EVALUATION OF THE MATURITY METHOD TO

ESTIMATE CONCRETE STRENGTH

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EVALUATION OF THE MATURITY METHOD TO ESTIMATE CONCRETE STRENGTH

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ESTIMATE CONCRETE STRENGTH

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THESIS ABSTRACT

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The strength of a newly constructed concrete structure or roadway is critically important to contractors and engineers who must decide when to safely allow construction loads, prestressing operations, or opening to traffic loads. The maturity method allows the user to estimate concrete strength at any given time using the structure's unique temperature history. The purpose of this project was to analyze the effectiveness and accuracy of the maturity method to estimate concrete strengths for a variety of commonly used mixtures. The mixtures were chosen to show the effects of using various types of cements, various types and doses of supplementary cementing materials, and various water-to-cementitious materials ratios. Each mixture was batched at three different temperatures selected to span the entire range of expected conditions;

with average batch temperatures of 55°F, 70°F, and 101°F. The 70°F batch was cured isothermally at normal laboratory temperatures (68°F-73°F). The 55°F and 101°F batches were cured in water baths that cycled between 40°F - 55°F and 90°F - 106°F, respectively. From each batch, nineteen 6x12 in. cylinders were prepared. Eighteen were used for compressive strength testing at 6 different ages. One cylinder was used to record the temperature history of the batch. Compressive strength versus age data was examined. Mixtures were evaluated based on the amount of long-term strength loss or gain due to curing temperatures and the amount of "temperature sensitivity." The time-temperature histories were then converted to maturity using the Nurse-Saul and Arrhenius maturity functions. Compressive strength versus maturity data were then analyzed to determine the accuracy of estimating strengths using the maturity method.

It was found that the maturity method was inaccurate for estimating concrete strengths beyond 7 days of equivalent age, especially for mixtures with severe long-term strength loss due to high curing temperatures. A "Modified ASTM" method was proposed to handle the late-age strength problems. Then, the mixtures were evaluated using a simplified approach employing constant values of temperature sensitivity. Finally, temperature sensitivity functions were proposed based on the concrete curing temperature. The results of this study indicated that the Nurse-Saul maturity function using a datum temperature of 32°F (0°C) was the most effective and practical method for estimating concrete strengths of all mixtures studied. However, if the Arrhenius function will be used, a temperature sensitivity function is recommended to allow for a higher temperature sensitivity at low curing temperatures and a lower temperature sensitivity at high curing temperatures.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

It has long been known that freshly placed concrete behaves differently in cold and hot environments. Concrete cured in high temperatures gains strength faster than concrete cured in low temperatures. This temperature dependency causes difficulty for contractors and engineers attempting to determine the strength of concrete placed and cured at various ambient conditions. Contractors need to know the strength of a structure or roadway in order to meet deadlines for formwork removal, traffic openings, transfer of prestress force, and other construction operations dependant on strength. The maturity method, developed progressively by McIntosh (1949), Nurse (1949), and Saul (1951), gives the contractor the ability to estimate concrete strength based on the time-temperature history of the concrete in question. This is very useful because current Alabama Department of Transportation (ALDOT) practices rely on the strength of laboratory-cured cylinders to ensure desired strengths have been achieved in the actual structure. This can cause unnecessary delays, since a structure's strength gain may be significantly different than that of a test specimen due to differences in concrete volume and environmental effects. The maturity method allows the contractor to estimate the strength of a structure based on the temperature history of the structure using a predetermined strength relationship, called a strength-maturity relationship.

There have been numerous research efforts verifying the use of the maturity method to estimate concrete strength (Bergstrom 1953; Tank and Carino 1991). However, the maturity method must be used with caution. Mixture proportions must remain fairly constant, or the predetermined strength-maturity relationship becomes invalid (ASTM C 1074 2004). Also, the structure and representative cylinders must have ample moisture supplied for proper hydration of the concrete (ASTM C 1074 2004). Severe curing temperatures at early ages can also cause errors in strength estimations using the maturity method (Alexander and Taplin 1962; Carino 1991).

This study evaluated the accuracy of the maturity method used to estimate concrete strength. Thirteen concrete mixtures were evaluated at three different curing temperatures. The mixtures were chosen to show the effect, with respect to strength gain, of various types and doses of supplementary cementing materials (SCMs), as well as varying cement types, and water-to-cementitious materials ratios.

1.2 RESEARCH SIGNIFICANCE

Currently there are few state departments of transportation that have implemented specifications for estimating concrete strength using the maturity method. Some techniques can be learned from these specifications; however, the maturity method should be tested using methods and standards already used by ALDOT. Also, many past studies (Tank and Carino 1991; Carino and Tank 1992) evaluated the accuracy of the maturity method using concrete cured under isothermal temperature conditions. In order to better simulate field conditions, concrete tested in this study was cured under fluctuating curing temperatures, except for control batches which were cured isothermally at normal laboratory temperatures (68°F - 73°F).

There are two functions that are recommended for computing the maturity of concrete: the Nurse-Saul maturity function and the Arrhenius maturity function (ASTM C 1074 2004). Carino (1991) concluded that the Arrhenius maturity function estimates concrete strength better than the Nurse-Saul maturity function. However, in practice, state DOT's tend to use the less complicated Nurse-Saul maturity function (Texas DOT 1999; Iowa DOT 2000). The mixtures used in this study will be evaluated using both functions, and recommendations based on the accuracy of both functions will be made for use on ALDOT projects.

1.3 PROJECT OBJECTIVES

The objectives of this study were as follows:

1) Determine the effect of various fluctuating curing temperatures on concrete strength behavior.
2) Determine the effect of various types and doses of SCMs, varying cement types, and water-to-cementitious materials ratios on the rate of strength gain at different temperatures.
3) Determine the accuracy of the maturity method in estimating concrete strength for numerous mixtures with varying types and doses of SCMs, varying cement types, and water-to-cementitious materials ratios using ASTM C 1074 maturity methods.

4) Develop modifications to the current ASTM C 1074 procedure to handle any deficiencies, if necessary, and determine the improvement in strength prediction accuracy.
5) Determine the maturity function to be used on ALDOT projects that minimizes strength estimation errors while maintaining ease of use.

1.4 REPORT SCOPE

Chapter 2 gives the technical background of the maturity method as well as describes in detail the methods used to estimate concrete strength on a construction project. Chapter 3 describes the mixtures used in this study as well as reports all raw materials and mixture proportions used. The research approach is also given, describing the plan of action. Chapter 4 details the experimental testing plan used for this study, including mixing procedures and tests performed on fresh and hardened concrete. Results of the testing are presented in Chapter 5. Also the effects of hot and cold fluctuating temperatures and the various types and doses of SCMs, varying cement types, and water-to-cementitious materials ratio on strength behavior are discussed. In Chapter 6, the accuracy of the maturity method in estimating concrete strengths is examined. First, the data are analyzed based on current ASTM C 1074 procedures. Then, modifications are made in an effort to improve accuracy. Next a simplified approach to using the maturity method is applied and finally, new models fitted to the strength data obtained in this study are proposed. Chapter 7 summarizes the study, offer conclusions, and presents recommendations for the methods to be used for ALDOT projects.

CHAPTER 2

LITERATURE REVIEW

This chapter provides the historical and technical background required to understand the use, effectiveness, accuracy, and limitations of the maturity method for estimating concrete strength.

2.1 CONCEPT AND DEFINITION OF THE MATURITY METHOD

The idea that the rate of concrete strength gain is based on the curing time and temperature history was first noted by McIntosh (1949). He hypothesized that the "rate of hardening at any moment is directly proportional to the amount by which the curing temperature exceeds the [datum] temperature." He defined this hardening index as "basic age." The datum temperature was defined as the temperature below which concrete will not harden, which McIntosh chose to be 30°F (-1°C). However, he found that specimens cured at higher temperatures, up to 200°F (93°C), did not have the same compressive strength versus basic age trend as specimens cured at control temperatures of 60°F (16°C). Therefore, the basic-age assumption did not hold true; however, McIntosh's hypothesis was not completely unfounded.

Soon after, Nurse (1949) published his findings on the effects of steam curing on concrete. In his study, Nurse cured different concrete mixtures at temperatures ranging from 64°F to 212°F (18°C to 100°C) and tested the compressive strength at various times. In order to compare the effects of time and temperature on the compressive strength of the different mixtures evaluated, Nurse expressed the strengths "as a percentage of the strength after 3 days' storage at normal temperature [64°F]." Then he plotted the strength percentages versus the product of the temperature at which the concrete had cured and the curing time. When the strength percentages were plotted against the temperature-time "products" they followed a distinct curve. As the temperature-time product increased, the percent of 3-day compressive strength increased as well. Some of Nurse's results are shown in Figure 2.1, where the x-axis is the temperature-time product (°C·hr), the y-axis is the percentage of 3-day strength, and the data sets—gravel aggregate and clinker B—are based on different mixture designs. However, Nurse found that other mixtures did not fall on the same strength versus temperature-time curve.

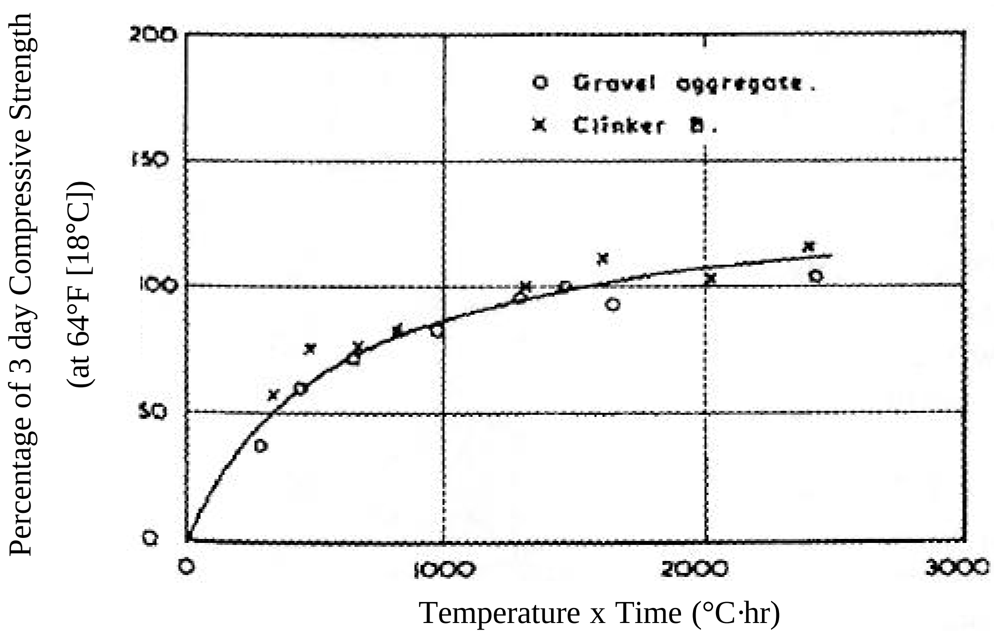


Figure 2.1: Results from experiments performed by Nurse (1949)

Later, in a follow-up to the findings of Nurse, Saul (1951) defined the "…'maturity' of concrete… as its age multiplied by the average temperature above freezing which it has maintained." With the combination of Nurse's time-temperature product and Saul's maturity definition, the first maturity function was born. The Nurse-Saul maturity (NSM) function, as it is commonly known, is defined in ASTM C 1074 as follows:

Nurse-Saul Maturity (NSM) Function:

$$M = \sum_{0}^{t} (T_c - T_o) \cdot \Delta t \qquad \text{Equation 2.1}$$

where,

M = maturity index at age t, (°F·hour or °C·hour),

T_c = average concrete temperature during the time interval, *Dt*, (°F or °C),

Dt = a time interval (hr), and

T_o = datum temperature (°F or °C).

The Nurse-Saul maturity function computes a maturity index, called the "Temperature-Time Factor." The maturity index is the quantitative amount of temperature and time a concrete mixture has accumulated. Computation of the Nurse-Saul maturity function can be explained by Figure 2.2. Basically, any time interval during which a concrete cures above the datum temperature cumulatively adds to the maturity index. Saul (1951) suggested using T_o = 32°F (0°C), but mentioned using a lower datum temperature if concrete will be subjected to lower temperatures after setting. More discussion on choosing proper datum temperatures will be given in Section 2.4.

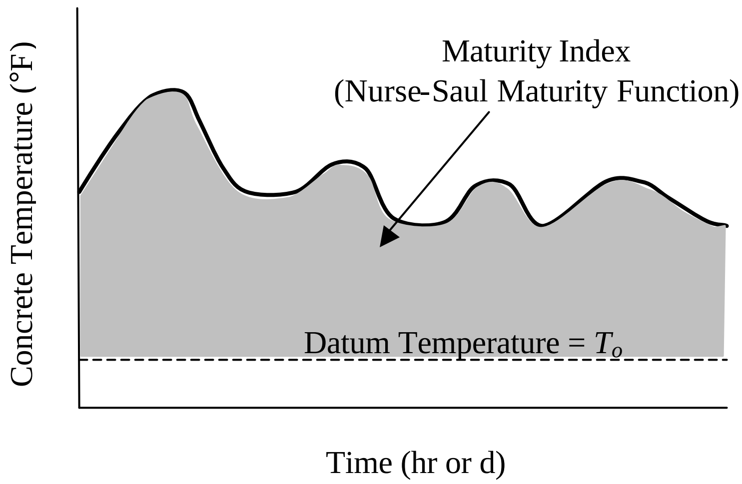


Figure 2.2: Diagram of concrete maturity using Nurse-Saul maturity function

Saul (1951) also defined the "maturity rule," stating that:

> Concrete of the same [mixture] at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity.

This rule is the basis of using the "maturity method" for estimating concrete strength. It means that, for a given concrete mixture, as long as the maturity index corresponding to a particular strength has been established, one can estimate when a concrete will reach that strength, even if the concrete of interest has a different curing history than the original concrete. A schematic of this concept is given in Figure 2.3. The figure shows the concept that, for the same mixture, concrete cured longer in a cold environment can have the same maturity index as concrete cured for a shorter period in a hot environment.

According to Saul’s maturity rule, the strength of these hot and cold batches of concrete will be approximately the same at that maturity.

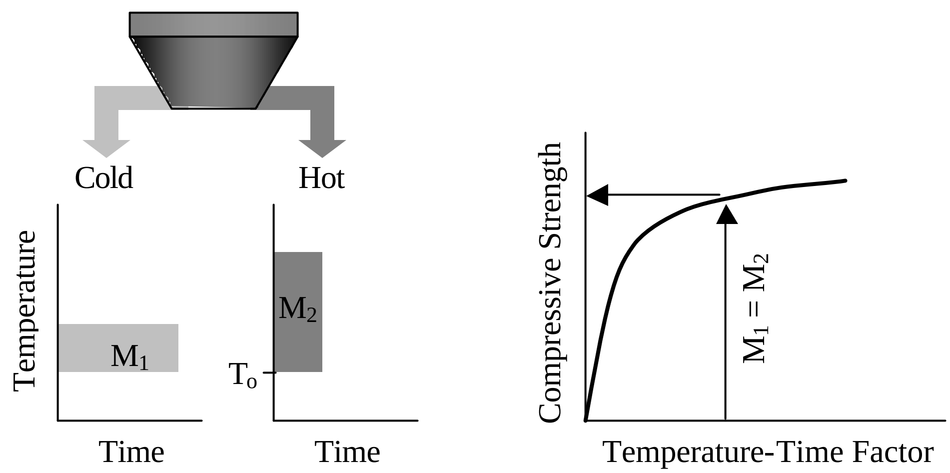


Figure 2.3: Diagram of Saul’s maturity rule

The Nurse-Saul maturity function is not the only function commonly used to compute a maturity index. Another function was introduced by Freiesleben Hansen and Pedersen (1977) and it is known as the Arrhenius maturity function. The maturity index that this function produces is called equivalent age. The Arrhenius maturity function, given in SI units, is defined in ASTM C 1074 as follows:

Arrhenius Maturity (AM) Function:

$$t_e = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T_c} - \frac{1}{273+T_r}\right]} \cdot \Delta t \qquad \text{Equation 2.2}$$

where,

t_e = equivalent age at the reference curing temperature (hr),

T_c = average concrete temperature for the time interval, *Dt*, (°C),

T_r = reference temperature, (usually either 20°C or 23°C),

E = activation energy, J/mol,

R = universal gas constant, 8.314 J/(mol·K), and

Dt = a time interval (hr).

The reference temperature is rather arbitrary, and usually either 20°C or 23°C is used. It serves as a neutral point with respect to temperature effects on concrete strength gain behavior. The Arrhenius maturity function is based on the same idea as Saul's maturity rule: once the time needed to reach a certain strength for a particular mixture is known at the reference curing temperature, the equivalent age to reach that strength will be the same, no matter the curing history. The Arrhenius maturity function accounts for time intervals that the concrete cures above or below the reference temperature, 73°F (23°C) in this study. If a mixture cures above the reference temperature, less actual time will be needed to reach the appropriate strength and if a mixture cures below the reference temperature, more actual time will be required to reach the same strength; however, the equivalent ages will be the same.

The activation energy is an unknown in Equation 2.2, and it has to be selected to characterize the temperature sensitivity of the mixture. It has to do with the energy required to begin the hardening process for a particular mixture (Carino 1997). Using an appropriate activation energy has a great deal to do with the accuracy of strength estimations using the Arrhenius maturity function (ASTM C 1074 2004). This will be examined further, along with using proper datum temperatures, in Section 2.4. The next section will describe the process of establishing a strength versus maturity relationship and how to estimate strengths using a maturity function, in other words, how to estimate strength using the maturity method.

2.2 USE OF MATURITY METHOD TO PREDICT CONCRETE STRENGTH

2.2.1 Strength-Maturity Relationships

Figure 2.4 shows how maturity functions convert concrete of the same mixture, cured at different temperatures, to one compressive strength versus maturity index plot. First, the temperature history of the hardening concrete is measured at regular intervals. Through the use of one of the maturity functions defined earlier, the maturity can be determined. In Figure 2.4, the cold- and hot-cured mixtures' test strengths shifted toward the lab-cured strength-time curve once the temperature histories were converted to maturity. Note that the data points only shift on the time axis; that is, the strength levels are not altered.

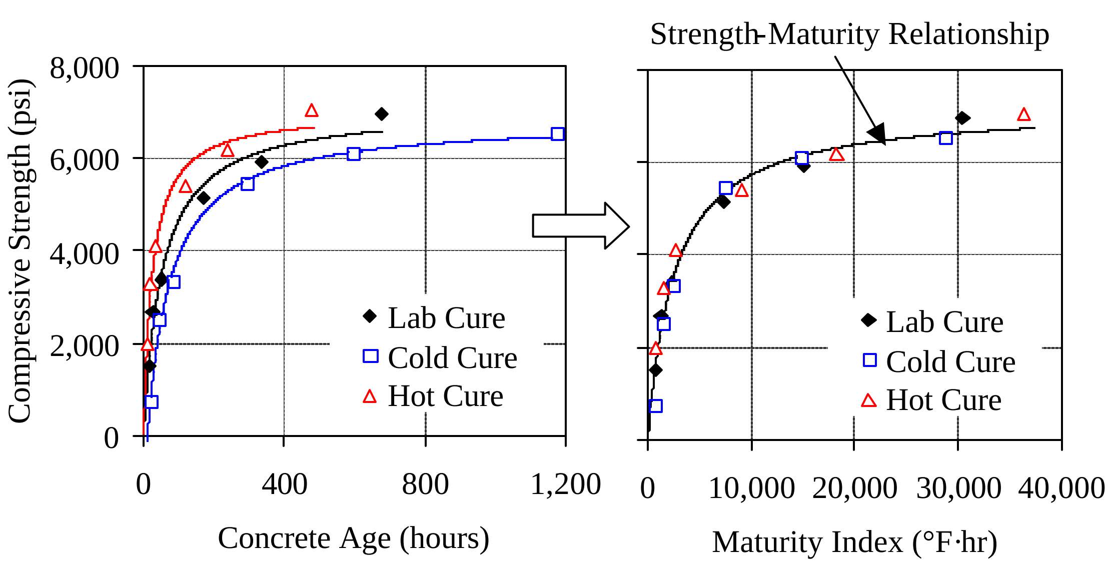


Figure 2.4: Converting strength-age data to strength-maturity data

The resulting strength versus maturity index plot is known as the *strength-maturity relationship* for a particular mixture (ASTM C 1074 2004). This relationship describes the strength of a particular concrete mixture at any maturity index. Accuracy of the strength-maturity relationship is based on the difference between the calculated strength from the relationship and the actual test strengths at the same maturity.

There are many functions that have been proposed by different researchers to model these strength-maturity relationships, but three have received the most attention. According to Carino (1991), they are as follows:

A) <u>Exponential Function:</u>

$$S = S_u e^{-\left[\frac{t}{M}\right]^a} \qquad \text{(Equation 2.3)}$$

where,

S	=	compressive strength at maturity M, (psi),
S_u	=	limiting compressive strength (psi),
M	=	maturity index (°F·hr or hr),
t	=	characteristic time constant (°F·hr or hr), and
a	=	shape parameter.

B) <u>Logarithmic Function:</u>

$$S = a + b\log(M) \qquad \text{(Equation 2.4)}$$

where,

a,b	=	constants (mixture dependent).

C) Hyperbolic Function:

$$S = S_u \frac{k(M - M_o)}{1 + k(M - M_o)} \qquad \text{(Equation 2.5)}$$

where,

M_o = maturity index when strength development is assumed to begin (°F·hr or hr), and

k = rate constant, initial slope of strength-maturity curve (1/(°F·hr) or 1/hr).

In order to determine which function best describes concrete strength gain, Carino fit the formulas to compressive strength data he obtained from a Type I mixture with a water-to-cement ratio of 0.45, cured at 73°F. His results are shown in Figure 2.5. The compressive strength results are reported in MPa, and the equivalent age has units of days. The hyperbolic and exponential equations produce almost identical curves, with slight variations in late-age strengths. These two equations (Equations 2.5 and 2.3) fit the data very well. The logarithmic equation (Equation 2.4) slightly underestimates strength around 5 days and "predicts ever increasing strength with increasing maturity" at late-ages, which is one of the major criticisms of the function (Carino 1991).

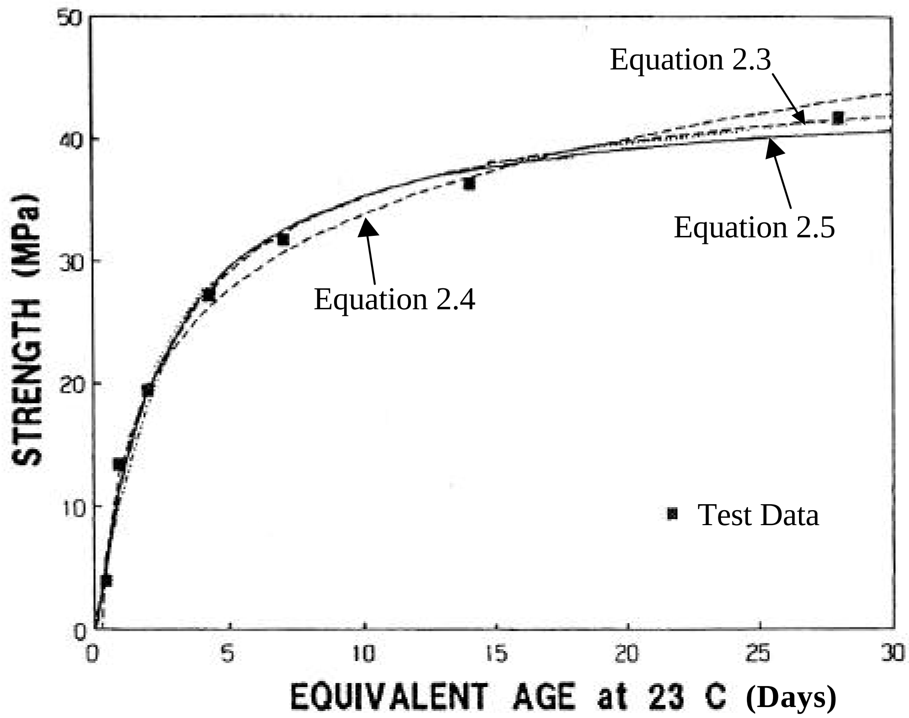


Figure 2.5: Various strength-maturity functions (Carino 1991)

2.2.2 Developing a Mixture-Specific Strength-Maturity Relationship

Now that the concept of a strength-maturity relationship has been introduced, its use with respect to actual construction practices can be explained. First, the strength-maturity relationship for the particular concrete mixture of interest must be established. This procedure is outlined in ASTM C 1074 (2004). First, a sample batch of concrete is prepared prior to construction of the actual roadway or structure. At least 15 cylinders are prepared. The cylinders are made according to ASTM C 192 (2004). Temperature sensors are placed in two of the cylinders to record the temperature history of the concrete. Acceptable temperature sensors include thermocouples, digital data-loggers, or commercial maturity meters. The sensors must be able to record temperature at least once every 30 min for the first 48 hr and at least once every hour after that. Also, they must be able to accurately read temperatures to within ±1.8°F (1°C).

The cylinders are moist-cured, and compressive strength tests are performed at 1, 3, 7, 14, and 28 days. The compressive strengths are tested according to ASTM C 39 (2004). If more cylinders were prepared from the sample batch, then additional testing times should fit estimated ages and strengths of interest for the actual structure. The strength and maturity at each test age is recorded. Maturity may be computed using either the Nurse-Saul or Arrhenius maturity functions. The data points are plotted on a strength versus maturity index graph. ASTM C 1074 (2004) allows a curve to be drawn through the data to establish the strength-maturity relationship; however, a regression analysis using any of the strength-maturity functions given in Equations 2.3 through 2.5 will give more accurate strength estimations.

2.2.3 Estimating Concrete Strength Using a Strength-Maturity Relationship

Once the unique strength-maturity relationship for the concrete of interest has been determined, strength can be estimated on the job-site. According to ASTM C 1074 (2004), temperature sensors are inserted in the structure of interest after the concrete has been placed, but before initial setting occurs. Sensors should be placed in critical locations at which strength estimations are most desired. When the strength at a sensor location is desired, the maturity index (using either Nurse-Saul or Arrhenius maturity functions) of the concrete at that location should be calculated and recorded. Then the estimated strength can be obtained from the strength-maturity relationship that was previously determined. Before this estimated strength can be accepted, the estimated strength must be validated by other methods. ASTM C 1074 recommends several methods of validation. These include in-place tests such as the "Standard Test Method for Penetration Resistance of Hardened Concrete" (ASTM C 803), "Standard Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds" (ASTM C 873), or "Standard Test Method for Pullout Strength of Hardened Concrete" (ASTM C 900); other methods such as "Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength" (ASTM C 918) or "Standard Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens" (ASTM C 684); or field-prepared cylinders, made from the same concrete as was used in the structure, that are compared to the estimated strength found from the strength-maturity relationship.

2.2.4 Examples from the Industry

Now that the standard procedure for estimating concrete strength using the maturity method has been presented, it may be helpful to present some specific techniques currently in use by other state departments of transportation (DOTs). First, the Texas Department of Transportation (TxDOT) specification (1999) for estimating concrete strength based on the maturity method will be discussed. For developing the strength-maturity relationship, TxDOT follows the methods outlined in ASTM C 1074, or Section 2.2.2 in this report, with the following changes or additions:

- Use of the Nurse-Saul maturity function with datum temperature of 14 °F (-10°C),
- Calibration of temperature sensors before use on a project or at least annually,
- Use a minimum batch size of 4 yd^3 to establish the strength-maturity relationship,

- Use of logarithmic strength-maturity equation as defined in Equation 2.4,
- Minimum allowable coefficient of determination (R^2) value of 0.9 for logarithmic equation, and
- Increased inspection of batching and raw materials.

TxDOT's procedure for estimating strength using the maturity method is the same as outlined in ASTM C 1074, or Section 2.2.3 in this report, except the temperature sensors are attached to, but not in direct contact with, reinforcing steel or formwork prior to concrete placement. TxDOT identifies critical temperature sensor locations as thin sections of slabs, concrete around steel tendons, concrete subjected to the worst environmental effects, and/or the last section of concrete placed in a day. TxDOT requires a new strength-maturity relationship to be determined if there are any changes in the mixture proportions including "change in type, source, or proportion of cement, fly ash, coarse aggregate, fine aggregate, or admixtures…[or] a change in water-to-cementitious material ratio greater than 0.05" (TxDOT 1999). ASTM C 1074 also warns of changes in mixture proportions, but does not give specific guidance on when to establish a new relationship. For large projects, TxDOT recommends verifying the strength-maturity relationship a minimum of either once every 600 yd^3 for structures and 30,000 yd^3 for roadways, or once a month.

For verification, TxDOT utilizes the last option provided by ASTM C 1074, which uses field-prepared and laboratory-cured cylinders to verify the strength-maturity relationship. TxDOT's specification explains the verification procedure as follows:

> For verifying design strength, the specimens will be broken when the TTFs of the specimens are at least equal to the Required TTF of the member. For verifying strength for safety- or structurally-critical

formwork or falsework or steel stressing operations, the specimens will be broken when the Required TTF of the member is achieved, regardless of the TTFs of the specimens at that time.

Recall that TTF refers to the maturity index obtained from the Nurse-Saul maturity function (Temperature-Time Factor). There is a distinct difference in these two types of verifications. The former statement means that the test cylinders must have the same maturity index required in the structure and therefore must have the required design strength. Thus, the cylinder may need considerably more time to reach the maturity index that the structure has achieved, due to the difference in mass of concrete and curing effects. The later statement means that the estimated safety or formwork strengths on the structure are sufficient as long as the cylinder's test strengths agree with the strength-maturity relationship, at the cylinder's maturity index. This is true even if the cylinder's test strength and maturity are less than the structure's strength and maturity.

An example of TxDOT's method of estimating concrete strength from the logarithmic strength-maturity function is shown in Figure 2.6. Again, they are using the Nurse-Saul maturity function and have determined that the structure or roadway needs to achieve a maturity index of 2,615 °C·hr to reach the required strength of 3,600 psi. The process for verifying design strengths, as described above, is shown in Figure 2.7. The cylinder must have achieved a maturity index within the 10% tolerance, in this case between 2350 °C·hr and 2880 °C·hr, and the test strength must be within 10% of the value obtained from the strength-maturity curve, 3,600 psi for this example. Finally, an example of the verification method used for safety, formwork, and prestress transfer strengths is shown in Figure 2.8. This was not shown in TxDOT's specification, but it has been included in this report in order to fully explain this method. The author has attempted to keep the format the same as the TxDOT examples. In Figure 2.8, assume the strength required for safety was 4,200 psi, which corresponds to a maturity index of about 4,000 °C·hr in the structure. When the structure reached this maturity (determined from its time-temperature history), suppose the cylinder maturity was only 2,000 °C·hr. In order to verify the safety, formwork, or prestress transfer strength, the cylinder strength must be within ±10% of the strength indicated by the strength-maturity curve—or in this case approximately 3,400 psi ±340 psi. In this example, the tested cylinder strength was approximately 3,490 psi. Since the measured strength closely corresponds to the estimated strength, the in-place maturity of 4,000 °C·hr should correspond to an in-place strength of 4,200 psi.

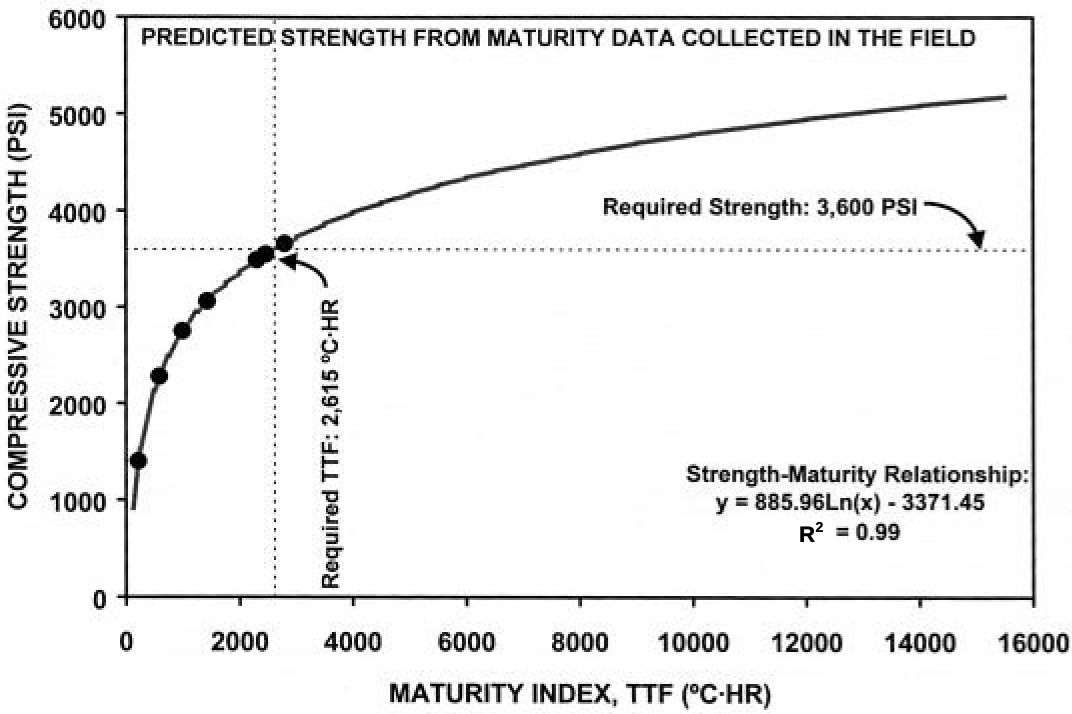


Figure 2.6: Example of estimating strength from strength-maturity relationship (TxDOT 1999)

The Iowa Department of Transportation specification (2000) for estimating concrete strength using the maturity method will now be discussed and compared to TxDOT's methods. Iowa DOT also suggests using the Nurse-Saul maturity function with a datum temperature of 14 °F (-10°C). When developing a strength-maturity relationship, Iowa DOT only requires 12 test specimens and a batch size of 3 yd^3. The specimens are moist cured in a saturated sand pit, instead of the common lime-bath or moist-cure room used by TxDOT and recommended by ASTM C 1074. In some cases, Iowa DOT allows the time intervals for temperature recording to be 2-3 hr for the first 24-36 hr and a minimum of twice per day thereafter.

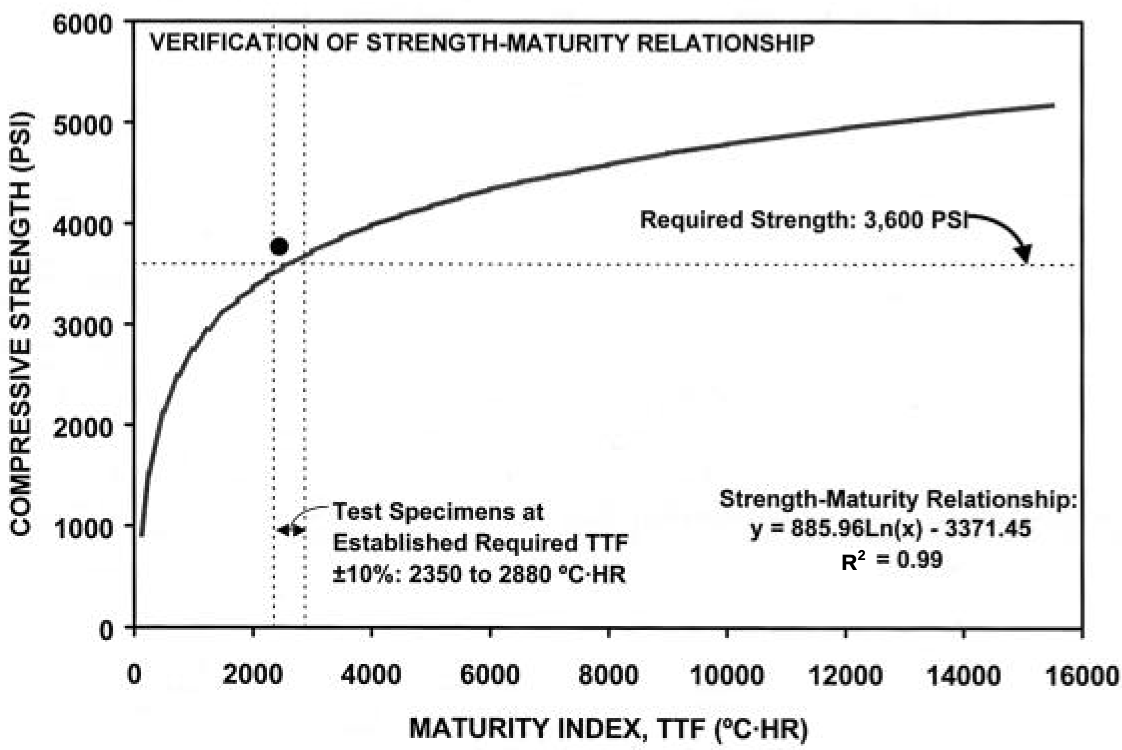


Figure 2.7: Example of verification of design strength (TxDOT 1999)

Iowa DOT requires validation of a strength-maturity curve to be performed once a month on all projects, although it seems that the Iowa DOT uses the maturity method mainly for concrete pavement applications. Three test specimens are prepared, and flexural strengths are tested at values as close as possible to the strengths required for the project, such as traffic-opening strengths. The average of the specimen flexural strengths must be within 50 psi of the estimated flexural strength from the strength-maturity curve. If the average flexural strength is more than 50 psi less than the estimated value, a new curve must be developed. If the average flexural strength is greater than 50 psi above the estimated value, a new curve is not required, but may be desired.

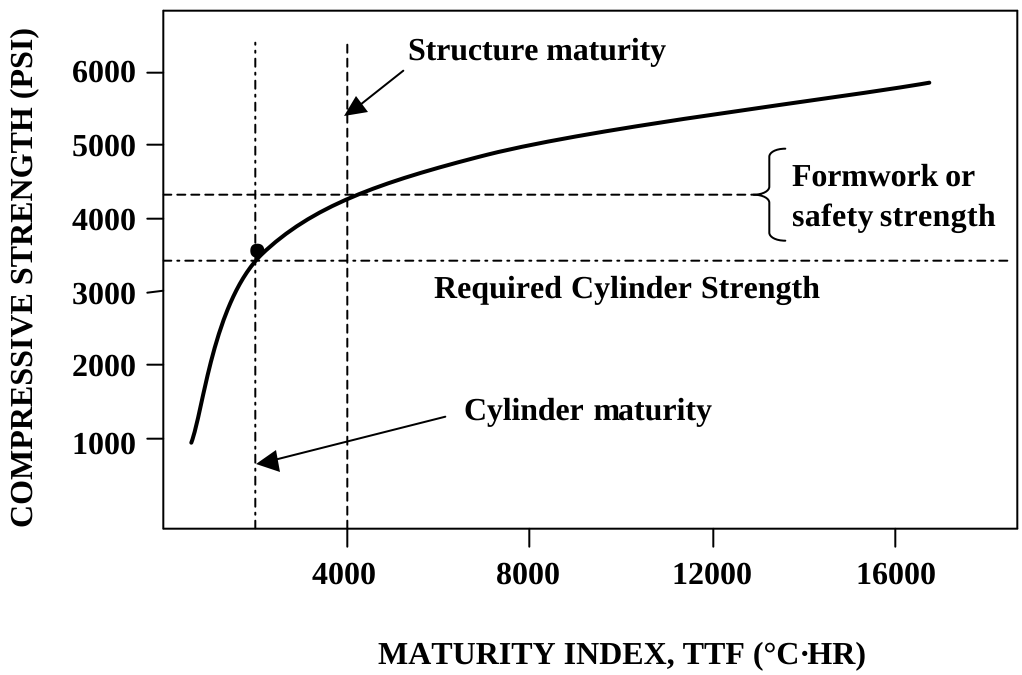


Figure 2.8: Example of verification of safety or formwork strength

As explained in this section, use of the maturity method to estimate the strength of concrete members requires establishment of a unique strength-maturity relationship. Also, some verification processes must be implemented. The maturity method is not perfect however. Users of the maturity method must be aware of certain issues; these limitations are discussed in the next section.

2.3 LIMITATIONS OF THE MATURITY METHOD

As noted in the previous section, there are certain factors and natural phenomena that can cause unreliable strength estimations from the maturity method. These include factors that affect concrete strength, such as temperature and mixture proportions, as well as other factors that only apply to the maturity method. This section will focus on all of these such issues.

2.3.1 Mixture-Specific Strength-Maturity Curve

In Section 2.2.4 it was stated that the TxDOT requires a new strength-maturity relationship to be established if there are any changes in mixture proportions or major changes in the water-to-cementitious materials ratio. This is because each strength-maturity relationship is unique. In other words, there is no universal maturity curve. Nurse (1949) noticed this in his experiments with temperature and time effects on concrete strength, as previously shown in Figure 2.1. Nurse plotted the maturity index, temperature-time product (°C·hr), on the x-axis and the percentage of 3-day strength on the y-axis. For the two mixtures shown in Figure 2.1, a single curve modeled the strength development well. However, Figure 2.9 shows the same curve plotted with data points from several of Nurse's other mixtures. It shows that the strength-maturity relationship that fit the two original mixtures well does not model the other mixtures well at all. This occurs because the different mixtures have different long-term strengths and rates of strength gain relative to their unique temperature histories.

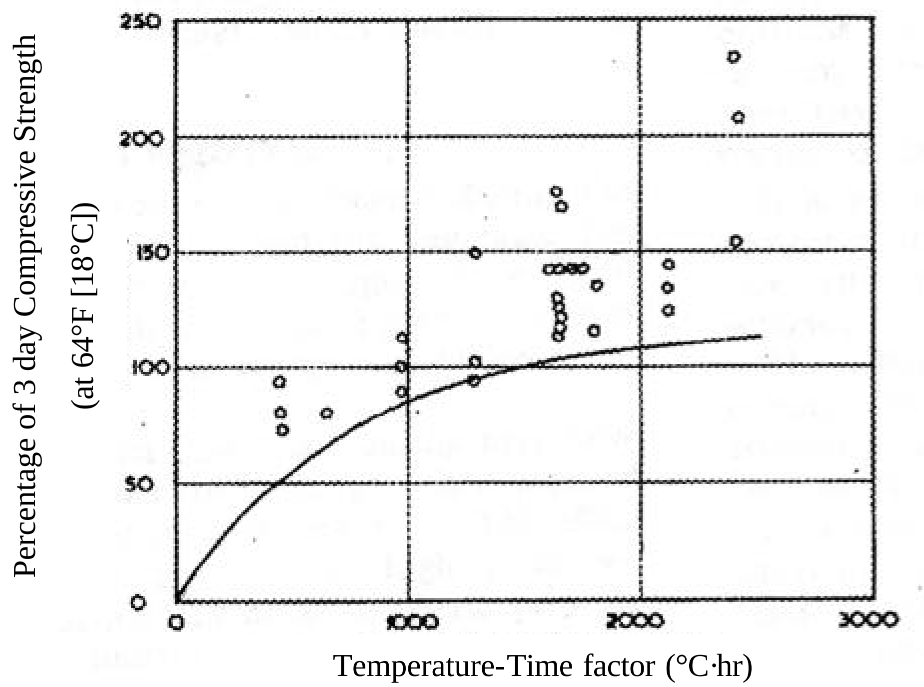


Figure 2.9: Further results from Nurse's experiments (1949)

Past researchers have attempted to find a single strength-maturity relationship for a certain range of mixtures. Plowman (1958) proposed a single strength-maturity equation based on past studies performed by various authors, with various mixtures, water-to-cement ratios, and curing temperatures between 11°F and 105°F (-12°C to 41°C). Using the logarithmic strength-maturity function (defined in Eq. 2.4), he proposed that the constants, *a* and *b*, have specific values based on four strength ranges up to 10,000 psi. With this equation, Plowman found that any concrete strength could be estimated based on a given maturity, regardless of water-to-cement ratio, curing temperature under 100°F, or aggregate-to-cement ratio, with an average error of 3%.

Plowman's equation seemed to be valid, although his equation was only based on 26 different compressive strength values. The formula did not hold up over time.

In a later study, Carino and Lew (1983) examined the effects of temperature on various strength-maturity relationships. Two mortar mixtures with water-to-cement ratios of 0.56 and 0.43 cured at both isothermal and fluctuating temperatures between 41°F and 109°F (5°C to 43°C) were studied. Hyperbolic strength-maturity equations (Eq. 2.5) were fit to each of the mixtures at the various curing temperatures. The best-fit k, S_u, and M_o values were determined and plotted versus temperature. The k and M_o values seemed to be independent of water-to-cement ratio; however, the S_u plot was much different. Carino and Lew's results are shown in Figure 2.10. It can be seen that for the same mixture, simply changing the water-to-cement ratio and curing temperature greatly affected the long-term strength of the batches. The high water-to-cement ratio mixture had an average limiting strength of approximately 4,500 psi while the lower water-to-cement ratio mixture had an average limiting strength of approximately 9,500 psi. Recall that the maturity index can only shift time values (see Figure 2.4). Thus, no strength-maturity function can account for strength differences such as those exhibited in Figure 2.10. This effect is uncontrollable and is the reason that specifications call for new strength-maturity curves when there are changes in mixture proportions, admixtures, water-to-cement ratio, and sources of materials. Note that the effect of various curing temperatures on long-term strength can also be seen in Carino and Lew's results. Figure 2.10 there indicates a general trend: as the curing temperature increases, the limiting strengths decrease. This phenomenon will be discussed further in the next section.

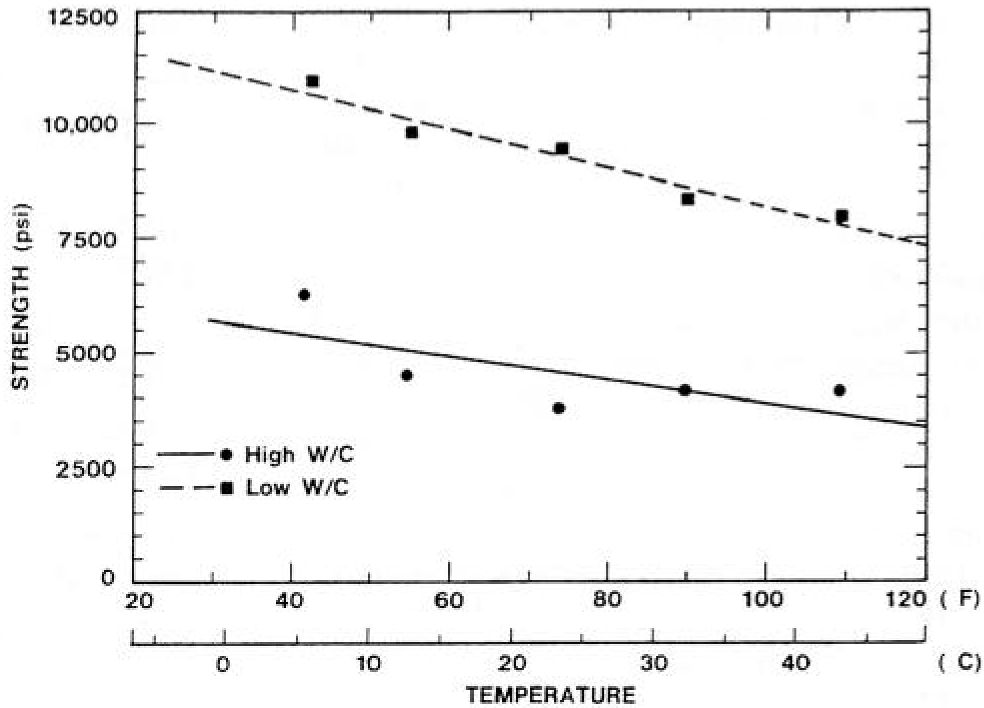


Figure 2.10: Ultimate compressive strength (S_u) values for Carino and Lew's experiment (1983)

2.3.2 Effects of Curing Temperature on Long-Term Strength

Another major problem that affects the accuracy of strength estimations based on the maturity method is early-age temperature effects on concrete strength. Since Saul's report on maturity in 1951, it has been well established that early-age curing temperatures may affect the long-term strength of concrete. Saul performed strength tests on rapid-hardening and ordinary concrete mixtures with water-to-cement ratios of 0.35 and 0.50. Saul noted that his maturity rule did not hold if the concrete was subjected to extremely high temperatures at early ages. Specifically, he stated that temperatures above approximately 120°F (50°C) during the first 2 hours and above 212°F (100°C) during the first 6 hours of curing produced the worst effects.

The results of Saul's experiments are shown in Figure 2.11. The solid line on the strength-versus-age graph is the behavior of one of the mixtures "normally cured" at 62°F (16°C). The dotted lines represent zones of test data for the same concrete mixture subjected to different curing conditions. "Zone A" represents the strengths of specimens heated to 212°F (100°C) within the first six hours then gradually lowered to approximately 105°F (41°C) within 24 hr. "Zone B" represents the strengths of specimens heated to 212°F (100°C) within the first six hours, held at that temperature for another eight hours, and then gradually reduced to approximately 130°F (54°C) within 24 hr. The strengths for the specimens represented by "Zone A" have higher early-age strengths than the "normally cured concrete" and only have a slight reduction in late-age strengths. The specimens represented by "Zone B" have slightly higher early-age strengths than the normally cured concrete but have significantly lower strengths at lateages. The 28-day strength for this group of specimens is more than 2,000 psi less than the normally cured specimens in some cases.

Figure 2.12 shows the same plot as Figure 2.11, with actual test data instead of the zones. The x-axis has dual units of the Nurse-Saul maturity index and actual age. The data sets represented by dark circles and triangles are the same specimens represented by Zones A and B in Figure 2.11, respectively. The open circle data points represent specimens cured at temperatures between the other two ranges. From Saul's results, the strengths for the triangle data points, with the worst environmental conditions, depart from the normally cured strength-maturity curve (i.e. the strength-maturity relationship) after less than 2 days. After that, strengths would be greatly over-estimated by the strength-maturity relationship. For the other two data sets, the strength-maturity relationship appears to be accurate only up to approximately 5 days.

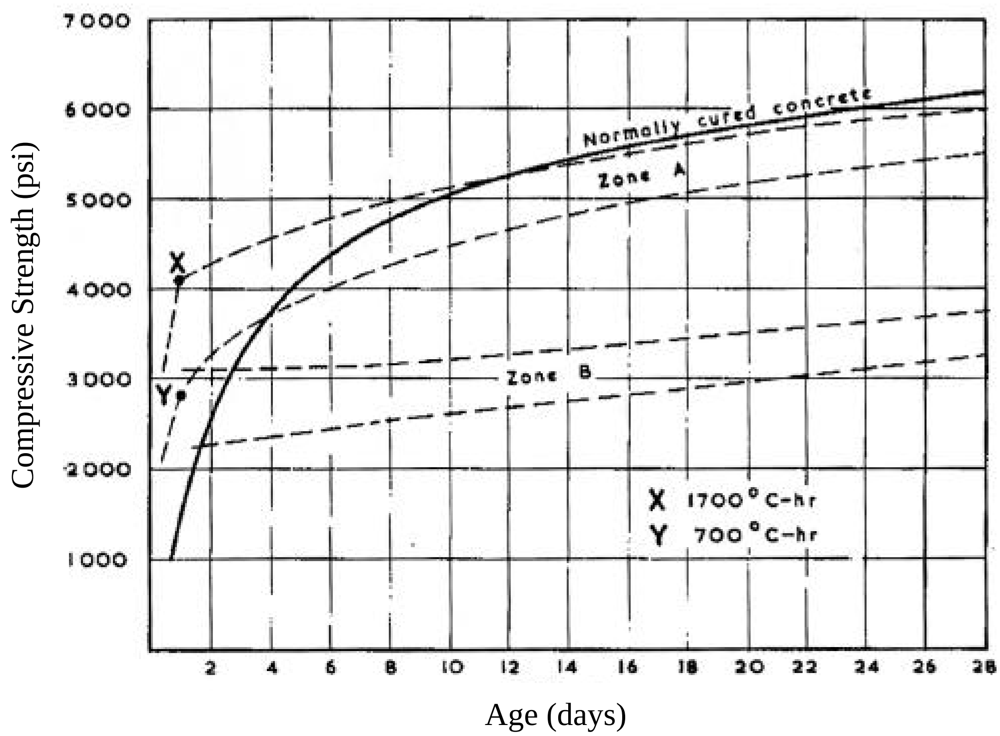


Figure 2.11: Temperature affects on long-term strength (Saul 1951)

In 1956, McIntosh presented results of experiments in which specimens of three mortar mixtures having variable aggregate-to-cement and water-to-cement ratios were cured at temperatures ranging from approximately 59°F to 43°F (15°C to 6°C). McIntosh found that at equal maturities (computed using the Nurse-Saul maturity function), specimens cured at lower temperatures had lower early-age strengths than specimens cured at laboratory temperature (59°F). Moreover, the specimens cured at the lower temperatures had higher 28-day strengths than specimens cured at laboratory temperature, at equal maturities. Thus he concluded that for concrete cured at low temperatures, the maturity method “may lead to an over-estimation of the strength at low maturities and an under-estimation at high maturities.”

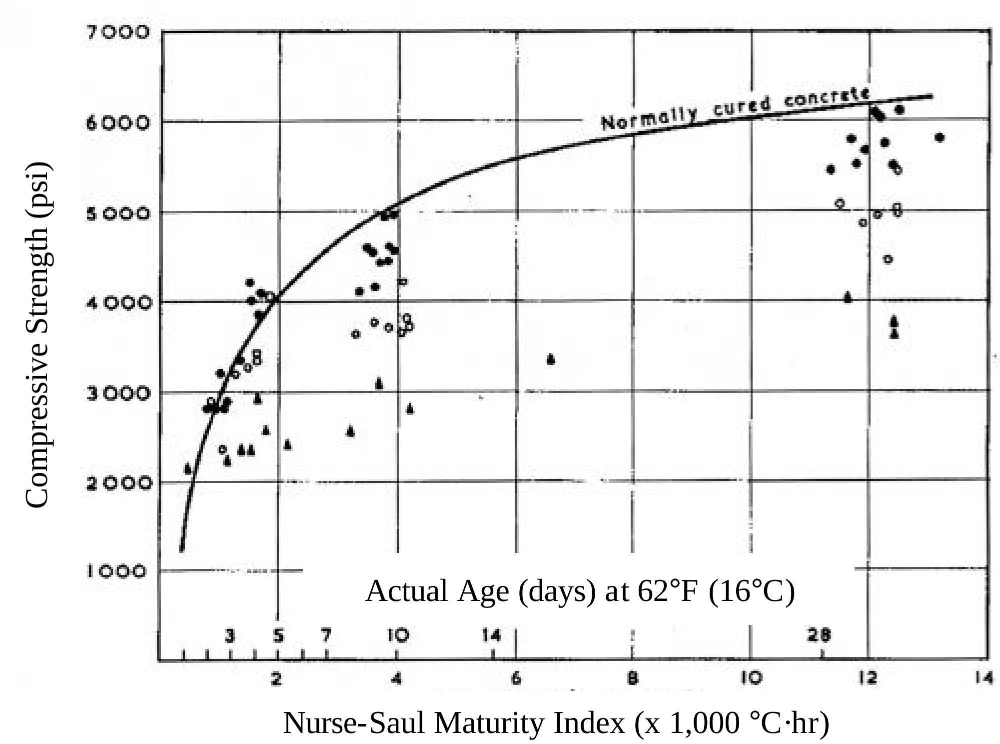


Figure 2.12: Temperature effects on estimating strength using strength-maturity relationship (Saul 1951)

Many other researchers such as Klieger (1958), Alexander and Taplin (1962), and Carino and Lew (1983) have verified what Saul and McIntosh found. The results from Alexander and Taplin’s experiment are shown in Figure 2.13. They tested the compressive strength of concrete specimens from a single mixture with a water-to-cement ratio of 0.35 cured at 41°F (5°C), 70°F (21°C), and 108°F (42°C). The x-axis in Figure 2.13 shows maturity given as “A(T+10).” This is the Nurse-Saul maturity function (Equation 2.1), where A stands for the age of the concrete in days, and the (T+10) term is the temperature term after taking a datum temperature of -10°C (14°F).

