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16. Abstract

The substitution of a portion of cement in concrete with supplementary cementing materials (SCM) frequently results in delayed setting and low early strength. When SCM-containing concrete is placed during cold weather and/or contains certain chemical admixtures, these problems can intensify and can seriously impact the performance of a pavement. This project investigated the setting time, early strength gain, maturity, bleeding, and plastic shrinkage cracking of several concrete pavement mixtures containing SCM under different temperature conditions (mimicking summer, spring, and winter weather). The data were used to develop guidelines for identifying slow-setting mixtures and preventing their use in pavements.

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Effects of Supplementary Cementing Materials on the Setting Time and Early Strength of Concrete

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Andre Edson

CTR Technical Report:	0-5550-1
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Abbreviations Used

ACI	American Concrete Institute
ASTM	American Society of Testing and Materials
FA	fly ash
FHP	Freiesleben-Hansen and Pederson
GGBFS	ground granulated blast furnace slag
OIF	omega index factor
OPC	ordinary portland cement
pcf	pounds per cubic foot
psi	pounds per square inch
SCM	supplementary cementing material
TS	time of set
TTF	temperature-time factor
w/c	water to cement ratio
w/cm	water to cementitious material ratio

Chapter 1. Introduction

The use of supplementary cementing materials (SCMs) in concrete is increasing internationally and in Texas. These materials, which include ground granulated blast furnace slag (GGBFS), fly ash, and silica fume, enhance the durability of concrete, providing protection against cracking due to alkali silica reaction, delayed ettringite formation, sulfate attack, thermal gradients, and more. Furthermore, they can be more economical than cement and may be more readily available in times of cement production shortages.

While they have many advantages, SCMs can also have negative effects on concrete properties and performance. One of the more notable disadvantages is that significant replacement of cement by fly ash or slag is known to increase setting time and decrease early strength gain. When the ambient temperature is low, these effects are exacerbated. This can be problematic on the job-site in terms of planning finishing operations and delaying opening to traffic, but can have much more far-reaching and long-term effects on the concrete as well. Delayed setting and low early strengths may result in subsidence, plastic shrinkage, and thermal stresses. These may cause unintentional cracking and subsequent pavement distress, examples of which are shown in Figure 1.1 for a concrete pavement containing 50% slag.

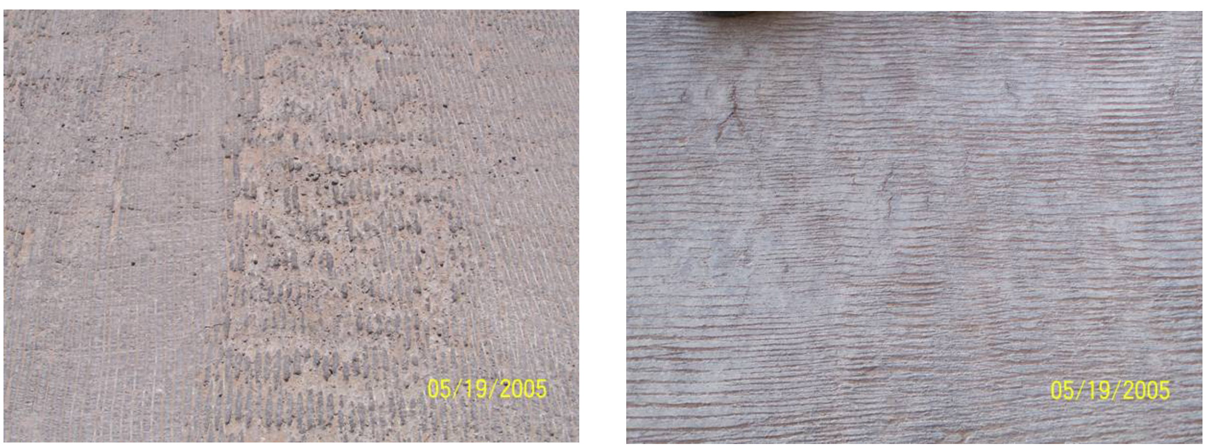

Figure 1.1: Concrete pavements with 50% slag exhibiting longitudinal cracking (M. Won)

In order to avoid problems such as those shown in Figure 1.1, it is important to understand the influence that fly ash and slag have on setting time and early strength gain, and to understand the role that temperature and chemical admixtures play in this process. Specifically, it would be useful to be able to predict the relative setting time of a concrete pavement based on its composition (cement type, SCM content and type, and chemical admixtures) and temperature. This can be done through testing and analysis of several concrete mixtures cured under realistic temperature regimes. Results could provide guidelines for concrete mixtures containing SCMs that would help avoid problems caused by delayed setting and low early strength gain.

A comprehensive prediction model for concrete setting time is outside of the scope of this project. Instead, the study focused on setting times and early strength development of concrete mixtures and temperatures for El Paso, Texas. The purpose of this project was to develop guidelines regarding the appropriate usage of SCMs in a variety of weather conditions for the El

Paso district. This report provides a detailed account of the research and testing conducted, along with recommendations regarding the use of SCMs in pavements. In order to provide a context for the testing, a review of previous research findings follows.

Chapter 2. Literature Review

2.1 Maturity

The "maturity method" is a widespread technique in the construction industry used to determine, in part, the appropriate time to remove formwork, reposition shoring, and open roads to traffic. The American Society for Testing and Materials [ASTM C 1074 (2004)] "Standard Practice for Estimating Concrete Strength by the Maturity Method," defines the maturity method as "a technique for estimating concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of the maturity index." In other words, if the strength and curing temperature of a particular mix are known, the strength of that same mix can be estimated when the mix is cured at a different temperature.

Two functions to obtain the maturity index of a concrete mixture are specified by ASTM: the *temperature-time factor* (TTF) and the *equivalent age*. The TTF is the most commonly used method and the only one that is discussed in this report.

2.1.1 Temperature-Time Factor

The TTF maturity function, also known as the Nurse-Saul function, is based on the assumption that a linear relationship exists between the time and temperature of a maturity index. Equation 1 is the TTF maturity function (ASTM C 1074 2004).

$$M(t) = \sum (T_c - T_0)\Delta t \qquad \textbf{\textit{Equation 1}}$$

where, $M(t)$ = the temperature-time factor at age t (degree-days or degree-hours),
Δt = a time interval (days or hours)
T_c = average concrete temperature during time interval Δt (°C), and
T_o = datum temperature (°C).

Although the TTF function is widely used and generally accurate, researchers have reported it to be unreliable in certain situations. For example, Suh (2000) found that it predicted early-age strength accurately but overestimated strength at later ages. Furthermore, Byfors found that the TTF function is poor at estimating maturity at low temperatures (Naik 1985).

2.2 Setting Times

Slag and fly ash affect concrete setting and strength in different ways because of their distinct physical and chemical characteristics. Likewise, slags from different sources will have varying effects as will fly ashes from different sources. ASTM C 618 (2005) class C and class F fly ashes will behave differently because of their compositions, and variations in composition and properties within the classes will also affect properties. These variations make generalizations difficult and prediction of behavior tricky. This section briefly reviews results reported in the literature on the effects of slag and fly ash on setting and early strength, including the interactions with temperature and admixtures. Additionally, attempts to predict setting time in SCM-containing concrete are summarized.

2.2.1 Slag

The influence of GGBFS on concrete setting time is dependent on curing temperature, cement replacement level, and slag composition. It is generally reported that replacement of cement with GGBFS increases setting time, particularly when replacement levels exceed 40% (Brooks et al. 2000). An ACI Committee 233 (2004) report states that delays in setting time can be expected when more than 25% slag cement is used as a replacement for portland cement in concrete mixtures. It also states that significant retardation has been observed at low temperatures. There are discrepancies in the literature regarding the "temperature threshold" above which slag does not delay setting. For example, Hooton (2000) reported that at temperatures greater than 20°C (68°F), slag did not extend setting time by more than a few minutes, if at all. Eren et al. (1995) reported that slag replacement (30 and 50%) actually decreased setting times at temperatures greater than 20°C (68°F). Alshamsi (2001) tested slag replacements of 30, 50, and 70% and at 25, 35 and 50°C and found no setting delays due to slag above 35°C (95°F). On the other hand, Yoshida et al. (1986) reported that up to 50% slag replacement caused delayed setting at all curing temperatures up to 80°C (176°F). These discrepancies in results are likely due to differing compositions of the slag or testing conditions. The contradictory nature of these results makes setting a temperature threshold value based on literature data impossible.

Increases in setting times are correlated with an increase in bleeding (Kanazawa et al. 1992). Slag replacement is generally observed to decrease early strength, often not "catching up" with control mixes until 90 days (Mailvaganam et al. 1983). Again, this effect is highly dependent on the curing temperature.

Chloride and non-chloride based accelerators were shown to have little effect on setting time when 30% of cement was replaced by slag (Mailvaganam et al. 1983). Excessive use of superplasticizer has been seen to increase setting times significantly in slag-containing concrete (Sivasundaran and Malhotra 1993; Alshamsi 2001). However, early strength may still be greater due to the w/cm reduction (Wang et al. 2007). Therefore, a proper balance is required to prevent the retarding effects of certain water reducers from surpassing the benefits of a reduced w/cm.

2.2.2 Fly Ash

It is generally agreed that class F fly ashes delay setting and reduce early strength of concrete significantly, the effect increasing with replacement amount. Class C fly ashes have mixed effects on setting and early strength gain. Often these have been shown to delay setting, as much as 4-6 hours at high replacement levels (Majko and Pistilli 1984). However, some class C ashes have been shown to reduce setting times (Dodson 1981; Naik and Singh 1997) or have no effect (Naik and Ramme 1987). Some class C ashes participate in cementitious reactions in addition to pozzolanic reactions, altering their setting behavior. It has been suggested that this may also disrupt the optimal gypsum content of the cement, causing accelerated and sometimes even flash setting (Naik and Singh 1997). The differences in behavior in class C ashes are related to composition, amount of glassy phase, and the reactivity of the glassy phase. Carette et al. (1993) investigated the behavior of several class C ashes with different compositions in concrete and could not arrive at a single characteristic that dominated setting. Early strength gain in concrete with class C ashes has been seen to be greater than with F ashes and bleeding less (Gebler and Klieger 1986).

Increasing temperature shortens setting time of fly ash concrete and increases early strength gain (Eren et al. 1995). However, unlike research performed with slag concretes, researchers have not attempted to isolate a temperature threshold above which fly ash does not retard setting. This is possibly due to the wider variety of behaviors of fly ashes compared to slag.

As with slag, chloride and non-chloride accelerators did not appear to affect setting times in fly ash containing concrete (Mailvaganam et al. 1983). Also similar to slag, the presence of some water reducers or superplasticizers can delay setting of concrete containing fly ash even further (Majko and Pistilli 1984; Brooks et al. 2000). A problem unique to fly ash, however, is that a combination of fly ash, cement, and chemical admixtures can produce a concrete mix that has extraordinarily delayed setting—sometimes taking days to set rather than hours. Wang and others (2006) found that a combination of class C fly ash and regular dosages of water-reducing and retarding admixtures can greatly delay the hydration of portland cement. This happens because the combination can increase the level of sulfates needed in the system for proper hydration of the calcium silicate and calcium aluminate phases (Roberts and Taylor 2007). Local Texas concrete producers have complained of concrete mixtures taking up to 3 days to set (Johnson 2005). This problem is being investigated in the Construction Materials Research Group at The University of Texas at Austin (UT Austin) currently, but the work has not yet been published (Poole 2006). Figure 2.1 shows plots from semi-adiabatic calorimetry, which examines the heat generated by a concrete cylinder under controlled heat-loss conditions. One mix had delayed heat generation, and thus delayed setting. This mix contained Daracem 19 and Daratard 17 chemical admixtures, 7.5% ultrafine fly ash, and 30% Oklaunion fly ash. The normal setting mixture contained Daracem 19, 8% silica fume, and 30% Oklaunion ash. These results demonstrate that slow setting concrete mix designs can thus be adjusted to mitigate extended setting times by using different chemical admixtures, more cement, less SCM, or a different cement type.

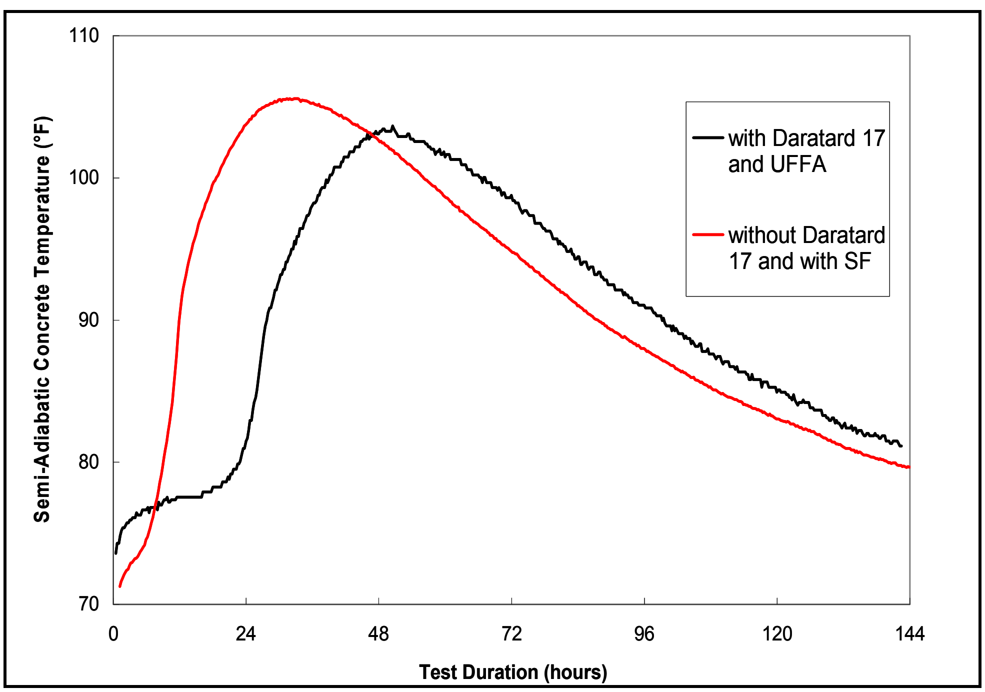

Figure 2.1: Semi-adiabatic calorimetry curves for concrete mixtures containing 30% Oklaunion fly ash. (J. Poole, unpublished data)

2.2.3 Prediction

While many research studies have simply tested the effects of fly ash and slag on concrete properties, a few have gone further and tried to either optimize mixture proportions or predict behavior based on mixture components and curing conditions. A study by Majko and Pistilli (1984) attempted to optimize the amount of class C fly ash in concrete with respect to 28-day strength. After extensive testing of several series of concrete mixtures, they arrived at a set of optimal fly ash replacement levels that depended on the cement content, the fly ash source, whether or not water-reducers were used, and more. The problem with this approach is that it requires extensive testing of several mixes each time a parameter is changed. For example, one could say that a 40% replacement is ideal when using fly ash X at a given cement content, cement type, and curing temperature. However all of the testing would have to be repeated if one wanted to use a different cement or chemical admixture supplier or place the concrete in a different season. This is inefficient and costly.

A few researchers have attempted to predict the behavior of SCM-containing concrete based on the composition of the SCM and other fundamental parameters. While this approach involves compiling an extensive database of information initially, successful application would eliminate future testing when conditions change. Dodson (1981) was one of the first to attempt to model the setting time of concrete. He found that, for portland cement concrete, setting time decreased with the ratio of cement content to w/c, a ratio he called the omega index factor (OIF). When low calcium fly ash was used, the setting time was still related to the OIF because the cement was simply diluted by the fly ash. With high calcium fly ashes that reacted cementitiously in addition to pozzolanically, the setting times deviated from the line defined by the OIF. Dodson did not attempt to quantify deviations from the OIF. A problem with this method is that the OIF does not take into account the effects of cement type, chemical admixtures, or temperature—variables that are known to affect setting time.

Brooks and his collaborators (Eren et al. 1995; Brooks et al. 2000; Brooks 2002) have been working on modeling setting times of SCM-containing concrete for a decade. Initial studies (Eren et al. 1995; Brooks et al. 2000) derived empirical equations based on data obtained through extensive testing. However, while the resulting prediction models may be applied to systems with different composition and curing conditions, the results would be suspect. In a later study, Brooks (2002) developed another model to predict setting time based on first principles and calibrated the model against data available from the literature. This model holds more promise for general application.

Pinto and Hover (1999) applied the maturity method of Freiesleben-Hansen and Pederson (1977) to the prediction of setting times. The FHP maturity function is a method for calculating the "equivalent age" of concretes cured at different temperatures compared to the development of the same concrete mixture at a reference temperature. Two concretes with the same equivalent age exhibit the same strength and other properties, regardless of their true age or temperature history. At the time of setting, therefore, all concrete should have the same equivalent age. It follows, therefore, that if this equivalent age can be determined, then the setting time can be predicted. A critical parameter in the FHP function is the apparent activation energy, E_a. This value can be obtained experimentally by using one of several methods, the most accurate of which is isothermal calorimetry (Poole et al. in press). Pinto and Hover (1999) outlined a method that successfully estimates setting time given empirically determined values for E_a. A similar approach was also presented by Abdelkader and others (2001).

Schindler also developed a method for predicting setting time as part of the Texas Department of Transportation's (TxDOT) project 1700 (Schindler 2002). From several field concrete mixes, he found that initial set occurs when the degree of hydration reaches 0.15 times the water-to-cementitious materials ratio (w/cm) and the final set is 0.26 times the w/cm. He also developed correction factors for admixtures. *Schindler observed that using maturity-based methods for predicting setting time worked in many cases, but was not successful for predicting setting of slag-containing mixes.* These types of prediction methods will be useful for developing guidelines for setting times of concrete mixtures from the results of laboratory tests discussed in the work plan of this proposal.

2.3 Plastic Shrinkage

Plastic shrinkage is a highly complex phenomenon, which has not been thoroughly researched and is not yet fully understood. This section will summarize the likely causes of plastic shrinkage, present a history of the research that has been performed, and outline several mitigation strategies.

2.3.1 Background

Plastic shrinkage cracks occur before paste, mortar, or concrete has fully hardened. Such shrinkage is the result of a loss of water due to evaporation and may occur if the rate of surface evaporation exceeds the rate at which bleed water rises to the surface (Mindess et al. 2003). Consequently, the rate of evaporation is regarded as a critical factor in the potential for plastic shrinkage cracking.

The ACI evaporation nomograph is a widely used method for predicting the potential of plastic shrinkage cracking. To use this graph, the user must know the ambient temperature, humidity, and wind speed. With these variables known, the estimated rate of evaporation can be obtained. Cracking is likely to occur if the rate of evaporation exceeds 0.2 lb/ft^2/hr (ACI 1982).

While this method is easy to understand and requires little calculation, its accuracy has been questioned by many researchers. Hasanain (1989) found that the rate of evaporation depends on the time of casting, ambient conditions, temperature of concrete, moisture condition of the concrete surface, and shading of the surface. He concluded that the ACI graphical method is a poor estimator of evaporation when a layer of bleed water is not on the concrete surface or the specimen is shaded.

The complexity of plastic shrinkage is due, in part, to the large number of variables that have an effect. Along with environmental conditions and construction methods, each ingredient in concrete may increase or decrease the probability of plastic shrinkage.

2.3.2 Previous Research

Most of the plastic shrinkage research has been performed using paste or mortar rather than concrete. It is well known that most aggregates do not undergo significant shrinkage as concrete dries. Rather, the paste fraction is the portion of concrete that experiences a relatively high volumetric reduction as water is lost. Therefore, plastic shrinkage increases with higher cement contents (Dias 2003).

Researchers agree that evaporation increases as wind velocity and temperature increase, and humidity decreases. The effects of SCMs and chemical admixtures on plastic shrinkage, however, are not as well known. For instance, Dias (2003) found that fly ash increases evaporation, reduces bleeding, increases the extent of cracking, and reduces the duration to onset of cracking. Wang and others (2001) found that, when using class F fly ash, water loss is greater with higher fly ash content—a phenomenon he attributed to the slow reaction of fly ash. In contrast, Ravina (1986) found no clear trend on the effect of fly ash on plastic shrinkage during drying.

A large number of the discrepancies in literature regarding plastic shrinkage can likely be attributed to the opposing effects that concrete ingredients and ambient conditions have on plastic shrinkage. For example, increasing the water-to-cement ratio increases bleeding, which lowers the potential for cracking (Topçu and Elgün 2003). However, a reduction in paste volume through the use of water-reducers lowers the potential of plastic shrinkage cracking (Shaeles and Hover 1988). Also, although shading concrete specimens can reduce the rate of evaporation by more than 50% (Hasanain et al. 1989), the time window during which plastic shrinkage can occur will be reduced when concrete is placed under direct sunlight due to the quicker strength gain.

In addition to environmental conditions and mixture proportions, construction methods can have a significant impact on the likelihood of plastic shrinkage. Campbell and others (1976) found that concrete cast on an impervious base will be more susceptible to shrinkage cracking. Furthermore, finishing methods can affect cracking. Screeding, in particular, has a significant impact on plastic shrinkage cracking. The severity of cracking increases with quicker screeding and the direction of screeding affects crack orientation (Shaeles and Hover 1988).

2.3.3 Mitigation Methods

If the environmental conditions are sufficiently severe (i.e., high temperature, low humidity, and high wind speed), precautions should be taken to prevent plastic shrinkage cracking. Fortunately, contractors can employ a variety of methods to produce nearly crack-free concrete.

Curing compounds, wet burlap, or plastic sheets can be placed over fresh concrete to prevent evaporation. Fog sprays can be used to provide adequate humidity. Wind breaks, although less practical, can help to reduce wind speed. Although generally not used in paving applications, a 0.1% addition of fibers (by volume) can reduce the total plastic shrinkage crack area by 30 to 40% (Wang et al. 2001). In addition, forms can be wetted to prevent absorption of the concrete moisture.

Regardless of the mitigation method, the objective in preventing plastic shrinkage is generally to reduce evaporation from the concrete surface. A reduction in evaporation will decrease the likelihood of shrinkage near the surface and provide adequate time for the development of concrete strength.

2.4 PavePro

While it is relatively simple to obtain information on the air temperature at a construction site for a given place and time, it is more complicated to obtain the temperature of the concrete in a pavement. The temperature of the concrete, rather than the air, is important when trying to study or predict setting time.

PavePro is a Microsoft Excel program developed by Schindler (2002) to predict the temperature of concrete pavements. PavePro accepts user inputs and produces graphs depicting the concrete temperature at various depths of the pavement section and at regular time intervals. The following list summarizes the sections of PavePro and their respective inputs.

- **General Inputs:** location and time of construction, reliability of prediction level, pavement thickness, and sub-base thickness and type
- **Mixture Proportion Inputs:** mixture proportions including cement, aggregates, and admixtures
- **Material Inputs:** chemical composition of cement, aggregate type, activation energy, and adiabatic constants
- **Environment Inputs:** local temperature and weather conditions
- **Construction Inputs:** fresh concrete temperature and curing method

The user inputs can readily be obtained except for the activation energy and hydration parameters. Activation energy values and hydration parameters of a particular mix can be obtained by conducting isothermal and semi-adiabatic calorimetry tests, respectively.

After the required inputs are entered and the analysis has been performed, a graph is produced showing the concrete temperature for the top, middle, and bottom surface of the pavement section as a function of time for a 48-hour duration after placement. A curve showing the ambient air temperature as selected by the user is also shown along with marks indicating the points of estimated final set. Figure 2.2 presents a graph produced for an OPC concrete mix cured under typical August temperatures in El Paso, Texas.

A unique and important aspect of the current project was the temperature conditions under which the time-of-set (TS) specimens were cured. Although much research has been performed to determine setting times under a constant curing temperature, the TS specimens tested in this project were subjected to a varying curing temperature, as predicted using PavePro, to better simulate temperature conditions in the field.

Figure 2.2 provides an example to illustrate the importance of the temperature under which concrete is cured. In this figure, the "Air Temp" curve has been produced from user inputs which specify the hourly air temperature for 48 hours. The predicted concrete temperature, however, can greatly exceed the ambient temperature. It follows then, that greater accuracy in setting time can be obtained by curing under realistic temperatures.

