

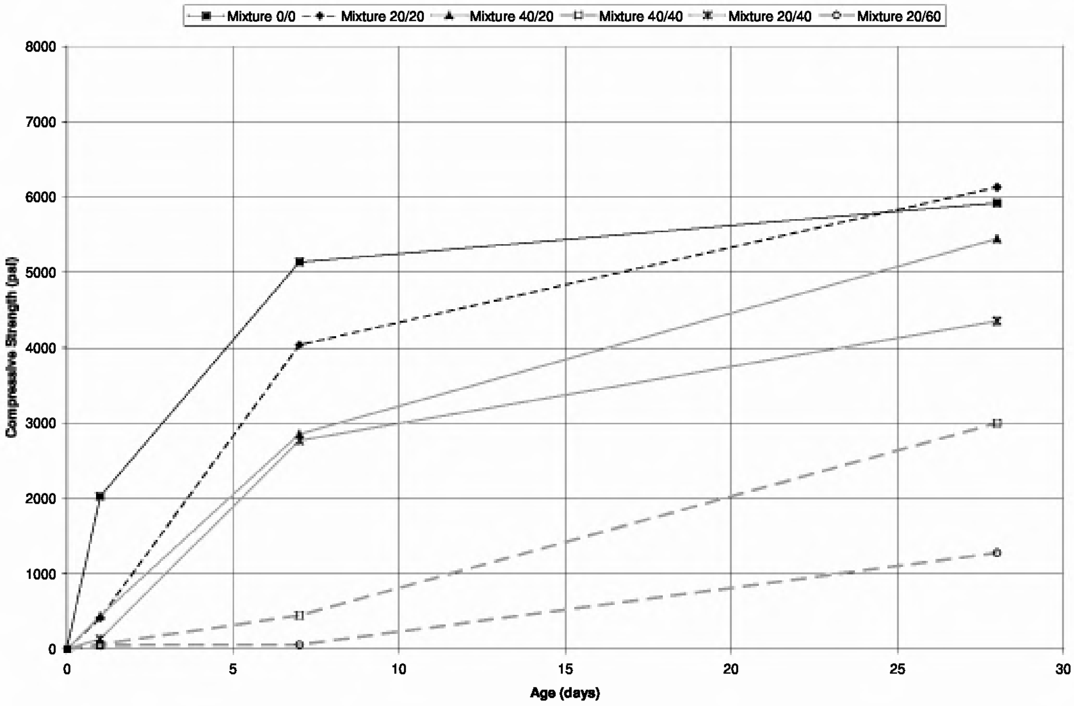


Figure 5-14. Slab Strength Gain Curve for All Mixtures Cured at 50°F.

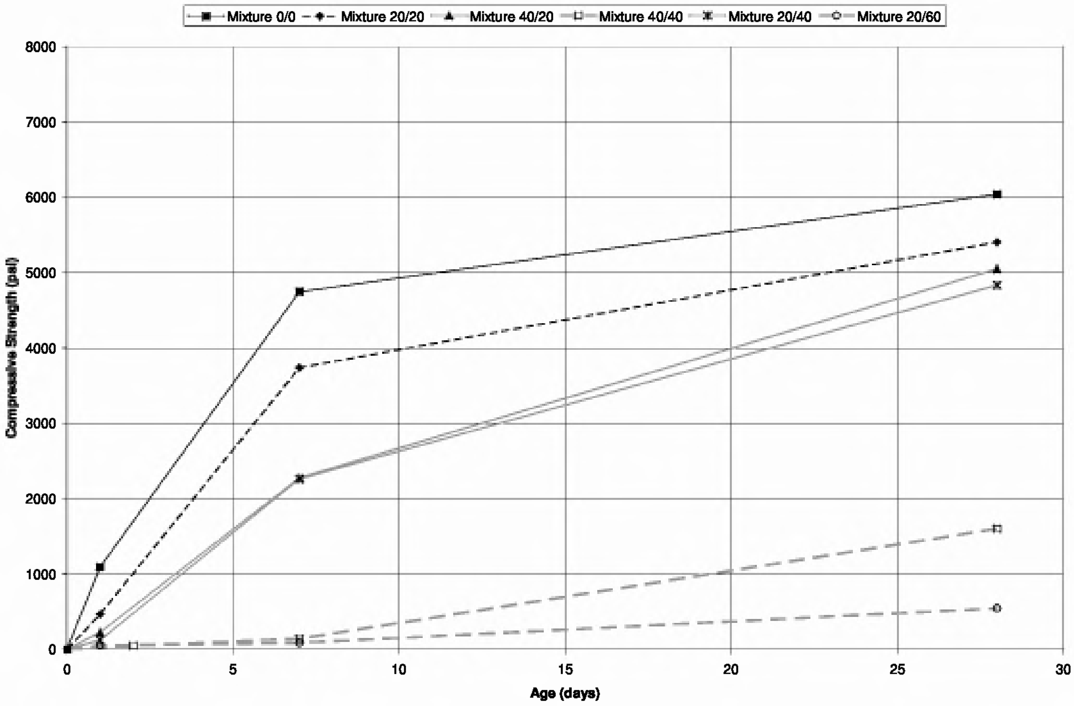


Figure 5-15. Slab Strength Gain Curve for All Mixtures Cured at 40°F.

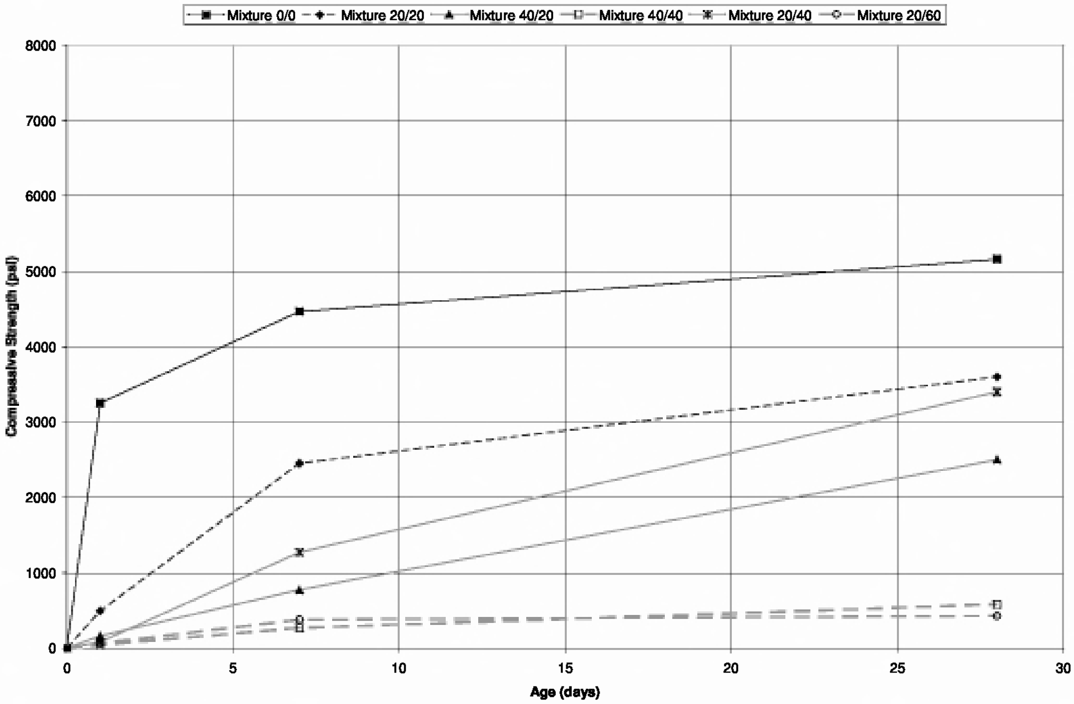


Figure 5-16. Slab Strength Gain Curve for All Mixtures Cured at 33°F.

The SCM mixtures also demonstrated greater temperature sensitivity when compared to the control mixture in terms of the magnitude of strength reduction over the range of curing temperatures (Figures 5-6 to 5-11). The control mixture with no SCM replacement was the least affected by curing temperature—the strengths at 28 days of age ranged from a high of 6600 psi when cured at 70°F to a low of 5160 psi at 33°F. The SCM mixtures however were more affected by curing temperature. The range of strengths at 28 days for Mixture 20/20 fell from 7200 psi at 70°F to 3600 psi at 33°F. Mixture 40/20 performed similarly with a high strength of 6800 psi (Batch 40/20 (70)) and a low of 2500 psi (Batch 40/20 (33)).

The SC mixtures with the least amount of PC replacement performed well when compared to the control mixture particularly at the 70°F and 60°F curing temperatures (Figures 5-12 to 5-14). The compressive strength at 28 days for Batches 20/20 (70), 20/20 (60), 40/20 (70), 40/20 (60), and 20/20 (50) exceeded the compressive strength for the control mixture batch at the corresponding curing temperature. The highest average strength reported in this study was 7220 psi for the Batch 20/20 (70) at 28 days of age.

Two of the mixtures, 40/40 and 20/60, performed poorly at all curing temperatures and all ages when compared to the control mixture. These two mixtures also contain a total of 80% PC replacement. At 70°F and 28 days of age, Mixture 40/40 developed a strength that was 3100 psi less than the control. Also at 70°F and 28 days, Mixture 20/60 performed even more poorly having developed an average strength of only 2660 psi when compared to 6600 psi developed by the control. These mixtures were also the worst performing mixtures at the 33°F curing temperature for the 28 day average strength—Mixture 40/40 developed only 580 psi, and Mixture 20/60 developed only 428 psi.

5.3.3 Comparison of Compressive Strength Results for Cylinders and Slabs

In this section, the slab compressive strength results and the cylinder compressive strength results were examined for differences—both sets of results were obtained from test data of identical age and from the same concrete mixture and batch. Due to the small number of samples tested at each test age, the investigator chose to examine the 90% confidence intervals (CI) for the analysis of cylinder and slab data for each concrete batch in the experimental program. This analysis was performed to determine if the test data from both types of samples were similar, and, therefore to determine the effectiveness of the slab to measure compressive strength development. A 90% confidence interval represents a range of values which is 90% likely to contain the true mean of a population. If the confidence intervals overlap, then the results are considered to be similar. A gap occurs between the confidence intervals when the intervals do not overlap. The gap is the difference between the lowest value of one interval and the highest value on the other interval. In other words, a gap is the measure of how far apart the confidence intervals are. If a gap between confidence intervals exists then the results are considered to be different.

The compressive strength results for the cylinders derived from the slabs (maturity study) were typically greater than or equal to the compressive strength results of the cylinders from the strength study for Mixtures 0/0, 20/20, and 40/20. This result was expected, because the slabs were thought to generate more heat of hydration due to the larger volume of concrete than the cylinders. The increase in heat of hydration was assumed to increase the rate of strength gain. Mixtures 40/40, 20/40, and 20/60 did not demonstrate significant differences between the slab results and the cylinder results. This may be explained by the reduced rate of strength gain and low strengths of the high replacement mixtures when compared to the control mixture.

For Mixture 0/0 at 50°F and 40°F, the gap between the confidence intervals of the slab and cylinder data was some 200 psi. Most notable for Mixture 0/0 were the results of Batch 0/0 (33). Here the difference between the 90% CI for the slab and the 90% CI for the cylinder was 2400 psi. This difference was attributed to the fact that the slab sample had a much larger volume of concrete requiring greater time for the concrete temperature to approach that of the curing chamber at early age. Conversely, the cylinders for the strength study have a much smaller volume than the slabs, and therefore temperature changes occur much more quickly. It was thought that in this instance, the cylinder reached the curing temperature much sooner than the slab, and during that time the slab was able to gain the additional 2400 psi over that of the cylinder. All the slab results were higher than the cylinder results for Mixture 20/20. The differences for Mixture 20/20 were often slight with Batches 20/20 (70) and 20/20 (40) demonstrating only 10 psi difference in 90% CI. The 90% CI gaps for Batches 20/20 (60) and 20/20 (33) were approximately 200 psi apart. Finally, Batch 20/20 (50) resulted in a difference of 150 psi at one day of age. For Mixture 40/20, all batches except Batch 40/20 demonstrated higher strengths from the slab samples. These differences however were slight ranging from 30 to 70 psi. In the case of Batch 40/20, the slab and cylinder confidence intervals overlapped and it was determined that no difference existed.

None of the other mixtures demonstrated a gap between the CI's of the slab and cylinder for the batches cured at 33°F as great as that seen with the control mixture. The control mixture tended to gain strength much more quickly than the ternary mixtures examined in this research program. The mixtures containing SCM's may have attained equal or greater strengths at later ages, but the control mixture had the highest rate of strength gain. For Batch 0/0 (33), the slabs contained a concrete with the highest rate of strength gain which coupled with a larger volume of concrete that required longer time to approach the curing temperature allowed for a large increase in strength over the cylinder sample.

The trend of slab samples developing higher strengths than the cylinder samples began to reverse itself when all of the 7 day compressive strength 90% CI's for all of the mixtures were examined. Mixtures 0/0 and 20/20 had several batches each where the cylinder strengths exceeded that of the slabs. The remaining mixtures showed typically no significant differences between the cylinders and slabs at 7 days of age. For Mixture 0/0, Batches 0/0 (60) and 0/0 (40) exhibited cylinder strengths of 200 and 130 psi over that obtained from the slab samples. The cylinder results for Batches 20/20 (60) and 20/20 (50) were greater than that of the slab samples by 150 psi (Figure H-8). The results of Mixture 40/20 were not conclusive. Batch 40/20 exhibited a slight increase of 150 psi for the cylinder samples over that of the slab samples. The slab sample results for Batch 40/20 (33) however were some 250 psi higher. The results of the slab samples and cylinder samples for the remaining mixtures at 7 days of age were not significantly different based on comparison of 90% CI's. The notable exception was batch 20/40 (33). The difference in CI's between the slabs and the cylinders was some 650 psi.

The 28 day results indicate that the cylinder samples were either equal to or greater than the slab samples in terms of compressive strength, and in some cases these differences were 800 to 1000 psi. The 90% CI for the cylinder samples of Batch 0/0 (60) and Batch 0/0 (50) were 820 and 480 psi respectively higher than the slab sample CI's. The remaining batches for this mixture exhibited no significant differences when the confidence intervals were compared. Mixture 20/20 behaved similarly to Mixture 0/0—Batches 20/20 (50) and 20/20 (40) demonstrated increases of 500 psi and 990 psi for the cylinder samples above the slab samples. Mixture 40/20 also demonstrated greater strengths from the cylinders samples. The difference in CI's ranged from 310 to 660 psi.

The exception was Batch 40/20 (33); the slab samples exceeded the cylinders by some 2000 psi. Typically, there were no significant differences for Mixture 40/40 at 28 days of age except for Batch 40/40 (70) where the difference in the 90% CI for the cylinders was approximately 320 psi higher. In the case of Mixture 20/40, most of the batches exhibited no significant differences between the 90% CI's. The low end of the 90% CI for the cylinder samples of Batch 20/40 (50) were 865 psi higher than the 90% CI of the slab samples. The difference in CI's for Batch 20/40 (33) was 2600 psi., but in this case it was the slab samples that developed higher strength. The cylinder and slab samples for Mixture 20/60 were typically similar except for Batch 20/60 (60). The difference in CI for the cylinders over that of the slabs was some 350 psi.

The cause of the increase in strength between some of the cylinders and slabs at seven days of age and beyond is unknown. It is suggested that the increased heat of hydration of the slabs at early ages which caused some of the slabs to develop higher strengths at early ages may have had a negative effect on strength at later ages. None of the cylinders in the strength study were instrumented, so it is not possible to make comparisons between the temperature histories of the slabs and of the cylinders.

5.3.4 Maturity Index Results

This section presents two sets of results for the maturity index calculations. The first set is the maturity index results derived from the time-temperature maturity function, and these results are named maturity and are expressed in units of °C-hrs. The second set is the maturity index results derived from the equivalent age maturity function. These results are named equivalent age and are expressed in units of days. The average compressive strength for the slabs associated with the maturity index is also shown in order to facilitate development of the maturity-compressive strength relationships discussed in the subsequent Section 5.4.

Just prior to the slab compression tests, the time-temperature data from the loggers were downloaded to the maturity meter. At that time, the age of the slabs was recorded and the test cylinders were pushed out of the slab and tested in compression. The time-temperature data in the loggers were then transferred to a computer spreadsheet program. Although the loggers independently calculated maturity indices based on initial datum temperature or activation energy values, the investigator subsequently recalculated the maturity indices using both the time-temperature and equivalent age functions. This was necessary, because it was later concluded that the initial values of datum temperature, 0°C, and activation energy, 41500 J/mol, used (following the suggestion of ASTM C 1074) were inappropriate after the experimentally derived values had been obtained. The final results reported here for the maturity index obtained from the time-temperature function were derived from calculations using neither the initially selected nor the experimentally derived datum temperature for reasons to be explained in detail as follows. When the final maturity indices were recalculated, the datum temperature used was -10°C and the activation energies used were the experimentally derived values shown in Table 5-10.

The datum temperature value used for the final maturity index calculations, -10°C, was selected instead of the experimentally derived datum temperatures (Section 5.2.4) based on the variable results of the datum temperature determinations and problems encountered during initial attempts to develop strength-maturity relationships.

The value was chosen arbitrarily, but it was intended to be well below the lowest temperatures recorded by the loggers for the slabs cured in the 33°F chamber. This decision was made to prevent two problems: decreasing maturity index coupled with increasing compressive strength, and constant maturity index coupled with increasing strength.

These problems with the maturity index results were discovered after preliminary calculations using the experimentally derived datum temperatures were conducted. In some cases for the batches cured at 40°F and 33°F, the internal temperature of the concrete as recorded by the maturity logger fell below the experimentally derived datum temperature resulting in a negative maturity result for the time increment. Recall from Chapter 2 that the maturity index at any time during the curing period is the summation of the difference between product of the actual concrete temperature and the datum temperature multiplied by a time increment for a finite number of equal time increments. A negative result for the product of temperature difference and time increment caused an overall reduction in the maturity index which is not possible. The standard practice for the maturity method, ASTM C 1074, does not provide the user any direction regarding negative maturity index results. In an attempt to overcome this problem, preliminary maturity indexes were recalculated substituting a value of zero for the product of the time increment multiplied by the temperature difference whenever the actual temperature fell below the datum temperature and a negative result for the product would have occurred. This substitution solved the problem of decreasing maturity by introducing a new problem, constant maturity indices.

After having solved the problem of negative maturity, a new problem was encountered. Where the concrete temperature fell below the datum temperature for a substantial period of time, in some cases the maturity index remained constant, but the strength continued to increase. Mixtures 0/0 and 20/60 at 40°F were particularly susceptible to the constant maturity index problem. The experimentally derived datum for Mixture 0/0 was 7.49°C (45.5°F) which was actually higher than the temperature maintained in the 40°F and 33°F curing chambers. Inspection of the preliminary maturity index results using the experimentally derived datum temperatures revealed that in some cases there was nearly constant maturity from one compression test interval to the next. Once again this was caused by the concrete temperature falling below the datum temperature. The datum temperature should represent the temperature below which compressive strength development ceases. When the maturity index remained constant due to sustained concrete temperatures below the datum temperature, compressive strength should also have remained constant. But for the preliminary results of Mixtures 0/0 and 20/60 at 40°F the strength continued to increase while the maturity index remained constant. This problem provided further evidence that the experimentally derived datum temperature did not accurately predict the temperature at which strength development should have ceased to occur, and that a new selection of datum temperature was necessary.

Subsequent inspection of the logger output files for the batches cured in the 33°F indicated failures with the temperature control system in the chamber. The actual temperatures of the concrete slabs cured in this chamber at times fell significantly below freezing and in some cases reached 17.6°F (-8°C). This problem was not discovered until after the compression tests had been performed, and insufficient time was available to recast the samples. The failure was attributed to poor air circulation in the chamber allowing for thermal stratification and isolated cold spots rather than a defect with the temperature controller itself.

The arbitrary selection of -10°C for the datum temperature was chosen to ensure good results for the maturity index calculations. The disadvantage of this choice was that it was now possible for there to be instances of increasing maturity without increasing strength at very low curing temperatures, but the investigator believed this to be an acceptable compromise. The problems encountered in this study regarding use of the time-temperature function, decreasing maturity index coupled with increasing compressive strength and constant maturity index coupled with increasing strength, highlight the limitation of using linear regression to describe the relationship between the rate constant and temperature. If linear regression were to adequately represent this relationship, then the datum temperature would accurately represent the temperature below which strength development would cease. Recall that the datum temperature was derived by setting the rate constant equal to zero and solving the linear regression equation for temperature. The preliminary maturity index and compressive strength results did not support the use of the datum temperatures derived from the activation energy/datum temperature study.

In order to provide a better understanding of activation energy and its impact on the equivalent age maturity index, the maturity indices for the control at all curing temperatures were calculated using both 41.5 kJ/mol recommended by ASTM C 1074 and 58.4 kJ/mol derived in this research program. Figures 5-17 and 5-18 are plots of the compressive strength on the y-axis and the equivalent age maturity index on the x-axis. This type of plot will be referred to as a compressive strength and maturity relationship. The impact of activation energy on the maturity index is graphically illustrated in Figures 5-17 and 5-18. Figure 5-17 shows the maturity index calculated using an activation energy constant of 58.4 kJ/mol. Figure 5-18 shows the maturity index calculated using 58.4 kJ/mol. Note that the compressive strength values for both plots are the same, but the maturity indices are shifted slightly to the right in Figure 5-18. The lower activation energy value causes the equivalent age function to calculate a larger index whenever the actual temperature falls below the reference temperature when compared to maturity indices calculated using a larger activation energy value. The highest maturity index attained for the control mixture at 33°F using the 58.4 kJ/mol activation energy was 87 hours (Figure 5-17). The 41.5 kJ/mol activation energy caused the maturity index to increase to 147 hours for the same mixture and curing temperature (Figure 5-18). This same trend occurred for all of the other curing temperatures, but the increase was larger the farther the curing temperature was from the reference temperature of 23°. Due to the exponential function contained within the equivalent age function, the increase in the maturity index caused by using a lower activation energy value increases the further away the actual temperature is from the reference temperature. Recall that activation energy describes the temperature sensitivity of a concrete mixture. The effect of activation energy is to impart the influence of a particular concrete mixture's temperature sensitivity on the magnitude of the maturity index.

In Chapter 2, the limitations of the temperature-time maturity index function were discussed. It was shown that the equivalent age maturity index function provided the advantage of using a nonlinear rate constant. The nonlinear rate constant better approximates the relationship between the time-temperature history and strength development. The activation energy is the nonlinear rate constant used in the equivalent age maturity function.

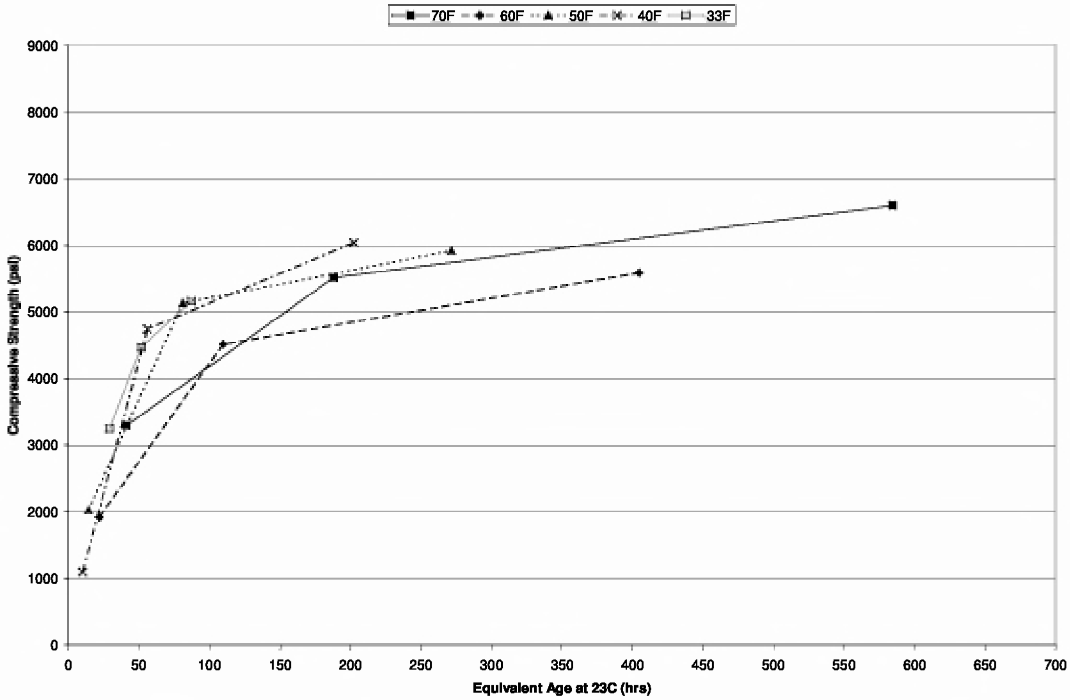


Figure 5-17. Compressive Strength and Maturity Index Relationship for Control Mixture Using Experimentally Derived Activation Energy.

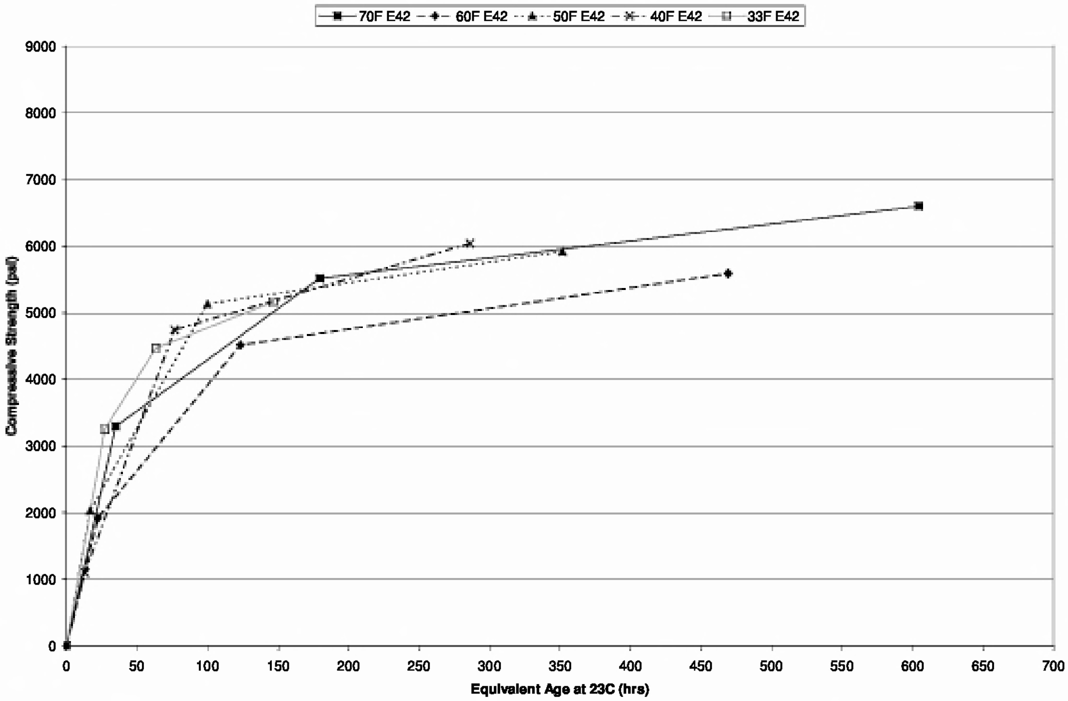


Figure 5-18. Compressive Strength and Maturity Index Relationship for Control Mixture Using ASTM C 1074 Recommended Activation Energy.

5.4 Compressive Strength and Maturity Relationships

The cumulative result of this research program is the development of the compressive strength and maturity relationship in order to allow for the measurement of the compressive strength of concrete for similar mixtures based on a temperature-time history record. Presented herein are maturity index results using both the temperature-time and equivalent age functions. This increases the usefulness of the work, because the equivalent age function is often used in academics while the temperature-time function due to its simplicity is favored for use in the field.