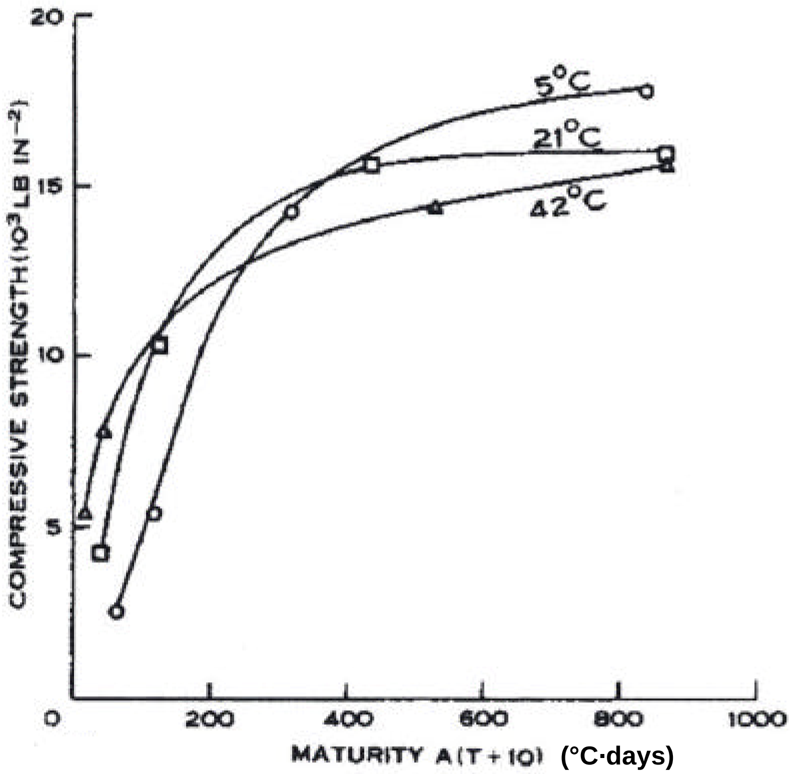


Figure 2.13: Crossover effect due to curing temperatures (Alexander and Taplin 1962)

Alexander and Taplin's results show exactly what McIntosh and Saul had found. The three data sets have their own unique curves. If the maturity method was valid given any curing history, only one strength-maturity curve would exist for all curing temperatures. However, at early ages, the strength-maturity relationship for the mixture cured at 70°F (21°C) underestimates the strength of specimens cured at higher temperatures and overestimates the strength of specimens cured at lower temperatures. At later ages this trend is reversed. The strength-maturity curve for the mixture cured at 70°F (21°C) underestimates the strength of specimens cured at lower temperatures and overestimates the strength of specimens cured at higher temperatures. Carino (1991) refers to this phenomenon as the "crossover effect," as the strength-maturity curves of mixtures cured at colder temperatures literally cross over the strength-maturity curves of mixtures cured at warmer temperatures. In Figure 2.13, the strength-maturity curve for the mixture cured at 41°F (5°C) crosses over the curves for the mixtures cured at 70°F (21°C) and 108°F (42°C) at approximately 375°C·d and 250°C·d, respectively. It could also be said that the strength-maturity curve for the mixture cured at 70°F (21°C) crosses over the curve for the mixture cured at 108°F (42°C) at approximately 150°C·d.

Verbeck and Helmuth (1968) investigated the rate of hydration of cement pastes cured at various temperatures in an effort to explain the mechanism responsible for the crossover effect. They proposed that a cement paste cured at high temperatures hydrated at a much higher rate than a paste cured at lower temperatures. The increased rate of hydration does not allow sufficient time for the proper distribution of hydration products, producing a weaker bond. Verbeck and Helmuth concluded that a "shell" or barrier forms around cement particles of mixtures cured at high temperatures, which hinders further hydration. Thus, concrete that is cured at high temperature gains strength so rapidly that the hydration process is disrupted and the late-age strengths suffer accordingly. The conclusions made by Verbeck and Helmuth have been verified by later researchers through the use of backscattered electron imaging (Kjellsen, Detwiller, and Gjørv 1991).

As seen by results from Saul, McIntosh, and Alexander and Taplin, the crossover effect can lead to severe deficiencies in the accuracy of strength estimations using the maturity method. Much research has been performed on this phenomenon in order to determine if there is a cutoff age beyond which strengths cannot be reliably estimated using the maturity method. From Saul's study, it seemed that as long as the most severe temperature curing regimens were not used, strengths could be accurately estimated by the strength-maturity relationship up to about 5 days, or approximately 65% of the normally cured mixture's 28-day strength. Kjellsen and Detwiler (1993) found that the strength-maturity relationships for the mixtures they examined were valid only up to a maturity that corresponded to 40% of the normal 28-day strength. Jonasson (1985) found that strength estimations using the maturity method were valid up to approximately 50% of the normal 28-day strength.

To date many researchers have attempted to develop methods of estimating the long-term strength of concrete using modified and more complex versions of the maturity method (Kjellsen and Detwiler 1993; Tank and Carino 1991), but none have been widely accepted in practice.

2.3.3 Other Factors Affecting Concrete Strength

There are other factors that affect the strength of concrete but not its heat of hydration, and thus affect strength estimations using the maturity method. Some of these factors include air entrainment, clay particles in aggregates, and inadequate moisture for curing.

Air Entrainment

It is well known in concrete technology that the more air voids that are in a certain concrete mixture, the lower the strength will be. A general rule is that for every 1% increase in air content, a 5% decrease in strength can be expected (Mindess, Young, and Darwin 2003). This strength loss can be seen in Figure 2.14. In an experiment performed by Cordon (1946), the 28-day compressive strengths of three mixtures with different cement contents and various air contents were examined. From the figure, a general trend can be seen: as the air content increases, the 28-day strength decreases. The mixture with 613 lb/yd^3 of cement loses almost 2,000 psi going from 0% to 9% air content. Therefore, if air content is not carefully monitored and controlled then the mixture-specific strength-maturity relationship established becomes inaccurate—as do any resulting strength estimates.

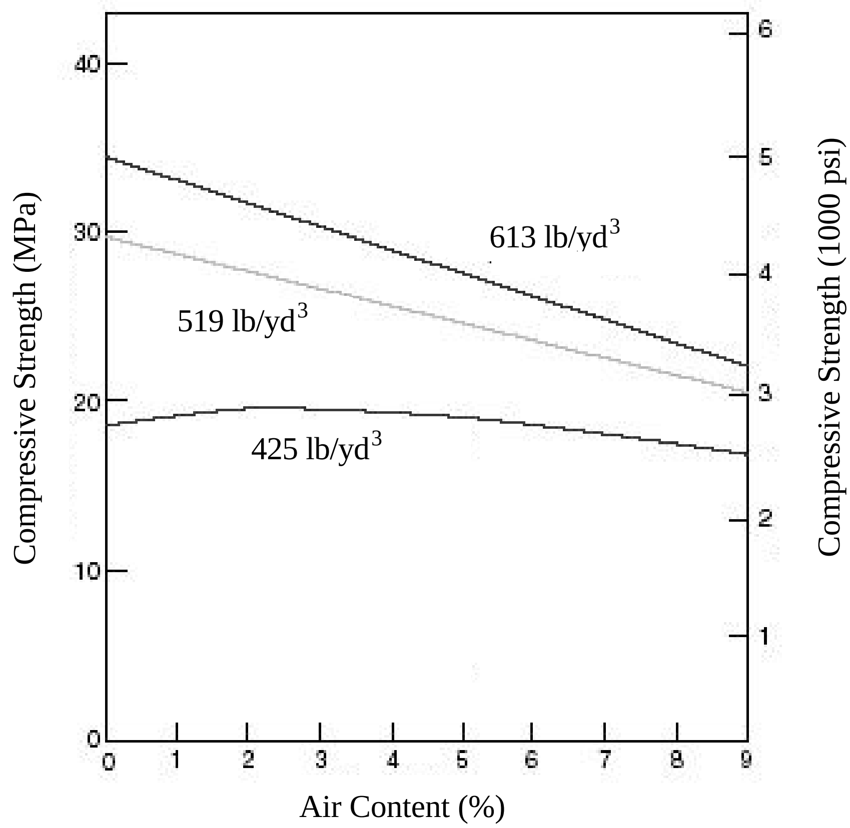


Figure 2.14: Effect of air content on concrete strength (Cordon 1946)

Clay Fines in Aggregates

Another important factor that affects the strength of concrete is the presence of clay fines in aggregates used in any concrete mixture. Topçu and Ugurlu (2003) examined the affect of very fine aggregates (those passing a No. 100 sieve) on concrete properties. According to Topçu and Ugurlu, clays have a very detrimental affect on the bond between cement and aggregates. They also found that clay slows the hydration process of the cement particles and can change the effective water-to-cement ratio. A simple solution to this problem is to wash aggregates before use. However, it is easy to see how this contamination could influence the predictions made by the maturity method by both affecting strength levels and the rate of hardening of a concrete.

Inadequate Moisture for Curing

In addition to air voids and fine particles in aggregates, a much more common and debilitating problem affecting the maturity method is moisture (or lack thereof) during curing. The maturity method uses the temperature history to predict the in-place strength of the concrete, but an adequate amount of moisture must be supplied to sustain the hydration while the concrete is gaining strength (ASTM C 1074 2004; Carino 1991).

Moisture is a crucial part of the hydration process of concrete. The hardening process of concrete occurs from a "chemical reaction between the cement and water, called hydration (Kosmatka, Kerkhoff, and Panarese 2002)." The hydration process begins with water supplied in the concrete mixture, but as the chemical reaction continues additional moisture is required. Concrete can continue to hydrate even when it is not fully saturated; however, if the relative humidity drops below approximately 80%, hydration will cease (Kosmatka, Kerkhoff, and Panarese 2002). Therefore, proper moist-curing of concrete is a crucial component in the construction process. Figure 2.15 shows the results of an experiment performed by Gonnerman and Shuman (1928) examining the effects of moist-curing time on the strength gain of concrete. The graph shows that the shorter the moist-cure time, the lower the late-age strength. The strength difference between the concrete moist cured for the entire year and the concrete cured in laboratory air for the entire year is almost 4,000 psi. Thus, if concrete is not cured properly, then the established strength-maturity relationship is no longer valid.

The research presented in this section indicates that all of the factors presented must be acknowledged and carefully monitored in order to obtain accurate strength estimations using the maturity method.

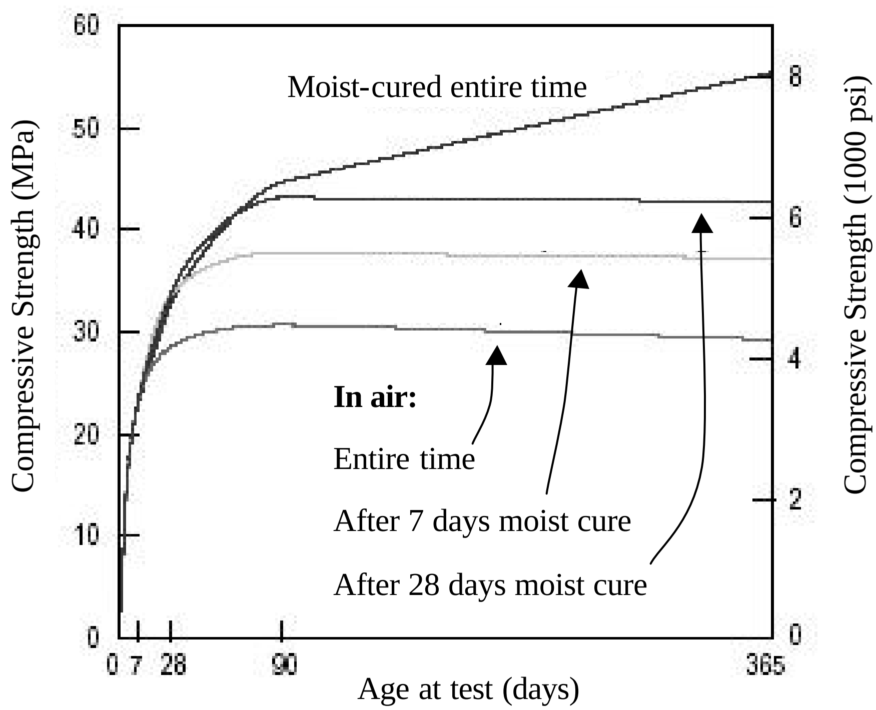


Figure 2.15: Effect of moist-curing time on strength gain of concrete (Gonnerman and Shuman 1928)

2.4 COMPARISON OF MATURITY FUNCTIONS

At this point, both maturity functions and their application have been presented but several questions remain:

- Does one maturity function model concrete behavior at different curing temperatures more accurately than the other?
- How does the datum temperature or activation energy relate to the accuracy of the strength estimate?
- What datum temperature or activation energy should be used for a particular mixture?

This section addresses these remaining issues. First, the mechanism of converting temperature histories to maturity will be examined for both functions. A term, known as the "*age conversion factor*" will be presented that will enable comparison of the two functions. Then, the two functions will be compared using actual concrete behavior from past experiments to see which function is believed to best model concrete behavior. Finally, previously determined datum temperatures and activation energies for different mixtures will be presented.

2.4.1 Maturity Function Trends Compared to Concrete Behavior

According to Carino (1991), Saul's maturity rule was based on "empirical evidence" and assumes specific concrete behavior that may have been erroneous. Later, Freisleben Hansen and Pedersen (1977) proposed the Arrhenius maturity function, a model based on scientific theory of the rates of chemical reactions (Carino 1997). Recall in Figure 2.4 it was shown that the strength versus age data for three mixtures cured at a hot, cold, and control temperature can be converted to one strength-maturity curve. The amount of correction needed to converge the data onto one curve is dependent on how a particular concrete mixture is affected by different curing temperatures, in other words, how the rate of reaction (strength gain) differs given different curing temperatures. However, Nurse-Saul and Arrhenius maturity functions convert temperature histories into maturity using different models. To determine which function estimates strength with the greatest accuracy over a range of temperatures, the approach used in each function to convert temperature histories to maturity must be examined. To do this, the concept of the *age conversion factor* must be presented.

The two maturity functions previously defined in this chapter may be easily compared when the Nurse-Saul maturity function is converted to produce equivalent age, instead of the Temperature-Time Factor. The Nurse-Saul maturity function, when converted to produce equivalent age, can be defined as follows (Carino 1991):

Nurse-Saul equivalent age function:

$$t_e = \sum_0^t \frac{(T_c - T_o)}{(T_r - T_o)} \Delta t \qquad \text{Equation 2.6}$$

where,

t_e = equivalent age at the reference curing temperature (hr),

T_c = average concrete temperature during the time interval, *Dt*, (°F or °C),

T_o = datum temperature (°F or °C),

T_r = reference temperature, (usually either 68°F or 73°F [20°C or 23°C]).

When this is done, the Nurse-Saul maturity function converts a curing time to an equivalent age at the reference temperature, analogous to the Arrhenius maturity function. Now both maturity functions, the Nurse-Saul and Arrhenius, are in comparable forms. They both compute equivalent age, and both have some temperature converting function multiplied by Δt. The temperature converting function is known as the "age conversion factor," and the equations can now be written in similar form (Carino 1991):

Equivalent Age Function:

$$t_e = \sum_0^t a \, \Delta t \qquad \text{Equation 2.7}$$

where,

α = age conversion factor, $\frac{(T_c - T_o)}{(T_r - T_o)}$, for Nurse-Saul Maturity (NSM) function,

α = age conversion factor, $e^{\frac{-E}{R}\left[\frac{1}{273+T_c} - \frac{1}{273+T_r}\right]}$, for Arrhenius Maturity (AM) function

Now the two maturity functions can be easily compared. The age conversion factor functions can be plotted versus temperature, given certain datum temperatures or activation energies. Some of these plots are presented in Figure 2.16 for a reference temperature of 73°F (23°C). In this figure, the NSM function's age conversion factors are plotted for datum temperatures of 32°F (0°C) and 14°F (-10°C) and the AM function's age conversion factors are plotted for activation energies of 40,000 J/mol and 30,000 J/mol. From this graph a distinct difference in the two function's age conversion factors can be seen. The AM function's age conversion functions have a non-linear trend versus curing temperature. The NSM function's age conversion functions have a linear trend versus curing temperature, which is to be expected from their respective formulas. The manner in which these functions fit the actual behavior of concrete at different temperatures is closely related to the accuracy of the maturity method when estimating the concrete strength at different temperatures (Carino 1991). In other words, the age conversion factor is the term that defines the temperature sensitivity for the maturity method. From Figure 2.16, it can be seen that different values of datum temperatures and activation energies produce much different age conversion factors over the temperature range shown. For example, given an average curing temperature of 92°F (33°C), the age conversion factor for the Nurse-Saul maturity function, with a datum temperature of 14°F (-10°C), is approximately 1.3, while the age conversion factor for the Arrhenius maturity function, using an activation energy of 40,000 J/mol, is approximately 1.6. The difference between the two age conversion factors at that temperature is approximately 20% and the difference gets larger as the temperature increases. Thus, using different maturity functions and different datum temperatures or activation energies can cause great deviations in the applied age conversion factor.

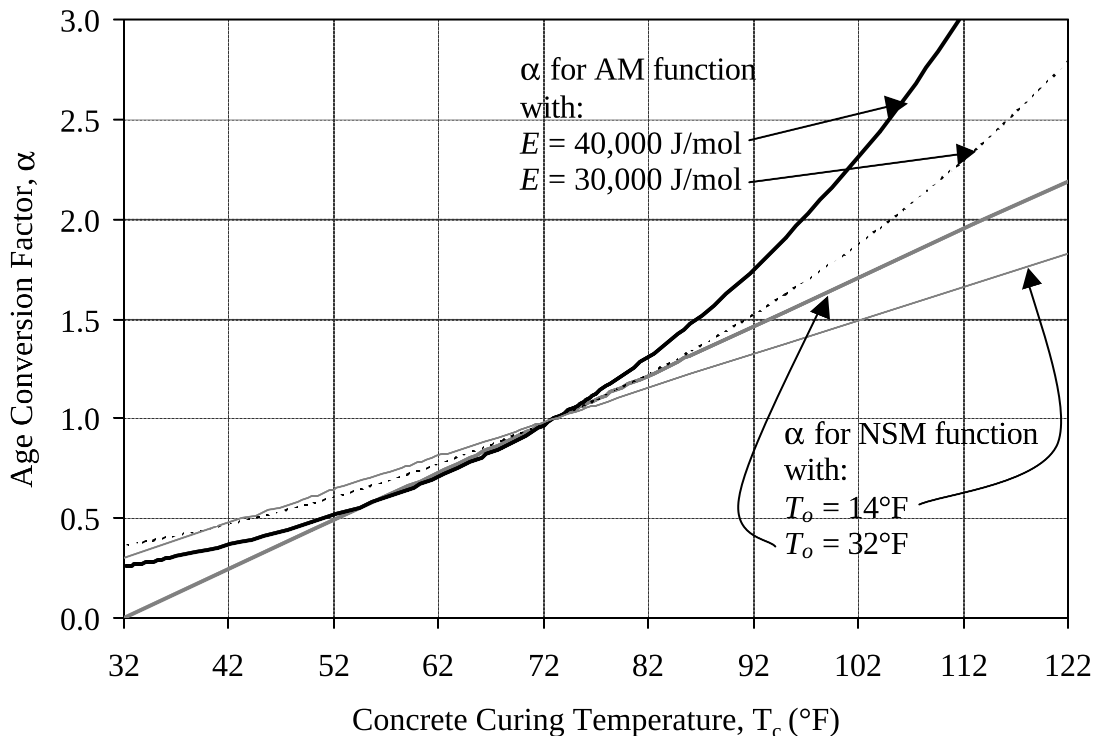


Figure 2.16: Age conversion factors for Nurse-Saul and Arrhenius maturity functions

To determine which age conversion factor, and thus which maturity function, models concrete strength gain behavior better, Carino (1991) performed a study to examine concrete strength gain behavior at different temperatures. Carino tested the strengths of two mortar mixtures with water-to-cement ratios of 0.43 and 0.56 cured at the following *isothermal* temperatures: 41°F (5°C), 54°F (12°C), 73°F (23°C), 90°F (32°C), and 109°F (43°C). The strength results were fitted by regression analysis to a hyperbolic strength-age function, which has the same form as Equation 2.5, except time is the independent variable instead of maturity. For clarity, it is shown as follows (Carino 1991):

Hyperbolic Strength-Age Function:

$$S = S_u \frac{k(t - t_o)}{1 + k(t - t_o)} \qquad \text{Equation 2.8}$$

where,

S = compressive strength at time, t, (psi),

S_u = limiting compressive strength (psi),

t = time interval (hour),

t_o = time when strength development is assumed to begin (hour), and

k = rate constant, initial slope of strength-age curve, (1/hour).

The S_u, t_o, and k-values were found from regression analysis, and the k-values were plotted versus curing temperature, since the k-value represents the initial rate of strength gain at the different temperatures. Figures 2.17 and 2.18 were created from Carino's reported k-values. In Figure 2.17, the k-values are plotted versus temperature, and a linear trendline was fitted. The equation of the line and the R^2 value are shown on the plot. Where this trendline crosses the x-axis, the rate constant (k) is zero. According to Carino, that is the datum temperature, to be used with the Nurse-Saul maturity function, that best models the behavior of this concrete mixture. The datum temperature for the mixture used in his experiment, according to the preceding logic, should be 40°F (4.4°C). However, the line does not fit the data very well, which is apparent from the R^2 value of 0.93.

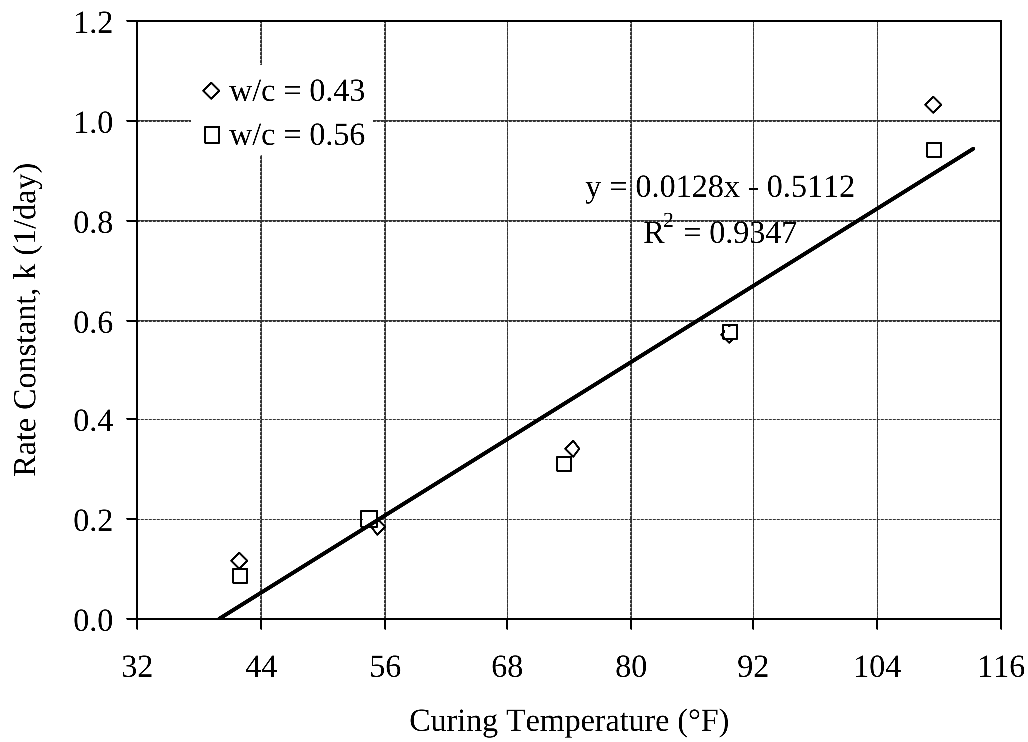


Figure 2.17: Rate constants used to find best-fit datum temperature (Carino 1991)

Next, according to Carino, the activation energy, to be used with the Arrhenius maturity function that best models the strength gain behavior for the mixture studied, may be obtained by plotting the natural logarithm of the *k*-values versus the inverse of the curing temperature, in Kelvin units. This plot is shown in Figure 2.18. From this figure, it can be seen that the R^2 value is 0.99, a much better fit than Figure 2.17. Through mathematical reasoning, Carino showed that the best-fit activation energy to be used for this mixture is the negative of the slope of the trend line multiplied by the universal gas constant. From his results, the activation energy should be 43,700 J/mol.

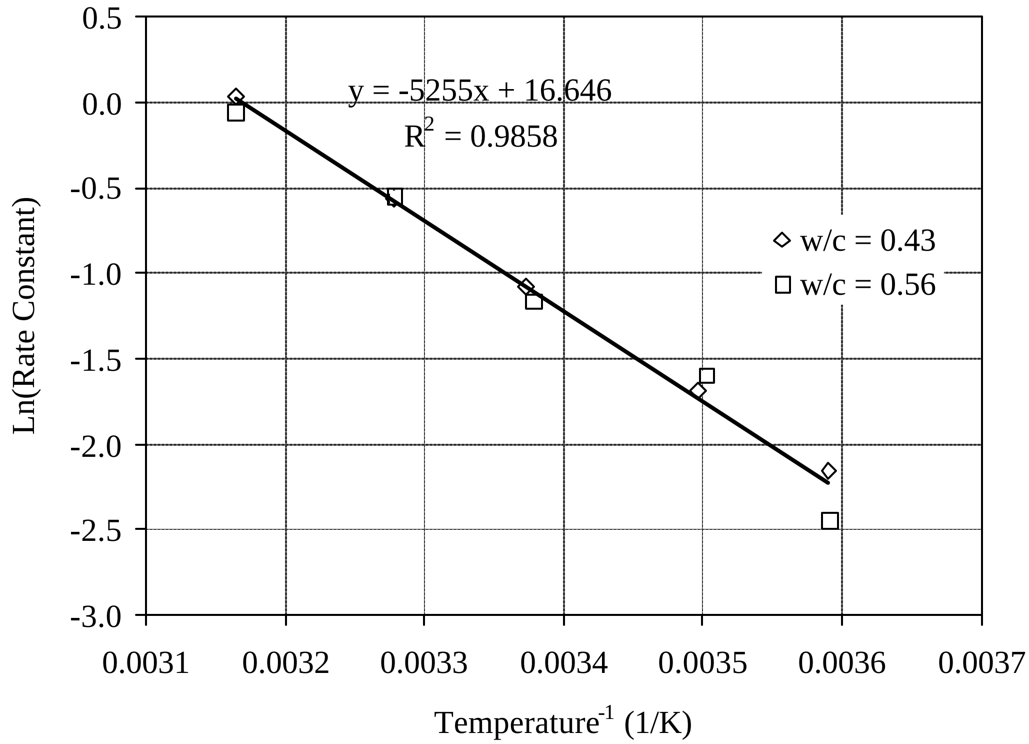


Figure 2.18: Rate constants used to find best-fit activation energy (Carino 1991)

Now, to analyze which maturity function best fits the rate of strength gain of the concrete evaluated in Carino's experiment, the *k*-values need to be converted into age conversion factors. Then the age conversion factors from his experiment can be plotted on a graph such as the one shown in Figure 2.16. According to Carino, the rate constant values can be converted into age conversion factors by dividing each of the *k*-values by the *k*-value at the reference temperature. The value of the rate constant at the reference temperature, 73°F (23°C), can be found from the trendline given in Figure 2.18. This value comes out to be approximately 0.326 day^{-1}, after transforming from logarithmic values.

Next, the newly converted age conversion factors for Carino's mixture were plotted versus curing temperature in Figure 2.19. The age conversion factor functions for the Nurse-Saul and Arrhenius maturity functions, with the best-fit values of datum temperature or activation energy found previously, were added to the graph as well. From Carino's findings, the Arrhenius maturity function fits the behavior of the examined mortar much better than the Nurse-Saul maturity function. The non-linear behavior of the mortar used for his study led Carino to conclude that the Arrhenius maturity function was much more suited to model the mortar's behavior over the curing temperature range of 41°F to 109°F (5°C to 43°C).

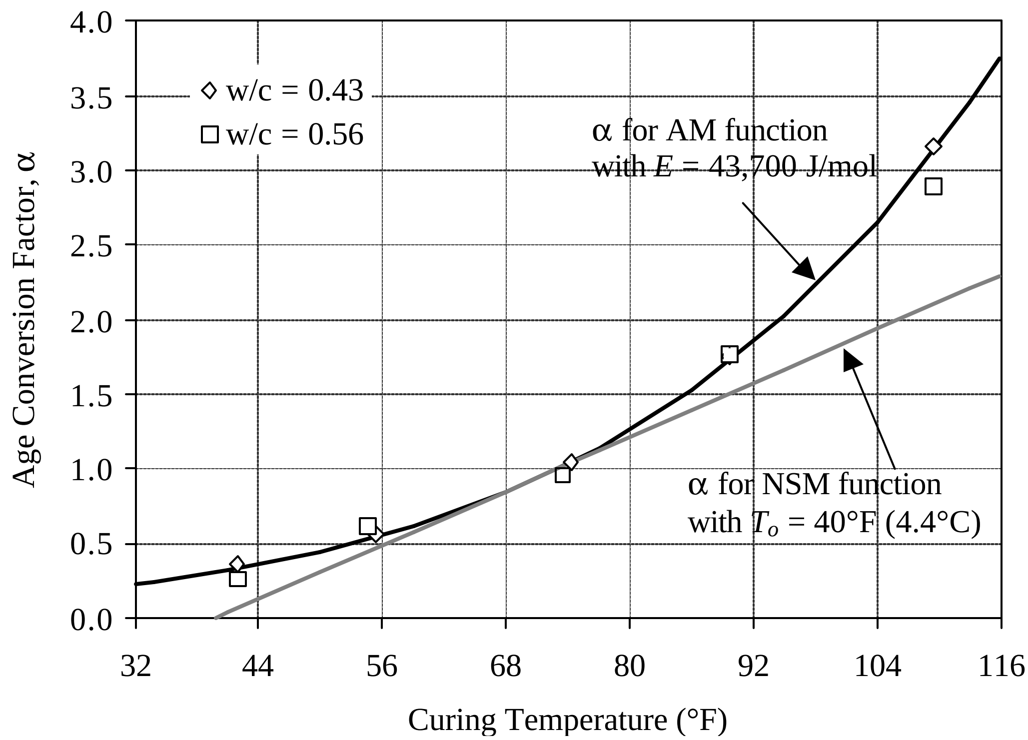


Figure 2.19: Age conversion factors with best-fit Nurse-Saul and Arrhenius age conversion factors (Carino 1991)

However, the age conversion factor for the Nurse-Saul maturity function with datum temperature of 40°F was always less than or equal to than the corresponding age conversion factors for the mortar. Therefore, Carino recognized that the Nurse-Saul maturity function would produce conservative results in this case. In other words, the Nurse-Saul maturity function would underestimate the actual age conversion factor that the concrete required at various temperatures and thus would underestimate the equivalent age. Therefore, strength estimated from the maturity method using an underestimated equivalent age would be conservative as the strengths would be underestimated.

Carino is not alone in his conclusions. Many other researchers believe the non-linear Arrhenius maturity function is superior to the linear Nurse-Saul maturity function (Freiesleben Hansen and Pedersen 1977; Guo 1989; Tank and Carino 1991). However, Carino noted the simplicity of the Nurse-Saul maturity function and concluded that if it were to be used on the mixture proposed in his study, a dual-datum temperature scheme should be implemented: one datum temperature for concrete cured below the reference temperature and one datum temperature for concrete cured above the reference temperature. From the data already presented in this section, Carino found a value of 36°F (2.2°C) should be used for concrete cured below 73°F and a value of 55°F (12.7°C) should be used for concrete cured above 73°F. The resulting function is shown in Figure 2.20. The function fits the concrete behavior much better over the entire curing range. However, it does overestimate the age conversion factor slightly around 90°F.

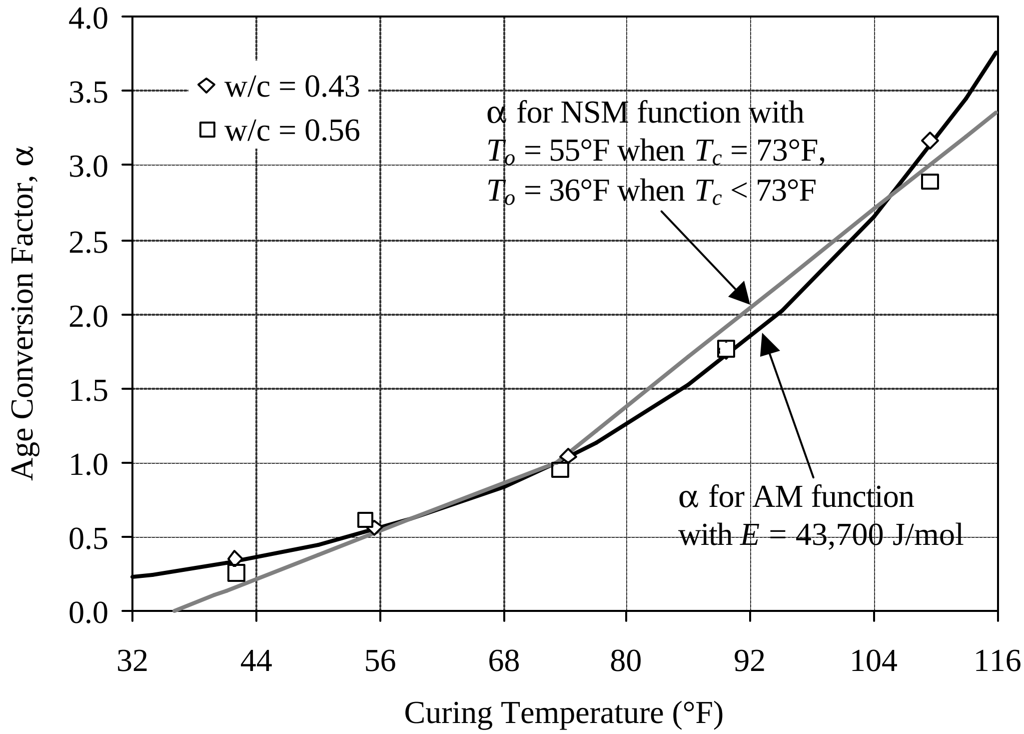


Figure 2.20: Two datum temperature scheme for Nurse-Saul maturity function (Carino 1991)

Now that the concept of age conversion factors has been presented and the two maturity functions have been compared, the next section discusses other published values of activation energies and datum temperatures for various mixtures proposed by various researchers. Incidentally, ASTM C 1074 outlines a procedure for determining datum temperatures and activation energies for any mixture in Annex A1. This procedure follows the same steps as Carino (1991) followed in his experiment explained above.

2.4.2 Temperature Sensitivity Values

As explained in the previous section, datum temperatures and activation energies greatly affect the accuracy of concrete strength estimated by the maturity method. The datum temperature and activation energy will be referred to in this report as “temperature sensitivity” values of a particular concrete mixture, because they change according to the manner in which the rate of reaction (strength development) of a concrete varies with temperature. In other words, the datum temperature and activation energy found in Carino’s experiment (discussed previously) are best suited for only the mixtures he evaluated. Changing the mixture proportions or adding SCMs would change the strength gain behavior (as explained in Section 2.3.1) and temperature sensitivity. Temperature sensitivity values can be: (1) calculated experimentally, as shown in Section 2.4.1, (2) obtained from equations (Freiesleben Hansen and Pedersen 1977), or (3) approximated from accepted values (ASTM C 1074; TxDOT 1999; Iowa DOT 2000). In this section, some published values of temperature sensitivity for various mixtures with different supplementary cementing materials, water-to-cement ratios, and proportions are reported.

2.4.2.1 Datum Temperatures

The datum temperature, to be used with the Nurse-Saul maturity function, represents the temperature below which a particular concrete ceases to gain strength (Bergstrom 1953). In Saul’s report on maturity (1951), he suggested that a temperature of 32°F (0°C) was the temperature below which concrete would cease to gain strength. However, Saul recognized that if concrete was able to set at temperatures above freezing, then cured in temperatures below 32°F (0°C), the datum temperature could be as low as 14°F (-10°C). Later, Plowman conducted a study to investigate at what temperature concrete ceases to gain strength and found 11°F (-12°C) to be the value. ASTM C 1074 (2004) recommends a datum temperature of 32°F (0°C) for use with a Type I cement when no admixtures are used. Should any other cement types or admixtures be used, ASTM recommends the use of the experimental procedure outlined in Annex A1 of ASTM C 1074 (explained in Section 2.4.1 of this thesis).

Carino and Tank (1992) conducted an extensive study of the isothermal strength development of concrete and mortar specimens made with different cementitious systems with two water-to-cement (*w/c*) ratios. Specimens in this study were cured at isothermal temperatures of 50, 73, and 104°F (10, 23, and 40°C), and strength tests were performed at regular age intervals. Carino and Tank obtained the best-fit datum temperatures to be used with the different mixtures using the same procedure as described in Section 2.4.1. Table 2.1 summarizes the datum temperature values obtained from their tests. Carino and Tank concluded that different mixtures called for different datum temperatures and that "none of the values were -10°C [14°F], which is the value of [T_o] in the traditional Nurse-Saul maturity function." Also, it is worth noting that most values found were greater than 32°F (0°C).

Table 2.1: Datum temperature values proposed by Carino and Tank (1992)

Cement Type	**Datum Temperature, T_o (°F (°C))**	
	w/c = 0.45	*w/c* = 0.60
Type I	52 (11)	48 (9)
Type II	48 (9)	43 (6)
Type III	45 (7)	45 (7)
Type I + 20% Fly Ash	23 (-5)	32 (0)
Type I + 50% Slag	46 (8)	50 (10)
Type I + Accelerator	46 (8)	48 (9)
Type I + Retarder	41 (5)	41 (5)

From Table 2.1, the datum temperatures increased with a decrease in the water-to-cement ratio for the Type I and Type II mixtures. The datum temperature for the Type III mixture was not affected by the change in water-to-cement ratio. Their Type I + 20% Fly Ash mixture was the Type I mixture with 20% of the cement replaced by fly ash. This mixture required the lowest datum temperature of 23°F (-5°C) at a water-to-cement ratio of 0.45. The Type I + 50% Slag mixture was the Type I mixture with 50% of the cement replaced by GGBF Slag. The datum temperature for that mixture increased with an increase in the water-to-cement ratio. Carino and Tank also experimented with the effect of adding chemical admixtures such as accelerator and retarder to the Type I mixture. The Type I + Accelerator mixture required a datum temperature of 46°F (8°C) and the Type I + Retarder mixture required a datum temperature of 41°F (5°C) for the lower water-to-cement ratio mixtures. The addition of chemical admixtures thus changed the datum temperature of the concrete. The average of Carino and Tank's results for the lower water-to-cement ratio mixtures, minus the Type I + 20% Fly Ash mixture, was approximately 46°F (8°C). These results, as well as those from Carino, Bergstrom, and Saul show that different mixtures can require very different datum temperatures for use with the Nurse-Saul maturity function.

2.4.2.2 Activation Energies

The concept of an activation energy came from Svante Arrhenius in 1888 and accounts for the extra energy required to begin a chemical reaction (Carino 1997). Carino gives an analogy of this process as the energy required to push a brick, standing upright, just enough to start the brick in motion, where gravity will control the remaining process. The initial push would be the activation energy in that analogy. Different mixtures require different energies to begin the hardening process. ASTM C 1074 (2004) recommends activation energies in the range of 40,000 to 45,000 J/mol for use with a Type I cement with no admixtures. Should any other cement types or admixtures be used, ASTM recommends the experimental procedure outlined in Section 2.4.1.

Freiesleben Hansen and Pedersen (1977) developed an equation to compute activation energies based on the concrete's curing temperature. The Freiesleben Hansen and Pedersen (FHP) equation is as follows:

FHP Model for Computing the Activation Energy: (Equation 2.9)

for $T_c \geq 20°C$ (68°F) $E = 33{,}500$ J/mol, and

for $T_c < 20°C$ (68°F) $E = 33{,}500 + 1{,}470\,(20 - T_c)$ J/mol.

This model was determined by computer analysis of early-age compressive strength data, where it was found that concretes cured at hot temperatures required a lower activation energy, in this case 33,500 J/mol. However, as curing temperatures dropped below the reference temperature, a much higher activation energy was needed. For example, a concrete cured at 41°F (5°C) would require an activation energy of approximately 56,000 J/mol, using the FHP model. To compare this equation to constant values of activation energy, Figure 2.21 shows the age conversion factors for the Arrhenius maturity function using the FHP model, as well as using the constant values of 40,000 J/mol and 30,000 J/mol. The Nurse-Saul maturity function is also plotted with a value of 32°F (0°C) as the datum temperature. The reference temperature for all of the curves in this figure is 68°F (20°C), to be consistent with the FHP model. The figure shows that at lower temperatures, the age conversion factors from the FHP model are less than those from E = 40,000 J/mol. At warmer temperatures the age conversion factors determined from the FHP model fall in between those determined with E = 30,000 J/mol and 40,000 J/mol. Note that the age conversion factor for the Nurse-Saul maturity function using 32°F (0°C) as the datum temperature is close to the FHP model at temperatures below the reference temperature.

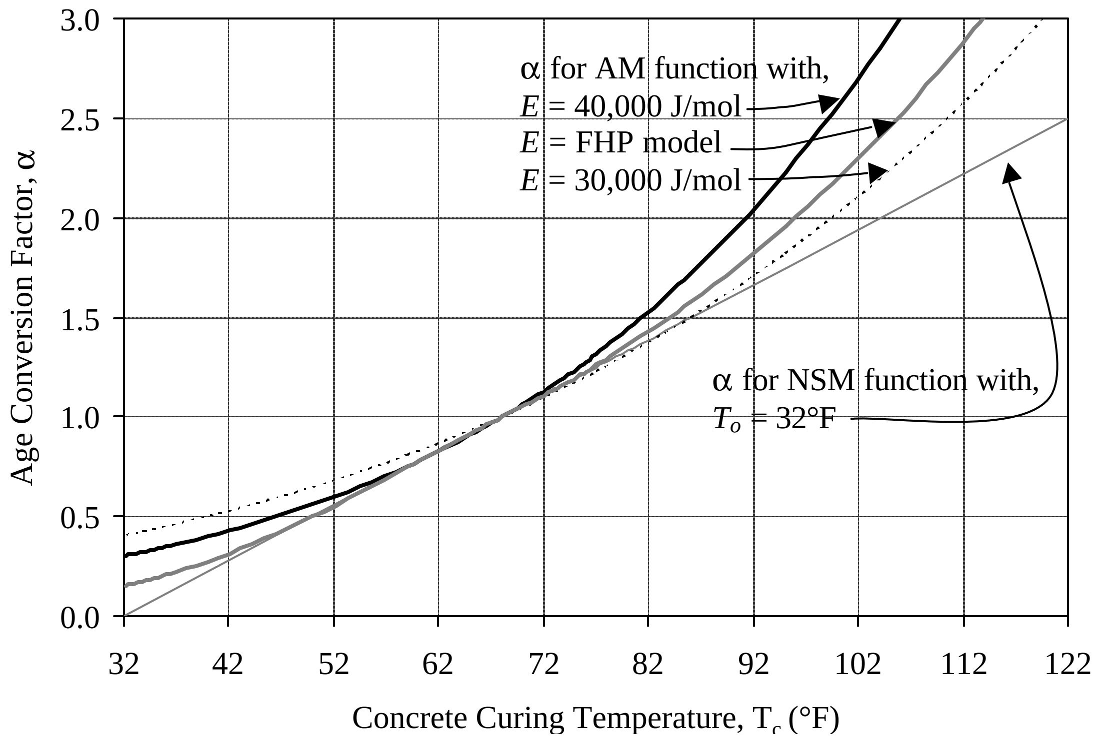


Figure 2.21: Comparing age conversion factors using FHP model to other functions

There have been numerous researchers who have determined and published their own activation energies for various mixtures. A list of some typical published values of activation energies, reported by Carino (1991), is given in Table 2.2. From the table, the Type I mixtures Carino reported required activation energies from 41,000 J/mol to 44,000 J/mol, which agrees with the values recommended by ASTM C 1074. The remaining values are the activation energies found from the various types of testing, such as heat of hydration and chemical shrinkage, and various mixture designs. The table shows elevated values of activation energy of 49,000 and 56,000 J/mol for mixtures with slag replacement doses of 50% and 70%, respectively.

Table 2.2: Activation energy values proposed by various research efforts (Carino 1991)

Cement Type	Type of Test	Activation Energy, E (J/mol)
Type I (Mortar)	Strength	42,000
Type I (Mortar)	Strength	44,000
Type I (Concrete)	Strength	41,000
OPC* (Paste)	Heat of Hydration	42,000 – 47,000
OPC* + 70% Slag	Heat of Hydration	56,000
OPC* (Paste)	Chemical Shrinkage	61,000
RHC* (Paste)	Chemical Shrinkage	57,000
OPC*(Paste)	Chemical Shrinkage	67,000
Type I/II (Paste)	Heat of Hydration	44,000
Type I/II + 50%Slag (Paste)	Heat of Hydration	49,000

*OPC = ordinary portland cement. RHC = rapid hardening cement.

The RILEM Technical Committee 119 - TCE recommends using the FHP model for all portland cements (Springenschmid 1998). However, for slag cement mixtures cured at any temperature, RILEM suggests using approximately 50,000 J/mol.

Carino and Tank (1992) also obtained the activation energy values for their experiment with different mixtures cured at various isothermal temperatures, as described above. Table 2.3 summarizes the activation energies found from their tests. From this table it can be seen that for the Type III and Type I + Retarder mixtures, the change in the water-to-cement ratio had no effect on the activation energies. However, with Type I and

Type II cements, the lower water-to-cement ratio mixtures had significantly higher activation energies. On the other hand, the Type I + 50% GGBF Slag mixtures had higher values of activation energy as the water-to-cement ratio increased. These trends are the same as those found for the datum temperatures, described earlier. Carino and Tank's results further indicate how changes to mixture proportions can alter the activation energy for a particular concrete mixture.

Table 2.3: Activation energy values proposed by Carino and Tank (1992)

Cement Type	Activation Energy, E (J/mol)	
	w/c = 0.45	*w/c* = 0.60
Type I	64,000	48,000
Type II	51,000	43,000
Type III	44,000	44,000
Type I + 20% Fly Ash	30,000	31,000
Type I + 50% Slag	45,000	56,000
Type I + Accelerator	45,000	50,000
Type I + Retarder	39,000	39,000

2.6 SUMMARY

As shown in this chapter, the maturity method can be used to estimate concrete strengths at various curing temperatures using either the Nurse-Saul or Arrhenius maturity functions with a mixture-specific strength-maturity relationship. The mixture-specific strength-maturity relationship must be predetermined prior to any strength estimations. Measures must be taken to verify the estimated in-place strength. Quality control of batching and raw materials and construction techniques must be maintained in order for the predetermined strength-maturity relationship to remain appropriate for that mixture. Long-term strength loss due to high curing temperatures, or crossover, must be taken into account as well.

A comparison of the two popular maturity functions was also given in this chapter. It should be reemphasized that the Nurse-Saul maturity (NSM) function has a linear age conversion factor function and the Arrhenius maturity (AM) function has a non-linear age conversion factor function. These trends were essential in determining the best maturity function to use to estimate concrete strengths of the mixtures in this study. It is possible that a linear age conversion factor function could be well suited for some mixtures, or types of mixtures, while a non-linear age conversion factor function may be better suited for others. The method for determining the mixture-specific datum temperatures and activation energies recommended by ASTM C 1074 (2004), described in Section 2.4.1, was used extensively in the portion of this study described in Chapter 6.

CHAPTER 3

LABORATORY TESTING PROGRAM

This chapter provides details of the experimental program developed to evaluate the accuracy of using the maturity method to estimate the strength development of hardening concrete cured under various temperature histories. This includes description of the concrete mixtures chosen to be evaluated as well as the raw materials, proportions, and curing methods used.

3.1 CONCRETE MIXTURES CONSIDERED

Thirteen concrete mixtures were evaluated in this study. A summary of the mixtures can be found in Table 3.1. The mixtures were selected in order to evaluate the effect of different dosages of supplementary cementing materials (SCMs), different SCM types, varying cement types, and changes in the water-to-cementitious materials (*w/cm*) ratio. The mixtures were chosen because they are similar to common mixtures used for ALDOT construction projects. For example, there are normal strength mixtures, bridge deck mixtures, repair mixtures for higher early strength, and prestressed concrete mixtures. The Type I HPC Bridge Deck mixture with a *w/cm* ratio of 0.41 can be compared to the Class C fly ash, Class F fly ash, and the GGBF Slag mixtures, since they all have the same mixture proportions, except that the SCM is used to replace the specified percentage of Type I cement. This percentage is based on mass of cement replaced by SCMs. For example, the 20% C mixture is the same as the Type I - 0.41 mixture, except with 20% of the cement by mass replaced with Class C fly ash. These mixtures allow the effect of various SCMs on concrete strength when cured under different temperatures to be examined.

Table 3.1: Types of mixtures evaluated

Mixture Identification	Cementitious Materials Content	*w/cm*	Classification
CEMENT ONLY			
Type I - 0.48	620 lb/yd^3	0.48	Normal: A-1a
Type I - 0.44	620 lb/yd^3	0.44	Normal: A-1c
Type I - 0.41	658 lb/yd^3	0.41	HPC Bridge Deck
Type III - 0.44	620 lb/yd^3	0.44	Repair: A-1c
Type III - 0.37	705 lb/yd^3	0.37	Prestressed Girder
CLASS F FLY ASH			
20% F	658 lb/yd^3	0.41	Bridge Deck
30% F		0.41	Bridge Deck
CLASS C FLY ASH			
20% C	658 lb/yd^3	0.41	Bridge Deck
30% C		0.41	Bridge Deck
GGBF SLAG			
30% Slag	658 lb/yd^3	0.41	Bridge Deck
50% Slag		0.41	Bridge Deck
SILICA FUME			
70/20/10 - 0.44	620 lb/yd^3	0.44	HPC Bridge Deck: A-1c
70/20/10 - 0.37	705 lb/yd^3	0.37	Prestressed girder

The mixtures with 620 lb/yd^3 of cement or cementitious material originate from the standard ALDOT mixtures, A-1c and A-1a, defined in Section 501.02 (ALDOT

2002). The A-1c mixture was modified by the type of cement and replacement of cement with SCMs. The 70/20/10 mixtures represent mixtures with cementitious material content made up of 70% Type I cement, 20% Class F fly ash, and 10% silica fume. These types of mixtures are commonly used by ALDOT in structures exposed to a marine environment. Mixures with SCMs require the use of a water-to-cementitious material (*w/cm*) ratio, as opposed to the water-to-cement ratio. This is done to show that, although the water-to-cement ratio changes from the straight cement mixtures to the mixtures with SCMs, the water-to-cementitious materials ratio stays constant.

3.2 RESEARCH APPROACH

All thirteen mixtures were batched at different temperatures and then cured under three different temperature histories in order to evaluate the maturity method over the full practical temperature range. The following curing conditions were used:

1. One batch of each mixture was mixed and cured at a constant “control” temperature (i.e. 68 - 73°F).
2. One batch of each mixture was batched and cured under a representative “hot” temperature history to simulate summer conditions.
3. One batch of each mixture was batched and cured under a representative “cold” temperature history to simulate winter conditions.

Both the “hot” and “cold” batches were cured under fluctuating temperatures, which simulate actual field conditions more realistically than isothermal conditions. These fluctuating curing conditions were achieved by constructing two insulated water tanks.

The water temperature in each tank was controlled by half-inch copper pipes that oscillated through the tank. The temperature of the water in the copper pipes was controlled by a programmable, heating and cooling water circulator. Figures 3.1 and 3.2 depict one of the tanks and circulator used to create the hot and cold curing temperatures. The tanks were approximately 8 x 2.5 x 2 ft surrounded by a wood frame that held 4-in.-thick closed-cell polystyrene insulation sheets. Each 1-ft^3 capacity programmable circulator (Polyscience, Model No. 9612) was connected to a circuit of ½-in. copper pipes, which transferred heat from the water in the circulator to the lime-saturated water in the appropriate tank. The tanks were designed to hold approximately forty 6x12 in. cylinders. From each batch of concrete, nineteen 6x12 in. cylinders were prepared and tested at various ages, in order to evaluate the strength gain behavior of the different mixtures. The tanks were designed to hold the fresh cylinders, without being fully submerged, as well as hold any late-age cylinders from different mixtures, yet to be tested. The cylinder testing plan is explained further in Chapter 4.

Figure 3.1: Curing tank and programmable heating/cooling circulator

The temperatures in the circulators had to be calibrated to achieve the desired temperatures in the lime-saturated water baths. The desired curing temperatures for the three batches of each mixture are shown in Figure 3.3. The curing temperature cycle in the lime-saturated water for the “hot” mixtures was 90°F to 106°F and back to 90°F in 24 hours. This range was cycled for the entire curing period. For the setup in this project, the “hot” circulator had to be programmed to run from 85°F to 120°F and back to 85°F in 24 hours to achieve the desired temperatures in the lime-bath. The curing temperature cycle in the lime-saturated water for the “cold” mixtures was from 55°F to 40°F and back to 55°F in 24 hours. For the setup in this project, the “cold” circulator was programmed to run between 28°F and 65°F. A mixture of approximately 30% to 80% of ethylene glycol to water was used in the cold circulator to prevent freezing.

The curing temperature ranges were chosen in order to fully cover the range of practical temperatures found on most ALDOT construction projects. The cold temperatures were chosen to meet the lowest temperature (i.e. 40°F) that concrete can be poured, according to ALDOT standard specifications (ALDOT 2002). The hot temperatures were chosen to show the effects of rapid hardening on strength-gain behavior of concrete and the resulting effects on strength estimations using the maturity method.

Once compressive strength testing was completed for each batch, the temperature history of the cylinders was obtained, and the data were converted to maturity values. More details of the testing procedures and methods are reported in Chapter 4.

Figure 3.2: Inside of a temperature-controlled curing tank

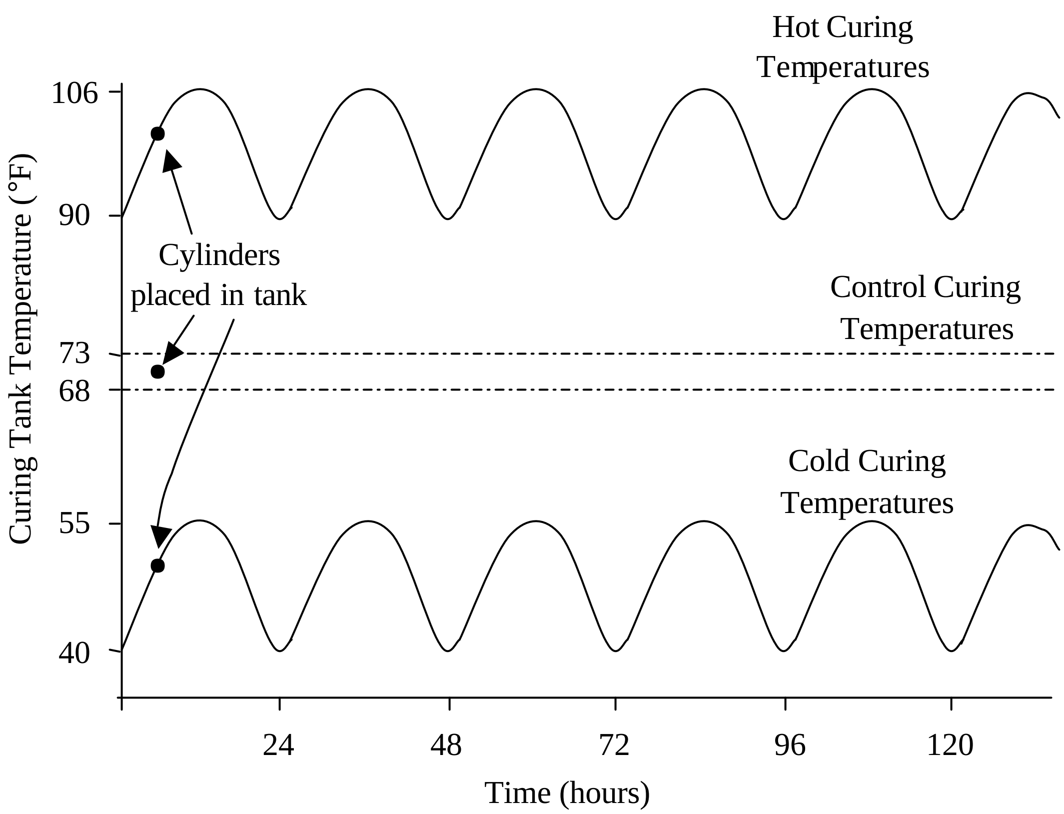


Figure 3.3: Curing tank cycles

3.3 RAW MATERIALS

3.3.1 Cements and Supplementary Cementing Materials

All Type I Cement was produced by LaFarge from their Roberta plant in Calera, Alabama. Due to the length of the project, four different orders of Type I cement were used. Although these cements came from the same producer, they were treated as coming from separate sources. All bridge deck mixtures with 658 lb/yd^3 of cementitious material content contained the Type I cement labeled Source A. The mixtures Type I - 0.44 and Type I - 0.48 contained the Type I cement named Source B. Source C was used for the Type I - 0.44 control batch. It came from a separate source because a data collection failure required the mixture to be reproduced. This was considered acceptable, as the two cements are nearly identical (see Table 3.2). Source D was used for the ternary mixtures (70/20/10). The Grade 120 ground-granulated blast-furnace slag was obtained from Buzzi Unicem USA, Inc. from their New Orleans Slag Facility. The Class C fly ash was obtained from Holcim US, Inc. from their plant in Quinton, AL, and only one source was used. Two sources of Class F fly ash were used in this project: one was used for the Class F fly ash bridge deck mixtures, and the other was used for the 70/20/10 mixtures in combination with Type I cement and silica fume. They are labeled Class F_1 and F_2 for the Class F fly ash bridge deck and 70/20/10 mixtures, respectively. Both sources of Class F fly ash were produced by Boral Material Technologies from their Plant Bowen, near Stilesboro, Georgia. The densified Silica Fume was produced by Simcala, Inc. located in Mt. Meigs, Alabama. The Type III mixtures used cement that was produced by Cemex out of their Demopolis, Alabama plant.