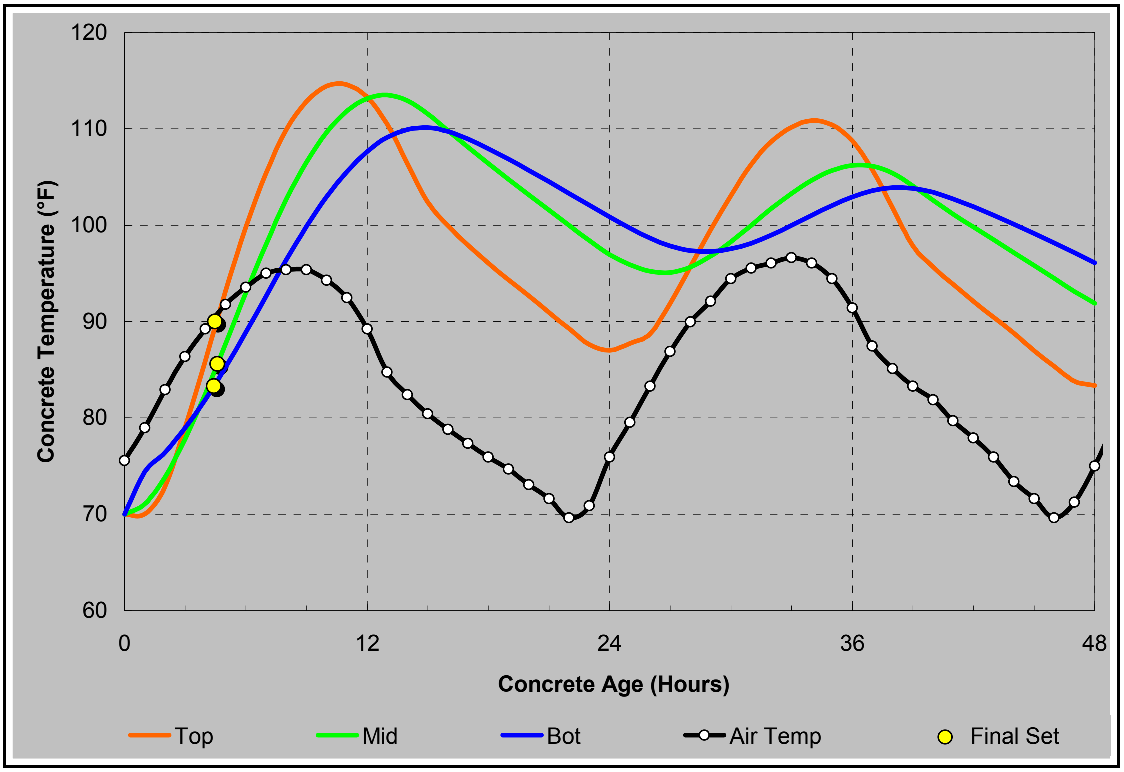

Figure 2.2: Temperature of an OPC concrete pavement as estimated by PavePro

2.5 Summary

A review of the literature has shown that there are many variables that influence setting time and plastic shrinkage, such that discerning trends and making predictions is very difficult. The following list summarizes the effect of various variables on setting time and plastic shrinkage.

Setting time:

- Decreases with increasing temperature
- Generally increases with a slag replacement
- Increases with excessive plasticizer
- Increases with a fly ash class F replacement
- May increase with a fly ash class C replacement
- Increases as the w/c increases

Plastic shrinkage:

- Increases as evaporation increases (evaporation increases as humidity decreases and wind speed and temperature increase)
- Decreases as bleeding increases

- Increases as paste fraction increases
- May increase when using fly ash
- Increases with quicker screeding
- Decreases with the use of fibers, wet burlaps, and curing compounds

The maturity method for estimating concrete strength and PavePro program for estimating concrete temperature are useful and well-established models that are used in the testing in this study. This testing program is described next.

Chapter 3. Laboratory Testing Program

The influence of SCMs on setting times, early strength gain, and plastic shrinkage has not yet been firmly established. Therefore, extensive testing and analysis of typical El Paso, Texas concrete pavement mixtures are needed in order to determine which mixtures are appropriate for use in various weather conditions. To enhance accuracy, we have used PavePro to model the temperature of each mix in a hypothetical pavement. We have tested each mix for setting time, bleeding, and early strength. In addition, specimens were made to develop maturity curves for each mixture. Furthermore, several mixtures have been tested to determine susceptibility to plastic shrinkage cracking.

The initial testing program for this project consisted of ten different mixes that each contained two types of batches: a maturity batch and a time of set (TS) batch. Within each maturity batch, concrete cylinders were made for semi-adiabatic calorimetry tests (used for PavePro inputs) and compressive strength tests (used to develop maturity curves). For each TS batch, concrete cylinders and mortar specimens (sieved from the concrete) were prepared and cured in temperature-controlled water tanks. All mixes had a target slump of 1.5 inches and a target air content of 5%. Three trial mixes were conducted to determine the amount of water reducer/retarder and air entraining agent to be used in each mix.

The tenth mixture was made to mimic a field mixture from El Paso, Texas and was re-tested three times using slightly different mixture design parameters. This mixture is labeled differently from the others, referred to as the "El Paso" mix, and is often discussed separately.

3.1 Materials

The materials used in the various concrete mixes were selected to represent typical concrete pavements in El Paso, Texas. Because an objective of this project was to investigate problems due to delayed setting in SCM-containing mixes, each mix (except for a control mix) contained varying amounts of ground granulated blast furnace slag (GGBFS) and fly ash. A matrix of all the mixes in this project is shown in Table 3.1. Other than the El Paso mixes, mix designs were based on a TxDOT requirement of a 5.5-sack paving mix (517 pounds of cementitious material per cubic yard of concrete) and a w/c of 0.42. El Paso mixes were based on previously used concrete mixtures and had a 5-sack paving mix (470 lb/yd^3) and varying w/c. All other material quantities were calculated from the ACI method (ACI 211.1 2002). Table 3.2 lists the materials used in this project and the suppliers. Mixture proportions for each mix are shown in Table 3.3. Material properties for the cement and SCMs can be found in Appendix A.

Once the aggregate had been received, an aggregate analysis was conducted according to TxDOT specifications 400-A through 403-A. Three samples were used to determine the gradation of the coarse aggregate and one sample was used to determine the gradation of the fine aggregate. To obtain a representative sample, aggregate properties such as specific gravity and absorption capacity were determined according to the appropriate TxDOT specification using three separate samples from the aggregate stockpile. The results of the aggregate analysis and the gradation curves can be found in Appendix A.

Table 3.1: Concrete mix matrix

MIX	Cement Type	W/C	Cement Replacement
1	Type I/II	0.42	None
2			20% Fly Ash #1
3			35% Fly Ash #1
4			20% Fly Ash #2
5			35% Fly Ash #2
6			35% GGBFS
7			50% GGBFS
8			35% GGBFS + 15% Fly Ash #1
9			35% GGBFS + 15% Fly Ash #1 (optimum gradation)**
EP.40*		0.40	50% GGBFS + Double WR***
EP.48		0.48	50% GGBFS + Double WR
EP.52		0.52	50% GGBFS + Double WR
EP.55		0.55	50% GGBFS + Double WR

* EP.XX: EP = El Paso, .XX= w/cm

** According to TxDOT Item 421.2 (using aggregate grade no. 2, 1.5 in. nominal size coarse aggregate)

*** WR = water reducer

Table 3.2: Materials and suppliers

Material	**Supplier**
Type I/II cement	Rio Grande - Samalayuca
Fly Ash #1	Boral - Monticello - Class F
Fly Ash #2	Phoenix Cement in Prewit, N.M. Escalante Plant - Class F
GGBFS	Buzzi Unicem - Grade 120
Coarse aggregate	McKelligon/Grade 2 Dolomitic Limestone
Fine aggregate	Section 10
Air entraining agent for mixes 1-9	Daravair AT 60
Air entraining agent for El Paso mixes	Monex Air-40
Water reducer for mixes 1-9	WRDA 64
Water reducer for El Paso mixes	Monex X-15

Table 3.3: Concrete mixture components

MIX	Component Amounts (lbs/yd^3)						Admixtures (oz/100 lb cement)	
	Cement	Slag	Fly Ash	Coarse Aggregate	Fine Aggregate	Water	Water Reducer	Air Entraining Agent
1	517	0	0	1958	1263	217	3	0.50
2	414	0	103	1947	1248	217	3	0.50
3	336	0	181	1935	1240	217	3	0.35
4	414	0	103	1947	1248	217	3	0.50
5	336	0	181	1935	1240	217	3	0.35
6	336	181	0	1954	1253	217	3	0.50
7	259	259	0	1950	1250	217	3	0.50
8	259	181	78	1942	1245	217	3	0.50
9	259	181	78	1942	1245	217	3	0.50
EP.40	235	235	0	2031	1310	188	25	0.34
EP.48	235	235	0	1970	1271	226	25	0.34
EP.52	235	235	0	1940	1251	244	25	0.34
EP.55	235	235	0	1917	1237	259	25	0.34

3.2 Maturity

For maturity testing, 19 6 in. x 12 in. concrete cylinders were made according to ASTM C 192 (2006), cast in molds and capped, and placed in a fog room at 100% relative humidity and 73 °F. After 24 hours, the cylinders were demolded and stored in the fog room until they were tested for compressive strength. One cylinder from each mix had a Thermochron iButton® (Dallas Semiconductor) placed into it at the time of casting to record the temperature and humidity at 30-minute intervals for 28 days. The remaining cylinders were tested for compressive strength according to ASTM C 1231 (2000) at 1, 3, 7, 14, 28, and 56 days after mixing. Compressive strength was determined by using the average strength of three cylinders.

Once compressive strength testing had been completed, the maturity index of each mix was calculated using the temperature-time-factor (TTF) method discussed in the previous chapter. The datum temperature of -10 °C was selected according to TxDOT test procedure TEX-426-A (2002).

3.3 Semi-Adiabatic Calorimetry

Semi-adiabatic calorimetry was performed to obtain hydration parameters to use in PavePro for simulating concrete pavement temperatures for the mixtures. The simulated temperatures are used to program the water baths used in the TS and early compressive strength testing.

A semi-adiabatic calorimetry test was conducted for each mix by storing a 6 in. x 12 in. concrete cylinder in a semi-adiabatic calorimeter for seven days after mixing, while a temperature history was recorded. A semi-adiabatic calorimeter, as shown in Figure 3.1, is composed of a steel drum that contains a very thick layer of insulation surrounding the cylinder placed into it. A thermocouple is placed into the concrete to record temperatures at 15-minute intervals. In addition, the heat flux out of the drum is measured at 15-minute intervals. Each semi-adiabatic test produced the following hydration parameters from a curve of hydration development:

- α_u, the ultimate degree of hydration,
- β, a hydration shape parameter, and
- τ, a hydration time parameter.

These hydration parameters were entered into PavePro as part of the variables required to generate a profile of the predicted concrete temperature.

Figure 3.1: Semi-adiabatic calorimeter

PavePro requires an "activation energy (E_A)" value which is typically obtained through isothermal calorimetry tests. E_A values for this project were estimated using a model developed by J. Poole (2006). The model is based on regression analysis of approximately 120 mixtures (600 isothermal tests). The 95% confidence limits from the regression analysis are approximately ±1500 kJ/mol (± 5%).

3.4 Time of Set and Early Strength

Time of set (TS) mixes were prepared to obtain specimens for testing setting time, early strength, and bleeding. Within each mix, sieved-mortar specimens and concrete cylinders were prepared and placed into tanks simulating three ambient temperature conditions: hot/summer, medium, and cold/winter. In addition, tests were conducted for each TS mix to determine air content, slump, and bleed water amount.

Preparation of the mortar specimens and calculation of setting times were conducted according to ASTM C 403 (2005), "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." Two mortar specimens were prepared for each temperature condition (hot, medium, and cold) by sieving fresh concrete through a 4.75 mm sieve which rested on a vibrating table. Figure 3.2 shows a picture of concrete being sieved. Once prepared, the specimens were immediately placed into the smaller water tanks shown in Figure 3.3. Once a TS specimen had begun to stiffen, the penetration resistance was determined at regular time intervals by inserting needles of various sizes into the mortar to a depth of 1 inch over a 10-second period. Initial and final set were defined as the time from mixing when the penetration resistance of the mortar reached 500 and 4000 psi, respectively.

Figure 3.2: Sieving concrete to produce mortar specimens for setting time determination

Forty-five 4-inch by 8-inch concrete cylinders were cast with each TS batch and immediately stored in the larger water tanks shown in Figure 3.4. Subsequently, the cylinders were tested for compressive strength at 12 hours, and 1, 2, 3, and 7 days after mixing. Compression tests were conducted according to ASTM C 1231 (2000) and the average strength of three cylinders was calculated.

Mixtures were also tested to determine slump, air content, and bleeding. The air content and slump were determined for each TS mix according to ASTM designations C 231 (2004) and

C 143 (2005), respectively. The bleed tests were conducted according to ASTM C 232 (2004), except that a plastic bucket was used in place of a steel container. Each bleed specimen was kept at room temperature (approximately 73 °F) until bleeding had ceased.

Figure 3.3: TS cans and cylinders

Figure 3.4: Water baths and tanks used in TS testing

The testing setup for the TS specimens and the concrete cylinders consisted of small and large water tanks connected by hose to a computer-controlled water bath. The small tanks held two TS cans each while the larger tanks each held fifteen cylinders, which were to be tested for early age strength. The TS cans and cylinders are shown in the tanks in Figure 3.3. The penetrometer used to determine penetration resistance of the mortar specimens can be seen in Figure 3.4 to the left of the tanks. The tank-water bath setups, shown in Figure 3.4 consisted of three separate temperature conditions: hot, medium, and cold.

Each temperature condition was selected to represent typical El Paso, Texas temperatures for the summer, spring, and winter. Average hourly El Paso temperatures for the last 30 years were used to create the ambient temperature profile shown in Figure 3.5. By inserting the ambient temperature profile, along with several other variables, into PavePro, hourly temperatures at the top surface of a concrete pavement were predicted for a 48-hour period. The predicted temperatures were then linearly interpolated at 5-minute intervals to permit a gradual temperature change. After 48 hours, the temperature profile between 24 to 48 hours was repeated for 5 more days. An example predicted concrete temperature profile for each weather condition is shown in Figure 3.6.

The predicted temperature profiles were then used to regulate the temperature of each water bath via a Labview program. To simulate the temperature of the cylinders, each large tank contained a thermocouple which was embedded in a cylinder mold filled with sand. The Labview program obtained the temperature of the sand every 90 seconds and adjusted the temperature set point of the water baths accordingly. Using this method of temperature control, the sand temperatures managed to stay within approximately 0.5-3 °F of the predicted temperature profile.

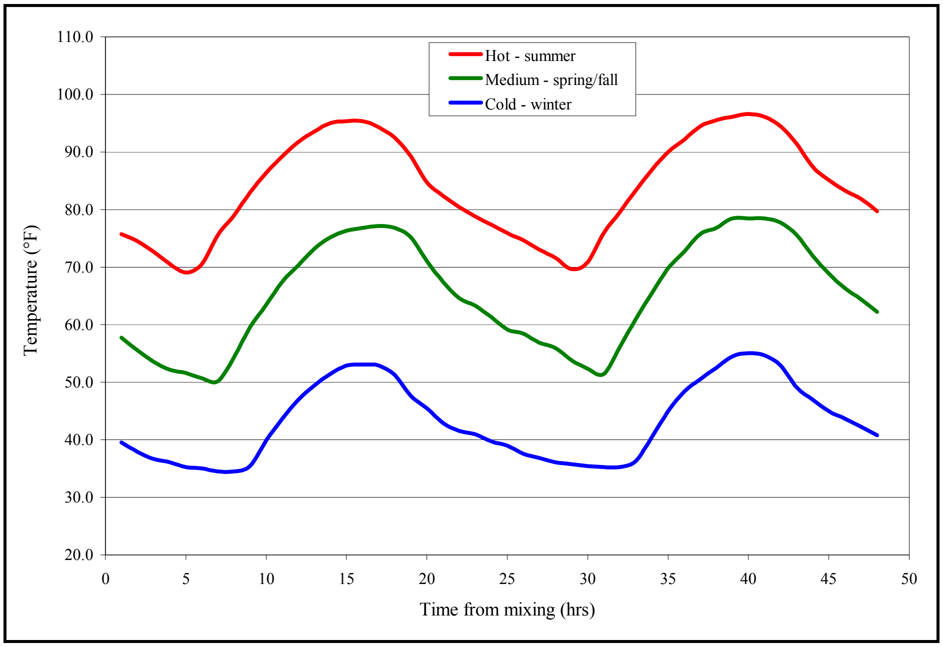

Figure 3.5: Ambient temperature profile used to predict concrete temperatures for a 48-hr period from mixing

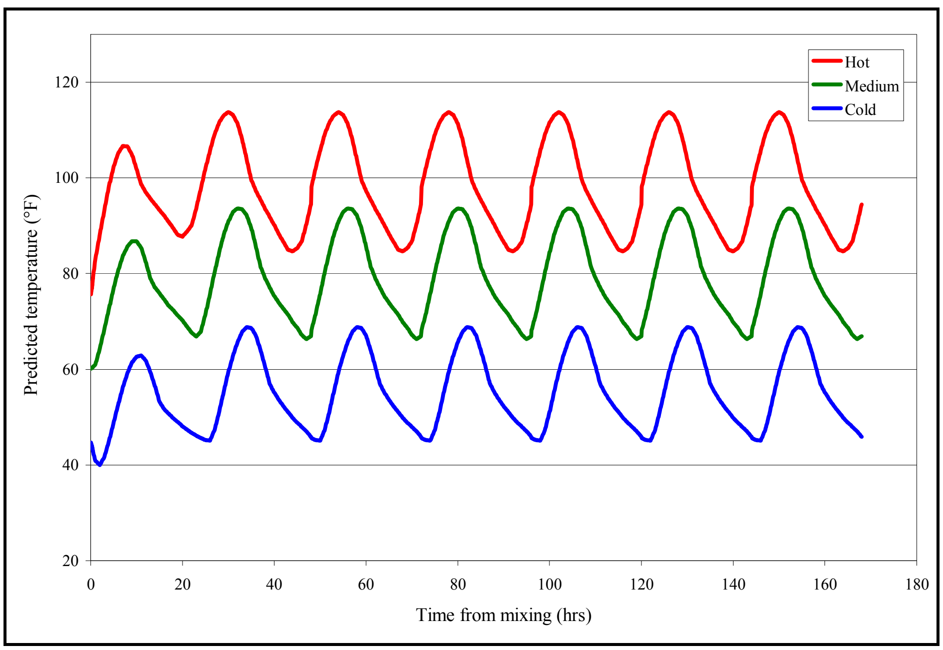

Figure 3.6: Predicted concrete temperature profiles for mix no. 8

3.5 Plastic Shrinkage

Plastic shrinkage tests were conducted using both mortar and concrete specimens. A floor fan was used to increase evaporation. The fan produced a maximum wind speed of 17 mph at approximately 6 inches above the specimen. In addition, the specimen was placed in a wind tunnel to maximize wind speed across the specimen. A Thermochron iButton® (Dallas Semiconductor) was placed on the specimen to measure humidity and the specimens were placed in an environmental chamber to control temperature. Table 3.4 presents the mixes used for plastic shrinkage tests. Two plastic shrinkage test setups can be seen in Figure 3.7 and Figure 3.8.

Table 3.4: Plastic shrinkage test matrix

Test No.	Material	Cement Replacement / mix	Specimen Dimensions (in.)	Curing/Testing Temperature
1	Concrete	None / #1	12 x 18 x 5.5	73 °F
2	Concrete	None / #1	18 x 24 x 5.5	73 °F
3	Concrete	35% FA1 / #3	18 x 24 x 5.5	110 °F
4	Mortar	35% FA1 / #3	36 x 12 x 5.5	50 °F
5	Mortar	35% FA1 / #3	36 x 12 x 5.5	110 °F
6	Concrete	50% Slag / EP.48	18 x 24 x 5.5	50 °F

Figure 3.7: Plastic shrinkage test no. 1. A fan was used to increase evaporation and thus maximize the potential for plastic shrinkage cracking.

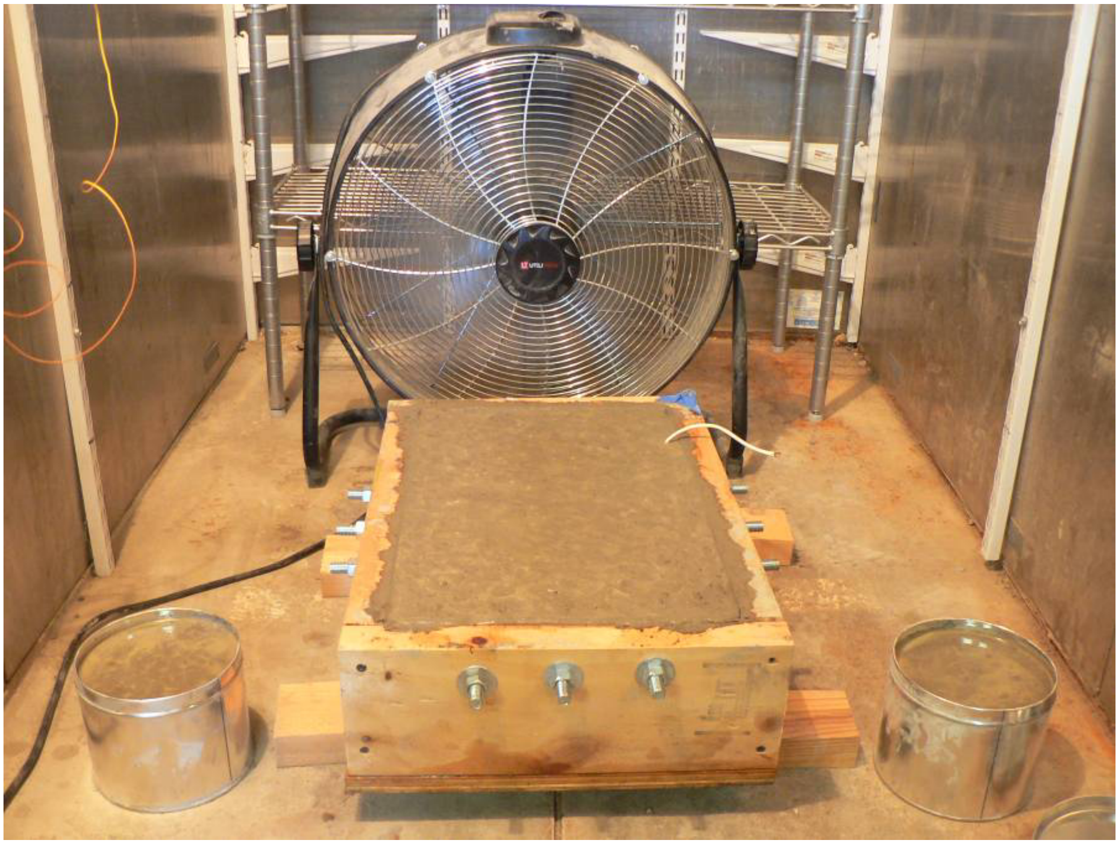

Figure 3.8: Plastic shrinkage test no. 3. The bolts sticking out from the specimen were used to provide restraint.

Chapter 4. Results and Discussion

The results of all tests conducted in this project are presented in this section, along with a brief discussion. In the interest of providing a concise report, graphs and tables that are not immediately necessary for the discussion are in the Appendices. For instance, fresh concrete properties (e.g., slump, air content, etc.) are included in Appendix B.

4.1 Maturity

The test results for the maturity cylinders consist of compressive strength data and maturity plots. All maturity cylinders measured 6 in. x 12 in. and were cured in a fog room at approximately 73 °F and 100% relative humidity. The purpose of the maturity testing was to obtain maturity curves for each mix so that compressive strengths of similar mixes could be estimated in the field.

4.1.1 Compressive Strength

Compressive strength tests were performed on the maturity cylinders at 1, 3, 7, 14, 28, and 56 days from mixing. Each strength value published in this report is the average value from three tests. The compressive strength results for the maturity mixes containing fly ash and the control mix are presented in Figure 4.1. Figure 4.2 shows the strength of the control mix and slag mixes. (Note: A 56-day compressive strength test was not conducted for maturity mix no.8.)

As seen in Figure 4.1, the control mix initially had a higher rate of increase in strength than the mixes containing fly ash. Eventually, however, the strength of each mix surpassed that of the control. As expected, the ternary blends had significantly higher strengths than the mixes with only a fly ash replacement.

Other than those containing excessive amounts of water reducer, the slag-containing mixes performed very well, reaching 56-day strengths of up to 7000 psi. Both early and later strengths were relatively high; 28-day strength was between 1000 to 2000 psi greater than the control mix. Although the El Paso mixes had low early strengths, they reached the strengths of the other slag mixes after approximately 7 to 14 days.