The maturity results are presented using the SI system rather than U.S. customary units, because 1) ASTM C 1074 "Standard Practice for Estimating Concrete Strength by the Maturity Method" utilizes the SI system, 2) the commercially available maturity meter used in this research program reports maturity results using the metric system, and

3) the equivalent age maturity index was determined using a reference temperature of 23°C.

Compressive strength and maturity nomographs developed from the experimental data are presented as well as predictive models developed for each of the mixtures. These graphical relationships are located in Appendix J, Figures J-1 to J-14. A discussion of the development of these nomographs and of the mixture and maturity index specific equations is presented.

The input parameters for the maturity functions are again stated here for clarification. Recall from Section 5.3.4 that the datum temperature used for the maturity index derived from the time-temperature function was arbitrarily chosen as -10°C. The reference temperature for the equivalent age function was chosen as 23°C which is the commonly accepted value. The activation energies used for equivalent age function differ for each mixture and can be found summarized in Table 5-10. In order to make use of the nomographs and predictive models, the time-temperature histories for other concretes of similar mixture proportioning may need to be adjusted accordingly.

Although the maturity loggers used in this research program will automatically determine the maturity index, the original input parameters chosen at the beginning of the program, datum temperature, 0°C, equivalent age reference temperature, 23°C, and activation energy, 41.5 kJ/mol, based on literature recommendations were adjusted to fit with the results of the activation energy and datum temperature study. This necessitated that the investigator transfer the logger output files to a spreadsheet program in order to recalculate the maturity indices. Had the final parameters been available at the beginning of the experimental program, this would not have been necessary. All of the maturity indices reported here reflect these changes.

Each of the compressive strength and maturity relationships presented in Appendix J is specific to a particular mixture and maturity index. Figures J-1 to J-6 are for use with the time-temperature maturity function. Figures J-7 to J-14 are for use with the equivalent age function. Each figure represents the maturity and compressive strength results for a particular mixture investigated in the research program. Each figure contains the five data sets corresponding to the five curing temperatures. Each data set represents all of the samples for a particular batch. The compressive strength and maturity relationships for both the equivalent age and time-temperature maturity indices are developed from the same time-temperature histories and compressive strength data.

The maturity-compressive strength curves behaved similarly to the strength gain versus age relationships discussed in Section 5.3.2. The concretes cured at higher temperatures typically gained more strength, and their compressive strength maturity curves show slightly elevated strengths over the entire range of maturity values. The compressive strength-maturity curves for concretes cured at lower temperatures tended to follow below that of the curves for the same mixture at higher temperature. The highest compressive strengths attained by the curves were developed by the concretes cured at 70°F. The exception was Mixture 40/40 where the highest compressive strength occurred for Batch 40/40 (60) which was cured at 60°F.

The batches cured at 33°F tended to develop the lowest compressive strengths. However, Batch 0/0 (33) performed very well equaling or exceeding all the other batches of that mixture over the range of its strength-maturity curve This anomaly may be partially explained initially by the high fresh concrete temperature which allowed the concrete to gain a large amount of strength early on. Note that the strength at the first test was some 3250 psi. This result far exceeded all of the other initial strength tests for this mixture except for batch 0/0 (70). Another significant exception is the behavior of batch 20/60 (33). The strength of 33°F batch exceeded all others of the same mixture (See Figure J-6). This surprising result was believed to have occurred because the test cylinders for batch 20/60 (33) had in fact frozen causing artificially higher strength from the crystallization of water in the samples while during this same curing period all of the batches for this mixture remained in the dormant period without strength development.

The ability of these compressive strength-maturity curves to generate a unique maturity and compressive strength relationship for a particular mixture can be evaluated by examining how closely the different curves representing the variety of curing temperatures used in the study match one another. Recall that this concept is the fundamental implication of the maturity method. The results for these curves should be considered acceptable. Some of the variation between the curves may be explained by the inherent variability of concrete. For example, the 28 day tests for batches 0/0 (40) and 0/0 (33) resulted in standard deviations of some 400 psi. Mixture 40/40 had the most variation between the curves for the different curing temperatures. The 28 day tests had an average standard deviation of some 120 psi. Beyond the problems of variability in the data, fresh concrete temperatures varying from 60°F to 80°F caused some of the initial test results to be elevated or depressed superseding some of the effect of the curing temperature. The behavior of batch 0/0 (33) as had been mentioned previously serves as an example of this explanation for variability at early ages.

There are some cases where strength-maturity curves are in good agreement adding evidence to the concept of a unique relationship between maturity and compressive strength. In Figure J-8, representing Mixture 20/20, at equivalent ages up to some 100 hrs there is good agreement between all of the curves except for that of the 33°F batch. Figure J-5 indicates very similar compressive strength-maturity relationships for all of the batches.

If these nomographs are to be used for measuring compressive strength for ternary concrete in the field, the maturity index developed from the time-temperature record or determined automatically will be required. The compressive strength for a concrete with similar mixture proportions and PC replacement can be estimated by first finding the position of the maturity index on the x-axis. A vertical line is drawn from the x-axis until reaching the curve for the curing temperature that best matched the curing conditions that the concrete of interest has experienced. The compressive strength estimate is then determined by drawing a horizontal line from the point of intersection between the previous vertical line and the maturity-compressive strength curve. Extend the horizontal line to the y-axis and read off the compressive strength.

Predictive models were determined by regression of the maturity and compressive strength data. All of the different batch data for a particular mixture were combined and placed in order from lowest to highest maturity value. The resulting set of data was plotted and a regression was performed by Kaleidagraph to get a least squares best fit curve to the data. Figures 5-19 to 5-30 represent the accumulated data for each mixture and a plot of the best fit curves to the data. Note that the hyperbolic equation provided a good fit for all of the mixtures except for the 80% total PC replacement mixtures, 40/40 and 20/60. Models were generated for these mixtures using linear regression rather than a generalized curve fitting technique. All of these models will be presented in the following discussion.

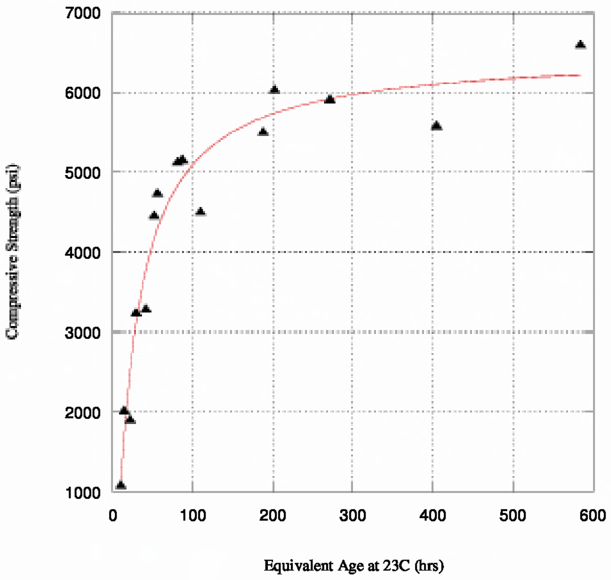


Figure 5-19. Best-fit Curve for Mixture 0/0 - Compressive Strength and Maturity Index (Equivalent Age at 23°C) Results.

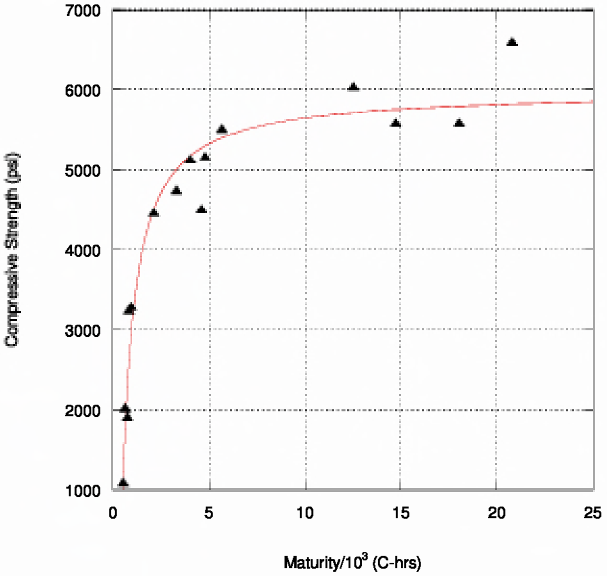


Figure 5-20. Best-fit Curve for Mixture 0/0 - Compressive Strength and Maturity Index (Time-Temperature) Results.

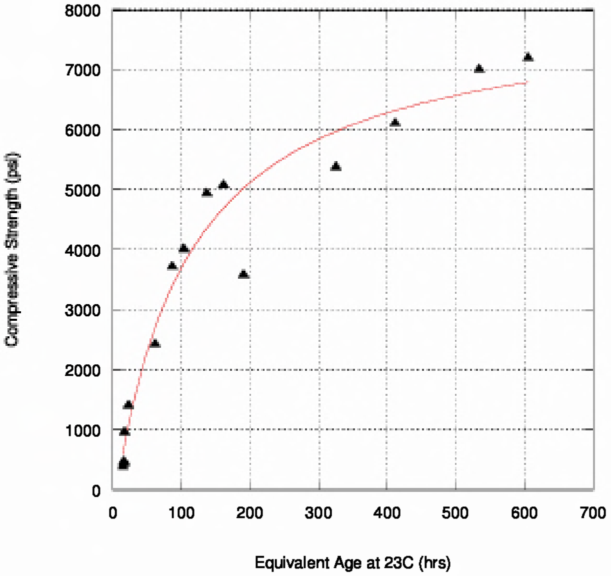


Figure 5-21. Best-fit Curve for Mixture 20/20 - Compressive Strength and Maturity Index (Equivalent Age at 23°C) Results.

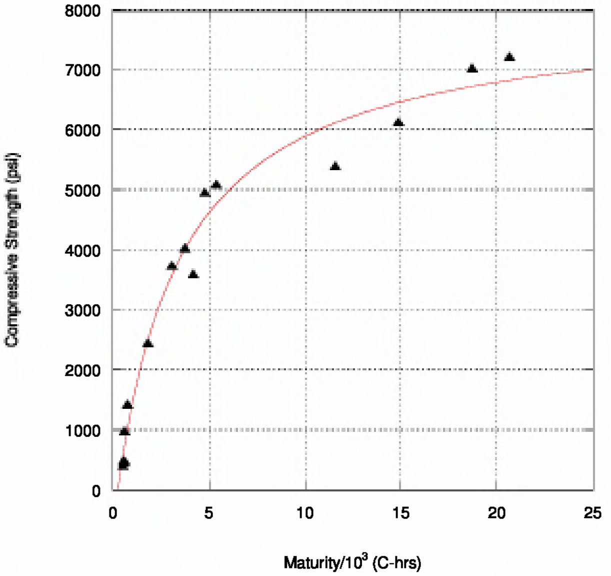


Figure 5-22. Best-fit Curve for Mixture 20/20 - Compressive Strength and Maturity Index (Time-Temperature) Results.

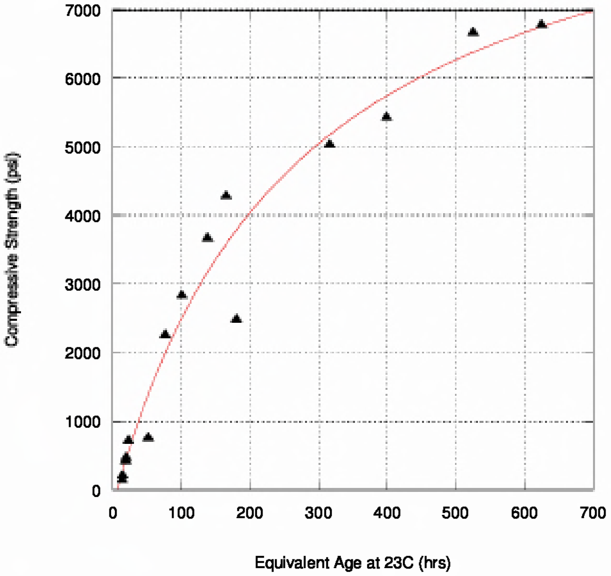


Figure 5-23. Best-fit Curve for Mixture 40/20 - Compressive Strength and Maturity Index (Equivalent Age at 23°C) Results.

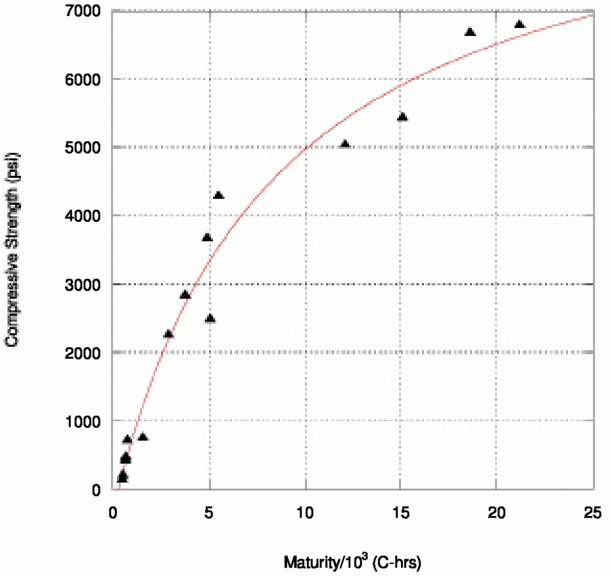


Figure 5-24. Best-fit Curve for Mixture 40/20 - Compressive Strength and Maturity Index (Time-Temperature) Results.

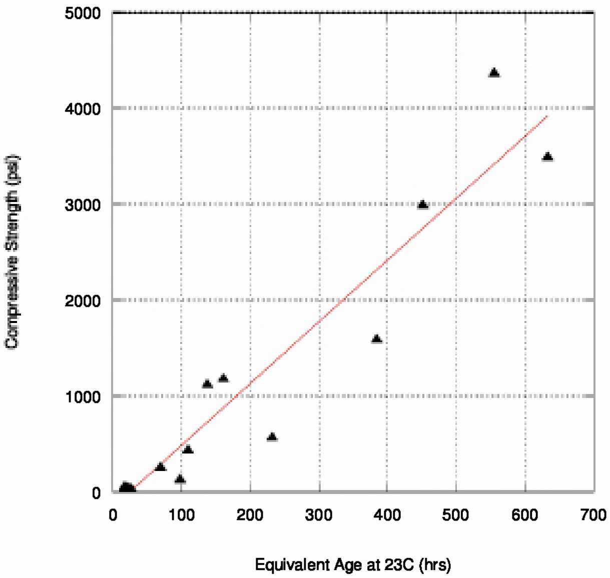


Figure 5-25. Best-fit Curve for Mixture 40/40 - Compressive Strength and Maturity Index (Equivalent Age at 23°C) Results.

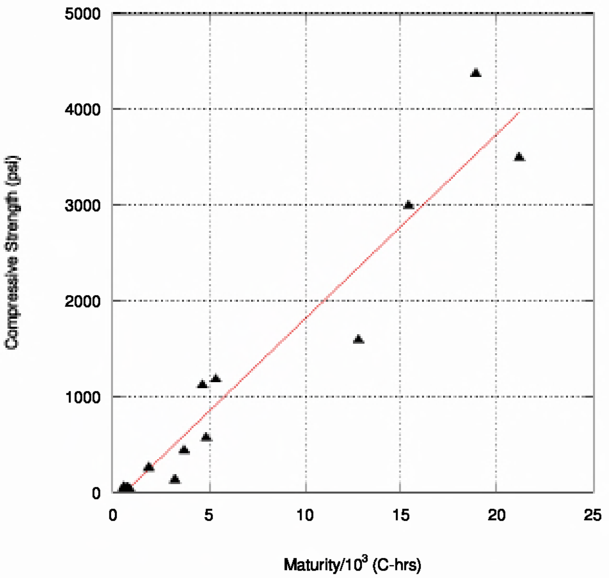


Figure 5-26. Best-fit Curve for Mixture 40/40 - Compressive Strength and Maturity Index (Time-Temperature) Results.

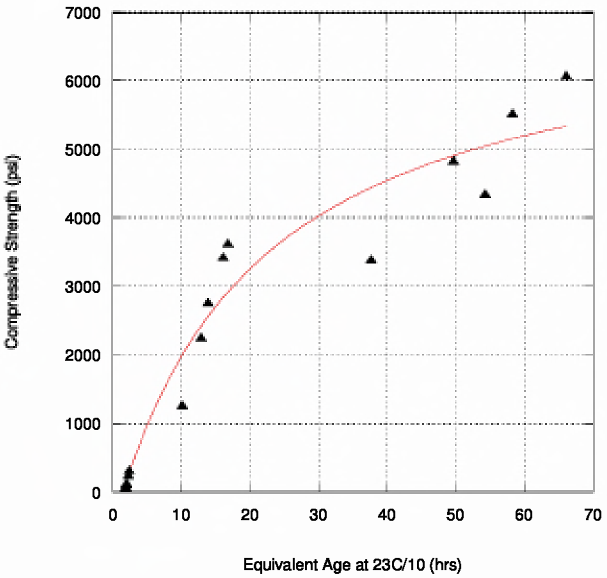


Figure 5-27. Best-fit Curve for Mixture 20/40 - Compressive Strength and Maturity Index (Equivalent Age at 23°C) Results.

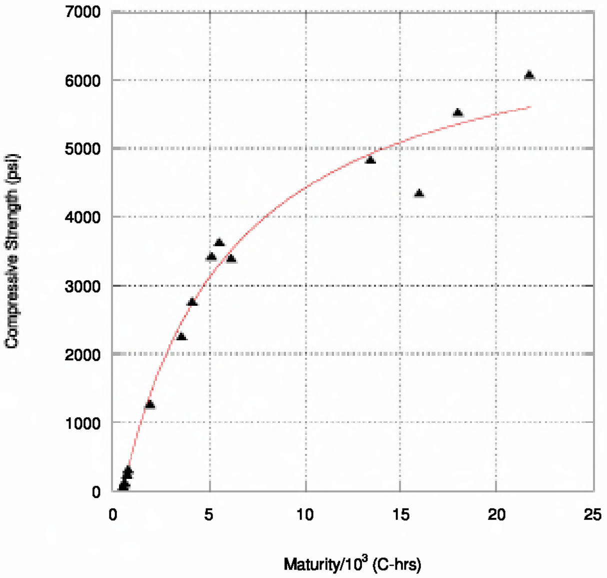


Figure 5-28. Best-fit Curve for Mixture 20/40 - Compressive Strength and Maturity Index (Time-Temperature) Results.

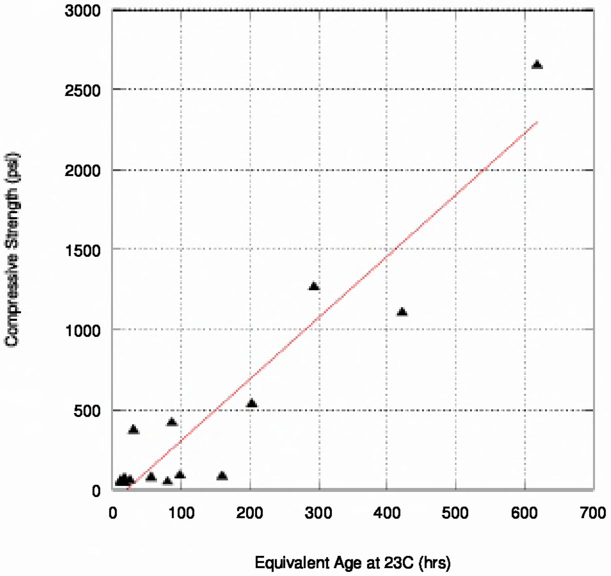


Figure 5-29. Best-fit Curve for Mixture 20/60 - Compressive Strength and Maturity Index (Equivalent Age at 23°C) Results.

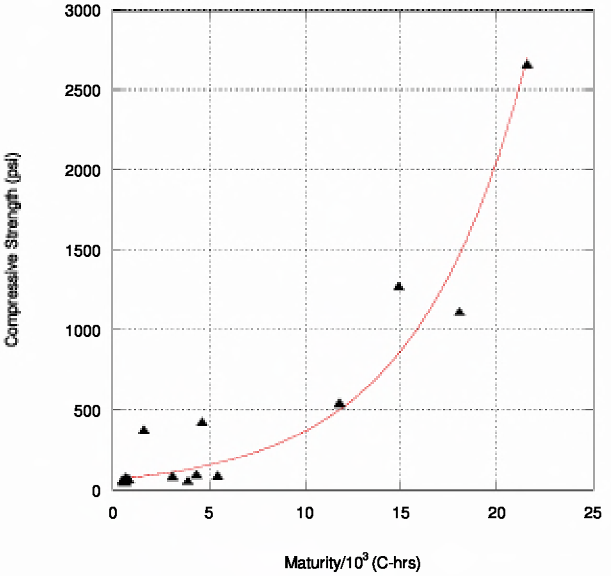


Figure 5-30. Best-fit Curve for Mixture 20/60 - Compressive Strength and Maturity Index (Time-Temperature) Results.

Table 5-12. Summary of Predictive Models for Ternary Concrete

Mixture ID	Maturity Function	Curve Description	Model	R^2
0/0	Eq. Age	Hyperbolic	$S = 6500(0.038(M_e-4.78))/(1+0.038(M_e-4.78))$	0.944
	Time-Temp.	Hyperbolic	$S = 5980(1.75(M_{tt}/1000-0.383))/(1+1.75(M_{tt}/1000-0.383))$	0.941
20/20	Eq. Age	Hyperbolic	$S = 8050(0.00898(M_e-5.68))/(1+0.00898(M_e-5.68))$	0.953
	Time-Temp.	Hyperbolic	$S = 7980(0.288(M_{tt}/1000-0.248))/(1+0.288(M_{tt}/1000-0.248))$	0.976
40/20	Eq. Age	Hyperbolic	$S = 9720(0.00367(M_e-6.2))/(1+0.00367(M_e-6.2))$	0.959
	Time-Temp.	Hyperbolic	$S = 9310(0.117(M_{tt}/1000-0.273))/(1+0.117(M_{tt}/1000-0.273))$	0.972
40/40	Eq. Age	Linear	$S = -156 + 6.43M_e$	0.906
	Time-Temp.	Linear	$S = -124 + 193(M_{tt}/1000)$	0.931
20/40	Eq. Age	Hyperbolic	$S = 7170(0.045(M_e/10-1.56))/(1+0.045(M_e/10-1.56))$	0.940
	Time-Temp.	Hyperbolic	$S = 7140(0.171(M_{tt}/1000-0.512))/(1+0.171(M_{tt}/1000-0.512))$	0.981
20/60	Eq. Age	Linear	$S = -73.8+3.83M_e$	0.886
	Time-Temp.	Exponential	$S = 65.4*EXP(0.172(M_{tt}/1000))$	0.937

Notes: S = Compressive Strength (psi), M_e = Equivalent Age at 23°C Maturity Index, M_{tt} = Time-Temperature Maturity Index (°C-hrs). Do not exceed M_e=650 hrs. or M_{tt} =22500 °C-hrs. For Mixture 20/60, do not exceed M_e=400 hrs. or M_{tt} =17500 °C-hrs.

Table 5-12 provides a summary of the models, appropriate mixtures and maturity functions for their use, curve description, and correlation coefficients. The compressive strength method presented by ASTM C 1074 directs the user to develop a single compressive strength-maturity relationship using the results of samples cured at room temperature; the models presented herein combine data from samples cured at a range of temperatures from 33°F to 70°F. Following the ASTM C 1074 method, five data points are used to develop the curve. Only three data points are available in this work for each curing temperature due to the large scope of work.

The predictive equations provided may be used with some qualifications. The models tend to under-predict concrete cured at 70°F and over-predict concrete cured at 33°F. The models then are only suitable for estimating strength over the range of these temperatures. For estimating strength of concrete cured at 33°F, these models should be used cautiously. The hydration reaction of concrete slows or ceases completely, as concrete temperatures near freezing. The significant reduction in strength development for the 33°F batches provides evidence for this conclusion. Therefore, these models may heavily over-predict strength for concretes that may experience this temperature condition. The reader is directed to favor use of the nomographs when freezing conditions are expected. These models are ideal for estimating concrete strength in cold weather conditions (40-60°F) when the ambient temperature conditions during the curing process are unknown (provided that the time-temperature history of the concrete itself was recorded, and the concrete does not experience freezing). ASTM C 1074 states that alternate methods of strength estimation such as field cured cylinders should be used to corroborate with the results of the maturity method, and this should also be followed regardless of whether the nomographs or predictive models presented here are used.

The models should only be used for maturity indexes in the range of 0 to 22500 °C-hours and equivalent ages from 0 to 650 hrs. The models associated with Mixture 20/60 should only be used for maturity indexes in the range of 0 to 17500 °C-hours and equivalent ages from 0 to 400 hrs. All of the models were developed using data for compressive strengths up to and including 28 days of age. Due to the asymptotic nature of the hyperbolic curves, use of maturity indexes greater than these ranges will not result in infinite strengths. The linear and exponential functions however will provide infinite strength estimates if maturity indexes outside of the recommended range are used.

Chapter 6

Conclusions and Recommendations

6.1 General

The first phase of the study explored the setting and strength gain characteristics of ternary concrete mixtures cured at low temperatures (at and below 70 F). For quality control, the fresh properties of these mixtures were measured and analyzed. In these ternary mixtures, various portions of the portland cement (PC) were replaced by two common supplementary cementing materials (SCMs), Class C fly ash (FA) and Grade 100 slag cement (SC). A control mixture containing only PC was prepared and tested. Five ternary mixtures were studied and compared to this control mixture. The replacement rates of the ternary mixtures represented a wide range of mixtures studied previously at the University of Arkansas (Becknell 2005). These rates included a low replacement mixture (20 percent SC, 20 percent FA), two very high replacement mixtures (one with 20 percent SC and 60 percent FA, another with 40 percent SC and 40 percent FA), and two mixtures with moderate replacement (one with 40 percent SC and 20 percent FA, another with 20 percent SC and 40 percent FA). All these mixtures exceeded the replacement rates currently allowed by the Arkansas State Highway and Transportation Department. Furthermore, AHTD does not currently allow ternary mixtures to be used (AHTD 2003). This chapter presents the conclusions drawn from the study and the recommendations resulting from those conclusions.

The second phase of the research program was composed of three studies: the activation energy and datum temperature study, the strength study, and the maturity study. The purpose of the activation energy and datum temperature study was to experimentally derive rate constant and temperature relationships for the different mixtures examined in the research program. These relationships were then analyzed to determine activation energy and datum temperature, the two parameters which are used to derive the equivalent age and time-temperature maturity index functions. The purpose of the strength study was to enable a correlation between the strength development of the experimental slabs used in the maturity study with traditional 4"x8" cylinders. The maturity study sought to develop compressive strength relationships for ternary concrete mixtures where various amounts of portland cement (PC) were replaced with fly ash (FA) and slag cement (SC). These relationships will enable estimation of strength development for similar mixtures in the field if the time-temperature history of the hardening concrete has been recorded.

6.2 Conclusions

6.2.1 Strength Gain Study – Phase I

The strength gain study, which also included a study of setting times of ternary concrete mixtures cured at low temperatures, was discussed in Chapter 3. The study was intended to provide a better understanding of the strength gain characteristics of various ternary mixtures containing different volumes of SCMs but otherwise identical. Each of the mixtures tested contained the same total weight of cementitious materials, coarse aggregate, and water, and identical w/cm. The only variables between mixtures were the sand content, replacement rates of SC and FA, fine aggregate content, and the temperatures at which the mixtures were cured. The study was also intended to provide a better understanding of the impact of subjecting these mixtures to curing temperatures at and below 70 F, and at what temperatures each mixture should be used.