All of the cementitious materials used in this study were sent to Wyoming Analytical Laboratory's Denver, Colorado branch to be tested for their chemical compositions. In addition, all the cementitious materials were tested for specific surface area, or Blaine, by Mactec, Inc in Atlanta, Georgia. The results of the analyses are summarized in Tables 3.2 and 3.3. All cements met the chemical requirements for ASTM C 150. The slag, Class F fly ash, Class C fly ash, and silica fume were all certified by the specific producers as passing the relevant ASTM specifications. From Table 3.2, it can be seen that the Type I cements, sources A through C, had similar compositions. Their C_3S percentages ranged from 67 to 55. The Type I, source D, had some slight variations from sources A, B, and C. Source D had the lowest percentage of CaO and the highest percentage of SiO_2 and Al_2O_3, which are the largest factors in calculating the percentage of C_3S as 48.76. Because the values were not far off and because source D was used only for the ternary mixtures, the deviation was considered acceptable for the purposes of this project.

Table 3.2: Chemical composition of cementitious materials

Parameter	Portland Cement					Fly Ash			GGBF Slag	Silica Fume
	Type I				Type III					
	I_A	I_B	I_C	I_D		Class C	Class F_1	Class F_2		
Silicon dioxide, SiO_2 (%)	20.32	20.85	20.79	21.31	20.23	39.94	53.09	54.85	32.68	95.57
Aluminum oxide, Al_2O_3 (%)	4.75	4.47	4.63	4.97	4.90	18.51	29.10	28.34	9.67	0.02
Iron oxide, Fe_2O_3 (%)	3.03	2.96	2.89	3.07	2.61	5.71	7.54	7.54	1.12	0.05
Calcium oxide, CaO (%)	65.12	64.11	63.14	62.96	63.74	23.01	1.56	1.31	45.32	0.41
Free CaO (%)	0.21	0.24	0.30	0.13	0.24	-	-	-	-	-
Magnesium oxide, MgO (%)	2.46	2.77	3.30	2.70	1.11	5.26	0.94	0.90	7.40	0.43
Alkalies (Na_2O + $0.658K_2O$) (%)	0.25	0.28	0.28	0.27	0.31	2.25	2.04	2.05	0.32	-
Sulfur trioxide, SO_3 (%)	2.56	2.90	2.89	2.75	4.45	1.56	0.10	0.03	1.66	0.10
Loss on ignition, (%)	1.10	1.19	1.52	1.46	1.86	0.23	2.19	1.94	0.84	2.43
Tricalcium silicate, C_3S (%)	67.08	60.01	55.54	48.76	56.33	-	-	-	-	-
Dicalcium silicate, C_2S (%)	7.66	14.51	17.72	24.32	15.52	-	-	-	-	-
Tricalcium aluminate, C_3A (%)	7.48	6.83	7.36	7.96	8.57	-	-	-	-	-
Tetracalcium aluminoferrite, C_4AF (%)	9.21	9.00	8.81	9.35	7.96	-	-	-	-	-

Table 3.3: Specific surface areas and specific gravities of all cementitious materials

Material	Blaine, Specific surface area (m^2/kg)	Specific gravity
Type I_A	380	3.15
Type I_B	360	3.15
Type I_C	380	3.15
Type I_D	350	3.15
Type III	490	3.15
Class C fly ash	380	2.63
Class F_1 fly ash	230	2.29
Class F_2 fly ash	210	2.29
GGBF Slag	550	2.91
Silica Fume	1200	2.30

3.3.2 Aggregates

Two sources of both coarse and fine aggregates were used in this study. A No. 67 crushed limestone from Martin Marietta's O'Neil, Alabama quarry was used with fine aggregate from Martin Marietta's Shorter, Alabama quarry for all mixtures except the prestressed concrete mixtures. A No. 78 crushed limestone from Vulcan Materials' Calera, Alabama quarry and fine aggregate from Superior Products' Jemison, Alabama quarry were used for the two prestressed concrete mixtures (the mixtures with water-to-cementitious material ratio of 0.37). The gradations can be seen in Figures 3.4 to 3.7. In these figures, the fine aggregates are labeled by their plant locations, and the coarse aggregates are labeled by their aggregate size. All four aggregates satisfied gradation requirements of ASTM C 33 and AASHTO M 43 specifications. The AASHTO (2003) specification was used since ASTM does not have a No. 78 gradation. The bulk specific gravities and absorption values also were obtained for mixture proportioning. The results from these tests, outlined in ASTM C 127 and C 128, are summarized in Table 3.5.

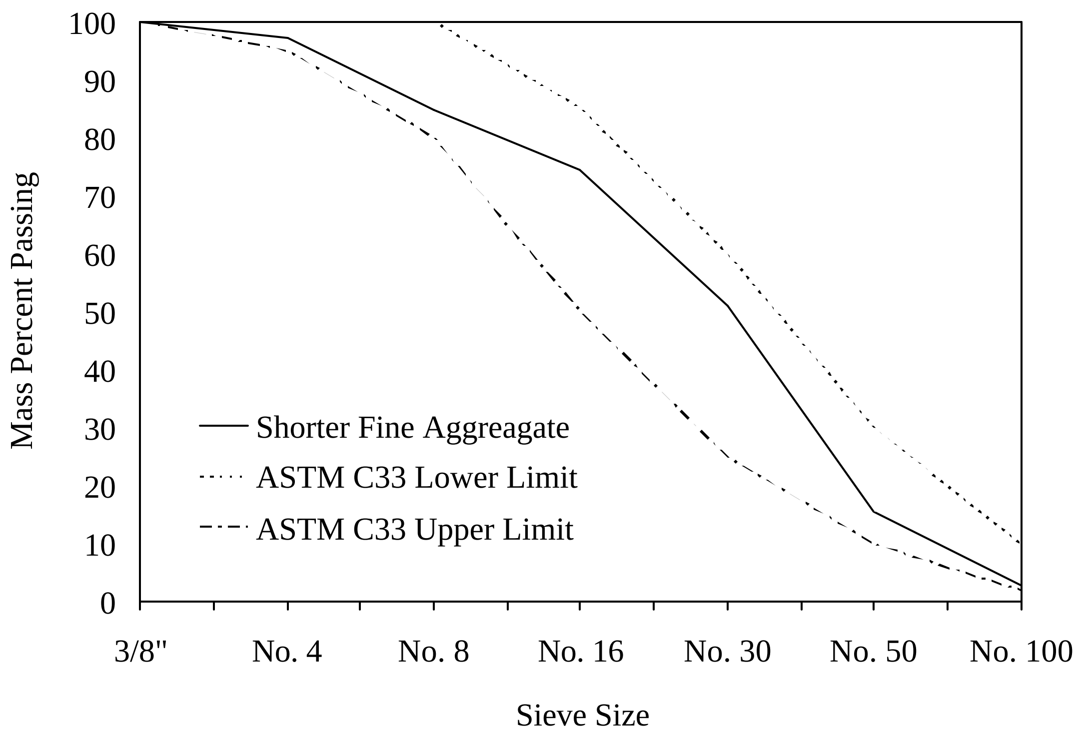


Figure 3.4: Gradation test results for Martin Marietta Fine Aggregate

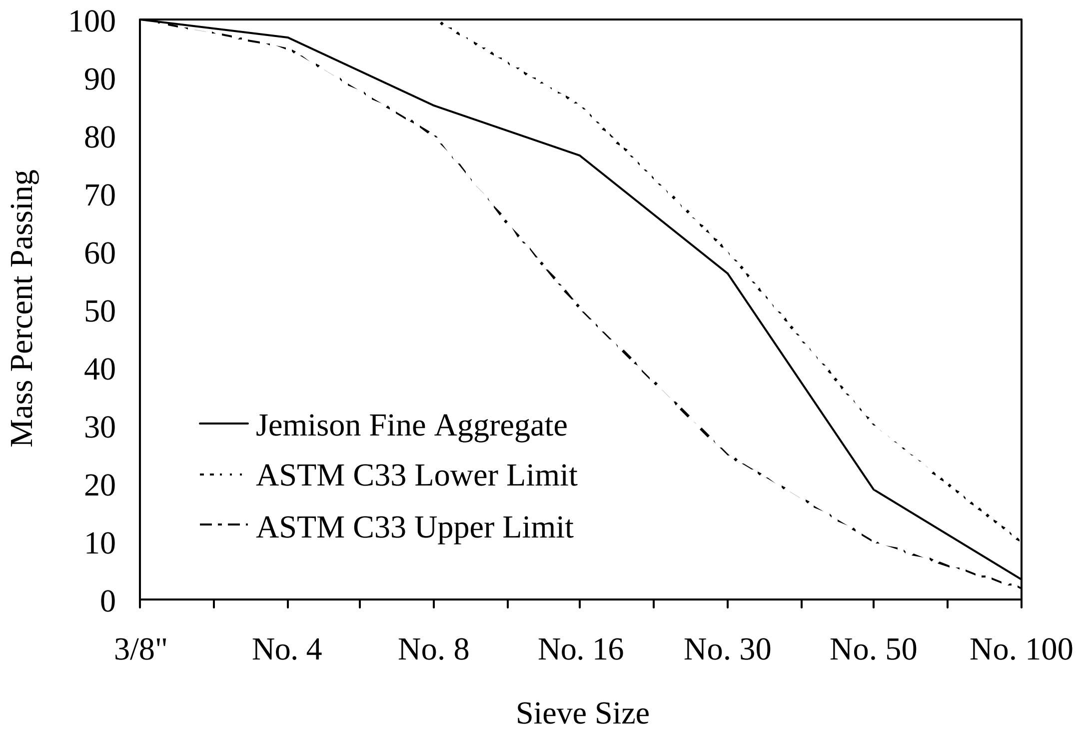


Figure 3.5: Gradation test results for Superior Products Fine Aggregate

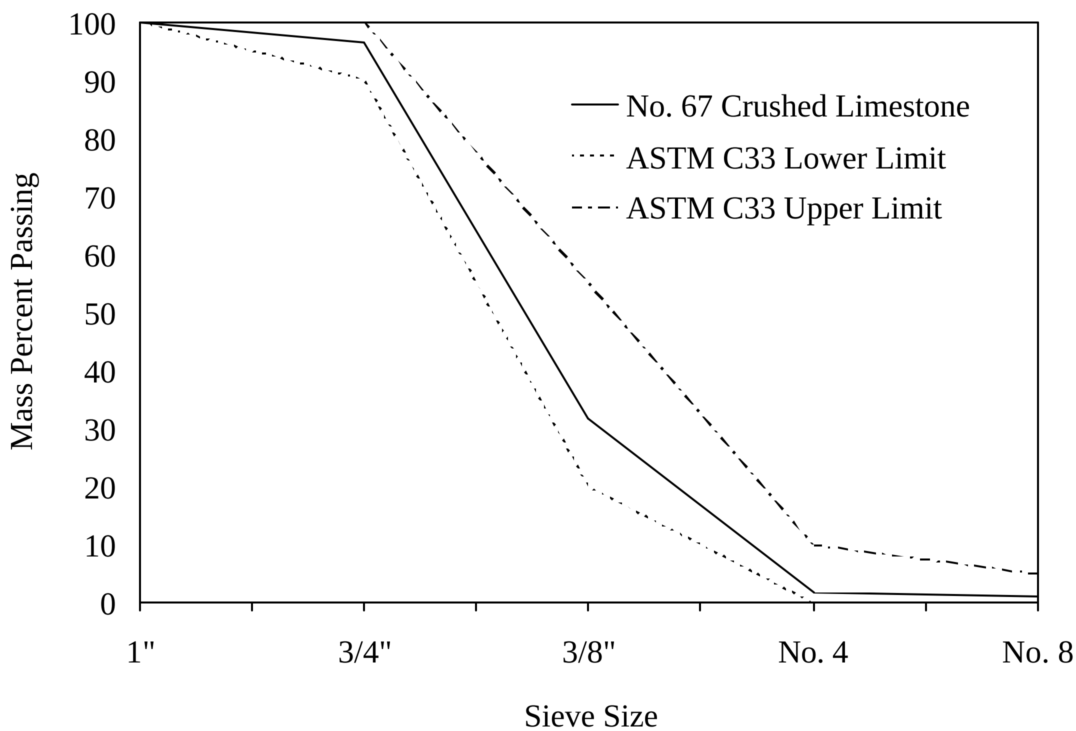


Figure 3.6: Gradation test results for Martin Marietta No. 67 Limestone

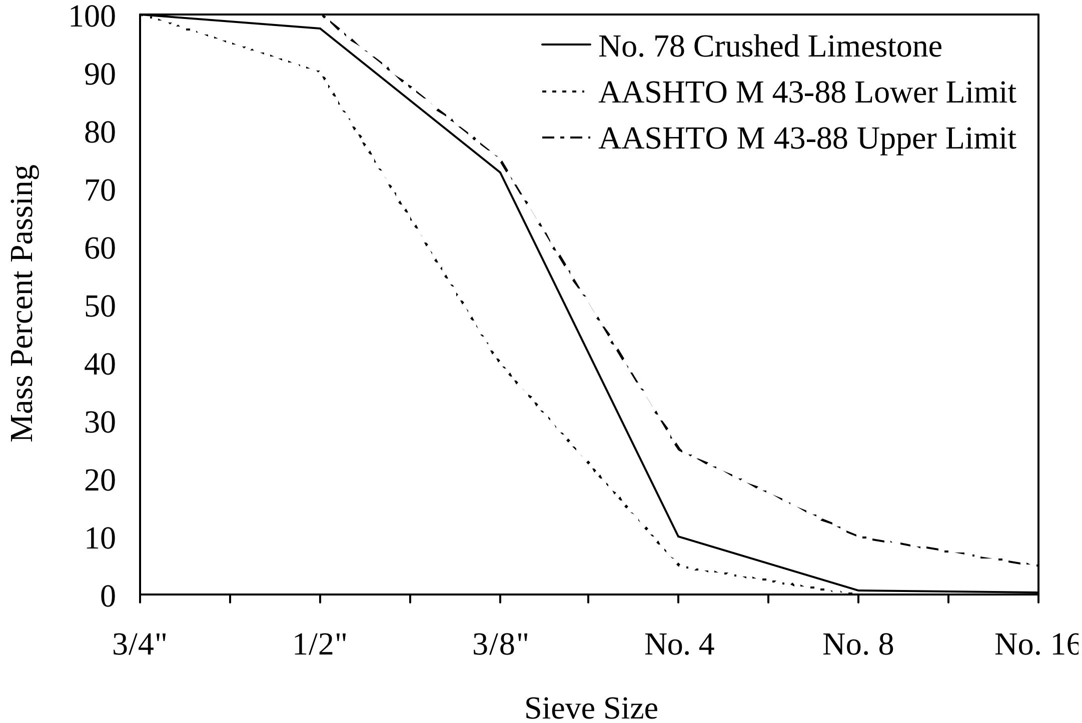


Figure 3.7: Gradation test results for Vulcan Materials No. 78 Limestone

Table 3.4: Specific gravities and absorptions for all materials

Aggregate	Bulk Specific Gravity	Absorption %
Martin Marietta's Fine Aggregate	2.66	0.67
Superior Products' Fine Aggregate	2.63	0.5
No. 67 Crushed Limestone	2.73	0.99
No. 78 Crushed Limestone	2.74	0.30

3.3.3 Chemical Admixtures

Chemical admixtures were used as needed in the mixtures to control the slump and air content of the fresh concrete. All chemical admixtures were supplied by Degussa Admixtures, Inc., and recommended dosages were used whenever possible. For all mixtures, except the prestressed concrete mixtures, Pozzolith 200N was used as a water-reducing admixture and MB AE 90 was used as the air-entraining admixture. Dosages are described in Section 3.4. For the prestressed concrete mixtures, where a higher slump was needed because of the lower *w/cm* ratio, Glenium 3200 HES was used as a high-range water-reducing admixture; Polyheed 1025 was used as a mid-range water-reducing admixture; and Micro Air was used as the air-entraining admixture. The individual chemical admixture specifications may be obtained from the manufacturer.

3.4 MIXTURE PROPORTIONS

The mixture proportions for all thirteen mixtures evaluated in this study are given in Table 3.5. Admixture doses used are given in both oz/yd^3 and ounces per hundred weight of cementitious material. The water-to-cementitious materials ratio (*w/cm*) is given as explained in Section 3.1. From Table 3.5, it can be seen that as the water-to-cementitious materials ratio increased for the Type I straight cement mixtures, the dosages of the water-reducing and air-entraining admixtures decreased. Also note that the bridge deck mixtures with cementitious material content of 658 lb/yd^3 all have the same mixture proportions except the SCM types and dosages are variable. This caused some variations in the fresh concrete properties, as reported in Chapter 5. However, this was necessary in order to isolate the effects of the various types and doses of SCMs.

Table 3.5 (a): Mixture proportions for all concrete mixtures used in this study (Continued…)

Constituent	Mixture Identification								
	Type I - 0.41	**Type I - 0.44**	**Type I - 0.48**	**20% F**	**30% F**	**20% C**	**30% C**	**30% Slag**	**50% Slag**
Water (lb/yd^3)	267	298	273	267	267	267	267	267	267
Type I Cement (lb/yd^3)	658	620	620	526	461	526	461	461	329
Class F Fly Ash (lb/yd^3)	-	-	-	132	197	-	-	-	-
Class C Fly Ash (lb/yd^3)	-	-	-	-	-	132	197	-	-
GGBF Slag (lb/yd^3)	-	-	-	-	-	-	-	197	329
Coarse aggregate (lb/yd^3)	1824	1921	1963	1824	1824	1824	1824	1824	1824
Fine aggregate (lb/yd^3)	1210	1115	1138	1168	1147	1188	1177	1196	1187
Water-reducing admixture, oz/yd^3, (oz/cwt)	19.7 (3.0)	9.3 (1.5)	-	19.7 (3.0)	19.7 (3.0)	19.7 (3.0)	19.7 (3.0)	19.7 (3.0)	19.7 (3.0)
Mid-range water-reducing admixture, oz/yd^3, (oz/cwt)	-	-	-	-	-	-	-	-	-
High-range water-reducing admixture, oz/yd^3, (oz/cwt)	-	-	-	-	-	-	-	-	-
Air-entraining admixture, oz/yd^3, (oz/cwt)	3.0 (0.46)	2.0 (0.32)	1.5 (0.24)	3.0 (0.46)	3.0 (0.46)	3.0 (0.46)	3.0 (0.46)	3.0 (0.46)	3.0 (0.46)
Water-to-cementitious material ratio (*w/cm*)	0.41	0.48	0.44	0.41	0.41	0.41	0.41	0.41	0.41

Table 3.5 (b): Mixture proportions for all concrete mixtures used in this study

Constituent	Mixture Identification			
	Type III - 0.37	**Type III - 0.44**	**70/20/10 - 0.37**	**70/20/10 - 0.44**
Water (lb/yd^3)	250	286	261	273
Type I Cement (lb/yd^3)	-	-	494	434
Type III Cement (lb/yd^3)	705	620	-	-
Class F Fly Ash (lb/yd^3)	-	-	141	124
Silica Fume (lb/yd^3)	-	-	71	62
Coarse aggregate (lb/yd^3)	1944	1947	1885	1926
Fine aggregate (lb/yd^3)	1111	1141	1092	1113
Water-reducing admixture, oz/yd^3, (oz/cwt)	-	17 (2.75)	-	21.7 (3.5)
Mid-range water-reducing admixture, oz/yd^3, (oz/cwt)	28.2 (4.0)	-	28.2 (4.0)	21.7 (3.5)
High-range water-reducing admixture, oz/yd^3, (oz/cwt)	42.3 (6.0)	-	42.3 (6.0)	-
Air-entraining admixture, oz/yd^3, (oz/cwt)	21.2 (3.0)	0.6 (0.1)	-	2.0 (0.32)
Water-to-cementitious material ratio (*w/cm*)	0.37	0.44	0.37	0.44

3.5 SUMMARY

In this chapter, the setup of the experiment and materials used were described. A total of thirteen mixtures were batched and cured at three different temperatures. The ranges of curing temperatures were 90°F to 106°F and 55°F to 40°F, for the 'hot' and 'cold' batches, respectively. These batches fluctuated between their respective temperatures on a 24-hour cycle. There was an additional "control" mixture that was batched and cured under normal laboratory conditions (i.e. 68 - 73°F). The cements and supplementary cementing materials (SCMs) used were defined, and the chemical analyses were given. The aggregates were tested for gradation, specific gravity, and absorption values and the results were shown. The mixture proportions for all thirteen mixtures were also defined.

The effect of the various curing temperatures on the compressive strength was evaluated for the following variables:

- different cement types (Type I and III)
- *w/cm* = 0.37, 0.41, 0.44, and 0.48
- Supplementary cementing materials type and dosage
  - Class F fly ash at 20 and 30% replacement levels
  - Class C fly ash at 20 and 30% replacement levels
  - Ground-granulated blast-furnace slag at 30 and 50% replacement levels
  - Silica fume at a 10% replacement level in a ternary blend with 20% Class F fly ash.

The testing performed to evaluate the effect of these variables on concrete strength is explained in the next chapter.

CHAPTER 4

LABORATORY PROCEDURES AND TESTS

The tests and procedures carried out in order to evaluate the accuracy of using the maturity method to estimate the concrete strength development of hardening concrete cured under various temperature histories are discussed in this chapter. This includes the documentation of the concrete production procedures, fresh concrete test procedures, and hardened concrete test procedures.

4.1 CONCRETE PRODUCTION PROCEDURES

4.1.1 Mixing Procedures

The concrete mixtures and the respective raw materials used were defined in Chapter 3. In order to achieve the correct proportions of chemical admixtures, trial batches were performed on all thirteen mixture designs. A trial batch was generally proportioned to be 2 ft^3. This allowed the mixture to be tested for slump, air content, unit weight, and to check compressive strength levels. Mixtures using the Glenium 3200 admixtures required an increase in trial batch sizes to 5.6 ft^3, because of problems scaling the batch size. All trial batches were mixed at room temperature (i.e. 68 - 73°F). The target air content and slump for all mixtures are listed in Table 4.1. These values are similar to those from ALDOT Standard Specifications Section 501.02 (ALDOT 2002). Target air content and slump were based on the mixtures batched at the control temperatures. It was necessary to keep all chemical admixture doses constant within a mixture. Therefore, some temperature effects on slump and air content were unavoidable.

Table 4.1: Target slump and air content for all mixtures

Mixture Type	Slump	Air Content
All mixtures except prestressed concrete	2 to 5 in.	3 to 6 %
Prestressed concrete	< 8 in.	3 to 6 %

After chemical admixture dosages and the mixture proportions were verified with trial batches, each mixture was mixed at "hot", "cold", and "control" temperatures as previously described. The batch size for all full mixtures was 5.6 ft^3. Prior to mixing, all materials used for a particular mixture were either cooled or heated in accordance with the desired mixing temperature. This was essential in order to reproduce actual batch-plant procedures, where stockpiles and materials are stored in ambient conditions. All aggregates, cement, supplementary cementing materials (SCMs), and water to be used in a certain batch were placed in an environmental room at the appropriate temperature for at least 2 days. For the hot mixtures, the room was set at approximately 115°F, which produced an average batch temperature of 101°F. The room was set to approximately 40°F for the cold mixtures, which resulted in an average batch temperature of 55°F.

Before weighing and batching the coarse aggregate, fine aggregate, and water, the moisture contents of the aggregates were calculated per ASTM C 566. It was important to wait until the mixing day to test moisture content, especially for the hot and cold mixtures, because of the potential moisture variations introduced by storing these materials in the environmental chamber. Before sampling the fine aggregate, it was mixed thoroughly to obtain a representative sample. A sample of about 800 g was weighed and then heated until dry. The sample was weighed and heated until the weight was within approximately 0.1 g of the previous reading. The moisture content was then compared to the absorption capacity of the aggregate, and the batch water was adjusted accordingly. For example, if the moisture content of the fine aggregate was less than the expected value for the saturated, surface-dry state, then the aggregate would absorb some of the batch water, thereby affecting the water-to-cementitious materials ratio. Thus, extra batch water and less fine aggregate would be required in this case to keep the water-to-cementitious materials ratio as designed.

Once the aggregate moisture contents were found and accounted for, all the raw materials were weighed and batched to the proper proportions. All mixing followed ASTM C 192 procedures. A "butter" batch of fine aggregate, water, and cement was used to coat the inside of the 15 ft^3 mixer. Generally 1/4 of a 5-gal. bucket of fine aggregate and two large scoops of cement were used. Water was then added to the mixer to obtain the correct consistency of the butter mixture. Care was exercised not to add excessive water, as this would affect the water-to-cementitious materials ratio. Once the mixer was prepared, the butter mixture was discarded. Next, all aggregates were added to start the actual mixing process. To ensure proper mixing, 5-gal buckets of coarse and fine aggregates were alternated as they were added into the mixer. Once all aggregates were in the mixer, 80% of the batch water was added along with any air-entraining chemical admixture. After two minutes of mixing, the cement and any SCMs were added, as well as any water-reducing chemical admixtures. The concrete was then mixed for three minutes, followed by three minutes of rest and a final two minutes of mixing. Next, testing of slump, air content, density, and temperature were performed.

4.1.2 Mixing with Silica Fume

Silica fume can cause high air content in concrete mixtures mixed in laboratory settings (Holland 2005). Because the silica fume particles are very small, the manufacturer densifies them into (relatively) larger conglomerates that make the material easier and safer to handle. However, these conglomerates can trap unwanted air in concrete mixtures if the proper care is not taken to separate all silica fume conglomerates. The procedure outlined by the Silica Fume Association was used (Holland 2005). The mixing procedure was the same as described above except that along with the coarse and fine aggregates and 80% water, the silica fume was added and mixed for approximately 5 minutes to break up the silica fume conglomerates. Next, the cement and Class F fly ash were added, and the mixing procedure followed as described above. This procedure was very successful in eliminating entrapped air due to the presence of densified silica fume conglomerates.

4.2 FRESH CONCRETE PROPERTY TESTING

Slump, air content, density, and temperature testing were all performed according to ASTM C 143, C 231, C 138, and C 1064, respectively. The author and his colleague performed all tests and they were ACI-certified as “Field Technician: Level I” before starting any testing for this project. Nineteen 6x12 in. cylinders were made for each batch, as previously explained. Cylinders were prepared according to ASTM C 192.

One cylinder was used to measure the temperature and thus the maturity of the concrete. The temperature was measured using a Dallas Semiconductor programmable i-Button®. Because the i-Buttons have a finite memory, they were programmed to read at time intervals appropriate to reach 28-days of equivalent age (this will be explained in Section 4.3.1). The intervals were generally 25, 20, and 30 minutes for the control, hot, and cold batches, respectively.

After the cylinders were made, they were covered by snap-on plastic lids to prevent moisture loss and transported to the water tanks to begin curing as soon as possible. Whenever possible, the concrete was mixed so that it would be placed in the lime-saturated bath while the curing tanks were heating. This was chosen to simulate a day-time placement on a job-site. As per ASTM C 1074 (2004), the first set of compressive strength tests were performed at twice the time that the concrete took to reach final set. Final set times were obtained from penetration resistance tests according to ASTM C 403 (2004). Mortar was sieved through a No. 4 sieve from the concrete mixed at the three different temperatures. The mortar specimen was placed in the appropriate curing tank to accurately assess the setting behavior of the concrete specimens. At 24 hours of equivalent age, all cylinders were stripped from their plastic molds; three were tested for compressive strength, and the remaining cylinders were returned to the lime-saturated water tank, fully submerged. The other tests were performed at the times specified in the next section.

4.3 HARDENED CONCRETE TESTING

Eighteen of the 6x12 in. cylinders were used for compressive strength testing. Three cylinders were tested according to AASHTO T 22 (2003) at each time of interest. The tests were carried out at the following equivalent ages: twice the final set time, 24 hr, 48 hr, 7 day, 14 day, and 28 day. Equivalent age was used so that data points on the strength-maturity plots would be at comparable strength levels for batches of the same mixture. The actual test times for the cold and hot batches were obtained by using the Nurse-Saul equivalent age formula (Equation 2.6) with a datum temperature of 14°F (-10°C). The average of the desired curing temperature ranges (given in Section 3.2) of the cold and hot batches were used: 47.5°F (9°C) and 98°F (37°C) for the cold and hot batches, respectively. The reference temperature used for these equivalent age calculations was 73°F (23°C). The given equivalent ages were approximately equal to the actual test times for the control batches because the control batches were cured so close to the reference temperature. To find the actual test times for the hot and cold mixtures, the age conversion factors (defined by Equation 2.7) for the respective curing temperatures were computed. The age conversion factors for the cold and hot mixtures were 0.57 and 1.42, respectively. To find the actual test times, the test time at the reference temperature was divided by the age conversion factor. For example, the 28 day equivalent age test for the hot batch should be tested at approximately 28 days/1.42, which equals approximately 20 days. The rest of the actual test times for the cold and hot mixtures are summarized in Table 4.2. Once the proper age was achieved, three of the nineteen cylinders were tested for compressive strength based on AASHTO T 22. The author and his colleague performed all tests and were also ACI certified in “Concrete Strength” testing during this project.

Table 4.2 Compressive strength testing schedule

	Batch Identification		
	Control	**Hot**	**Cold**
Actual Age of Concrete at Testing	$2t_s$	$2t_s$	$2t_s$
	24 hr	18 hr	42 hr
	48 hr	35 hr	84 hr
	7 day	5 day	12 day
	14 day	10 day	25 day
	28 day	20 day	49 day

Note: t_s = final setting time

Neoprene pads were used for all compressive strength tests. This system was chosen as it allowed the research team to test the strengths as soon as the specimens were removed from the curing tanks. Sulfur capping would have required the cylinders to be removed from the curing tanks two or more hours before testing. Pads were purchased from M.A. Industries, Inc. Pad durometer hardness was chosen based on ASTM C 1231, Table 1. Durometer 50, 60, or 70 pads were used depending on the expected level of compressive strength. A log of the number of uses of each set of pads was kept, and pads were discarded as required by ASTM C 1231.

All cylinders remained moist until time of testing. This was especially critical for the hot-cured cylinders at later ages. If they had not been kept moist, the heat would have caused the cylinders to dry quicker than a cylinder cured at cold or control temperatures. The potential moisture loss may seem small, but could have caused significant deviations in compressive strength test results if it had not been prevented.

After the 28-day equivalent age test, the temperature and time data were downloaded from the i-Button. With the temperature and time history and the compressive strength test results, analysis with the maturity method could be performed.

4.4 SUMMARY

In this chapter the experimental testing procedures were explained. Mixing procedures were given. For each batch, nineteen 6x12 in. cylinders were made, and the temperature history was recorded. The compressive strength testing schedule was given as the following six equivalent ages: 2 x final set time, 24 hr, 48 hr, 7 d, 14 d, and 28 d. The results of the testing described above are presented in the next chapter.

CHAPTER 5

PRESENTATION OF RESULTS

In this chapter, the results are given for the tests described in Chapter 4 for all mixtures considered in this project. The fresh concrete properties are reported first, and then the hardened concrete properties are examined. The effects of the various temperature histories, supplementary cementing materials (SCMs), and other changes to mixture proportions are analyzed, when appropriate.

5.1 FRESH CONCRETE PROPERTY RESULTS

The results of the fresh concrete testing are summarized in Table 5.1. There are some temperature effects on the air content and slump that could not be controlled because the chemical admixture dosages had to remain constant between batches of the same mixture. The target slump and air content are given in Chapter 4.

Slump

The Type I - 0.41 control batch had a slump of 1 in., which was less than the 2 to 4.5-in. target. This was deemed acceptable since the same mixture proportions were used for the 20% C, 30% C, 20% F, 30% F, 30% Slag, and 50% Slag mixtures, and additions of SCMs generally increase workability (Kosmatka, Kerkhoff, and Panarese 2002). The Class C fly ash and Class F fly ash mixtures did increase the slump, from 1 in. up to 6 in. for the control batches. However, the GGBF slag mixtures showed a small increase or no change in slump relative to the Type I - 0.41 mixture. The Type I - 0.48 control batch had a slump of 6.25 in., but since the air content and density agreed with the other batches of that mixture, it was considered acceptable. Both of the prestressed concrete control mixtures, the Type III - 0.37 and 70/20/10 - 0.37, stayed under the 8-in. limit for slump.

Air Content

The Type I - 0.41 control batch was within the target air content range of 3 to 6%. The 20% F, 30% F, 30% Slag, and 50% Slag mixtures all showed a decrease in air content when compared to the Type I - 0.41 mixture. The Class C fly ash mixtures showed a slight increase in air content, but were considered acceptable once strength levels were checked. The cold batches from the Class C fly ash mixtures had high air contents and low densities, but this was uncontrollable as the mixture proportions were kept constant between batches of the same mixture. Also, the strength levels were comparable to the other batches of the same mixtures, which is reported in the next section. The air content for the control batches of the prestressed concrete mixtures were within the target air content of 3 to 6%. Also, note that the air contents of the mixtures with silica fume (70/20/10) were within the target range after using the procedure described in Section 4.1.2 to remove the excess entrapped air.

Curing Temperature

As soon as fresh concrete testing was finished and all cylinders were prepared, the cylinders were placed in their appropriate curing tanks. Due to heat from the hydration process, the concrete cylinders deviated from the curing tank’s cycle for the first few days. A graph of a typical cylinder temperature history versus the curing tank’s temperature history is shown in Figure 5.1. From the figure, it can be seen that the research team placed the cold and hot batches in the curing tanks as the lime-water temperature in the tanks was rising, as explained in Section 4.2. The hot batch in this case reached the desired curing temperature range of 106°F to 90°F at approximately 36 hours, and the cold batch reached the desired curing temperature range of 55°F to 40°F at approximately 65 hours after placement. The importance of heating or cooling the raw materials to replicate ambient field temperatures can be seen in the figure. If all the mixtures had been batched at 73°F and then placed in their appropriate curing tanks, then the true effects of the curing temperatures on the strength gain behavior of the mixtures could not be evaluated.

Table 5.1: Fresh concrete properties of all mixtures

Mixture ID	Batch ID	Slump (in.)	Temperature (°F)	Air Content (%)	Density (lb/ft^3)
Type I - 0.41	Hot	2.50	96	4.50	148
	Control	1.00	68	6.00	145
	Cold	2.75	61	5.75	142
Type I - 0.44	Hot	1.50	102	3.75	150
	Control	4.00	73	7.50	146
	Cold	3.25	58	9.00	146
Type I - 0.48	Hot	2.75	104	4.50	147
	Control	6.25	74	4.75	147
	Cold	3.00	56	5.25	146
20% F	Hot	2.50	100	2.25	149
	Control	5.75	70	2.75	150
	Cold	6.50	53	3.00	147
30% F	Hot	1.25	104	2.50	149
	Control	3.50	70	2.00	149
	Cold	4.00	53	2.75	148
20% C	Hot	2.50	101	4.00	147
	Control	6.00	71	6.75	144
	Cold	7.25	55	8.00	140
30% C	Hot	2.75	101	3.50	147
	Control	6.00	74	6.25	144
	Cold	7.50	56	8.00	141
30% Slag	Hot	0.50	100	3.75	150
	Control	1.50	74	4.50	149
	Cold	2.00	53	7.75	146
50% Slag	Hot	1.00	98	3.00	149
	Control	1.00	72	3.50	149
	Cold	3.00	50	4.50	147
Type III - 0.37	Hot	1.00	101	3.75	151
	Control	5.25	71	3.50	150
	Cold	8.75	55	9.50	145
Type III - 0.44	Hot	1.25	98	2.75	149
	Control	3.50	76	5.50	146
	Cold	5.75	55	8.25	144
70/20/10 - 0.37	Hot	2.00	98	3.25	148
	Control	7.75	71	3.00	148
	Cold	8.75	56	3.50	148
70/20/10 - 0.44	Hot	2.50	105	2.00	147
	Control	3.75	75	2.50	148
	Cold	5.75	51	3.25	146

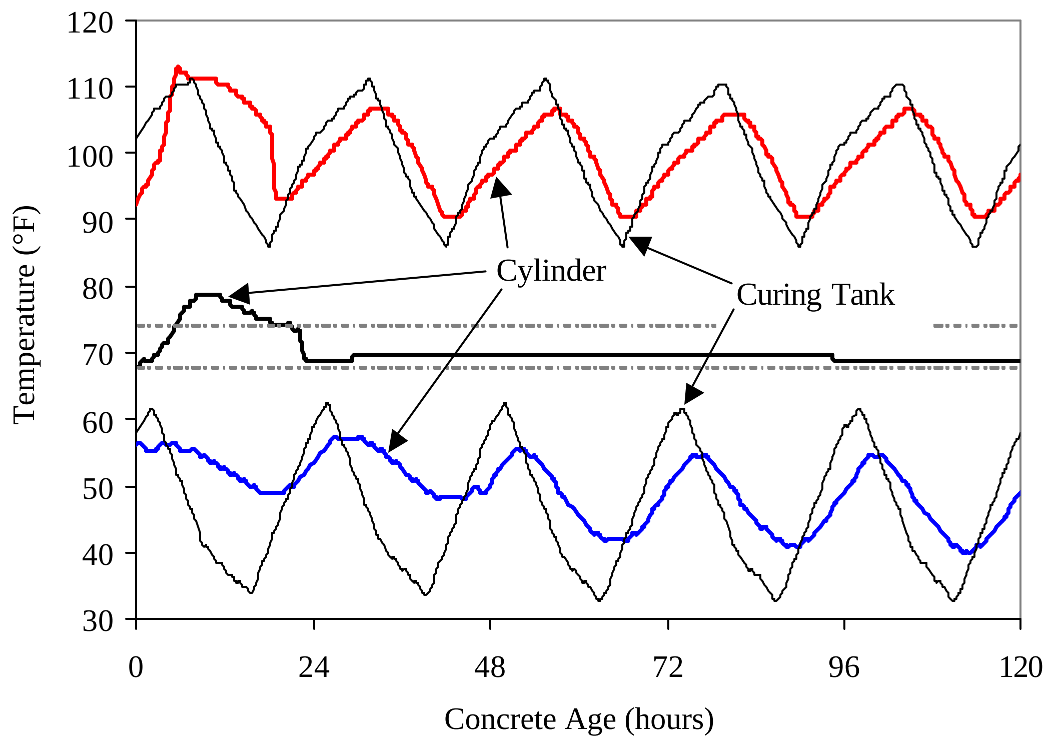


Figure 5.1: Typical temperature history of concrete cylinders

5.2 HARDENED CONCRETE TEST RESULTS

The results from the compressive strength tests for all mixtures can be found in Appendix A. The average test result for each age was plotted versus chronological time for all three batches of all thirteen mixtures in Figures 5.2 through 5.14. A least-squares regression analysis was performed to fit the best hyperbolic strength-age function to the strength versus age data as prescribed by ASTM C 1074. The equation is as follows:

$$S = S_u \frac{k(t-t_o)}{1+k(t-t_o)} \qquad \text{Previously Equation 2.8}$$

where,

S = average compressive strength at age, t, (psi),

S_u = limiting strength (psi),

t = test age (hr),

t_o = age when strength development is assumed to begin (hr), and

k = the rate constant (1/hour).

The actual test data were compared to estimated strength values computed from the hyperbolic strength-age equation, and the difference between the actual and estimated strength was computed. The differences were then squared, to eliminate negative values, and summed. This was performed for all three batch temperatures of all mixtures. The "Solver" function in Microsoft Excel was utilized to minimize the sum of the squares of the errors by varying the k, S_u, and t_o values.

The least-squares k, S_u, and t_o values determined for all mixtures are reported in Table 5.2. The best-fit t_o value was computed as negative for some batches, such as the Type I - 0.44 hot and 20% F hot and control batches, due to extremely rapid initial strength gain. These were corrected because they are not realistic values. As it is defined above, t_o is the time at which the concrete begins to gain strength. Thus, t_o should never be less than zero, and whenever this error occurred, t_o was limited to 0 hrs and the least-squares regression was re-solved.

After examination the strength versus age plots in Figures 5.2 through 5.14, it is obvious that all of the mixtures were affected by the various temperature histories. If this was not true, then all the test points for one mixture would fall on a single curve, and there would be no need to apply the maturity method to estimate the strength. As a precursor to estimating the strengths using the maturity method, it is important to evaluate and quantify the effect of the temperature histories on the strength-age behavior. For this, the amount of crossover, as described in Section 2.3.2, and the amount of temperature correction required by the different mixtures will be examined.