4.1.2 Temperature-Time Factor

As explained in sections 2.1 and 3.2, a maturity graph was prepared for each mix by plotting the compressive strength of 6 in. x 12 in. cylinders versus the temperature-time factor (TTF). Figure 4.3 shows the maturity graph of the control mix. Appendix C contains maturity graphs of all the maturity mixes.

Figure 4.3 contains two curves of the estimated compressive strength. The equations of these maturity curves can be used to estimate the strength of a particular mix if the temperature is variable or different than that tested to and is recorded at regular intervals. The blue curve labeled “28-day results” was calculated using the compressive strength and temperature data for 28 days. The “7-day results” curve was generated by only using data up to 7 days. While using 28 days of data to determine the curved is standard, it has been suggested that early-age strength can be estimated accurately and quickly using only 7 days of data (Suh, 2005). Therefore, both are plotted in Figure 4.3 and in Appendix C. However, in this study it is clear that using the 28-day data is preferred as the resulting curve produces more accurate estimates.

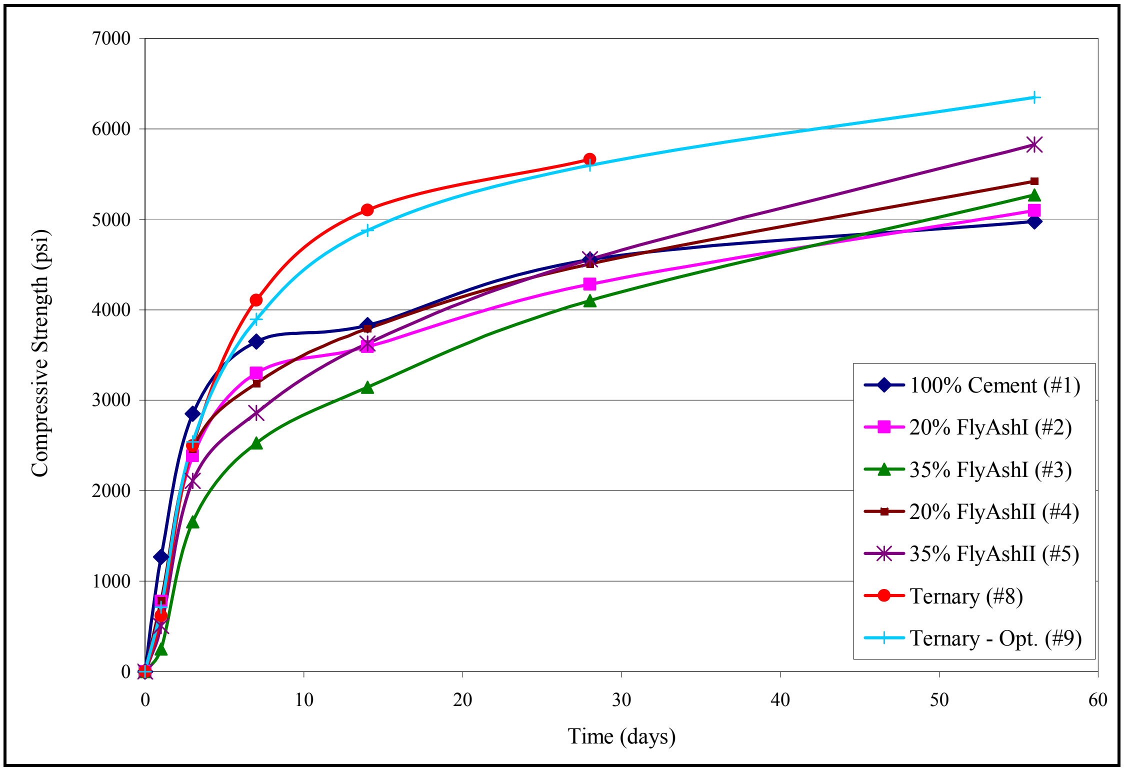

Figure 4.1: Compressive Strength: Maturity mixes 1-5, 8, and 9

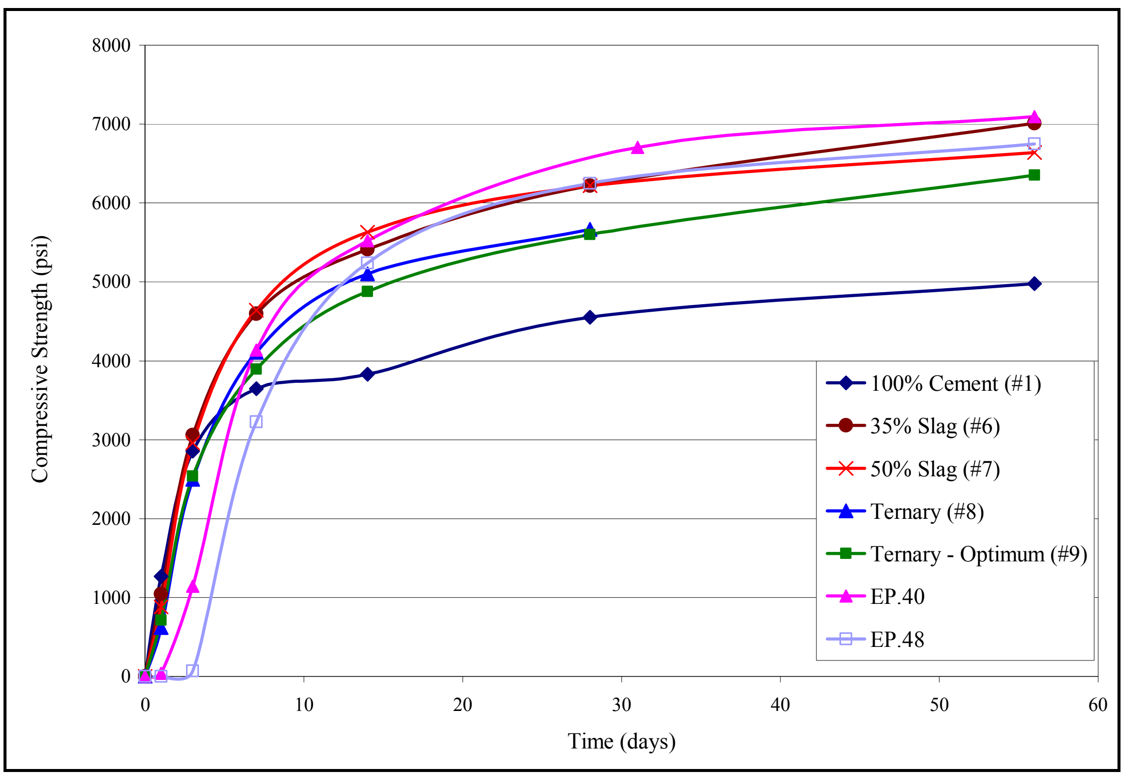

Figure 4.2: Compressive Strength: Maturity mixes 1 and 6-11

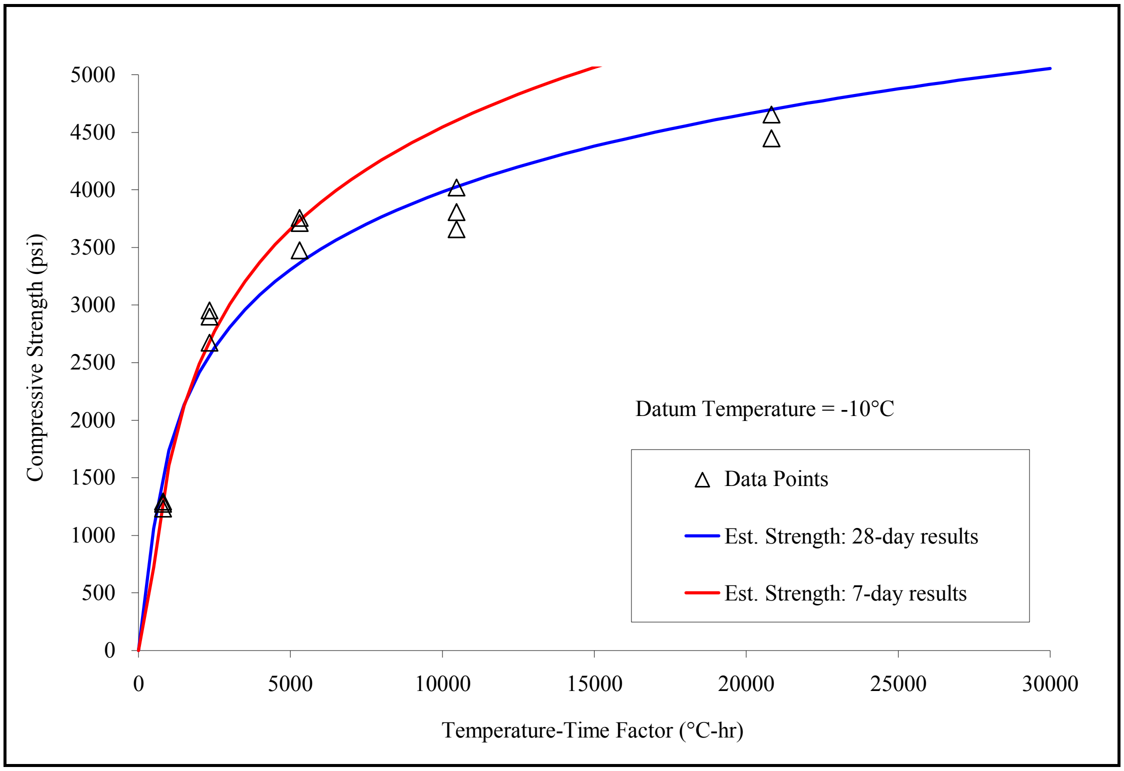

Figure 4.3: Maturity plot of compressive strength vs. TTF for the control mix

If the mixes tested in this project are used in the field, their compressive strengths can be estimated by inserting the appropriate maturity coefficients and the TTF into Equation 2. The maturity coefficients for each maturity mix are shown in Table 4.1. An explanation on how to obtain the TTF is included section 2.2.1.

$$y = a * \log(TTF) + b$$ ***Equation 2***

where, y = compressive strength (psi),
a = slope of maturity curve,
TTF = temperature-time factor (°C-hr), and
b = datum temperature (°C).

Table 4.1: Maturity coefficients for TTF maturity method

MIX	Method	Slope (a)	Intercept (b)	R^2 value
1	28-day TTF	2245.3	-4998.0	0.940
	7-day TTF	2940.1	-7215.4	0.977
2	28-day TTF	2406.8	-5944.5	0.959
	7-day TTF	3044.7	-7978.1	0.990
3	28-day TTF	2613.9	-7261.4	0.992
	7-day TTF	2737.2	-7645.2	0.994
4	28-day TTF	2517.4	-6297.4	0.978
	7-day TTF	2904.5	-7536.0	0.976
5	28-day TTF	2735.9	-7314.5	0.988
	7-day TTF	2839.7	-7639.7	0.980
6	28-day TTF	3640.8	-9301.4	0.986
	7-day TTF	4245.4	-11250.6	0.998
7	28-day TTF	3823.1	-9971.5	0.980
	7-day TTF	4491.3	-12138.7	0.998
8	28-day TTF	3634.2	-9747.3	0.981
	7-day TTF	4164.5	-11472.5	0.999
9	28-day TTF	3455.5	-9165.5	0.989
	7-day TTF	3805.3	-10301.9	0.998
EP.40	28-day TTF	5313.5	-16090.2	0.962
	7-day TTF	5466.8	-16638.5	0.877
EP.48	28-day TTF	4903.9	-15050.9	0.911
	7-day TTF	3684.7	-11183.2	0.702

As shown in Table 4.1, the R-squared value is very high for all mixes except the El Paso ones, which were excessively retarded. This indicates a strong correlation between the estimated and actual compressive strength. Therefore, for the regular mixes (1-9), the TTF maturity method can be used to obtain an accurate estimate of the in-place concrete strength.

4.2 Semi-adiabatic Calorimetry

A semi-adiabatic calorimetry test was performed for each mix using a 6 in. x 12 in. concrete cylinder. Hydration parameters, along with activation energy and total heat of hydration, are shown in Table 4.2.

Table 4.2: Hydration properties

MIX	α_u	β	τ	H_U (J/kg)	E_a (J/mol)
1	0.696	0.956	17.947	496329	29732
2	0.923	0.672	29.679	444367	29740
3	0.672	0.792	25.061	405396	29548
4	0.653	0.839	20.97	444367	28156
5	0.739	0.864	24.709	354744	27467
6	0.695	0.839	24.672	483964	32609
7	0.694	0.830	28.080	465939	34929
8	0.744	0.774	28.162	444992	33190
9	0.678	0.821	25.691	444992	33190
EP.40	0.698	1.381	57.942	478664	25000
EP.48	0.687	1.273	33.073	466804	18912

- α_u = the ultimate degree of hydration
- β = a hydration shape parameter
- τ = a hydration time parameter
- H_U = total heat of hydration
- E_a = activation energy

The hydration parameters shown above were used in PavePro to estimate the temperature of a concrete pavement and thus determine the temperature at which cylinders would be cured in the TS tests. However, because the temperature was estimated at the surface of the pavement, ambient conditions were the controlling factor. The model, therefore, indicates that temperatures of actual pavements reflect ambient conditions, so the temperatures used in this study are representative of those in actual pavements. The predicted temperature profiles were nearly the same for all mixes, depending only on the chosen ambient conditions, but not significantly on the mixture design.

4.3 Time of Set and Early Strength Testing

The test results for the TS mixes are divided into three sections: setting time, compressive strength, and bleeding. Each section presents the test data followed by a brief discussion of the results. A fourth section presents an analysis of the combined results.

4.3.1 Setting Time

The initial and final setting time of each mix was determined by plotting the penetration strength as a function of time. A typical setting time chart is shown in Figure 4.4. By interpolating between data points, the initial and final setting time was calculated using penetration resistance values of 500 and 4000 psi, respectively. Setting time charts for all mixes are included in Appendix D.

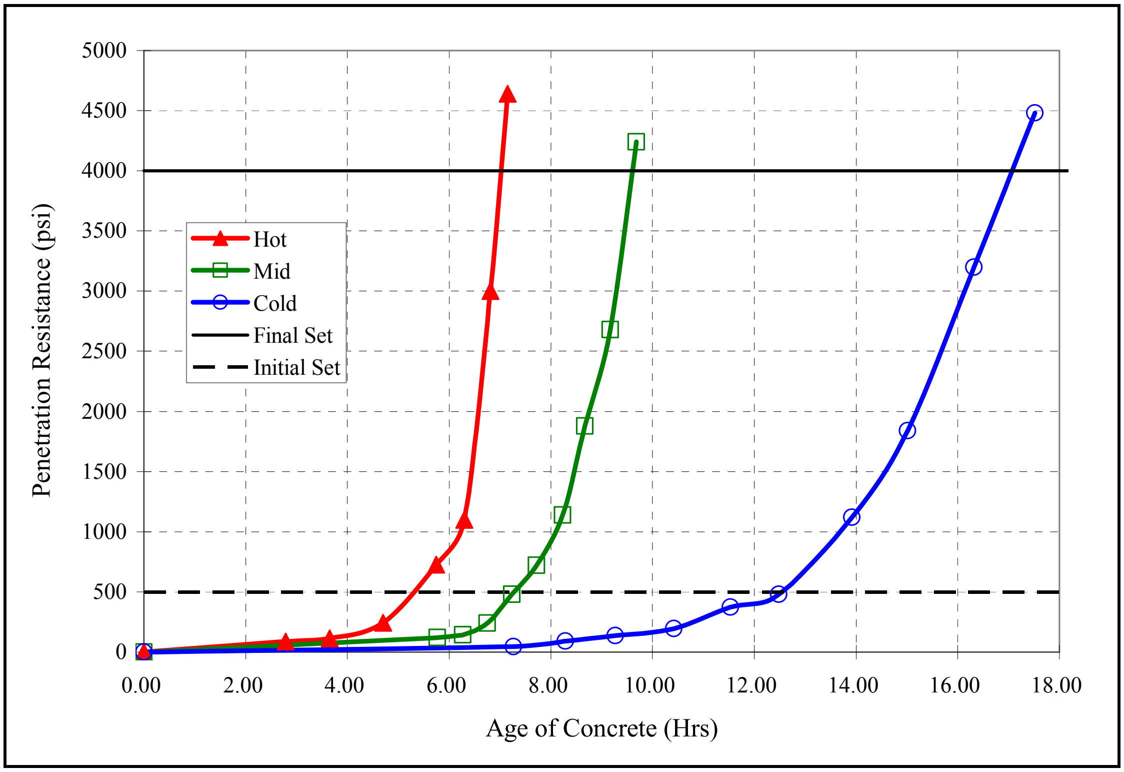

Figure 4.4: Example of penetration resistance as a function of time for mix no. 3

Setting times were calculated for the three temperature conditions under which the mortar specimens were cured. Initial and final setting times are shown in Figure 4.5 and Figure 4.6, respectively, for each mix and temperature condition. The test results show a direct correlation between the curing temperature and setting time; within each mix, setting time decreased as the temperature increased.

Setting time is dependent on the cementitious material in concrete. Figure 4.6 shows slag has little effect on the final setting time of concrete. Although the setting time of mortar with a 35% slag replacement is higher than the control mix, the setting time is lower with a 50% slag replacement. These differences in setting times are minimal and are probably within the error of the test.

In general, the fly ash mixes exhibited an increase in setting time compared to the control mix. Furthermore, mortar with a 35% fly ash replacement took longer to set than mortar with a 20% fly ash replacement. Within the fly ash mixes, the fly ash from the Monticello plant (FA1) took longer to set than fly ash from the Escalante plant (FA2).

The effect of a high water reducer dosage is clearly seen in the “El Paso” mixes. (Note: The El Paso mixes are labeled EP followed by the w/cm.) These mixes were designed to simulate the mixes that had been used in the field and took approximately 2 to 4 times as long to set as mix #7, which also had a 50% slag replacement and a regular water reducer dosage. Another interesting observation seen in the El Paso mixes is the increase in setting time as the w/cm increases.

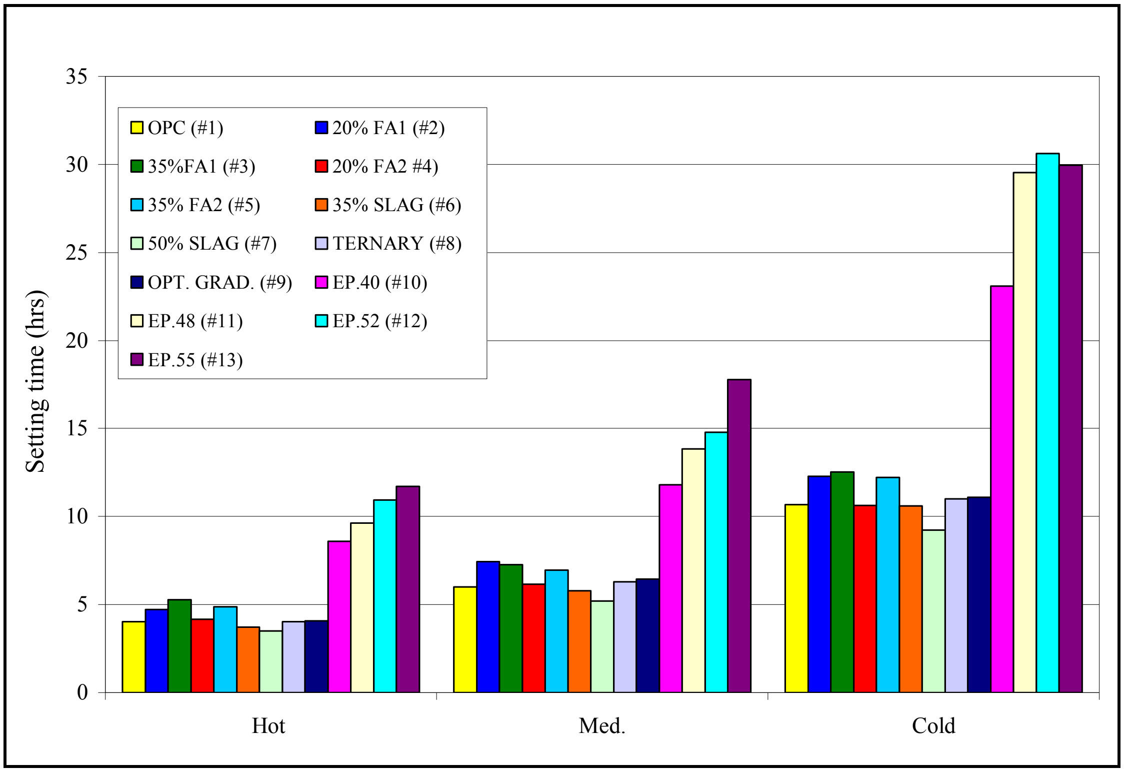

Figure 4.5: Initial setting times

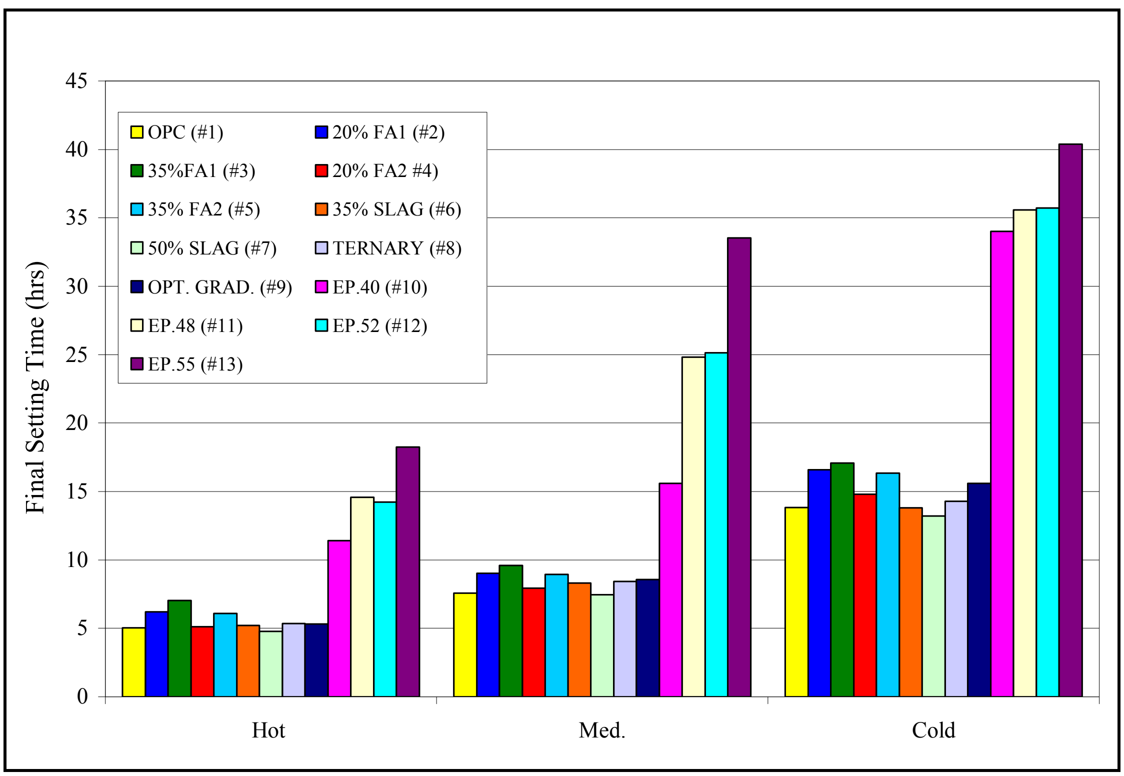

Figure 4.6: Final setting times

4.3.2 Compressive Strength

The cylinders cured under hot, medium, and cold conditions were tested in compression at 12 hours, and 1, 2, 3, and 7 days after mixing. Each strength value published in this report is the average value from three tests. Examples of compressive strength curves for selected mixes are presented in Figure 4.7 to Figure 4.11. Strength values are tabulated in Table 4.3.

The early strength of each mix significantly increased as the temperature increased. However, the concrete cylinders cured under medium and high temperatures generally had approximately equal 7-day strengths. All of the cylinders cured under cold conditions had lower 7-day strengths than the other cylinders.