The research program showed that, at appropriate replacement rates and reasonable curing temperatures, ternary concrete mixtures perform adequately; in fact, in many respects these ternary mixtures proved to be superior to ordinary PC concrete. The following is a summary of the conclusions drawn from the examinations of the fresh concrete properties, the times of setting, and the compressive strengths and strength gain:

1. The slumps of the mixtures tested ranged from 1.25 in. to 8.75 in. Slump tended to increase as FA content increased. Mixtures containing more FA than SC displayed the highest average slumps. Mixtures containing more SC showed lower slumps, but in mixtures with equal quantities of FA and SC, the slumps were increased. The slumps of the mixtures also depended on the fresh concrete temperatures. Specifically, slump decreased at higher fresh temperatures.
2. The average unit weights for the mixtures ranged from 148.1 to 150.5 lb/ft^3. Generally, unit weights of the mixtures tested decreased as the PC replacement increased. Mixtures with high FA contents displayed higher unit weights than those with high SC contents. At low replacement (20 percent SC, 20 percent FA), the unit weights were equal to otherwise identical ordinary PC concrete mixtures. All mixtures with total replacement rates higher than 40 percent were lighter than the control mixture.

3. The average relative yield of the mixtures ranged from 0.9753 to 0.9817. These numbers indicate that all the batches tested yielded approximately 98 percent of the design volume of material.
4. Measured air contents for the mixtures tested ranged from 0.5 to 1.7 percent. As no air-entraining admixture (AEA) was used, these air contents represent the air that was entrapped in the mixtures, and fall well within the accepted range of values for entrapped air. Increased FA content resulted in mixtures with less entrapped air. Average air content was less than 1.0 percent in all cases when more than 40 percent of the PC was replaced by FA. The content of SC did not appear to affect the amount of entrapped air in the mixture. Air content was related to the slump; mixtures with the highest slumps contained less air than stiffer mixtures.
5. Generally, time of initial setting increased as replacement increased. These times ranged from nearly 5 hours for the control mixture to almost 58 hours for Mixture 40/40. Practically, the times of initial setting were unaffected by curing temperature for the control mixture, ranging from 4.78 hours to 7.64 hours. Mixtures 40/20 and 20/40, each with 60 percent total replacement displayed significant increases in initial set times as curing temperature was decreased. Mixture 20/40 displayed a wider range of times than did Mixture 40/20. Mixture 40/20 displayed times of initial setting ranging from 9.13 hours to 24.72 hours, while the times for Mixture 20/40 ranged from 9.81 hours to 32.74 hours. Mixtures 40/40 and

20/60, each with 80 percent total replacement, followed a trend similar to that of Mixtures 40/20 and 20/40, with time of initial setting increasing as temperature decreased. However, Mixture 40/40 required considerably more time to reach initial set than any other mixture. This mixture required more than 57 hours to reach initial set when cured at or below 40 F. Mixture 20/20, with 40 percent total replacement, behaved somewhat differently from the other mixtures, with setting times increasing as temperature decreased until the curing temperature fell below 50 F. The 40 and 33 F batches each displayed decreased times of initial setting. This unexpected trend might be explained by the decreased slumps of the 40 and 33 F batches, which may have accelerated the initial set.

6. Times of final setting followed the same general trends as the times of initial setting, with time increasing as replacement rates increased and curing temperatures decreased. The mixture containing 100 percent PC was significantly affected by varying curing temperatures, with setting times ranging from 6 to 12 hours. Mixtures with very high total replacement rates (80 percent) required the most time to reach final setting. Mixtures containing 60 percent total replacement reached final set in about one day, except in the most extreme cases (Batch 40/20 (33), 36.2 hours; Batch 20/40 (33), 46.6 hours). The mixture with only 40 percent total replacement reached final set within a range of 10.3 to 16.5 hours.
7. The interval between initial and final setting tended to increase as curing temperature decreased. When mixtures containing less than 80 percent

total replacement were cured at or above 50 F, the increase in this time interval was of little concern, ranging between 1 and 5 hours. Mixtures containing 80 percent total replacement experienced significant increases in elapsed time between initial and final set when compared to mixtures with lower replacement rates. Also, some mixtures experienced longer setting times when cured below 50 F. Mixtures 0/0 and 20/20 did not experience severe delays at low curing temperatures.

8. At late ages (28 and 90 days), the use of total replacement rates at and below 60 percent increased the compressive strength relative to the control mixture. At 90 days of age, Mixtures 20/20 and 40/20 displayed more than adequate compressive strength, exceeding 8000 psi in most cases. Mixture 20/20 exceeded 6000 psi at 90 days of age when cured at 33 F. Mixture 40/20 attained less than 4000 psi when cured at 33 F. Mixture 40/40 attained approximately 6000 psi when cured at or above 60 F, and the average compressive strength was greater than 4000 psi when this mixture was cured at or above 40 F. When cured at 33 F, Mixture 40/40 attained less than 600 psi at 90 days of age. Mixture 20/40 performed reasonably well at both 28 and 90 days of age. Though this mixture did not perform as well as Mixtures 20/20 and 40/20 at 28 days of age, when cured at and above 40 F, it performed similarly to the these mixtures at 90 days of age, with compressive strengths exceeding 6000 psi, and in some cases (Batches 20/40 (60) and 20/40 (50)) exceeding 8000 psi. Mixture 20/60 performed poorly at all curing temperatures. The 70 F batch of this

mixture (Batch 20/60 (70)) attained 6320 psi. However, when cured at lower temperatures, the strength of this mixture was much less than that of the same mixture at other temperatures, remaining below 4000 psi in all cases. The worst performing batch of the study was Mixture 20/60 cured at 33 F, which attained only 260 psi.

9. Strength tended in many cases to be less as curing temperature decreased, especially up to 28 days of age. At 90 days of age, however, some mixtures displayed greater compressive strengths at lower temperatures. Mixture 40/20 attained its highest strength (9020 psi) when cured at 50 F, as did Mixture 5 (8080 psi). The highest strength attained by Mixture 20/20 (9040 psi) occurred when cured at 40 F, and Mixture 20/20 displayed a general trend of increasing compressive strength as temperature decreased, with the exception of the 33 F batch.

6.2.2 Maturity Study – Phase II

6.2.2.1 Activation Energy and Datum Temperature Study

The mortar batches were proportioned similarly to the corresponding concrete mixtures used in the strength and maturity studies. The results of the compressive strength tests on the mortar were used for a generalized curve fitting procedure using the hyperbolic equation (12) in order to determine the rate constant and curing temperature relationships. The findings from the activation energy and datum temperature study are summarized below:

1. Rate constant results for the control mixture indicate that the rate constant is temperature dependent. The control mixture demonstrated a large rate constant, k_T, increase with increased curing temperature. The highest k_T recorded in this study was 1.20 1/day for M 0/0 (100).
2. For the ternary mixtures, the rate constant increased with increased temperature, but the rate constant increase with temperature is not large when compared to the control mixture.
3. Datum temperature results were highly variable ranging from 45.5°F for the control to –30.1°F for Mixture 20/40. This high variability led the investigator to utilize the arbitrary value of 14°F as the datum temperature for all of the time-temperature maturity index calculations in the maturity study. The procedure suggested by ASTM C 1074 to experimentally derive the datum temperature using a linear model does not accurately determine for ternary mixtures the temperature below which strength development no longer occurs. Therefore, a datum temperature was chosen that was below any of the curing temperatures maintained in the research program.
4. Typically, an exponential model provided a better fit to the rate constant and temperature relationships for both the control mixture and the ternary mixtures than the linear model. R^2 values for the exponential models typically exceeded R^2 values for the linear models; however the difference was small. But because of the small change in the rate constant with temperature when compared to the control mixture, a linear relationship

provides good agreement for the interaction of the rate constant with temperature in the case of the ternary mixtures.

5. The use of SCM's tended to reduce the activation energy as compared to the control. The range of values for the ternary mixtures, 16.5 to 32.0 kJ/mol, was lower than the activation energy for the control, 58.4 kJ/mol. The exception was Mixture 20/40 with an activation energy of 54.3 kJ/mol.

6.2.2.2 Strength and Maturity Studies

The strength study was intended to provide correlation for the experimental slabs from the maturity study in order to validate the experimental slabs results. The strength study examined compressive strength development at low temperatures for all of the mixtures examined in this research program using traditional 4"x8" cylinders. The maturity study utilized 20"x8"x8" experimental slabs containing (3) 4"x8" cardboard push out molds. The slabs and the push out molds were cast monolithically and the 4"x8" cylinders from the cardboard molds were extruded from the slabs at time of testing using a hydraulic jack.

The maturity study focused on the compressive strength and maturity index relationships using both the time-temperature and equivalent age maturity functions. Nomographs as well as numerical models were generated to represent these relationships for all of the mixtures using both functions. These were developed in order to enable future estimation of compressive strength of similar mixtures in the field provided that the time-temperature history was recorded following an instrumented approach like that used in this research program. The findings are summarized below.

1. Of all the curing temperatures examined, 33, 40, 50, 60, and 70°F, the 70°F curing temperature tended to produce concrete with the highest compressive strength at 28 days. This trend was evident for all of the concrete mixtures examined.
2. Analysis of the strength data from the experimental slabs indicated that the concrete mixtures containing SCM typically demonstrated greater temperature sensitivity in terms of the magnitude of the strength reduction between samples belonging to the same mixture tested at 28 days from different curing temperatures when compared to the control mixture. The reduction in strength over the range of curing temperatures from 70°F to 33°F was 1440 psi for the control at 28 days. Mixture 20/20 decreased 3600 psi over the same temperature range and at the same age. Mixture 40/40 demonstrated a reduction of 3800 psi across the range of curing temperatures at 28 days. Strength test results for Mixture 40/20 at 28 days indicated a reduction of 4300 psi between the 70°F and 33°F curing temperatures.
3. Mixtures with the lowest PC replacement performed well at 60°F and 70°F compared to the control. At these curing temperatures, the 20/20 and 40/20 mixtures exceeded the compressive strength of the control at 28 days. The highest reported compressive strength for the experimental slabs, 7220 psi, was developed by batch 20/20 (70) at 28 days. The

highest strength reported for the experimental slabs cast from the control mixture, 6600 psi, was produced by batch 0/0 (70).

4. Mixtures containing 80% total PC replacement performed poorly at all curing temperatures and ages compared to the control. At 28 days, the slabs from Mixture 40/40 cured at 70°F developed 3500 psi compared to the control which developed 6600 psi under the same conditions. When cured at 70°F, the slabs from Mixture 20/60 only had developed 2660 psi at 28 days of age.
5. At one day of age, the strength test results for the experimental slabs were typically greater than or equal to the results of the traditional 4"x8" cylinders which were cast and cured simultaneously with the slabs based on an analysis of the 90% confidence intervals (CI). When slabs strengths exceeded the cylinders, the differences between the CI tended to range from 10 to 200 psi.
6. At seven days of age, the trend began to reverse itself with the traditional cylinders tending to either outperform or equal the experimental slabs in terms of compressive strength based on the CI. In the cases where the cylinder strength exceeded the slab strength the difference in the CI was typically at most some 200 psi.
7. At 28 days of age the cylinders continued to either outperform or equal the experimental slabs in terms of compressive strength. When the CI did not overlap and an increase in strength was observed, the increase in strength of the traditional cylinders was highly variable. In some cases, the

increases were as great as 800 and 1000 psi. The CI results for approximately half of the 28 day batch comparisons indicated that there were no differences in the strength results between the cylinders and slabs.

8. Due to the low temperature curing conditions in this research program, use of the datum temperatures derived from the activation energy and datum temperature study caused two problems in the time-temperature maturity index results: 1. decreasing maturity index coupled with increasing compressive strength, and 2. constant maturity index coupled with increasing strength. Following the discussion in Chapter 4, Section 4.3.4, and the conclusions of the activation energy/datum temperature study, the investigator chose 14°F as the datum temperature for all of the time-temperature maturity index calculations.
9. The maturity-compressive strength relationships behaved similarly to the strength gain versus age relationships. Examination of the nomographs, Appendix J, Figures J-1 to J-12, which show the strength and maturity index relationships for all of the different curing temperatures for each mixture indicate that the concretes cured at higher temperatures typically gained more strength, and their compressive strength maturity curves show slightly elevated strengths above the curves generated for the lower temperature curing temperatures over the entire range of maturity index values. The compressive strength-maturity curves for concretes cured at lower temperatures tended to follow below that of the curves for the same

mixture at higher temperature. The highest compressive strengths tended to be developed by the concretes cured at 70°F.

10. Predictive models were generated from the results of all the maturity index and compressive strength data from all of the curing temperatures for each mixture (Table 5-12). The hyperbolic equation (Equation 12) provided a good fit to the data for the mixtures containing 60% total PC replacement or less. The correlation coefficient, R^2, for these models ranged from 0.94 to 0.98. The mixtures with 80% PC replacement were described by linear models and in one case by an exponential model. The R^2 values for these models ranged from 0.89 to 0.94. These models may be used for strength estimation following qualifications discussed in Chapter 5, Section 5.4, and in the following section.

6.3 Recommendations

6.3.1 Strength Gain Study – Phase I

The results of the research program showed that ternary concrete mixtures can produce strength comparable to ordinary PC concrete (at 90 days) when cured below 70 F. PC replacement of 40 percent resulted in average 90-day compressive strengths exceeding those of the control mixture at all temperatures. Quality concrete was produced with total replacements as high as 60 percent when cured at or above 50 F. Mixtures containing more SC than FA displayed decreased workability; however, this effect could be overcome with the addition of high-range water reducer (HRWR).

Based on the 90-day compressive strengths measured in the study, mixtures in which more than 80 percent of the PC was replaced by SCMs performed worse than other mixtures under most conditions. This replacement rate should not be used for any structural application where loading is a concern, especially with 60 percent FA, due to inadequate 28-day compressive strength (less than 3000 psi). Specifically, this mixture should not be used for PCCP under any circumstance. Properties of Mixture 20/60 were inconsistent. Mixtures with 80 percent total replacement and equal SC and FA rates produced 90-day compressive strengths slightly above 4000 psi when cured at 70 F, but were not consistent under other conditions.

In general, when cured at or above 50 F, mixtures containing 60 percent total replacement or less displayed more than adequate times of setting and compressive strengths. Mixtures containing 40 percent total replacement may prove successful when cured at or above 40 F.

Further research is needed to determine appropriate AEA dosages to achieve adequate air contents for these mixtures. No AEA was added to the mixtures tested in the research program. In addition, studies should be conducted to examine the effects of using superplasticizers (HRWRs) on the properties of these mixtures, such as time of setting. The slumps varied widely, and most exceeded the maximum slump of 2 in. established by AHTD for Portland Cement Concrete Pavements, but could be reduced significantly with the addition of HRWRs (2003).

6.3.2 Strength and Maturity Study – Phase II

The nomographs presented in Appendix J and the predictive models summarized in Table 5-12 can be used to estimate strength development for hardening concrete in the field under cold weather conditions, if mixture proportions similar to that used in this research are followed and maturity indices derived from a recorded time-temperature history are available. A commercially available maturity meter, Intellirock II, was used to record the temperature history and automate maturity index calculations for the experimental slabs used in this research program. Although the maturity indices calculated by the maturity meter were subsequently corrected using the datum temperature and activation energy parameters developed during the course of this investigation, it is recommended that maturity index calculations and recording of time-temperature histories be automated. Therefore, a maturity meter is recommended for application of the maturity method. Through the use of a maturity meter and automated maturity index calculation, the process is greatly simplified.

The reader is cautioned to use the same input values for the time-temperature or equivalent age functions that were used to develop the nomographs and predictive models. In the case of the time-temperature maturity index function, the datum temperature of 14°F (-10°C) was used in all of the maturity index calculations. Activation energy values for the different mixtures are summarized in Table 4-10. The input values are entered into the maturity meter prior to activating the data logger. In this way, the maturity meter will calculate a maturity index which may be used directly with the nomographs (Appendix J) and predictive models (Table 5-12) produced in this research program.

The predictive models were determined by combining all of the data for a particular mixture representing all of the strength and maturity index data for all curing temperatures (33, 40, 50, 60, and 70°F) into one ordered data set. A model was then determined using a regression procedure that provided the best fit to the data. Because of the strength development behavior of ternary concrete in terms of temperature and the range of temperatures investigated, the models tend to under-predict for concrete cured at 70°F and over-predict for mixtures cured at 33°F. For temperatures above 70°F, the user may opt instead to use the nomograph and read strengths from the 70°F curve rather than use the models to lessen the effect of over-prediction. The relationships presented herein are not suitable for measuring concrete strength development under hot weather conditions. While the models provide for conservative estimations at higher temperatures, it also is under-conservative for temperatures near freezing. For this reason, users of the models are cautioned to avoid casting and curing concrete in prolonged freezing conditions. The strength development behavior of concrete near freezing is unknown, and given the high degree of variability associated with the datum temperature determinations, it is difficult to accurately determine the temperature at which strength development effectively stops.

The maturity and compressive strength relationships presented were developed using compressive strength data for concrete with ages up to 28 days. The predictive models should not be used to estimate strength gain of hardening concrete beyond 28 days of age. This recommendation should be heeded in particular for the linear and exponential models. These two models are capable of predicting infinite strength; they will with certainty over-predict compressive strength for large maturity index values.

Conversely, the hyperbolic models approach an asymptotic value of strength for large maturity index values, and there is a decreased danger of over-prediction. In either case, the models should be used cautiously for concrete over 28 days of age. The predictive models for Mixture 20/60 may not be used for equivalent ages beyond 400 hr and temperature-time maturity indices above 17500 °C-hrs.

The predictive models should also be used cautiously for early age (0-24 hr) concrete. The largest errors between the strengths predicted by the model and the actual strengths obtained through strength tests occurred with the 1 day of age strength data. Appropriate factors of safety should be applied for early age concrete, given that for PC replacement up to 60% the percent error may be as high as 50% for strength estimation of concrete at 1 day of age. At 7 days of age and beyond, the highest percent error between the predicted and the actual was some 20%. Wilhite (2007) provides detailed research on the time of setting behavior for these mixtures, and this work should also be consulted if the performance behavior of these mixtures at early ages must be known.

The 80% PC replacement mixtures performed poorly compared to the control, and in addition the lowest correlation coefficient values, R^2, indicating that in terms of goodness-of-fit these models are the least adequate. Although it is unlikely that any type of structural or pavement concrete will be specified using these mixtures, this investigator further recommends that additional caution be applied to these models. The dormant period for the 20/60 mixture was determined to be some 14 days. It is therefore suggested that the models be used only to estimate strength for 80% PC replacement mixtures that are between 14 and 28 days of age.

Either the time-temperature or the equivalent age maturity function is recommended for use. For field construction, the time-temperature function is likely simpler to use, but, given the automated maturity index calculation feature of the maturity meter, the equivalent age function is not difficult to implement. Due to the variability encountered with the determination of activation energy, whatever advantages are to be gained from the use of an arguably more accurate maturity index for compressive strength and temperature behavior of hardening concrete such as the equivalent age function are counteracted by the variation in the activation energy determined in this research program. Therefore, investigators which make use of the nomographs and predictive models presented herein are encouraged to use either the time-temperature or equivalent age maturity index function.

Experimental determination of the datum temperatures or equivalent age for ternary concrete following the techniques suggested by ASTM C 1074 is difficult to achieve. The magnitude of the rate constant increase for ternary concrete over the range of curing temperatures 40, 70, and 100°F used in this program is small in comparison to concrete mixtures containing only PC. The small amounts of error caused from the regression procedure used to obtain the rate constants make it difficult to accurately determine the behavior of the rate constant with changing temperature.

For datum temperature and activation energy determination, it is suggested that for future research more curing temperatures be used in order to produce more data points for the curing temperature and rate constant relationships. Because datum temperature and activation energy determination involves regression in order to find a model that fits the data, increasing the number of data points will decrease the influence that any one potentially erroneous data point has on the model. ASTM C 1074 suggests using three curing temperatures to produce the rate constant temperature relationship. It is recommended that at least five to six curing temperatures be used. This will involve greatly increasing the scope of work, but it will allow for a more accurate depiction of the rate constant behavior.

In addition to increasing the number of curing temperatures, it is suggested that more than three sample mortar cubes be tested at any one test age. The average compressive strength is the mean value of three samples tested at each test age. The generalized curve fitting procedure used to determine the rate constant will be improved if the average strength of the sample population is closer to the true mean. Increasing the number of samples tested at each test age is the best way to make this improvement. But like increasing the number of curing temperatures, this recommendation will also increase the scope of the work required.

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Appendix A

Compressive Strength Data – Mortar Mixtures

Table A-1. Strength Data for Mortar Mixture 0/0						
Batch ID	**Age (day)**	**Sample 1**	**Sample 2**	**Sample 3**	**Average Strength (psi)**	**Std. Dev. (psi)**
M 0/0 (40)	1.06	275	315	330	307	28
	1.96	1320	1268	1448	1345	93
	4.16	2968	2943	2945	2952	14
	8.27	3938	3800	3525	3754	210
	16.27	4350	4525	4175	4350	175
	31.95	5225	5925	5513	5554	352
	66.12	7363	7575	8075	7671	366
M 0/0 (70)	0.50	335	320	345	333	13
	0.98	1368	1355	1525	1416	95
	1.97	3050	2623	2938	2870	221
	3.97	3288	4525	3838	3884	620
	8.85	4813	5275	4988	5025	233
	17.05	4600	6050	5275	5308	726
	34.88	6675	6888	6213	6592	345
	64.10	7425	7400	7325	7383	52
M 0/0 (100)	0.30	1365	1313	1463	1380	76
	0.51	2825	2445	2720	2663	196
	1.02	2725	2445	3150	2773	355
	2.04	3875	4450	4675	4333	413
	4.06	4275	5100	4850	4742	423
	7.91	5225	4850	5875	5317	519
	15.88	5250	5450	4500	5067	501
	31.20	5425	6538	5800	5921	566

Table A-2. Strength Data for Mortar Mixture 20/20

Batch ID	Age (day)	Sample 1	Sample 2	Sample 3	Average Strength (psi)	Std. Dev. (psi)
M 20/20 (40)	0.97	45	50	55	50	5
	2.00	1385	758	725	956	372
	4.29	1788	1945	2013	1915	115
	8.08	2938	3138	2913	2996	123
	16.07	3588	4188	3500	3759	374
	31.80	5213	5425	5350	5329	108
	64.96	5675	6625	5975	6092	486
M 20/20 (70)	0.48	50	48	53	50	3
	1.02	905	885	913	901	14
	2.05	1590	1758	1813	1720	116
	3.94	3363	3175	3288	3275	95
	7.89	4350	4100	3925	4125	214
	16.11	4688	4150	5000	4613	430
	33.93	6338	6575	6388	6434	125
	64.86	8075	7163	7313	7517	489
M 20/20 (100)	0.29	180	180	180	180	0
	0.56	935	1068	1045	1016	71
	0.94	1713	1938	1925	1859	126
	2.00	2675	2845	2670	2730	100
	3.79	4750	3575	3838	4054	617
	6.81	5975	4363	5700	5346	862
	17.11	6788	7438	6525	6917	470
	31.79	6050	7300	6775	6708	628

Table A-3. Strength Data for Mortar Mixture 40/20

Batch ID	Age (day)	Sample 1	Sample 2	Sample 3	Average Strength (psi)	Std. Dev. (psi)
M 40/20 (40)	1.14	45	55	60	53	8
	2.08	320	388	400	369	43
	4.26	963	1038	963	988	43
	8.24	1763	1675	1775	1738	55
	17.14	2255	2313	1805	2124	278
	32.15	3213	2825	3200	3079	220
	65.15	4275	4438	4450	4388	98
M 40/20 (70)	0.67	173	188	168	176	10
	1.07	400	370	393	388	16
	2.21	1208	825	895	976	204
	3.90	1968	1760	1488	1739	241
	7.20	2645	2280	2495	2473	183
	17.01	3850	3750	3175	3592	364
	32.16	4775	3425	4300	4167	685
	63.26	7188	8200	7738	7709	507
M 40/20 (100)	0.24	33	43	53	43	10
	0.48	358	358	395	370	21
	1.01	1145	1270	1263	1226	70
	1.88	2355	2213	2158	2242	102
	3.89	4175	3800	3975	3983	188
	8.14	5475	4238	5188	4967	647
	15.93	7438	6825	7813	7359	499
	31.89	9313	8450	8725	8829	441

Table A-4. Strength Data for Mortar Mixture 40/40						
Batch ID	**Age (day)**	**Sample 1**	**Sample 2**	**Sample 3**	**Average Strength (psi)**	**Std. Dev. (psi)**
M 40/40 (40)	2.10	38	35	30	34	4
	3.97	35	38	40	38	3
	7.96	55	45	55	52	6
	15.89	460	480	313	418	91
	31.74	1218	1295	1268	1260	39
	63.95	1555	1420	1545	1507	75
	87.73	1820	1605	1320	1582	251
	101.75	1668	1743	1735	1715	41
M 40/40 (70)	1.16	35	33	33	34	1
	2.11	40	38	30	36	5
	4.00	95	98	98	97	2
	9.39	725	735	705	722	15
	16.94	1110	1078	1058	1082	26
	20.25	1105	1263	1485	1284	191
	31.64	1373	1373	1485	1410	65
	63.22	3588	3625	2753	3322	493
M 40/40 (100)	1.05	58	58	60	59	1
	1.98	365	360	355	360	5
	4.16	1108	1050	1125	1094	39
	7.89	3538	2830	3425	3264	380
	15.83	4025	6000	6325	5450	1245
	23.77	6088	6938	5400	6142	770
	30.75	5938	4475	7825	6079	1679
	44.78	4975	6450	6725	6050	941

Table A-5. Strength Data for Mortar Mixture 20/40

Batch ID	Age (day)	Sample 1	Sample 2	Sample 3	Average Strength (psi)	Std. Dev. (psi)
M 20/40 (40)	1.87	138	145	143	142	4
	3.17	430	355	455	413	52
	4.07	645	643	600	629	25
	8.01	1508	1205	1293	1335	156
	15.81	1938	2420	2655	2338	366
	32.08	3575	2845	3475	3298	396
	63.97	4313	4400	3650	4121	410
	88.14	4050	3900	NA	3975**	106**
M 20/40 (70)	0.70	35	30	33	33	3
	1.09	185	180	175	180	5
	1.93	670	655	675	667	10
	4.01	1920	1623	1748	1764	149
	7.82	2910	2435	2700	2682	238
	16.14	3350	3000	3713	3354	357
	31.41	3958	3950	3900	3936	31
	63.87	3538	5000	5613	4717	1066
M 20/40 (100)	0.48	33	33	30	32	2
	1.04	358	455	470	428	61
	1.99	1605	1555	1670	1610	58
	3.95	2908	2605	2838	2784	159
	8.89	4488	5125	4388	4667	400
	16.13	5600	4325	6075	5333	905
	30.94	6775	7050	7338	7054	282

**Average and standard deviation from two mortar cube tests.

Table A-6. Strength Data for Mortar Mixture 20/60

Batch ID	Age (day)	Sample 1	Sample 2	Sample 3	Average Strength (psi)	Std. Dev. (psi)
M 20/60 (40)	2.29	55	63	43	54	10
	4.11	63	58	70	64	6
	8.87	63	65	63	64	1
	16.97	68	95	93	85	15
	34.00	730	775	720	742	29
	64.16	1433	1388	1280	1367	79
	89.97	1943	1423	1688	1685	260
	104.77	1990	1983	1903	1959	48
M 20/60 (70)	1.09	30	35	38	34	4
	1.98	48	43	43	45	3
	4.04	38	40	43	40	3
	7.93	38	43	30	37	7
	17.19	675	698	695	689	13
	22.18	1055	945	980	993	56
	31.97	1593	1270	1275	1379	185
	63.92	2718	2678	1743	2380	552
M 20/60 (100)	1.17	20	38	28	29	9
	2.38	43	58	58	53	9
	4.23	583	663	655	634	44
	8.21	3175	2875	2838	2963	185
	16.01	3463	4213	4113	3930	407
	23.20	3938	4850	4150	4313	477
	29.23	5200	5063	4575	4946	329
	42.99	5175	6438	4200	5271	1122

Appendix B

Results of Hyperbolic Curve Fitting Procedure – Mortar Mixtures

Table B-1. Results of Generalized Hyperbolic Curve Fitting Procedure for Mortar Mixture 0/0