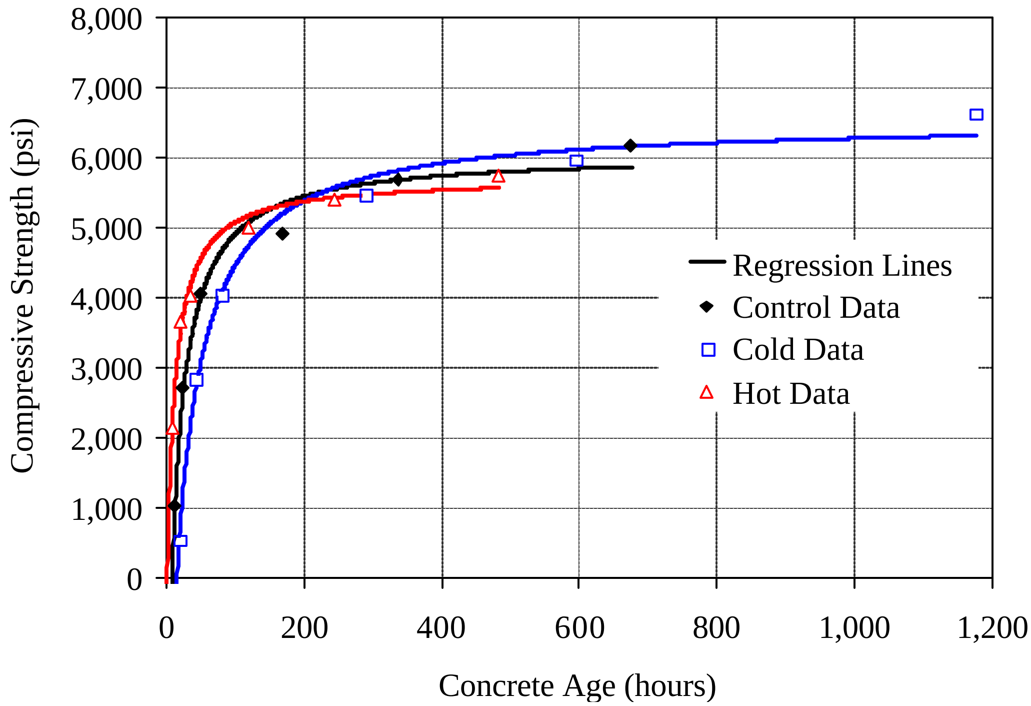


Figure 5.2: Compressive strength versus age results for Type I - 0.41 mixture

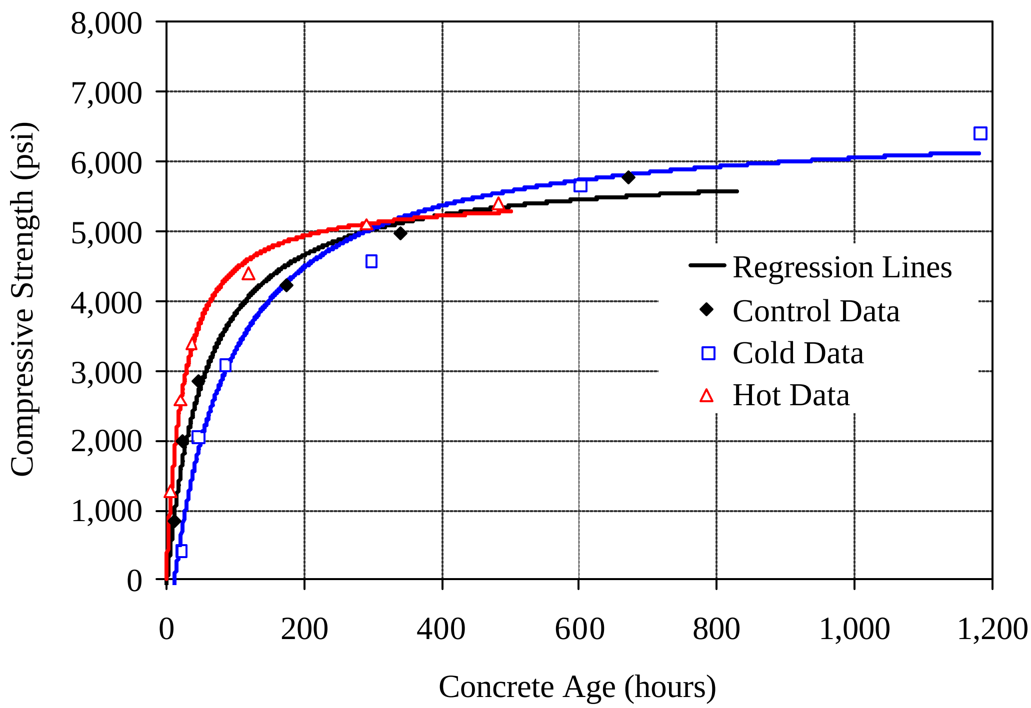


Figure 5.3: Compressive strength versus age results for Type I - 0.44 mixture

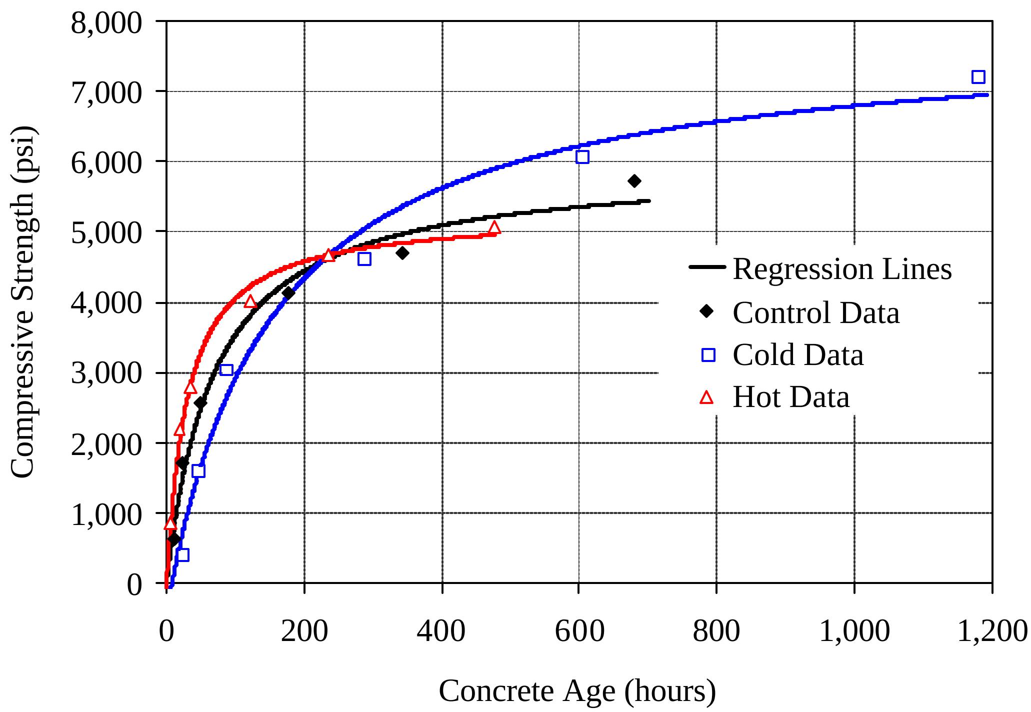


Figure 5.4: Compressive strength versus age results for Type I - 0.48 mixture

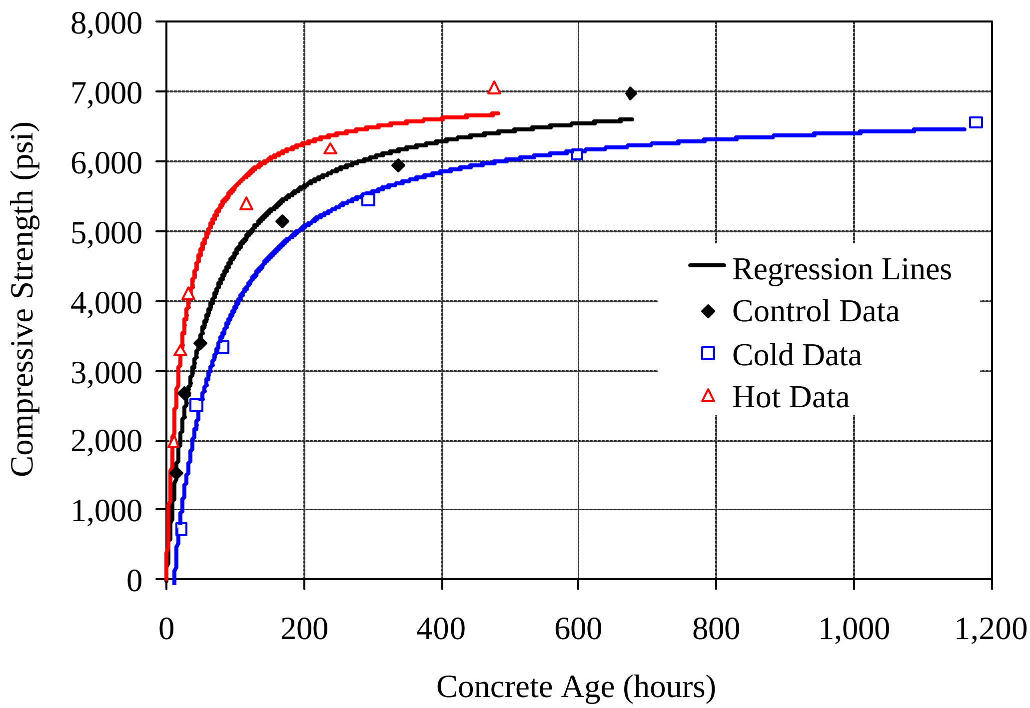


Figure 5.5: Compressive strength versus age results for 20% F mixture

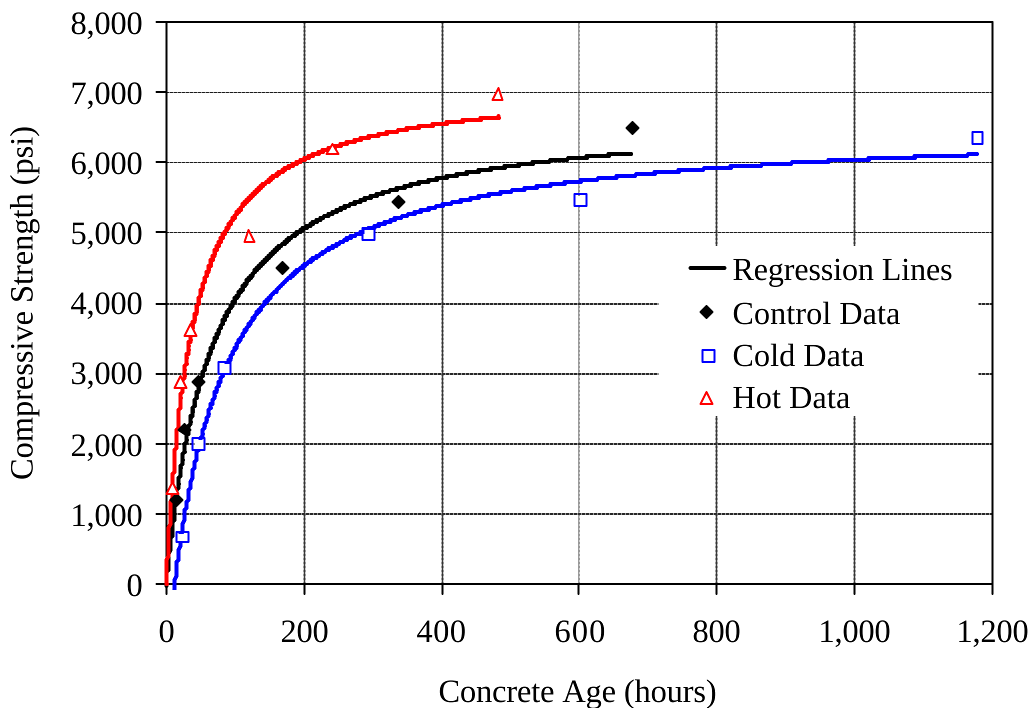


Figure 5.6: Compressive strength versus age results for 30% F mixture

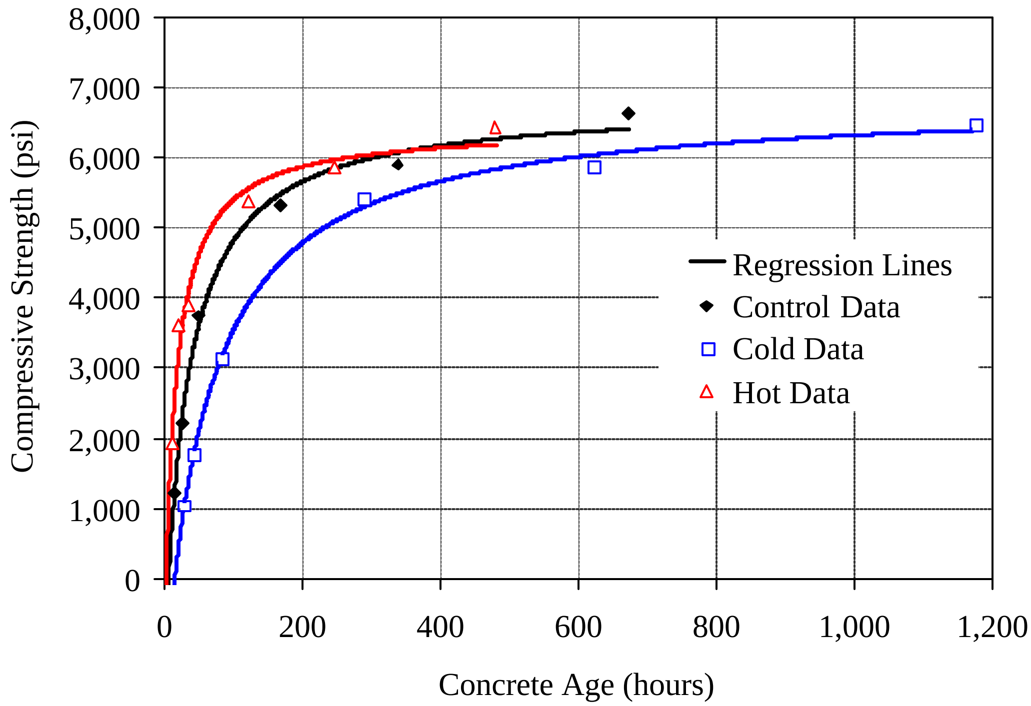


Figure 5.7: Compressive strength versus age results for 20% C mixture

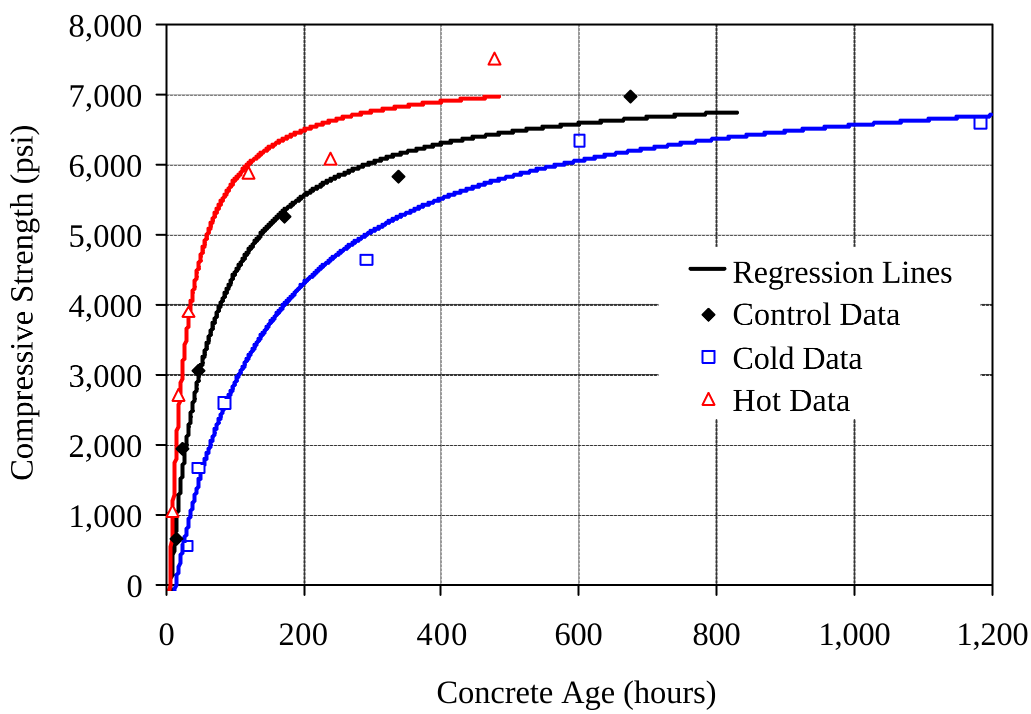


Figure 5.8: Compressive strength versus age results for 30% C mixture

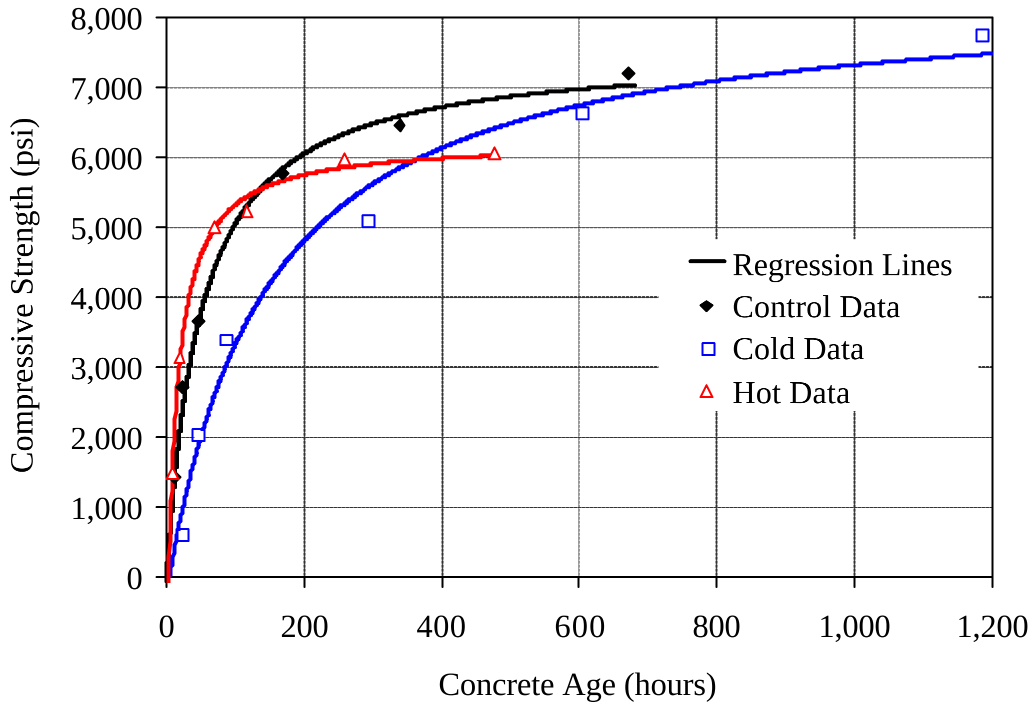


Figure 5.9: Compressive strength versus age results for 30% Slag mixture

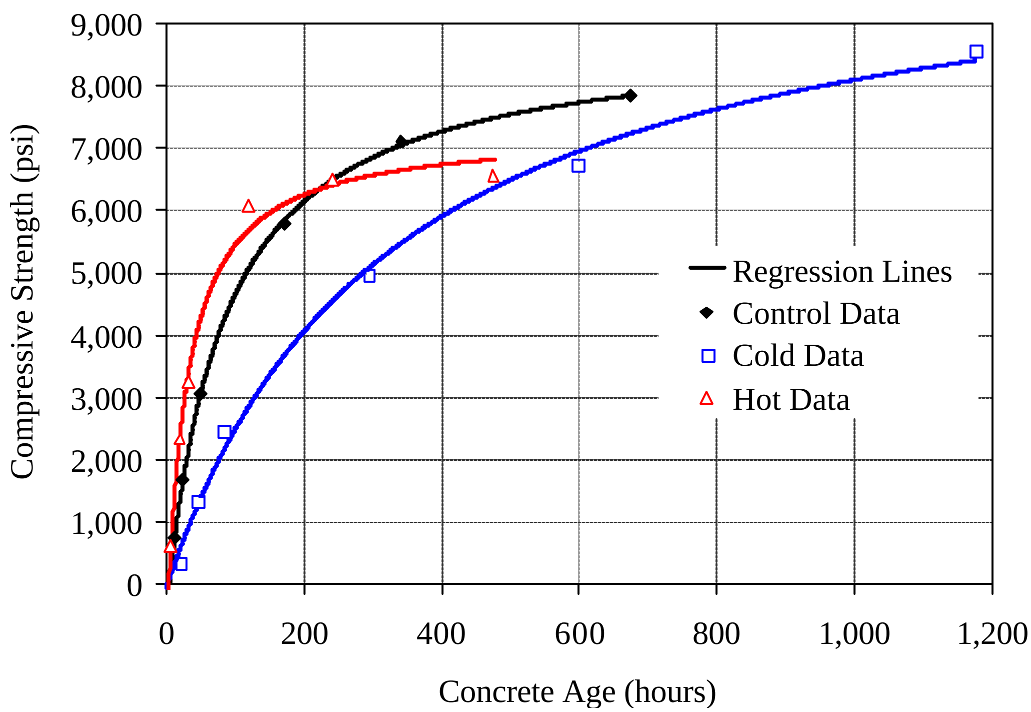


Figure 5.10: Compressive strength versus age results for 50% Slag mixture

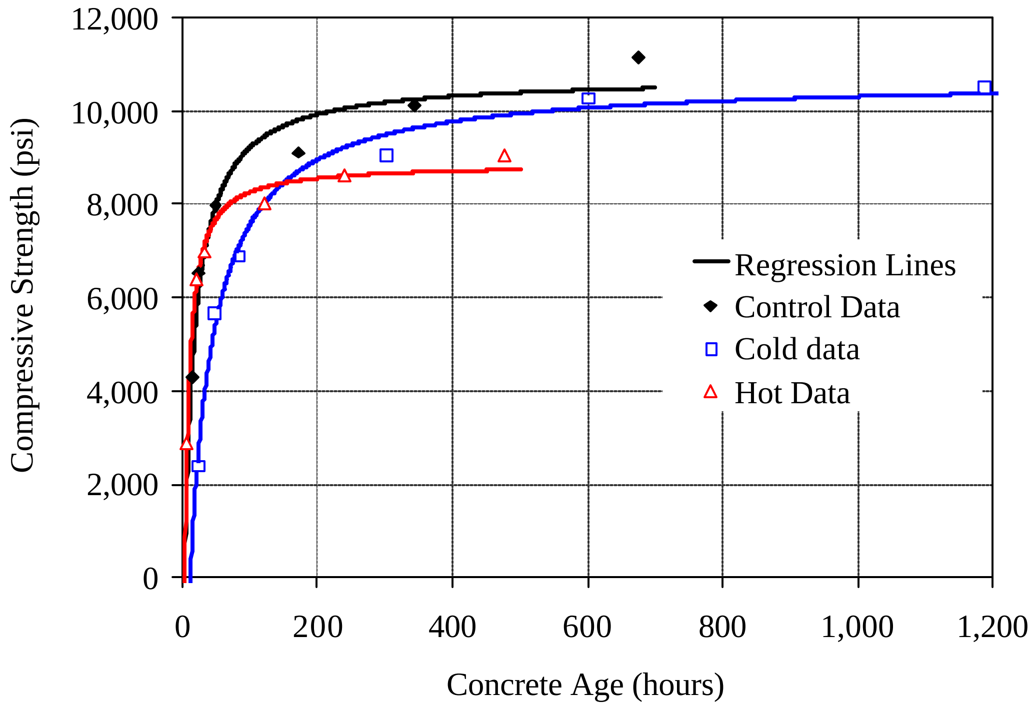


Figure 5.11: Compressive strength versus age results for Type III - 0.37 mixture

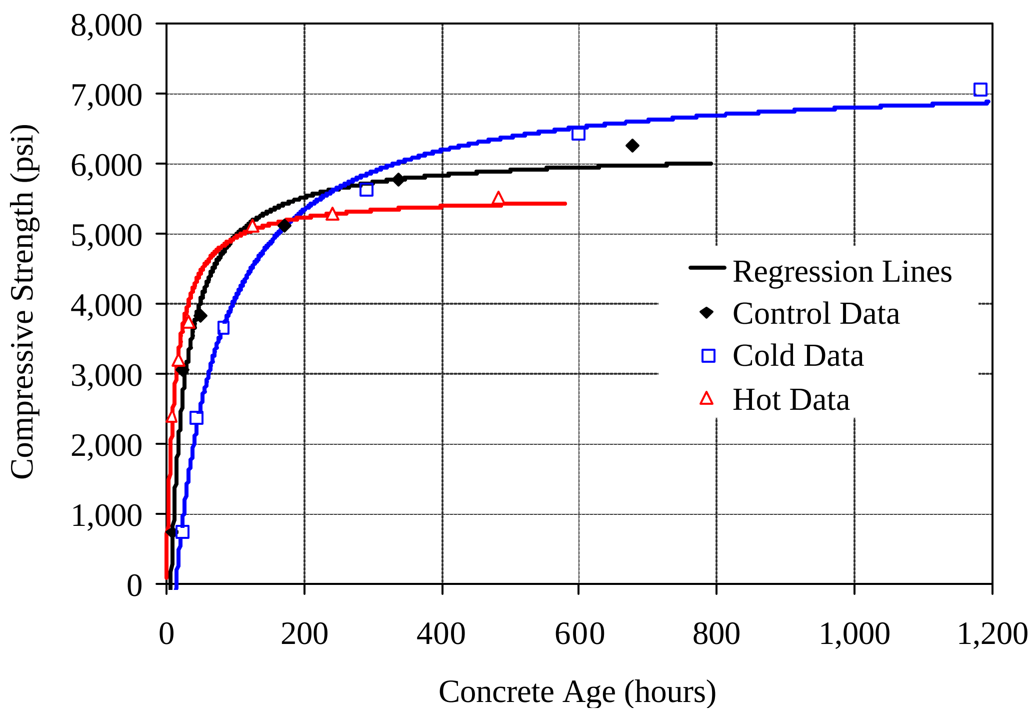


Figure 5.12: Compressive strength versus age results for Type III - 0.44 mixture

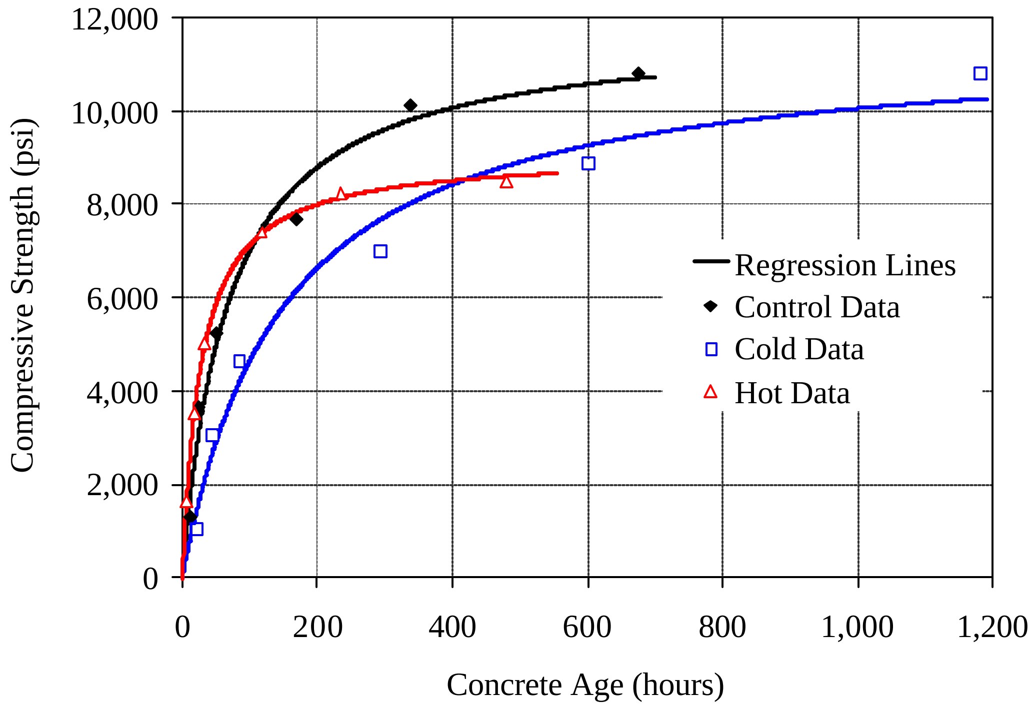


Figure 5.13: Compressive strength versus age results for 70/20/10 - 0.37 mixture

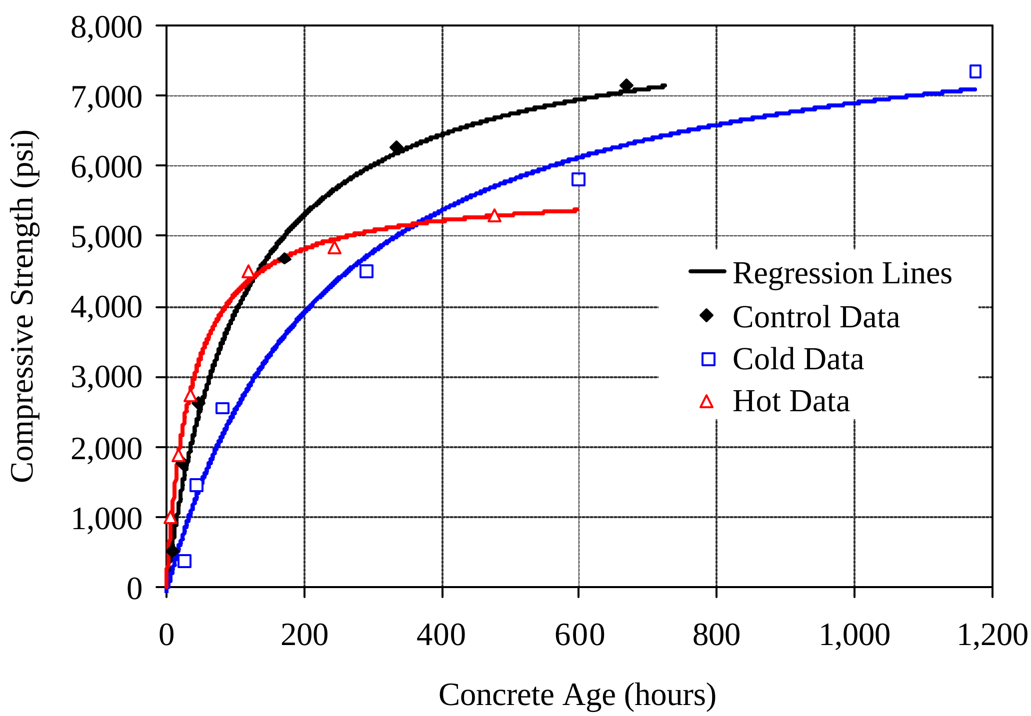


Figure 5.14: Compressive strength versus age results for 70/20/10 - 0.44 mixture

Table 5.2: Regression values for strength-age curves

Mixture ID	Batch ID	t_o (hr)	S_u (psi)	k (hr^{-1})
Type I - 0.41	Hot	1.4	5,710	0.082
	Control	8.3	6,060	0.047
	Cold	15.3	6,530	0.026
Type I - 0.44	Hot	0.0	5,530	0.041
	Control	1.4	5,950	0.018
	Cold	11.9	6,590	0.011
Type I - 0.48	Hot	0.9	5,260	0.034
	Control	0.8	5,970	0.015
	Cold	8.3	7,870	0.006
20% F	Hot	0.0	7,020	0.041
	Control	0.0	7,100	0.019
	Cold	11.2	6,840	0.015
30% F	Hot	0.0	7,150	0.028
	Control	0.0	6,840	0.015
	Cold	11.9	6,550	0.012
20% C	Hot	1.8	6,420	0.054
	Control	5.5	6,770	0.026
	Cold	14.2	6,820	0.013
30% C	Hot	5.7	7,350	0.039
	Control	7.0	7,230	0.017
	Cold	14.1	7,480	0.007
30% Slag	Hot	3.4	6,240	0.060
	Control	0.4	7,550	0.020
	Cold	4.5	8,390	0.007
50% Slag	Hot	4.0	7,290	0.031
	Control	4.5	8,850	0.012
	Cold	1.8	10,740	0.003
Type III - 0.37	Hot	3.6	8,860	0.142
	Control	3.3	10,730	0.063
	Cold	11.4	10,690	0.027
Type III - 0.44	Hot	0.0	5,550	0.081
	Control	6.5	6,180	0.044
	Cold	14.4	7,260	0.015
70/20/10 - 0.37	Hot	0.2	9,080	0.037
	Control	0.0	11,770	0.015
	Cold	0.0	11,530	0.007
70/20/10 - 0.44	Hot	0.0	5,670	0.027
	Control	0.0	8,220	0.009
	Cold	2.1	8,510	0.004

To quantify crossover, the late-age strength difference between the control batch and the hot and cold batches, as well as the amount of time until crossover, was examined. The amount of crossover will affect how accurate the strength estimations using the maturity method analyzed in Chapter 6 can be. Also, the amount of temperature correction required for convergence of the three individual strength-age curves onto one unique strength-maturity curve will be discussed. This affects the selection of datum temperatures or activation energies, as discussed in Section 2.4, which are needed in to apply the maturity method to estimate strengths as discussed in Chapter 6.

The amount of crossover was quantified from the best-fit limiting strength (S_u) values reported in Table 5.2, from the following equation:

Crossover Factor (COF)

$$COF = \frac{(S_u - S_{u\,control})}{S_{u\,control}} \times 100 \qquad \text{Equation 5.1}$$

where,

COF	=	Crossover factor, %,
S_u	=	Limiting strength found from regression analysis for hot or cold batch (psi), and
$S_{u\,control}$	=	Limiting strength found from regression analysis for control batch (psi).

The crossover factor (COF) gives the percent difference between the control batch's limiting strength and the hot or cold batch's limiting strength. The COF is negative if there was crossover for the hot batches and positive if there was crossover for the cold batches. Otherwise, no crossover occurred. The crossover factors for the hot and cold batches of all mixtures are given in Table 5.3. If no crossover occurred, the term "N/A" is used as "not applicable." Also in the table are the times at which crossover occurred, in hours and days. The mixtures are compared and analyzed based on the crossover data and temperature sensitivity and the effect of SCMs, varying cement types, and water-to-cementitious materials ratios.

Table 5.3: Crossover factors and crossover time for all mixtures

Mixture ID	Batch ID	COF (%)	Crossover Time, hr (day)
Type I - 0.41	Hot	-6	160 (7)
	Cold	8	250 (10)
Type I - 0.44	Hot	-7	390 (16)
	Cold	11	290 (12)
Type I - 0.48	Hot	-12	260 (11)
	Cold	32	230 (10)
20% F	Hot	-1	2300 (96)
	Cold	N/A	N/A
30% F	Hot	N/A	N/A
	Cold	N/A	N/A
20% C	Hot	-5	360 (15)
	Cold	1	5300 (220)
30% C	Hot	N/A	N/A
	Cold	3	2300 (96)
30% Slag	Hot	-17	140 (6)
	Cold	11	790 (33)
50% Slag	Hot	-18	230 (10)
	Cold	21	1100 (46)
Type III - 0.37	Hot	-17	40 (2)
	Cold	N/A	N/A
Type III - 0.44	Hot	-10	100 (4)
	Cold	18	250 (10)
70/20/10 - 0.37	Hot	-23	110 (5)
	Cold	N/A	N/A
70/20/10 - 0.44	Hot	-31	130 (5)
	Cold	3	3400 (140)

Note: N/A = No crossover occurred

5.2.1 Crossover Effect

Straight Type I Mixtures

From Figures 5.2 through 5.4 and Table 5.3, it can be seen that all straight Type I cement mixtures experienced crossover. The Type I - 0.41 and Type I - 0.44 hot batches both had long-term strength losses of about 7% relative to their respective control batches. The Type I - 0.41 mixture had crossover for the hot batch at approximately 7 days, while the Type I - 0.44 hot batch had crossover much later, at 16 days. The Type I - 0.48 mixture had the highest long-term strength loss due to high curing temperatures, for all the straight Type I cement mixtures at 12%, and crossover occurred at approximately 11 days. The crossover factors for the cold mixtures are not as much of a concern as for the hot batches, since the maturity method would estimate a lower strength value than that of the actual concrete and thus would be conservative.

Effect of Replacement Dosages of SCMs on the Type I - 0.41 mixture

The effect of replacement dosages of SCMs on the Type I - 0.41 mixture can be seen for the 20% F, 30% F, 20% C, 30% C, 30% Slag, and 50% Slag mixtures in Table 5.3 and Figures 5.5 through 5.10. From the table and figures, it can be seen that the replacement of cement with Class F fly ash at doses of 20% and 30% effectively eliminated the crossover effect. (The 20% F hot batch had a 1% long-term strength loss due to crossover that only occurred after 96 days; thus for all practical purposes, the crossover effect was eliminated.) The replacement of cement with Class C fly ash at 20% by mass did not completely eliminate the crossover effect for the hot batch, when compared to the Type I - 0.41 mixture, but it did delay the time until crossover from 7 days to 15 days. The replacement dosage of 30% Class C fly ash by mass did effectively eliminate the crossover effect when compared to the Type I - 0.41 mixture. The replacement doses of GGBF slag increased the long-term strength loss due to high curing temperatures relative to the loss for the Type I - 0.41 mixture. The crossover factor went from 6% strength loss, for the Type I - 0.41 mixture, to 17% strength loss for the 30% Slag hot batch and 18% for the 50% Slag hot batch. These long-term strength losses are important to note because the maturity method cannot correct for them, and the accuracy of estimating strengths using the maturity method will suffer accordingly.

Effect of Replacement Dosages of SCMs and Varying Cement Types on the Type I - 0.44 mixture

The effect of changing cement types and replacement dosages of SCMs on the Type I - 0.44 mixture (ALDOT standard mixture A1-c) can be seen from the Type III - 0.44 and 70/20/10 - 0.44 mixtures in Figures 5.12 and 5.14 and Table 5.3. The effect of changing from Type I cement to Type III cement increased the long-term strength loss attributable to high curing temperatures slightly, from 7% to 10%, but also decreased the time until crossover occurred, from 16 days to 4 days. Replacing the Type I cement with 20% Class F fly ash and 10% silica fume greatly increased the long-term strength loss due to high curing temperatures from 7% to 31% strength loss when compared to their respective control batches. The time until crossover also decreased from 16 days for the Type I - 0.44 to 5 days for the 70/20/10 - 0.44 mixture.

Prestressed Concrete Mixtures

The prestressed concrete mixtures (Type III and the ternary mixture with water-to-cementitous materials ratios of 0.37) had some of the worst long-term strength loss effects due to high curing temperatures and earliest crossover ages. This can be seen in

Figures 5.11 and 5.13 and Table 5.3. The Type III - 0.37 hot batch had a long-term strength loss of 17% when compared to its respective control batch. Also, the plateau of strength of the hot batch, seen in Figure 5.11, is quickly reached at approximately 40 hrs. Thus, any strength estimated by the maturity method, for this mixture, after 40 hrs will probably be overestimated (unconservative). The ternary-blend prestressed concrete mixture had a long-term strength loss attributable to high curing temperatures of 23% relative to its respective control batch. Also, this strength loss began at approximately 5 days.

5.2.2 Temperature Sensitivity

The amount of correction due to temperature effects needed for the maturity method refers to how far the hot and cold batches must shift on the time scale (once converted to maturity) to converge onto an unique strength-maturity relationship. Some common temperature sensitivity trends are shown schematically in Figure 5.15. Some mixtures may have a high temperature sensitivity, which requires a large correction by the maturity method, as shown by the first schematic in the figure. Others may require a small correction, which would be referred to as low temperature sensitivity. There could also be some mixtures that have different temperature sensitivities for the hot and cold batches, i.e. the hot batch could require a smaller temperature correction than the cold batch, which is shown in the final schematic.

The temperature sensitivities for the hot and cold batches of each mixture were evaluated qualitatively based on visual observations from Figures 5.2 through 5.14. If the crossover effect occured, the temperature sensitivity is only discussed for ages before the point of crossover. In Chapter 6, these temperature sensitivity trends are referred to when values of datum temperatures and activation energies are determined.

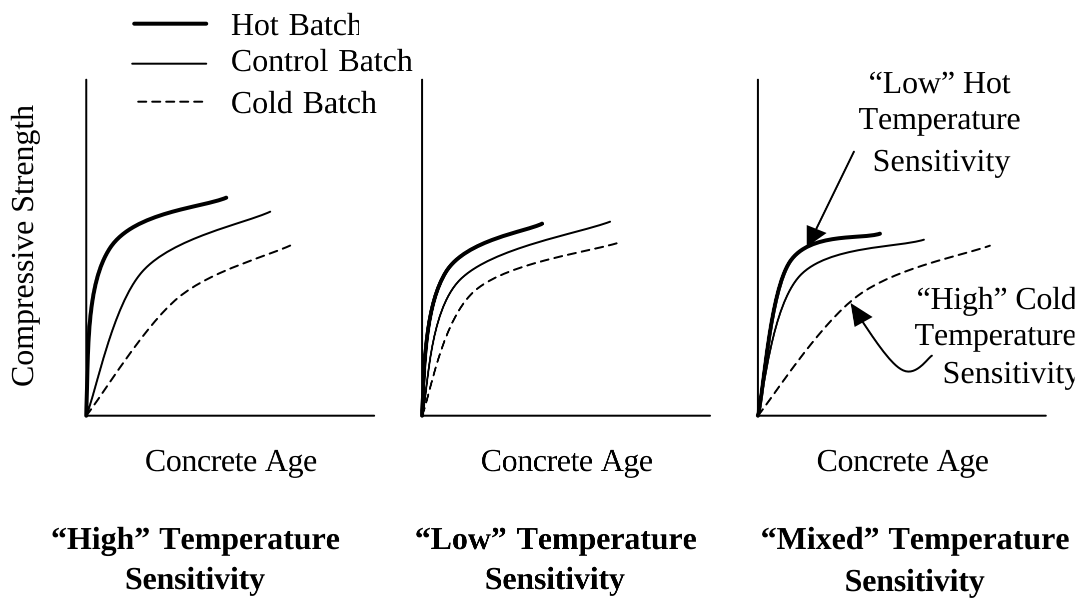


Figure 5.15: Schematic of various degrees of temperature sensitivity

Straight Type I Mixtures

From Figure 5.2, it appears that the Type I - 0.41 mixture does not need much of a correction due to temperature effects, since all three strength-age curves are relatively close to each other. For the Type I - 0.44 mixture the hot batch may require a slightly higher temperature sensitivity value than the cold batch, but overall the mixture does not require a high temperature sensitivity value. The Type I - 0.48 mixture also only requires a small temperature correction.

Effect of Replacement Dosages of SCMs on Type I - 0.41 Mixture

The replacement of cement with 20% Class F fly ash increased the temperature sensitivity of the Type I - 0.41 mixture slightly. Increasing the replacement dosage to

30% increased the temperature correction needed for the hot batch, but not for the cold batch. The replacement of cement with 20% Class C fly ash increases the temperature sensitivity of the cold batch significantly, but not the hot batch. However, increasing the dosage to 30% Class C fly ash further increased the temperature sensitivity of both batches substantially. The replacement of cement with 30% GGBF slag greatly increases the temperature correction required for the cold batch and does not affect the hot batch's sensitivity. Increasing the dosage of GGBF slag to 50% only increases the temperature correction needed for the cold batch and again does not affect the hot batch's temperature sensitivity significantly.

Effect of Replacement Dosages of SCMs and Varying Cement Types on Type I - 0.44 Mixture

For the Type I - 0.44 mixture, changing the Type I cement to Type III cement decreases the temperature correction needed for the hot batch and increases the correction needed for the cold batch. Replacing the Type I cement with 20% Classs F fly ash and 10% silica fume decreases the temperature sensitivity of the hot batch and significantly increases the temperature sensitivity of the cold batch.

Prestressed Concrete Mixtures

The temperature correction required for the Type III - 0.37 hot batch is minimal. The cold batch requires a moderate correction value. The 70/20/10 - 0.37 hot mixture requires a low temperature correction value, while the cold batch requires a larger correction.

5.3 SUMMARY

In this chapter, the results for testing of all thirteen mixtures considered in this project were discussed. The fresh concrete properties were reported, and though there were some deviations in slump and air content from the desired values due to temperature and the replacement dosages of SCMs, the concrete was of good quality. The compressive strength versus concrete age graphs were given and compared. Hyperbolic strength-age regression curvess were fit to the data, and the best-fit parameters were reported. It was obvious that all mixtures were affected in some way by the various curing temperature histories. The crossover factor was defined and computed for all mixtures. All mixtures were then analyzed based on the amount of crossover and time until crossover occurred.

Based on the work documented in this chapter, the following conclusions can be made:

- All straight cement mixtures had crossover, with long-term strength losses ranging from 7% to 12%, and crossover occurring between 7 days and 16 days.
- The replacement of cement with 20 and 30% Class F fly ash for the Type I - 0.41 mixture effectively eliminated the crossover effect.
- The replacement of cement with 20% Class C fly ash for the Type I - 0.41 mixture delayed, but did not completely eliminate, the crossover effect. An increased replacement dosage of 30% Class C fly ash for the Type I - 0.41 mixture effectively eliminated crossover.

- The replacement of cement with 30% or 50% GGBF slag for the Type I - 0.41 mixture increased the long-term strength loss, or crossover, attributed to high curing temperatures from 6% to more than 17% in some cases.
- Changing the cement from Type I to Type III for the Type I - 0.44 mixture increased the crossover effect only slightly, but decreased the time at which crossover occurs from 16 days to 4 days.
- The replacement of cement with 20% Class F fly ash and 10% silica fume for the Type I - 0.44 mixture increased the long-term strength loss attributed to high curing temperatures from 7% to 31% and decreased the time at which crossover occurred.
- The Type III - 0.37 mixture had a 17% strength loss due to the crossover effect and crossover occurred less than two days after mixing for the hot batch.
- The ternary blend prestressed concrete mixture had a long-term strength loss of 23% for the hot batch.

Finally, the mixtures were examined based on the visible amount of temperature correction, or temperature sensitivity, required to cause convergence of the hot and cold batches onto one strength-maturity relationship. A summary of these conclusions follows:

- The Type I - 0.41 and Type I - 0.48 mixtures have low temperature sensitivity for both hot and cold batches.

- The Type I - 0.44 mixture had low temperature sensitivity, possibly with a slightly higher sensitivity for the hot batch.
- The replacement of cement with 20% Class F fly ash for the Type I - 0.41 mixture increased the temperature sensitivity slightly and increasing the dose to 30% Class F fly ash increased the hot batch's temperature sensitivity.
- The replacement of cement with 20% Class C fly ash for the Type I - 0.41 mixture increased the temperature sensitivity of the cold batch, and increasing the dose to 30% Class C fly ash increased both batches' temperature sensitivities significantly relative to that of the Type I - 0.41 sensitivities.
- The replacement of cement with 30 and 50% GGBF slag for the Type I - 0.41 mixture increased the temperature sensitivity of the cold batch, but did not affect the hot batches.
- Changing the cement from Type I to Type III for the Type I - 0.44 mixture increased the temperature sensitivity for the cold batch and decreased that for the hot batch.
- The replacement of cement with 20% Class F fly ash and 10% silica fume for the Type I - 0.44 mixture increased the temperature sensitivity for the cold batch and decreased that for the hot batch.
- The Type III - 0.37 mixture's hot batch had little to no temperature sensitivity, while the cold batch required a higher temperature sensitivity.
- The ternary blend prestressed concrete mixture (70/20/10 - 0.37) had a low temperature sensitivity for the hot batch and a higher value for the cold batch.

Now that the effects of the various curing temperature histories, types and doses of SCMs, cement types, and water-to-cementitious material ratios have been established, the accuracy of the maturity method to estimate concrete strength is evaluated in the next chapter.

CHAPTER 6

ANALYSIS OF RESULTS

The effect of various curing temperatures on the development of compressive strength was discussed in Chapter 5. Next, the accuracy of the maturity method to estimate the strength development of hardening concrete is evaluated. As stated in the Chapter 2, there are two well known functions used to compute the maturity index. These are known as the Nurse-Saul maturity (NSM) and Arrhenius maturity (AM) functions. In this chapter, the accuracy of these two maturity functions to estimate concrete strength is examined. Different methods are proposed in order to find the simplest and most accurate way to compute the maturity index and accurately estimate the concrete strength.

As described in Chapter 2, a strength-maturity relationship is mixture-specific. This is due in part to the fact that variables such as water-to-cementitious materials ratio, SCM type and dosage, cement type, etc. all affect the strength and temperature development in a complex manner. The mixture's temperature sensitivity refers to the degree to which the concrete will be affected by curing temperatures different than the reference temperature and how much correction will be needed to convert the strength-age curves into one unique strength-maturity relationship. This was previously described with Figure 5.15. In Section 5.2.2 it was shown that some mixtures such as the Type I - 0.41 had a low temperature sensitivity, while others like the 30% C mixture needed a much larger temperature correction in order to converge the strength-age curves to a single strength-maturity relationship. Other mixtures such as the GGBF slag mixtures had a low temperature sensitivity for the hot batch but a very high sensitivity for the cold batch.

The mechanisms that account for temperature sensitivity when using the maturity method are the datum temperature and activation energy, depending on the maturity function used. These values were defined as temperature sensitivity values in Section 2.4.2. In this chapter, several methods are presented to find or compute proper temperature sensitivity values that maximize the accuracy of the maturity method to estimate concrete strength. Based on these different methods, the most accurate and simplest method for computing maturity and estimating concrete strength is recommended.

The strength data were analyzed using the current ASTM C 1074 (2004) specification, which explains how to find the mixture-specific activation energies or datum temperatures for any mixture. The data were then analyzed using the same methods as the ASTM C 1074 specification, with some modifications. After the results of the analyses are presented, results will be presented based on analysis ofa simplified approach using constant temperature sensitivity parameters for all the mixtures. Finally, an evaluation of formulaic determination of temperature sensitivities will be presented. In each case, three mixtures will be shown as examples, and an assessment of the accuracy of the maturity method to estimate the compressive strength for all 13 mixtures will be discussed.

6.1 ANALYSIS OF DATA BASED ON THE ASTM C 1074 METHOD

ASTM C 1074 (2004) has several different methods to determine a mixture-specific datum temperature or activation energy. This is described in detail in ASTM C 1074 under Annex A1. In this study, the option Section A1.1.8 was used, which is considered the most accurate and requires the use of regression analysis techniques. This method is identical to the method shown in Section 2.4.1, which uses the rate constants from the strength-age data to determine temperature sensitivity values. The k, S_u, and t_o values from the hyperbolic strength-age formula, already computed in Chapter 5 and summarized in Table 5.2, are utilized for this method.

6.1.1 Nurse-Saul Maturity Function

As described in Chapter 2, the equation for computing the maturity index using the Nurse-Saul maturity (NSM) function is:

$$M = \sum_{0}^{t} (T_c - T_o) \cdot \Delta t \qquad \text{Previously Equation 2.1}$$

where,

M = maturity index at age t, (Temperature-Time Factor), (°F·hours),

T_c = Average concrete temperature during the time interval (°F),

Dt = a time interval (hours), and

T_o = datum temperature (°F).

In this equation, all values are known except T_o, the datum temperature. As explained before, this value is related to the temperature sensitivity of a mixture and will affect how well the maturity method can estimate the strength at all curing temperatures. In this section, the mixture-specific datum temperature, based on ASTM C 1074 (2004) methods, for all mixtures is given. Later, in Section 6.1.3, an analysis of the accuracy of using these mixture-specific datum temperatures with the NSM function will be given.

In order to find the mixture-specific datum temperatures, the *k*-values from the hyperbolic strength-age function for each batch of one mixture are plotted versus temperature. As explained by Carino (1991) and ASTM C 1074 (2004), the mixture-specific datum temperature is the x-intercept of a linear trendline fitted through the points. An example of this process is shown in Figure 6.1. This procedure thus gives the temperature that corresponds to a *zero* rate of strength development. From the plot, the three *k*-values can be seen for each batch temperature for the Type I - 0.41 mixture. The cold batch had a *k*-value of approximately 0.025 hr^{-1}, the control batch's *k*-value was approximately 0.046 hr^{-1}, and the hot batch's *k*-value was about 0.082 hr^{-1}. A linear trendline was fit to the data, and, after extending the line to the x-axis, the mixture-specific datum temperature for the Type I - 0.41 mixture based on ASTM C 1074 methods was calculated to be 23°F (-5°C).

This procedure was used on all thirteen mixtures, and the resulting mixture-specific datum temperatures are presented in Table 6.1. The values with asterisks represent mixture-specific datum temperatures that are greater than some of the temperatures reached during the cold curing conditions. Recall that in the Nurse-Saul maturity function the temperature of the concrete is subtracted from the datum temperature. However, if the datum temperature is lower than the curing temperature, the maturity index becomes negative. As Saul (1951) stated, the datum temperature is the temperature at which concrete ceases to gain strength. However, neither maturity nor strength should ever be subtracted when temperatures fall below the datum temperature. For this reason, it was assumed that the cold mixtures that had curing temperatures less than the datum temperatures accumulated zero maturity during the time intervals where the concrete temperature was less than the datum temperature.

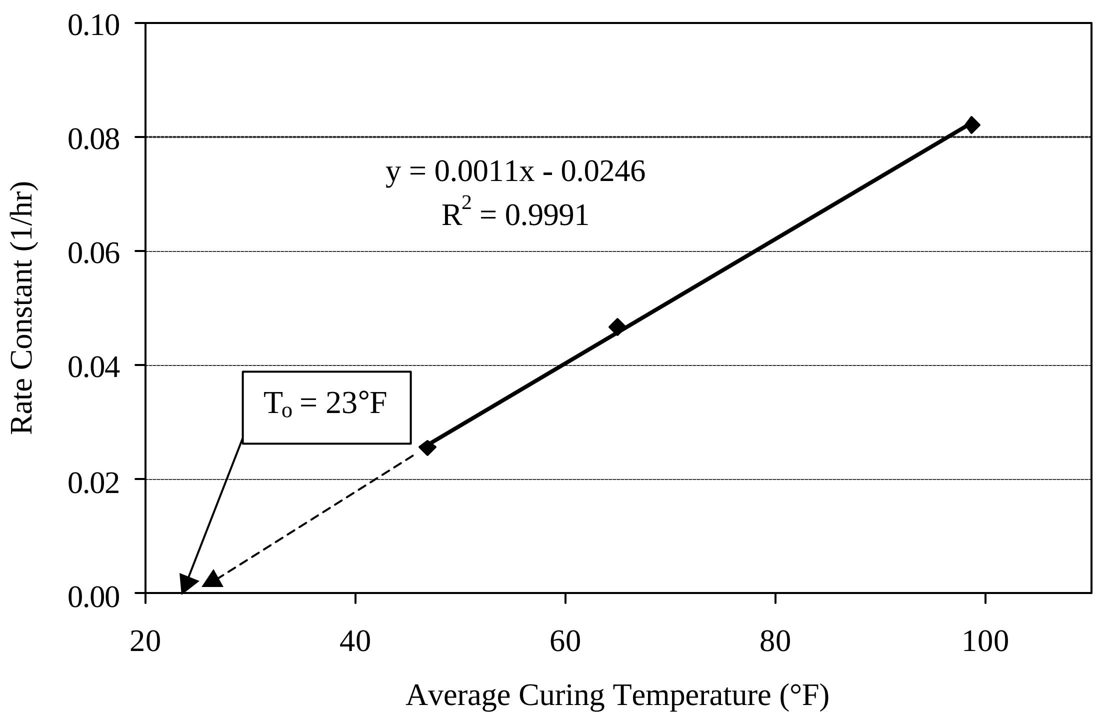


Figure 6.1: Method used to find the best-fit datum temperature, ASTM C 1074 method for Type I – 0.41 mixture

After each mixture-specific datum temperature was found, the maturity index could be computed using the NSM function for all mixtures and batches. To illustrate how the maturity method works with different cementitious systems and mixtures, three examples will be used throughout this chapter:

1. The 20% F mixture, a mixture that has no long-term strength loss effects due to curing at high temperatures,
2. The Type I - 0.41 mixture, a mixture that has some long-term strength loss effects due to curing at high temperatures, and
3. The Type III - 0.37 mixture, a mixture that has severe long-term strength loss effects due to curing at high temperatures.

Table 6.1: Mixture-specific datum temperatures based on ASTM C 1074

Mixture ID	**Datum Temperature, T_o (°F (°C))**
Type I - 0.41	23 (-5)
Type I - 0.44	35 (2)
Type I - 0.48	39 (4)
20% F	23 (-5)
30% F	19 (-7)
20% C	37 (3)
30% C	42 (5)*
30% Slag	46 (8)*
50% Slag	47 (9)*
Type III - 0.37	38 (3)
Type III - 0.44	37 (3)
70/20/10 - 0.37	39 (4)
70/20/10 - 0.44	43 (6)*

* Value higher than some temperatures reached during cold temperature history

For ease of comparison, the compressive strength versus age plots, shown in Chapter 5, are repeated above the accompanying compressive strength versus maturity plots. These plots can be seen in Figures 6.2 through 6.4. Strength-maturity (S-M) plots for all other mixtures can be seen in Appendix B. The strength-maturity (S-M) relationships shown in the figures were calculated using the hyperbolic S-M equation, discussed in Chapter 2, fit by least-squares regression to the control-batch data. The equation is repeated here:

$$S = S_u \frac{k(M - M_o)}{1 + k(M - M_o)} \qquad \text{Previously Equation 2.5}$$

where,

S = average compressive strength at maturity, M, (psi),

M = maturity index (°F·hr or hr),

S_u = limiting compressive strength (psi),

M_o = maturity index when strength development is assumed to begin (°F·hr or hr), and

k = the rate constant [1/(°F·hr or hr)].

This equation is also used later to determine the accuracy of the strength estimated by the maturity method.

From Figures 6.2 through 6.4, it can be seen that mixtures that have little to no long-term strength loss due to curing at high temperatures, such as the 20% F mixture, have the least deviation from their S-M relationship. This means the maturity method will produce low errors when used to estimate strengths for these mixtures. From Figure 6.3 it can be seen that for a mixture that has a relatively small crossover effect, the maturity method will estimate strength well until the point of crossover, i.e. approximately 160 to 250 hours of actual age, in this case. After crossover occurs the hot strengths are overestimated (un-conservative) and the cold strengths are underestimated (conservative). And finally, for a mixture with a severe crossover effect, as in Figure 6.4, the maturity method will estimate strength well until crossover and then grossly overestimate strengths for hot mixtures, while in this case the cold mixture's strengths fit the strength-maturity curve very well. This illustrates the fact that the maturity method can only shift data values on the age (horizontal) scale and cannot correct for long-term strength loss or gain due to the crossover effect. The observations made in this paragraph are also valid for all the other mixtures evaluated.

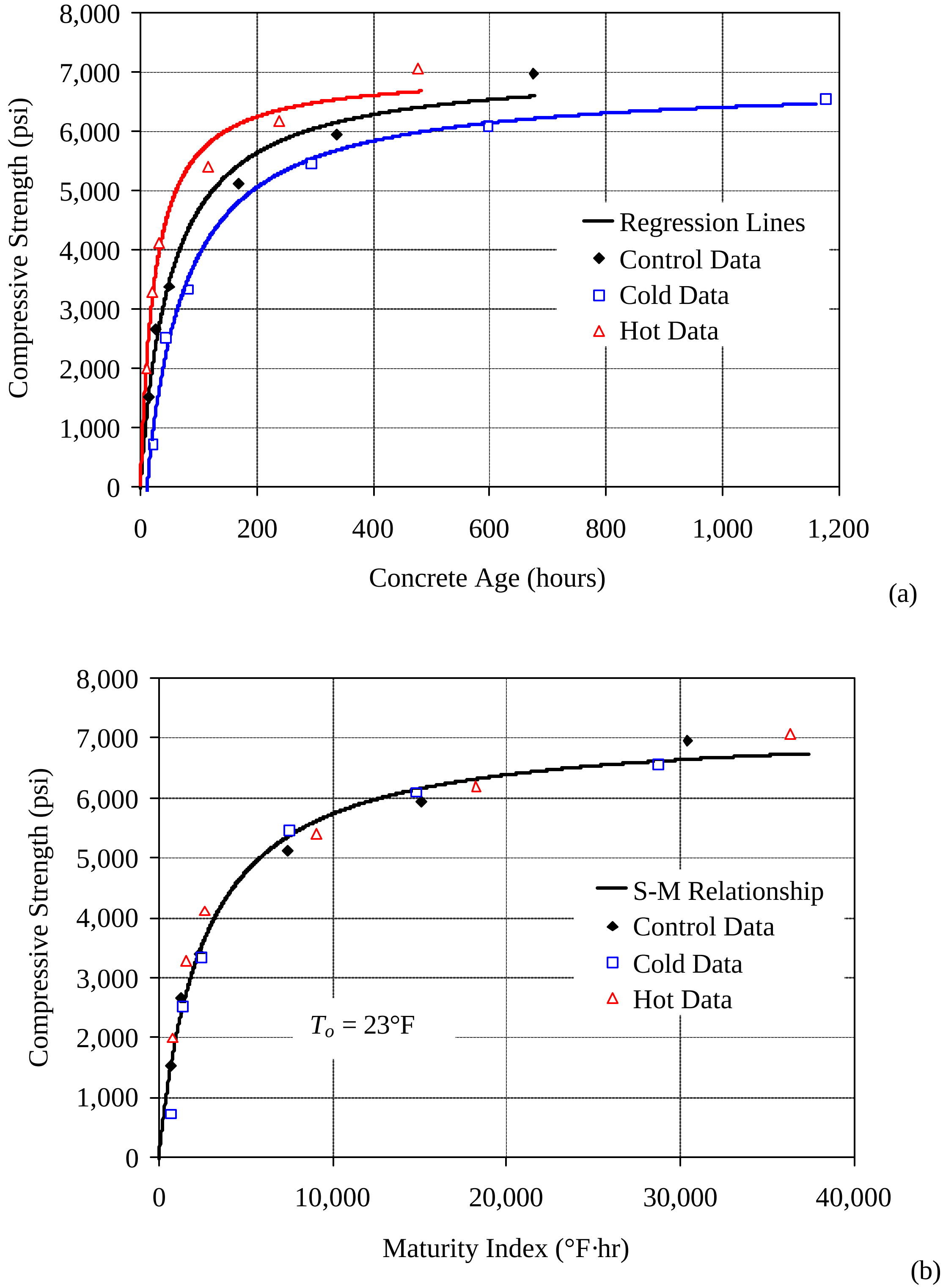
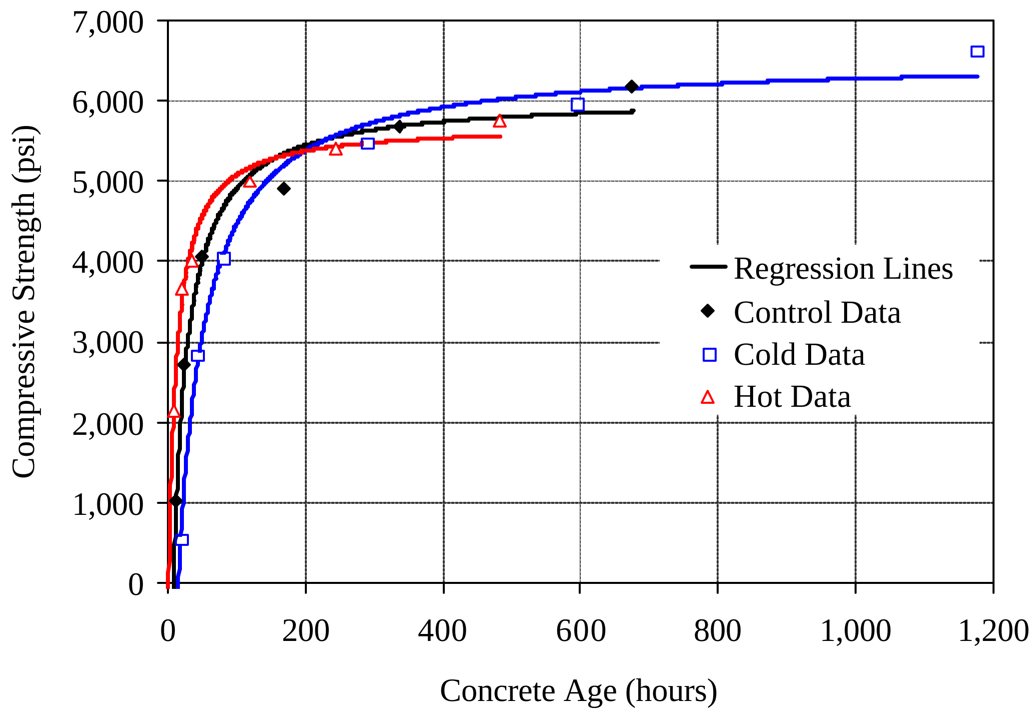
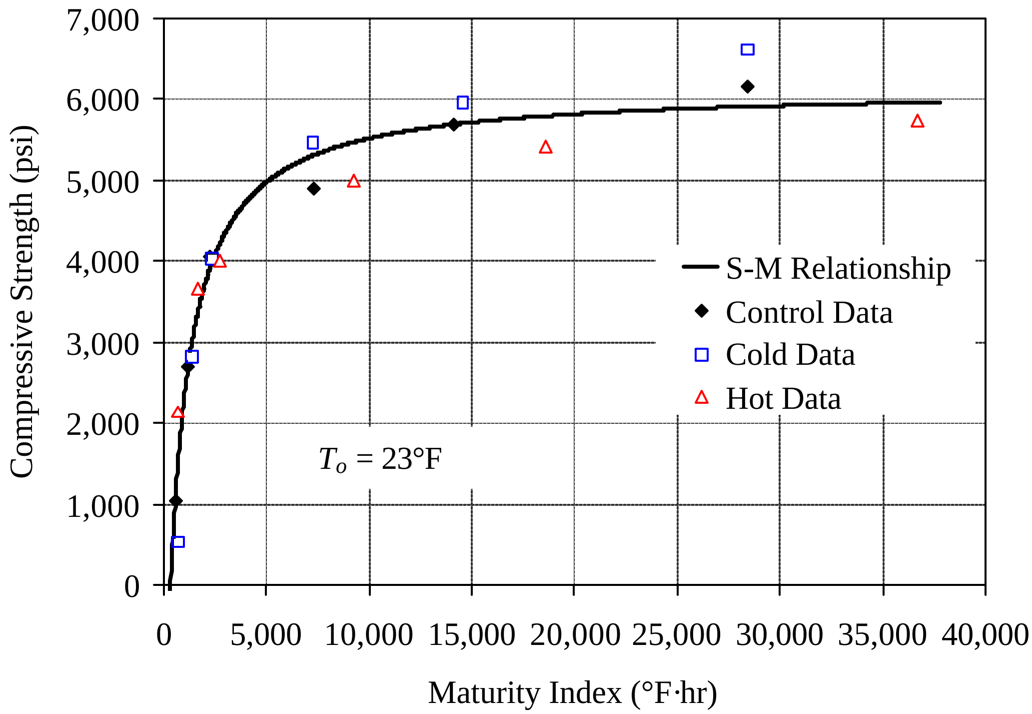


Figure 6.2: 20% F mixture, (a) compressive strength versus age, (b) strength-maturity plot, ASTM C 1074 method

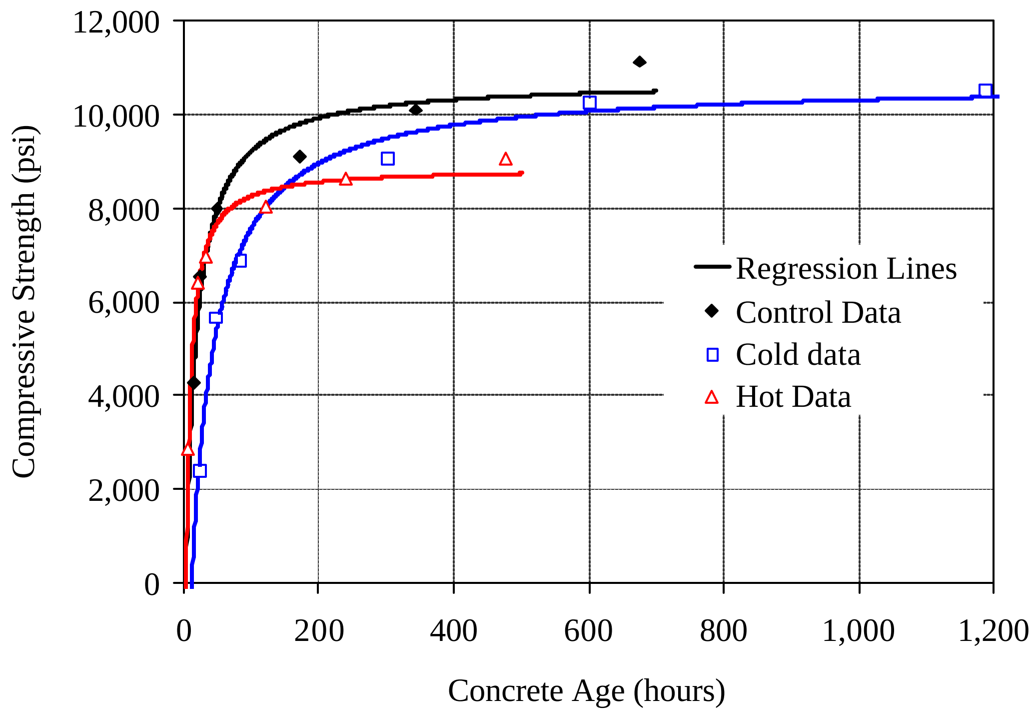


(a)

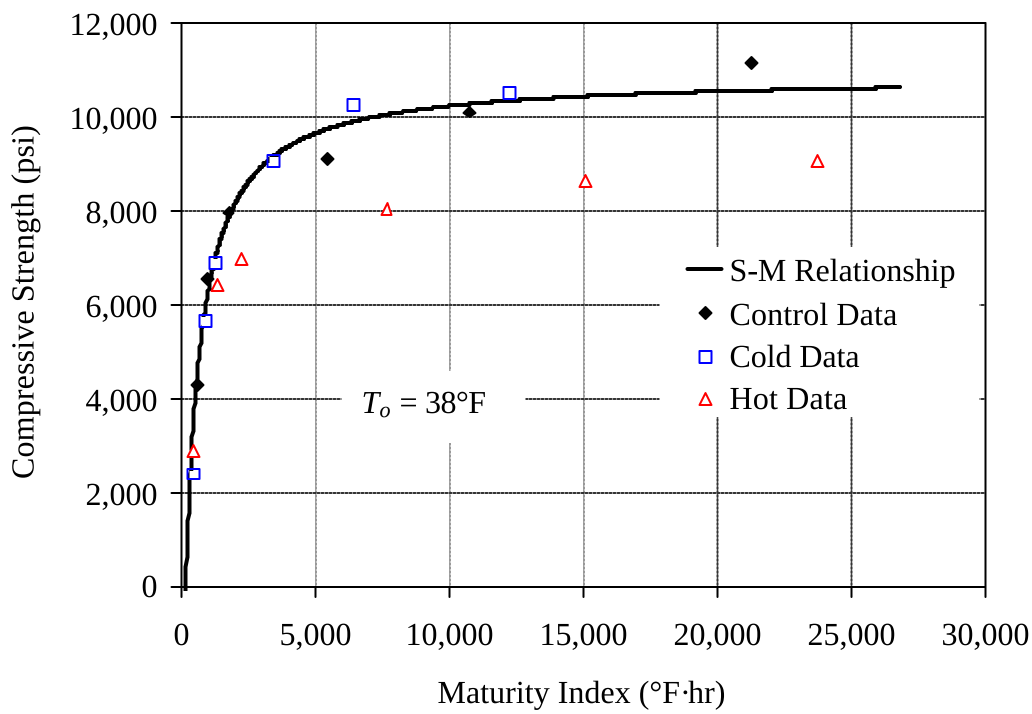


(b)

Figure 6.3: Type I - 0.41 mixture, (a) compressive strength versus age, (b) strength-maturity plot, ASTM C 1074 method



(a)



(b)

Figure 6.4: Type III - 0.37 mixture, (a) compressive strength versus age, (b) strength-maturity plot, ASTM C 1074 method

Comparison of Results to Previously Published Findings

When the datum temperatures found in this study are compared to previously published reports and literature, some similarities can be found as well as some differences. Table 6.2 repeats the previous Table 2.1. As Carino and Tank (1992) found in their study, none of the computed T_o values were equal to the commonly used 14°F (-10°C), which was also true in this study. The lowest values reported in Table 6.1, 23°F (-5°C) and 19°F (-7°C), were calculated for the Type I - 0.41 mixture and the 20 and 30% Class F fly ash mixtures. Carino and Tank also found 23°F (-5°C) for their Type I + 20% fly ash mixture (class of fly ash was not specified). Also, the mixtures with GGBF Slag dosages in both studies required higher datum temperatures that ranged between 46°F (8°C) and 50°F (10°C). However, the datum temperature of 37°F (3°C) found in this study for the Type III mixtures is lower than Carino and Tank's value of 45°F (7°C). Also in Carino and Tank's study, as the water-to-cement ratio increased for the straight cement mixtures, it was found that the datum temperatures generally decreased. In this study, as the water-to-cement ratio increased for the straight Type I cement mixtures, so did the datum temperatures. This could be related to the diminishing need of water-reducer required as the water-to-cement ratio increased (See Table 3.5). Alternatively, the fact that fluctuating curing conditions were used may have produced differences in behavior, since Carino and Tank used isothermal curing conditions.