Except for the ternary-blend cylinders (no. 8 and no. 9) cured under hot conditions, the early strength of the control mix was higher than each fly ash mix (at the same curing condition). In contrast, the mixes containing slag initially had lower strengths but eventually surpassed the strength of the control mix between approximately 3 to 7 days after mixing. Exceptions to this trend were the ternary blends and the El Paso (EP.XX) mixes with w/cm between 0.48 and 0.52. For these mixes, only the cylinders cured under hot conditions surpassed the strength of the control mix. Furthermore, the El Paso mixes with w/cm above 0.40 had lower early strengths (0-3 days) than the control mix at each temperature condition.

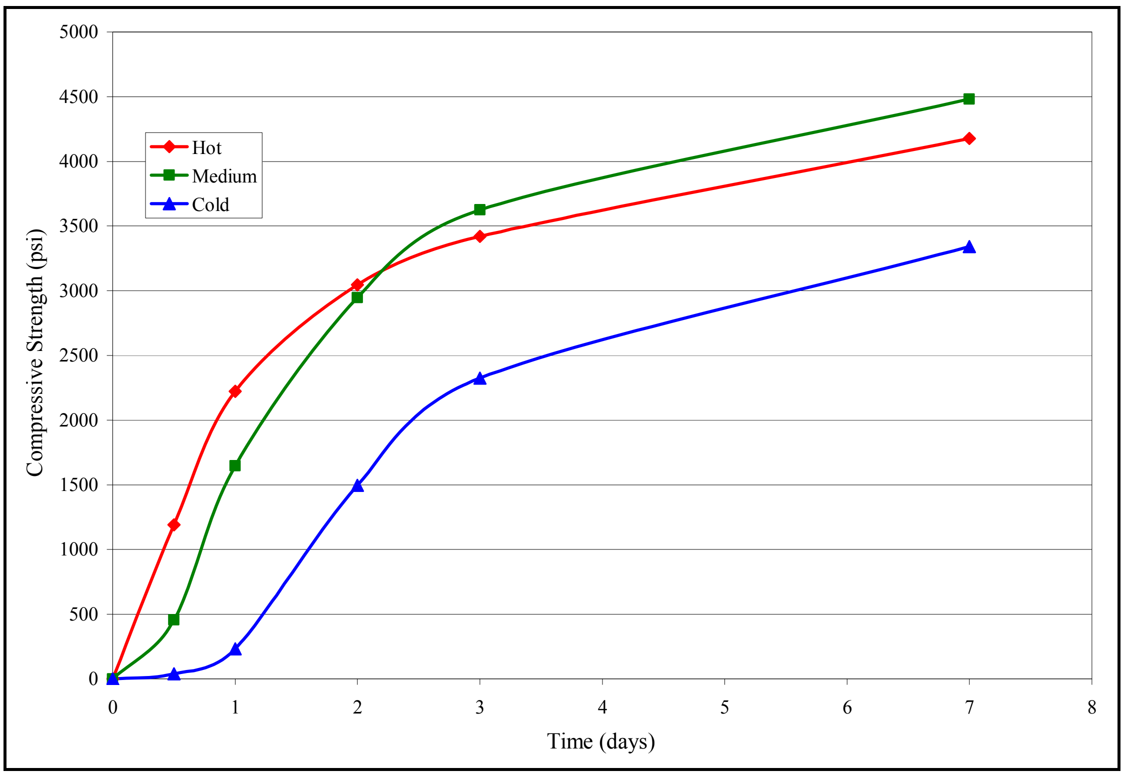

Figure 4.7: Compressive strength vs. time: mix 1 (control mix-OPC)

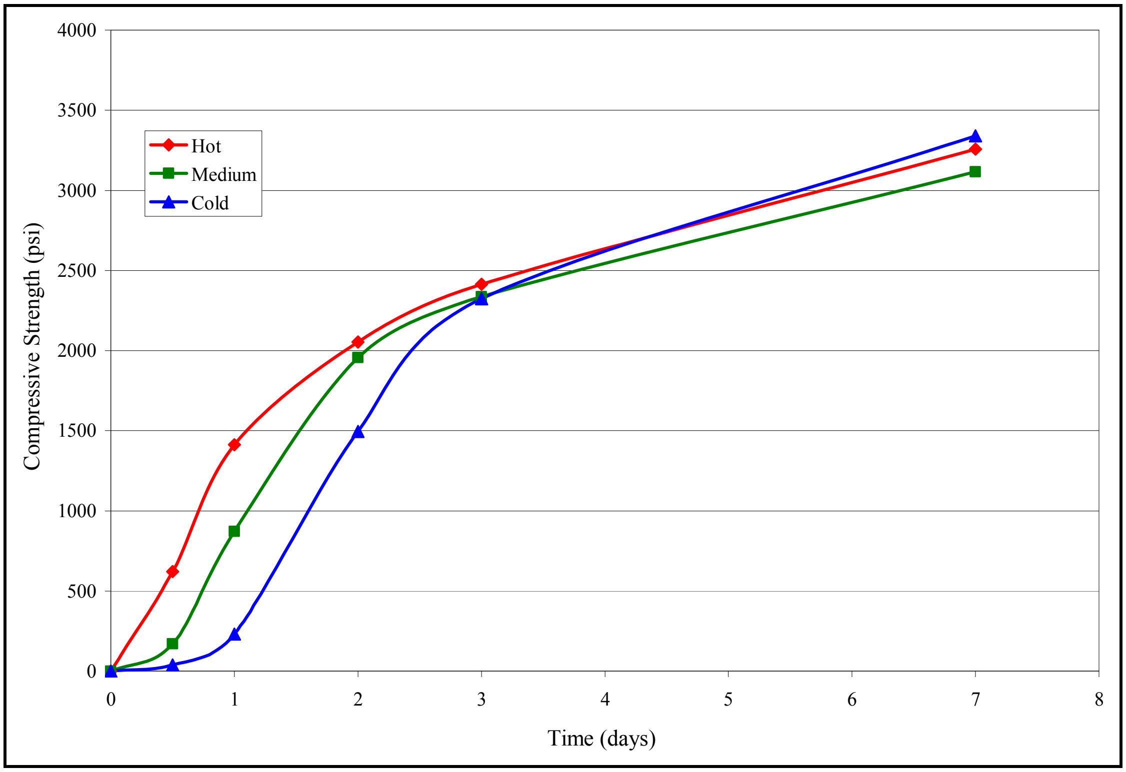

Figure 4.8: Compressive strength vs. time: mix 2 (20% FA1)

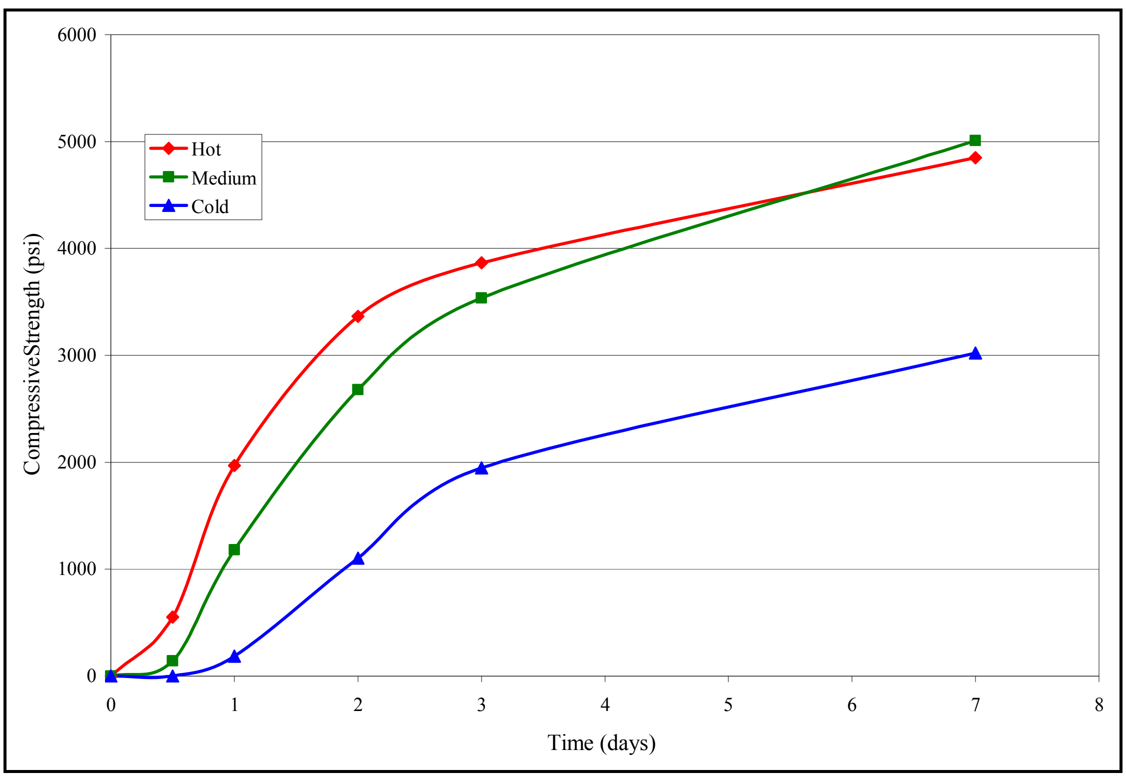

Figure 4.9: Compressive strength vs. time: mix 6 (35% Slag)

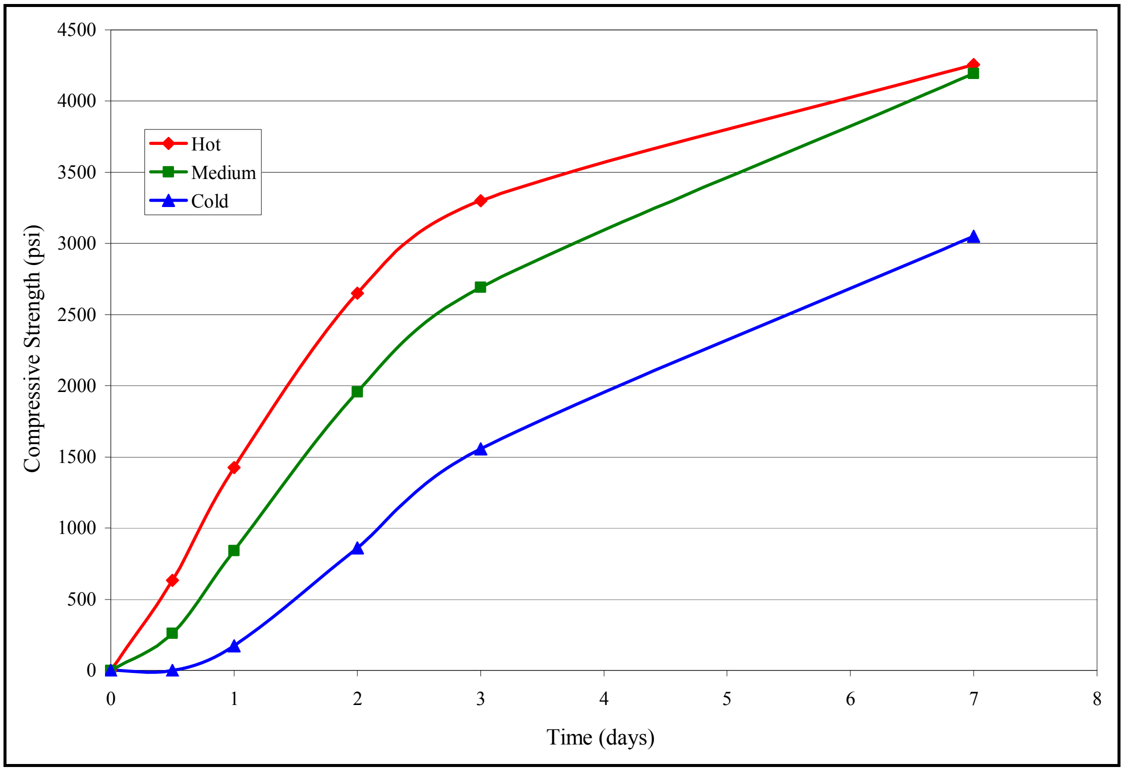

Figure 4.10: Compressive strength vs. time: mix 8 (35% Slag, 15% FA1)

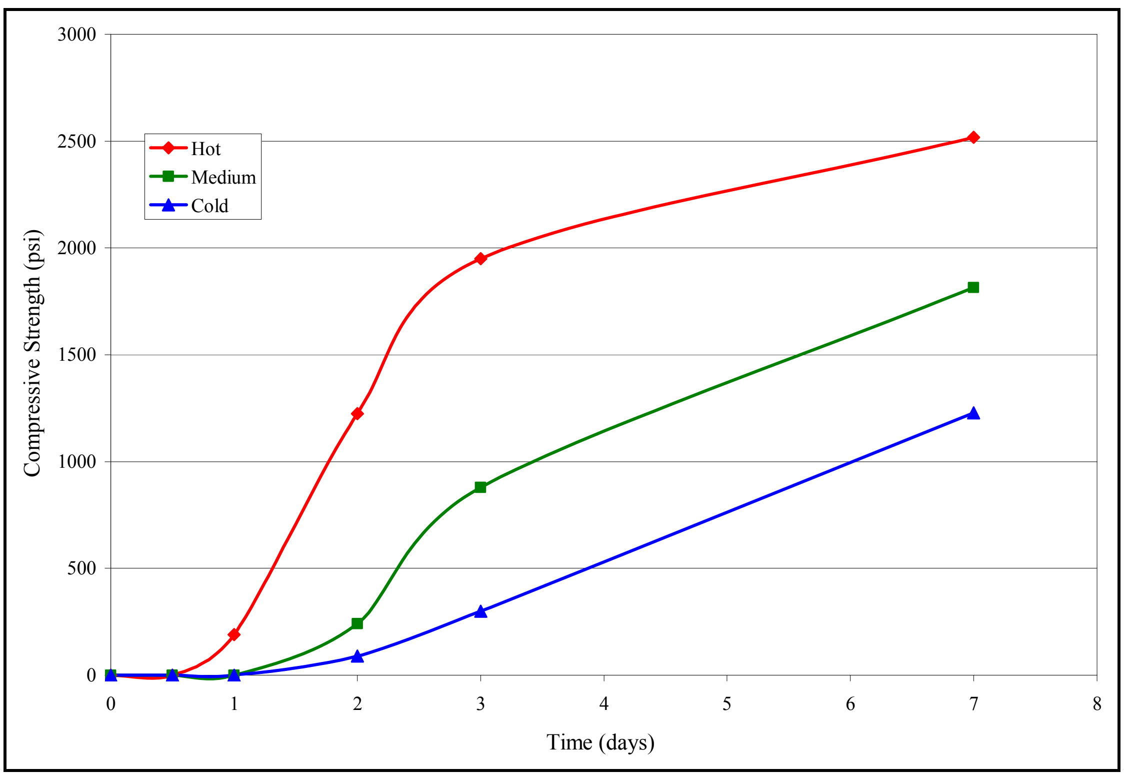

Figure 4.11: Compressive strength vs. time: El Paso mix (50% Slag, w/c = 0.55)

Table 4.3: Compressive Strength of TS Mixes

Age (days)	MIX (hot)												
	1	2	3	4	5	6	7	8	9	EP.40	EP.48	EP.52	EP.55
0.5	1191	620	279	821	551	551	803	633	662	0	0	0	0
1	2221	1413	775	1603	1305	1970	1815	1426	1566	709.4	252.8	285.7	190.5
2	3045	2055	1624	2386	1954	3364	3152	2649	2589	3088	2154	1649	1224
3	3421	2413	2064	2806	2283	3865	3816	3300	3119	4076	3149	3160	1949
7	4176	3257	3259	3503	3590	4850	5000	4255	4292	5419	4448	4481	2518
Age (days)	MIX (medium)												
	1	2	3	4	5	6	7	8	9	EP.40	EP.48	EP.52	EP.55
0.5	456	171	187	346	144	144	322	261	272	0	0	0	0
1	1646	872	797	1214	713	1179	1015	840	816	125.4	0	0	0
2	2946	1955	2009	2303	1826	2679	2338	1956	2041	1714	228.5	568.2	241
3	3624	2337	2385	2732	2148	3536	3253	2690	2524	3176	1401	1834	879.6
7	4482	3116	3334	3547	3142	5010	4919	4193	4009	5560	4320	4318	1815
Age (days)	MIX (cold)												
	1	2	3	4	5	6	7	8	9	EP.40	EP.48	EP.52	EP.55
0.5	40	0	33	0	0	0	0	0	0	0	0	0	0
1	231	98.6	127	209	122	188	216	172	141	0	0	0	0
2	1497	942	865	1276	896	1105	1087	861	760	377.1	132.9	185.4	88.98
3	2325	1630	1659	2022	1502	1949	1915	1556	1330	1364	514.3	670.2	299.1
7	3341	2975	3002	3193	2695	3021	3519	3052	3010	3977	2856	2890	1227

4.3.3 Bleeding

As a part of the tests conducted for each time of set mix, a bleeding specimen was prepared with one-half cubic foot of concrete maintained at approximately 73 °F. Bleed water generally appeared within 1 to 2 hours after mixing and was measured at approximately 30 to 40-minute intervals. The total amounts of bleed water for each mix are presented in Figure 4.12. Additionally, bleeding times are shown in Figure 4.13, and cumulative bleed water curves are shown in Figure 4.14 and Figure 4.15.

Relative bleeding times roughly correlated with relative setting times. For the El Paso mixes, both bleeding time and bleed water increased as the water to cement ratio increased. Except for the El Paso mixes, bleeding ceased within 9 hours. Mixes containing fly ash #1 replacements had the longest bleed times and the most bleed water. In contrast, mixes with fly ash #2 had a relatively small amount of bleed water.

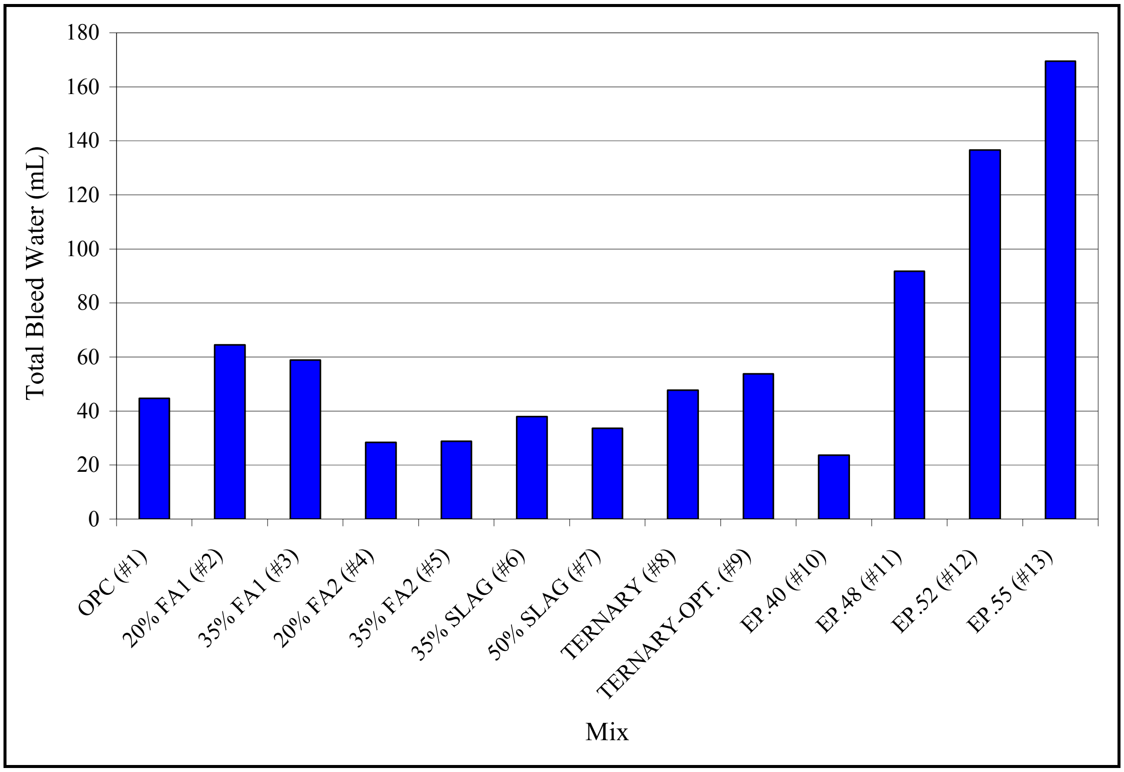

Figure 4.12: Bleed water amounts

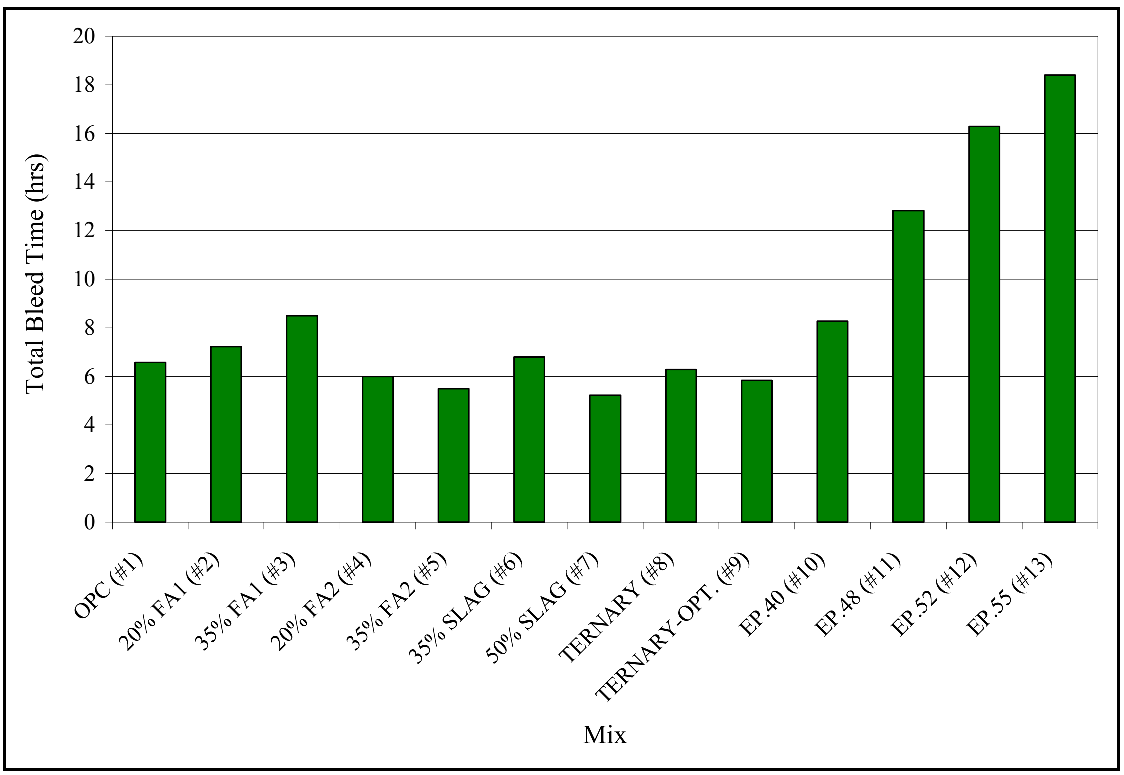

Figure 4.13: Bleeding Times

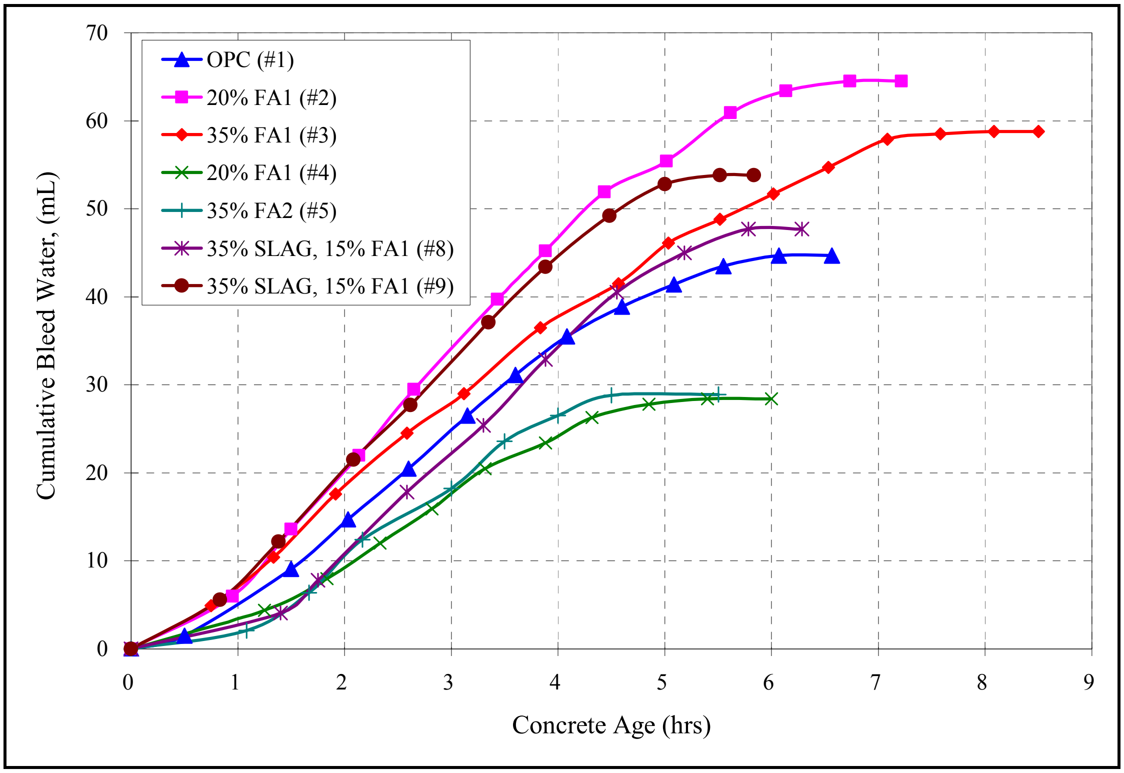

Figure 4.14: Cumulative bleed water vs. time from mixing for control and fly ash mixes