	M 0/0 (40)		M 0/0 (70)		M 0/0 (100)	
	Parameter	**Error**	**Parameter**	**Error**	**Parameter**	**Error**
S_u	8429	1157	7212	398	5768	293
K	0.083	0.040	0.296	0.081	1.202	0.429
t_o	-0.19	1.16	0.21	0.25	-0.01	0.16
Chi square	1704500		1027700		734260	
R^2	0.954		0.976		0.979	
$S_{u\ in}$	9000		9000		9000	
K_{in}	1		1		1	
$t_{o\ in}$	0.001		0.001		0.001	
All. Error	0.1		0.1		0.1	
N	7		8		8	

Table B-2. Results of Generalized Hyperbolic Curve Fitting Procedure for Mortar Mixture 20/20

	M 20/20 (40)		M 20/20 (70)		M 20/20 (100)	
	Parameter	**Error**	**Parameter**	**Error**	**Parameter**	**Error**
S_u	7145	412	7884	612	7669	323
K	0.089	0.017	0.138	0.041	0.334	0.056
t_o	0.56	0.38	0.15	0.42	0.15	0.10
Chi square	254910		1261300		414980	
R^2	0.992		0.974		0.991	
$S_{u\ in}$	9000		9000		9000	
K_{in}	1		1		1	
$t_{o\ in}$	0.001		0.001		0.001	
All. Error	0.1		0.1		0.1	
N	7		8		8	

Table B-3. Results of Generalized Hyperbolic Curve Fitting Procedure for Mortar Mixture 40/20

	M 40/20 (40)		M 40/20 (70)		M 40/20 (100)	
	Parameter	**Error**	**Parameter**	**Error**	**Parameter**	**Error**
S_u	6017	889	15823	7376	10764	679
K	0.037	0.014	0.013	0.011	0.133	0.025
t_o	0.03	1.06	-2.62	2.57	0.12	0.17
Chi square	277630		1905100		595080	
R^2	0.980		0.956		0.992	
$S_{u\ in}$	5000		9000		9000	
K_{in}	1		1		1	
$t_{o\ in}$	0.001		0.001		0.001	
All. Error	0.1		0.1		0.1	
N	7		8		8	

Table B-4. Results of Generalized Hyperbolic Curve Fitting Procedure for Mortar Mixture 40/40

	M 40/40 (40)		M 40/40 (70)		M 40/40 (100)	
	Parameter	**Error**	**Parameter**	**Error**	**Parameter**	**Error**
S_u	2091	233	7181	4588	7774	825
K	0.047	0.018	0.012	0.013	0.127	0.048
t_o	7.92	1.37	2.71	3.77	1.94	0.53
Chi square	55929		322210		1179200	
R^2	0.976		0.946		0.968	
$S_{u\ in}$	1300		2500		9000	
K_{in}	1		1		1	
$t_{o\ in}$	0.001		0.001		0.001	
All. Error	0.1		2		0.1	
N	6		6		7	

Table B-5. Results of Generalized Hyperbolic Curve Fitting Procedure for Mortar Mixture 20/40

	M 20/40 (40)		M 20/40 (70)		M 40/40 (100)	
	Parameter	Error	Parameter	Error	Parameter	Error
S_u	4879	217	4981	210	8456	567
K	0.067	0.011	0.155	0.026	0.137	0.027
t_o	1.90	0.48	0.83	0.22	0.47	0.19
Chi square	78243		122180		322220	
R^2	0.995		0.993		0.992	
$S_{u\ in}$	4000		9000		9000	
K_{in}	1		1		1	
$t_{o\ in}$	0.001		0.001		0.001	
All. Error	0.1		0.1		0.1	
N	7		7		7	

Table B-6. Results of Generalized Hyperbolic Curve Fitting Procedure for Mortar Mixture 20/60

	M 20/60 (40)		M 20/60 (70)		M 20/60 (100)	
	Parameter	Error	Parameter	Error	Parameter	Error
S_u	3438	555	4949	350	6344	541
K	0.014	0.005	0.016	0.002	0.121	0.035
t_o	14.76	1.75	7.36	0.45	2.54	0.37
Chi square	9728		2460		432040	
R^2	0.996		0.999		0.983	
$S_{u\ in}$	1000		2500		6000	
K_{in}	1		1		1	
$t_{o\ in}$	0.001		0.001		0.001	
All. Error	0.1		0.1		0.1	
N	5		5		7	

Appendix C

Rate Constant versus Temperature Plots – Mortar Mixtures

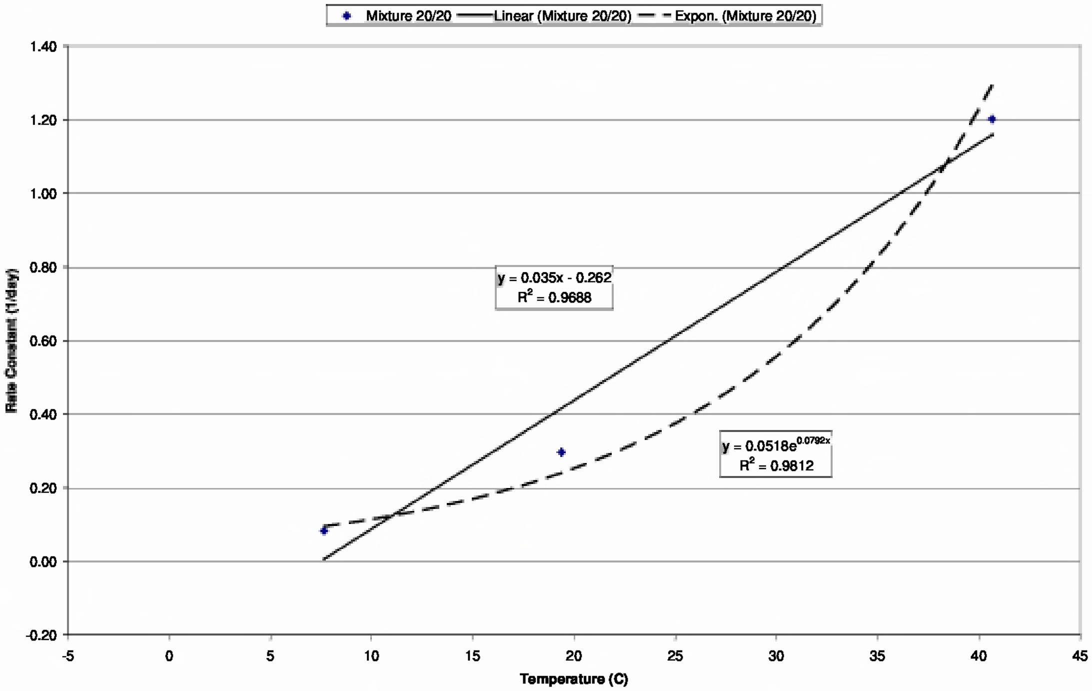

Figure C-1. Rate Constant and Temperature Relationship for Mixture 0/0.

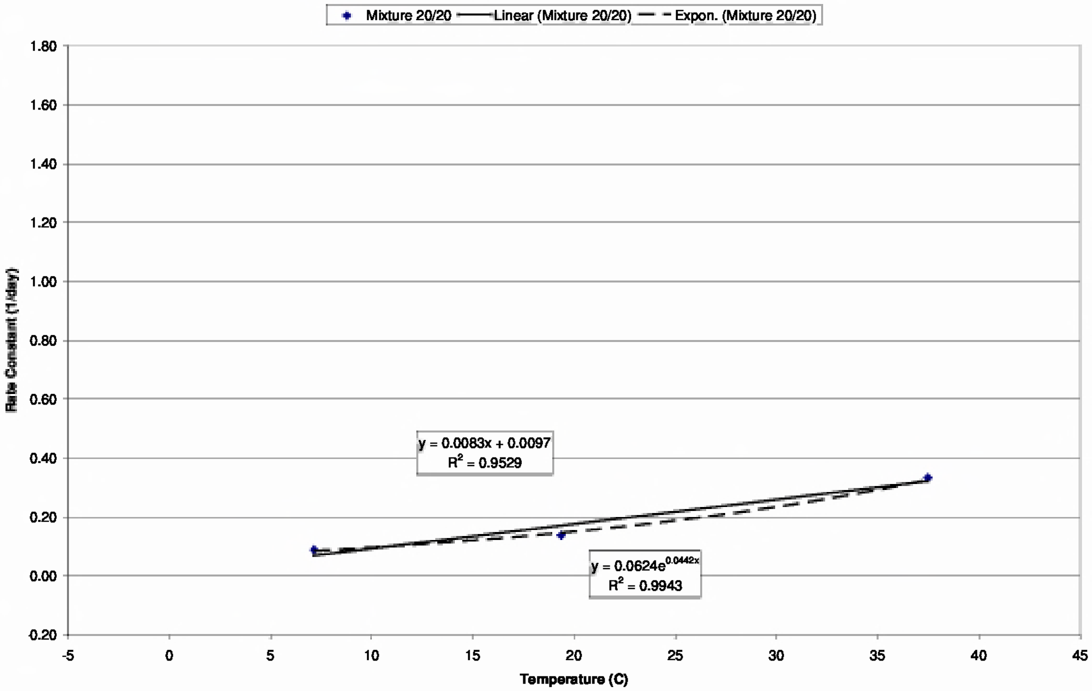

Figure C-2. Rate Constant and Temperature Relationship for Mixture 20/20.

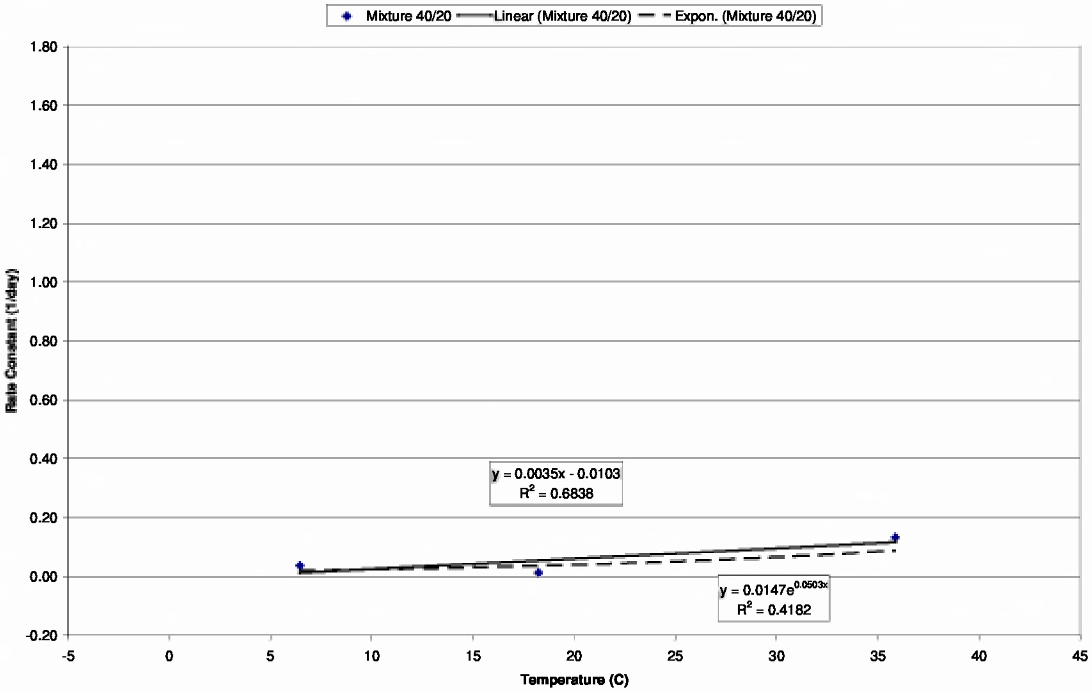

Figure C-3. Rate Constant and Temperature Relationship for Mixture 40/20.

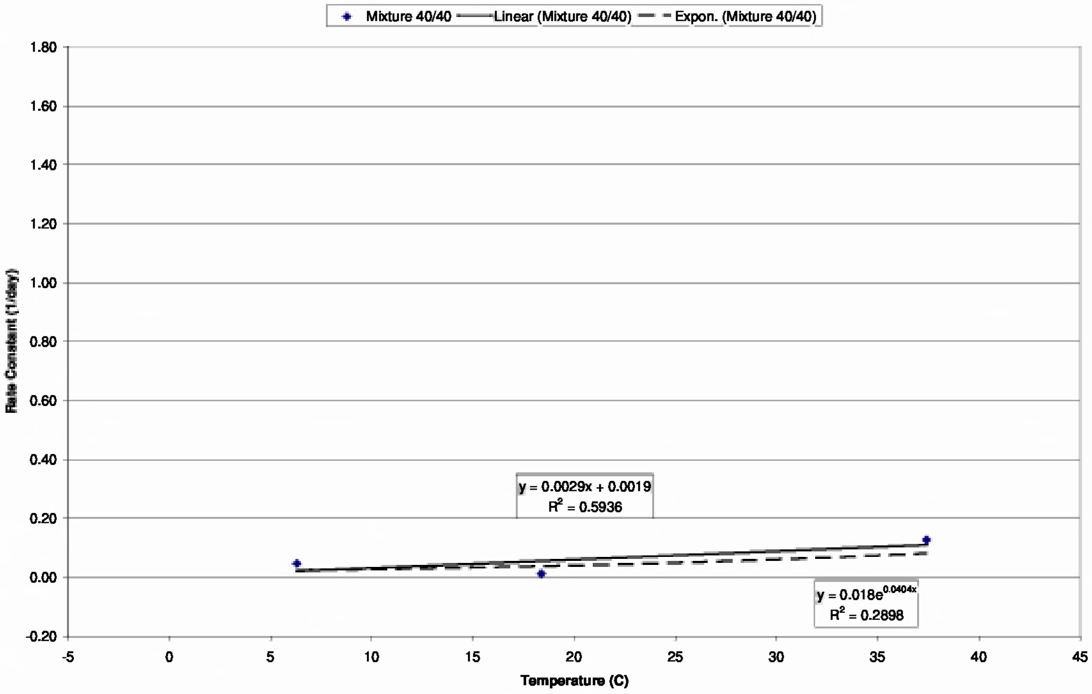

Figure C-4. Rate Constant and Temperature Relationship for Mixture 40/40.

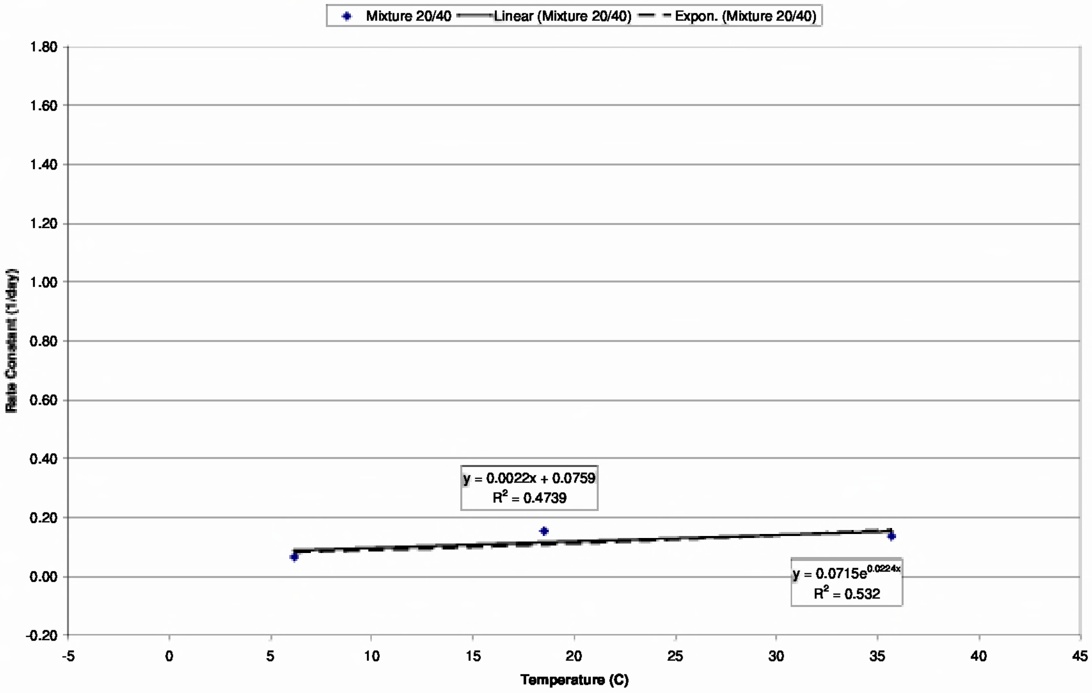

Figure C-5. Rate Constant and Temperature Relationship for Mixture 20/40.

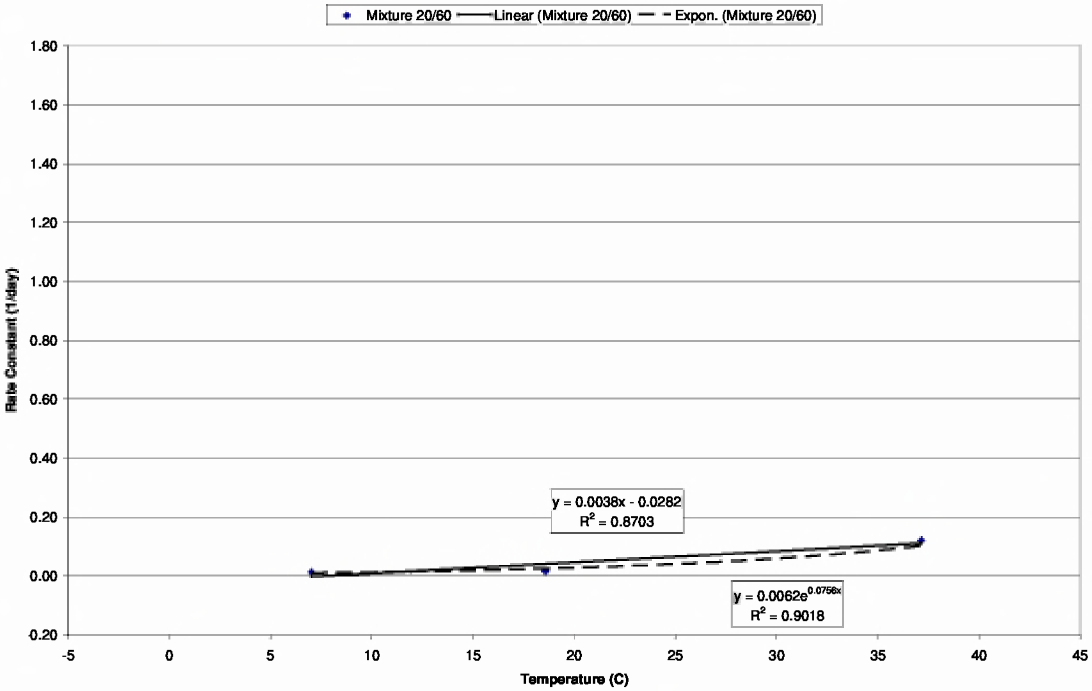

Figure C-6. Rate Constant and Temperature Relationship for Mixture 20/60.

Appendix D

ACTIVATION ENERGY AND DATUM TEMPERATURE DERIVATION EXAMPLE

A software program is used to perform generalized curve fit of the mortar cube compressive strength and age data. The data is fit to the hyperbolic equation (12), and the program determines the best fit values that produce the least error for the dormant period, ultimate strength, and rate constant. The rate constant is the only parameter determined by the curve fit that is necessary for the determination of activation energy and datum temperature. In these examples, the rate constant and curing temperature results for the control mixture are used to illustrate the derivations (Table D-1).

Table D-1. Control Mixture - Rate Constant and Curing Temperature Results

Batch ID	Temp. (°C)	Rate Constant, K (1/day)
M 0/0 (40)	7.66	0.083
M 0/0 (70)	19.38	0.296
M 0/0 (100)	40.65	1.202

Example Datum Temperature Derivation

For each mixture examined in this research program, three different rate constants were determined representing the three curing temperatures studied. These three rate constants were plotted on the y-axis. The curing temperatures in Celsius units were plotted on the x-axis. A spreadsheet program was used to generate the plot. This program was also used to produce a linear least squares trend-line that best fit the rate constant and temperature data. The spreadsheet program was also directed to display the equation for the trendline.

The datum temperature represents the temperature below which strength development ceases. It can be determined by two methods:

> **Method 1**—The linear trend line is extended until it crosses the x-axis. The line is forecast backward until the line crosses the x-axis at y=0. The datum temperature is the intercept between the trend line and the temperature axis. Figure D-1 illustrates a rate constant and temperature relationship where the trend line has been forecast through the x-axis. Note that in this example the datum temperature occurs at the point 7.5,0. Therefore, the datum temperature is 7.5°C.

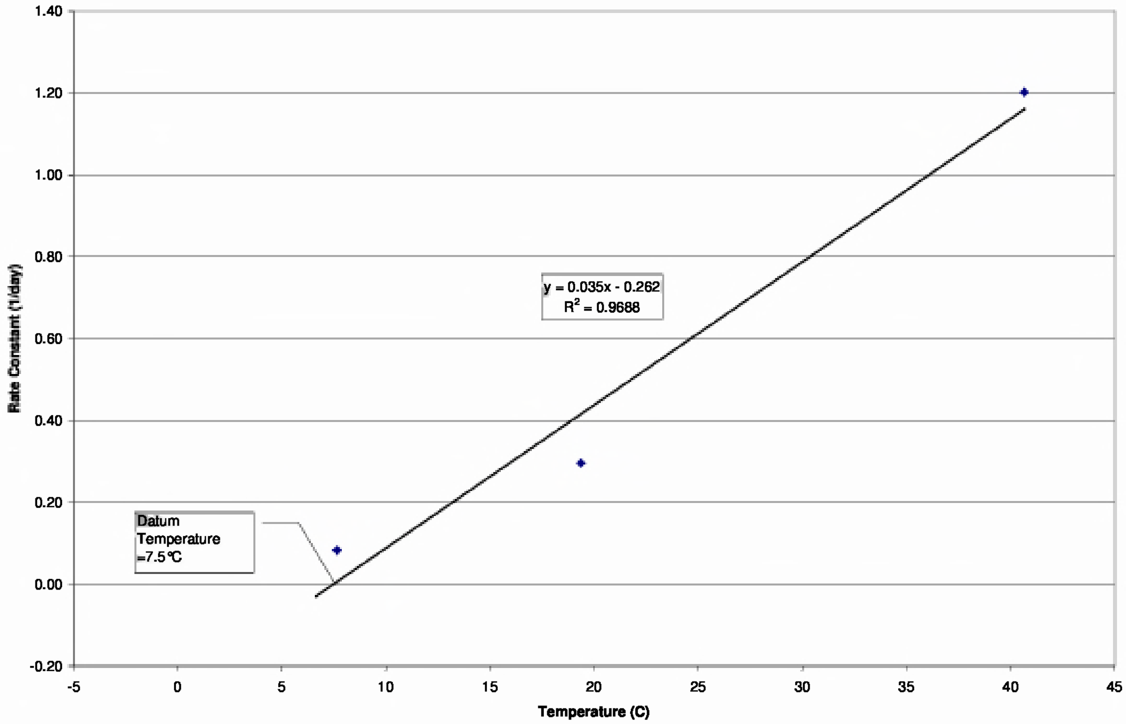

Figure D-1. Rate Constant and Temperature Relationship.

Method 2—The equation of the best-fit linear trend-line for the rate constant and temperature data is used to calculate the datum temperature. The variable y for the equation is set to equal zero. The equation now only can be solved for the temperature variable. The solution to this equation is the datum temperature for the mixture. For example:

The equation for the rate constant and temperature relationship in Figure D-1 is obtained.

$y=0.035x-0.262$

The value of the rate constant variable is set to zero in order to determine the point at which the rate of strength gain is equal to zero. In this case the y variable is the rate constant, therefore $y=0$.

$0=0.035x-0.262$

The resulting equation is solved for the value of x.

$x=7.49$

Therefore the datum temperature for the control mixture is 7.5°C.

Example Activation Energy Derivation

The process of determining activation energy involves plotting the natural log of the rate constants versus the inverse of the curing temperature. A linear trend line is fit to the data. The activation energy is determined by finding the slope of the trend line and dividing that slope by the ideal gas constant. An example of this process is provided.

For each mixture examined in this research program, three different rate constants were determined representing the three curing temperatures studied. First the curing temperatures must be converted to Kelvin units.

Kelvin = °C + 273

7.66 °C + 273 = 280.66 K

Then the inverse of the curing temperature was calculated by dividing one by the temperature in Kelvin.

1 / 280.66 K = .00356 1/K

The temperature conversion step and the inverse step were taken for all of the curing temperature data. Afterwards, the natural log of the rate constant was calculated.

ln(K) = ln(0.083) = -2.489

Table D-2. Control Mixture - Preliminary Calculation Results

Batch ID	**Temp (K)**	**1/Temp (1/K)**	**ln(K)**
M 0/0 (40)	280.66	0.00356	-2.489
M 0/0 (70)	292.38	0.00342	-1.217
M 0/0 (100)	313.65	0.00319	0.184

The results of these calculations are shown in Table D-2. The natural log of the rate constant corresponding to each curing temperature was plotted on the y-axis (Figure D-2). The inverse of temperature corresponding to each curing temperature was plotted on the x-axis. A spreadsheet program was used to generate the plot. This program was also used to produce a linear least squares trend-line that best fit the data. The spreadsheet program was also directed to display the equation for the trend line.

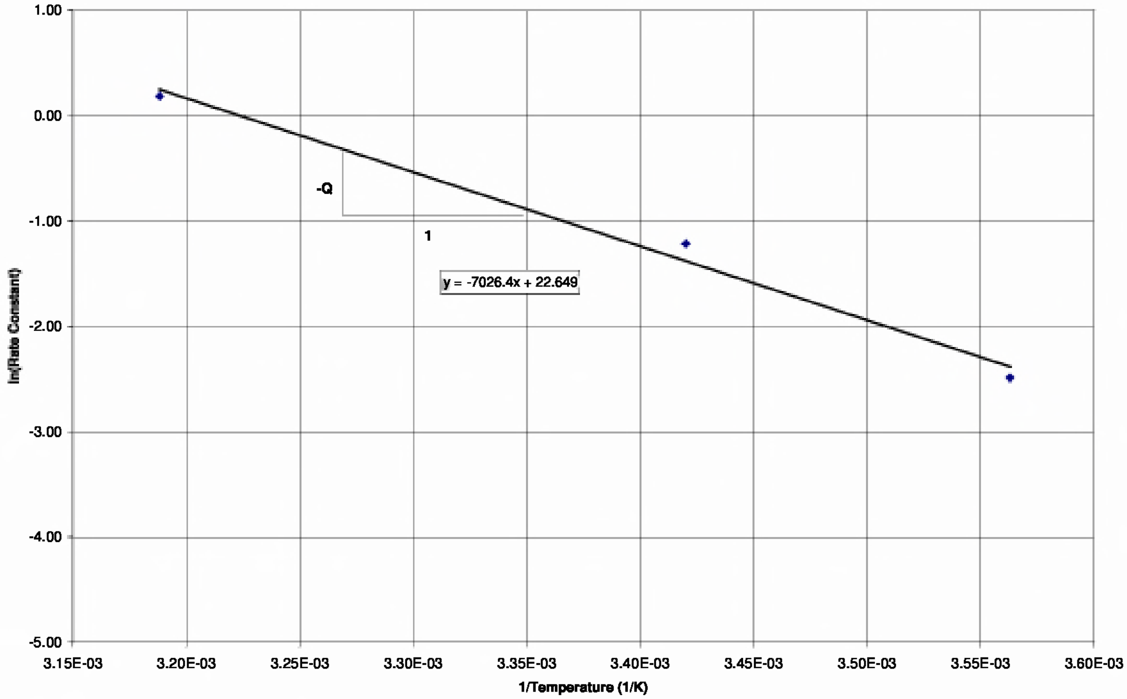

Figure D-2. Activation Energy Example Derivation.