Table 6.2: Datum temperature values proposed by Carino and Tank (1992)

Cement Type	**Datum Temperature, T_o (°F (°C))**	
	***w/c* = 0.45**	***w/c* = 0.60**
Type I	52 (11)	48 (9)
Type II	48 (9)	43 (6)
Type III	45 (7)	45 (7)
Type I + 20% Fly Ash	23 (-5)	32 (0)
Type I + 50% Slag	46 (8)	50 (10)
Type I + Accelerator	46 (8)	48 (9)
Type I + Retarder	41 (5)	41 (5)

6.1.2 Arrhenius Maturity Function

Next, the ASTM C 1074 (2004) method for determining mixture-specific temperature sensitivity values was used for the Arrhenius maturity (AM) function. As described in Section 2.1, the Arrhenius-based equation for converting chronological time to equivalent age is defined by the following equation:

$$t_e = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T_c}-\frac{1}{273+T_r}\right]} \cdot \Delta t \qquad \text{Previously Equation 2.2}$$

where,

t_e = equivalent age at the reference curing temperature (hours),

T_c = average concrete temperature during the time interval, *Dt*, (°C),

T_r = reference temperature, 23°C,

E = activation energy, J/mol, and

R = universal gas constant, 8.314 J/(mol·K).

Again, all of the values are known except for the temperature sensitivity term, which is the activation energy, *E,* in this method. The *k*-values from the strength-age functions were again used. As explained in Section 2.4.1, in order to find the mixture-specific activation energy, the natural logarithms of the *k*-values were plotted versus the inverse of the absolute batch temperatures, in Kelvin units. Figure 6.5 shows an example of this plot, often called the *Arrhenius plot*, for the Type I - 0.41 mixture. To find the mixture-specific activation energy, the slope of the fitted linear trendline was determined. The mixture-specific activation energy is the negative of the slope of the trendline multiplied by the universal gas constant, 8.314 J/(K·mol). As shown in Figure 6.5, the mixture-specific activation energy for the Type I - 0.41 mixture was calculated to be 28,600 J/mol. Note that all the activation energy values were rounded to the nearest 100 J/mol. This procedure was used on all thirteen mixtures, and the resulting mixture-specific activation energies are summarized in Table 6.3.

The same three mixtures that were shown in Section 6.1.1 above will be analyzed in this section using the AM function. Their strength-maturity (S-M) plots are found in Figures 6.6, 6.7, and 6.8. The remaining mixtures' S-M plots can be found in Appendix C. From Figures 6.6 to 6.8, it can be seen that the trends are similar to those found using the NSM function; that is, mixtures with little to no crossover were modeled well with these S-M relationships, and mixtures with more crossover generally were accurately modeled by the S-M relationships only until the point of crossover. Again, maturity can only translate values on the horizontal axis of the strength versus maturity plots. Later in this section, assessment of the accuracy of the two maturity functions using the ASTM C 1074 methods is discussed.

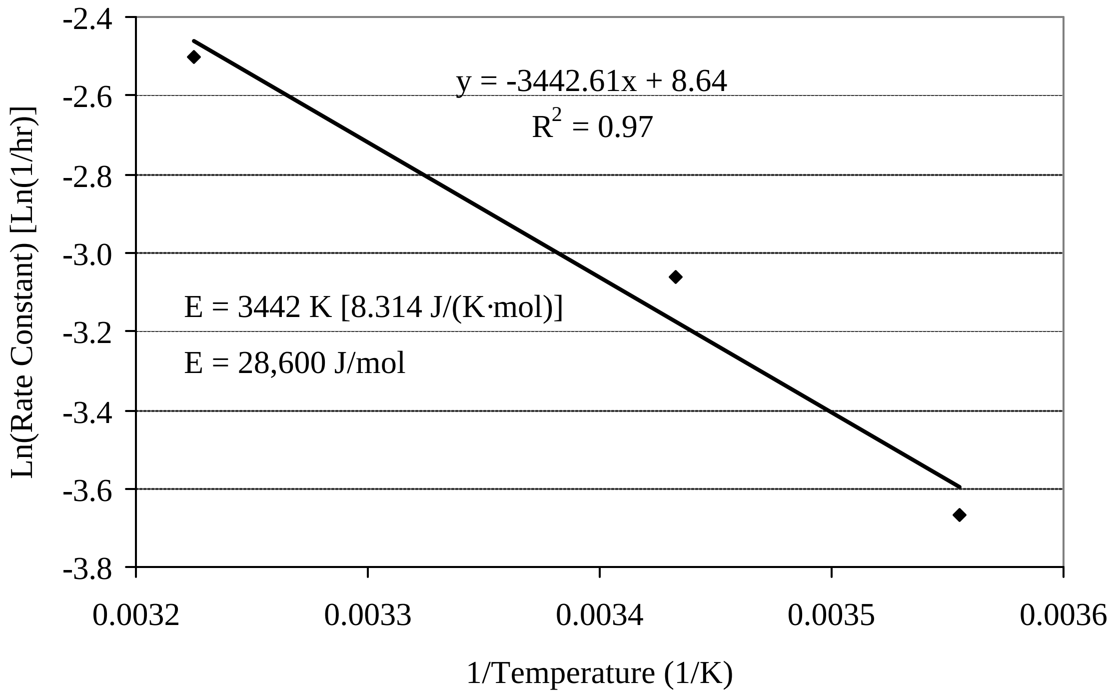


Figure 6.5: Method for computing activation energy based on ASTM C 1074 for the Type I - 0.41 mixture

Table 6.3: Mixture-specific activation energies based on the ASTM C 1074 method

Mixture ID	**Activation Energy, E (J/mol)**
Type I - 0.41	28,600
Type I - 0.44	34,800
Type I - 0.48	42,300
20% F	25,800
30% F	23,200
20% C	37,800
30% C	45,100
30% Slag	55,700
50% Slag	61,500
Type III - 0.37	41,400
Type III - 0.44	42,900
70/20/10 - 0.37	42,600
70/20/10 - 0.44	47,300

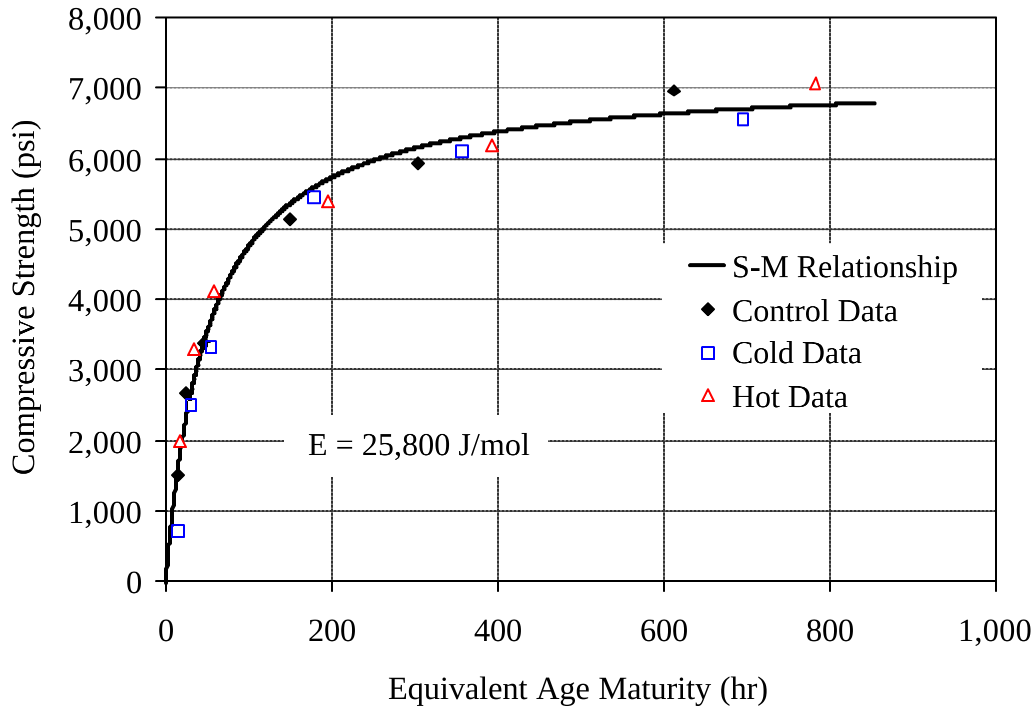


Figure 6.6: Strength-maturity plot, ASTM C 1074 method for 20% F mixture

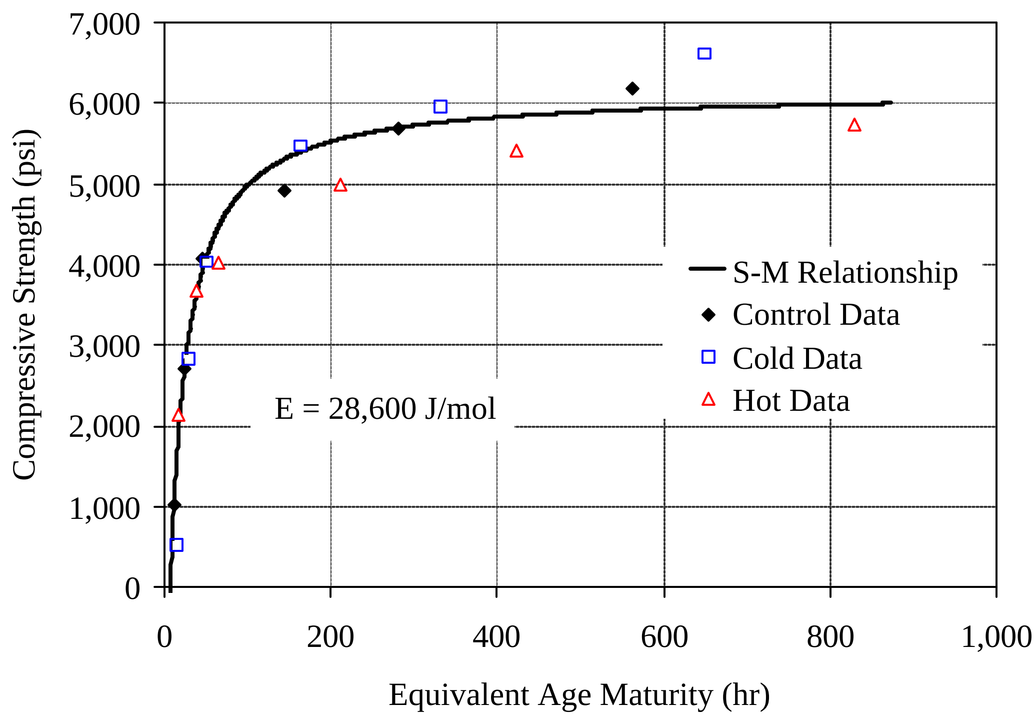


Figure 6.7: Strength-maturity plot, ASTM C 1074 method for Type I - 0.41 mixture

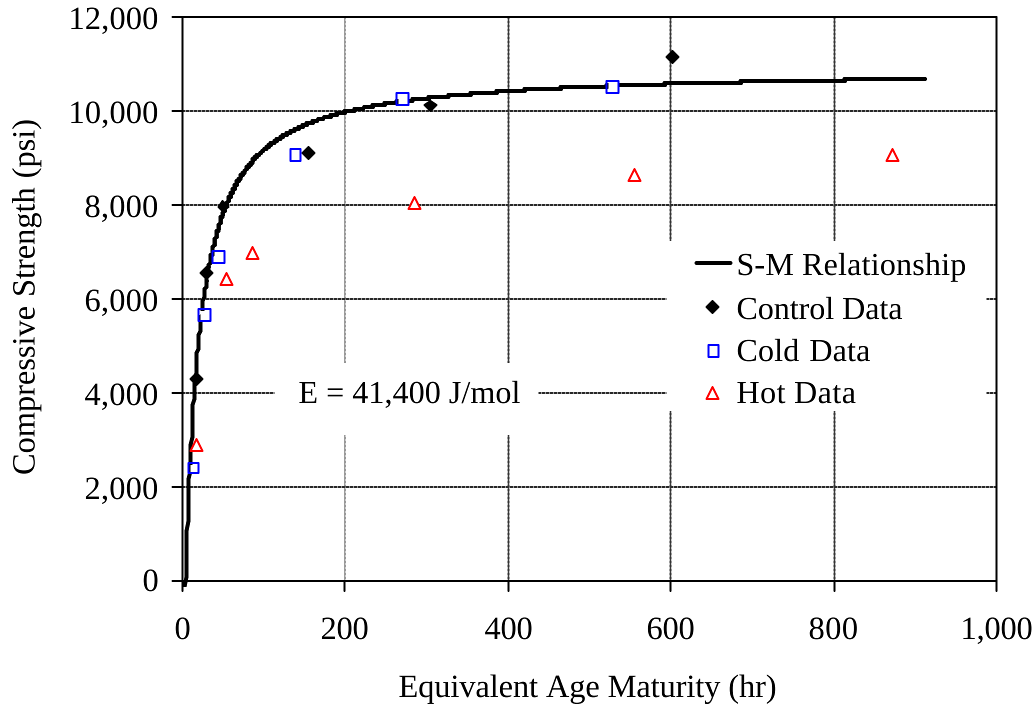


Figure 6.8: Strength-maturity plot, ASTM C 1074 method for Type III - 0.37 mixture

Comparison of Results to Previously Published Findings

Next the values obtained from the ASTM C 1074 mixture-specific activation energy analysis will be compared to other published values for similar mixtures. Again, for ease of comparison, the values reported from Carino and Tank's study in 1992 are summarized in Table 6.4. As with the datum temperature values, the Type I - 0.41 mixture and the 20 and 30% Class F fly ash mixtures had the lowest temperature sensitivity values of 28,600 J/mol to 23,200 J/mol in this study. Carino and Tank also obtained values around 30,000 J/mol for their Type I + 20% Fly Ash mixture. However, their value for a straight Type I cement is much higher than the value of 29,000 J/mol found in this study. As reported in Section 2.4.2, the following activation energy values have also been recommended previously for use with straight Type I cement mixtures:

- 40,000 to 45,000 J/mol for a Type I cement mixture with no admixtures or additions (ASTM C 1074 2004).
- 42,000 to 44,000 for a Type I cement mortar or concrete mixture (Carino 1991).

Table 6.4: Activation energy values proposed by Carino and Tank (1992)

Cement Type	**Activation Energy, E (J/mol)**	
	w/c ratio = 0.45	**w/c ratio = 0.60**
Type I	64,000	48,000
Type II	51,000	43,000
Type III	44,000	44,000
Type I + 20% Fly Ash	30,000	31,000
Type I + 50% Slag	45,000	56,000
Type I + Accelerator	45,000	50,000
Type I + Retarder	39,000	39,000

These values are also higher than some of the activation energies found for straight Type I cement mixtures in this study. However, the Type I - 0.48 mixture had an activation energy of 42,300 J/mol, which does agree with past research. This difference could be due to the removal of the water-reducing admixture as the water-to-cement ratio increased, or to the use of fluctuating curing conditions. As was the case with the datum temperature values, the activation energies increased as the water-to-cement ratio increased for the straight Type I cement mixtures. The values for the GGBF Slag mixtures have higher values than those reported by Carino and Tank at 45,000 J/mol for the lower water-to-cement ratio Type I/II + 50% Slag mixture. However, the 55,000 J/mol to 61,500 J/mol found in this study is closer to the values recommended by Carino (1991) of 49,000 J/mol and RILEM (Springenschmid 1998) of 50,000 J/mol.

6.1.3 Accuracy of Maturity Functions Based on the ASTM C 1074 Method

Finally, the accuracy of using the ASTM C 1074 method to determine mixture-specific temperature sensitivity values was analyzed and is reported here. Reported errors are based on the difference between the actual compressive strength test values and the strength estimated from the hyperbolic strength-maturity relationship (Equation 2.5) using the NSM or AM functions. Average absolute errors (which have been used by Tank and Carino [1991]) were calculated as well from the following formula:

Average Absolute Error (AAE)

$$AAE = \frac{\sum_{i}^{n} \left| Est.Strength_i - Strength_i \right|}{n} \qquad \text{Equation 6.1}$$

where,

AAE	=	Average absolute error for n strength estimations (psi),
$Strength_i$	=	Compressive strength test result, for the i^{th} maturity index, M_i, (psi),
$Est.\ Strength_i$	=	Estimated strength from hyperbolic strength-maturity function, at the same maturity, M_i, (psi), and,
n	=	number of strength estimations (6 for each batch; 18 for the total AAE for each mixture).

The errors, based on the NSM and AM functions, for the three mixtures considered in this chapter, can be found in Tables 6.5 to 6.7 and 6.8 to 6.10, respectively. The remaining error tables can be found in Appendix D. The AAEs for each batch are reported as well as the percent error of the strength estimate, which was computed from the following equation:

Error of Estimate (EoE)

$$EoE = \frac{Est.Strength_i - Strength_i}{Strength_i} \times 100 \qquad \text{Equation 6.3}$$

where,

EoE = Error of estimate (%).

The error of estimate (EoE) gives the percent of over- or underestimation produced by the S-M functions. A positive EoE indicates that the estimated strength was more than the measured strength, which means the strength was overestimated. A negative EoE indicates that the estimated strength was less than the measured strength, which means the strength was underestimated. To better visualize this, after each error table, the estimated strengths are plotted versus the corresponding actual test values. These can be found in Figures 6.9 through 6.14. On these “45°-line” error plots, the center dark line represents the line of equality (zero error) between the estimated strength and the actual measured strength at each batch temperature. The other two sets of dotted lines represent ±10% and ±20% error. Points above the center line are overestimated strengths (unconservative), and points below the center line are underestimated strengths (conservative). The EoE values are evaluated by how far the points lie from the dark center line. The acceptable error tolerance for the purposes of this chapter will be ±10%, which is a value that is commonly used in the concrete industry for the evaluation of cylinder strengths.

The average absolute error of estimate was also computed for each batch of each mixture and for the total mixture. This value uses the same approach as Tank and Carino (1991) used to calculate the average absolute error. However, the average absolute error of estimate takes the average of the EoE values, neglecting signs. For clarification the equation is presented as follows:

Average Absolute Error of Estimate (Abs. EoE)

$$Abs.EoE = \frac{\sum_{i}^{n} \left| EoE_i \right|}{n} \qquad \text{Equation 6.3}$$

where,

Abs. EoE	=	Average absoute error of estimate (%),
EoE	=	Error of estimate for i^{th} test strength (%)
n	=	Number of EoE values (6 for each batch; 18 for total abs. EoE).

Table 6.5: Error using NSM function based on ASTM C 1074 methods for the 20% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,510	1,540	30	2	190	5
	1.0	2,660	2,360	-300	-11		
	2.0	3,380	3,420	40	1		
	7.0	5,120	5,350	230	4		
	14.1	5,930	6,160	230	4		
	28.2	6,960	6,640	-320	-5		
Cold	0.9	720	1,480	760	106	180	19
	1.8	2,510	2,510	0	0		
	3.4	3,340	3,460	120	4		
	12.2	5,460	5,360	-100	-2		
	24.9	6,100	6,140	40	1		
	49.0	6,560	6,610	50	1		
Hot	0.4	1,990	1,720	-270	-14	320	9
	0.8	3,280	2,740	-540	-16		
	1.4	4,110	3,650	-460	-11		
	4.9	5,400	5,610	210	4		
	10.0	6,180	6,310	130	2		
	19.8	7,060	6,730	-330	-5		

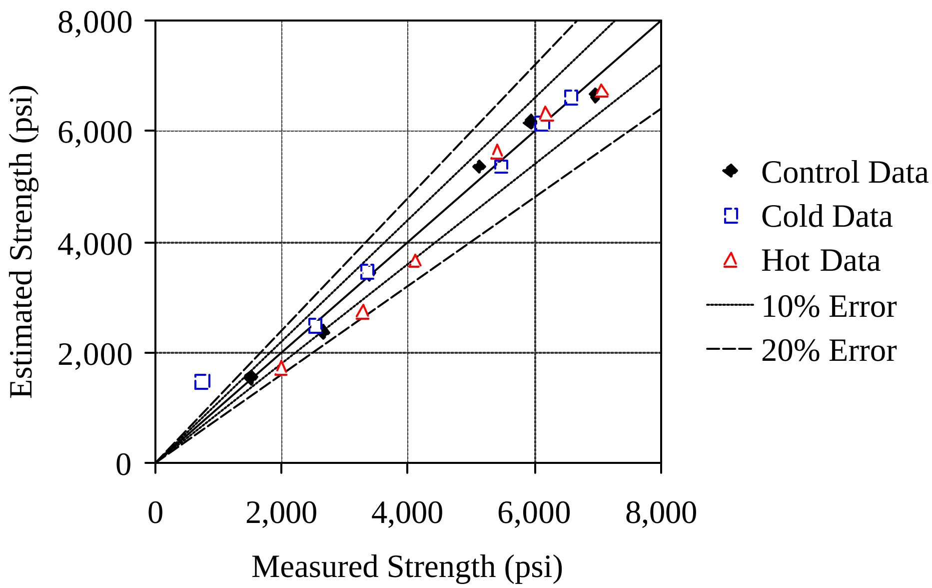


Figure 6.9: Estimated strength versus actual strength for 20% F mixture

Table 6.6: Error using NSM function based on ASTM C 1074 methods for the Type I - 0.41 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,030	1,060	30	3	150	3
	1.0	2,700	2,670	-30	-1		
	2.1	4,060	3,910	-150	-4		
	7.1	4,900	5,300	400	8		
	14.0	5,690	5,690	0	0		
	28.1	6,170	5,910	-260	-4		
Cold	0.8	540	1,310	770	143	360	28
	1.8	2,830	2,950	120	4		
	3.4	4,040	3,950	-90	-2		
	12.1	5,480	5,300	-180	-3		
	24.8	5,970	5,700	-270	-5		
	49.0	6,620	5,910	-710	-11		
Hot	0.4	2,140	1,570	-570	-27	370	10
	0.8	3,670	3,320	-350	-10		
	1.4	4,010	4,230	220	5		
	5.0	4,990	5,470	480	10		
	10.2	5,410	5,790	380	7		
	20.1	5,740	5,960	220	4		

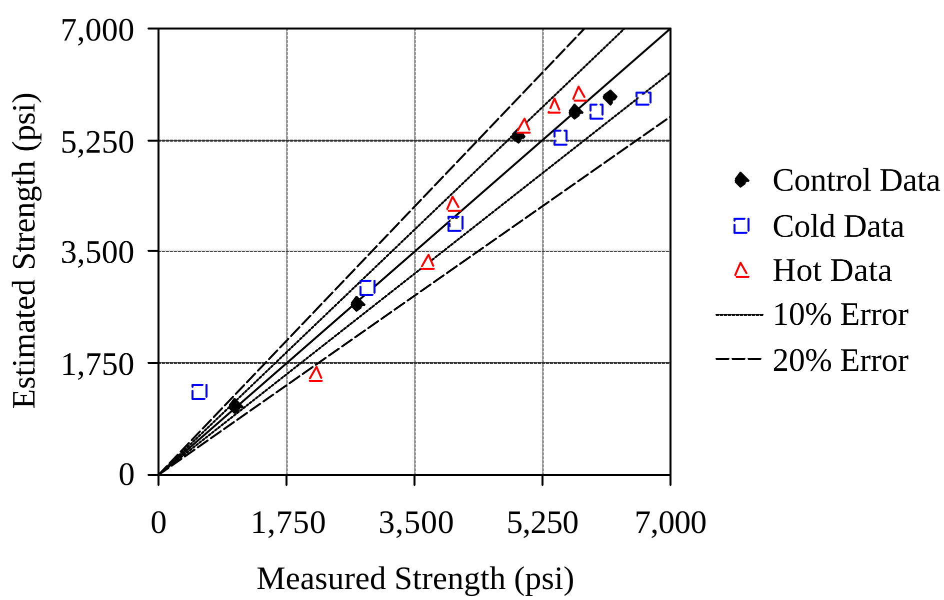


Figure 6.10: Estimated strength versus actual strength for the Type I - 0.41 mixture

Table 6.7: Error using NSM function based on ASTM C 1074 methods for the Type III - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	4,280	4,410	130	3	310	4
	1.0	6,530	6,290	-240	-4		
	2.1	7,970	7,850	-120	-2		
	7.1	9,110	9,730	620	7		
	14.3	10,100	10,270	170	2		
	28.2	11,120	10,560	-560	-5		
Cold	0.9	2,400	3,330	930	39	300	8
	2.0	5,670	5,870	200	4		
	3.5	6,900	6,880	-20	0		
	12.6	9,060	9,130	70	1		
	25.1	10,270	9,890	-380	-4		
	49.4	10,520	10,340	-180	-2		
Hot	0.3	2,860	3,650	790	28	1,400	21
	0.8	6,400	7,200	800	13		
	1.4	6,960	8,390	1,430	21		
	5.0	8,030	10,040	2,010	25		
	10.0	8,610	10,430	1,820	21		
	19.8	9,030	10,590	1,560	17		

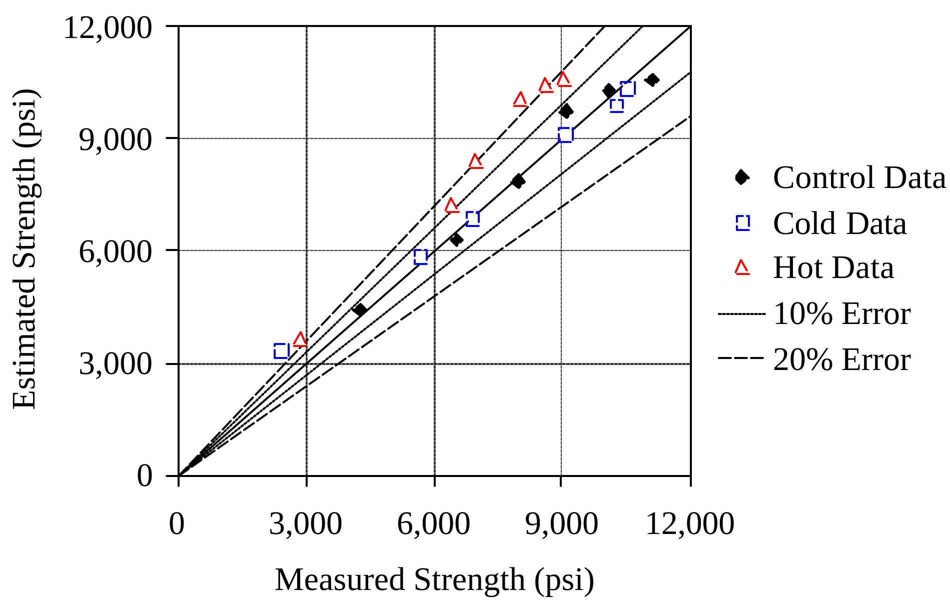


Figure 6.11: Estimated strength versus actual strength for the Type III - 0.37 mixture

Table 6.8: Error using AM function based on ASTM C 1074 methods for the 20% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,510	1,540	30	2	190	5
	1.0	2,660	2,360	-300	-11		
	2.0	3,380	3,420	40	1		
	7.0	5,120	5,360	240	5		
	14.1	5,930	6,160	230	4		
	28.2	6,960	6,640	-320	-5		
Cold	0.9	720	1,560	840	117	290	23
	1.8	2,510	2,630	120	5		
	3.4	3,340	3,670	330	10		
	12.2	5,460	5,580	120	2		
	24.9	6,100	6,290	190	3		
	49.0	6,560	6,700	140	2		
Hot	0.4	1,990	1,840	-150	-8	270	6
	0.8	3,280	2,920	-360	-11		
	1.4	4,110	3,820	-290	-7		
	4.9	5,400	5,700	300	6		
	10.0	6,180	6,360	180	3		
	19.8	7,060	6,750	-310	-4		

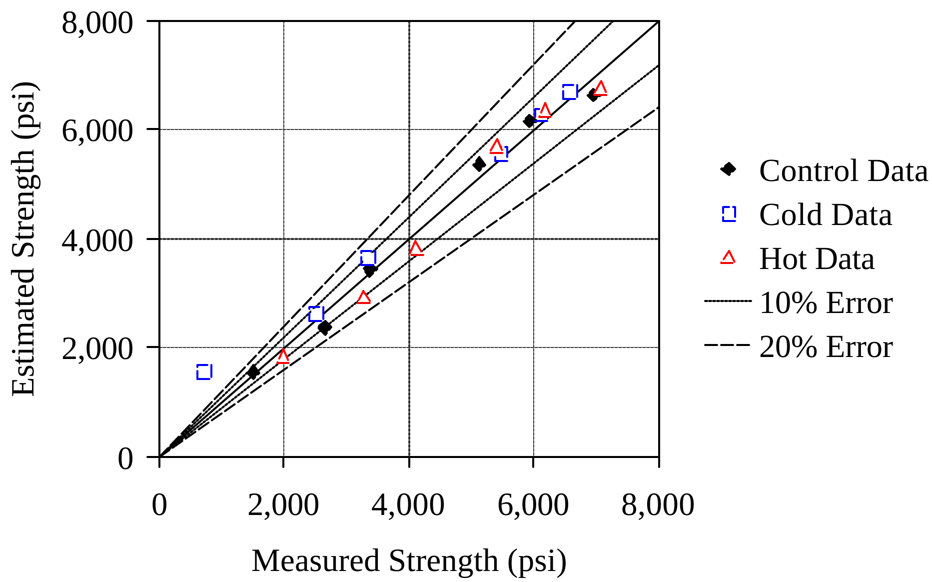


Figure 6.12: Estimated strength versus actual strength for the 20% F mixture

Table 6.9: Error using AM function based on ASTM C 1074 methods for the Type I - 0.41 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,030	1,060	30	3	150	3
	1.0	2,700	2,670	-30	-1		
	2.1	4,060	3910	-150	-4		
	7.1	4,900	5,300	400	8		
	14.0	5,690	5,690	0	0		
	28.1	6,170	5,910	-260	-4		
Cold	0.8	540	1360	820	152	340	29
	1.8	2,830	3,030	200	7		
	3.4	4,040	4,070	30	1		
	12.1	5,480	5,390	-90	-2		
	24.8	5,970	5,750	-220	-4		
	49.0	6,620	5,940	-680	-10		
Hot	0.4	2,140	1,950	-190	-9	310	7
	0.8	3,670	3,660	-10	0		
	1.4	4,010	4,460	450	11		
	5.0	4,990	5,550	560	11		
	10.2	5,410	5,840	430	8		
	20.1	5,740	5,980	240	4		

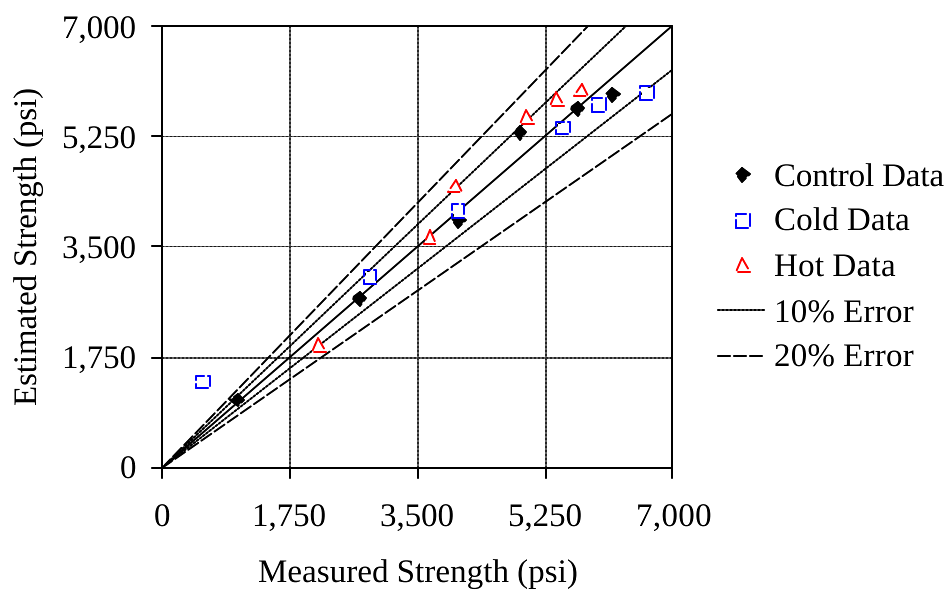


Figure 6.13: Estimated strength versus actual strength for the Type I - 0.41 mixture

Table 6.10: Error using AM function based on ASTM C 1074 methods for the Type III - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	4,280	4,400	120	3	300	4
	1.0	6,530	6,310	-220	-3		
	2.1	7,970	7,830	-140	-2		
	7.1	9,110	9720	610	7		
	14.3	10,100	10,270	170	2		
	28.2	11,120	10,570	-550	-5		
Cold	0.9	2400	3,590	1,190	50	460	12
	2.0	5,670	6,120	450	8		
	3.5	6,900	7,420	520	8		
	12.6	9,060	9,600	540	6		
	25.1	10,270	10,200	-70	-1		
	49.4	10,520	10,520	0	0		
Hot	0.3	2,860	4,670	1,810	63	1,850	31
	0.8	6,400	7,960	1,560	24		
	1.4	6,960	8,920	1,960	28		
	5.0	8,030	10,230	2,200	27		
	10.0	8,610	10,540	1,930	22		
	19.8	9,030	10,670	1,640	18		

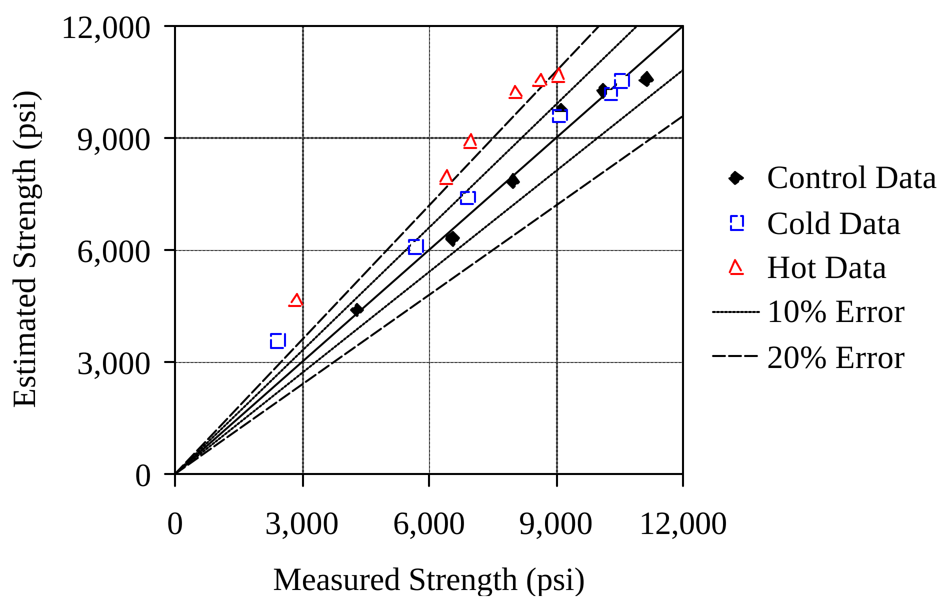


Figure 6.14: Estimated strength versus actual strength for the Type III - 0.37 mixture

For ease of comparison, the total absolute average errors and total average absolute error of estimates for each mixture and both maturity functions are reported in Table 6.11. The total average absolute errors are computed from Equation 6.1, using all strength calculations for a single mixture. The total average absolute error of estimate was computed from Equation 6.3. First, the accuracy of the Nurse-Saul maturity function using the ASTM C 1074 method for obtaining a mixture-specific datum temperature will be discussed for the three selected mixtures. Next, the accuracy of the Arrhenius maturity function using the ASTM C 1074 method for obtaining a mixture-specific activation energy will be discussed. Finally, the two maturity functions will be compared based on their total error values for all mixtures considered ,and the overall evaluation of accuracy of the ASTM C 1074 mixture-specific temperature sensitivity method will be discussed.

6.1.3.1 Accuracy of the Nurse-Saul Maturity Function

1. 20% F Mixture

The accuracy of the strength estimations for the 20% F mixture using the NSM function and the mixture-specific datum temperature obtained from the ASTM C 1074 method is presented in Table 6.5 and Figure 6.9. From the table, it can be seen that the highest average absolute error came from estimating the hot batch's strengths, with an AAE of 320 psi. Most of this error was attributed to underestimating the early-age strengths, which is conservative; estimated values were around 15% inaccurate at 0.4 and 0.8 days. The cold batch's strengths were all estimated well, except for the earliest strength estimation. In fact, if the first point is dropped out of the AAE calculation, the

AAE goes from 180 psi to 60 psi. Also, because this mixture has little to no late-age strength loss or gain due to the crossover effect, all of the strengths from 7 days to 28 days equivalent age were estimated within ±5% of the actual values for all three batches. Also, the average absolute errors of estimates (abs. EoEs) for the hot and control batches were less than or equal to 9%. If the first strength estimation for the cold batch was neglected, its abs. EoE would be reduced from 19% to 2%.

Table 6.11: Comparison of maturity functions for all mixtures, ASTM C1074 method

Mixture ID	**Nurse-Saul Maturity (NSM)**		**Arrhenius Maturity (AM)**		**Function that Produced the Lowest Total Error**
	Total AAE (psi)	Total Abs. EoE (%)	Total AAE (psi)	Total Abs. EoE (%)	
Type I - 0.41	290	14	270	13	AM
Type I - 0.44	380	16	290	14	AM
Type I - 0.48	580	17	530	18	NSM
20% F	230	11	250	11	NSM
30% F	290	12	280	12	AM
20% C	250	6	220	7	NSM
30% C	280	11	270	11	AM
30% Slag	680	15	580	17	NSM
50% Slag	900	28	750	30	NSM
Type III - 0.37	670	11	870	15	NSM
Type III - 0.44	450	12	420	11	AM
70/20/10 - 0.37	700	13	870	19	NSM
70/20/10 - 0.44	730	23	660	26	NSM

2. Type I - 0.41 Mixture

The accuracy of the Type I - 0.41 mixture using the NSM function and the mixture-specific datum temperature obtained from the ASTM C 1074 method can be seen in Table 6.6 and Figure 6.10. The AAE for both the hot and cold batches was around 360 psi. The first strength estimation for both the hot and cold batches was more than 20% inaccurate, where the cold batch's strength was overestimated and the hot batch's strength was underestimated. After the first test strength, all the estimated strengths for the hot and cold batches had 11% or less error. For the 7-day through 28-day equivalent age tests, the crossover effect was present and the hot strengths were overestimated and the cold strengths were underestimated. The average absolute error of estimate (Abs. EoE) for the hot batch was 10%. Again, neglecting the first strength estimation for the cold batch significantly reduces the abs. EoE, from 28% to 5%.

3. Type III - 0.37 Mixture

The accuracy of the Type III - 0.37 mixture using the NSM function and the mixture-specific datum temperature obtained from the ASTM C 1074 method is shown in Table 6.7 and Figure 6.11. From this figure and table, it may be seen again that the first estimated strength for both the cold and hot batches was overestimated by more than 20%. Beyond that point, the cold batch's strengths were estimated within ±4% of the actual strength values. Also, neglecting the first strength estimation, the remaining cold strength estimations had an AAE of 170 psi, a 2% abs. EoE, down from 300 psi for the full cold batch. All six of the hot batch's strength estimations were overestimated by more than 10%. This shows how late-age strength losses due to high curing temperatures can adversely affect the accuracy of strength estimations using the maturity method.

Recall that in Chapter 5, Section 5.2.1, it was reported that this mixture had a 17% crossover factor for the hot batch versus the control batch.

6.1.3.2 Accuracy of the Arrhenius Maturity Function

The accuracy of the Arrhenius maturity function using the mixture-specific activation energies, found from the ASTM C 1074 method, can be seen in Tables 6.8 through 6.10 and Figures 6.12 through 6.14.

1. 20% F Mixture

The accuracy of the 20% F mixture using the AM function and the mixture-specific activation energy obtained from the ASTM C 1074 method can be seen in Table 6.8 and Figure 6.12. All of the strength estimations for the hot batch produced ±11% or less error. The first test strength for the cold batch was greatly overestimated, as was the case for the 20% F mixture when evaluated with the NSM function that was discussed earlier. However, the remaining strength estimations for the cold batch were all estimated within the ±10% error tolerance.

2. Type I - 0.41 Mixture

The accuracy of the Type I - 0.41 mixture using the AM function and the mixture-specific activation energy obtained from the ASTM C 1074 method is shown in Table 6.9 and Figure 6.13. The strengths for the hot batch were all estimated within ±11% error. Again, the first strength estimation for the cold batch was greatly overestimated; however, the remaining strength estimations produced an abs. EoE of 5%.

3. Type III - 0.37 Mixture

The accuracy of the Type III - 0.37 mixture using the AM function and the mixture-specific activation energy obtained from the ASTM C 1074 method can be found in Table 6.10 and Figure 6.14. Again, the first strength value for the cold batch was overestimated by more than 20%, while the remaining values for the cold batch were estimated within the ±10% error tolerance. The strength values for the hot batch were all overestimated by more than 10% and most by more than 20%. The average absolute error of estimate for the hot batch was 23%, which is caused by the presence of the crossover effect as discussed in Chapter 5, Section 5.2.1.

Comparison of Maturity Functions for All Mixtures

The total absolute average errors and total absolute average errors of estimate for all mixtures can be seen in Table 6.11. It is important to consider both the average error in strength units as well as the corresponding percentage error, because of the different strength-levels of the mixtures evaluated.

Using the NSM function and the ASTM C 1074 method for obtaining mixture-specific datum temperatures, only 1 out of 13 mixtures produced total absolute average errors of estimate (total abs. EoE) of 10% or less. However, 9 out of 13 of the mixtures produced total abs. EoEs of 15% or less. As was observed from the three example mixtures discussed above, if the first strength estimation for the cold batch is neglected the total abs. EoEs would decrease significantly. Using the AM function and the ASTM method for obtaining mixture-specific activation energies, only 1 mixture produced a total abs. EoE of 10% or less. However, 8 out of 13 mixtures produced total abs. EoE of

15% or less and the same large early-age error trends were noticed from the cold batches. Overall, the Nurse-Saul maturity function produced the lower total abs. EoEs for 8 out 13 of the mixtures. However, it should be noted that for many of the mixtures (10 out of 13) the two functions were only 2% different in total abs. EoEs.

The mixtures producing the worst total abs. EoEs, those producing more than 15% total abs. EoE, were the Type I - 0.48, 50% Slag, and 70/20/10 - 0.44 mixtures. These were all mixtures that had high (more than 20%) crossover factors for either their respective hot or cold batches. From Appendix D and the figures and tables presented above, it can be seen that the other mixtures that had high crossover factors for either the hot or cold batches, such as the 30% Slag mixture, both Type III mixtures, and the 70/20/10 - 0.37 mixture, also had high average absolute errors of estimate for their corresponding batches. For these mixtures, the crossover factors given in Table 5.3 are very similar to the late-age strength errors of estimate using the maturity method. For example, the crossover factor for the 70/20/10 - 0.44 hot batch was -31%; in other words, the hot batch's late-age strengths were 31% less than the control batch's late-age strengths. The last two strength estimations for the 70/20/10 - 0.44 hot batch using the NSM function were more than 40% overestimated. For the Type III - 0.37 mixture, the last three strength estimations were on average 21% overestimated, and the crossover factor for this batch was -17%. The Type III - 0.44 mixture had crossover factors of -10% and 18% for the hot and cold batches respectively. The last three strength estimations for each of these batches were on average 10% overestimated and 16% underestimated for the hot and cold batches, respectively. Based on these late-age strength estimation errors, it may be hypothesized that the late-age strength values should not be used in determining the accuracy of the maturity method to estimate concrete strength.

As explained in Section 2.3.2, others (Kjellsen and Detwiler 1993; Jonasson 1985) also believe the maturity method should not be used to estimate late-age strengths. Kjellsen and Detwiler concluded that the maturity method is only valid up to 40% of the laboratory-cured 28-day strength, while Jonasson suggested 50% was the cutoff. Based on these facts, it is recommended that strength values should not be estimated after crossover has occurred. From the values presented in Table 5.3, the average time until crossover for the hot batches occurred at 10 days (excluding batches where crossover occurred after 28 days). The equivalent age for a 10-day hot batch strength, using the age conversion factor given in Section 4.3, is 14 days. Thus the 14 day and 28 day equivalent age test strengths will not be used to evaluate the accuracy of the maturity method in the following sections.

It is also hypothesized that the rates of initial strength gain for the hyperbolic strength-age function (*k*-values), found in Chapter 5, were also affected by the long-term strength losses due to high curing temperatures. Therefore the least-squares regression analysis was repeated for the strength-age data only up to 7 days of equivalent age. If the *k*-values change, this would affect the mixture-specific temperature sensitivity values found using the ASTM method and, hence, the strength estimations. The next section describes evaluation of the accuracy of the maturity method using this “Modified ASTM” method.

6.2 MODIFICATIONS TO THE ASTM C 1074 METHOD

As was observed in the previous section, the crossover effect can cause severe errors when estimating late-age strengths using the maturity method. Therefore, it is proposed that the maturity method be used only to estimate strengths up to 7 days of equivalent age. Accordingly, the *k*-value method of determining the mixture-specific temperature sensitivity values should be based only on the strength-age data up to 7 days of equivalent age. By neglecting the later-age strengths, the influence of the crossover effect on early-age strength estimates should be reduced. The use of only early-age strength values should change the *k*-values, or the rates of initial reaction. Most notably, the *k*-value for hot batches should increase for mixtures with crossover, because the plateau of strength gain at the later-ages will not affect the determination of the *k*-value. An example of this rate increase and subsequent temperature sensitivity change is shown in Figure 6.15 for the Type I - 0.41 mixture. In the figure, the diamond data points represent the new *k*-values found by only considering strength data up to 7 days of equivalent age. The square data points represent the *k*-values found when all the strength data up to 28 days of equivalent age are considered. The figure shows that the cold *k*-value did not change significantly; however, the control and hot batch's *k*-values increased greatly, bringing the mixture-specific datum temperature up to 27°F (-3°C).

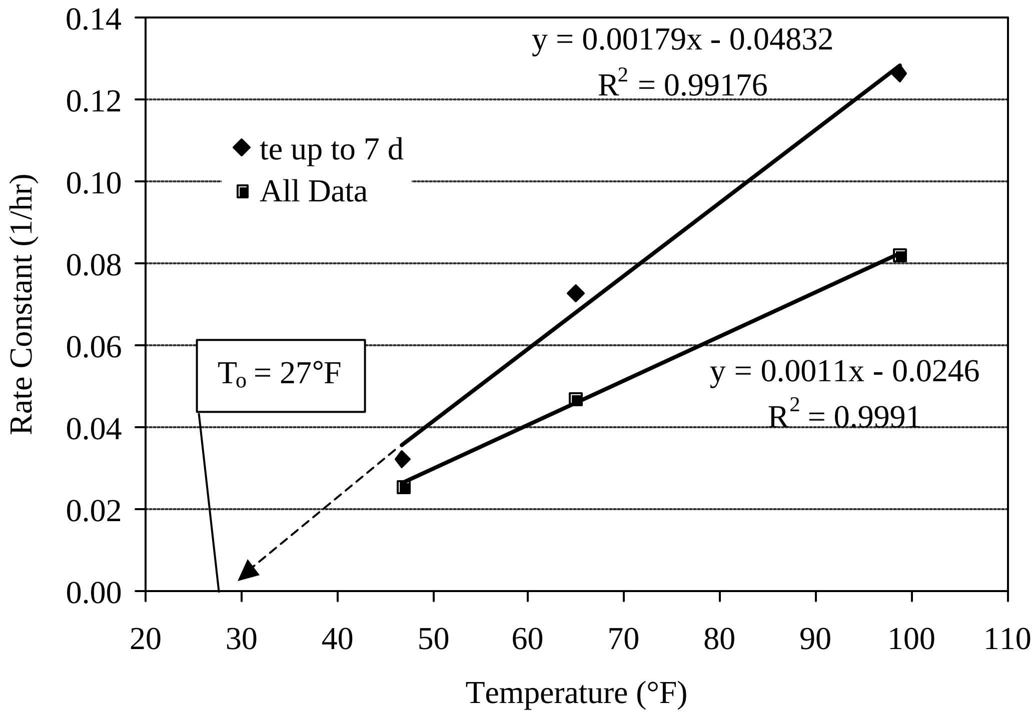


Figure 6.15: Change in rate values and datum temperature for Type I - 0.41 mixture

Throughout this section, this new method of determining mixture-specific temperature sensitivity values is referred to as the "Modified ASTM" method, as calculation of the temperature sensitivity values remains the same as documented in ASTM C 1074; however, only data up to an equivalent age of 7 days are considered. Again, S-M relationships are shown for the three example mixtures. Next, temperature sensitivity values are given and compared to the ASTM method and previously published values. Strength estimation errors determined with both maturity functions using the Modified ASTM method will be reported and compared to those obtained from the ASTM C 1074 method. The results from the least-squares regression analysis of the strength-age data for all mixtures evaluated only up to 7 days of equivalent age are reported in Table 6.12.

Table 6.12: Regression values for strength-age curves up to 7 days of equivalent age

Mixture ID	Batch ID	t_o (hr)	S_u (psi)	k (hr^{-1})
Type I - 0.41	Hot Control Cold	3.6 9.7 16.1	5,270 5,370 6,070	0.126 0.073 0.032
Type I - 0.44	Hot Control Cold	1.2 7.4 16.6	5,090 4,850 5,350	0.054 0.038 0.021
Type I - 0.48	Hot Control Cold	2.7 6.3 17.5	4,670 4,970 5,810	0.050 0.027 0.015
20% F	Hot Control Cold	3.5 2.8 12.5	6,040 6,110 6,530	0.074 0.030 0.017
30% F	Hot Control Cold	4.3 4.4 13.7	5,610 5,440 6,270	0.063 0.028 0.014
20% C	Hot Control Cold	4.9 7.1 12.8	5,790 6,370 7,190	0.090 0.033 0.011
30% C	Hot Control Cold	7.0 9.7 21.4	6,880 6,520 5,880	0.051 0.025 0.014
30% Slag	Hot Control Cold	4.5 2.7 15.4	5,900 7,110 6,200	0.077 0.025 0.017
50% Slag	Hot Control Cold	2.8 5.3 1.8	8,480 8,420 10,740	0.021 0.013 0.003
Type III - 0.37	Hot Control Cold	4.4 8.3 13.9	8,300 9,510 9,820	0.207 0.132 0.038
Type III - 0.44	Hot Control Cold	0.0 7.6 16.6	5,380 5,500 6,660	0.089 0.066 0.020
70/20/10 - 0.37	Hot Control Cold	0.0 5.2 12.3	9,190 9,130 8,420	0.035 0.031 0.018
70/20/10 - 0.44	Hot Control Cold	0.0 4.8 19.1	6,030 6,180 5,720	0.025 0.018 0.014

6.2.1 Nurse-Saul Maturity Function

The newly found *k*-values given in Table 6.12 were used to find the appropriate datum temperatures for each mixture. The new datum temperatures are shown in Table 6.13, along with the values found previously in Section 6.1.1. There are various differences in the datum temperatures found from the Modified ASTM method and ASTM C 1074 method.

Table 6.13: Datum temperatures obtained from different methods

Mixture ID	Modified ASTM	ASTM C 1074
	Datum Temperature T_o (°F (°C))	**Datum Temperature T_o (°F (°C))**
Type I - 0.41	27 (-3)	23 (-5)
Type I - 0.44	17 (-9)	35 (2)
Type I - 0.48	28 (-2)	39 (4)
20% F	36 (2)	23 (-5)
30% F	39 (4)	19 (-7)
20% C	46 (8)*	37 (3)
30% C	35 (2)	42 (5)*
30% Slag	40 (5)	46 (8)*
50% Slag	25 (-4)	47 (9)*
Type III - 0.37	33 (1)	38 (3)
Type III - 0.44	29 (-2)	37 (3)
70/20/10 - 0.37	-15 (-26)	39 (4)
70/20/10 - 0.44	-17 (-27)	43 (6)*

* Value higher than some temperatures reached during cold temperature history

The Type I - 0.41 mixture's datum temperature increased from 23°F (-5°C) to 27°F (-3°C), as was shown in Figure 6.15. The straight Type I and Type III cement mixtures' datum temperatures have a much smaller spread, from 27°F to 33°F, excluding the Type I - 0.44 mixture. Both Class F fly ash mixtures increased in datum temperature, while both GGBF Slag mixtures decreased. The biggest difference is noticed for the ternary blend mixtures. These mixtures contain silica fume, which has a very high rate of reaction when used in concrete (Holland 2005). Recall that Saul (1951) defined the datum temperature as the temperature at which a concrete ceases to gain strength, after it has enough time to set. With that in mind, these low datum temperatures may indicate that once the silica fume begins to react, it is very insensitive to the curing temperature. Referring back to Table 6.2, the datum temperature values found from the Modified ASTM method are much different than those Carino and Tank (1992) found, but this is to be expected as only early-age data was considered and the rate constants changed in this study.

Next, the strength-maturity (S-M) relationships are shown for the Nurse-Saul maturity function with the mixture-specific datum temperatures found from the Modified ASTM method. These plots along with the measured data can be seen in Figures 6.16, 6.17, and 6.18. These figures may be compared to Figures 6.2, 6.3, and 6.4; however, note that the horizontal scales have been changed to only include data up to 7 days of equivalent age. The remaining S-M relationships for the Nurse-Saul Function, using the Modified ASTM method, may be found in Appendix E. The accuracy of strength estimations using this method are discussed at the end of this section.