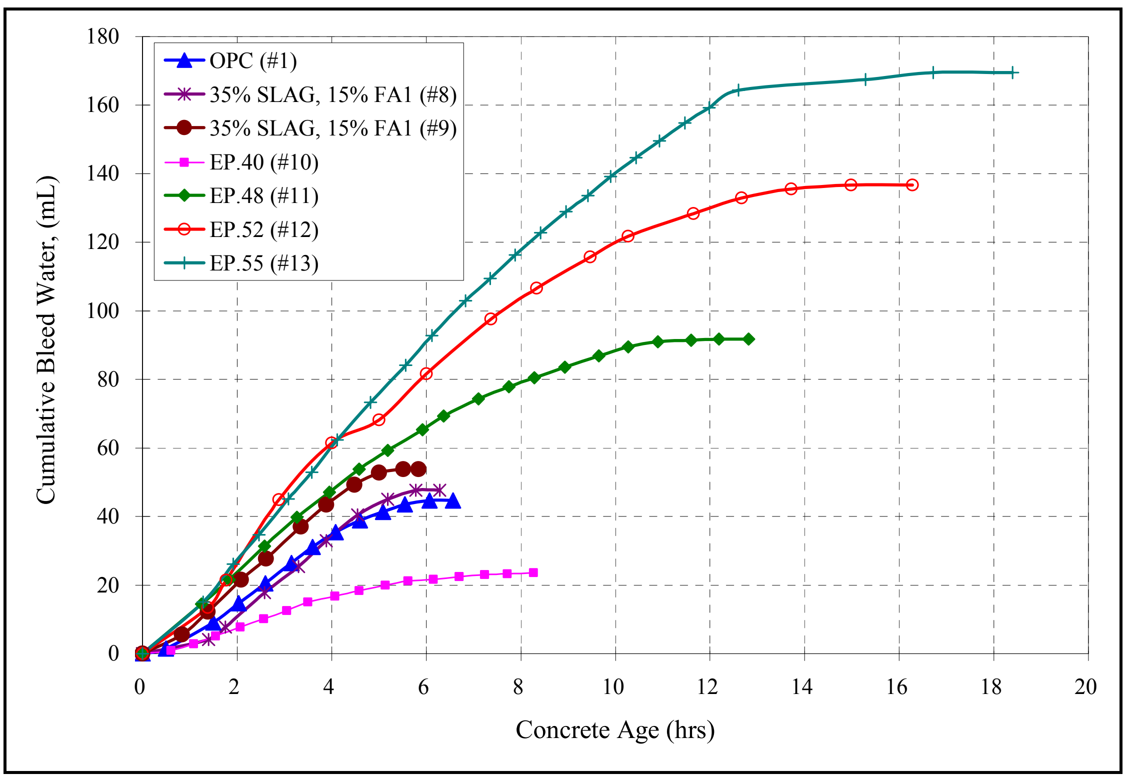

Figure 4.15: Cumulative bleed water vs. time from mixing for control and slag mixes

4.3.4 Analysis of Results

Although much information can be gained from plots of compressive strength and setting time versus concrete age, even more can be obtained by examining the plots of compressive strength versus final set time as shown in Figure 4.16 and Figure 4.17. The mixes are divided into two plots: mixes 1-9 are shown in Figure 4.16 and the El Paso mixes are shown in Figure 4.17. Trend lines have been added to the data points of all the cylinders broken at the same time (e.g., 1-day). As a result, the trend lines generally decrease from the cylinders cured under hot conditions to those cured under cold conditions.

TxDOT specifications for Class P concrete (Specification 360, 2004) currently state that the designed 7-day compressive strength should meet a minimum average of 3,500 psi. The 7-day job control compressive strength requirement is 3,200 psi. Both are marked on Figures 4.16 and 4.17. The 7-day strengths are indicated by circles in Figures 4.16 and 4.17. The specimens with 7-day strengths higher than the lines indicating the specifications pass the specification. It can be seen that some samples that have significantly delayed final setting times (> 10 hours) still pass the 7-day strength specifications. This is true for the cold mixes 1-9 (one exceeds the 3,500-psi requirement and two exceed the 3,200-psi requirement) and many of the El Paso mixes at all temperatures. Because "false positives" are unacceptable, the 7-day strength is not a good indicator of whether or not the concrete had an adequate setting time.

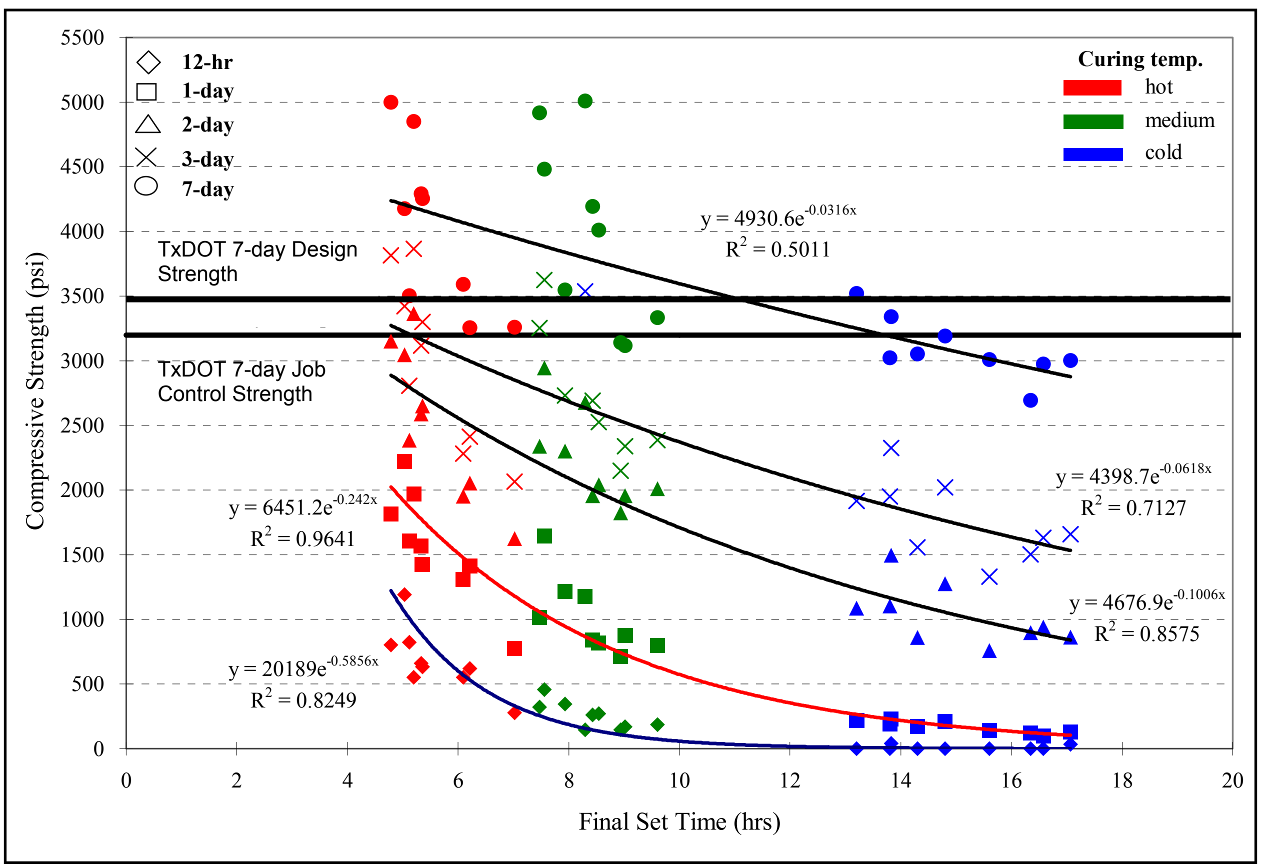

Figure 4.16: Compressive strength vs. final set time for mixes 1-9

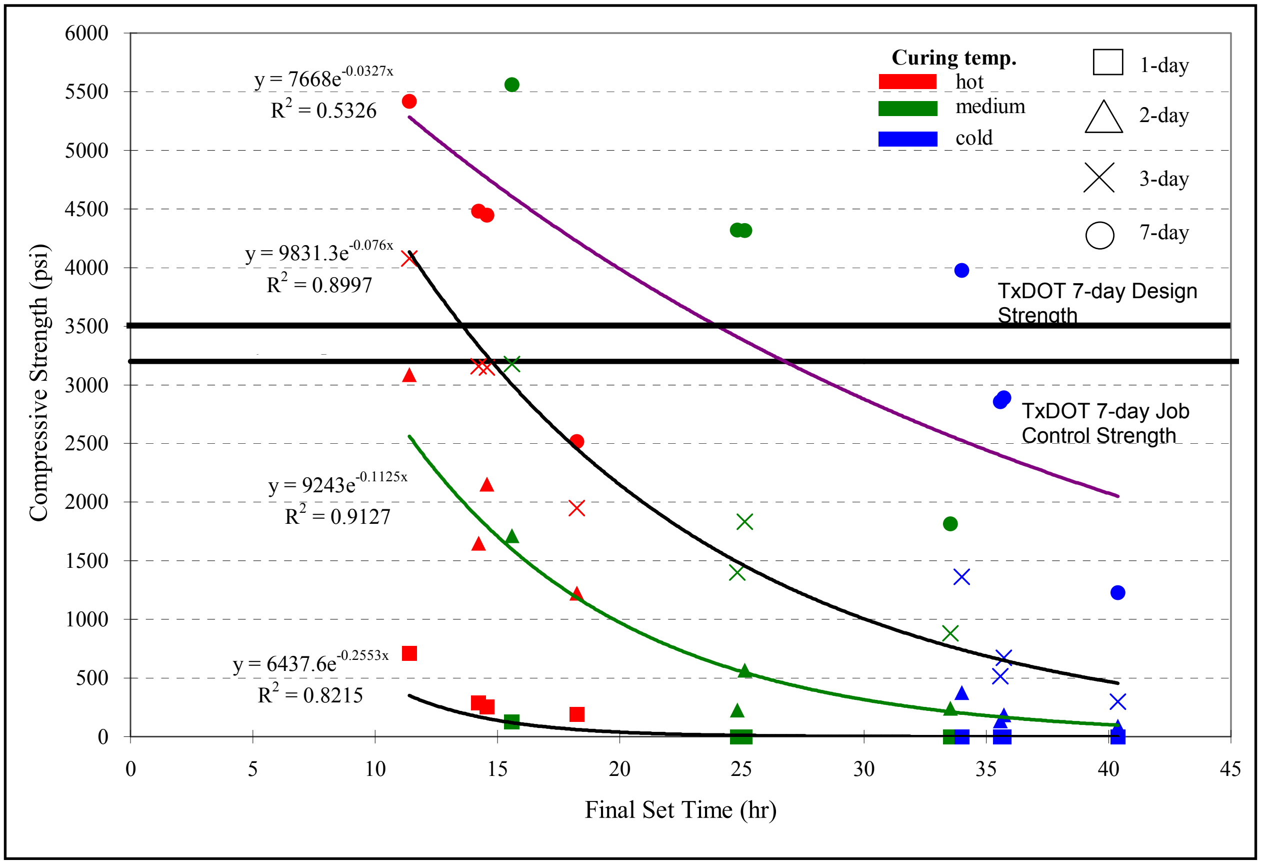

Figure 4.17: Compressive strength vs. final set time for El Paso mixes

While the 7-day strength is not a good way to identify delays in final setting time, the 1-day strength is. Mixes with significantly delayed setting all had very low 24-hour strengths (< 500 psi). Mixes with adequate final set times all had 24-hour strengths above 500 psi. It appears, therefore, that the 1-day strength of concrete is a much better indicator of delayed setting than the 7-day strength

The following observations can be noted from Figures 4.16 and 4.17 and Table 4.3. These observations are true for the mixes used in this project but may not be accurate for different curing temperatures and mix proportions.

1. 1-day strength is the best indicator of a delayed set time. Almost all mixes with 1-day strengths of 500 psi or greater have adequate setting times.
2. 7-day strength is a poor indicator of delayed set time. A few mixes pass the TxDOT 7-day strength specifications of 3,200 and 3,500 psi, yet have final set times greater than 10 hours, particularly the El Paso mixtures. However, most mixes that reach final set within 10 hours satisfy the TxDOT 7-day strength specifications. This means that the test has many false positives, but few false negatives.

4.4 Plastic Shrinkage

Although six plastic shrinkage tests were conducted, none of the specimens cracked. This can be attributed, in part, to the relatively small dimensions of the specimens, which were restricted by the size of the environmental chamber. There is currently no standard procedure for this test, and standards that are being developed are not suitable for correlating laboratory results to field results. The standard plastic shrinkage tests under development are being used to gauge the effectiveness of fibers, for example, to reduce cracking, not to predict crack susceptibility in the field.

We recommend that any future plastic shrinkage tests use concrete specimens of at least several feet in length to provide the restraint necessary for shrinkage cracking to occur.

Chapter 5. Proposed Guidelines

5.1 Findings

1. 1-day strength is the best indicator of a delayed set time. Almost all mixes with 1-day strengths of 500 psi have adequate setting times.
2. 7-day strength is a poor indicator of delayed set time. Many mixes pass the TxDOT 7-day strength specifications of 3200 and 3500 psi, yet have final set times greater than 10 hours, particularly the El Paso mixtures. However, most mixes that reach final set within 10 hours satisfy the TxDOT 7-day strength specification. This means that the test has many false positives, but few false negatives.

5.2 Recommendations

Based on the results from this project as well as a review of the literature, recommendations can be divided into two categories: prevention of delayed setting and early identification of potential problems related to delayed setting.

5.2.1 Prevention of delayed setting

Ideally, concrete mixtures that will experience delayed setting should be identified prior to placement in the field. This demands that all concrete mixtures to be used in the field first be evaluated for set times and early strength at the temperatures expected during paving on the project. At this point, the most accurate technologies available for detecting the potential for delayed setting of concrete mixtures are not simple enough for use in the field. However, in most cases, delayed setting can be prevented by following the recommendations below:

- Setting time problems should be identified before field placement through testing of the trial batches. Testing the 24-hour compressive strength of a mix cured *under similar temperature conditions to the field* gives an indication of setting time. The results of this project show that 24-hour strength greater than 500 psi indicates that the mix set in a reasonable window of time (final set < 10 hours).
- Actual delivered mixture proportions in field concrete should be monitored to ensure that they do not deviate from the approved mix designs. If the source of fly ash, cement or chemical admixtures changes, the mixture must be re-evaluated as specified in Item 421 and appropriate adjustments made.
- *The manufacturer's recommended dosage of chemical admixtures should not be exceeded.* The dosage should be calculated using the manufacturer's guidelines, particularly with regard to dosing based on the total weight of cement in the mixture or based on the total weight of cementitious material (cement + SCM). Dosing based on cementitious material may result in the addition of too much admixture, causing delayed setting, especially during cold weather. The intended admixture dosage and SCM proportions should be discussed with the manufacturer's representative to identify any unforeseen problems with cold weather concreting.

- Admixture dosage *in the field* must be monitored closely and recorded accurately on the batch ticket.

5.2.2 Early identification of problems related to setting

If the described procedures are not followed, it is possible that some concrete mixtures will experience delayed setting. Early identification of potentially problematic mixtures is possible, before performance problems set in. Compressive testing of field cylinders (stored outdoors) at 24-hours will help identify problems. 24-hour compressive strengths less than 500 psi indicate that the concrete might have potential problems due to delayed setting. The mixture designs must then be evaluated to identify the cause of the delayed setting, and appropriate adjustments must be made.

Chapter 6. Summary and Conclusions

The substitution of a portion of cement in concrete with supplementary cementing materials (SCM) occasionally results in delayed setting and low early strength. When SCM-containing concrete is placed during cold weather and/or contains certain chemical admixtures, these problems can intensify and can seriously impact the performance of a pavement. The El Paso district was particularly concerned with these problems, so this project investigated setting time and early strength of concrete mixtures specific to El Paso. The mixtures were examined for setting and early strength under three realistic pavement temperature conditions (mimicking hot, medium, and cold weather). Concrete mixtures were also examined for maturity, bleeding, and plastic shrinkage cracking.

For the mixtures and materials tested, it was observed that slag had no significant effect on setting time. Fly ash increased setting time, with the fly ash from the Monticello (FA1) plant delaying set more than that from the Escalante plant (FA2). Slag had little effect on early compressive strength and actually increased strength at 3 to 7 days. Fly ash decreased early strength. For mixtures where the amount of water reducer substantially exceeded the manufacturer's recommended dosage, both the setting time and early strength were seriously compromised. Bleeding time roughly correlated with setting time. Slag slightly decreased the amount of bleed water, as did the Escalante ash (FA2). The fly ash from the Monticello plant (FA1) increased the amount of bleed water. None of the plastic shrinkage specimens cracked during testing.

Because a goal of this project was to find a means of identifying and avoiding concrete mixtures that will experience slow setting times, particularly in cold weather, the data collected were analyzed to discern trends in setting time. It was observed that all mixtures that experienced significant delays in setting time (final set > 10 hours) also had 1-day strengths less than 500 psi. Because the current TxDOT specification is limited to 7-day testing, the 7-day strengths were also examined. Many mixes with final setting times greater than 10 hours passed the 7-day strength criteria of 3,200 or 3,500 psi. Therefore, compressive strength testing at 7 days will not identify mixes with setting time problems. Testing trial mix laboratory specimens cured under realistic temperature conditions at 1 day will identify mixtures with delayed setting times. Testing field mixtures at 1 day will enable identification of slow-setting mixtures in the field.

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Appendix A: Material Properties

Table A-1: Mill sheet for Rio Grande - Samalayuca Type I/II cement

STANDARD CHEMICAL REQUIREMENTS	ASTM SPECIFICATIONS Type II		Rio Grande Samalayuca Cement
Silicon Dioxide (SiO_2) - %	Minimum >	20.0	20.73
Aluminum Oxide (Al_2O_3) - %	Maximum >	6.0	4.73
Ferric Oxide (Fe_2O_3) - %	Maximum >	6.0	3.22
Calcium Oxide (CaO) - %		*	64.34
Magnesium Oxide (MgO) - %	Maximum >	6.0	1.81
Sulfur Trioxide (SO_3)- %	Maximum >	3.0	2.63
Loss on Ignition - %	Maximum >	3	2.40
Insoluble Residue - %	Maximum >	0.75	0.28
Tricalcium Silicate (C_3S) - %		*	60.50
Dicalcium Silicate (C_2S) - %		*	13.79
Tricalcium Aluminate (C_3A) - %	Maximum >	8.0	7.09
Tetracalcium Aluminoferrite (C_4AF) - %		*	9.80
C_4AF + 2 (C_3A) or C_4AF + C_2F - %		*	23.97
Alkalis (Sodium Oxide Equivalent) - % *	Maximum >	0.6	0.51
STANDARD PHYSICAL REQUIREMENTS			
Specific Surface , Wagner ,m^2/kg	Minimum >	160	215
Specific Surface , Blaine ,m^2/kg	Minimum >	280	330
- 325 Mesh - %		*	91.3
Compressive Strengths, psi (MPa)(C 109 cubes)			
1 DAY		*	1555 (10.7)
3 DAYS	Minimum >	1500 (10.0)	3045 (21.0)
7 DAYS	Minimum >	2500 (17.0)	4030 (27.8)
28 DAYS	Minimum >	*	
Time of Setting (Vicat)			
Initial, minutes	Minimum >	45	130
Final, minutes	Maximum >	375	185
False Set - % *	Minimum >	50	94
Air Content of Mortar - %	Maximum >	12	8.3
Autoclave Expansion - %	Maximum >	0.8	0.09
Mortar Bar Expansion (ASTM C -1038) - %	Maximum >		
(Sodium Oxide Equivalent) MIN.	0.49	MAX	0.54

*Optional

Table A-2: Chemical components of fly ash #1

SiO_2 – 55.72
Al_2O_3 – 19.42
Fe_2O_3 – 4.23
CaO – 13.14
MgO – 2.94
SO_3 – 0.47
Na_2O – 0.82
K_2O – 0.85

Table A-3: Material properties of fly ash #2

Date	SiO_2	Al_2O_3	Fe_2O_3	Sum	CaO	MgO	SO_3	M.C.	L.O.I	Avail Alk as Na_2O	Na_2O
Last two mill certs											
8/9/2005	60.81	24.73	5.25	90.79	3.83	1.76	0.22	0.06	0.21	1.1767	0.42
9/8/2005	61.85	25.03	4.81	91.69	3.86	1.87	0.22	0.1	0.2	1.6944	0.51
Most recent chemical analysis performed by TXDOT											
2/7/2006	60.96	25.13	4.49	90.58	4.28	1.09	0.28	0.07	0.36	1.08	0.38
3/15/2006	59.88	24.21	4.82	88.91	5.10	1.19	0.33	0.06	0.18	1.09	0.34
Date	K_2O	R-factor	Fineness	Variation	Density	Variation	7-day	28-day	Water Req	Soundness	
Last two mill certs											
8/9/2005	1.15	-0.22	30.2	0.13	2.14	0.03	83.86	84.11	97.52	0.01	
9/8/2005	1.8	-0.24	30.2	0.19	2.26	0.1	76.07	85.11	98.35		
Most recent chemical analysis performed by TXDOT											
2/7/2006	0.38	1.07									
3/15/2006	0.34	1.14									

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New Orleans Slag Facility

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MILL TEST REPORT
AUCEM GGBFS - ASTM C-989
Grade 120

Slag Activity Index

	Month Avg		5 Day Moving Avg	
	(% of Reference)			
	Aucem	ASTM(min)	Aucem	ASTM(min)
7 Day	102	90	102	95
28 Day	126	110	126	115

Compressive Strength

	7 Day Psi	28 Day Psi
Slag/Reference Cement Performance	5,100	7,680

Slag Chemical Data

	Aucem	ASTM(max)
Sulfide Sulfur	0.75%	2.5%
Sulfate (SO3)	0.35%	4.0%

Slag Physical Data

	Aucem	ASTM(max)
Blaine	5520	n/a
#325 (Ret.)	0.45%	20.0
Spec.Gravity	2.91	n/a
Air Content	5.3%	12.0

By____________________________
Ronald J. Rajki
Quality Manager

Figure A-1: Slag material properties

Table A-4: Coarse aggregate properties from 3 stockpile samples

Sample	G_{SSD}	G_{BULK}	AC
1	2.70	2.68	0.646%
2	2.71	2.70	0.638%
3	2.70	2.68	0.616%
Average	2.70	2.69	0.633%

G_{SSD} = Saturated surface- dry specific gravity
G_{BULK} = Bulk specific gravity
AC = absorption capacity