The slope of the trend line is the quantity –Q. Q is the activation energy divided by the ideal gas constant, R, which is equal to 8.3144 J/(mol*K). The –Q term is obtained from the linear equation calculated by the spreadsheet program.

$y = -7026.4x + 22.649$

Therefore,

$-Q = -7026.4$

Activation energy, E, is determined by dividing Q by R.

$E = Q / R$

$E = 7026.4 / 8.3144 = 58420$ J/mol = 58.4 kJ/mol

The activation energy for the control mixture is 58.4.

Appendix E

Activation Energy Determination Plots – Mortar Mixtures

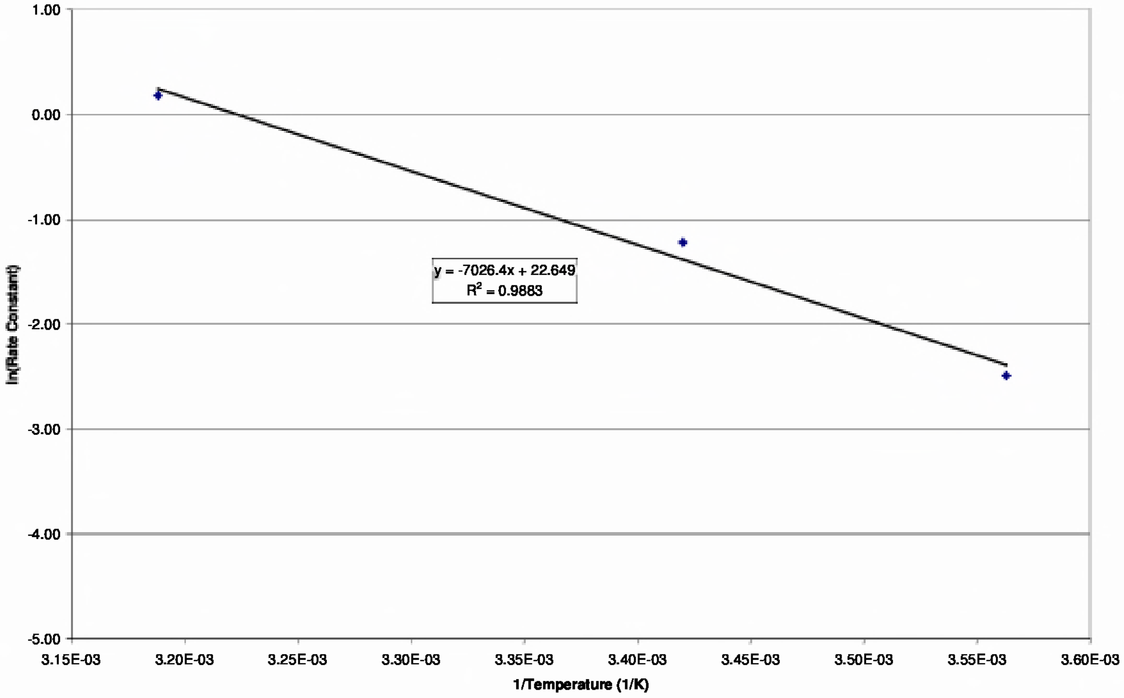

Figure E-1. Natural Log of the Rate Constant versus the Inverse of the Temperature for Mixture 0/0.

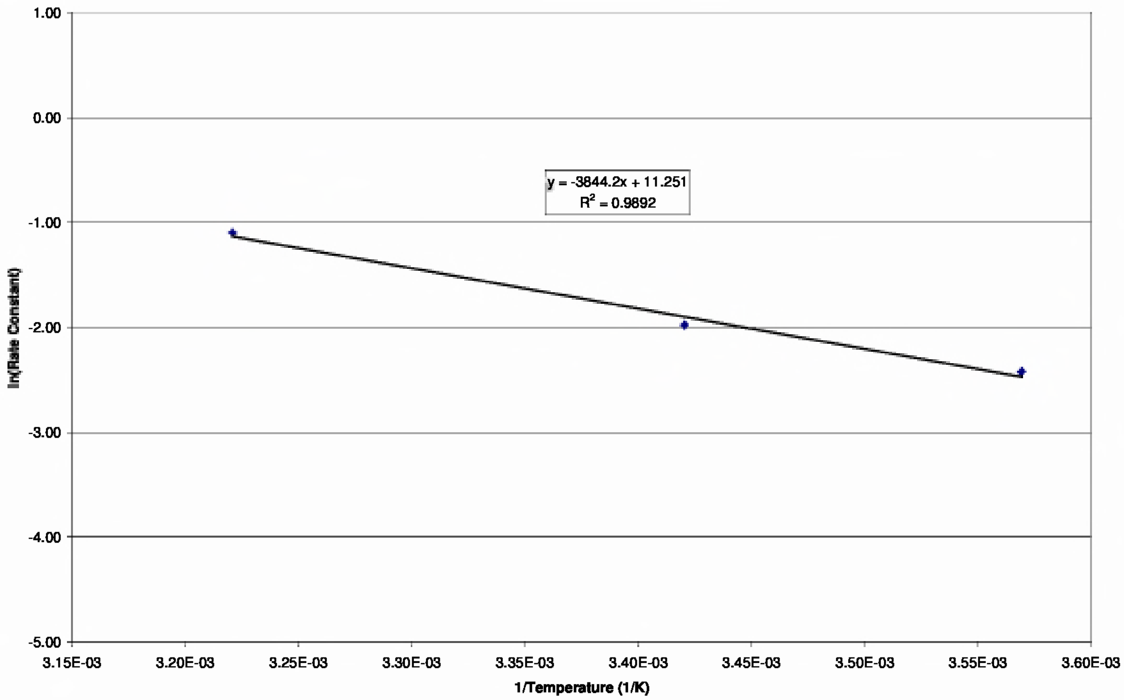

Figure E-2. Natural Log of the Rate Constant versus the Inverse of the Temperature for Mixture 20/20.

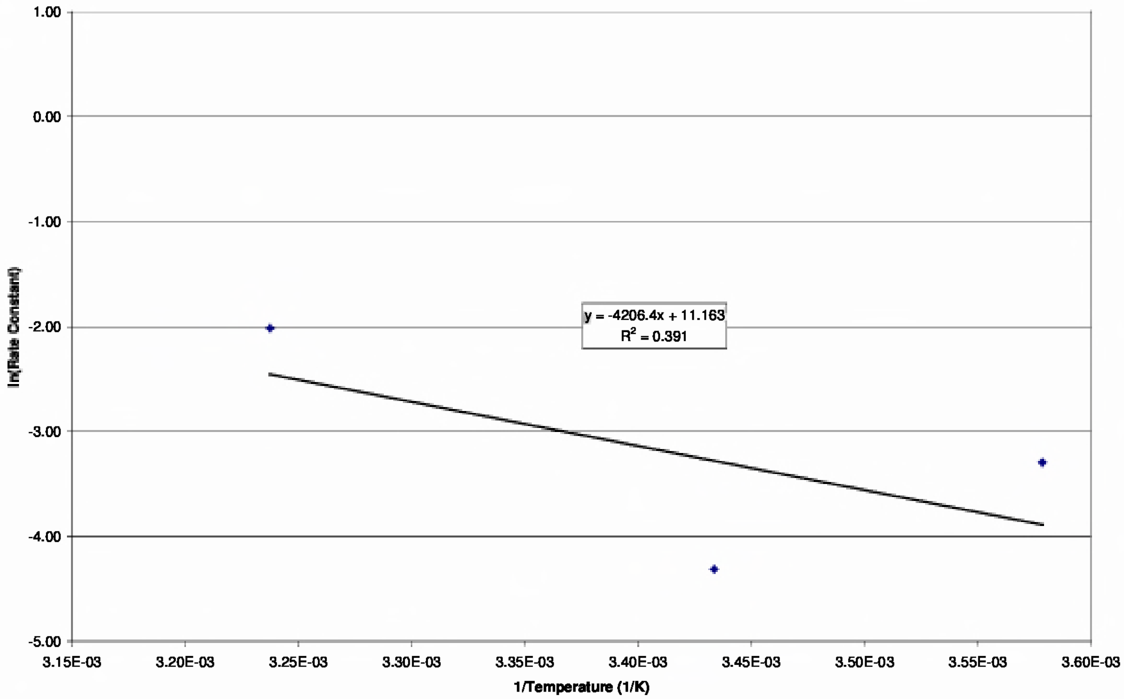

Figure E-3. Natural Log of the Rate Constant versus the Inverse of the Temperature for Mixture 40/20.

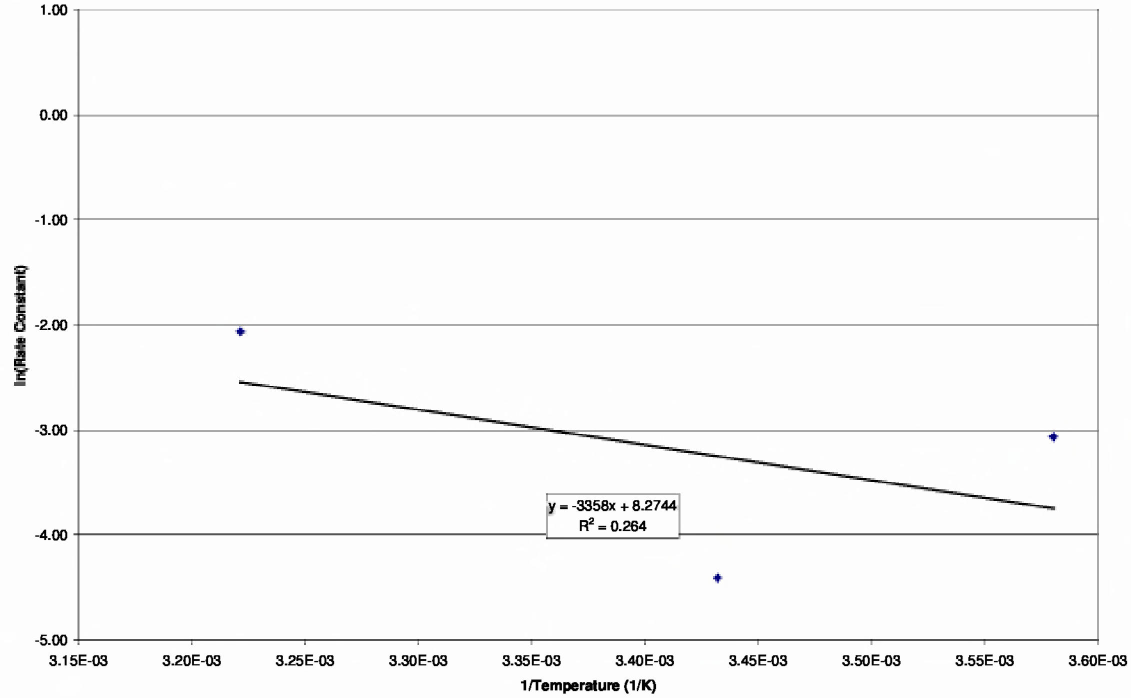

Figure E-4. Natural Log of the Rate Constant versus the Inverse of the Temperature for Mixture 40/40.

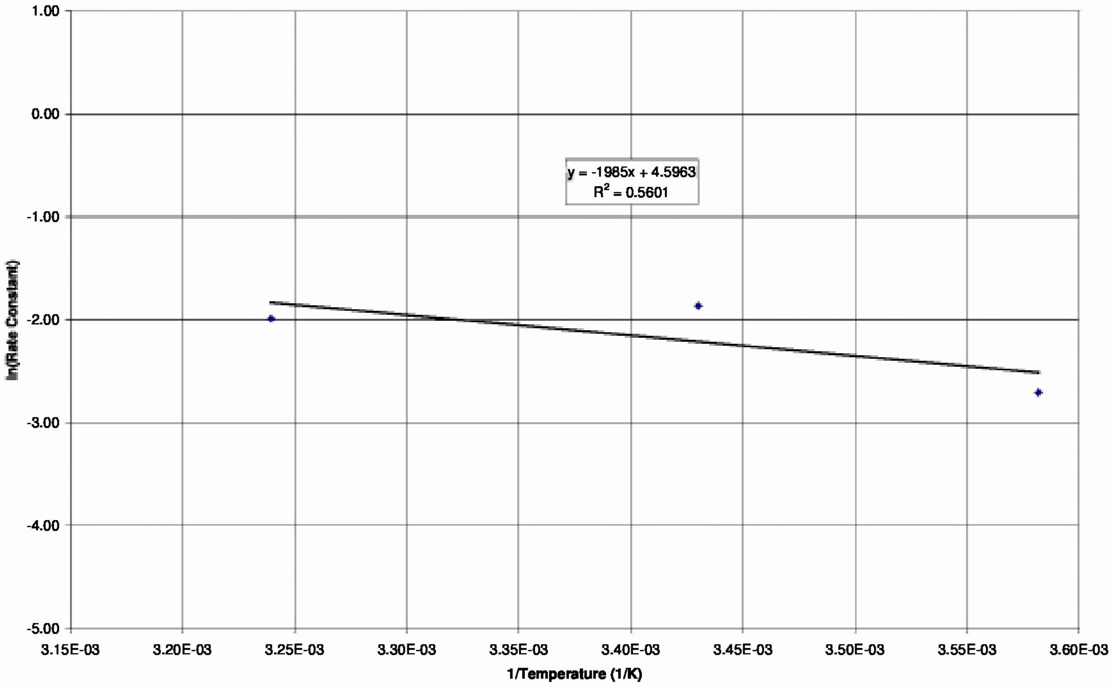

Figure E-5. Natural Log of the Rate Constant versus the Inverse of the Temperature for Mixture 20/40.

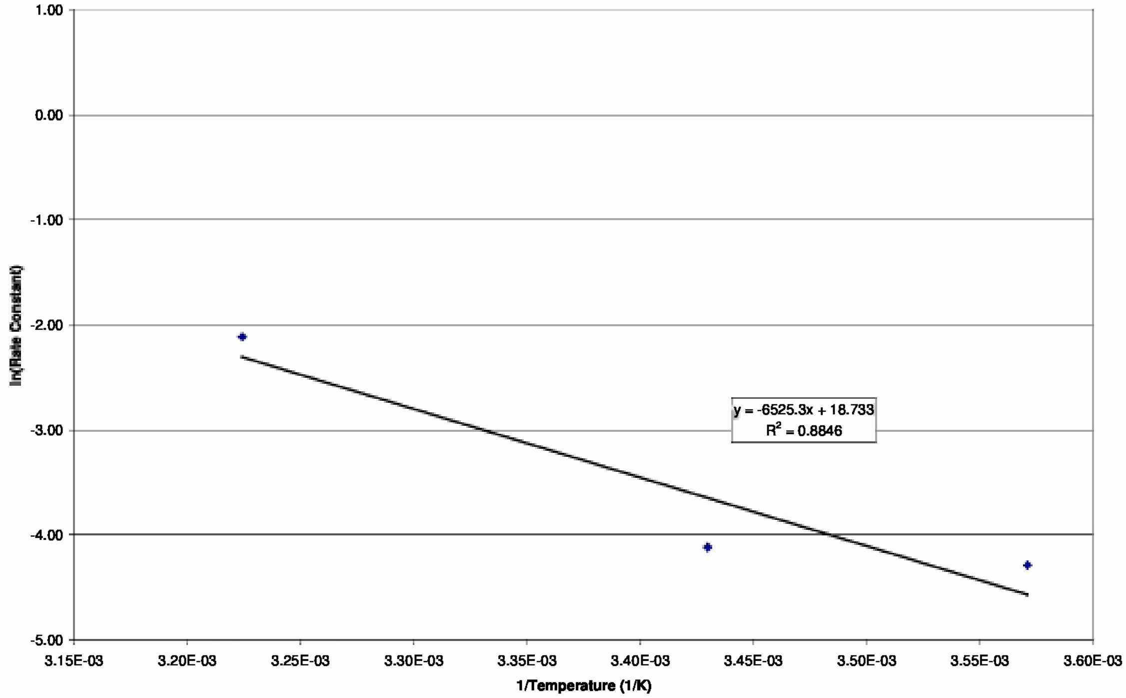

Figure E-6. Natural Log of the Rate Constant versus the Inverse of the Temperature for Mixture 20/60.

Appendix F

Fresh Concrete Properties – Strength and Maturity Studies

Table F-1. Fresh Concrete Properties for Mixture 0/0

Batch ID	Temperature (°F)	Slump (in)	Unit Weight (lb/ft^3)	Air Content (%)
0/0 (70)	66	7.25	149.84	1.2
0/0 (60)	68	5.25	150.32	1.2
0/0 (50)	65	3.75	151.12	1.4
0/0 (40)	58	3.50	151.20	1.3
0/0 (33)	80	1.25	149.84	1.7
Average	67	4.20	150.46	1.4
Std. Deviation	8	2.22	0.67	0.2
C.O.V.	12	52.97	0.44	15.2

Table F-2. Fresh Concrete Properties for Mixture 20/20

Batch ID	Temperature (°F)	Slump (in)	Unit Weight (lb/ft^3)	Air Content (%)
20/20 (70)	60	7.00	150.32	1.0
20/20 (60)	55	5.00	150.80	1.0
20/20 (50)	64	6.50	150.32	1.1
20/20 (40)	65	4.25	150.16	1.1
20/20 (33)	68	3.75	148.72	1.3
Average	62	5.30	150.06	1.1
Std. Deviation	5	1.41	0.79	0.1
C.O.V.	8	26.56	0.53	11.1

Table F-3. Fresh Concrete Properties for Mixture 40/20				
Batch ID	**Temperature (°F)**	**Slump (in)**	**Unit Weight (lb/ft^3)**	**Air Content (%)**
40/20 (70)	73	3.50	149.28	1.2
40/20 (60)	74	3.50	148.96	1.1
40/20 (50)	76	4.25	149.28	1.2
40/20 (40)	75	5.75	148.60	1.0
40/20 (33)	63	6.00	148.16	1.2
Average	72	4.60	148.86	1.1
Std. Deviation	5	1.21	0.48	0.1
C.O.V.	7	26.23	0.32	7.8

Table F-4. Fresh Concrete Properties for Mixture 40/40				
Batch ID	**Temperature (°F)**	**Slump (in)**	**Unit Weight (lb/ft^3)**	**Air Content (%)**
40/40 (70)	73	4.00	148.56	1.2
40/40 (60)	68	5.00	148.64	0.9
40/40 (50)	70	6.00	148.48	1.0
40/40 (40)	70	8.00	147.28	0.6
40/40 (33)	71	5.50	147.76	0.9
Average	70	5.70	148.14	0.9
Std. Deviation	2	1.48	0.60	0.2
C.O.V.	3	26.02	0.40	23.9

Table F-5. Fresh Concrete Properties for Mixture 20/40				
Batch ID	**Temperature (°F)**	**Slump (in)**	**Unit Weight (lb/ft^3)**	**Air Content (%)**
20/40 (70)	62	8.50	149.92	0.8
20/40 (60)	67	7.50	149.52	0.9
20/40 (50)	70	7.75	148.72	0.7
20/40 (40)	67	8.75	148.32	0.8
20/40 (33)	64	8.00	148.32	0.8
Average	66	8.10	148.96	0.8
Std. Deviation	3	0.52	0.73	0.1
C.O.V.	5	6.40	0.49	8.8

Table F-6. Fresh Concrete Properties for Mixture 20/60				
Batch ID	**Temperature (°F)**	**Slump (in)**	**Unit Weight (lb/ft^3)**	**Air Content (%)**
20/60 (70)	65	8.50	148.72	0.7
20/60 (60)	71	7.50	148.08	0.6
20/60 (50)	66	8.25	148.96	0.8
20/60 (40)	62	8.50	148.24	0.5
20/60 (33)	63	8.00	148.72	0.5
Average	65	8.15	148.54	0.6
Std. Deviation	4	0.42	0.37	0.1
C.O.V.	5	5.13	0.25	19.8

Appendix G

Compressive Strength Results - Strength and Maturity Studies

Table G-1. Average Compressive Strength Results from Strength Study Cylinders.

Mixture ID	Curing Temp (°F)	Age (day)	Average Compressive Strength (psi)	Standard Deviation (psi)	90% Confidence Interval (psi)
0/0	**70**	**1**	3185	140	133
		7	5725	247	234
		28	6887	230	219
	60	**1**	1617	284	269
		7	5184	144	137
		28	6644	67	63
	50	**1**	1650	106	101
		7	5455	260	247
		28	6581	133	126
	40	**1**	664	83	79
		7	5207	247	234
		28	6776	522	496
	33	**1**	605	143	136
		7	4381	147	140
		28	5474	279	265
20/20	**70**	**1**	1299	71	68
		7	5201	158	150
		28	7168	539	512
	60	**1**	607	22	21
		7	5491	40	38
		28	6959	106	100
	50	**1**	269	12	12
		7	4419	108	102
		28	7276	255	242
	40	**1**	304	121	115
		7	4043	371	352
		28	6840	278	264
	33	**1**	201	15	14
		7	2109	193	183
		28	4266	82	78

Table G-1 Contd. Average Compressive Strength Results from Strength Study Cylinders.					
Mixture ID	**Curing Temp (°F)**	**Age (day)**	**Average Compressive Strength (psi)**	**Standard Deviation (psi)**	**90% Confidence Interval (psi)**
40/20	**70**	**1**	616	23	21
		7	4432	41	39
		28	7756	136	129
	60	**1**	446	32	30
		7	3868	85	80
		28	6856	823	782
	50	**1**	339	14	13
		7	3088	38	36
		28	6574	296	281
	40	**1**	151	23	22
		7	2297	98	93
		28	5861	409	388
	33	**1**	63	35	33
		7	282	228	216
		28	303	49	47
40/40	**70**	**1**	48	4	4
		7	1161	121	115
		28	4269	324	307
	60	**1**	63	10	10
		7	1018	135	128
		28	3775	886	842
	50	**1**	60	4	4
		7	311	45	42
		28	3088	94	89
	40	**2**	50	10	10
		7	108	6	5
		28	1772	70	66
	33	**1**	50	22	20
		7	306	231	219
		28	401	205	194

Table G-1 Contd. Average Compressive Strength Results from Strength Study Cylinders.

Mixture ID	Curing Temp (°F)	Age (day)	Average Compressive Strength (psi)	Standard Deviation (psi)	90% Confidence Interval (psi)
20/40	**70**	**1**	256	13	13
		7	3741	63	59
		28	6277	102	97
	60	**1**	202	11	10
		7	3666	112	106
		28	5874	397	377
	50	**1**	121	9	9
		7	2624	236	224
		28	5893	533	506
	40	**1**	89	11	10
		7	2249	101	96
		28	5399	267	254
	33	**1**	21	2	2
		7	490	40	38
		28	422	98	93
20/60	**70**	**1**	56	13	12
		7	80	6	5
		28	2466	214	204
	60	**1**	76	8	8
		7	83	12	12
		28	1560	49	46
	50	**1**	43	8	8
		7	62	15	14
		28	1464	82	78
	40	**1**	64	3	3
		7	90	6	5
		28	579	41	39
	33	**1**	60	19	18
		7	226	128	122
		28	485	325	309

** Table G-1 reproduced from Wilhite (2007).

Table G-2. 1 Day Strength Results for Maturity Study Slabs.						
		Curing Temperature (°F)				
		70	**60**	**50**	**40**	**33**
Mixture		**Compressive Strength (psi)**				
0/0	**Cyl. 1**	3294	1812	2049	1063	3170
	Cyl. 2	3412	2132	2092	1178	3212
	Cyl. 3	3037	1805	1935	1046	3373
	Average	3248	1916	2025	1096	3252
	Std. Dev.	192	187	81	72	107
	90% C.I.	182	177	77	68	102
20/20	**Cyl. 1**	1381	1162	398	438	450
	Cyl. 2	1496	998	452	509	449
	Cyl. 3	1413	789	389	454	583
	Average	1430	983	413	467	494
	Std. Dev.	59	187	34	37	77
	90% C.I.	56	178	32	35	73
40/20	**Cyl. 1**	688	512	495	203	166
	Cyl. 2	757	497	405	244	166
	Cyl. 3	770	472	421	237	164
	Average	738	494	440	228	165
	Std. Dev.	44	20	48	22	1
	90% C.I.	42	19	46	21	1
40/40	**Cyl. 1**	65	70	68	42*	41
	Cyl. 2	59	63	60	58*	48
	Cyl. 3	61	60	67	48*	44
	Average	62	64	65	49	44
	Std. Dev.	3	5	4	8	4
	90% C.I.	3	5	4	8	3
20/40	**Cyl. 1**	277	261	134	110	78
	Cyl. 2	377	236	151	138	83
	Cyl. 3	314	244	117	127	83
	Average	323	247	134	125	81
	Std. Dev.	51	13	17	14	3
	90% C.I.	48	12	16	13	3
20/60	**Cyl. 1**	56	84	49	67	66
	Cyl. 2	76	81	53	45	64
	Cyl. 3	73	76	51	47	64
	Average	68	80	51	53	65
	Std. Dev.	11	4	2	12	1
	90% C.I.	10	4	2	12	1

*Mixture 40/40 too weak for demolding at day one. Test occurred on day 2.

Table G-3. 7 Day Strength Results for Maturity Study Slabs.