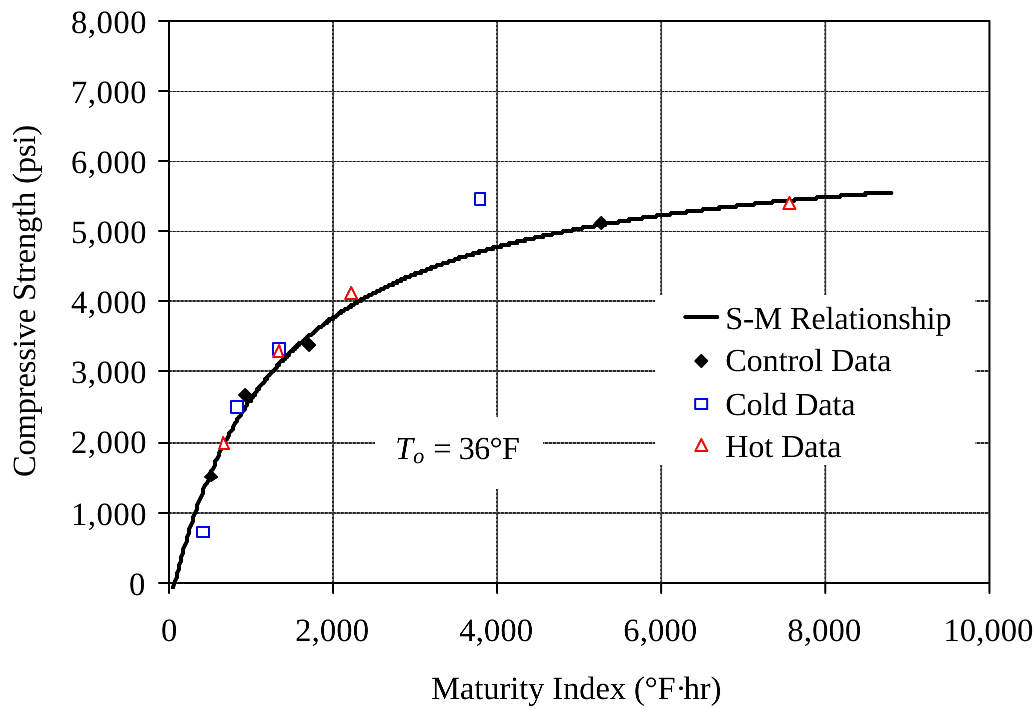


Figure 6.16: Strength-maturity plot, Modified ASTM method for 20% F mixture

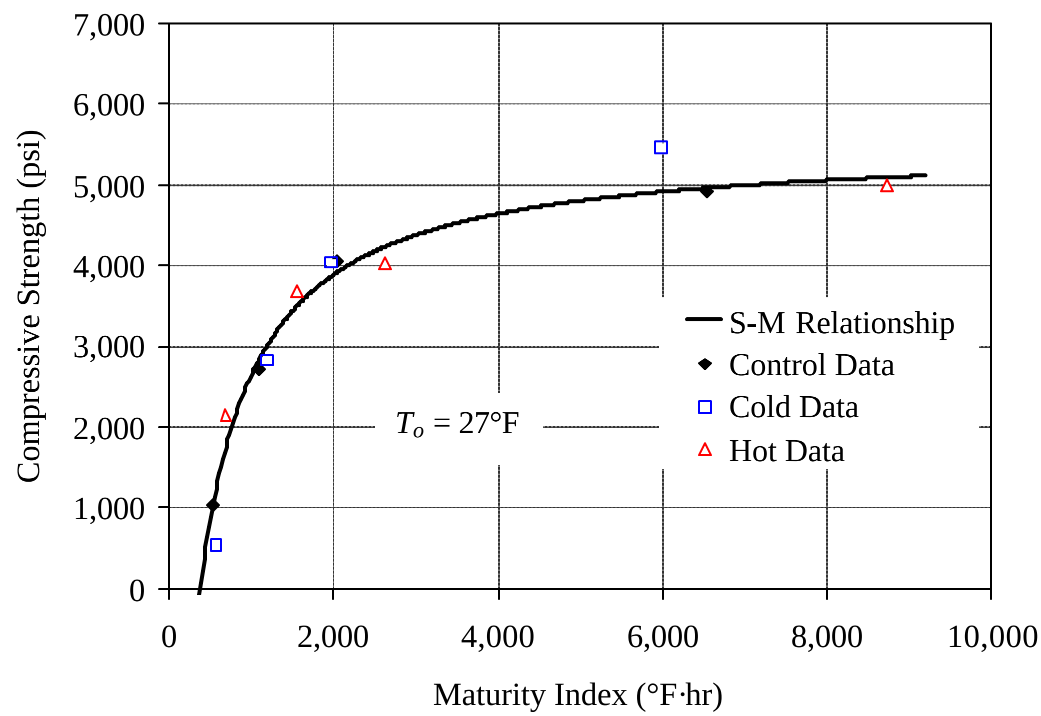


Figure 6.17: Strength-maturity plot, Modified ASTM method for Type I - 0.41

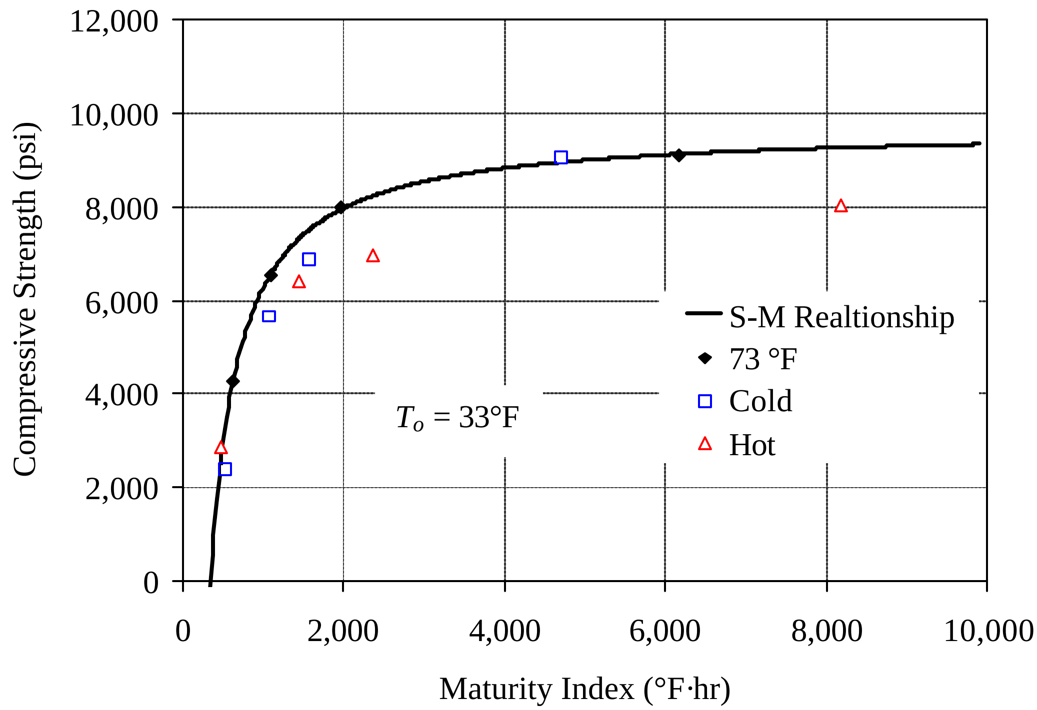


Figure 6.18: Strength-maturity plot, Modified ASTM method for Type III - 0.37 mixture

6.2.2 Arrhenius Maturity Function

Next, the Modified ASTM method of determining mixture-specific temperature sensitivity values was applied to the Arrhenius maturity function. New activation energies, based on the *k*-values given in Table 6.12, were found and are reported in Table 6.14. The trends for the new activation energies are similar to those found earlier with the Modified ASTM datum temperatures. The Type - 0.41 activation energy increased, and the Type I - 0.44 and Type I - 0.48 activation energies decreased. The Type I straight cement mixtures are closer together, around 30,000 J/mol. However, the straight Type III mixtures' activation energies remained high, averaging approximately 40,000 J/mol. Both Class F fly ash mixtures increased activation energies, just as the Modified ASTM datum temperatures increased for these mixtures. Also, both ternary mixtures had an extreme reduction in activation energy, from about 45,000 J/mol to 15,000 J/mol, which suggests that the ternary mixtures have very low temperature sensitivity, as was discussed with the datum temperatures previously.

Table 6.14: Activation energies based obtained from different methods

Mixture ID	Modified ASTM	ASTM C1074
	Activation Energy, E (J/mol)	**Activation Energy, E (J/mol)**
Type I - 0.41	33,100	28,600
Type I - 0.44	25,000	34,800
Type I - 0.48	30,800	42,300
20% F	37,000	25,800
30% F	40,200	23,200
20% C	54,100	37,800
30% C	35,300	45,100
30% Slag	39,000	55,700
50% Slag	28,600	61,500
Type III - 0.37	42,000	41,400
Type III - 0.44	38,100	42,900
70/20/10 - 0.37	16,700	42,600
70/20/10 - 0.44	14,800	47,300

The S-M relationships for the three example mixtures, using the Arrhenius maturity function and mixture-specific activation energies found using the Modified ASTM method, are shown in Figures 6.19, 6.20, and 6.21. These plots may be compared to Figures 6.6, 6.7, and 6.8, respectively; however, the horizontal scales were changed to only include data up to 7 days of equivalent age. The remaining S-M relationships for the Arrhenius Maturity Function, using the Modified ASTM method, may be found in

Appendix F. The accuracy of strength estimations using the NSM and AM functions using the Modified ASTM method will be discussed in the next section.

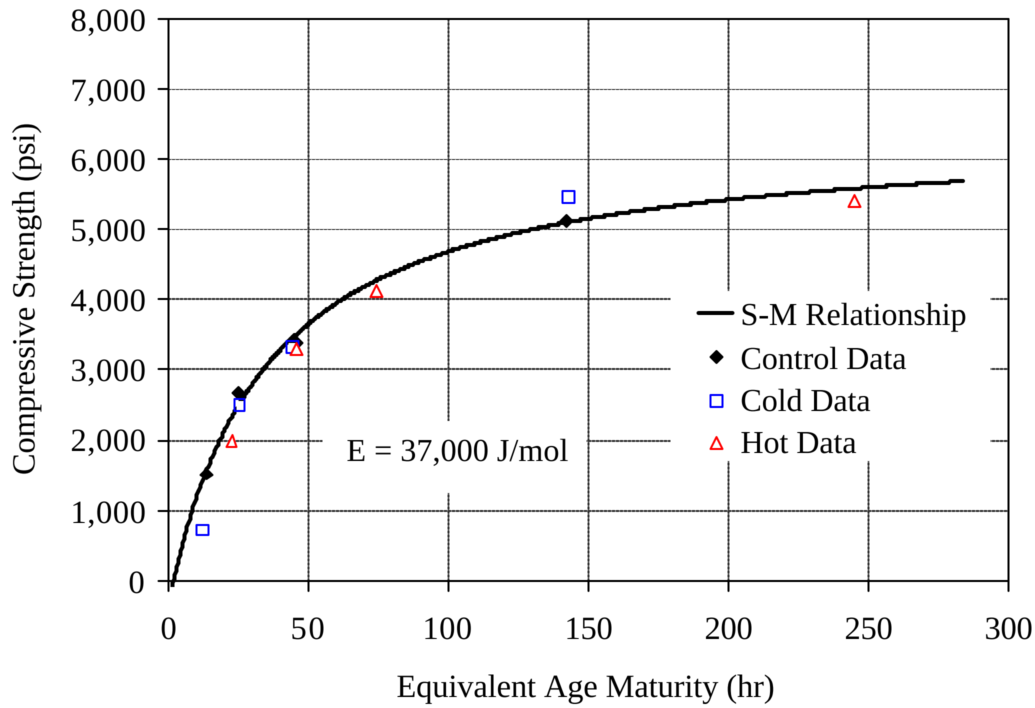


Figure 6.19: Strength-maturity plot, Modified ASTM method for 20% F mixture

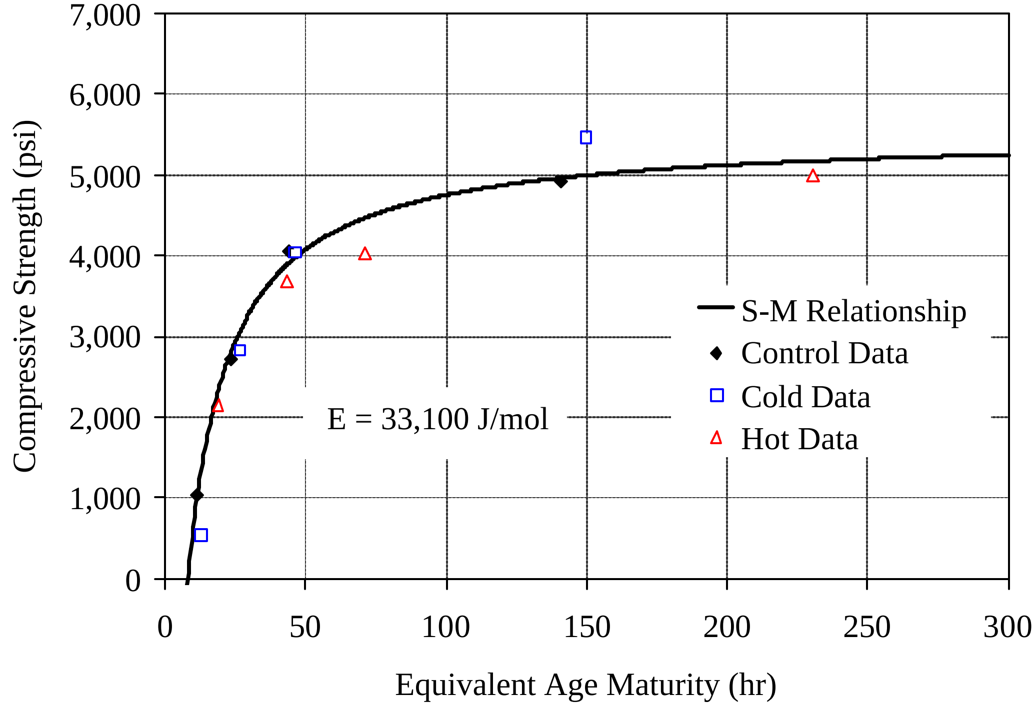


Figure 6.20: Strength-maturity plot, Modified ASTM method for Type I - 0.41 mixture

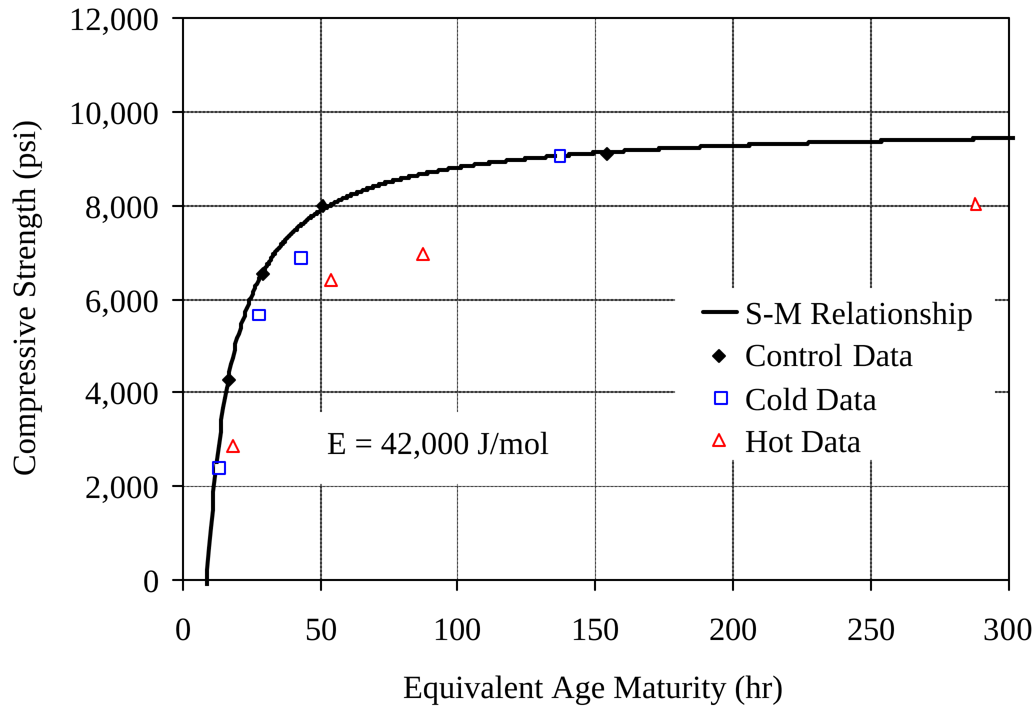


Figure 6.21: Strength-maturity plot, Modified ASTM method for Type III - 0.37 mixture

6.2.3 Accuracy of Maturity Functions Based on the Modified ASTM Method

The errors of the three example mixtures using the Modified ASTM method are shown in Tables 6.15 through 6.17 using the NSM function and Tables 6.18 to 6.20 using the AM function. The remaining mixtures' error tables can be found in Appendix G. In these tables, the errors from the ASTM C 1074 method are shown for ease of comparison. The AAEs for the ASTM C 1074 method were recalculated to include strengths only up to 7 days of equivalent age. The 45°-line error plot for each mixture using the ASTM C 1074 and Modified ASTM methods can be seen on each page following the corresponding error tables.

Table 6.15: Error using NSM function based on Modified ASTM method for 20% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,510	1,540	30	2	150	5	1,570	60	4	100	4
	1.0	2,660	2,360	-300	-11			2,500	-160	-6		
	2.0	3,380	3,420	40	1			3,510	130	4		
	7.0	5,120	5,350	230	4			5,090	-30	-1		
Cold	0.9	720	1,480	760	106	250	28	1,260	540	75	440	26
	1.8	2,510	2,510	0	0			2,290	-220	-9		
	3.4	3,340	3,460	120	4			3,100	-240	-7		
	12.2	5,460	5,360	-100	-2			4,700	-760	-14		
Hot	0.4	1,990	1,720	-270	-14	370	11	1,960	-30	-2	110	3
	0.8	3,280	2,740	-540	-16			3,090	-190	-6		
	1.4	4,110	3,650	-460	-11			3,930	-180	-4		
	4.9	5,400	5,610	210	4			5,440	40	1		

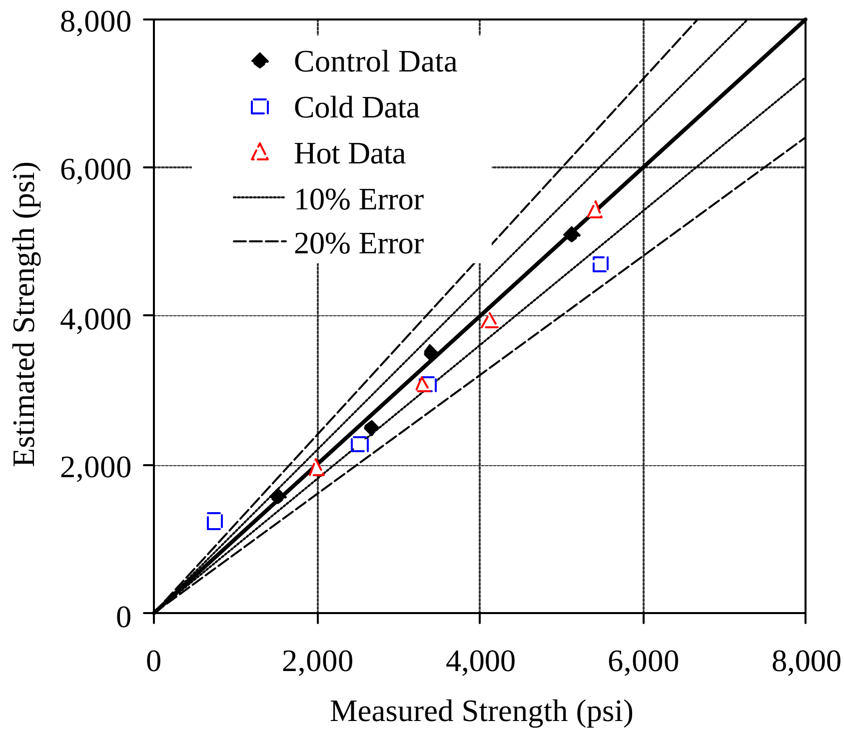


Figure 6.22: Error plot for the 20% F mixture, Modified ASTM method, NSM

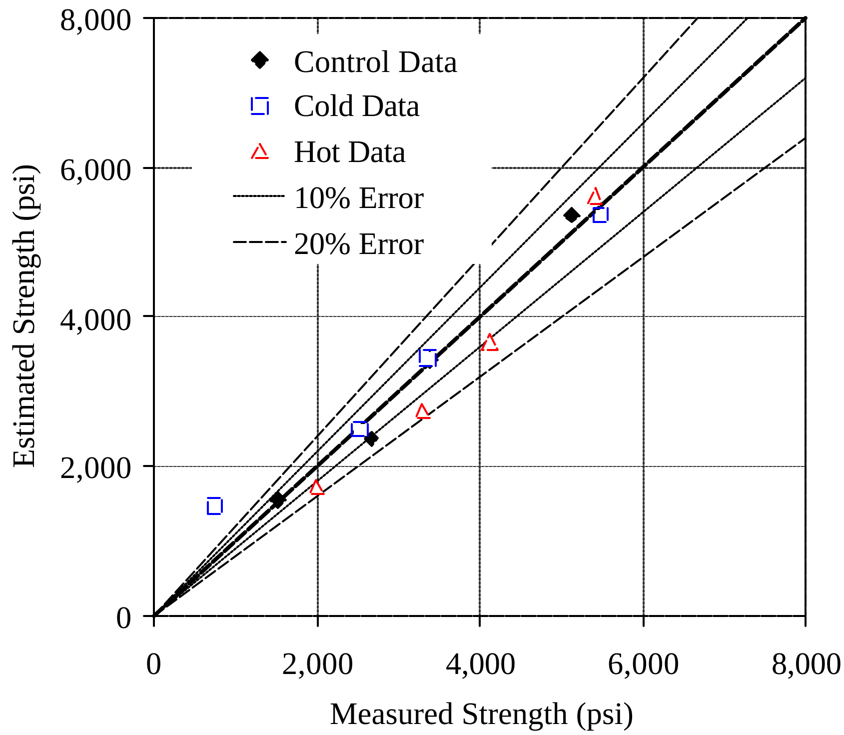


Figure 6.23: Error plot for the 20% F mixture, ASTM C 1074 method, NSM

Table 6.16: Error using NSM function based on Modified ASTM method for Type I - 0.41 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,030	1,060	30	3	150	4	1,000	-30	-3	85	3
	1.0	2,700	2,670	-30	-1			2,810	110	4		
	2.1	4,060	3,910	-150	-4			3,920	-140	-3		
	7.1	4,900	5,300	400	8			4,960	60	1		
Cold	0.8	540	1,310	770	143	290	38	1,210	670	124	393	36
	1.8	2,830	2,950	120	4			2,980	150	5		
	3.4	4,040	3,950	-90	-2			3,860	-180	-4		
	12.1	5,480	5,300	-180	-3			4,910	-570	-10		
Hot	0.4	2,140	1,570	-570	-27	410	13	1,740	-400	-19	223	8
	0.8	3,670	3,320	-350	-10			3,490	-180	-5		
	1.4	4,010	4,230	220	5			4,220	210	5		
	5.0	4,990	5,470	480	10			5,090	100	2		

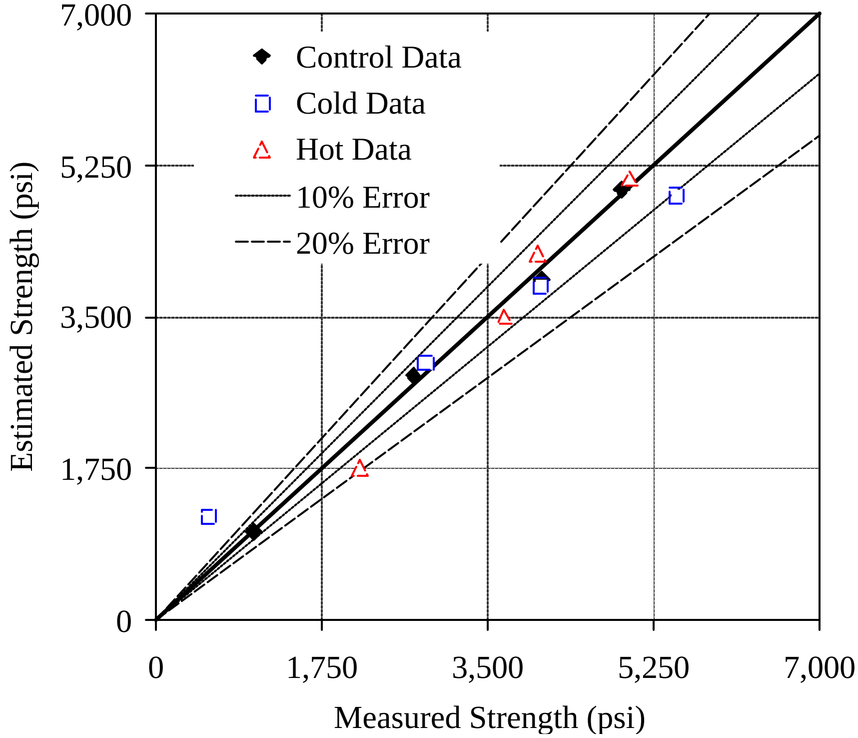


Figure 6.24: Error plot for the Type I - 0.41 mixture, Modified ASTM method, NSM

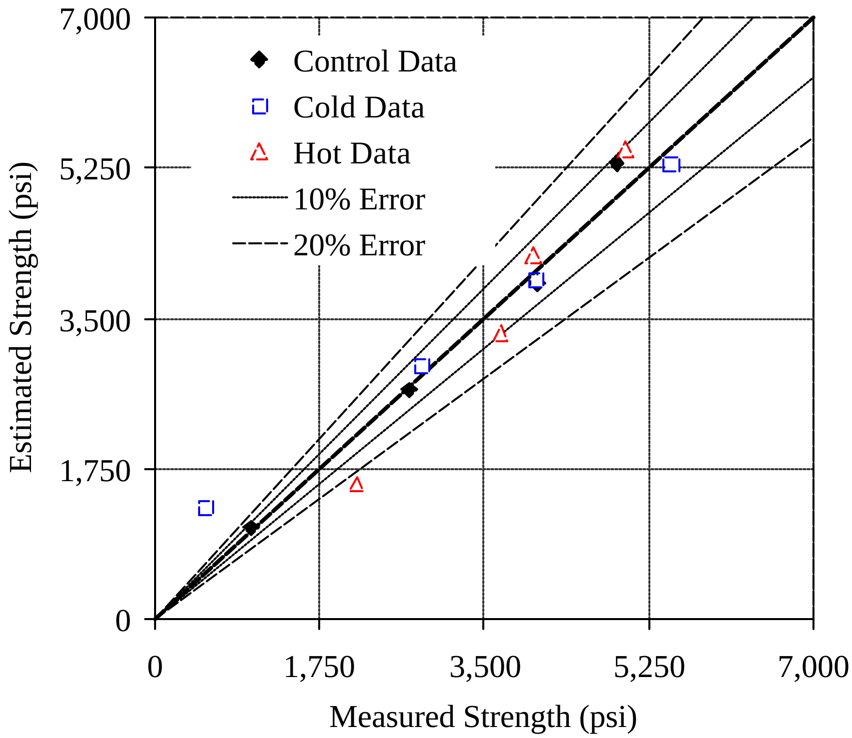


Figure 6.25: Error plot for the Type I - 0.41 mixture, ASTM C 1074 method, NSM

Table 6.17: Error using NSM function based on Modified ASTM method for Type III - 0. 37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	4,280	4,410	130	3	280	4	4,270	-10	0	20	0
	1.0	6,530	6,290	-240	-4			6,560	30	0		
	2.1	7,970	7,850	-120	-2			7,930	-40	-1		
	7.1	9,110	9,730	620	7			9,120	10	0		
Cold	0.9	2,400	3,330	930	39	310	11	3,100	700	29	560	13
	2.0	5,670	5,870	200	4			6,500	830	15		
	3.5	6,900	6,880	-20	0			7,500	600	9		
	12.6	9,060	9,130	70	1			8,950	-110	-1		
Hot	0.3	2,860	3,650	790	28	1260	21	2,720	-140	-5	890	13
	0.8	6,400	7,200	800	13			7,300	900	14		
	1.4	6,960	8,390	1,430	21			8,230	1,270	18		
	5.0	8,030	10,040	2,010	25			9,260	1,230	15		

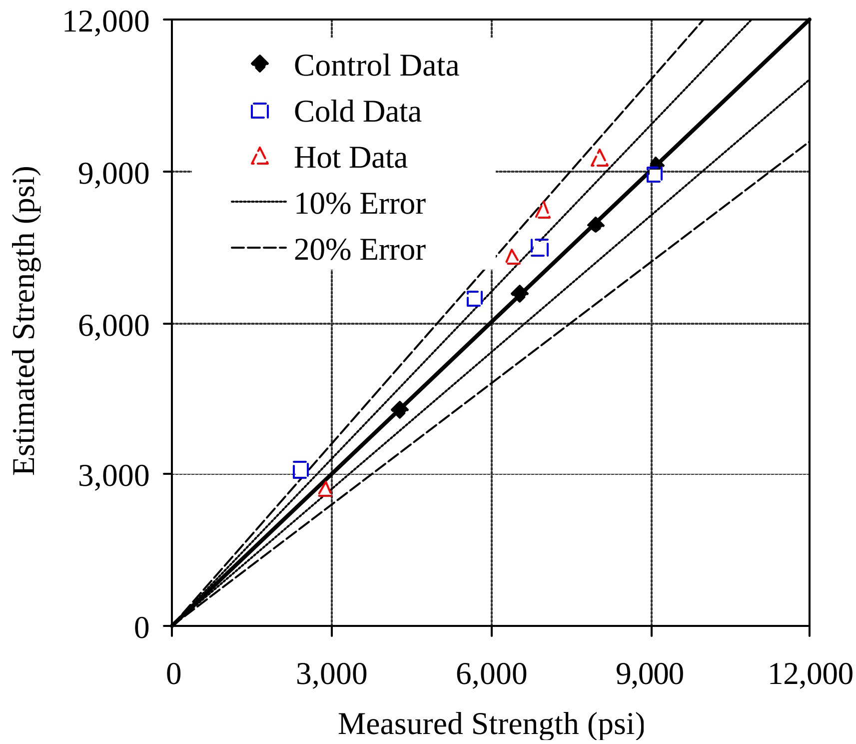


Figure 6.26: Error plot for the Type III - 0.37 mixture, Modified ASTM method, NSM

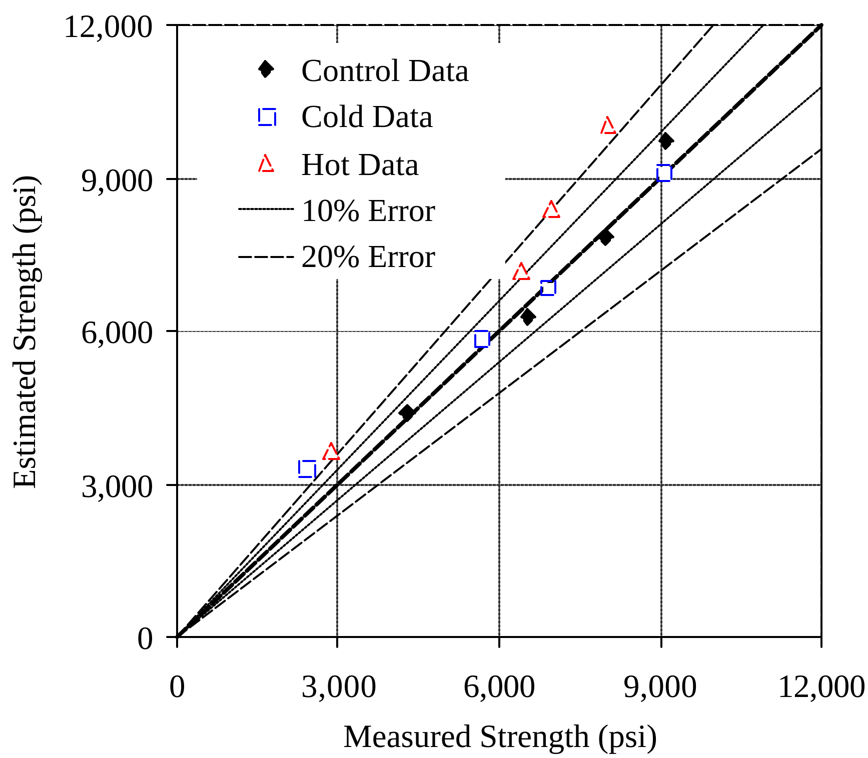


Figure 6.27: Error plot for the Type III - 0.37 mixture, ASTM C 1074 method, NSM

Table 6.18: Error using AM function based on Modified ASTM method for 20% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,510	1,540	30	2	150	5	1,570	60	4	95	4
	1.0	2,660	2,360	-300	-11			2,500	-160	-6		
	2.0	3,380	3,420	40	1			3,510	130	4		
	7.0	5,120	5,360	240	5			5,090	-30	-1		
Cold	0.9	720	1,560	840	117	350	33	1,390	670	93	290	26
	1.8	2,510	2,630	120	5			2,490	-20	-1		
	3.4	3,340	3,670	330	10			3,450	110	3		
	12.2	5,460	5,580	120	2			5,100	-360	-7		
Hot	0.4	1,990	1,840	-150	-8	280	8	2,320	330	17	225	8
	0.8	3,280	2,920	-360	-11			3,510	230	7		
	1.4	4,110	3,820	-290	-7			4,270	160	4		
	4.9	5,400	5,700	300	6			5,580	180	3		

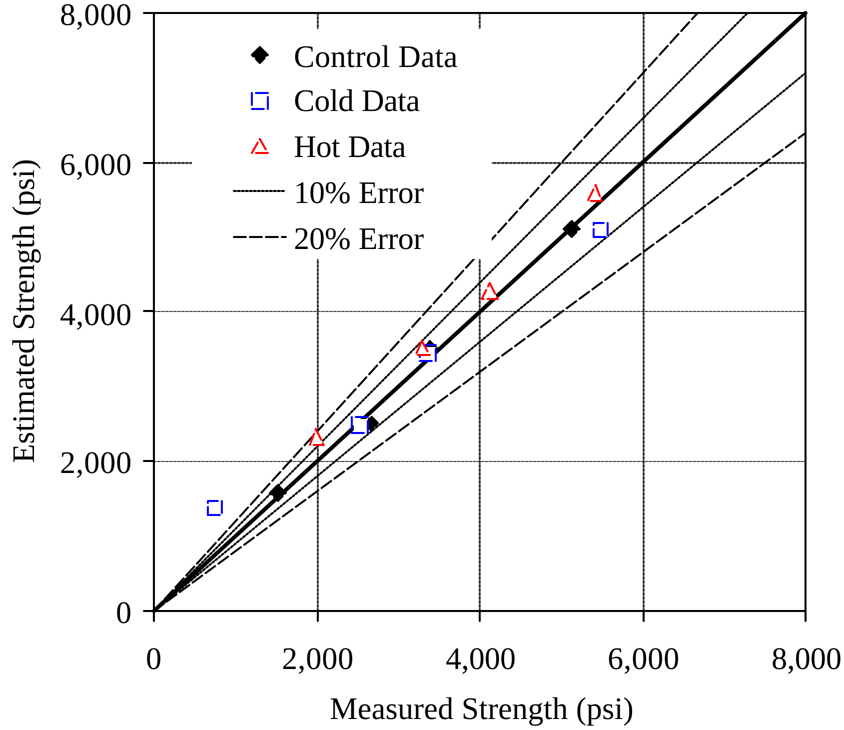


Figure 6.28: Error plot for the 20% F mixture, Modified ASTM method, AM

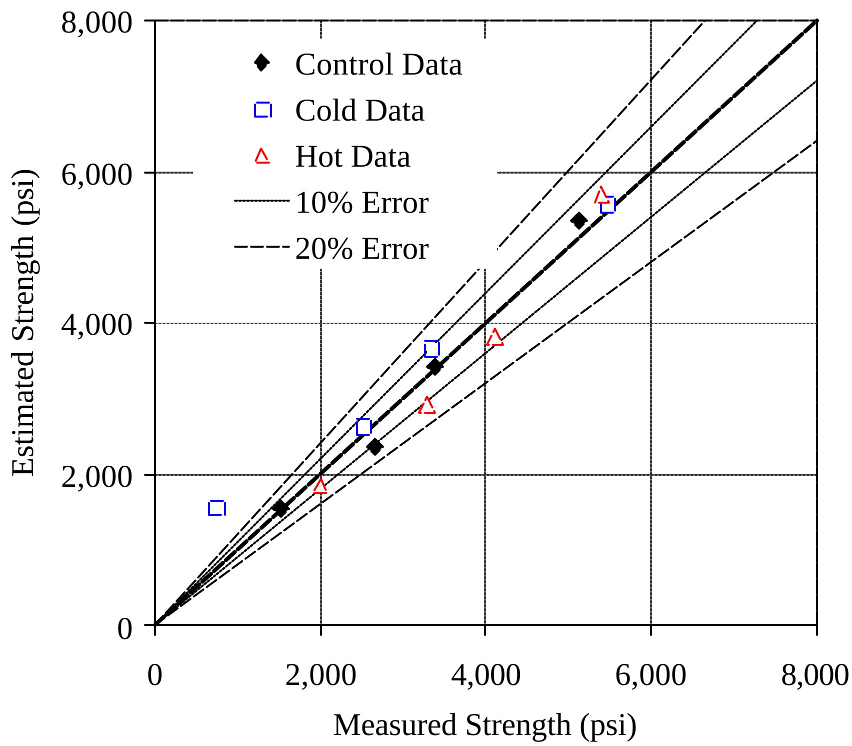


Figure 6.29: Error plot for the 20% F mixture, ASTM C 1074 method, AM

Table 6.19: Error using AM function based on Modified ASTM method for Type I - 0.41 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,030	1,060	30	3	150	4	1,000	-30	-3	90	3
	1.0	2,700	2,670	-30	-1			2,820	120	4		
	2.1	4,060	3,910	-150	-4			3,910	-150	-4		
	7.1	4,900	5,300	400	8			4,960	60	1		
Cold	0.8	540	1,360	820	152	290	40	1,260	720	133	370	38
	1.8	2,830	3,030	200	7			3,040	210	7		
	3.4	4,040	4,070	30	1			3,970	-70	-2		
	12.1	5,480	5,390	-90	-2			4,990	-490	-9		
Hot	0.4	2,140	1,950	-190	-9	300	8	2,320	180	8	260	7
	0.8	3,670	3,660	-10	0			3,880	210	6		
	1.4	4,010	4,460	450	11			4,460	450	11		
	5.0	4,990	5,550	560	11			5,170	180	4		

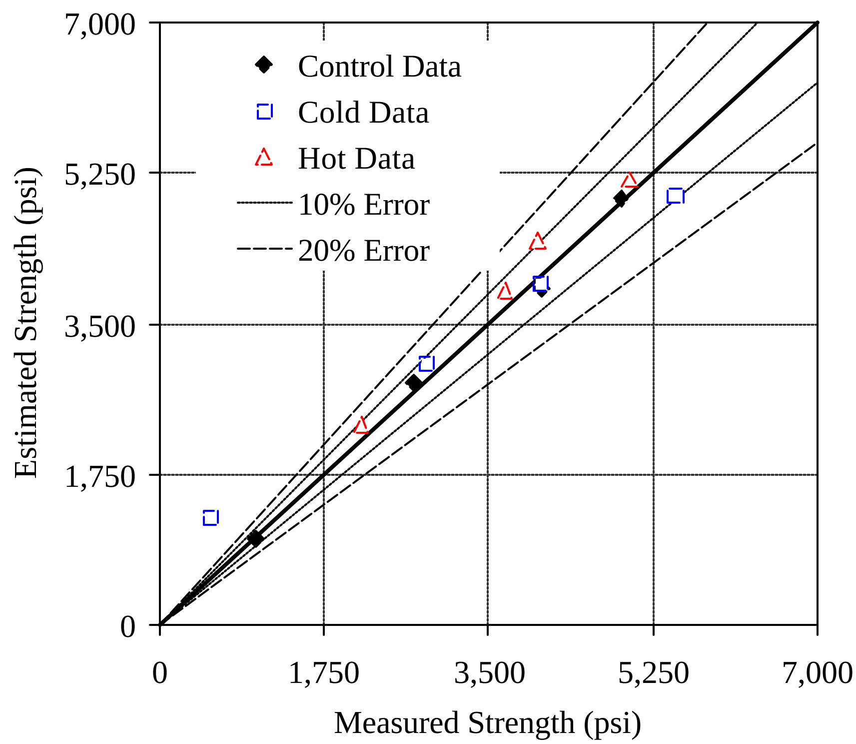


Figure 6.30: Error plot for the Type I - 0.41 mixture, Modified ASTM method, AM

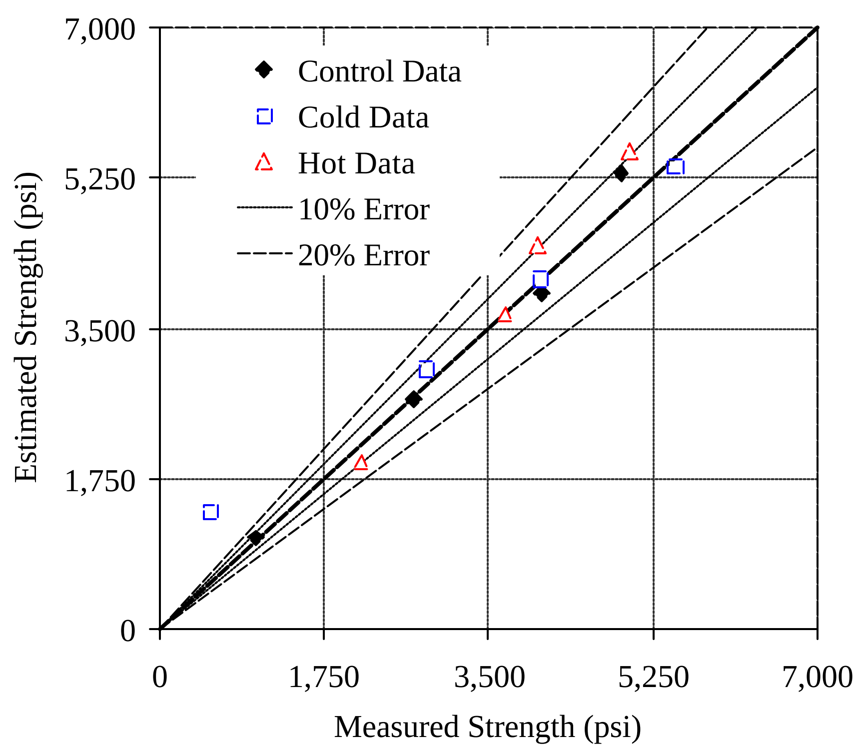


Figure 6.31: Error plot for the Type I - 0.41 mixture, ASTM C 1074 method, AM

Table 6.20: Error using AM function based on Modified ASTM method for Type III - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**ASTM C 1074**					**Modified ASTM**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	4,280	4,400	120	3	270	4	4,270	-10	0	40	1
	1.0	6,530	6,310	-220	-3			6,580	50	1		
	2.1	7,970	7,830	-140	-2			7,900	-70	-1		
	7.1	9,110	9,720	610	7			9,130	20	0		
Cold	0.9	2,400	3,590	1,190	50	680	18	2,870	470	20	460	10
	2.0	5,670	6,120	450	8			6,360	690	12		
	3.5	6,900	7,420	520	8			7,560	660	10		
	12.6	9,060	9,600	540	6			9,050	-10	0		
Hot	0.3	2,860	4,670	1,810	63	1880	36	4,720	1,860	65	1640	33
	0.8	6,400	7,960	1,560	24			8,020	1,620	25		
	1.4	6,960	8,920	1,960	28			8,670	1,710	25		
	5.0	8,030	10,230	2,200	27			9,410	1,380	17		

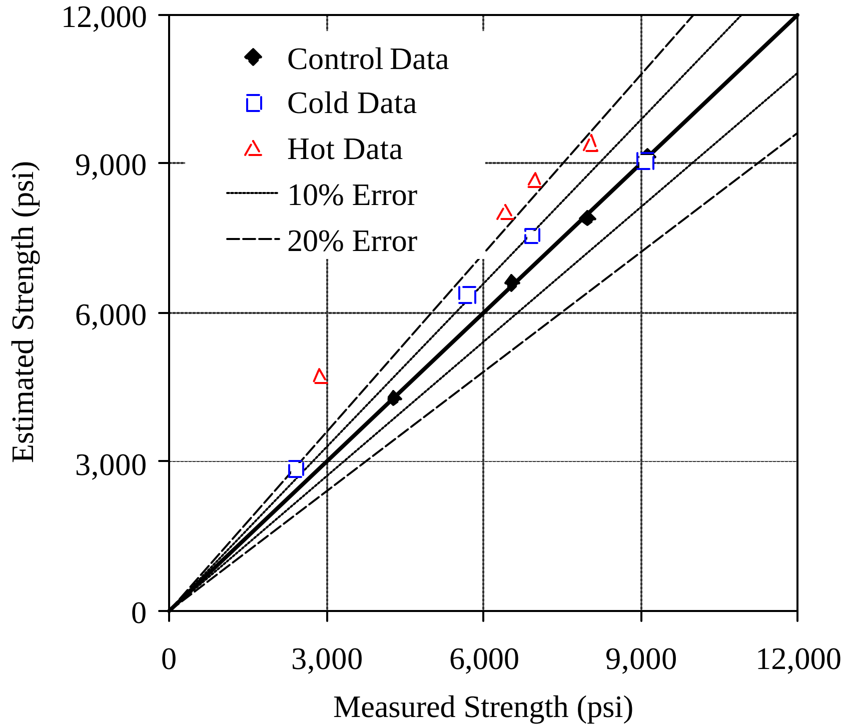


Figure 6.32: Error plot for the Type III - 0.37 mixture, Modified ASTM method, AM

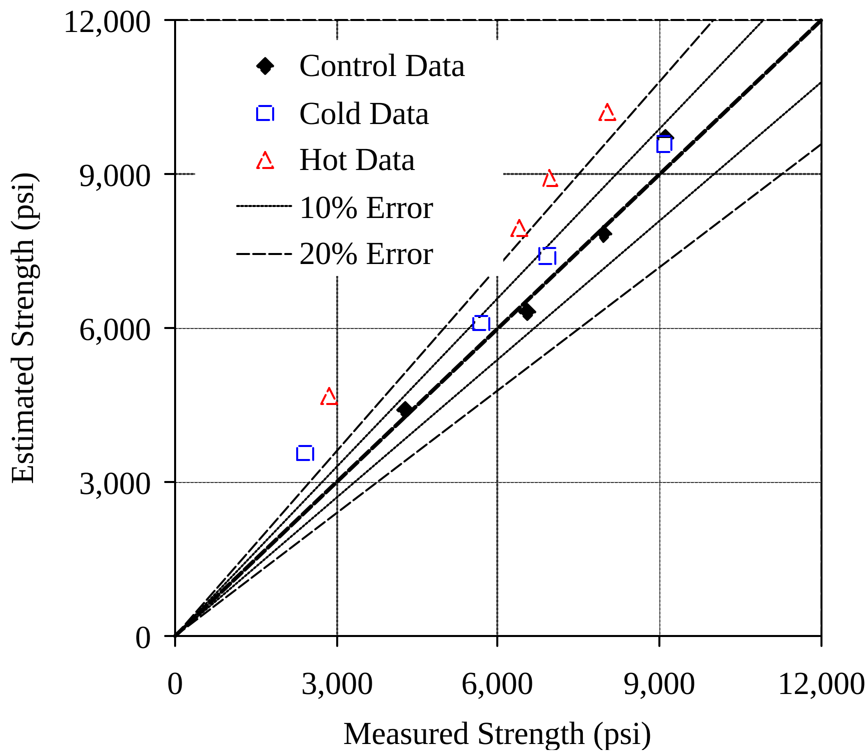


Figure 6.33: Error plot for the Type III - 0.37 mixture, ASTM C 1074 method, AM

Accuracy of the Nurse-Saul Maturity Function

1. 20% F Mixture

From Table 6.15, it can be seen that the Modified ASTM method did help reduce the hot batch's error from an abs. EoE of 11% to 3%. The first test strength for the cold batch was still highly overestimated and the Modified ASTM method made the other three strength estimates for the cold batch worse than the normal ASTM C 1074 method.

2. Type I - 0.41 Mixture

The error for the Type I - 0.41 mixture using the NSM function and the Modified ASTM method can be seen in Table 6.16. Again, the Modified ASTM method reduced the average percent error for the hot batch, down from 13% using the ASTM C 1074 method to 8% using the Modified ASTM method. The strength estimation for the 0.4 day strength was still overestimated by 19%, but the remaining strengths were estimated within ±5% of the actual test values. The Modified method decreased the average percent error for the cold batch from 38% to 36%, but increased the error for the 12-day strength estimation from -3% to -10%.

3. Type III - 0.37 Miixture

The strength estimation errors using the NSM function and the Modified ASTM method can be seen in Table 6.17. As before, the Modified ASTM method reduced the average percent error of estimate, from 21% to 13%, for the hot batch. However, it slightly increased the error of estimate from 11% to 13% for the cold batch. The Modified method lowered all of the strength estimations for the hot batch to 18% error or less.

Accuracy of the Arrhenius Maturity Function

1. 20% F Mixture

The strength estimation errors for the 20% F mixture using the Arrhenius maturity function and the mixture-specific activation energy found from the Modified ASTM method can be seen in Table 6.18. This method reduced the percent error of estimate for all three batches. Aside from high errors for the first strength estimation for the hot and cold batches, the remaining estimations were all within ±7% of the actual test value.

2. Type I - 0.41 Mixture

The strength estimation errors using the AM function with the mixture-specific activation energy found from the Modified ASTM method are shown in Table 6.19. There was a slight decrease in abs. EoE for estimating the hot batch's strengths. The Modified ASTM method slightly decreased the average percent error for the cold batch from 40% to 38%. Again, the earliest test age is the bulk of the error or estimations for the cold batch.

3. Type III - 0.37 Mixture

The strength estimation errors for the Type III - 0.37 mixture using the AM function and the mixture-specific activation energy found from the Modified ASTM method are shown in Table 6.20. The Modified method reduced the average percent errors for all three batches. The earliest strength estimation for the cold batch was about 40% more accurate using the Modified ASTM method versus the ASTM C 1074 method; however, both methods provide reasonable results for the cold curing condition thereafter. The average percent error for the hot batch was reduced slightly from 36% to

33% by using the Modified ASTM method, but still none of the estimations were within ±10% of the actual values.

Comparison of Functions for All Mixtures

Table 6.21 shows the total average absolute percent errors and average absolute errors for all mixtures using the NSM and AM functions with the mixture-specific temperature sensitivity values found using the Modified ASTM method. From the table it can be seen that the Nurse-Saul maturity function produced the lowest percent error of estimations for 7 out of the 13 mixtures considered. However, 7 out the 13 mixtures have only 2% or less difference in total error between the two functions. When using the NSM function, the Modified ASTM method produced less total error than the ASTM C 1074 method for all mixtures except the 20% C, Type III - 0.44, and ternary-blend mixtures. When using the AM function, the Modified ASTM method produced less error than the ASTM C 1074 method for all mixtures except the 20% C and ternary-blend mixtures.

Because of the increased accuracy of the estimated strengths that resulted from using the maturity method only up to 7 days equivalent age, the remaining analysis reported in this chapter only considered the accuracy of the maturity method based on data up to 7 days equivalent age.

Table 6.21: Comparison of maturity methods for all mixtures, Modified ASTM method

Mixture ID	**NSM**		**AM**		**Function that Produced Lowest Error**	**Error lower than ASTM C 1074?**	
	Total AAE (psi)	Total abs. EoE (%)	Total AAE (psi)	Total abs. EoE (%)		NSM	AM
Type I - 0.41	230	16	240	16	NSM	☑	☑
Type I - 0.44	230	19	170	17	AM	☑	☑
Type I - 0.48	210	14	200	13	AM	☑	☑
20% F	220	11	200	12	NSM	☑	☑
30% F	250	10	210	12	NSM	☑	☑
20% C	640	24	450	16	AM	⊠	⊠
30% C	150	7	210	13	NSM	☑	☑
30% Slag	250	10	390	18	NSM	☑	☑
50% Slag	160	14	250	17	NSM	☑	☑
Type III - 0.37	490	9	710	15	NSM	☑	☑
Type III - 0.44	310	15	275	11	AM	⊠	☑
70/20/10 - 0.37	540	23	530	22	AM	⊠	⊠
70/20/10 - 0.44	320	35	310	34	AM	⊠	⊠

⊠ = NO, ☑ = YES

6.3 SIMPLIFIED MATURITY APPROACH

After some methods of finding mixture-specific temperature sensitivity values were evaluated, researchers investigated the difference in using constant, commonly used values for all mixtures, relative to using mixture-specific values for each mixture. This would obviously be a more practical approach to using the maturity method for actual construction projects. As mentioned previously, the remainder of this chapter reports only evaluations using data up to 7 days of equivalent age.

To choose the constant temperature sensitivity values, an age conversion factor versus temperature plot was constructed, as explained in Section 2.4.1. The procedure to find age conversion factors for a particular mixture was also explained in Section 2.4.1. In summary, to get the age conversion factor (ACF) for each mixture, the rate constant (*k*-value) at each temperature is divided by the rate constant at the reference temperature, taken as 73°F (23°C) in this study. This can be performed easily with the linear trendline that was used earlier in order to find the best-fit datum temperatures or activation energies for each mixture. An illustration of this process for the Type I - 0.41 mixture is provided in Figure 6.34. The value of the rate constant at the reference temperature is shown to be 0.083 hr^{-1}. The ACFs for the hot, control, and cold batches were found by dividing their respective rate constants by 0.083 hr^{-1}.

As was explained in Section 2.4.1, to find the rate constant at the reference temperature, Carino (1991) compared the linear trendline used to find the mixture-specific datum temperatures to the trendline used to find the mixture-specific activation energies. The line that fit the data best was the line he used to determine the *k*-value at the reference temperature. Carino used the R^2 values of the two trendlines to determine which equation to use. This procedure was also used in this study. The R^2 values for the trendlines of all mixtures are reported in Table 6.22. Also the corresponding rate constant at the reference temperature, obtained from the equation with the highest R^2, for each mixture is given.

The age conversion factors were computed for all mixtures, and the ACF versus temperature plot for all mixtures is shown in Figure 6.35. The ACFs for the NSM function, defined by Equation 2.7, using T_o = 14°F (-10°C) and 32°F (0°C) are the two straight lines shown on the plot. The ACFs for the AM function, also defined in Equation 2.7, using E = 40,000 J/mol and 25,000 J/mol are the two non-linear relationships shown. This type of plot is the same as those shown in Figures 2.16, 2.19, and 2.20.

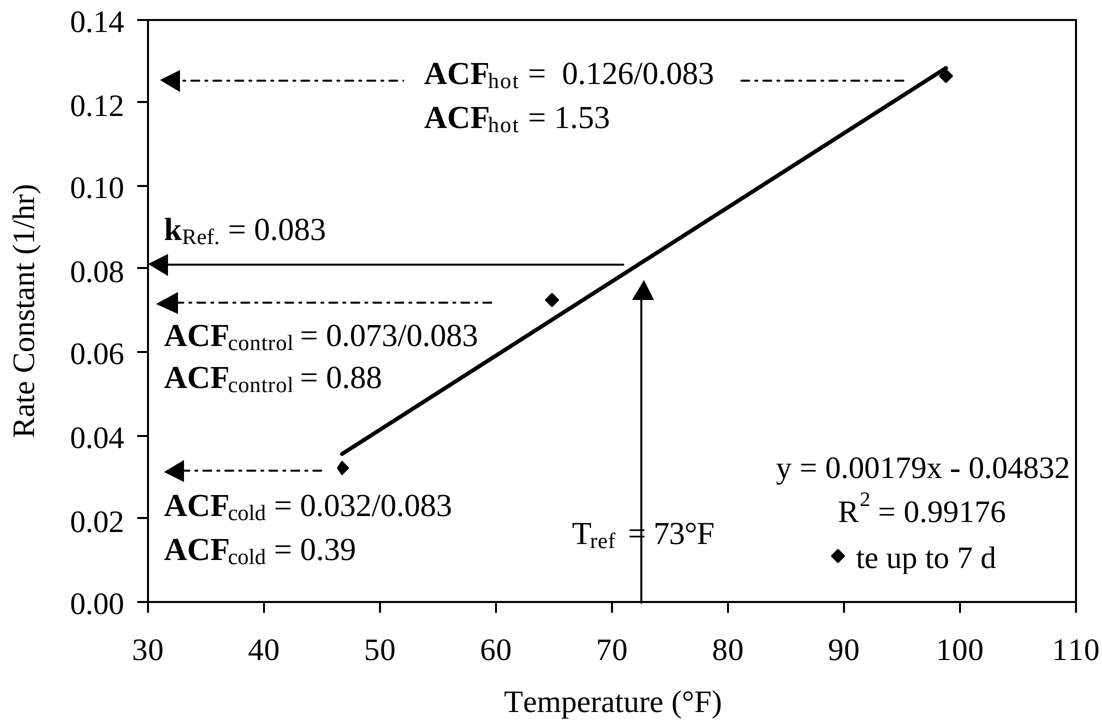


Figure 6.34: Obtaining age conversion factors for Type I - 0.41 mixture

When examining an age conversion factor versus temperature plot, the further an age conversion factor, for a certain mixture, deviates from an age conversion factor of 1.0, the greater the temperature sensitivity requirements are for that mixture. Therefore, mixtures with behavior similar to the ternary-blends, with age conversion factors of approximately 1.25 and 0.6, for the hot and cold batches, respectively, would have low temperature sensitivity requirements. The maturity function that best models a concrete's temperature sensitivity behavior at different temperatures, theoretically, will be the function that produces the least amount of strength estimation errors. From Figure 6.35

several other temperature sensitivity trends may be seen. Several of the mixtures, such as the Type III mixtures and the Type I - 0.41 mixture, require a high temperature sensitivity at low curing temperatures and a lower temperature sensitivity at high curing temperatures. The behavior provided by a linear ACF function, like the Nurse-Saul maturity function, would be ideal for these mixtures. Other mixtures, like the 30% Slag, 20% F, 20% C, and 30% C, require high temperature sensitivity values at high and low curing temperatures. The behavior provided by a non-linear ACF function, like the Arrhenius maturity function, would be better suited for these mixtures.