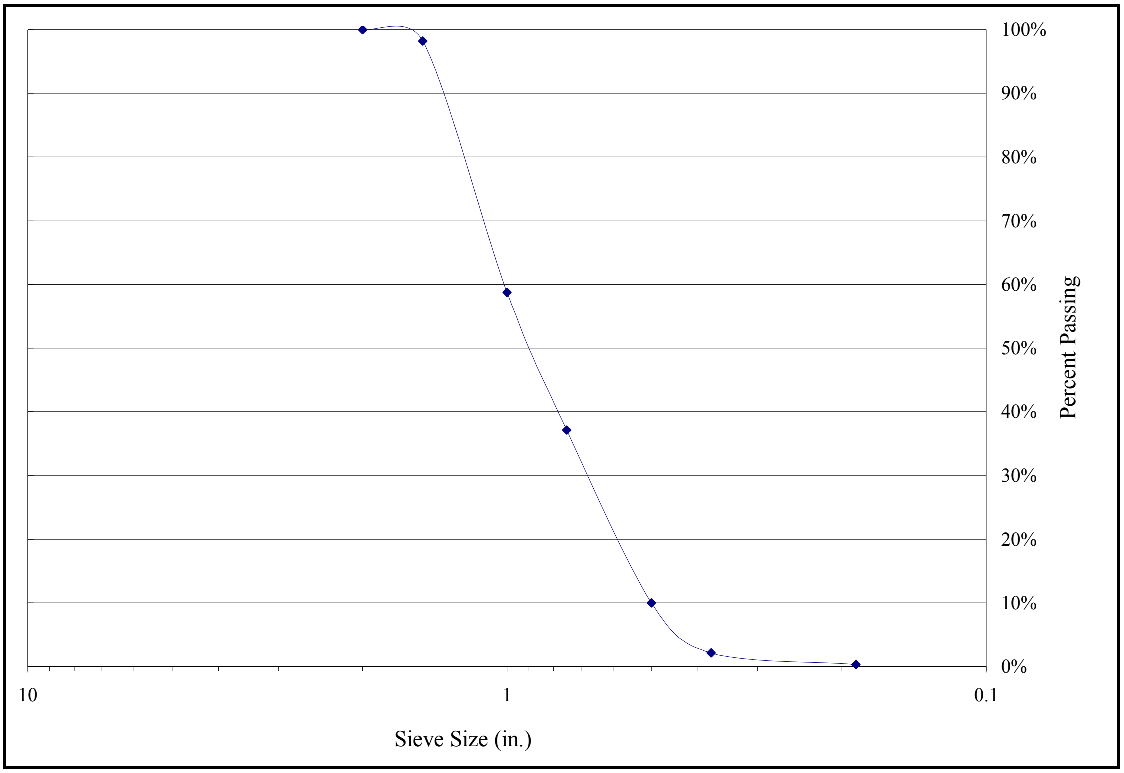

Figure A-2: Average coarse aggregate gradation from 3 stockpile samples

Table A-5: Fine aggregate properties (from 3 stockpile samples)

Sample	G_{SSD}	G_{BULK}	AC
1	2.58	2.56	0.950%
2	2.60	2.57	1.068%
3	2.60	2.57	1.080%
Average	2.60	2.57	1.033%

G_{SSD} = Saturated surface- dry specific gravity
G_{BULK} = Bulk specific gravity
AC = absorption capacity

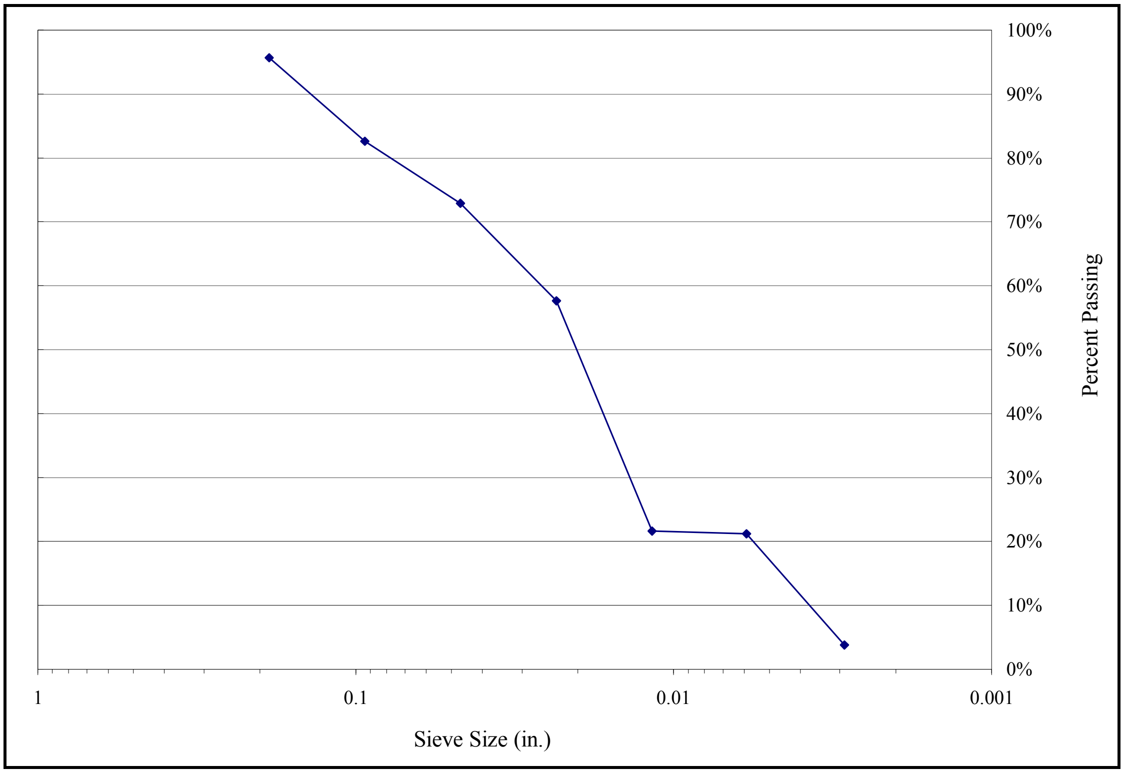

Figure A-3: Fine aggregate gradation

Appendix B: Fresh Concrete Properties

Table B-1: Fresh Concrete Properties

MIX		Slump (in.)	Air (%)	Unit weight (lb/ft^3)	Conc. temp (°F)
1	Maturity	0.75	6.0	145.2	72
	Set Time	0.75	5.6	145.0	78
2	Maturity	1.50	5.8	146.0	72
	Set Time	2.25	6.3	143.9	76
3	Maturity	3.20	7.0	143.2	70
	Set Time	1.50	5.5	147.4	80
4	Maturity	1.25	5.2	146.0	76
	Set Time	1.00	5.8	145.6	82
5	Maturity	1.50	3.5	148.0	78
	Set Time	1.00	4.2	146.8	78
6	Maturity	1.00	4.4	150.8	81
	Set Time	1.00	4.7	149.6	80
7	Maturity	1.00	4.1	149.4	81
	Set Time	0.50	4.3	149.6	73
8	Maturity	1.00	5.0	147.6	81
	Set Time	1.00	5.2	149.0	72
9	Maturity	1.25	4.4	148.0	68
	Set Time	1.50	4.5	146.8	67
EP.40	Maturity	0.50	4.0	147.2	76
	Set Time	0.50	3.6	151.6	74
EP.48	Maturity	3.25	3.7	146.0	77
	Set Time	3.50	3.4	147.0	77
EP.52	Set Time	7.75	3.9	147.4	74
EP.55	Set Time	8.50	7.6	136.0	67

Appendix C: Maturity Graphs

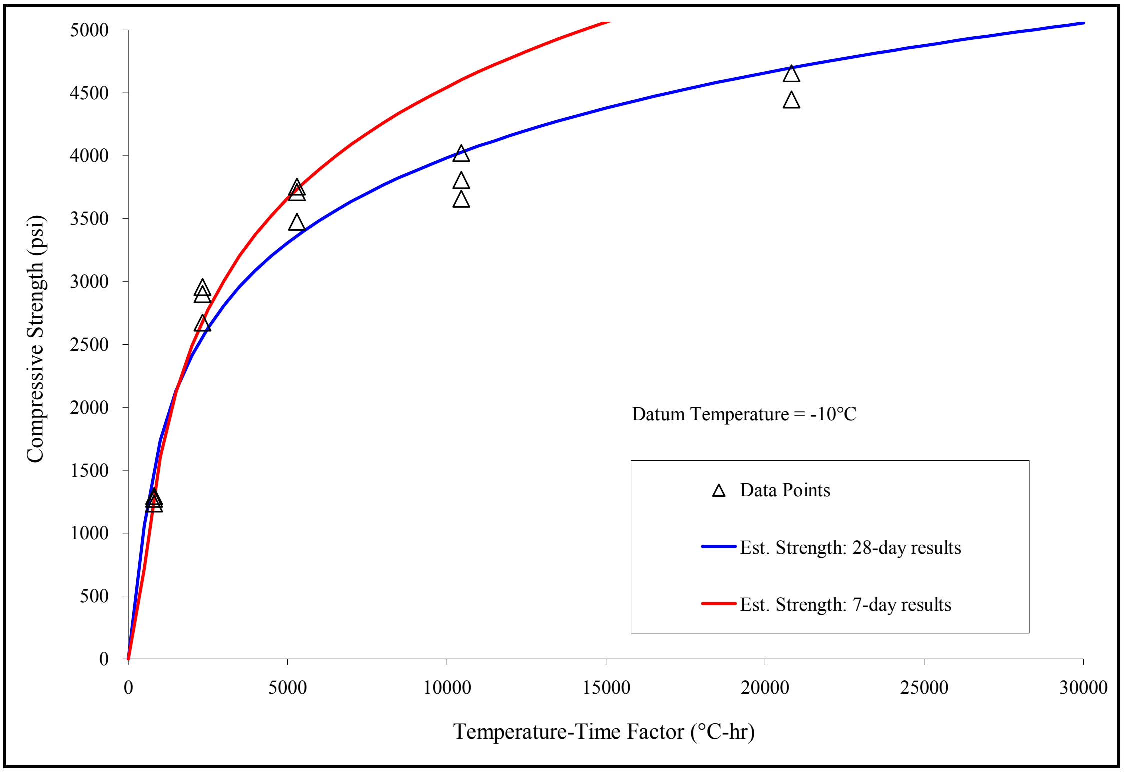

Figure C-1: Compressive strength vs. TTF: Mix 1 (OPC)

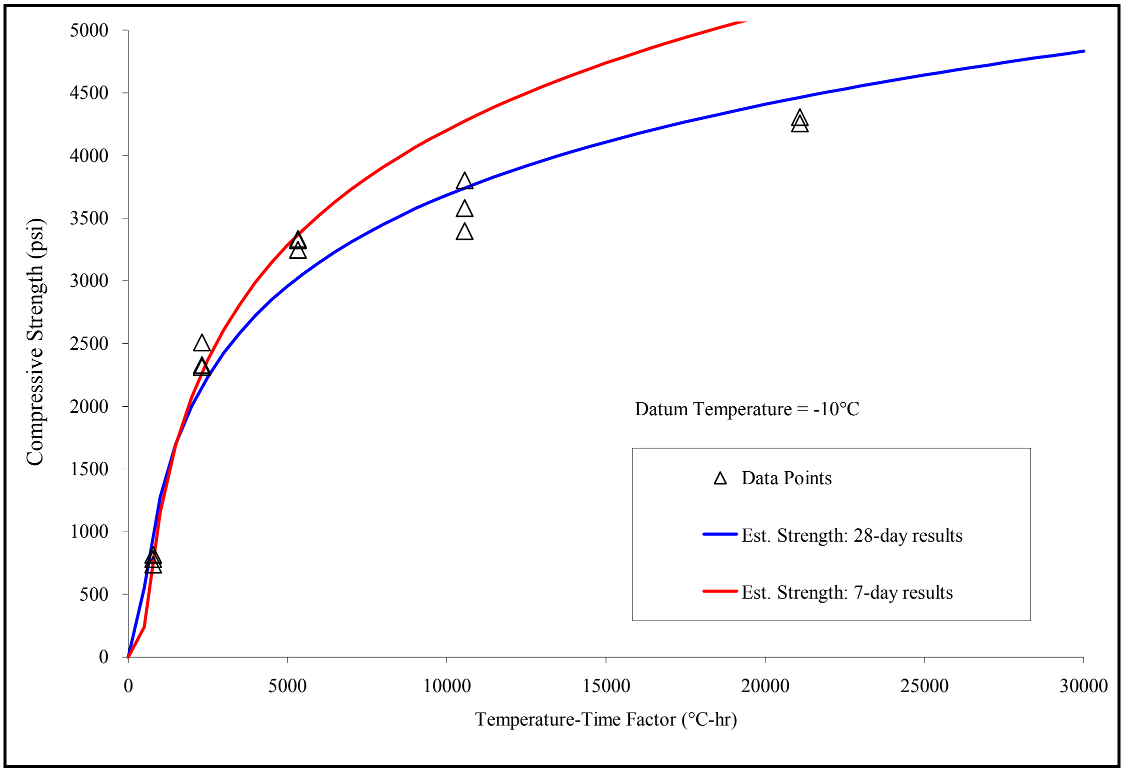

Figure C-2: Compressive strength vs. TTF: Mix 2 (20% FA1)

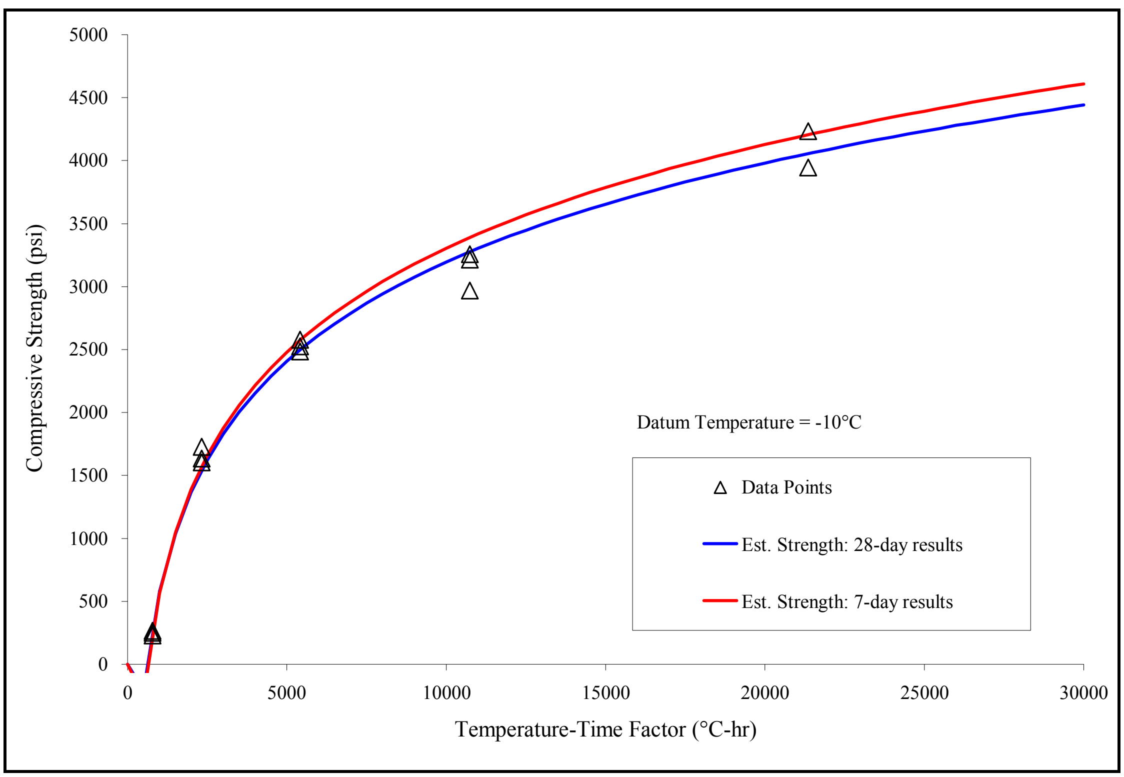

Figure C-3: Compressive strength vs. TTF: Mix 3 (35% FA1)

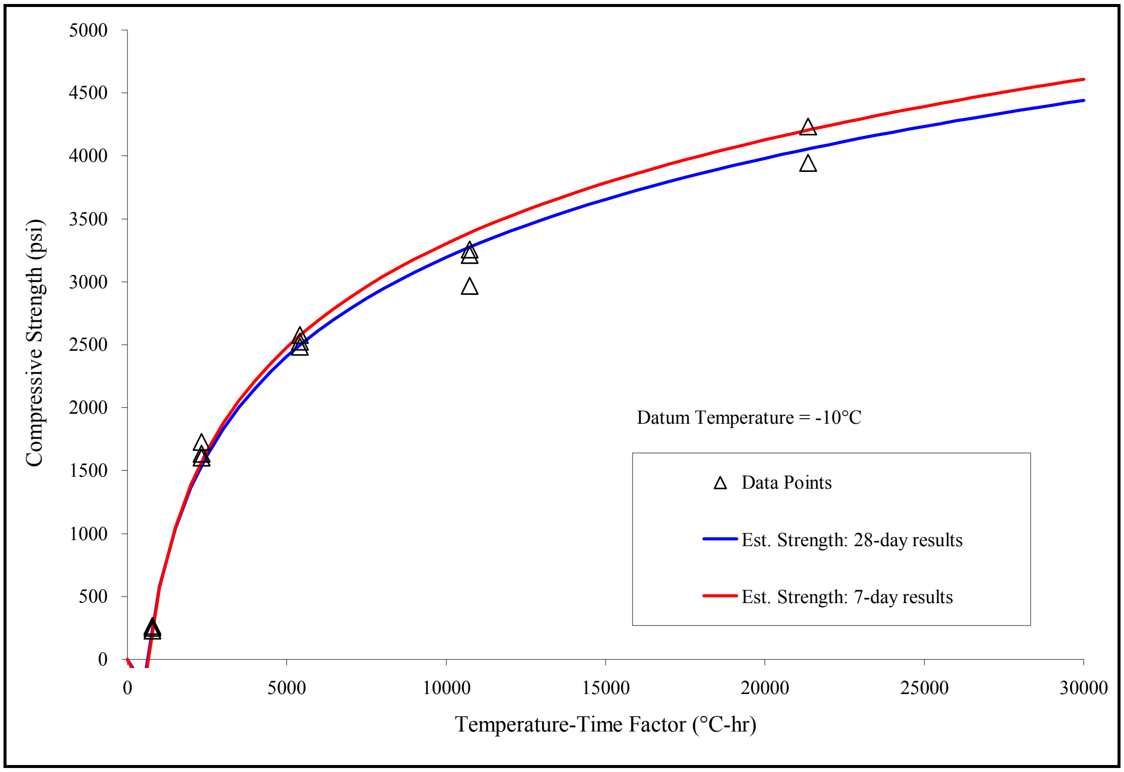

Figure C-4: Compressive strength vs. TTF: Mix 4 (20% FA2)

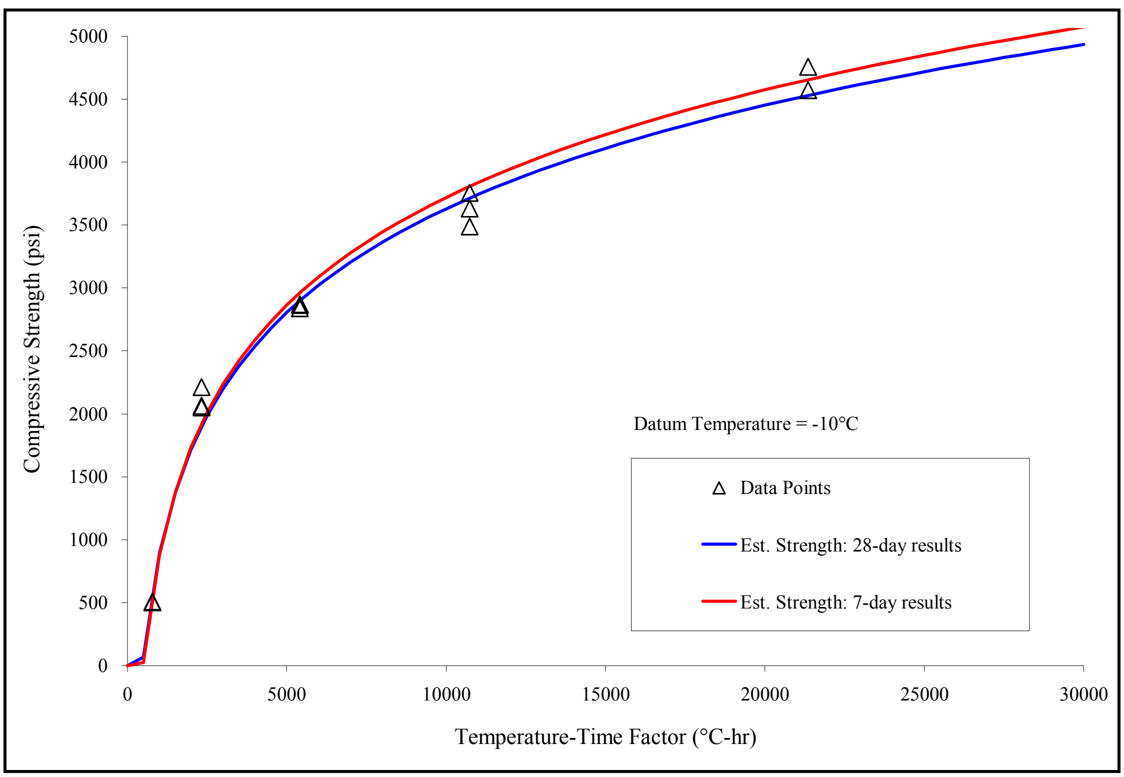

Figure C-5: Compressive strength vs. TTF: Mix 5 (35% FA2)

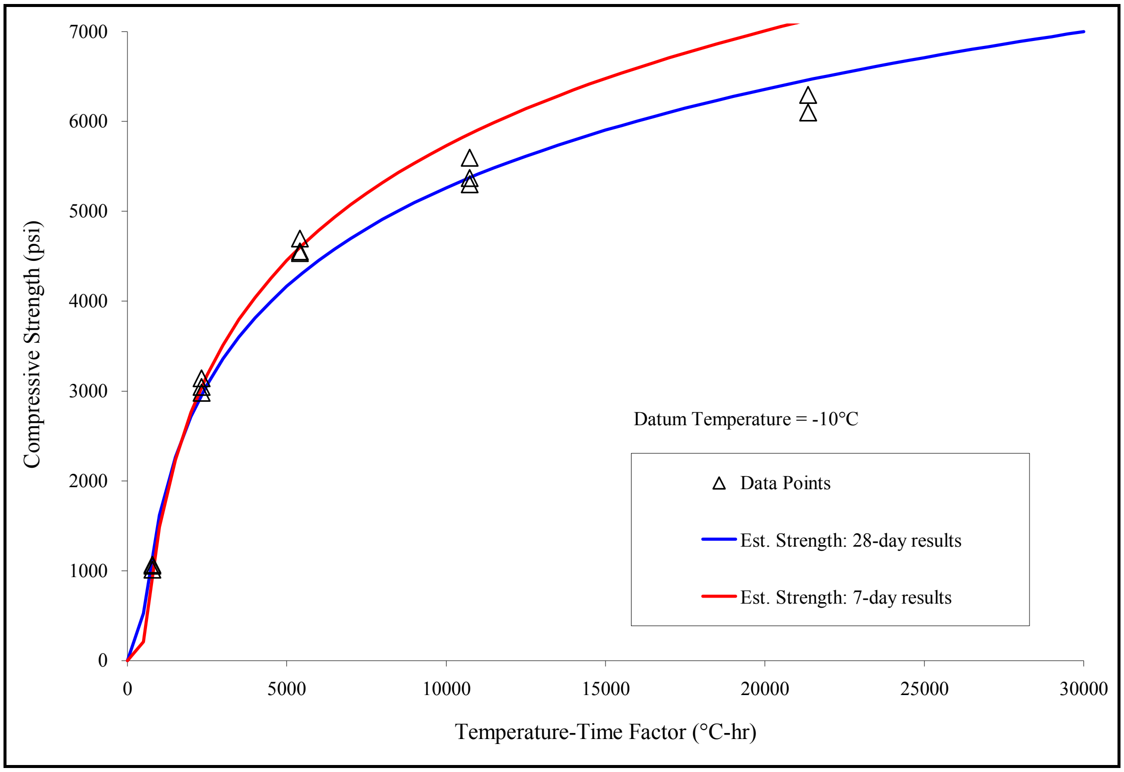

Figure C-6: Compressive strength vs. TTF: Mix 6 (35% Slag)