		Curing Temperature (°F)				
		70	**60**	**50**	**40**	**33**
Mixture		**Compressive Strength (psi)**				
0/0	**Cyl. 1**	5514	4143	5153	4855	4518
	Cyl. 2	5398	4791	5212	4643	3867
	Cyl. 3	5488	4612	5039	4734	5021
	Average	5467	4515	5135	4744	4469
	Std. Dev.	61	335	88	106	579
	90% C.I.	58	318	84	101	549
20/20	**Cyl. 1**	5221	5340	4108	3690	2374
	Cyl. 2	4967	4549	4125	3718	2567
	Cyl. 3	5118	5001	3874	3811	2420
	Average	5102	4963	4036	3740	2454
	Std. Dev.	128	397	140	63	101
	90% C.I.	121	377	133	60	96
40/20	**Cyl. 1**	4217	3582	2804	2391	793
	Cyl. 2	4379	3606	2843	2155	746
	Cyl. 3	4317	3863	2908	2276	779
	Average	4304	3684	2852	2274	773
	Std. Dev.	82	156	53	118	24
	90% C.I.	78	148	50	112	23
40/40	**Cyl. 1**	1286	1205	450	111	344
	Cyl. 2	1148	1052	426	158	299
	Cyl. 3	1139	1142	466	160	165
	Average	1191	1133	447	143	269
	Std. Dev.	82	77	20	28	93
	90% C.I.	78	73	19	26	88
20/40	**Cyl. 1**	3599	3489	2583	2317	1197
	Cyl. 2	3587	3366	2844	2098	1242
	Cyl. 3	3711	3439	2878	2375	1378
	Average	3632	3431	2768	2263	1272
	Std. Dev.	68	62	161	146	94
	90% C.I.	65	59	153	139	89
20/60	**Cyl. 1**	89	92	58	88	355
	Cyl. 2	92	102	58	87	437
	Cyl. 3	94	99	60	87	344
	Average	92	98	59	87	379
	Std. Dev.	3	5	1	1	51
	90% C.I.	2	5	1	1	48

Table G-4. 28 Day Strength Results for Maturity Study Slabs

		Curing Temperature (°F)				
		70	**60**	**50**	**40**	**33**
Mixture		**Compressive Strength (psi)**				
0/0	**Cyl. 1**	6599	5748	NA	5584	5555
	Cyl. 2	6330	5620	5960	6202	5173
	Cyl. 3	6303	5397	5878	6338	4760
	Average	6411	5588	5919	6041	5163
	Std. Dev.	164	178	58	402	398
	90% C.I.	155	169	55	382	378
20/20	**Cyl. 1**	7144	7074	6128	5535	3950
	Cyl. 2	7170	6330	5699	5183	3250
	Cyl. 3	7334	7687	6561	5494	3598
	Average	7216	7030	6129	5404	3599
	Std. Dev.	103	680	431	192	350
	90% C.I.	98	645	409	183	332
40/20	**Cyl. 1**	6446	6593	5282	5176	2355
	Cyl. 2	7069	6660	5388	4936	2502
	Cyl. 3	6876	6806	5661	5041	2651
	Average	6797	6686	5444	5051	2503
	Std. Dev.	319	109	196	120	148
	90% C.I.	303	103	186	114	141
40/40	**Cyl. 1**	3468	4476	2909	1562	684
	Cyl. 2	3662	4181	3058	1748	582
	Cyl. 3	3369	4473	3032	1495	481
	Average	3500	4377	3000	1602	582
	Std. Dev.	149	169	80	131	102
	90% C.I.	142	161	76	124	96
20/40	**Cyl. 1**	5802	5602	4148	5077	3543
	Cyl. 2	6063	5467	4464	4484	3599
	Cyl. 3	6365	5525	4448	4935	3061
	Average	6077	5531	4353	4832	3401
	Std. Dev.	282	68	178	310	296
	90% C.I.	268	64	169	294	281
20/60	**Cyl. 1**	2471	1045	1249	503	449
	Cyl. 2	2678	1232	1245	531	417
	Cyl. 3	2832	1066	1334	602	418
	Average	2660	1114	1276	545	428
	Std. Dev.	181	102	50	51	18
	90% C.I.	172	97	48	48	17

Appendix H

Cylinder and Slab Comparison

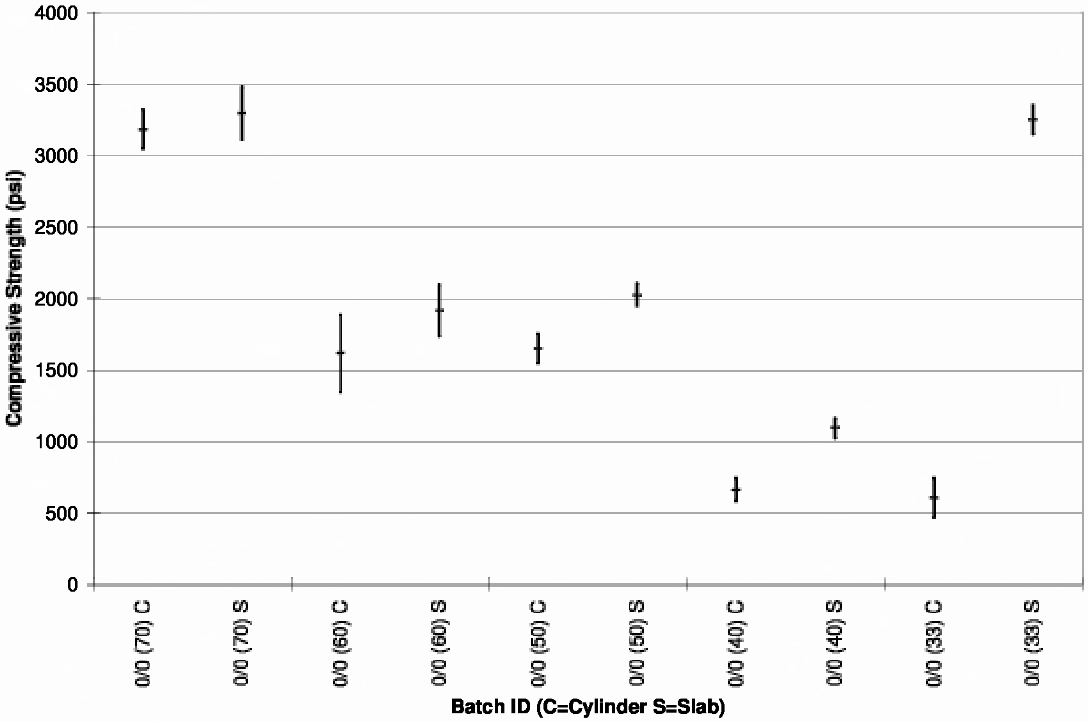

Figure H-1. Comparison of Cylinder and Slab 1 Day Compressive Strength 90% Confidence Intervals for Mixture 0/0 at All Curing Temperatures.

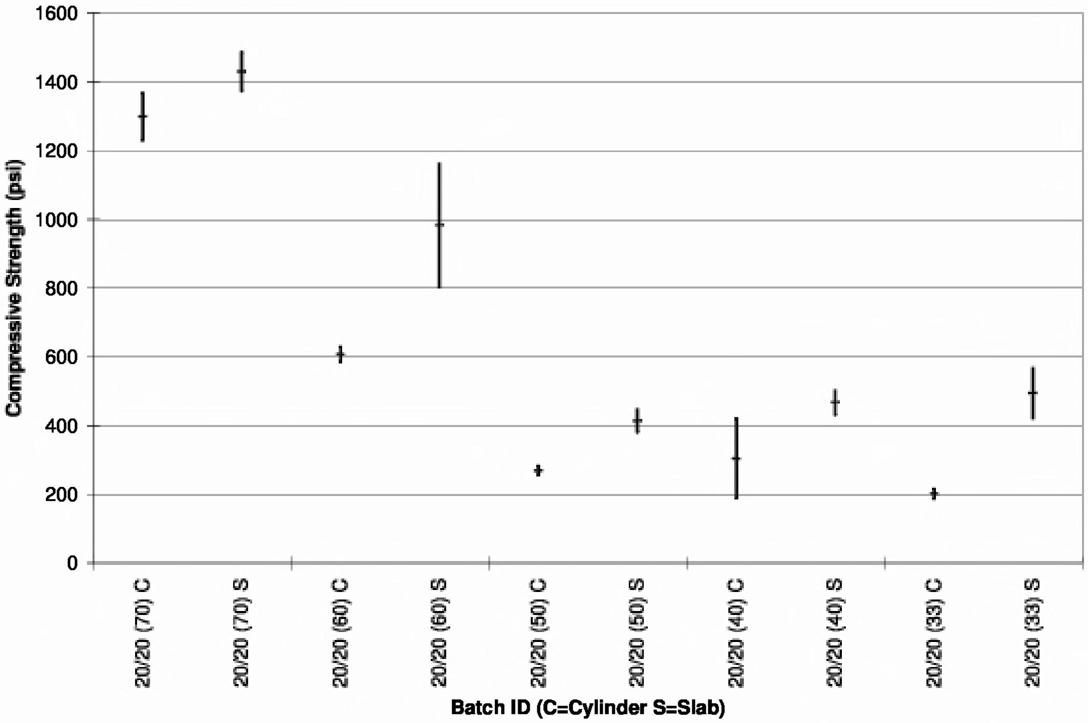

Figure H-2. Comparison of Cylinder and Slab 1 Day Compressive Strength 90% Confidence Intervals for Mixture 20/20 at All Curing Temperatures.

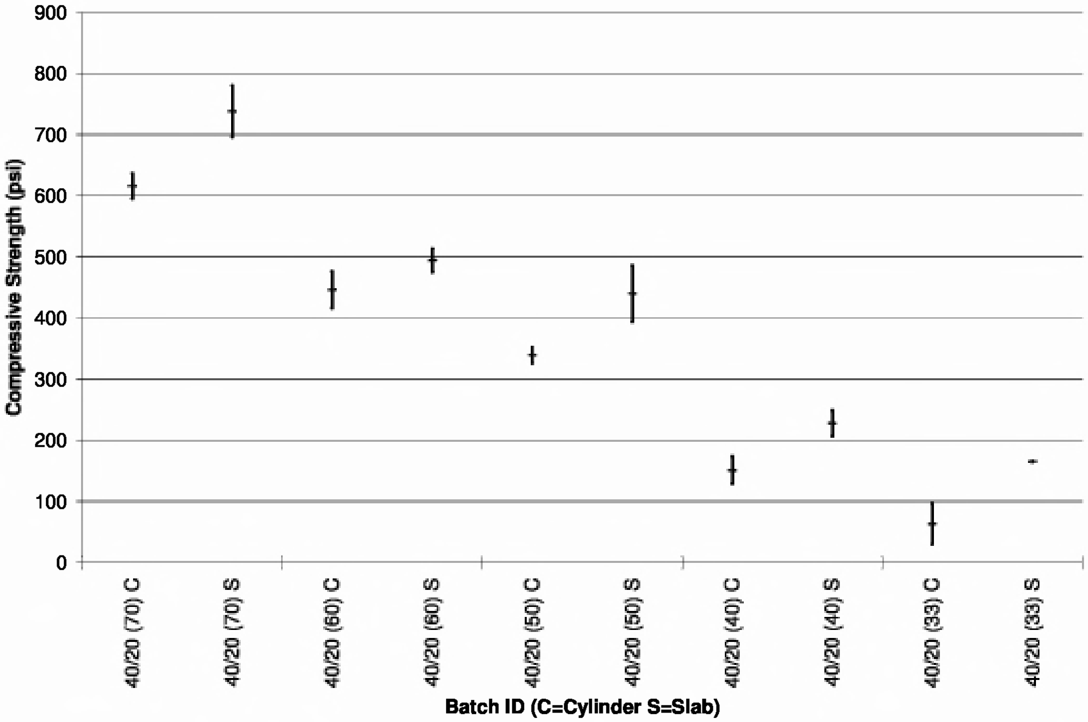

Figure H-3. Comparison of Cylinder and Slab 1 Day Compressive Strength 90% Confidence Intervals for Mixture 40/20 at All Curing Temperatures.

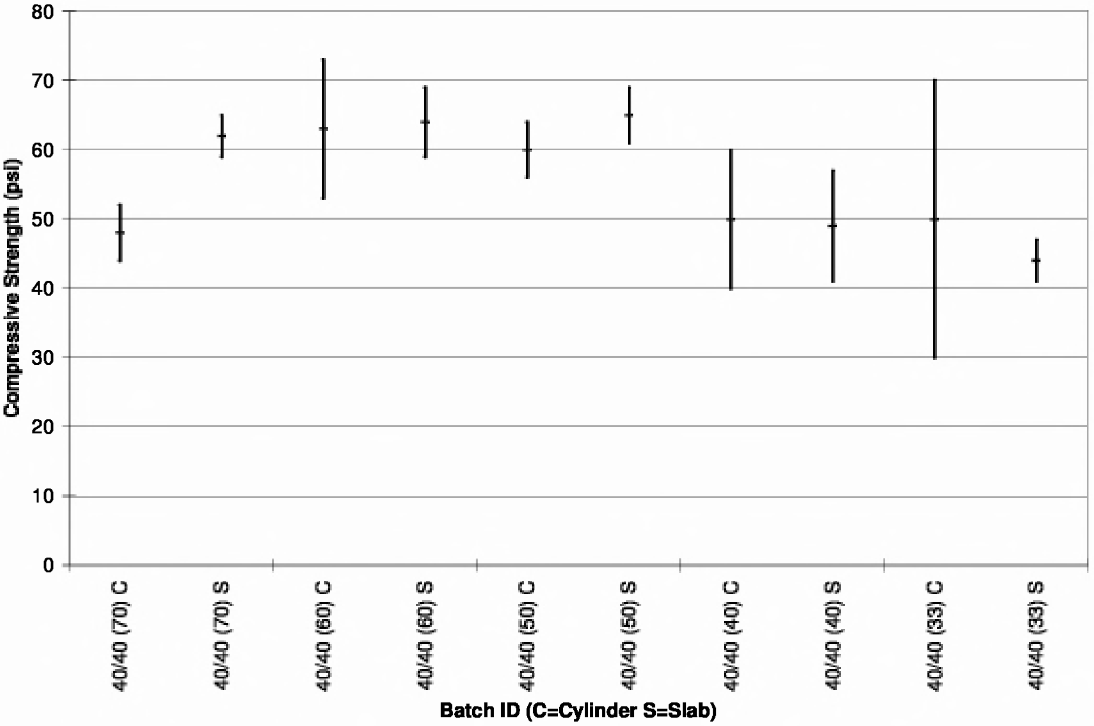

Figure H-4. Comparison of Cylinder and Slab 1 Day Compressive Strength 90% Confidence Intervals for Mixture 40/40 at All Curing Temperatures.

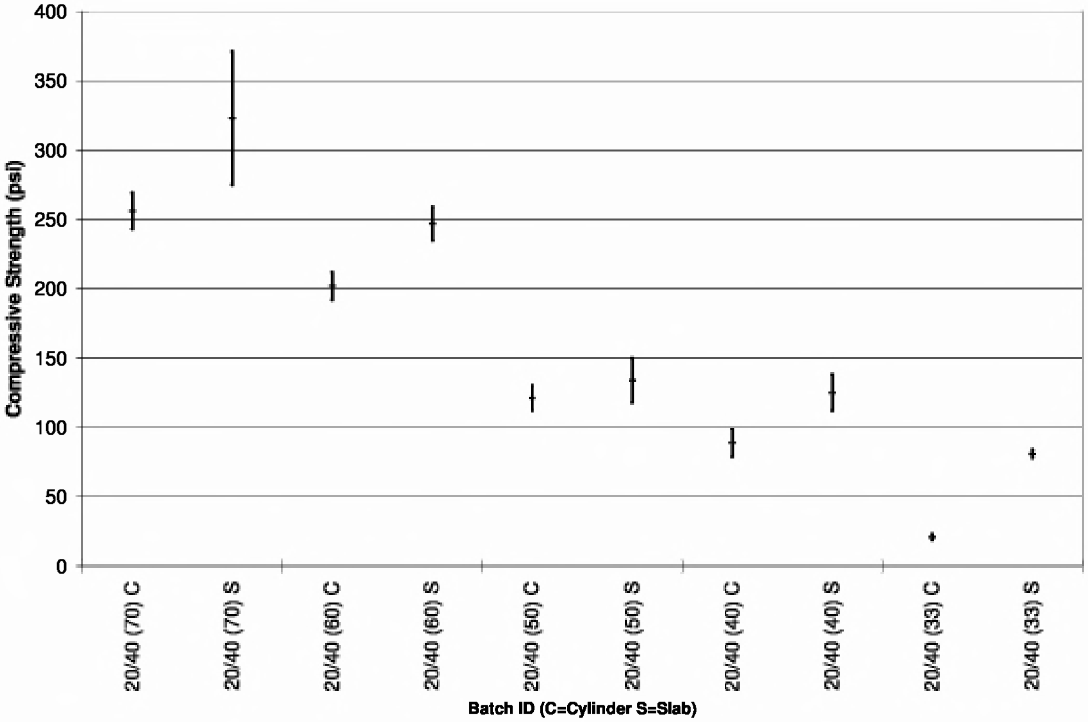

Figure H-5. Comparison of Cylinder and Slab 1 Day Compressive Strength 90% Confidence Intervals for Mixture 20/40 at All Curing Temperatures.

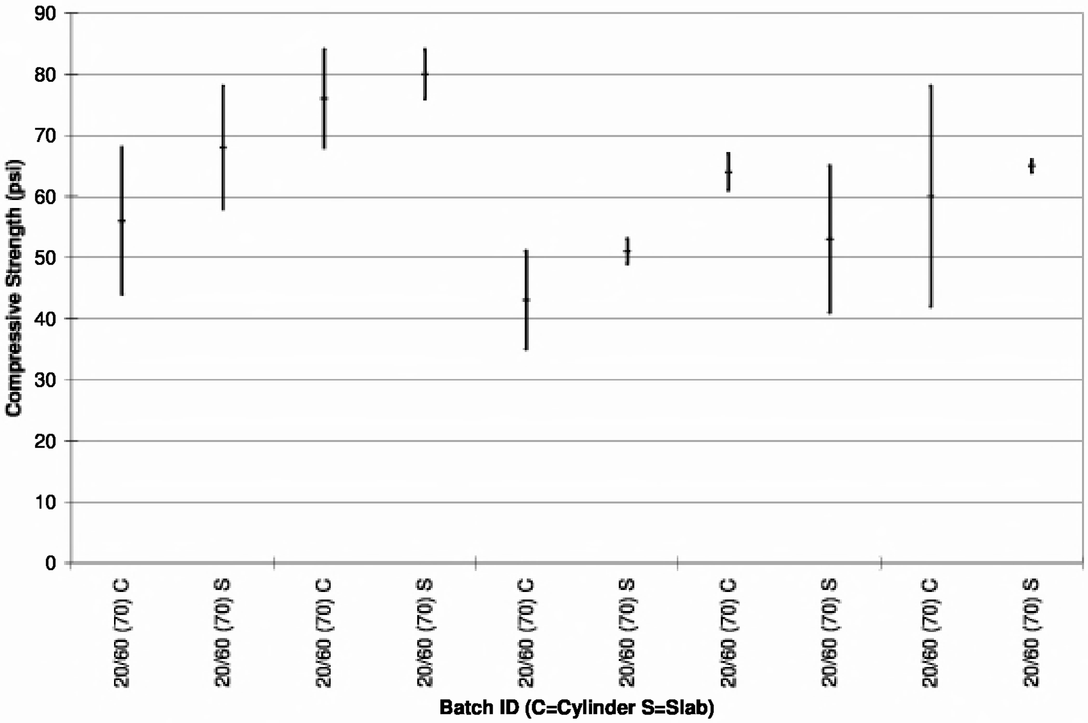

Figure H-6. Comparison of Cylinder and Slab 1 Day Compressive Strength 90% Confidence Intervals for Mixture 20/60 at All Curing Temperatures.

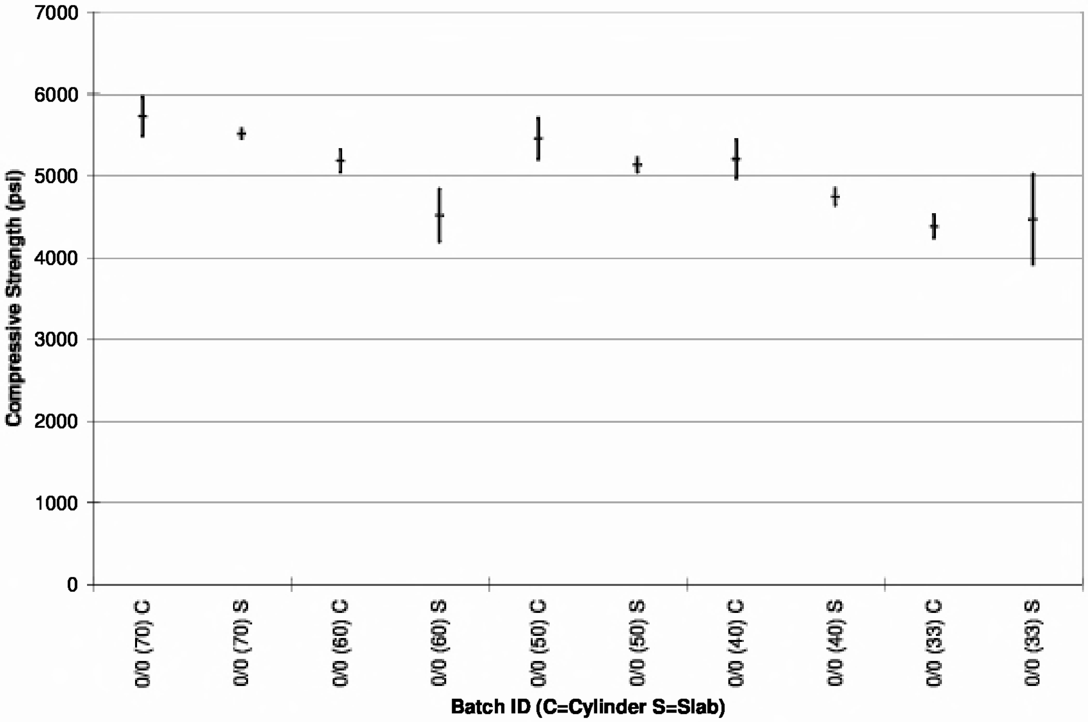

Figure H-7. Comparison of Cylinder and Slab 7 Day Compressive Strength 90% Confidence Intervals for Mixture 0/0 at All Curing Temperatures.

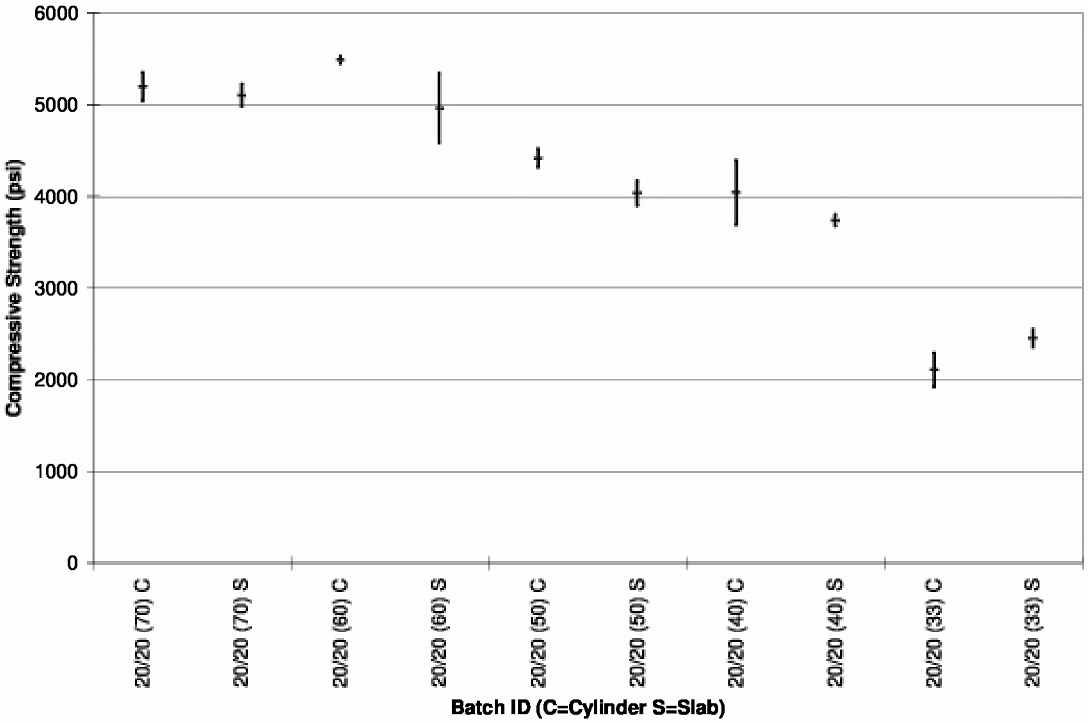

Figure H-8. Comparison of Cylinder and Slab 7 Day Compressive Strength 90% Confidence Intervals for Mixture 20/20 at All Curing Temperatures.

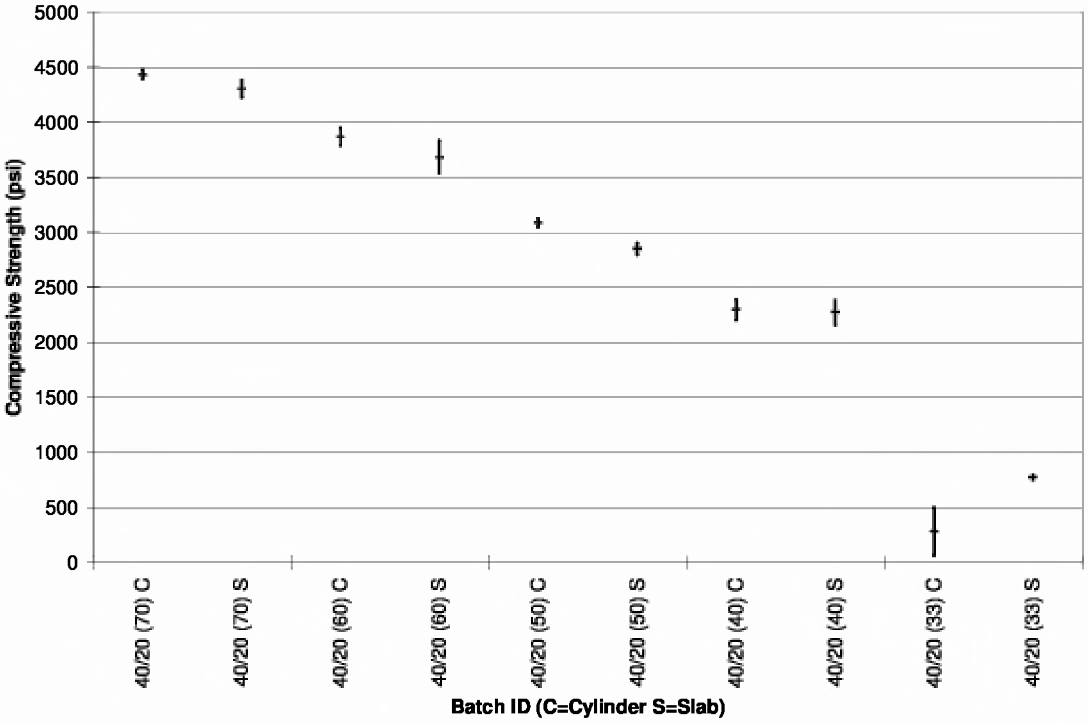

Figure H-9. Comparison of Cylinder and Slab 7 Day Compressive Strength 90% Confidence Intervals for Mixture 40/20 at All Curing Temperatures.

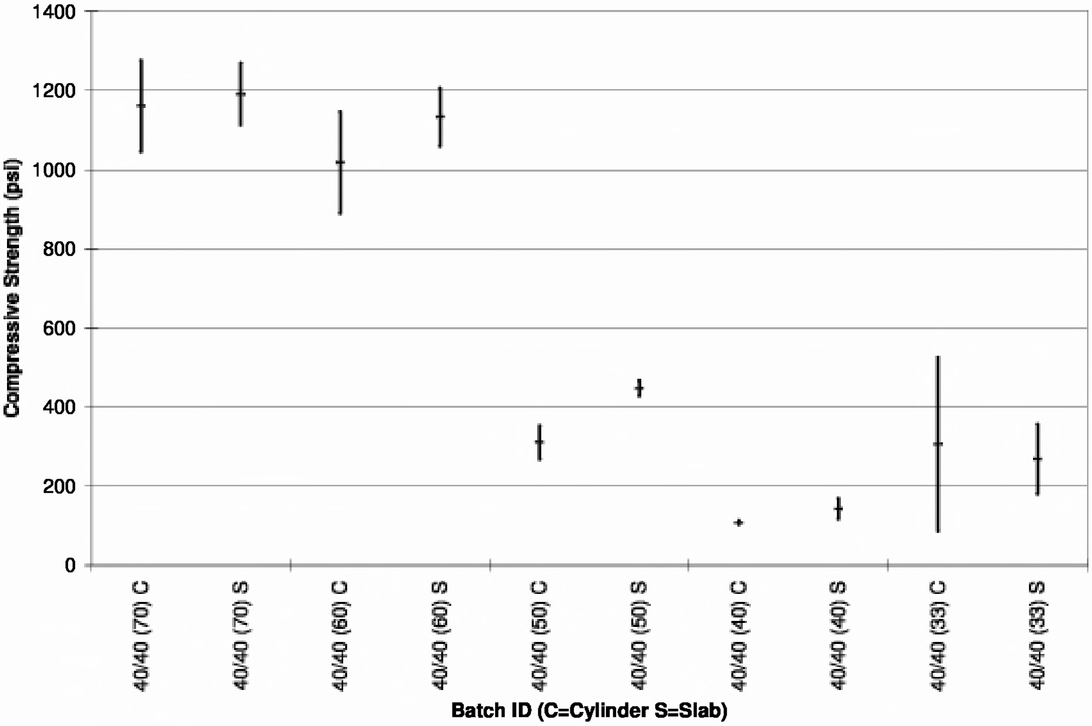

Figure H-10. Comparison of Cylinder and Slab 7 Day Compressive Strength 90% Confidence Intervals for Mixture 40/40 at All Curing Temperatures.