Table 6.22: R^2 values and rate constants at the reference temperature for all mixtures

Mixture ID	R^2 **from trendline of:**		k at 73°F (1/hr)
	k versus T(°F) plot	Ln(k) versus T(K) plot	
Type I - 0.41	0.992	0.936	0.083
Type I - 0.44	0.987	0.954	0.038
Type I - 0.48	0.988	0.998	0.028
20% F	0.964	0.998	0.036
30% F	0.998	0.980	0.035
20% C	0.991	0.977	0.043
30% C	0.993	0.996	0.027
30% Slag	0.861	0.925	0.032
50% Slag	0.995	0.960	0.014
Type III - 0.37	0.972	0.888	0.129
Type III - 0.44	0.937	0.868	0.059
70/20/10 - 0.37	0.829	0.806	0.029
70/20/10 - 0.44	0.997	0.987	0.019

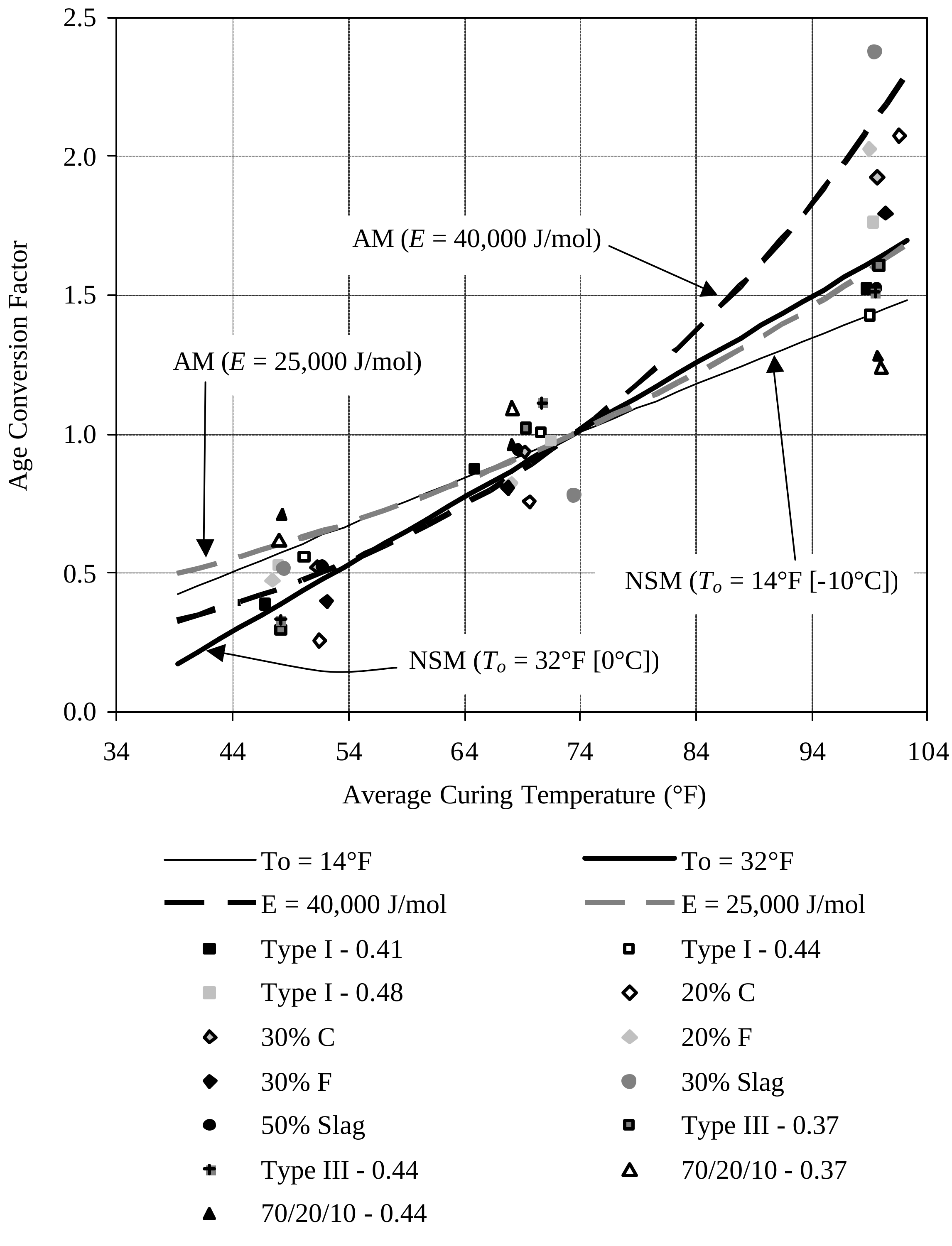


Figure 6.35: Age conversion factors for all mixtures

Constant temperature sensitivity values were chosen after visual inspection of the results in Figure 6.35. A datum temperature of 32°F (0°C) appears to accurately model the temperature sensitivity of mixtures with behavior like the Type I - 0.41 and Type III mixtures; however, 14°F (-10°C) was also analyzed as it is another commonly used value (as discussed in Section 2.2.4). An activation energy of 25,000 J/mol models the average of the hot batch's data well, while an activation energy of 40,000 J/mol models specific mixtures like the 30% Slag better. Both maturity functions were analyzed using the appropriate two constant temperature sensitivity values mentioned above. Accuracy was compared to the Modified ASTM method to determine if there is any loss/gain in accuracy and, if so, to what degree.

6.3.1 Nurse-Saul Maturity Function

First, the compressive strength data was analyzed using the Nurse-Saul maturity (NSM) function. The results for the three example mixtures are summarized in Tables 6.23 through 6.25. Figures 6.36 to 6.41 also show the 45°-line error plots associated with the NSM function using the constant datum temperatures. The remaining error tables and accompanying 45°-line error plots can be found in Appendix H. For the three example mixtures, the NSM function using 32°F (0°C) as the datum temperature produces less error than using 14°F (-10°C) as the datum temperature. The total absolute errors and percent errors for all thirteen mixtures can be found in Table 6.26. For all thirteen mixtures, the NSM function using 32°F (0°C) as the datum temperature produced lower total AAE than using 14°F (-10°C) as the datum temperature. For 11 out of the 13 mixtures the NSM function use of 32°F (0°C) as the datum temperature produced lower average percent errors for both the hot and cold batches. The two mixtures for which this did not occur were the ternary-blend mixtures. Recall that the mixture-specific datum temperatures for the ternary-blend mixtures using the Modified ASTM method averaged -16°F (-26°C). For these mixtures using 14°F (-10°C) as the datum temperature produced less error for the hot batch's strength estimations, while the 32°F (0°C) datum temperature produced lower errors for the cold batch's strength estimations. This suggests that the ternary-blend mixtures have a very low temperature sensitivity for the hot batch and a higher temperature sensitivity for the cold batch.

These results suggest that some mixtures may have different temperature sensitivity values for the hot- and cold-cured batches and that a constant mixture-specific temperature sensitivity value may not always be appropriate for all curing temperatures. Table 6.26 also shows that using a datum temperature of 32°F (0°C) produced less total average error than using mixture-specific datum temperatures found from the Modified ASTM method for 8 out of the 13 mixtures evaluated. For 6 out of the 13 mixtures, using 32°F (0°C) as the datum temperature produced total average absolute errors only 2% different than those produced using mixture-specific datum temperatures found from the Modified ASTM method. From these results it seems that the 32°F (0°C) datum temperature may not be the ideal value for all curing temperatures of all mixtures; however, the average error resulting from using this value as opposed to mixture-specific values is approximately the same if not less.

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Table 6.23: Error using NSM function based on simplified method for 20% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**T_o = 14°F (-10°C)**					**T_o = 32°F (0°C)**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,510	1,660	150	10	110	5	1,580	70	5	100	4
	1.0	2,660	2,460	-200	-8			2,490	-170	-6		
	2.0	3,380	3,460	80	2			3,510	130	4		
	7.0	5,120	5,110	-10	0			5,090	-30	-1		
Cold	0.9	720	1,680	960	133	430	39	1,350	630	88	350	26
	1.8	2,510	2,730	220	9			2,410	-100	-4		
	3.4	3,340	3,650	310	9			3,270	-70	-2		
	12.2	5,460	5,240	-220	-4			4,870	-590	-11		
Hot	0.4	1,990	1,750	-240	-12	380	11	1,900	-90	-5	160	5
	0.8	3,280	2,720	-560	-17			3,010	-270	-8		
	1.4	4,110	3,560	-550	-13			3,860	-250	-6		
	4.9	5,400	5,240	-160	-3			5,380	-20	0		

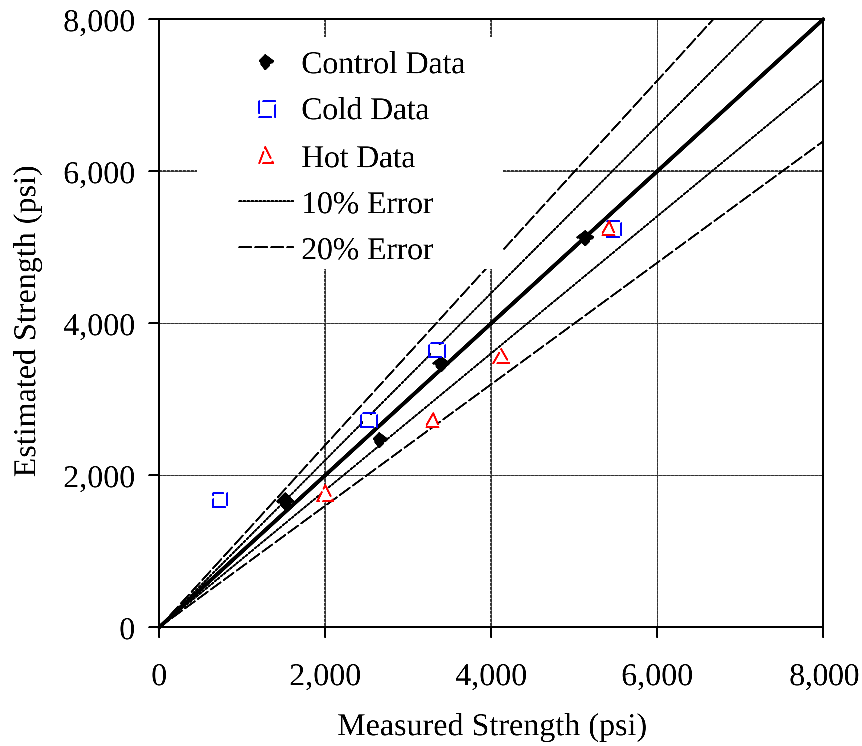

Figure 6.36: Error plot for the 20% F mixture, simplified method, T_o = 14°F

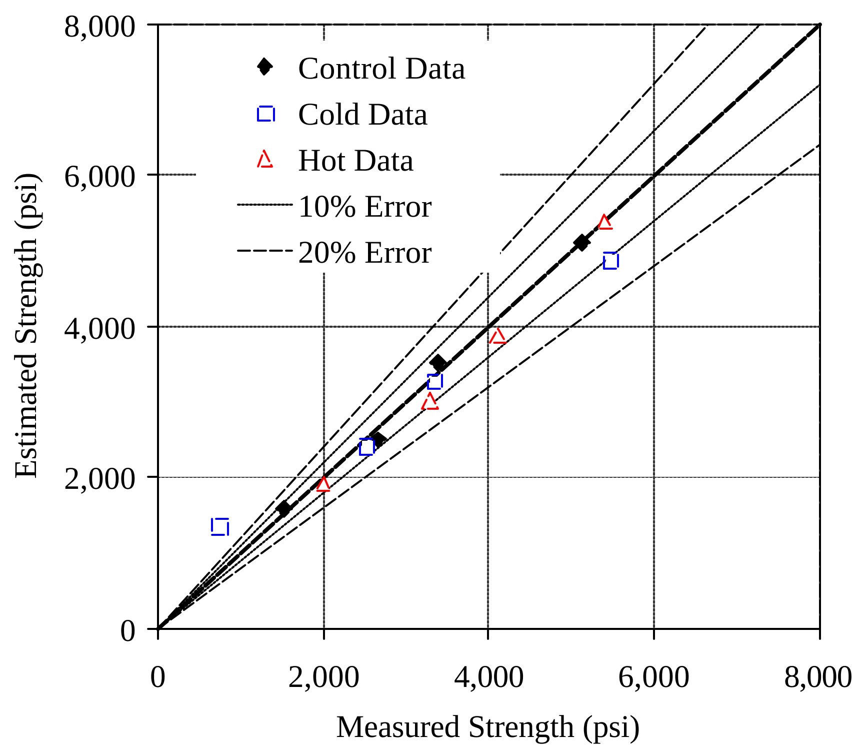

Figure 6.37: Error plot for the 20% F mixture, simplified method, T_o = 32°F

Table 6.24: Error using NSM function based on simplified method for Type I - 0.41 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,030	1,000	-30	-3	80	3	1,000	-30	-3	90	3
	1.0	2,700	2,800	100	4			2,820	120	4		
	2.1	4,060	3,930	-130	-3			3,910	-150	-4		
	7.1	4,900	4,950	50	1			4,960	60	1		
Cold	0.8	540	1,470	930	172	460	49	1,050	510	94	380	29
	1.8	2,830	3,220	390	14			2,830	0	0		
	3.4	4,040	4,080	40	1			3,700	-340	-8		
	12.1	5,480	5,000	-480	-9			4,820	-660	-12		
Hot	0.4	2,140	1,450	-690	-32	300	11	1,880	-260	-12	190	6
	0.8	3,670	3,310	-360	-10			3,580	-90	-2		
	1.4	4,010	4,100	90	2			4,290	280	7		
	5.0	4,990	5,030	40	1			5,120	130	3		

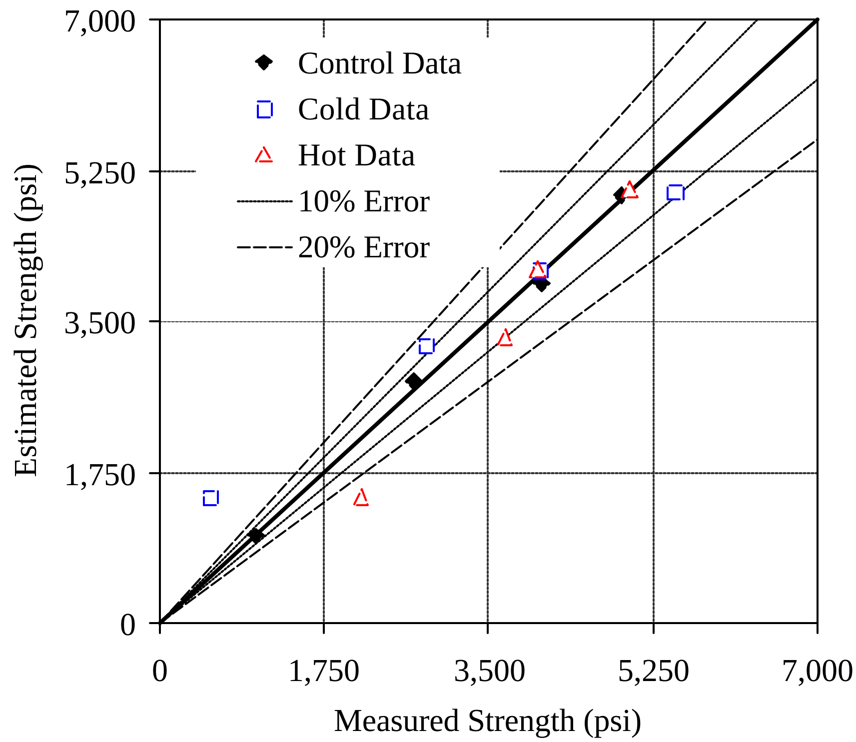

Figure 6.38: Error plot for the Type I - 0.41 mixture, simplified method, T_o = 14°F

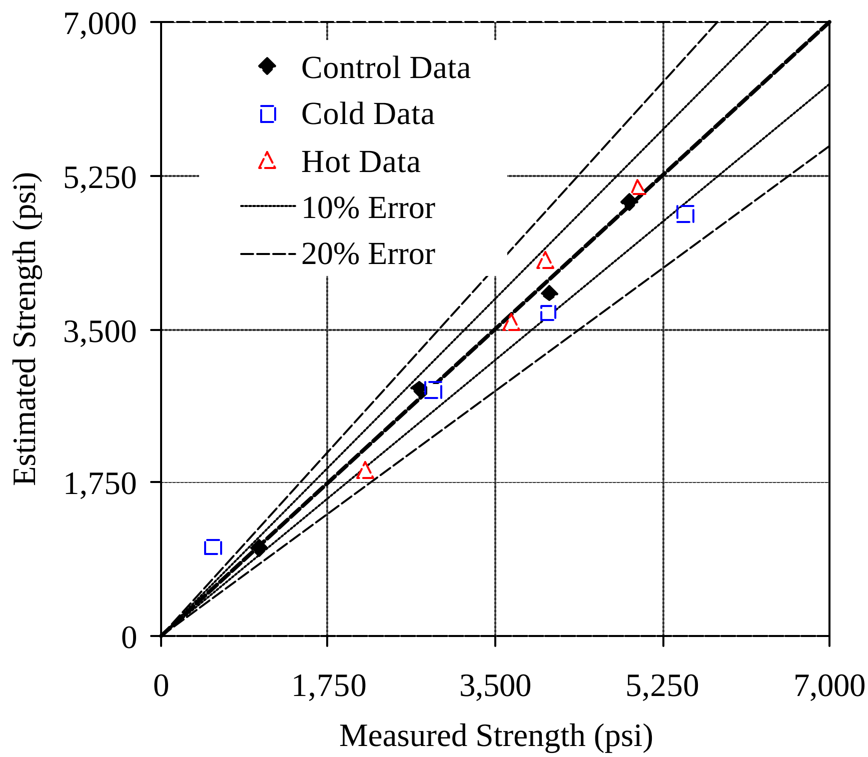

Figure 6.39: Error plot for the Type I - 0.41 mixture, simplified method, T_o = 32°F

Table 6.25: Error using NSM function based on simplified method for Type III - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**T_o = 14°F (-10°C)**					**T_o = 32°F (0°C)**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	4,280	4,280	0	0	10	0	4,270	-10	0	20	0
	1.0	6,530	6,540	10	0			6,560	30	0		
	2.1	7,970	7,960	-10	0			7,930	-40	-1		
	7.1	9,110	9,110	0	0			9,120	10	0		
Cold	0.9	2,400	4,510	2,110	88	1230	33	3,280	880	37	640	16
	2.0	5,670	7,190	1,520	27			6,590	920	16		
	3.5	6,900	8,100	1,200	17			7,580	680	10		
	12.6	9,060	9,160	100	1			8,980	-80	-1		
Hot	0.3	2,860	1,710	-1,150	-40	980	20	2,630	-230	-8	890	14
	0.8	6,400	6,960	560	9			7,260	860	13		
	1.4	6,960	8,020	1,060	15			8,210	1,250	18		
	5.0	8,030	9,160	1,130	14			9,250	1,220	15		

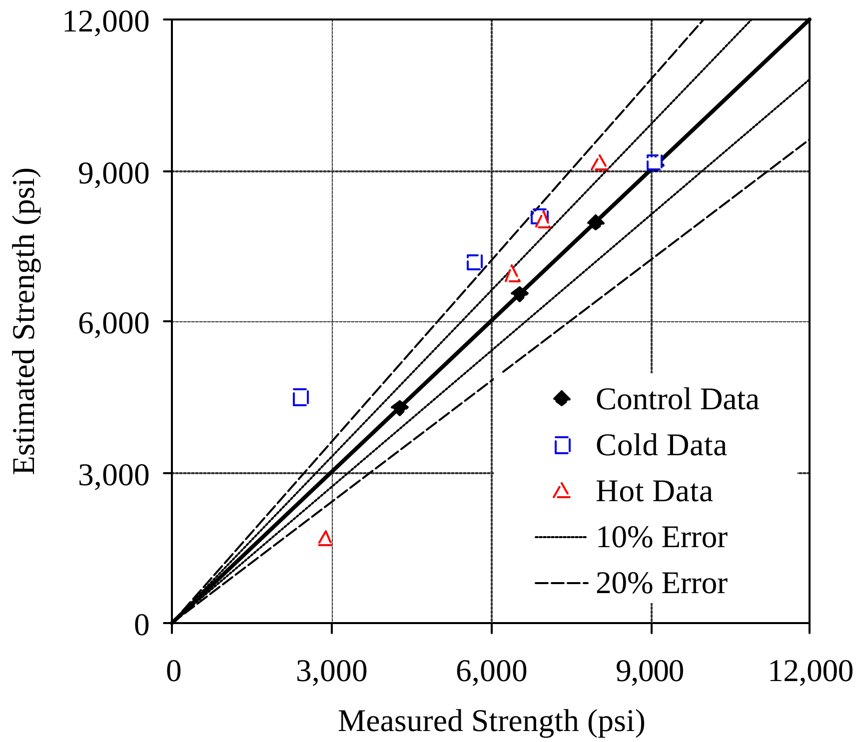

Figure 6.40: Error plot for the Type III - 0.37 mixture, simplified method, T_o = 14°F

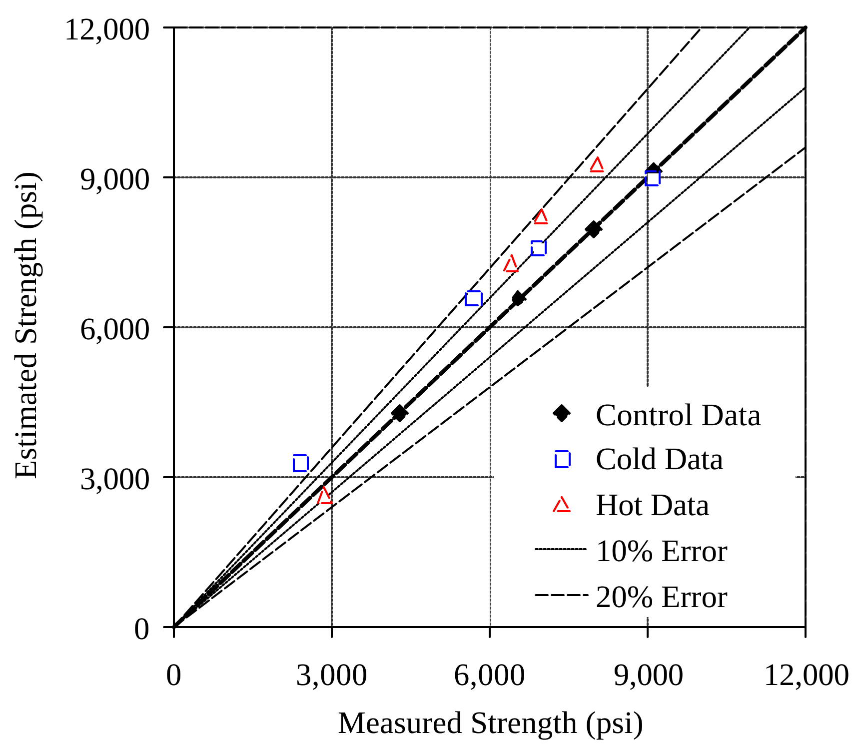

Figure 6.41: Error plot for the Type III - 0.37 mixture, simplified method, T_o = 32°F

Table 6.26: Comparison of NSM functions for all mixtures, simplified method

Mixture ID	T_o = 14°F (-10°C)		T_o = 32°F (0°C)		Modified ASTM		Function that Produced Lowest Error
	Total AAE (psi)	Total abs. EoE (%)	Total AAE (psi)	Total abs. EoE (%)	Total AAE (psi)	Total abs. EoE (%)	
Type I - 0.41	280	21	220	13	230	16	T_o = 32°F
Type I - 0.44	240	20	200	12	230	19	T_o = 32°F
Type I - 0.48	230	20	260	12	210	14	T_o = 32°F
20% F	310	18	200	12	220	11	Modified
30% F	290	16	220	10	250	10	Modified
20% C	330	16	210	8	640	24	T_o = 32°F
30% C	440	26	190	9	150	7	Modified
30% Slag	400	23	250	14	250	10	Modified
50% Slag	300	23	70	6	160	14	T_o = 32°F
Type III - 0.37	740	18	520	10	490	9	Modified
Type III - 0.44	400	23	300	14	310	15	T_o = 32°F
70/20/10 - 0.37	450	18	310	11	540	23	T_o = 32°F
70/20/10 - 0.44	230	26	200	17	320	35	T_o = 32°F

6.3.2 Arrhenius Maturity Function

Next, the mixtures will be analyzed with activation energies of 25,000 J/mol and 40,000 J/mol using the Arrhenius maturity function. The errors using these activation energies are shown in Tables 6.27 through 6.29. The 45°-line error plots are also shown in Figures 6.42 to 6.47. The remaining error plots and accompanying 45°-line error plots can be found in Appendix I. For the 20% F mixture, the higher activation energy produced lower errors for the cold batch and the lower activation energy produced lower errors for the hot batch. However, from Figure 6.35 one would think that the higher activation energy would produce the lower errors for the hot and cold batches. This suggests that the rate constants computed for the Modified ASTM method, for this mixture, does not accurately describe the actual temperature sensitivity requirements of this mixture. It may be seen in Table 6.12 that the k-value is not the only parameter affected by curing temperature. Both the S_u and t_o values are affected by the curing temperature, yet the procedure to determine the mixture-specific temperature sensitivity values only accounts for changes in the rate constant, k. This fundamental flaw could be to blame for such obscure trends, like that seen from the 20% F mixture.

For the Type I - 0.41 and Type III - 0.37 mixtures, the higher activation energy also produced lower errors for the cold batches, while the lower activation energy produced lower errors for the hot batches. This, however, does agree with trends observed from the ACF versus temperature plot.

For the 10 remaining mixtures, eight had the same activation energy trend as the Type I - 0.41 and Type III - 0.37 mixtures. The higher activation energy produced lower errors for the lower curing temperature mixtures and the lower activation energy produced lower errors for the higher curing temperature mixtures.

The total average errors and percent errors for all mixtures are reported in Table 6.30. Nine out of the 13 mixtures considered had lower total average errors using 40,000 J/mol as an activation energy. This concurs with the recommendation for activation energy outlined in ASTM C 1074. However, from the error tables and the conclusions stated above, it is evident that the best Arrhenius function would use a lower activation energy value at high curing temperatures and a higher value at lower curing temperatures. This has been observed and applied in previous studies, as seen with the FHP model (see Section 2.4.2). This occurrence is the motivation for the last analysis presented in this chapter.

Table 6.27: Error using AM function based on simplified method for 20% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,510	1,570	60	4	90	3	1,580	70	5	110	4
	1.0	2,660	2,500	-160	-6			2,480	-180	-7		
	2.0	3,380	3,500	120	4			3,520	140	4		
	7.0	5,120	5,100	-20	0			5,090	-30	-1		
Cold	0.9	720	1,340	620	86	290	25	1,610	890	124	440	38
	1.8	2,510	2,420	-90	-4			2,780	270	11		
	3.4	3,340	3,370	30	1			3,750	410	12		
	12.2	5,460	5,050	-410	-8			5,260	-200	-4		
Hot	0.4	1,990	2,430	440	22	330	11	1,900	-90	-5	180	5
	0.8	3,280	3,630	350	11			3,010	-270	-8		
	1.4	4,110	4,370	260	6			3,840	-270	-7		
	4.9	5,400	5,650	250	5			5,320	-80	-1		

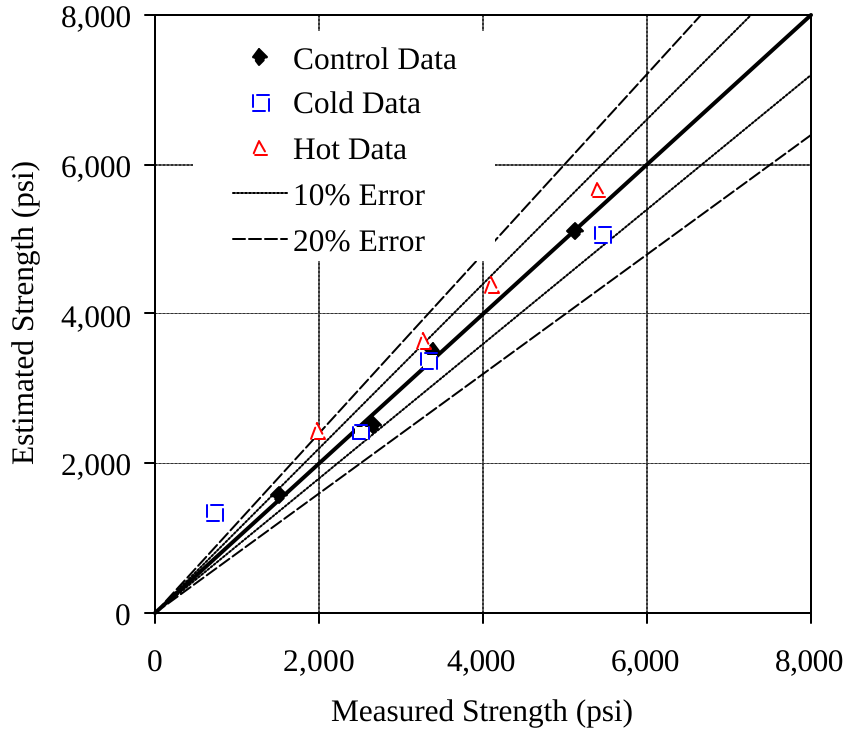

Figure 6.42: Error plot for the 20% F mixture, simplified method, *E*= 40 kJ/mol

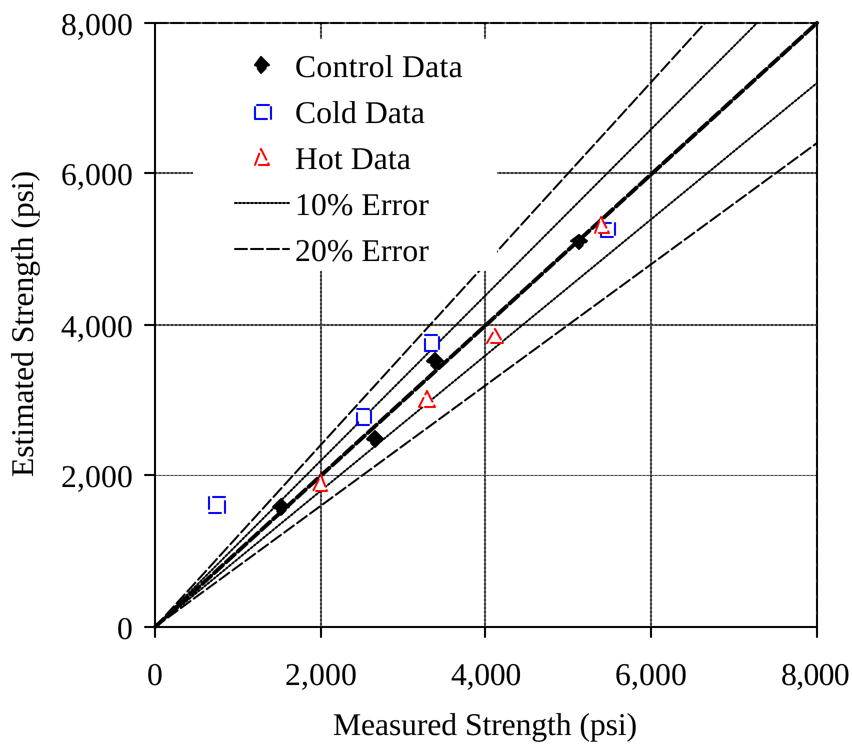

Figure 6.43: Error plot for the 20% F mixture, simplified method, *E* = 25 kJ/mol

Table 6.28: Error using AM function based on simplified method for Type I - 0.41 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,030	1,000	-30	-3	100	3	1,000	-30	-3	80	3
	1.0	2,700	2,830	130	5			2,810	110	4		
	2.1	4,060	3,900	-160	-4			3,920	-140	-3		
	7.1	4,900	4,960	60	1			4,950	50	1		
Cold	0.8	540	1,060	520	96	330	28	1,490	950	176	470	50
	1.8	2,830	2,860	30	1			3,240	410	14		
	3.4	4,040	3,820	-220	-5			4,120	80	2		
	12.1	5,480	4,940	-540	-10			5,030	-450	-8		
Hot	0.4	2,140	2,700	560	26	470	15	1,830	-310	-14	190	6
	0.8	3,670	4,120	450	12			3,570	-100	-3		
	1.4	4,010	4,620	610	15			4,260	250	6		
	5.0	4,990	5,240	250	5			5,080	90	2		

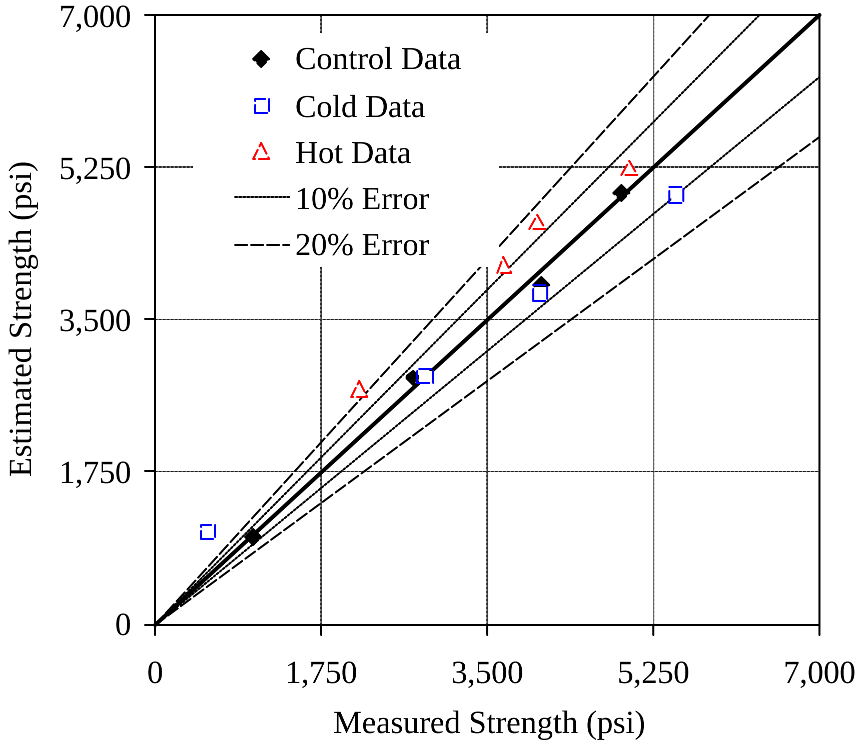

Figure 6.44: Error plot for the Type I - 0.41 mixture, simplified method, *E*= 40 kJ/mol

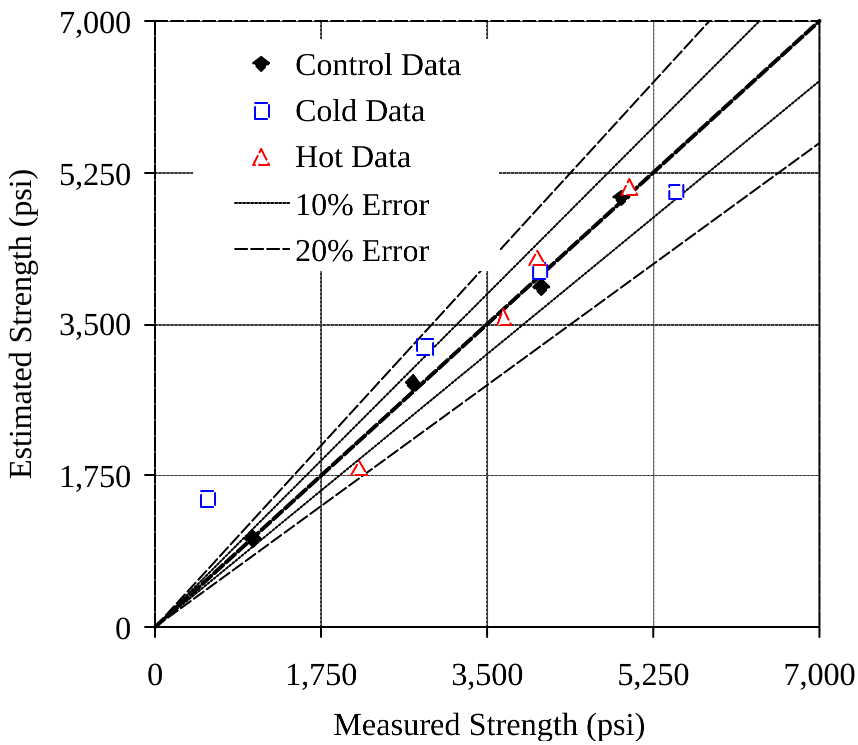

Figure 6.45: Error plot for the Type I - 0.41 mixture, simplified method, *E* = 25 kJ/mol

Table 6.29: Error using AM function based on simplified method for Type III - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**E = 40,000 J/mol** Estimated Strength (psi)	**E = 40,000 J/mol** Error (psi)	**E = 40,000 J/mol** EoE (%)	**E = 40,000 J/mol** AAE (psi)	**E = 40,000 J/mol** Abs. EoE (%)	**E = 25,000 J/mol** Estimated Strength (psi)	**E = 25,000 J/mol** Error (psi)	**E = 25,000 J/mol** EoE (%)	**E = 25,000 J/mol** AAE (psi)	**E = 25,000 J/mol** Abs. EoE (%)
Control	0.6	4,280	4,270	-10	0	40	0	4,280	0	0	10	0
	1.0	6,530	6,580	50	1			6,550	20	0		
	2.1	7,970	7,910	-60	-1			7,950	-20	0		
	7.1	9,110	9,130	20	0			9,110	0	0		
Cold	0.9	2,400	3,080	680	28	560	13	4,470	2,070	86	1230	33
	2.0	5,670	6,470	800	14			7,170	1,500	26		
	3.5	6,900	7,640	740	11			8,130	1,230	18		
	12.6	9,060	9,070	10	0			9,190	130	1		
Hot	0.3	2,860	4,520	1,660	58	1560	31	2,710	-150	-5	875	13
	0.8	6,400	7,940	1,540	24			7,300	900	14		
	1.4	6,960	8,620	1,660	24			8,220	1,260	18		
	5.0	8,030	9,390	1,360	17			9,220	1,190	15		

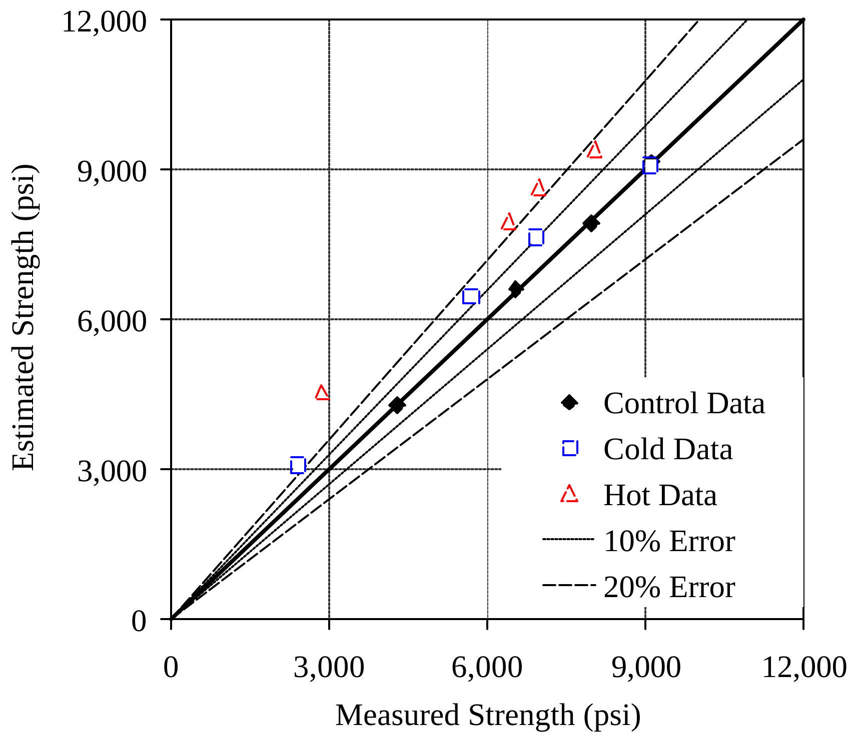

Figure 6.46: Error plot for the Type III - 0.37 mixture, simplified method, *E*= 40 kJ/mol

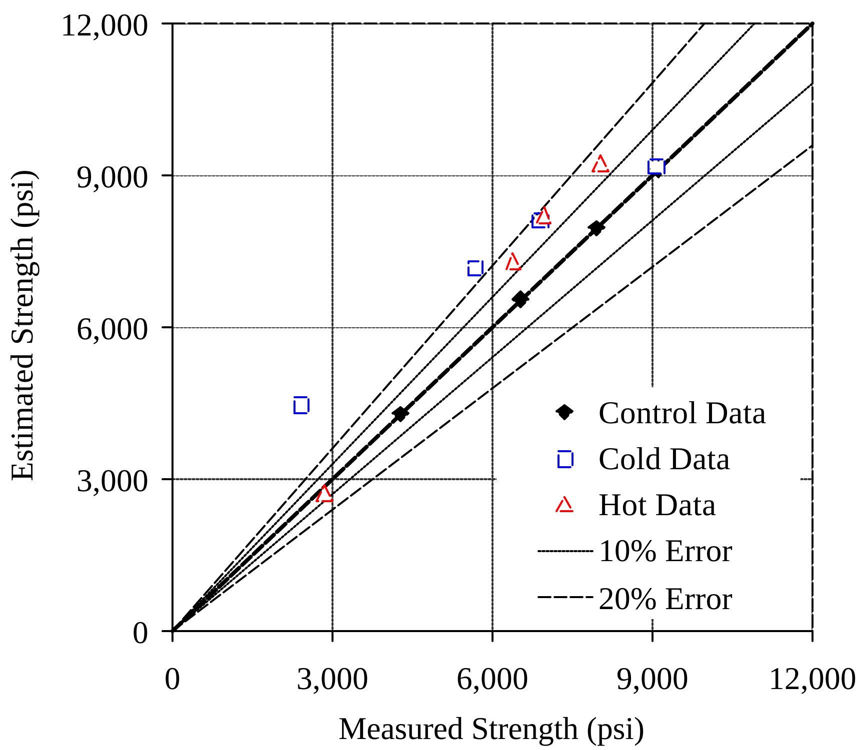

Figure 6.47: Error plot for the Type III - 0.37 mixture, simplified method, *E* = 25 kJ/mol

Table 6.30: Comparison of AM functions for all mixtures, simplified method

Mixture ID	E = 40,000 J/mol		E = 25,000 J/mol		Modified ASTM		Function that Produced Lowest Error
	Total AAE (psi)	Total abs. EoE (%)	Total AAE (psi)	Total abs. EoE (%)	Total AAE (psi)	Total abs. EoE (%)	
Type I - 0.41	300	15	250	20	240	16	Modified
Type I - 0.44	170	8	170	17	170	17	40,000
Type I - 0.48	260	11	200	17	200	13	25,000
20% F	230	13	240	16	200	12	Modified
30% F	210	12	240	14	210	12	40,000 or Modified
20% C	240	9	290	15	450	16	40,000
30% C	200	12	380	23	210	13	40,000
30% Slag	390	18	400	22	390	18	40,000 or Modified
50% Slag	280	16	270	21	250	17	40,000
Type III - 0.37	720	15	710	15	710	15	-
Type III - 0.44	270	10	360	20	280	11	40,000
70/20/10 - 0.37	520	17	500	18	530	22	40,000
70/20/10 - 0.44	310	21	260	26	310	34	40,000

6.4 VARIABLE TEMPERATURE-SENSITIVITY MODELS

As discussed in Section 2.4, researchers such as Carino (1991) and Freiesleben Hansen and Pedersen (FHP) (1977) have shown the need for two different temperature sensitivity values: one below the reference temperature and one above. In Carino's study, he proposed using the Nurse-Saul maturity (NSM) function, with 28°F (-2.2°C) used as a datum temperature for mixtures curing below 73°F, and 55°F (12.7°C) used for mixtures curing above 73°F. Carino proposed this modification to overcome the linearity of the NSM function in order to better model his data. The FHP model is used with the Arrhenius maturity function. It uses the following equations:

FHP Model for Computing the Activation Energy (Previously Equation 2.9)

for $T_c \geq 20°C$ (68°F) E = 33,500 J/mol, and

for $T_c < 20°C$ (68°F) $E = 33{,}500 + 1{,}470\ (20-T_c)$ J/mol.

This allows for an increase in activation energy for low curing temperatures and a decreased activation energy for high curing temperatures. It was desirable to find similar models to fit the data found in this project. The least-squares regression approach was utilized for this process. The ACFs from the actual mixture data were compared to the calculated ACFs from the proposed temperature sensitivity functions. The mixtures containing silica fume were left out of the models because they do not follow the same trends as the other mixtures. The best-fit models were determined and the resulting functions are given as:

Nurse-Saul Maturity Function: (Equation 6.4)

for $T_c \geq 73°F$ $T_o = 40°F$, and

for $T_c < 73°F$ $T_o = 30°F$.

Arrhenius Maturty Function: (Equation 6.5)

for $T_c \geq 23°C$ (73°F) E = 30,300 J/mol,

for $T_c < 23°C$ (73°F) $E = 30{,}300 + 950\ (23-T_c)$ J/mol.

The functions are plotted with the ACF data from all mixtures in Figure 6.48. Along with the new models, the ACFs for the AM function using the FHP activation energy model, as well as the NSM function using 32°F (0°C) as the datum temperature, are plotted on the graph.

The figure shows that both new models are essentially the same and that the FHP model produces a higher activation energy at hot temperatures than needed, except for the 30% Slag mixture, the Class C fly ash mixtures, and the 20% F mixture. It is also apparent that the datum temperature of 32°F (0°C) results in approximately the same behavior as the two best-fit models at low temperatures and, for all practical purposes, results in approximately the same behavior at high temperatures. This is essential, as a variable temperature sensitivity model complicates the maturity method and because the Nurse-Saul function is considered easier to apply than the Arrhenius maturity function.

Although using a datum temperature of 32°F (0°C) with the NSM function seems to give a good average value of temperature sensitivity for curing temperatures ranging from 40°F (4°C) to 104°F (40°C), different values may be desired for maximum accuracy, if the maturity method will be used to estimate strengths in only a hot environment. For example, Figure 6.48 shows that in hot conditions, a datum temperature of 40°F (4°C) or greater may produce lower strength estimation errors for mixtures with Class F or Class C fly ash doses up to 30% than a datum temperature of 32°F (0°C). It is difficult to determine a similar trend for mixtures with GGBF slag from the data found in this study, as the 30% and 50% dose mixtures do not exhibit similar temperature sensitivity behavior. However, in hot conditions a datum temperature of

32°F (0°C) or less may produce less error for straight cement mixtures (Type I or Type III).

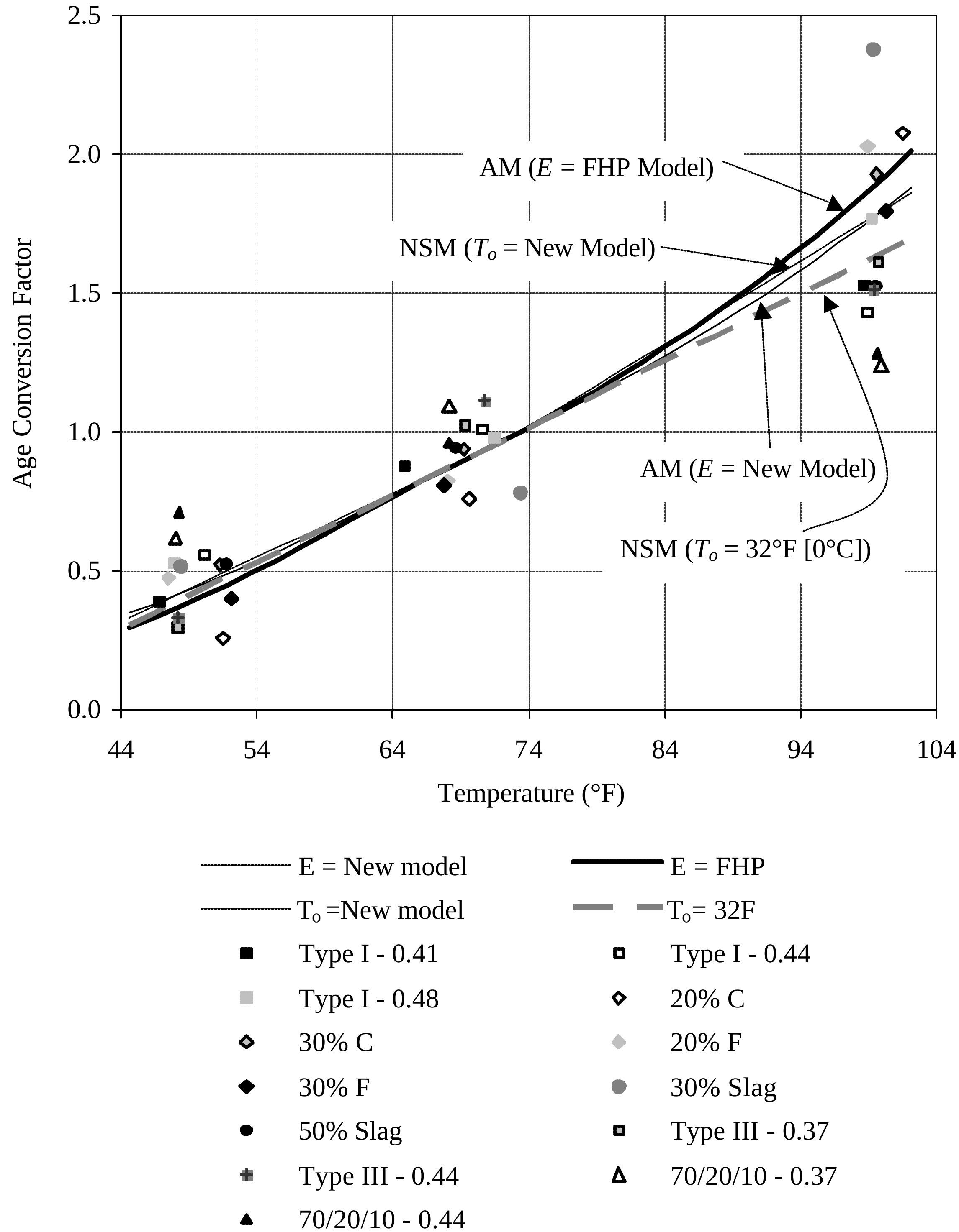

Figure 6.48: Proposed temperature sensitivity functions

Analysis of the accuracy of the maturity method to estimate strengths using the new temperature sensitivity models is not presented here because their accuracy should be the same as or slightly better than the results presented for the NSM function using 32°F (0°C) as the datum temperature, which were presented in Section 6.3.1. However, as the new activation energy model and ACF graph show, if the Arrhenius maturity function is used, one should use a model that allows the cold mixtures to have a higher activation energy, around 44,000 J/mol for an average curing temperature of 48°F, while allowing the hot mixtures to have a lower activation energy, in this case 30,300 J/mol.

6.5 SUMMARY AND CONCLUSIONS

The maturity method, used to estimate concrete strength, was examined in four different ways using both the Nurse-Saul maturity (NSM) and the Arrhenius maturity (AM) functions. The two functions were first evaluated using current ASTM C 1074 (2004) standards to obtain mixture-specific temperature sensitivity values. Temperature sensitivity values refer to the appropriate datum temperature or activation energy, with respect to the NSM or AM functions, that are required to convert strength-age data for different curing temperatures onto one unique strength-maturity relationship. It was determined that the late-age strength loss due to high curing temperatures, referred to as crossover, resulted in a great deal of error in estimating late-age strengths (beyond 7 days of equivalent age). Thus, it was decided to only evaluate the accuracy of the maturity method based on values up to 7 days equivalent age (i.e. 5 days for the hot mixtures and 12 days for the cold).

This strategy led to a method referred to in this report as the Modified ASTM method. Although the datum temperatures and activation energies did not always match commonly accepted values, the errors associated with estimating strengths with the Modified ASTM method were smaller for almost all of the mixtures evaluated. This Modified ASTM method is recommended for estimating concrete strengths when a mixture-specific temperature sensitivity value is desired.

The thirteen mixtures were also evaluated using a value of temperature sensitivity that was held constant for all mixtures. This evaluation was performed twice for each type of function. The NSM function was evaluated with 14°F (-10°C) and 32°F (0°C) as datum temperatures. The NSM function using the 32°F (0°C) datum temperature produced much smaller strength estimate errors than the NSM function using the 14°F (-10°C) datum temperature. The AM function was evaluated using activation energies of 40,000 and 25,000 J/mol. The mixtures varied as to which activation energy produced the smaller error. The best use of the AM function, for most mixtures evaluated, would be to use a lower activation energy at high curing temperatures and a higher activation energy at lower curing temperatures. This approach, similar to the one proposed by Freiesleben Hansen and Pedersen (1977), led to the fourth method analyzed, which employed a variable temperature sensitivity dependent on the curing temperature.

Two new temperature sensitivity models were developed to best fit the mixtures evaluated in this study. The accuracy of using the proposed temperature sensitivity functions was not given, as their behavior was very similar to using a constant datum temperature of 32°F (0°C) for the NSM function. However, if the Arrhenius maturity function is used, a variable activation energy function, like the one proposed in Equation

6.5, should be used. Also, it was observed that in hot conditions, mixtures with up to 30% replacement doses of Class F or Class C fly ashes may require datum temperatures around 40°F (4°C), while straight cement mixtures may require datum temperatures of 32°F (0°C) or lower.

Based on the results of this study, the most accurate, practical, and straightforward method recommended for estimating concrete strength using the maturity method is the Nurse-Saul maturity function using a datum temperature of 32°F (0°C). This method works for Type I mixtures, such as ALDOT standard mixture A1-c, as well as for Type I mixtures with up to 30% replacement of Class F or C fly ash or up to 50% replacement with GGBF Slag. The Type III mixtures as well as the ternary mixtures resulted in larger errors, but these mixtures also had some of the worst crossover effects. The environmental conditions in which the concrete was mixed and cured represent *extreme* effects on the hydration process of the various mixtures. The results shown in this chapter show the benefits of using the maturity method to estimate concrete strength as well as the limitations. As described in the literature review, proper measures should always be taken to verify strength estimations provided by the maturity method.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Since it's beginnings in the 1950's, there have been numerous studies performed to evaluate the accuracy of the maturity method to estimate concrete strengths. The idea of concrete "maturity" began with researchers, such as Nurse (1949), Saul (1951), and McIntosh (1949). They found that given a certain well consolidated, moist-cured concrete, the strength was directly related to the length of cure and the curing temperature. This led to the Nurse-Saul function which computes a maturity index, or as it is commonly known, the Temperature-Time Factor. Later, in the 1977 Freiesleben Hansen and Pederson proposed using the Arrhenius-based maturity equation, for computing an equivalent age. Some researchers preferred the Arrhenius maturity function over the Nurse-Saul maturity function because their data showed that it more accurately modeled concrete behavior. Users of the maturity method to estimate strength on construction projects tend to favor the Nurse-Saul maturity function because of the ease of calculations. There are many limitations and complications involving both approaches to the maturity method. These issues are discussed in Section 2.3.

In order to thoroughly evaluate the accuracy of the maturity method to estimate concrete strength, thirteen concrete mixtures were evaluated in this study. The mixtures were chosen in order to examine the effect of the following variables on concrete strength-gain behavior:

- different cement types (Type I and III)
- water-to-cementitious materials ratios = 0.37, 0.41, 0.44, and 0.48
- Supplementary cementing materials (SCMs) type and dosage
    - Class F fly ash at 20 and 30% replacement levels
    - Class C fly ash at 20 and 30% replacement levels
    - Ground-granulate blast-furnace slag at 30 and 50% replacement levels
    - Silica fume at a 10% replacement level in a ternary blend with 20% Class F fly ash.

In the past, researchers have evaluated the maturity method based on constant curing temperatures. However, in field operations curing temperatures actually oscillate with the ambient temperature. Therefore the concrete in this study was cured under fluctuating temperatures. Three batches were made of each mixture: cold, hot, and control batches. The cold batch temperatures simulated concrete placed in winter conditions by cycling between 40°F and 55°F (4°C and 13°C) over a 24-hour period. The hot batch temperatures modeled concrete placed in summer conditions by cycling between 90°F and 105°F (32°C and 41°C) over a 24-hour period. The control batch was cured in laboratory conditions with temperatures ranging between 68°F and 73°F (20°C and 23°C). The temperature ranges were chosen in order to effectively cover the full range of practical of temperatures to be expected on Alabama Department of Transportation (ALDOT) projects. All mixing materials used for the hot and cold batches were heated or cooled to a temperature close to their respective curing environments prior to mixing. This was done to simulate conditions at a ready-mix concrete plant, where aggregates and cementitious materials are exposed to ambient temperatures. Chemical admixtures were used to achieve desired slump and air content, as would be required with ready-mix concrete. All chemical admixture doses were kept constant within each mixture independent of temperature.