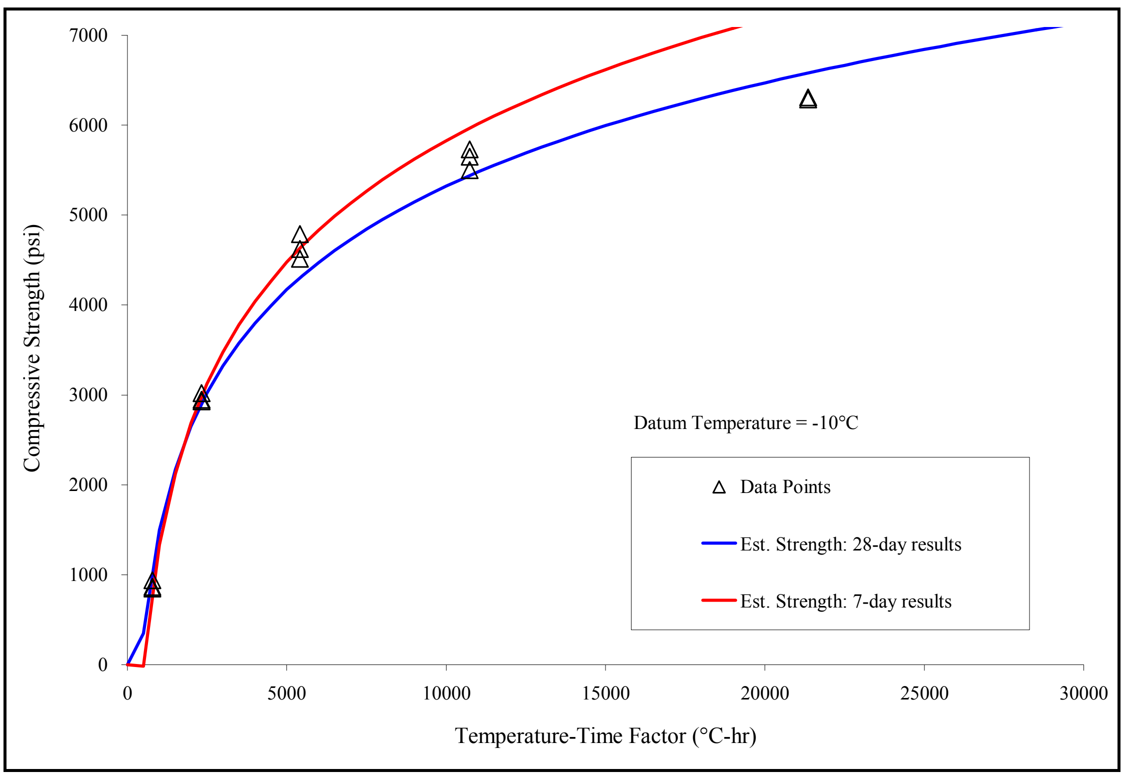

Figure C-7: Compressive strength vs. TTF: Mix 7 (50% Slag)

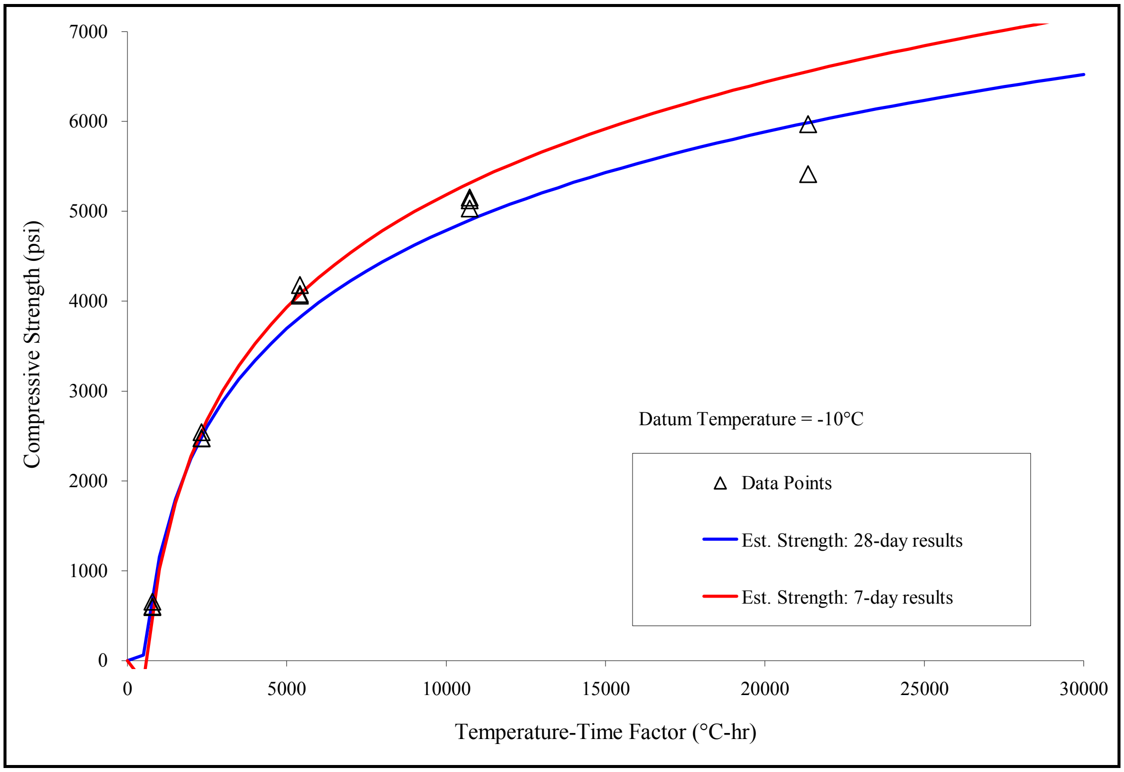

Figure C-8: Compressive strength vs. TTF: Mix 8 (35% Slag, 15% FA1)

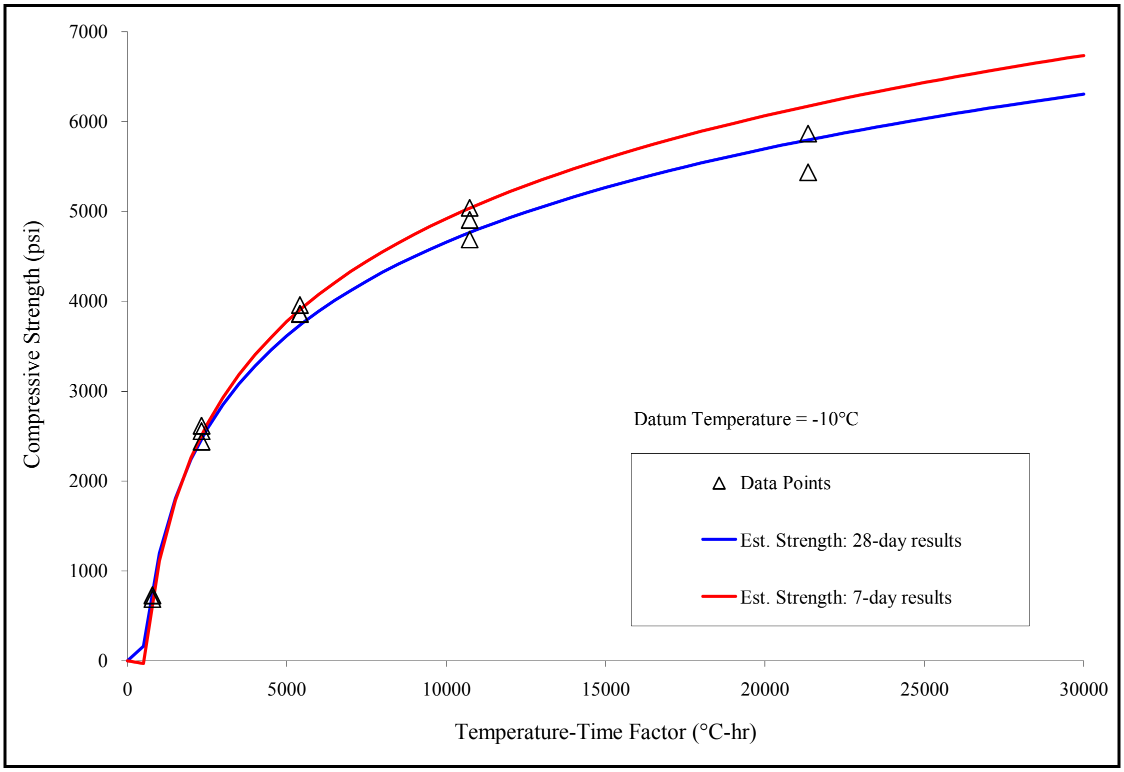

Figure C-9: Compressive strength vs. TTF: Mix 9 (35% Slag, 15% FA1, Optimum)

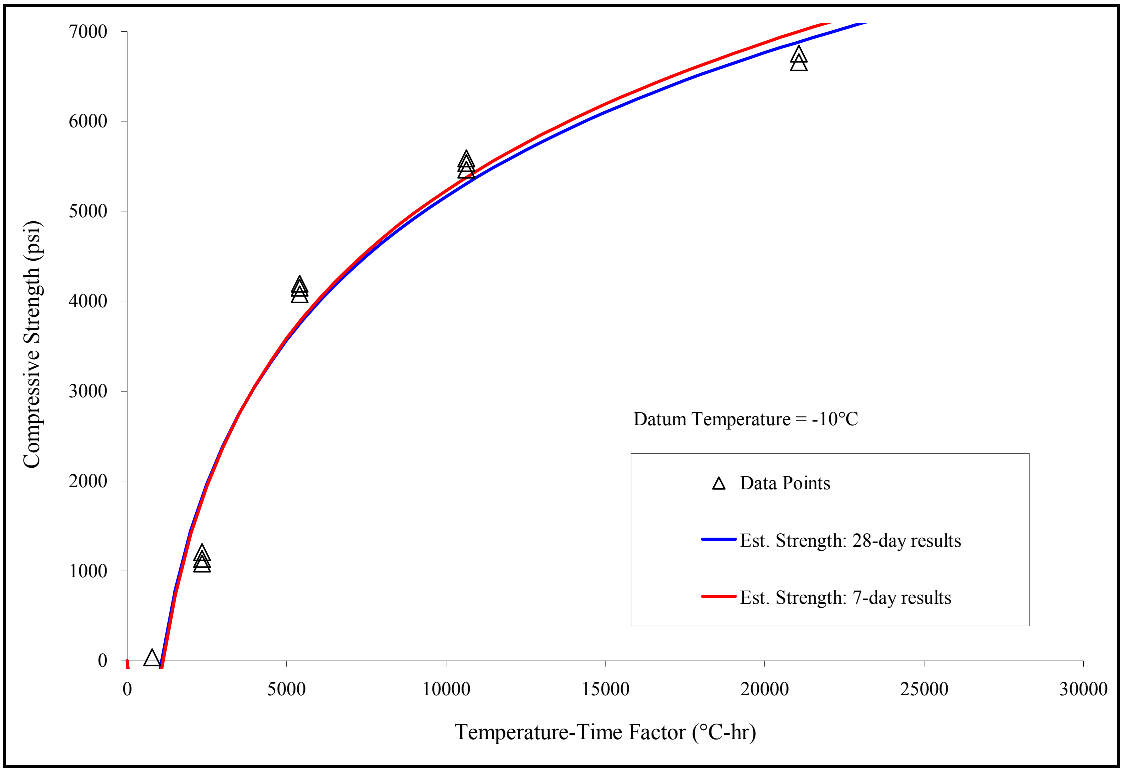

Figure C-10: Compressive strength vs. TTF: El Paso mix (w/c = .40)

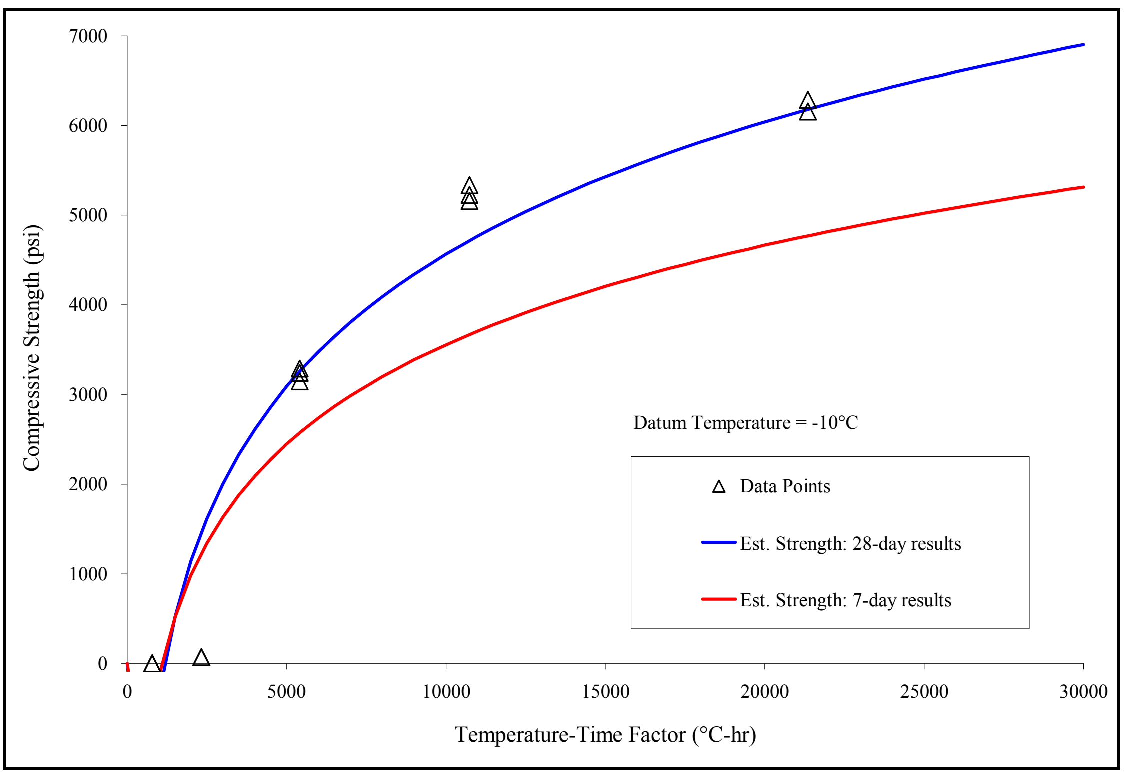

Figure C-11: Compressive strength vs. TTF: El Paso mix (w/c = .48)

Appendix D: Setting Time Graphs

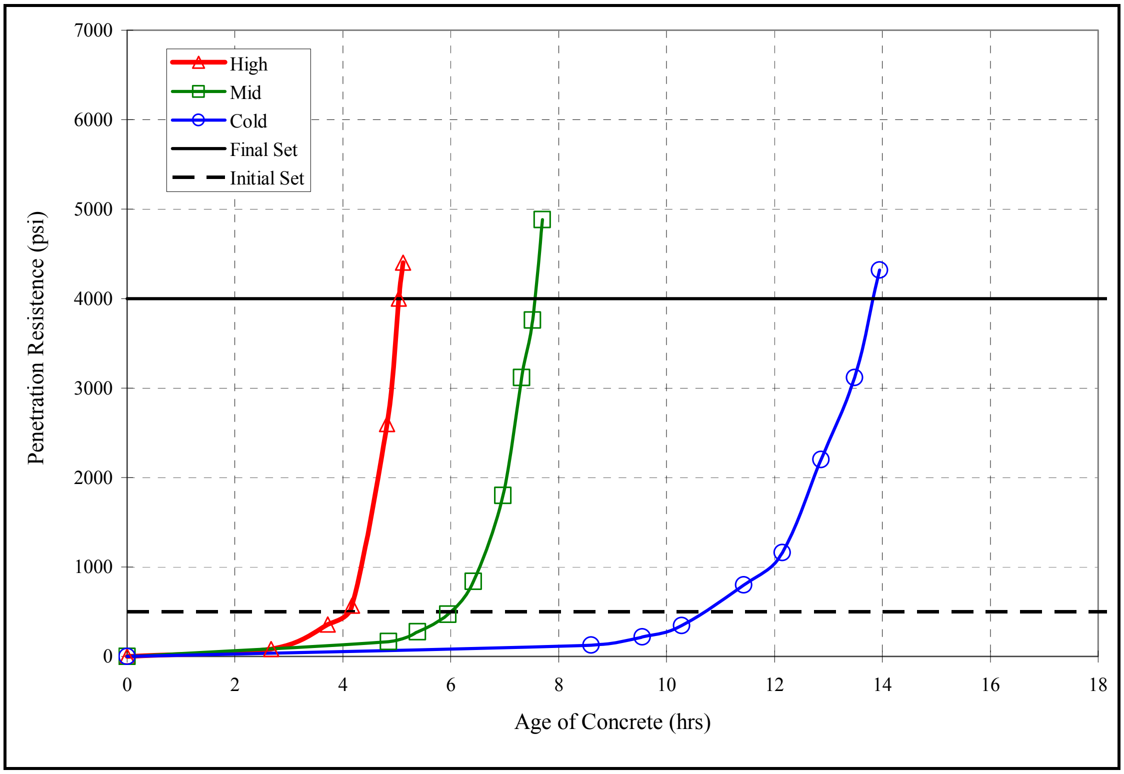

Figure D-1: Penetration resistance vs. time: Mix 1 (OPC)

Please note that lines are provided in these plots to guide the eye and do not necessarily reflect the behavior of the material between the measured data points.

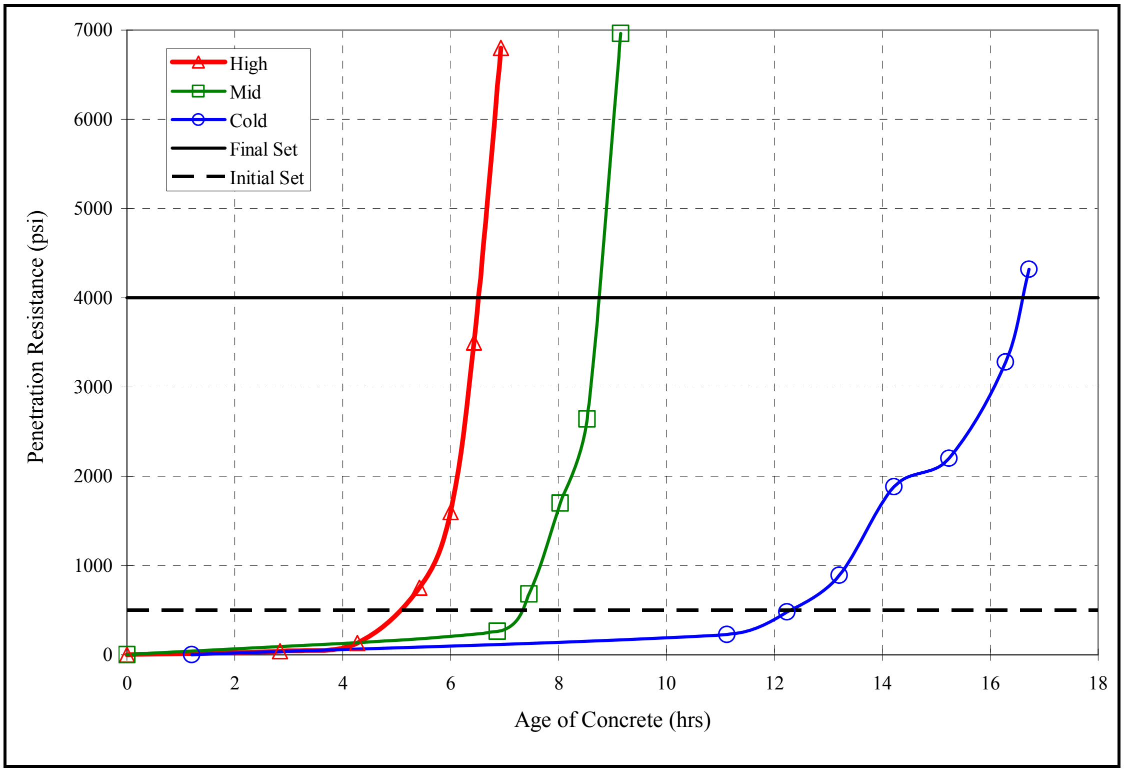

Figure D-2: Penetration resistance vs. time: Mix 2 (20% FA1)

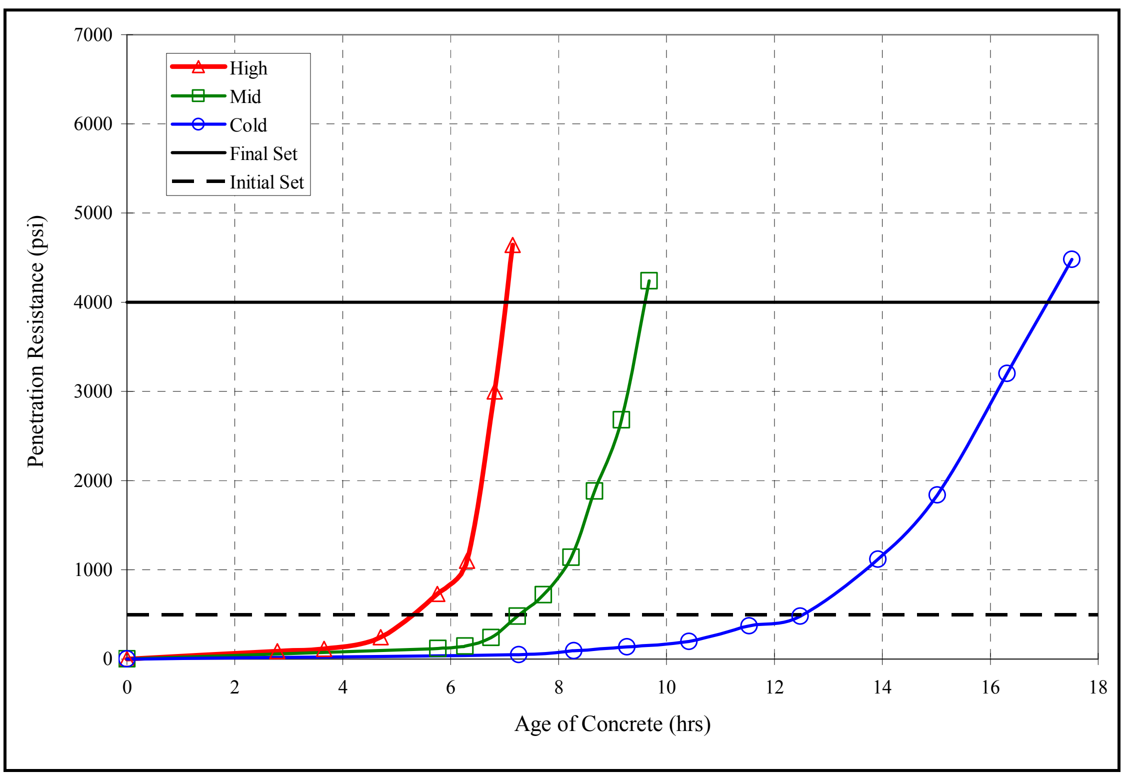

Figure D-3: Penetration resistance vs. time: Mix 3 (35% FA1)