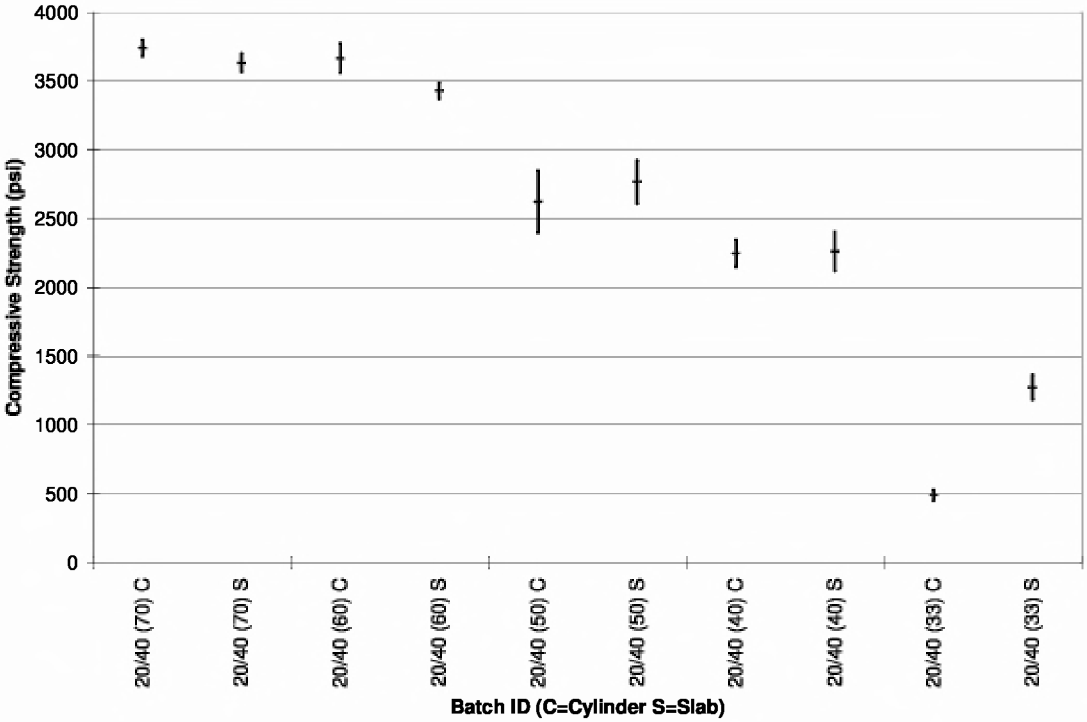

Figure H-11. Comparison of Cylinder and Slab 7 Day Compressive Strength 90% Confidence Intervals for Mixture 20/40 at All Curing Temperatures.

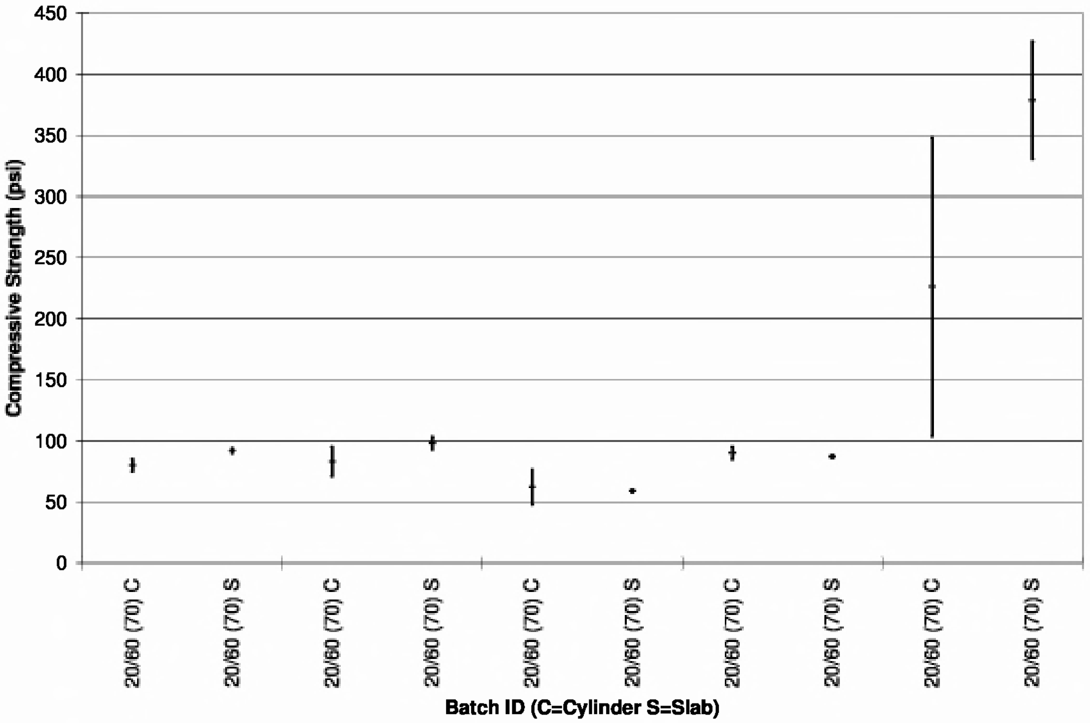

Figure H-12. Comparison of Cylinder and Slab 7 Day Compressive Strength 90% Confidence Intervals for Mixture 20/60 at All Curing Temperatures.

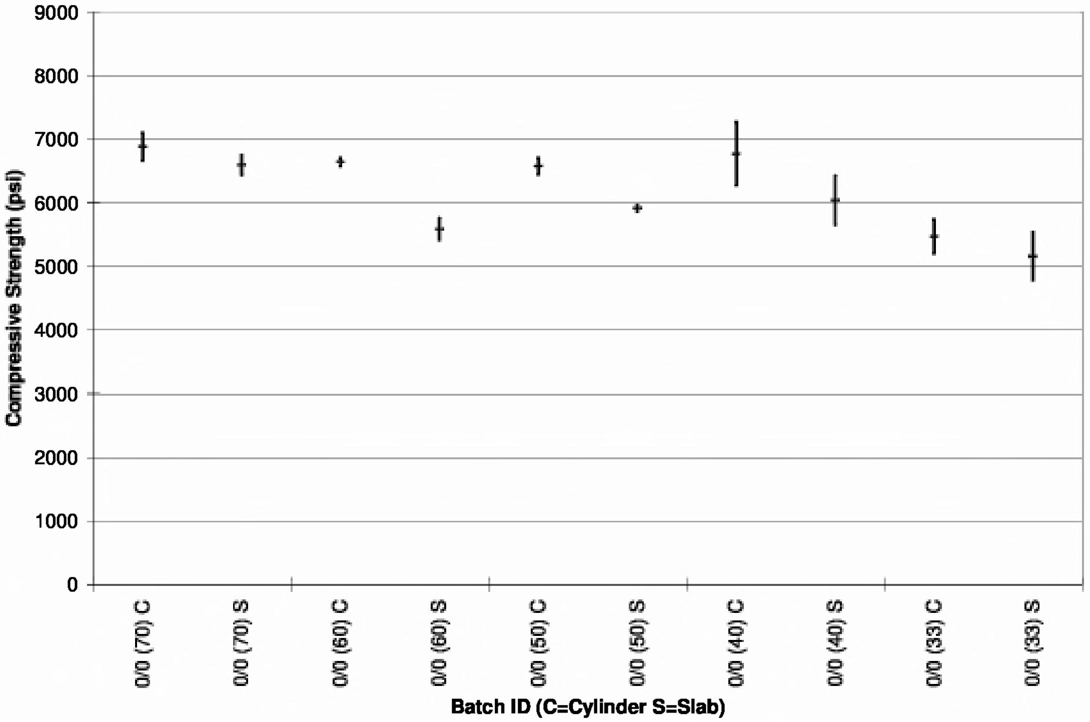

Figure H-13. Comparison of Cylinder and Slab 28 Day Compressive Strength 90% Confidence Intervals for Mixture 0/0 at All Curing Temperatures.

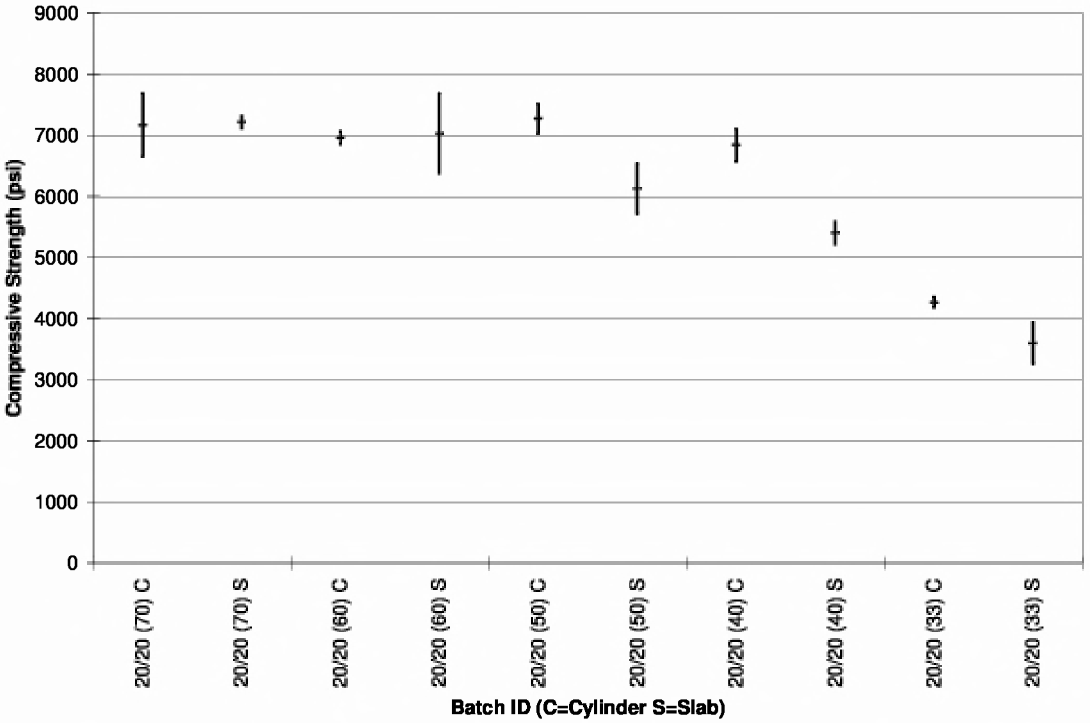

Figure H-14. Comparison of Cylinder and Slab 28 Day Compressive Strength 90% Confidence Intervals for Mixture 20/20 at All Curing Temperatures.

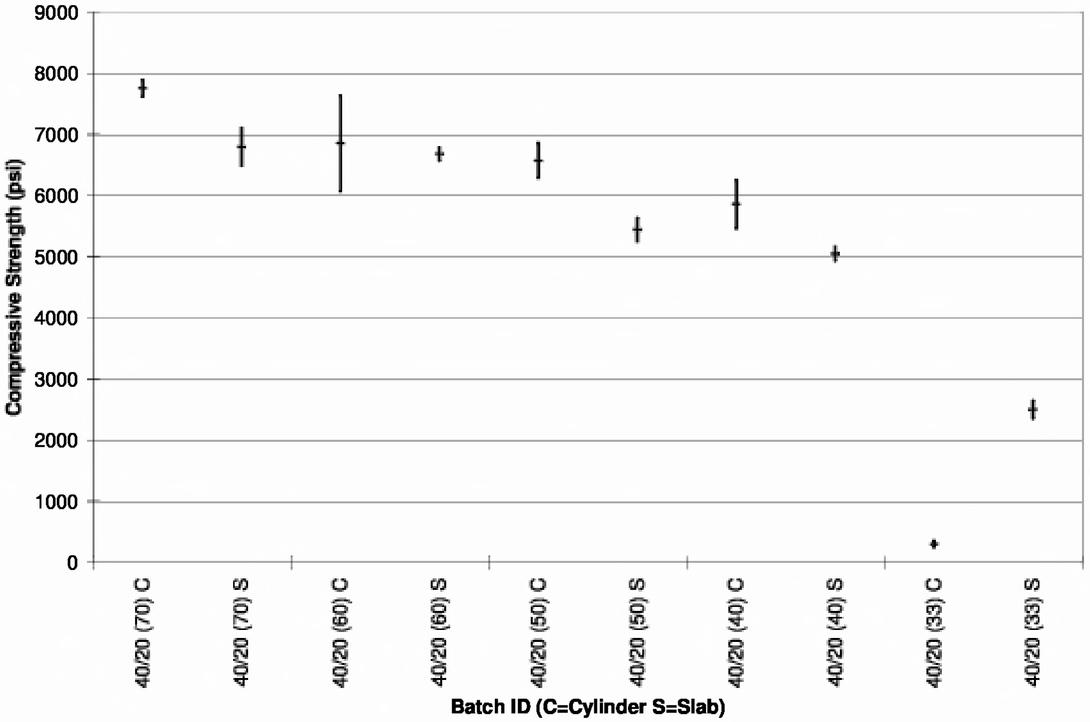

Figure H-15. Comparison of Cylinder and Slab 28 Day Compressive Strength 90% Confidence Intervals for Mixture 40/20 at All Curing Temperatures.

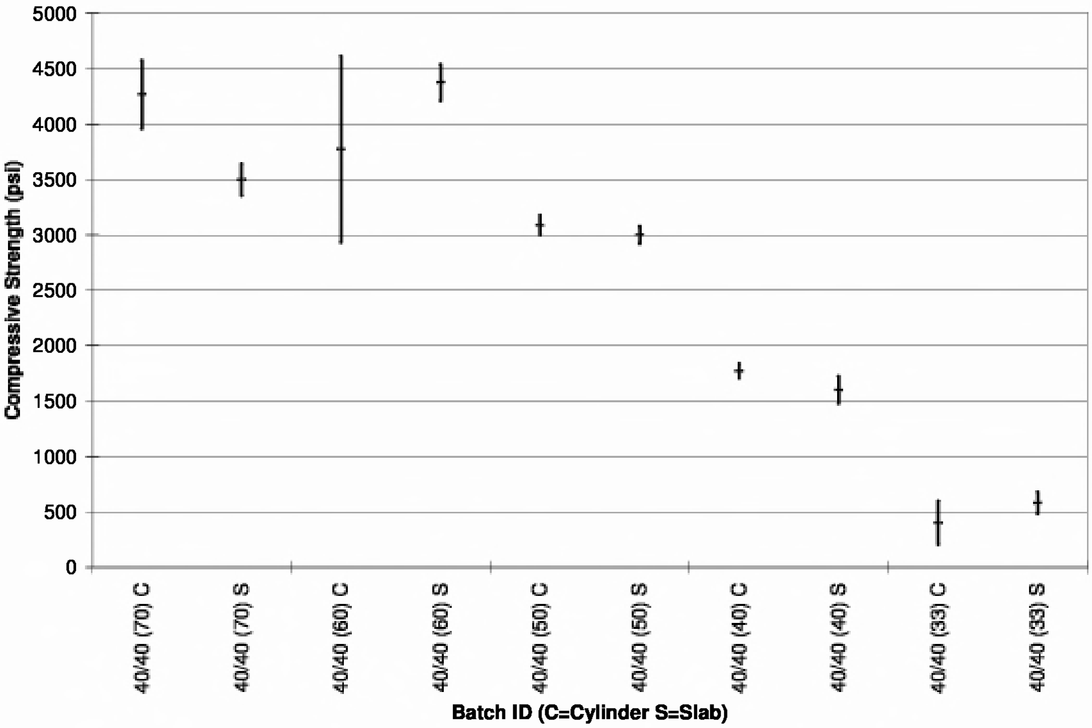

Figure H-16. Comparison of Cylinder and Slab 28 Day Compressive Strength 90% Confidence Intervals for Mixture 40/40 at All Curing Temperatures.

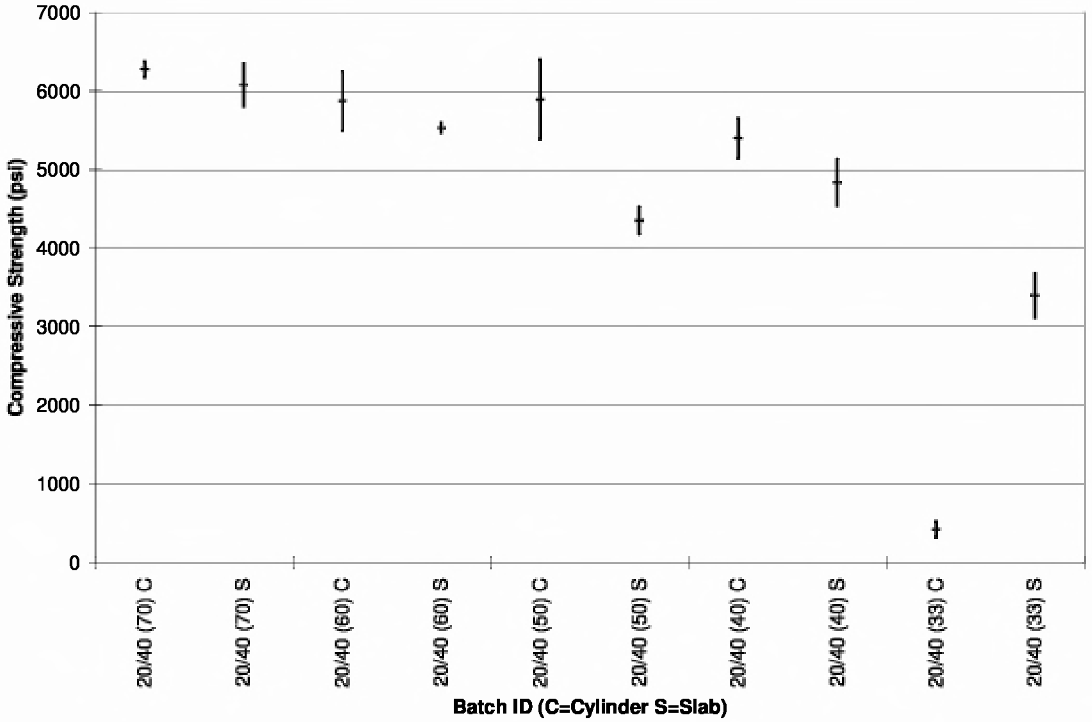

Figure H-17. Comparison of Cylinder and Slab 28 Day Compressive Strength 90% Confidence Intervals for Mixture 20/40 at All Curing Temperatures.

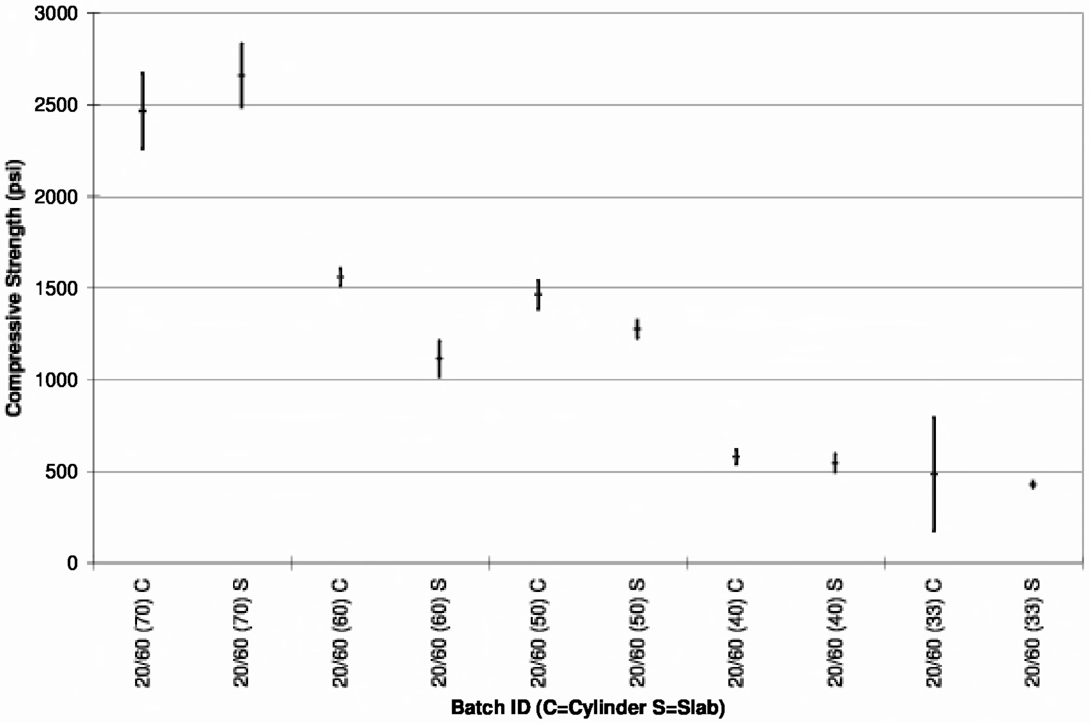

Figure H-18. Comparison of Cylinder and Slab 28 Day Compressive Strength 90% Confidence Intervals for Mixture 20/60 at All Curing Temperatures.

Appendix I

Maturity Index Results

Table I-1. Maturity Index Results for Mixture 0/0.

Curing Temp. (°F)	Maturity (°C-hrs)	Equivalent Age (days)	Average Compressive Strength (psi)
70	953	41.1	3294
	5683	188.0	5514
	20803	584.4	6599
60	761	21.8	1916
	4621	109.7	4515
	18032	404.7	5588
50	654	14.2	2025
	4038	81.0	5135
	14738	271.4	5919
40	546	10.1	1096
	3319	55.9	4744
	12540	202.4	6041
33	829	29.2	3252
	2138	51.6	4469
	4822	87.1	5163

Table I-2. Maturity Index Results for Mixture 20/20.

Curing Temp. (°F)	Maturity (°C-hrs)	Equivalent Age (days)	Average Compressive Strength (psi)
70	758	22.8	1430
	5387	161.3	5102
	20658	605.9	7216
60	614	17.2	983
	4789	137.0	4963
	18723	534.2	7030
50	524	14.5	413
	3757	103.8	4036
	14889	411.6	6129
40	577	16.3	467
	3079	86.6	3740
	11577	325.3	5404
33	569	16.2	494
	1825	61.9	2454
	4180	190.7	3599

Table I-3. Maturity Index Results for Mixture 40/20.			
Curing Temp. (°F)	**Maturity (°C-hrs)**	**Equivalent Age (days)**	**Average Compressive Strength (psi)**
70	773	23.1	738
	5500	165.4	4304
	21190	625.1	6797
60	688	19.3	494
	4907	138.0	3684
	18623	525.6	6686
50	669	18.8	440
	3768	100.5	2852
	15090	399.4	5444
40	529	14.3	228
	2897	76.3	2274
	12102	316.2	5051
33	497	13.5	165
	1562	51.5	773
	5073	180.3	2503

Table I-4. Maturity Index Results for Mixture 40/40.			
Curing Temp. (°F)	**Maturity (°C-hrs)**	**Equivalent Age (days)**	**Average Compressive Strength (psi)**
70	745	22.3	62
	5367	160.8	1191
	21156	633.5	3500
60	624	18.3	64
	4684	137.7	1133
	18908	555.9	4377
50	579	17.2	65
	3724	109.6	447
	15404	451.6	3000
40	872.8	27	49
	3234.4	97.6	143
	12793.4	384.7	1602
33	529	16.3	44
	1869	69.7	269
	4871	232.1	582

Table I-5. Maturity Index Results for Mixture 20/40.

Curing Temp (°F)	Maturity (°C-hrs)	Equivalent Age (days)	Average Compressive Strength (psi)
70	806	24.4	323
	5544	168.1	3632
	21694	661.4	6077
60	744	22.8	247
	5143	160.9	3431
	17967	583.0	5531
50	611	20.4	134
	4130	138.5	2768
	15959	543.2	4353
40	597.7	20.2	125
	3578.0	129.1	2263
	13424.1	496.7	4832
33	544	19.0	81
	1942	101.4	1272
	6156	376.7	3401

Table I-6. Maturity Index Results for Mixture 20/60.

Curing Temp (°F)	Maturity (°C-hrs)	Equivalent Age (days)	Average Compressive Strength (psi)
70	828	25.4	68
	5450	159.5	92
	21576	618.8	2660
60	671	17.0	80
	4367	98.0	98
	18066	421.8	1114
50	672	17.3	51
	3917	80.0	59
	14904	293.1	1276
40	537.8	12	53
	3103.3	55.8	87
	11814.4	202.8	545
33	507	11.3	65
	1619	30.3	379
	4649	86.4	428

Appendix J

Compressive Strength and Maturity Relationships

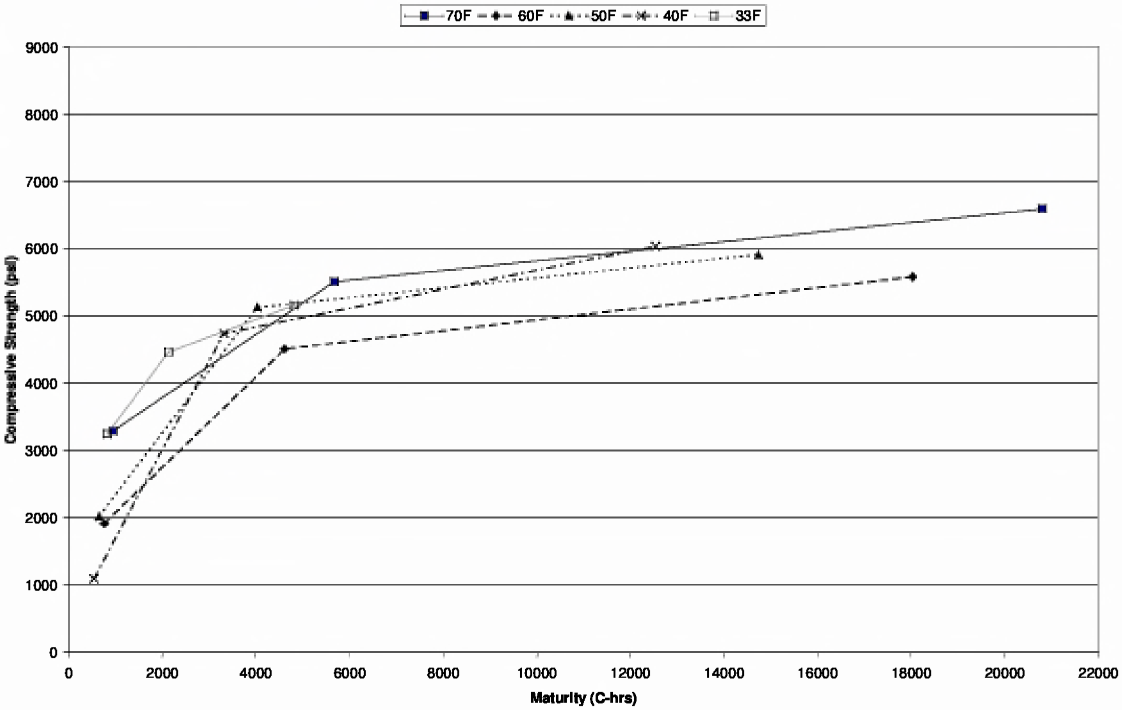

Figure J-1. Compressive Strength versus Maturity Index (Time-Temperature Function) for Mixture 0/0.

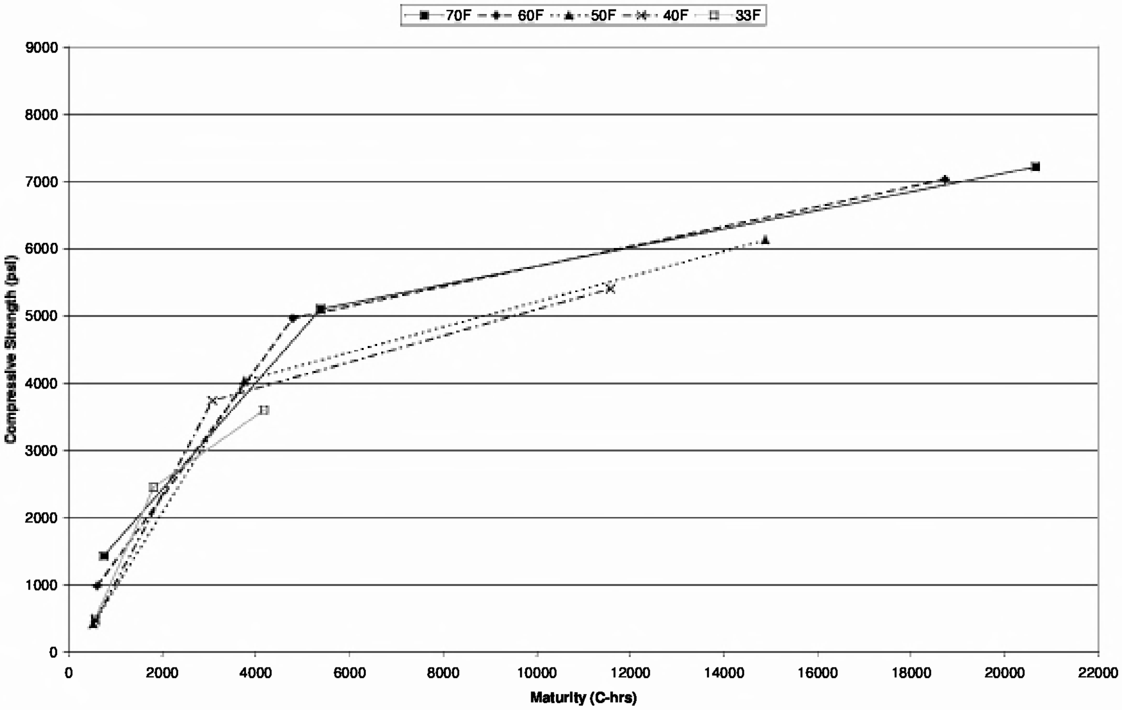

Figure J-2. Compressive Strength versus Maturity Index (Time-Temperature Function) for Mixture 20/20.

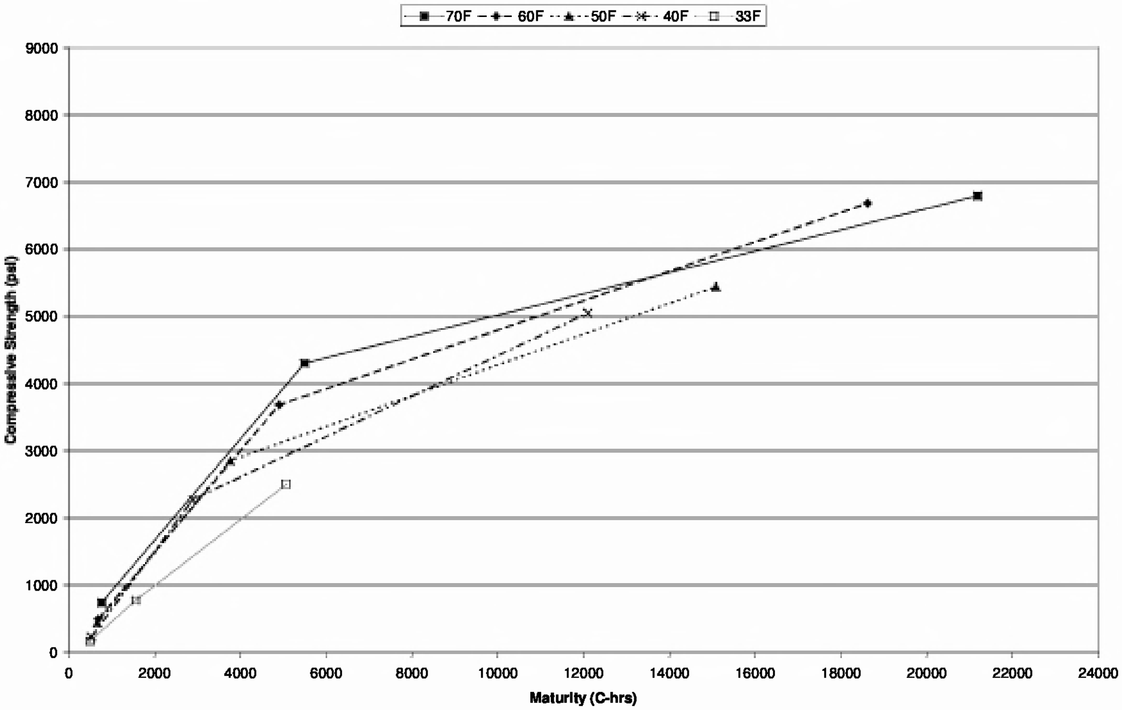

Figure J-3. Compressive Strength versus Maturity Index (Time-Temperature Function) for Mixture 40/20.

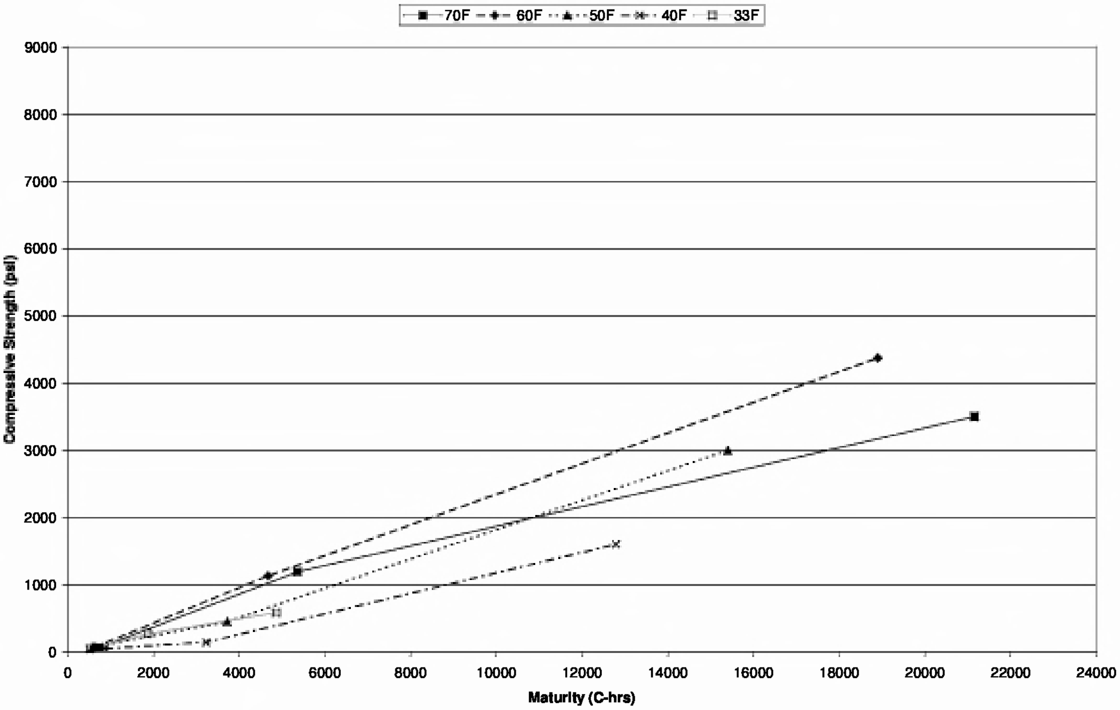

Figure J-4. Compressive Strength versus Maturity Index (Time-Temperature Function) for Mixture 40/40.

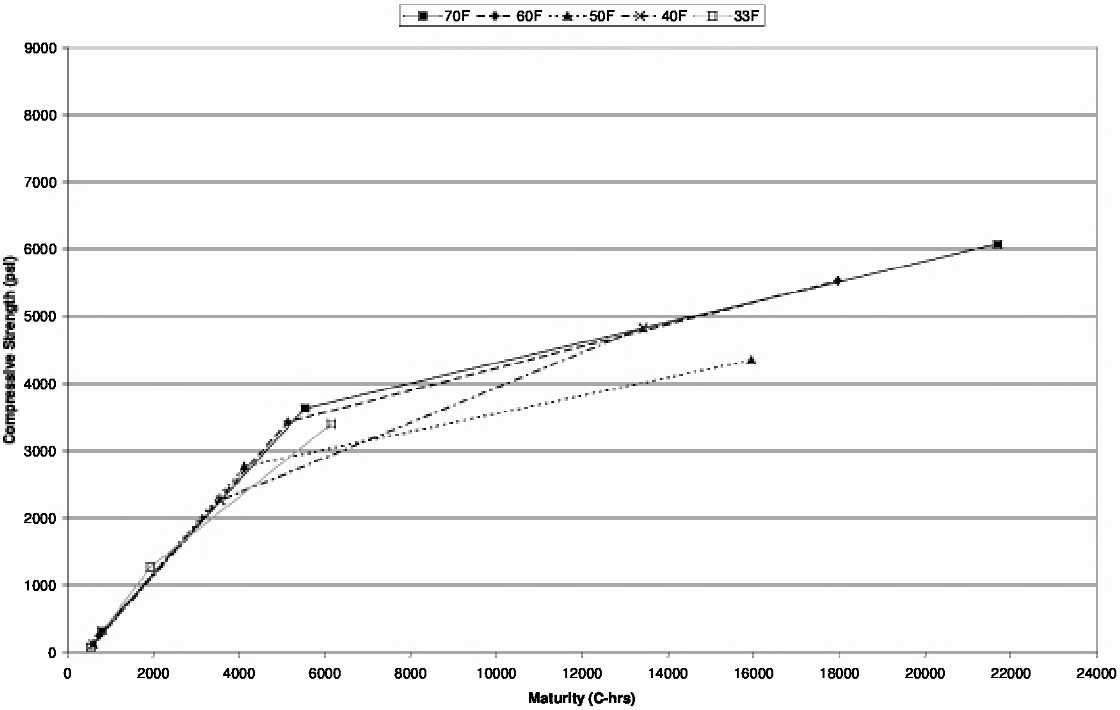

Figure J-5. Compressive Strength versus Maturity Index (Time-Temperature Function) for Mixture 20/40.

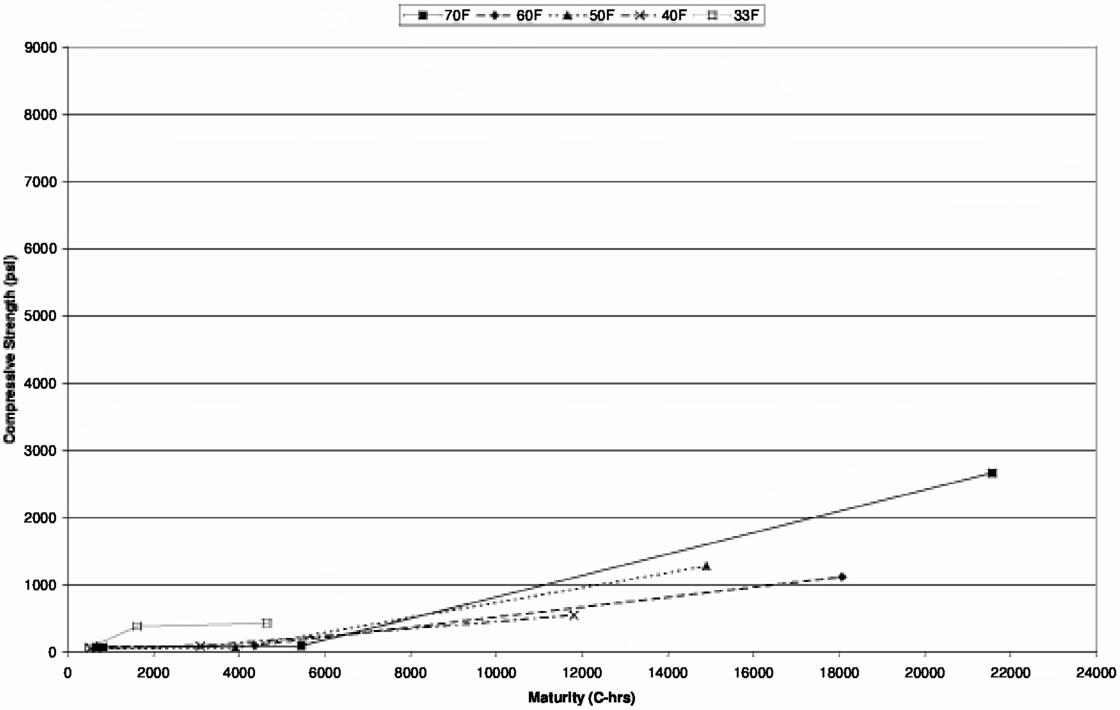

Figure J-6. Compressive Strength versus Maturity Index (Time-Temperature Function) for Mixture 20/60.

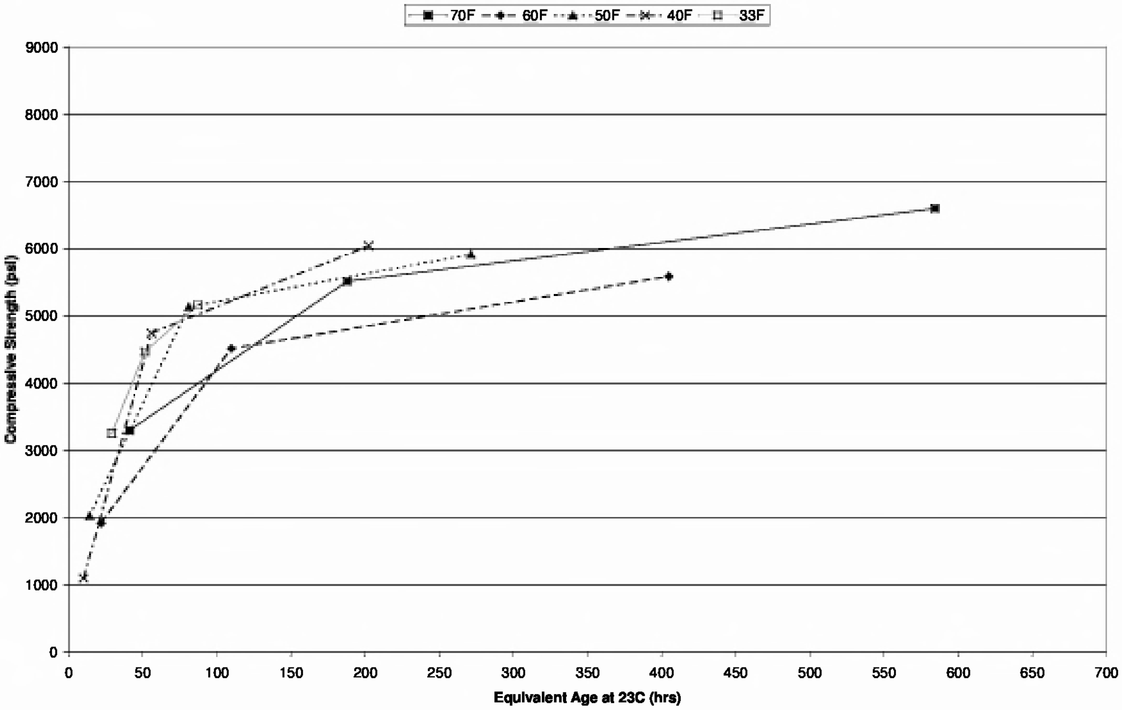

Figure J-7. Compressive Strength versus Equivalent Age at 23°C for Mixture 0/0.

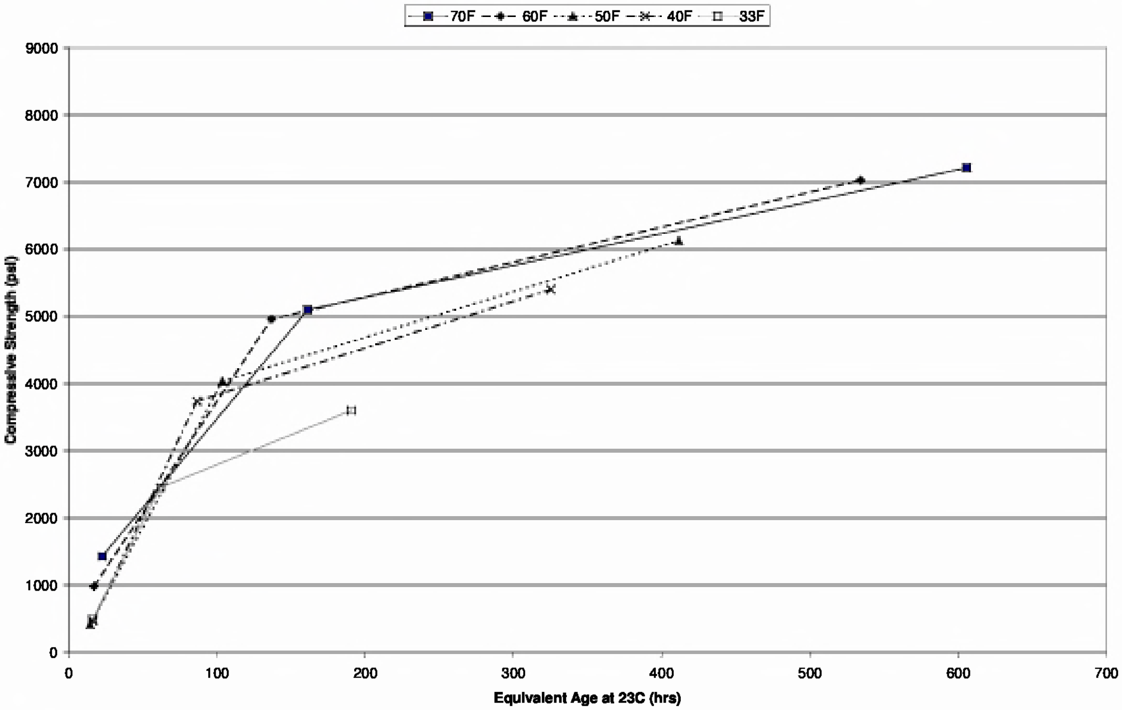

Figure J-8. Compressive Strength versus Equivalent Age at 23°C for Mixture 20/20.

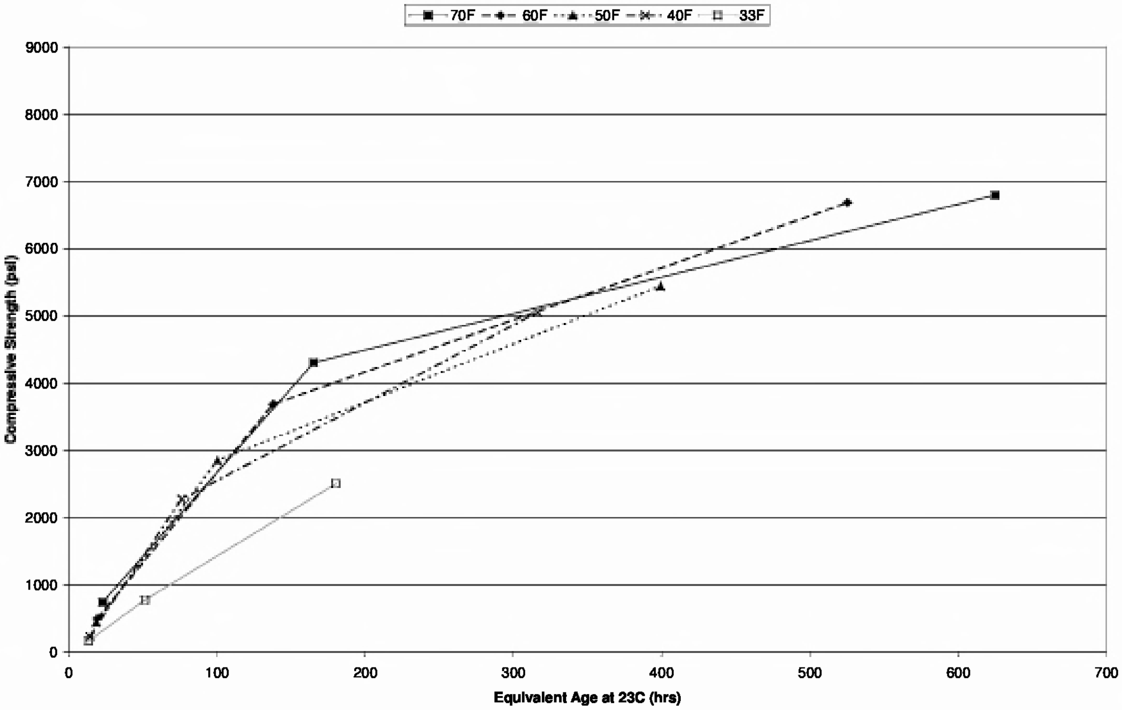

Figure J-9. Compressive Strength versus Equivalent Age at 23°C for Mixture 40/20.

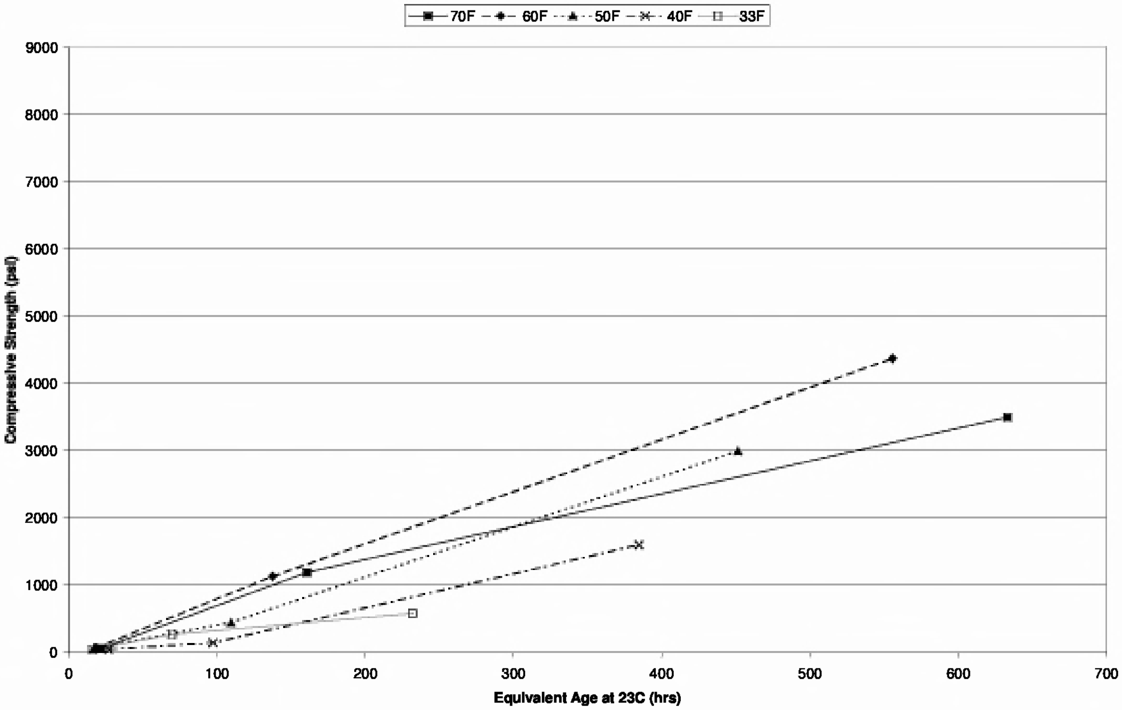

Figure J-10. Compressive Strength versus Equivalent Age at 23°C for Mixture 40/40.

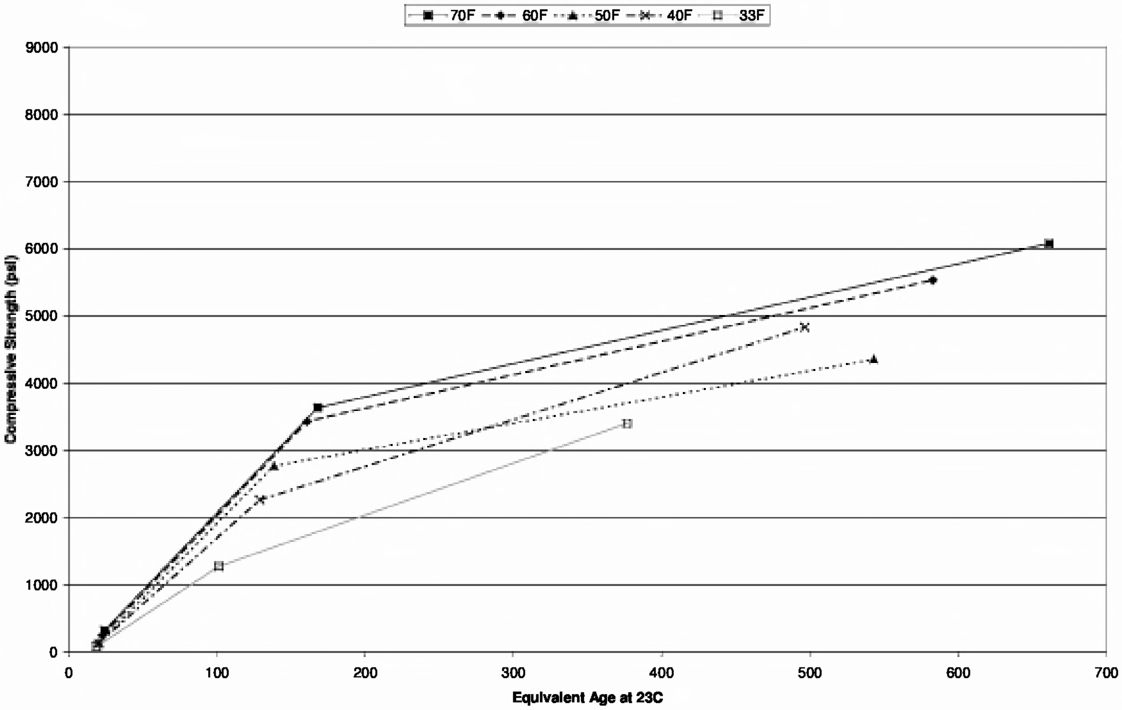

Figure J-11. Compressive Strength versus Equivalent Age at 23°C for Mixture 20/40.

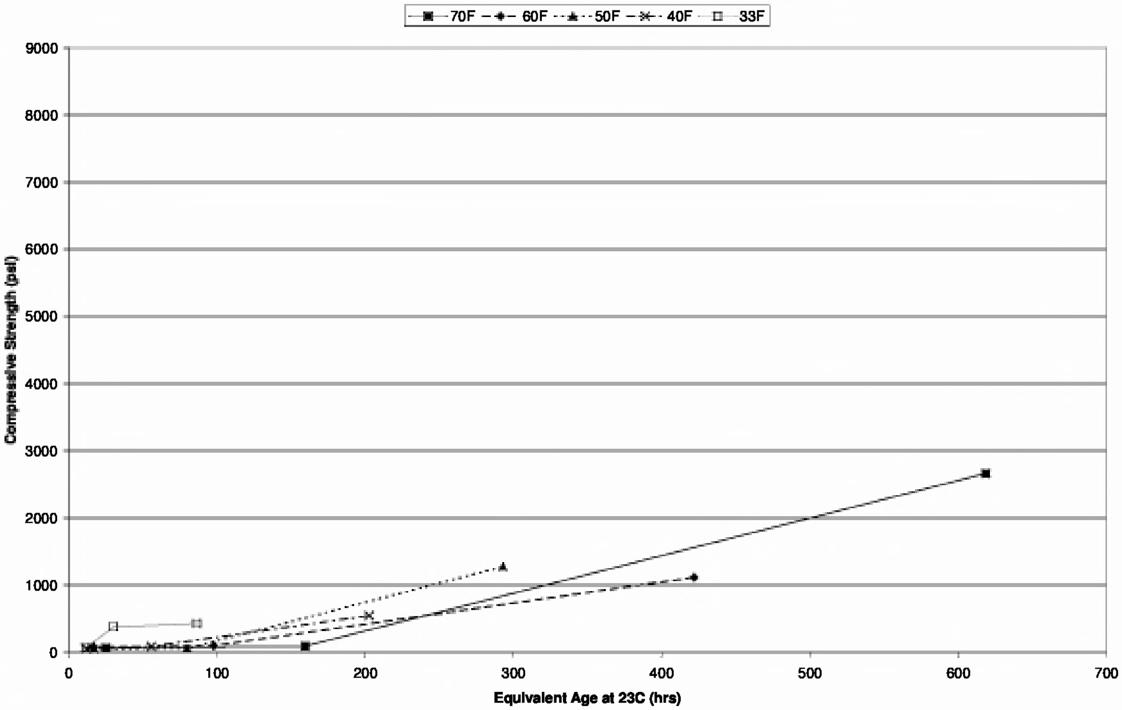

Figure J-12. Compressive Strength versus Equivalent Age at 23°C for Mixture