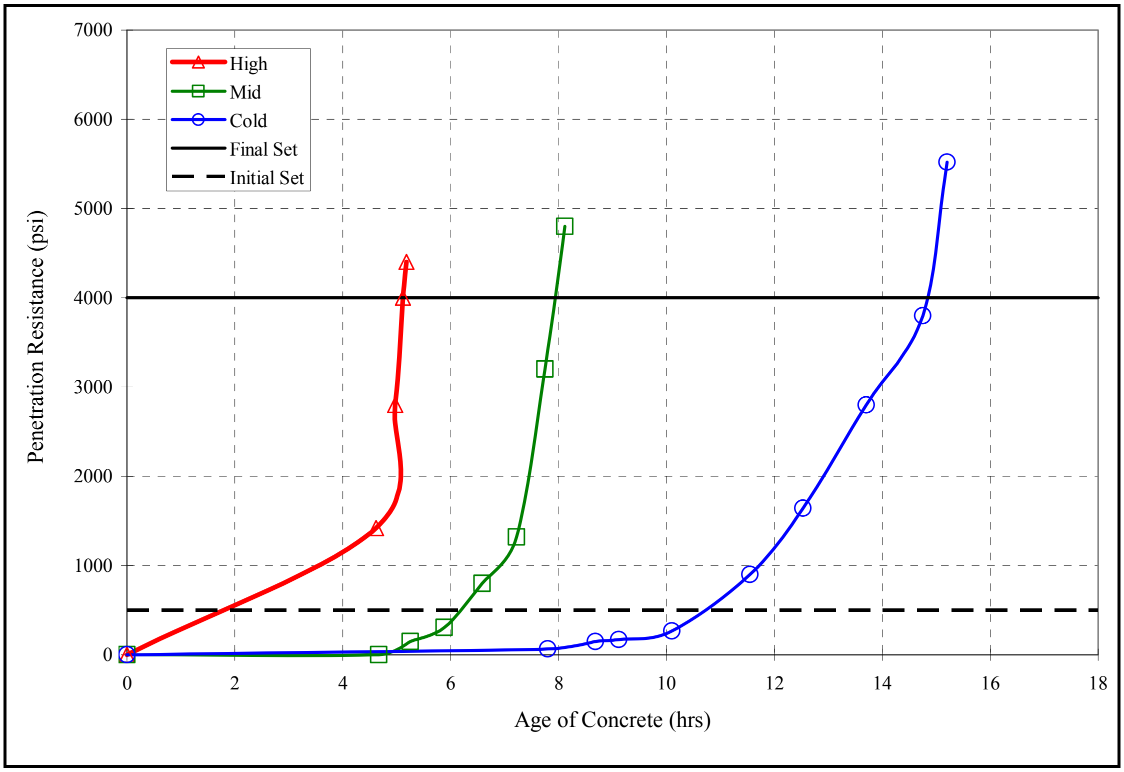

Figure D-4: Penetration resistance vs. time: Mix 4 (20% FA2)

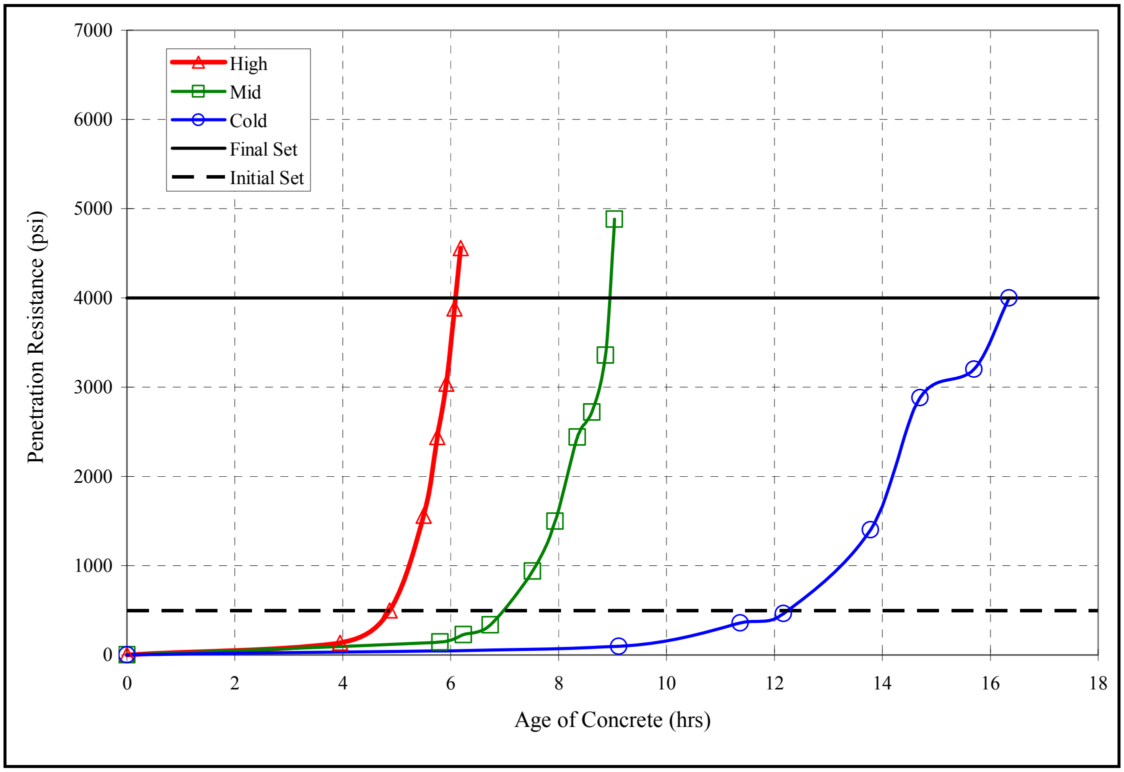

Figure D-5: Penetration resistance vs. time: Mix 5 (35% FA2)

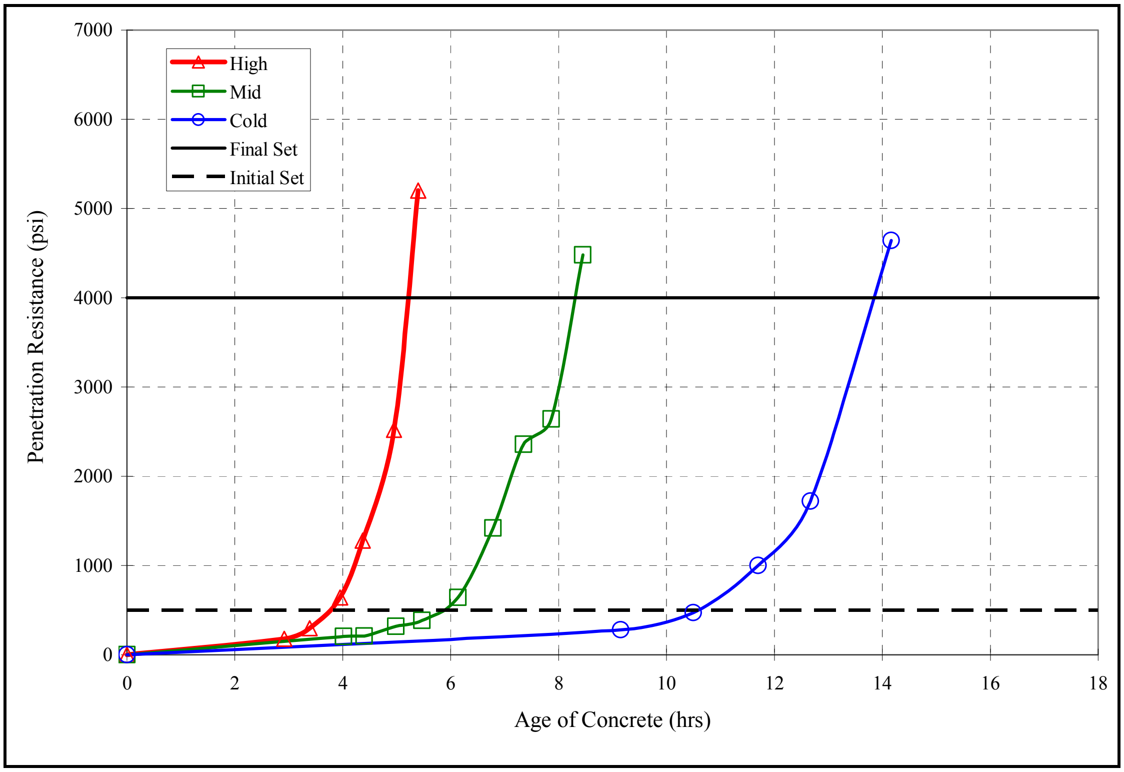

Figure D-6: Penetration resistance vs. time: Mix 6 (35% Slag)

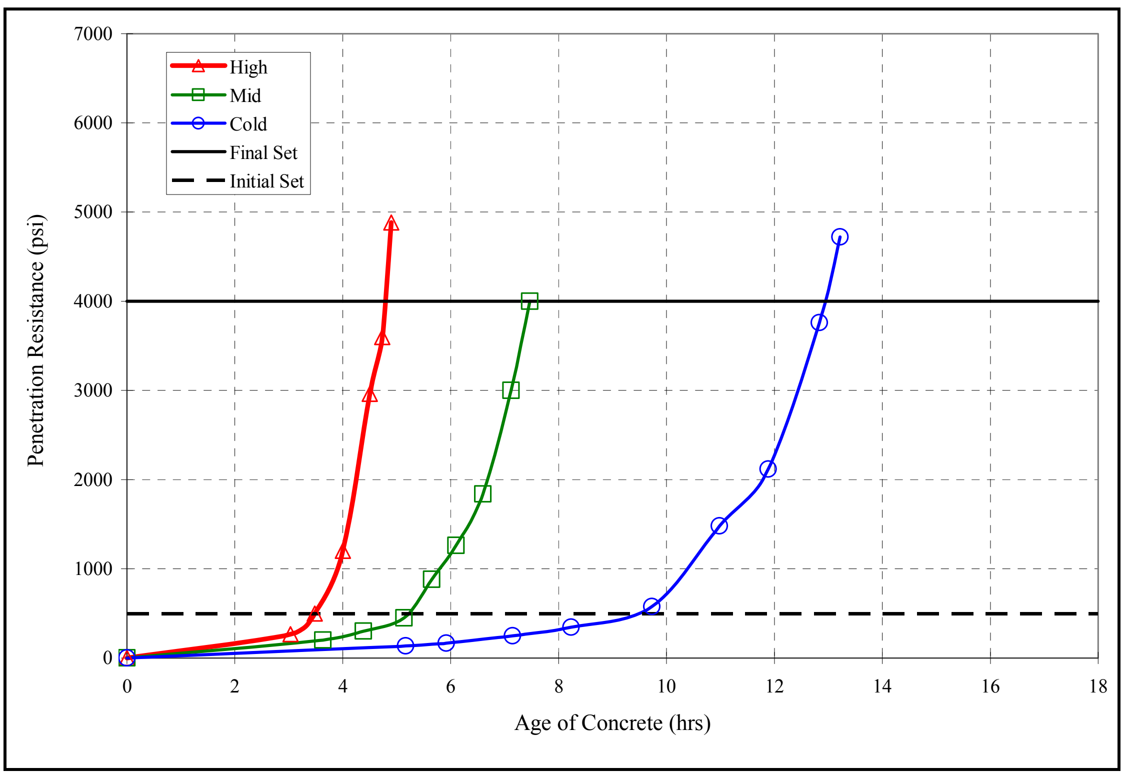

Figure D-7: Penetration resistance vs. time: Mix 7 (50% Slag)

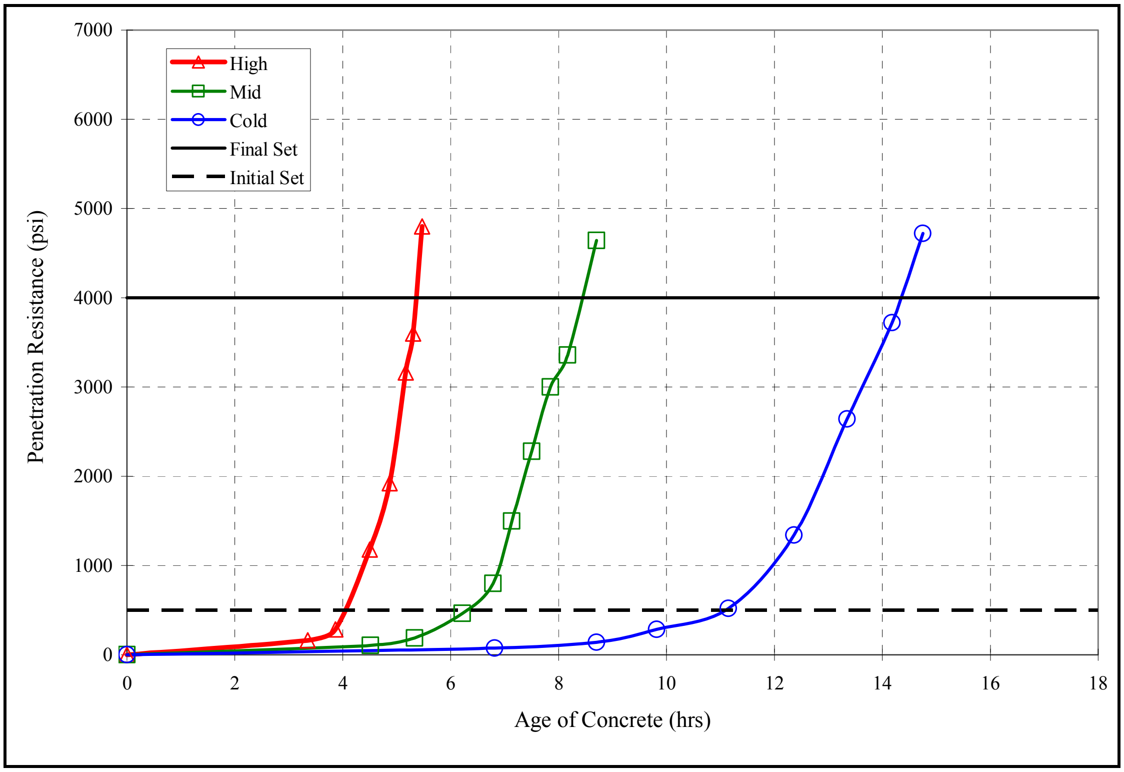

Figure D-8: Penetration resistance vs. time: Mix 8 (35% Slag, 15% FA1)

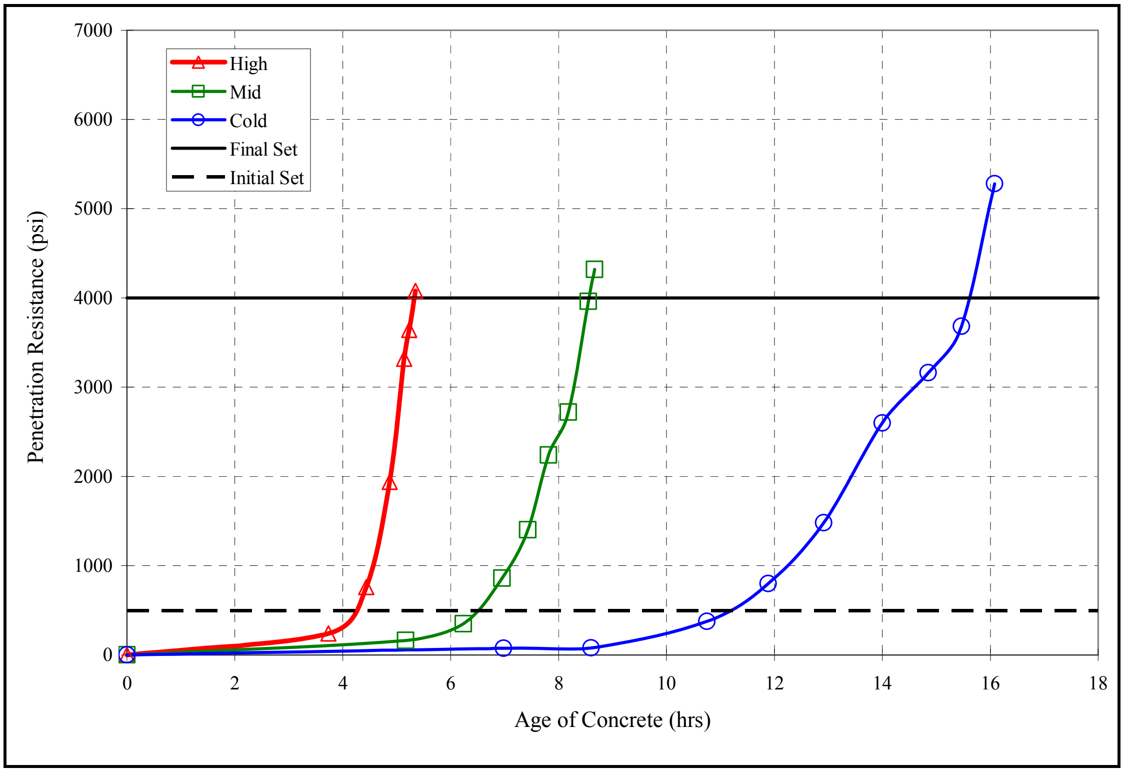

Figure D-8: Penetration resistance vs. time: Mix 9 (35% Slag, 15% FA1, Optimum)

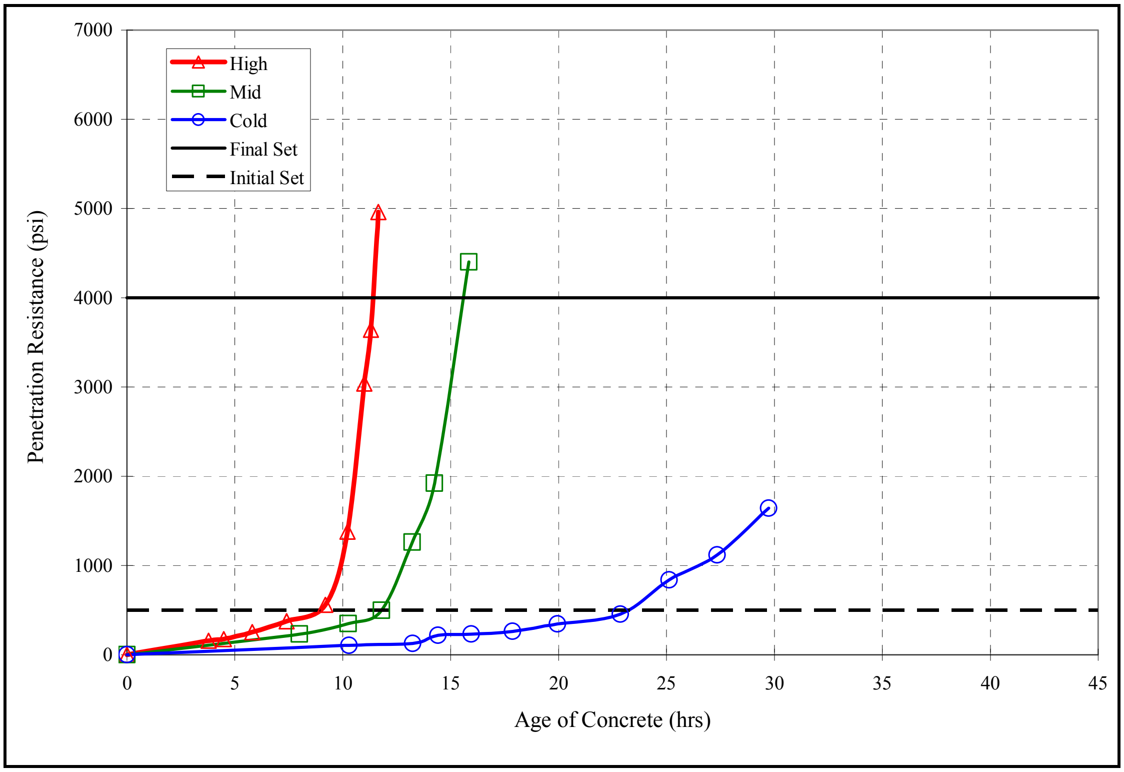

Figure D-9: Penetration resistance vs. time: El Paso mix (w/c = .40)

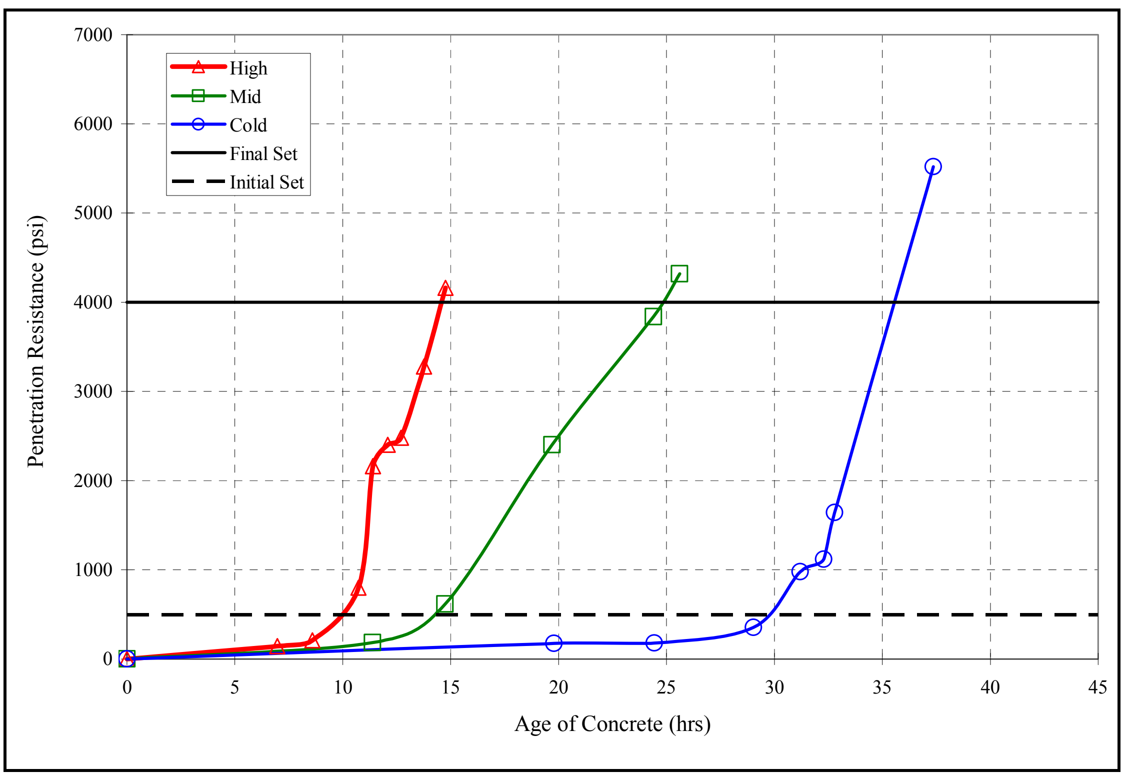

Figure D-10: Penetration resistance vs. time: El Paso mix (w/c = .48)

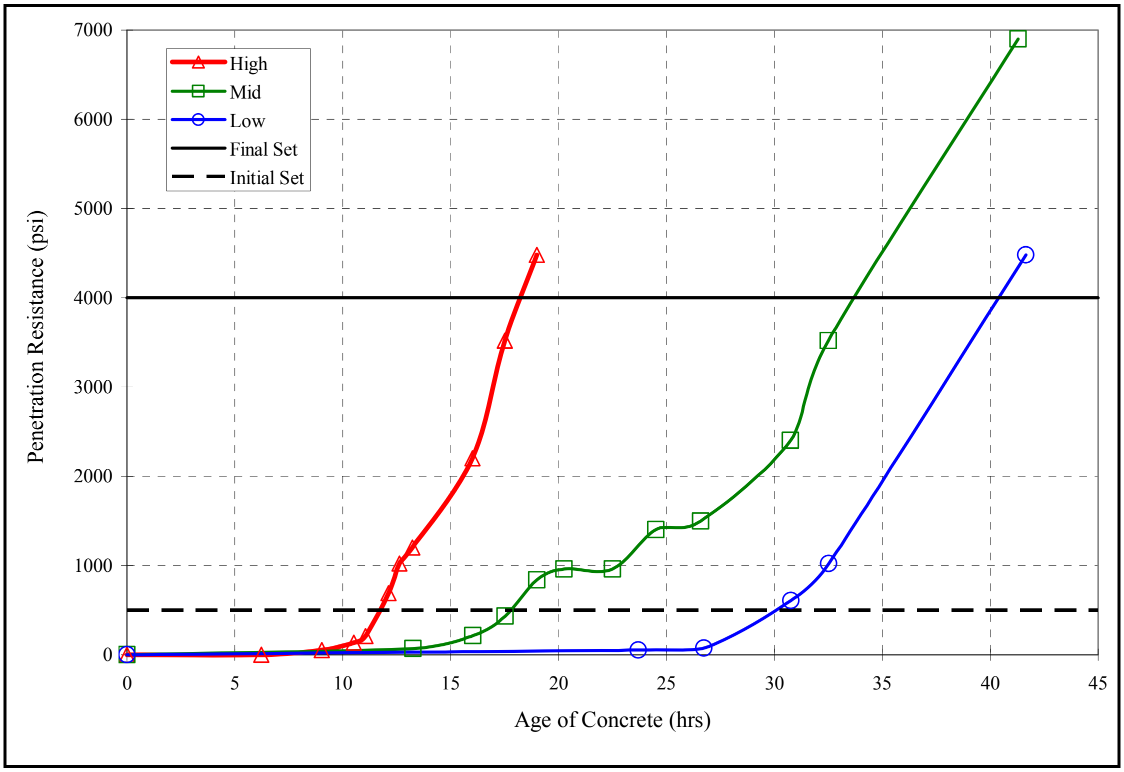

Figure D-11: Penetration resistance vs. time: El Paso mix (w/c = .55)