From each batch nineteen 6x12 in. cylinders were prepared. A temperature sensor was inserted into one of the freshly prepared cylinders. The sensor was programmed to record the temperature every 30 minutes, on average. The remaining 18 cylinders were used for compressive strength testing was performed on sets of three cylinders at six different ages. The equivalent age at testing was as follows: twice the time of final set, 24 hrs, 48 hrs, 7 days, 14 days, and 28 days. These ages were adjusted for the cold and hot batches to account for the temperature dependent strength-gain. After the final compressive strength tests were completed, the temperature data were downloaded.

Compressive strength test data versus chronological age was then analyzed based on the amount of late-age strength loss or gain, referred to as "crossover," due to early-age curing temperatures. The mixtures were also evaluated based on their apparent "temperature sensitivity," or the correction required to converge the data from the three batches onto a single strength-maturity relationship.

The strength-age relationships for each batch were then converted to strength-maturity relationships. Maturity was computed using the Nurse-Saul and Arrhenius maturity functions. Four methods to determine temperature sensitivity values were presented. First, mixture-specific temperature sensitivity values were computed based on present ASTM C 1074 methods. These temperature sensitivity values were used to determine the unique strength-maturity (S-M) relationship for each mixture. The S-M relationship was used to estimate concrete strength of a single mixture, given the temperature history of any batch. The accuracy of the maturity method was determined from the difference in the estimated strength found from the S-M relationship and the actual test strengths at the same maturity. The data was then reanalyzed using the ASTM methods, only slightly modified to exclude late-age data.

Next, a method using commonly used constant values of temperature sensitivity for all mixtures was presented. The values chosen were based on an age conversion factor versus temperature plot for all the mixtures. The values chosen were datum temperatures of 32°F (0°C) and 14°F (-10°C) for the Nurse-Saul maturity function and activation energies of 25,000 J/mol and 40,000 J/mol for the Arrhenius maturity function. Finally, temperature dependent models used to calculate values of datum temperatures or activation energies were presented.

Given the scope of this project, the maturity method provides a practical and effective means to estimate early-age concrete strengths for mixtures with various cement types, various SCM types and dosages, and various water-to-cementitious materials ratios when cured at fluctuating temperatures.

7.1 CONCLUSIONS

The conclusions based on the project objectives defined in Section 1.3 are discussed in this section. The conclusions based on the effect of various fluctuating curing temperatures on concrete strength behavior are as follows:

- Each batch of all the mixtures did follow a unique strength versus age curve.
- The hot batch gained strength rapidly, but generally had lower late-age strengths when compared to those from control and cold batches.

- The cold batch gained strength slowly, but continued to gain strength at late-ages.
- This phenomena is known as the “crossover effect.”

The conclusions based on the effect of various types and doses of SCMs, varying cement types, and water-to-cementitious materials ratios on the rate of strength gain at different temperatures were based on the amount of crossover and the amount of temperature sensitivity required to converge the data onto a single-strength-maturity relationship. The conclusions related on the crossover effect are as follows:

- All straight cement mixtures exhibited crossover, with long-term strength losses ranging from 7% to 12%; crossover occurred between 7 days and 16 days.
- The replacement of cement with 20% and 30% Class F fly ash for the Type I - 0.41 mixture effectively eliminated the crossover effect.
- The replacement of cement with 20% Class C fly ash for the Type I - 0.41 mixture delayed, but did not completely eliminate, the crossover effect. An increased replacement dosage of 30% Class C fly ash for the Type I - 0.41 mixture effectively eliminated crossover.
- The replacement of cement with 30% or 50% GGBF slag for the Type I - 0.41 mixture increased strength losses for the hot batch from 6% to more than 17% in some cases.
- Changing the cement from Type I to Type III for the Type I - 0.44 mixture increased the crossover effect only slightly, but greatly decreased the time at which crossover occured from 16 days to 4 days.

- The replacement of cement with 20% Class F fly ash and 10% silica fume for the Type I - 0.44 mixture increased the strength loss from 7% to 31% and decreased the time at which crossover occurred from 16 days to 5 days.
- The Type III - 0.37 mixture had a 17% strength loss attributable to the crossover effect, and crossover occurred less than two days after mixing for the hot batch.
- The ternary blend prestressed concrete mixture had a long-term strength loss of 23% from the crossover effect.

The conclusions observed from each mixture's temperature sensitivity trends are as follows:

- The Type I - 0.41 and Type I - 0.48 mixtures have low temperature sensitivity for both hot and cold batches. The Type I - 0.44 had low temperature sensitivity, possibly a slightly higher sensitivity for the hot batch compared to the cold batch.
- The replacement of cement with 20% Class F fly ash for the Type I - 0.41 mixture increased the temperature sensitivity slightly. Increasing the dose to 30% Class F fly ash increased the hot batch's temperature sensitivity.
- The replacement of cement with 20% Class C fly ash for the Type I - 0.41 mixture increased the temperature sensitivity of the cold batch, and increasing the dose to 30% Class C fly ash increased both the hot and cold batch's temperature sensitivity significantly relative to that of the Type I - 0.41 mixture.

- The replacement of cement with 30% and 50% GGBF slag for the Type I - 0.41 mixture increased the temperature sensitivity of the cold batch, but did not affect the hot batches.
- Changing the cement from Type I to Type III for the Type I - 0.44 mixture increased the temperature sensitivity for the cold batch and decreased that for the hot batch.
- The replacement of cement with 20% Class F fly ash and 10% silica fume for the Type I - 0.44 mixture increased the temperature sensitivity for the cold batch and decreased that for the hot batch.
- The Type III - 0.37 hot batch had little to no temperature sensitivity, while the cold batch required a higher temperature sensitivity.
- The ternary blend prestressed concrete mixture (70/20/10 - 0.37) had a low temperature sensitivity for the hot batch and a higher sensitivity for the cold batch.

The conclusions based on the accuracy of the maturity method to estimate concrete strength for numerous mixtures with varying types and doses of SCMs, varying cement types, and water-to-cementitious materials ratios using ASTM C 1074 maturity methods are as follows:

- Average absolute percent error in estimating strengths ranged from 6% to 27% for some mixtures.
- Mixtures that produced the highest errors in estimating concrete strengths also had high strength loss due to the crossover effect.

It was determined that strength estimations are not accurate beyond 7 days of equivalent age. Also the late-age strength losses associated with the hot batches were believed to be affecting the temperature sensitivity determination. Thus, temperature sensitivity values were recalculated and the accuracy of strength estimations using the maturity method were reanalyzed. This was referred to as the "Modified ASTM" method.

The conclusion found from modifications to the current ASTM C 1074 procedure to handle strength estimation deficiencies the improvement in strength prediction accuracy are as follows:

- Temperature sensitivity values did change when only data up to 7 days of equivalent age was used.
- When using the Nurse-Saul maturity function, the Modified ASTM method produced less total error than the ASTM C 1074 method for all mixtures except the 20% C, Type III - 0.44, and ternary-blend mixtures.
- When using the AM function, the Modified ASTM method produced less error than the ASTM C 1074 method for all mixtures except the 20% C and ternary-blend mixtures.
- The Modified ASTM method should be used to determine mixture-specific temperature sensitivities.
- Due to the increased accuracy of the estimated strengths that resulted from using the maturity method only up to 7 days equivalent age, it was determined that strengths should not be estimated beyond 7 days of equivalent age.

- Total percent errors from strength estimations ranged between 7% and 35%. However, for many mixtures the initial strength estimation for the cold batch was the main source of error.

The conclusions from analysis of the accuracy of the maturity method using constant temperature sensitivity values for all mixtures are as follows:

- When using the Nurse-Saul maturity function, a datum temperature of 32°F (0°C) produced less error than that found by using 14°F (-10°C) for all mixtures.
- A datum temperature of 32°F (0°C) produced less total average error than using mixture-specific datum temperatures found from the Modified ASTM method for 8 out of the 13 mixtures evaluated.
- When using the Arrhenius maturity function, an activation energy of 40,000 J/mol for cold batches and 25,000 J/mol for hot batches produced the least error in strength estimations for 10 out of the 13 mixtures evaluated.

Lastly, the use of variable temperature sensitivity models was evaluated. The conclusions from that analysis are as follows:

- The best-fit temperature sensitivity models had very similar behavior to the Nurse-Saul maturity function with a datum temperature of 32°F (0°C).
- If the Arrhenius function is used, a model should be used, such as the one proposed in Equation 6.5, which allows a higher activation energy at low temperatures and a lower activation energy at high temperatures.

7.2 RECOMMENDATIONS

From the analysis in this study, the following recommendations were made based on the experimental results of this study:

- Strength estimations using the maturity method may not be accurate beyond 7 days of equivalent age.
- If a mixture-specific temperature sensitivity value is desired, use the Modified ASTM method, as shown in Section 6.2.
- If the Arrhenius maturity function is to be used, employ a temperature dependent model, such as the FHP model (Section 2.4.2) or the new model (Section 6.4), that allows for a high temperature sensitivity at low temperatures and a lower sensitivity at high temperatures.
- Select a datum temperature of 40°F (4°C) or greater when using cement-replacement dosages of 20 to 30% of Class F or Class C fly ash in hot conditions.

Finally, the maturity function to be used on ALDOT projects that minimizes strength estimation errors while maintaining ease of use is the Nurse-Saul maturity function with a constant datum temperature of 32°F (0°C).

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APPENDICES

APPENDIX A: COMPRESSIVE STRENGTH TEST RESULTS

Appendix A-1: Compressive strength test results for Type I- 0.41 mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.4	2,076	2,123	2,225
	0.8	3,653	3,721	3,646
	1.4	4,051	4,071	3,935
	5.0	5,119	4,944	4,928
	10.2	5,557	5,330	5,353
	20.1	5,353	5,836	5,684
Control	0.5	1,010	1,040	1,040
	1.0	2,650	2,780	2,690
	2.1	3,990	4,210	3,990
	7.1	4,840	4,990	4,900
	14.0	5,450	5,850	5,770
	28.1	6,220	6,130	6,160
Cold	0.8	550	850*	540
	1.8	2,770	2,860	2,880
	3.4	3,360*	4,170	3,930
	12.1	5,440	5,520	5,050*
	24.8	6,150	5,740	6,030
	49.0	6,160*	6,600	6,650

*Not used for average strength

Appendix A-2: Compressive strength test results for Type I- 0.44 mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	1,250	1,280	1,300
	0.9	2,610	2,590	2,520
	1.5	3,450	3,380	3,340
	5.0	4,380	4,380	4,400
	12.1	5,070	5,100	5,100
	20.1	5,410	5, 400	5,380
Control	0.5	850	810	1,090*
	1.0	1,970	1,930	2,090
	2.0	2,890	2,790	2,470*
	7.3	4,350	4,080	4,220
	14.2	5,180	4,820	4,930
	28.0	5,780	5,760	-
Cold	0.9	410	440	540*
	1.9	2,100	1,780	2,010
	3.5	3,180	2,950	3,140
	12.4	4,600	4,560	5,030
	25.0	5,730	5,490	5,800
	49.2	6,210	6,470	6,560

*Not used for average strength

Appendix A-3: Compressive strength test results for Type I- 0.48 mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	780*	870	850
	0.8	2,170	2,260	2,120
	1.4	2,730	2,740	2,880
	5.1	4,020	4,150	3,880
	9.8	4,55760	4,770	4,710
	19.8	5,050	5,200	5,000
Control	0.5	630	640	570*
	1.0	1,690	1,560*	1,740
	2.0	2,650	2,510	2,550
	7.4	4,280	4,110	3,990
	14.2	4,710	4,790	4,600
	28.3	5,930	5,640	5,580
Cold	0.9	420	550*	420
	1.9	1,810*	1,570	1,640
	3.6	3,110	3,120	2,900
	12.0	4,450	4,780	4,630
	25.1	6,160	6,010	5,510*
	49.1	7,030	7,310	7,300

*Not used for average strength

Appendix A-4: Compressive strength test results for 20% F mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.4	1,950	2,110	1,920
	0.8	3,490	3,180	3,190
	1.4	4,020	4,200	4,120
	4.9	5,400	5,560	5,260
	10.0	6,240	6,290	6,020
	19.8	7,150	6,990	7,070
Control	0.6	1,510	1,280*	1,530
	1.0	2,670	2,370*	2,650
	2.0	3,310	3,560	3,300
	7.0	5,280	4,900	5,200
	14.1	5,980	6,070	5,750
	28.2	6,830	7,260	6,810
Cold	0.9	730	730	480*
	1.8	2,510	2,210*	2,530
	3.4	3,420	3,340	3,270
	12.2	5,670	5,430	5,300
	24.9	6,030	6,180	6,110
	49.0	6,600	6,690	6,400

*Not used for average strength

Appendix A-5: Compressive strength test results for 30% F mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.4	1,370	1,350	1,350
	0.8	2,770	2,860	2,960
	1.5	3,690	3,600	3,600
	5.0	4,970	5,050	4,870
	10.1	6,240	5,830*	6,140
	20.0	7,470*	7,070	6,860
Control	0.6	1,180	1,360*	1,190
	1.1	2,240	2,170	2,200
	2.0	2,820	3,250*	2,910
	7.0	4,420	4,570	4,970*
	14.1	5,430	5,360	5,490
	28.2	6,550	6,510	6,390
Cold	0.9	460*	690	670
	1.9	2,250*	1,940	2,050
	3.5	3,163	3,122	3,000
	12.2	5,040	5,140	4,800
	25.0	5,500	5,470	5,470
	49.0	6,270	6,320	6,470

*Not used for average strength

Appendix A-6: Compressive strength test results for 20% C mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.5	1,880	2,020	1,910
	0.8	3,210*	3,630	3,590
	1.4	3,820	3,980	4,370*
	5.0	4,990*	5,460	5,280
	10.3	5,850	5,910	5,800
	20.0	6,510	6,280	6,530
Control	0.6	880*	1,180	1,260
	1.0	2,410*	2,200	2,230
	2.0	3,740	3,780	3,700
	7.0	5,420	5,220	5,350
	14.1	5,740	6,070	5,900
	28.0	6,560	6,800	6,530
Cold	1.2	1,050	1,040	670*
	1.8	2,170*	1,710	1,830
	3.4	3,240	2,760*	3,040
	12.0	5,450	5,360	5,450
	25.9	6,050	5,870	5,690
	49.0	6,010*	6,350	6,580

*Not used for average strength

Appendix A-7: Compressive strength test results for 30% C mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.4	1,030	1,040	1,100
	0.8	2,720	2,690	2,740
	1.4	4,520*	3,930	3,880
	5.0	5,991	5,940	5,700
	9.9	5,940	5,990	6,300
	19.9	7,540	6,690*	7,490
Control	0.6	680	700	660
	1.0	1,620*	1,990	1,900
	2.0	3,090	3,040	3,470*
	7.2	5,070	5,450	5,240
	14.1	5,690	5,950	6,380*
	28.1	6,990	5,940*	6,960
Cold	1.3	560	840*	590
	1.9	1,710	1,300*	1,660
	3.5	2,540	2,700	2,630
	12.1	4,690	5,140*	4,630
	25.0	6,360	5,710*	6,360
	49.2	6,730	6,590	6,540

*Not used for average strength

Appendix A-8: Compressive strength test results for 30% Slag mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.4	1,540	1,640*	1,470
	0.8	3,100	2,830*	3,170
	2.9	4,840	5,090	5,060
	4.9	5,120	4,840*	5,360
	10.8	5,840	6,040	6,010
	19.8	6,090	6,050	5,900*
Control	0.6	1,420	1,440	1,270*
	1.0	2,520*	2,700	2,760
	2.0	3,620	3,670	3,680
	7.1	5,610	5,810	5,930
	14.1	6,340	6,560	6,950*
	28.0	7,050	7,170	7,340
Cold	0.9	630	610	590
	1.9	2,040	2,040	2,090
	3.6	3,380	3,370	3,450
	12.2	5,100	4,990	5,170
	25.1	6,460	6,730	6,740
	49.4	7,710	7,810	7,750

*Not used for average strength

Appendix A-9: Compressive strength test results for 50% Slag mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	620	600	620
	0.8	2,290	2,390	2,320
	1.4	3,200	3,220	3,320
	5.0	5,920	6,210	5,610*
	10.1	6,340	6,720	6,430
	19.8	6,510	6,630	6,510
Control	0.5	740	750	790
	1.0	1,710	1,610	1,730
	2.1	3,020	3,110	3,080
	7.2	5,740	5,850	5,750
	14.2	7,160	7,000	7,130
	28.1	7,660	7,860	8,10
Cold	0.9	340	360*	330
	1.9	1,400	1,330	1,300
	3.4	2,740*	2,420	2,490
	12.3	5,070	4,860	4,980
	24.9	6,720	6,820	6,700
	49.0	8,510	8,680	8,510

*Not used for average strength

Appendix A-10: Compressive strength test results for Type III - 0.37 mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	2,820	2,920	3,400*
	0.8	6,400	6,300	6,500
	1.4	6,980	6,940	6,990
	5.0	8,050	8,110	7,940
	10.0	8,930	8,520	8,400
	19.8	9,190	8,900	9,040
Control	0.6	4,230	4,970*	4,340
	1.0	6,280	6,620	6,710
	2.1	8,150	7,880	7,890
	7.1	9,360	9,060	8,910
	14.3	10,070	9,760	10,470
	28.2	10,690	11,510	11,180
Cold	0.9	2,360	2,450	1,500*
	2.0	5,690	5,660	4,500*
	3.5	6,850	6,950	5,790*
	12.6	9,590	8,540	7,370*
	25.1	10,680	9,880	7,820*
	49.4	10,560	10,490	9,180*

*Not used for average strength

Appendix A-11: Compressive strength test results for Type III - 0.44 mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	1,920*	2,360	2,440
	0.7	3,340	3,120	3,190
	1.4	3,650	3,830	4,040*
	5.3	5,170	5,010	5,140
	10.0	5,220	5,850*	5,370
	20.2	5,560	5,480	5,480
Control	0.4	900*	720	750
	1.0	3,070	2,920	3,150
	2.0	3,660	3,850	3,980
	7.2	4,960	5,210	5,150
	14.0	5,990	5,760	5,590
	28.2	6,120	6,560	6,070
Cold	1.0	720	970*	780
	1.8	2,310	2,330	2,490
	3.4	3,670	3,540	3,770
	12.1	5,780	5,400	5,730
	24.9	6,410	6,390	6,500
	49.2	7,220	6,870	7,140

*Not used for average strength

Appendix A-12: Compressive strength test results for 70/20/10 - 0.37 mixture

Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	1,710	1,570	1,910*
	0.7	3,970*	3,460	3,620
	1.4	4,960	4,900	5,220
	4.9	7,590	7,320	7,280
	9.8	8,030	8,370	8,330
	20.0	8,670	8,270	8,550
Control	0.5	1,270	1,350	830*
	1.0	3,630	3,680	3,340*
	2.1	5,190	5,360	5,190
	7.0	7,580	7,760	7,560*
	14.1	10,040	10,300	10,020
	28.1	10,760	10,840	11,280*
Cold	0.9	1,070	1,030	1,170*
	1.8	3,070	3,150	2,980
	3.5	4,450	4,740	4,780
	12.2	6,980	7,040	7,750*
	25.0	8,920	9,070	8,630
	49.2	11,020	10,630	10,820

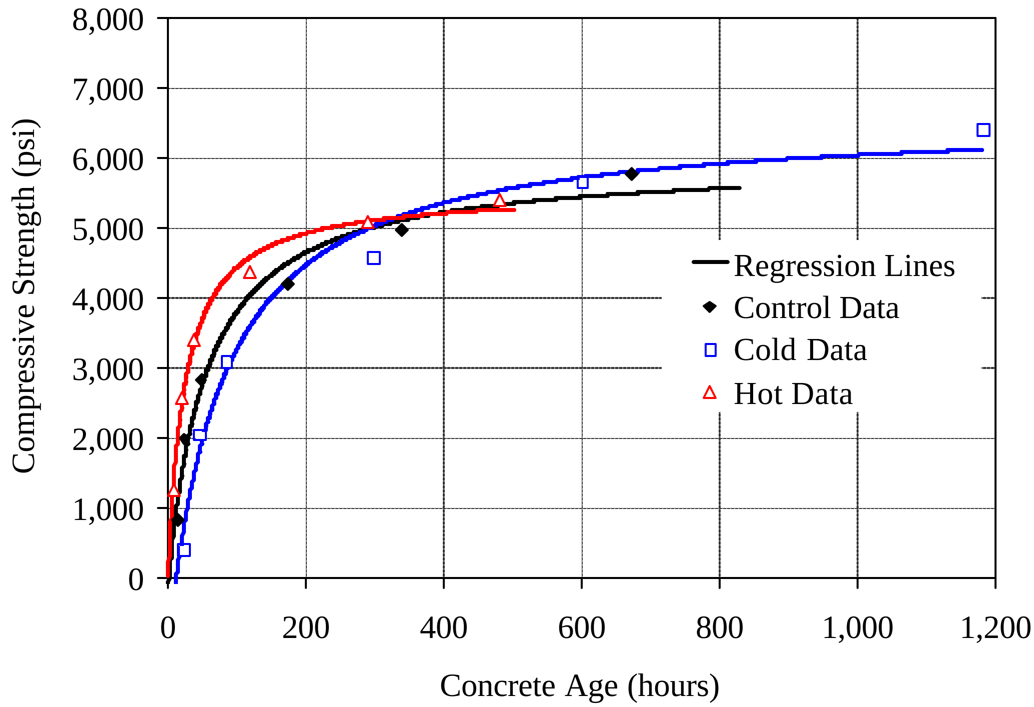
*Not used for average strength

Appendix A-13: Compressive strength test results for 70/20/10 - 0.44 mixture

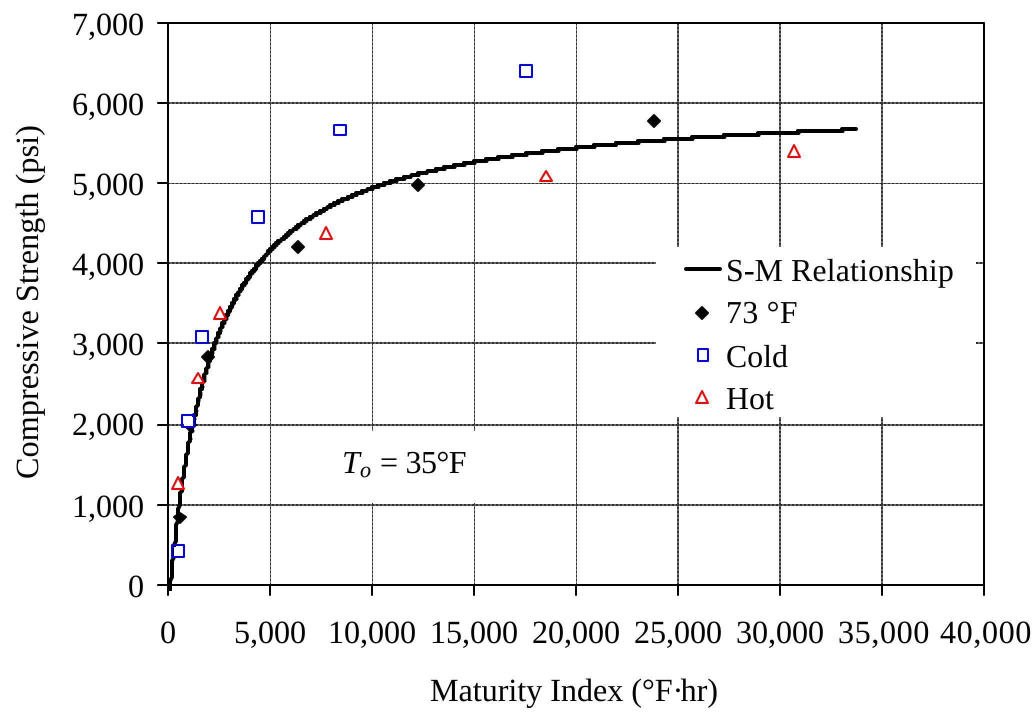
Batch ID	Age (days)	Compressive Strength (psi)		
Hot	0.3	910*	960	1,010
	0.8	1,870	1,890	1,850
	1.5	2,430*	2,830	2,630
	5.0	4,510	4,510	4,510
	10.2	4,850	4,880	4,820
	19.9	5,320	5,360	5,240
Control	0.4	500	530	530
	1.0	1,820	1,810	1,700
	2.0	2,540	2,750	2,550
	7.2	4,610	4,730	4,710
	13.9	6,340	6,140	6,290
	27.9	7,070	7,280	7,090
Cold	1.0	440*	380	380
	1.8	1,300*	1,470	1,440
	3.4	2,490	2,640	2,340*
	12.1	4,410	4,530	4,600
	24.9	5,730	5,950	5,800
	48.9	7,360	7,580	7,150

*Not used for average strength

APPENDIX B: STRENGTH-MATURITY RELATIONSHIPS FOR NURSE-SAUL MATURITY FUNCTION, ASTM C 1074 METHOD

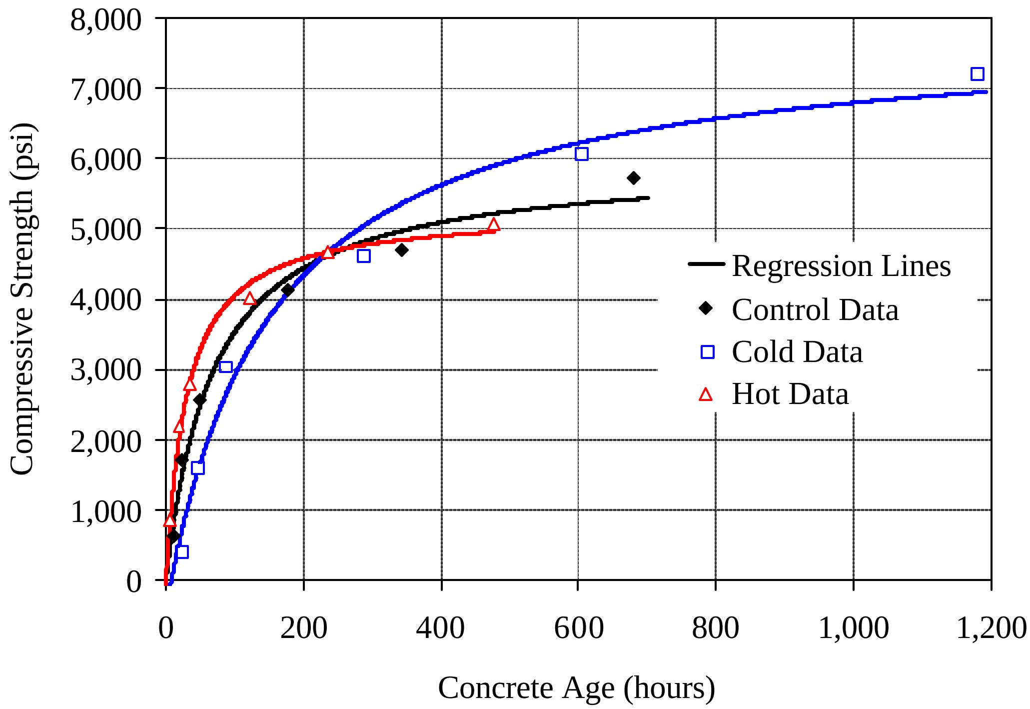


(a)

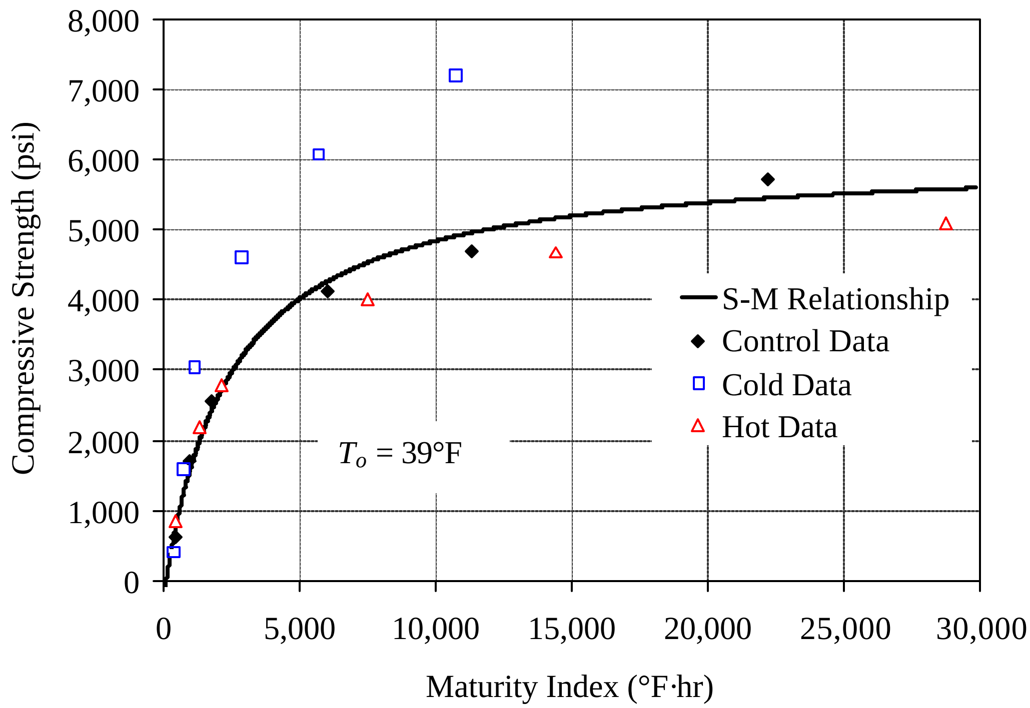


(b)

Figure B-1: Type I - 0.44 mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method

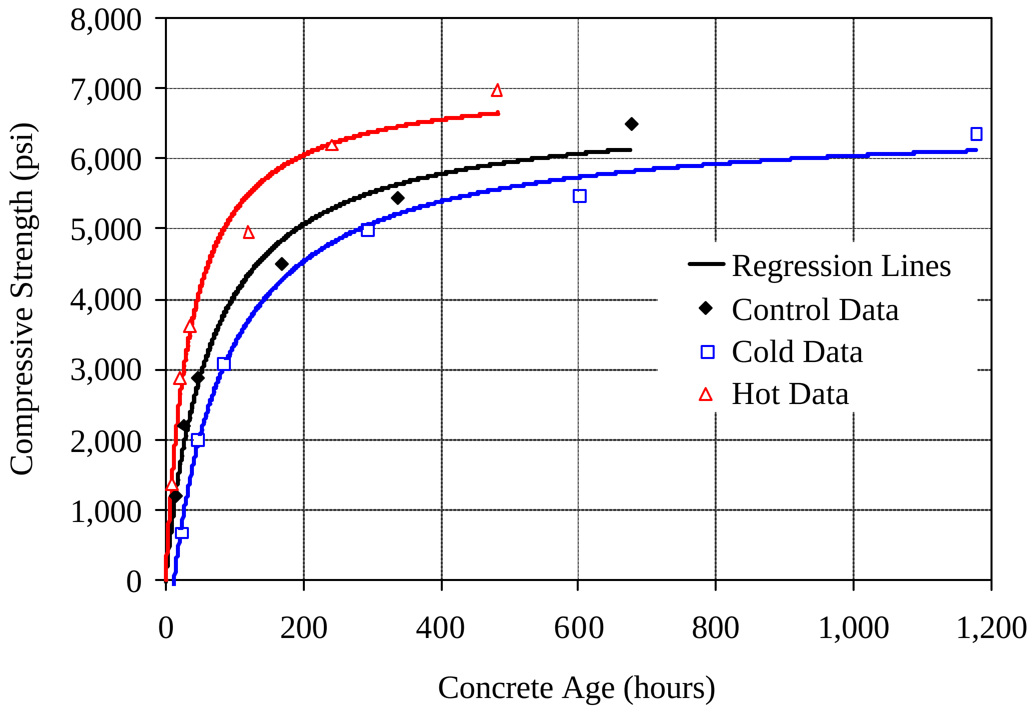


(a)

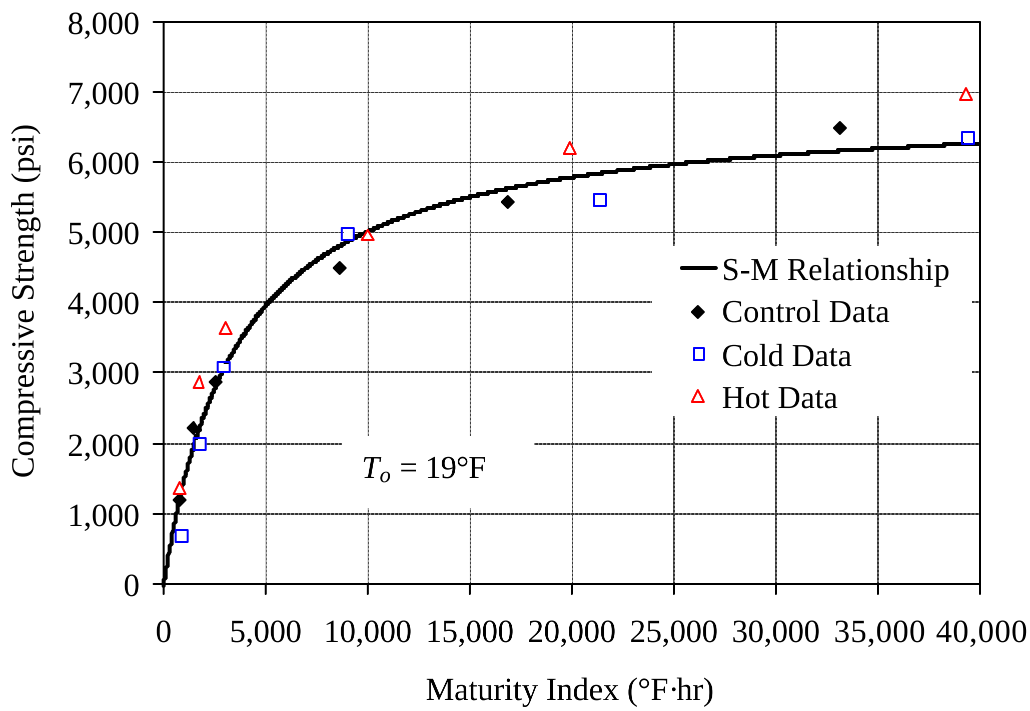


(b)

Figure B-2: Type I - 0.48 mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method

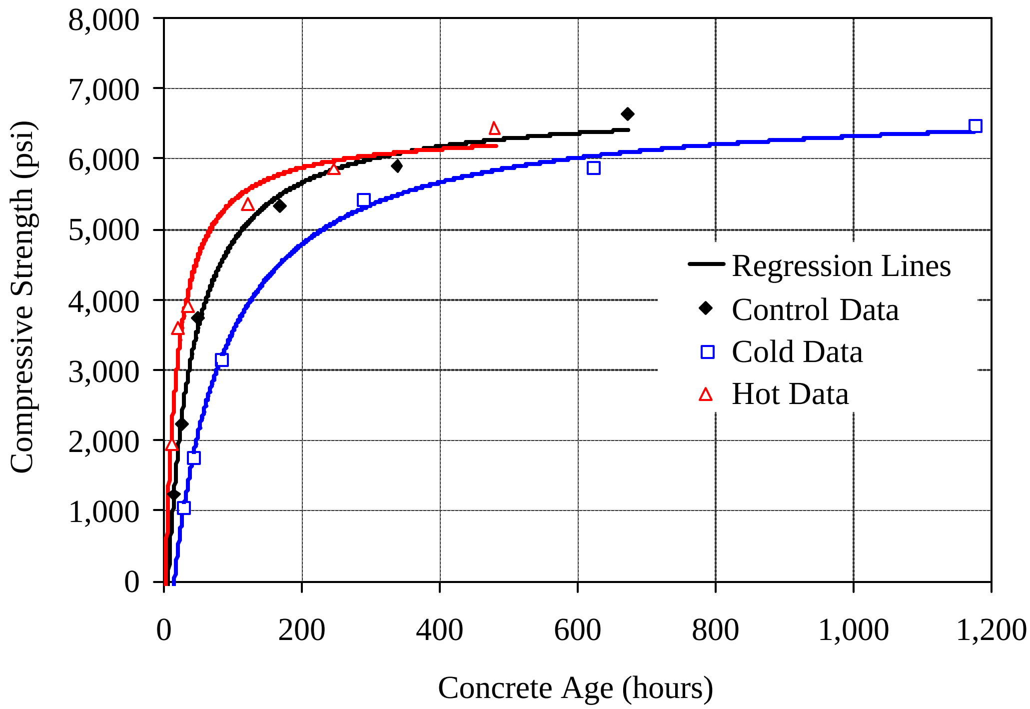


(a)

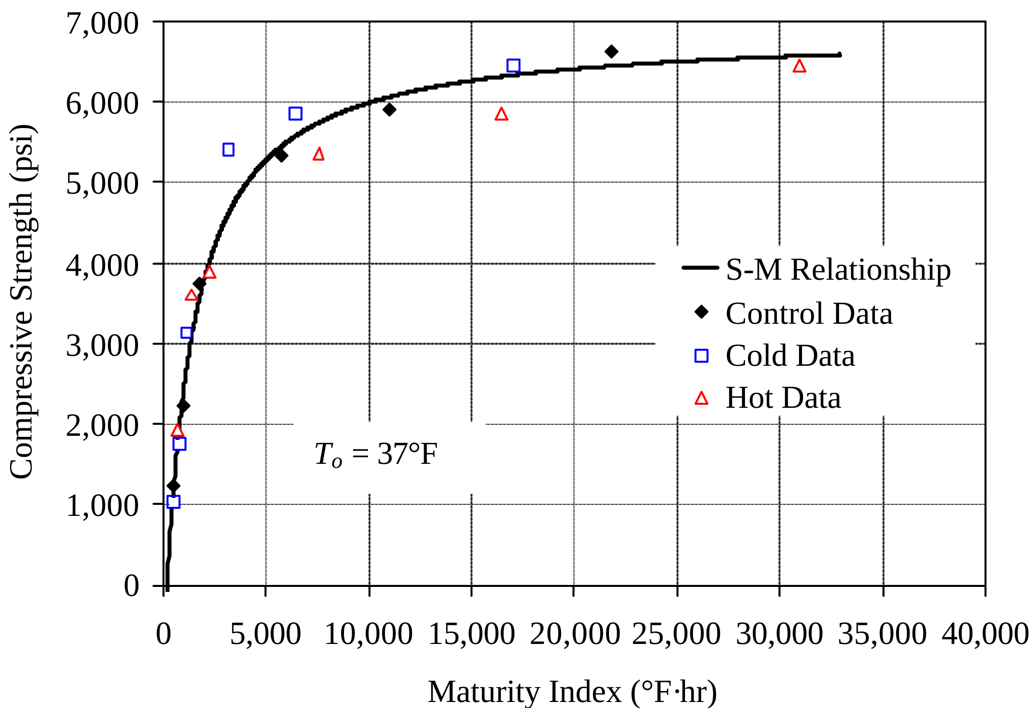


(b)

Figure B-3: 30% F mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method



(a)



(b)

Figure B-4: 20% C mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method

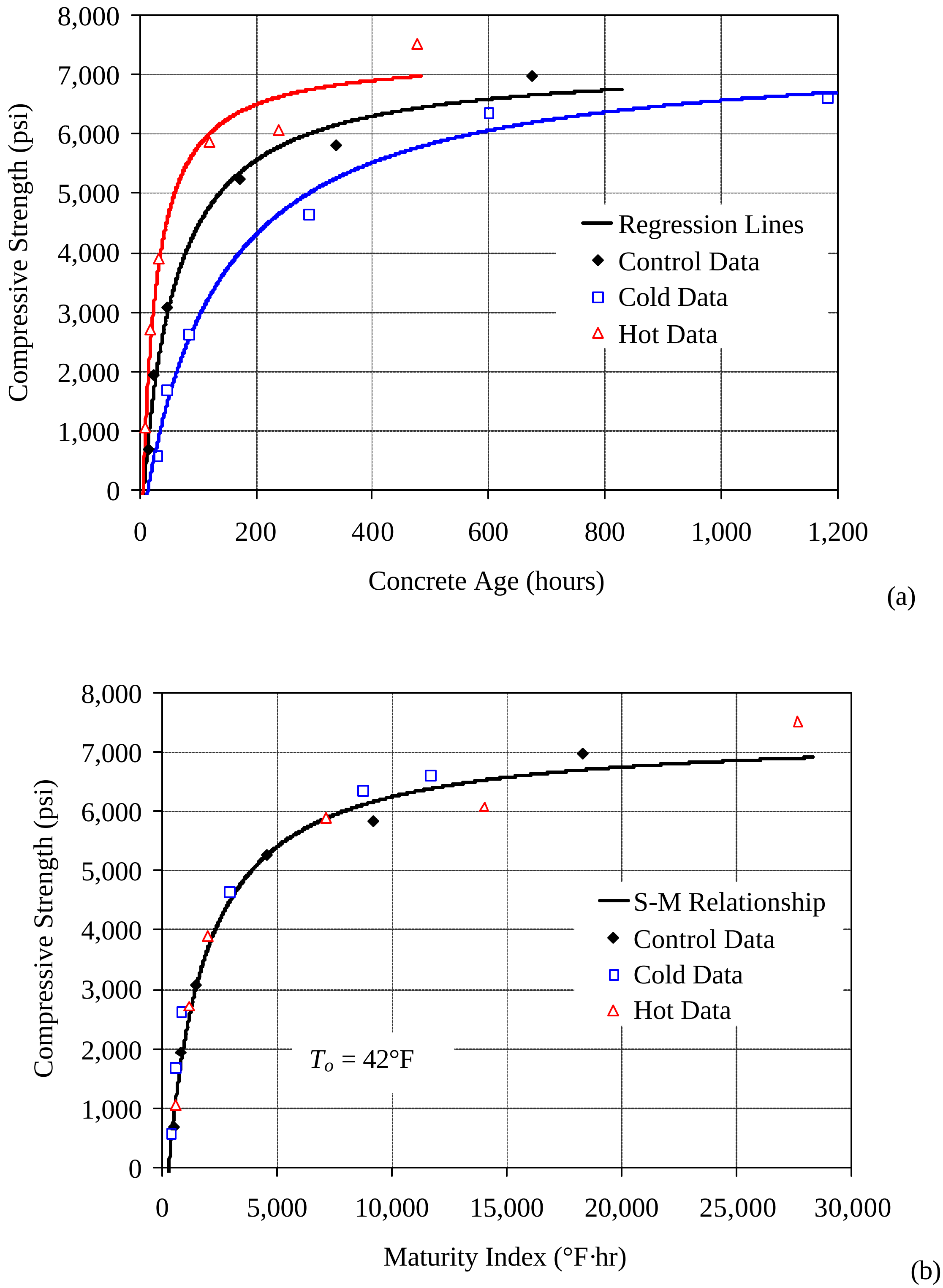
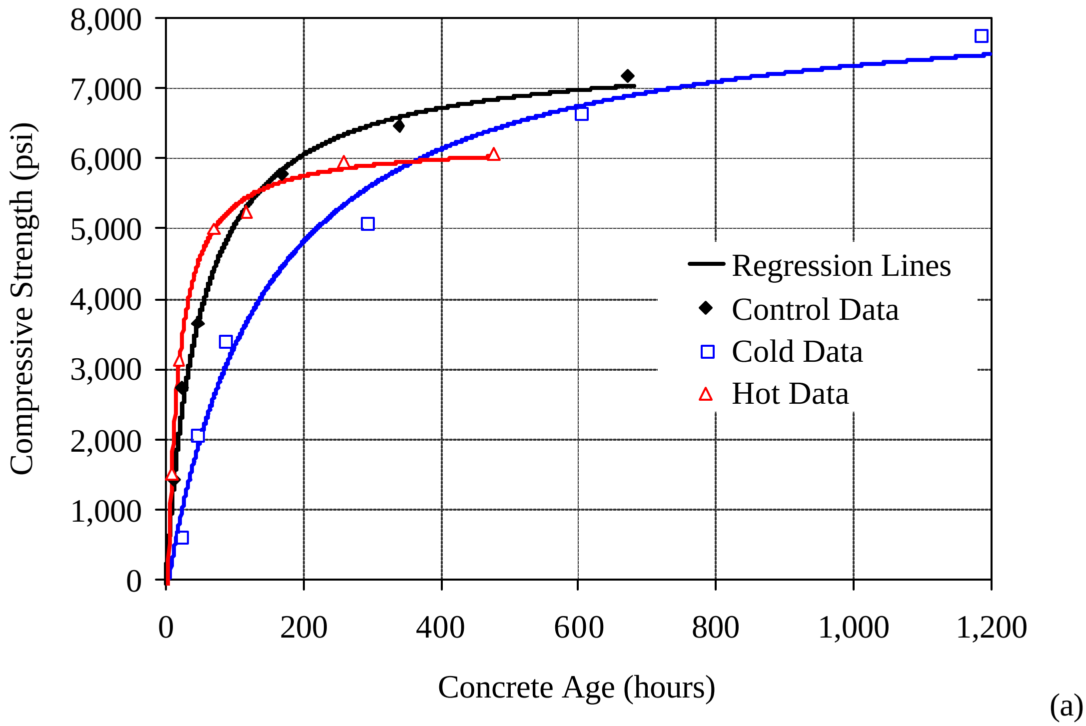


Figure B-5: 30% C mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method



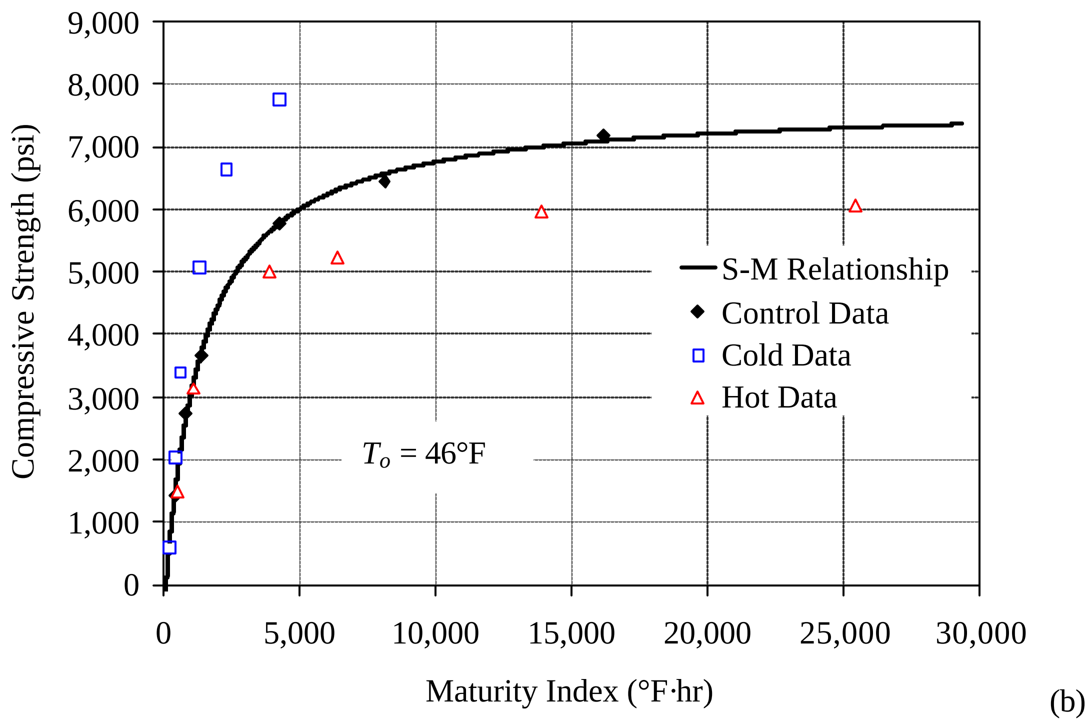
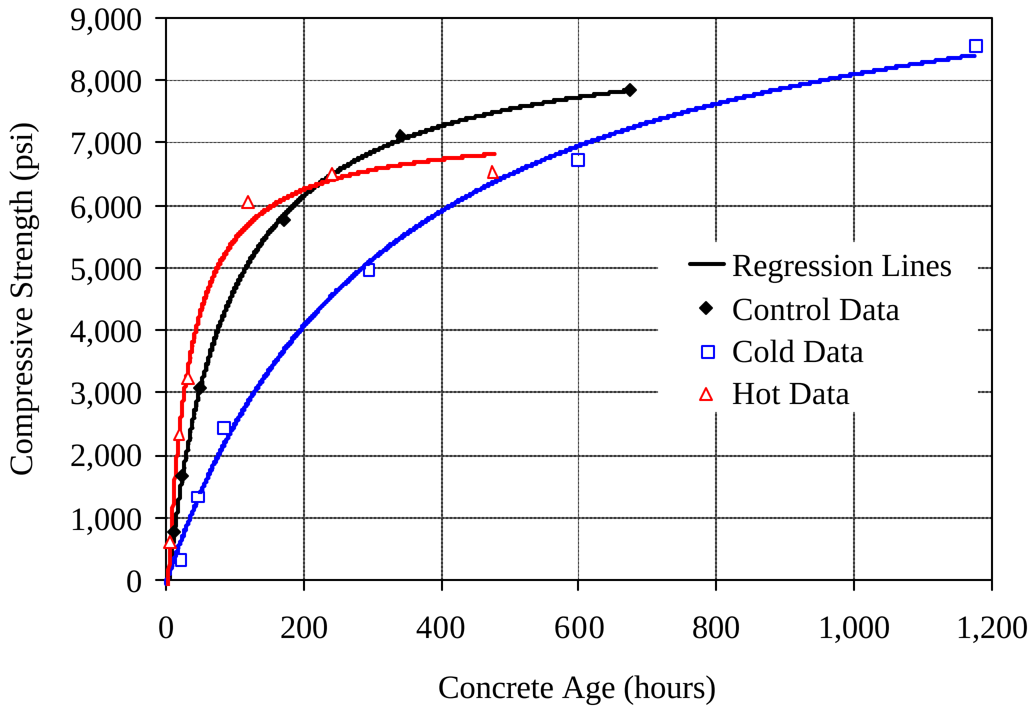
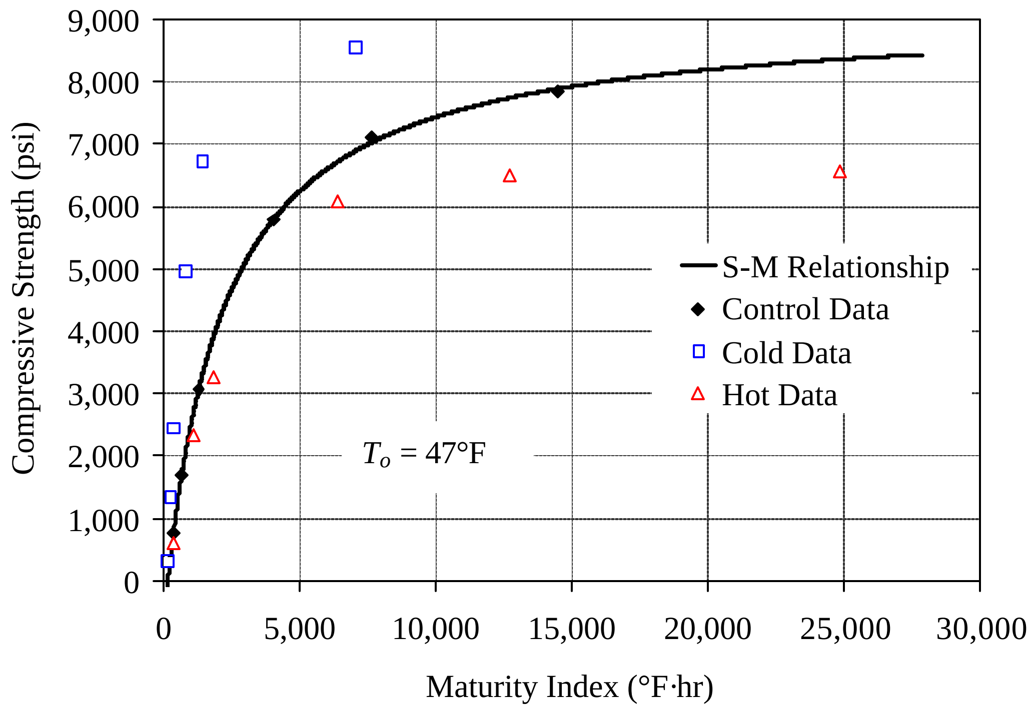


Figure B-6: 30% Slag mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method

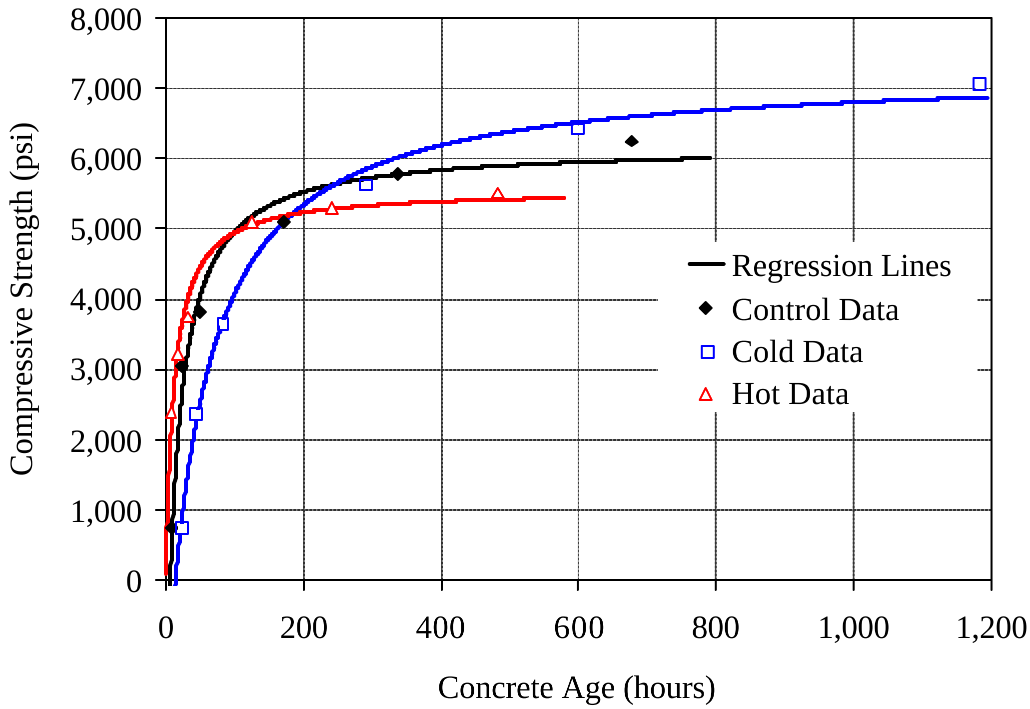


(a)

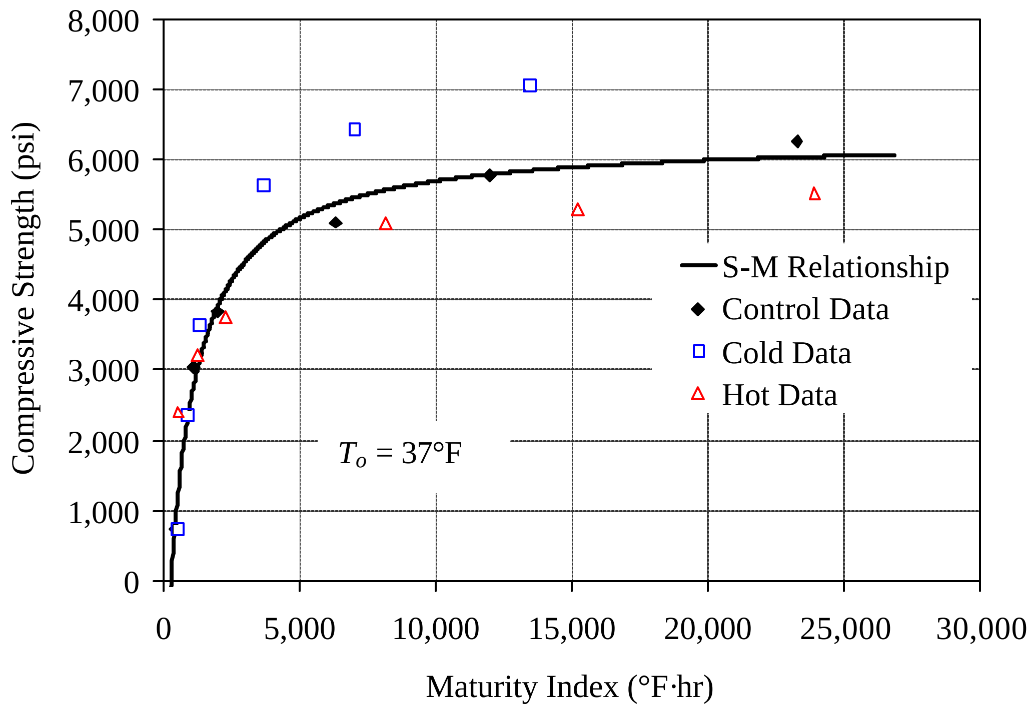


(b)

Figure B-7: 50% Slag mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method

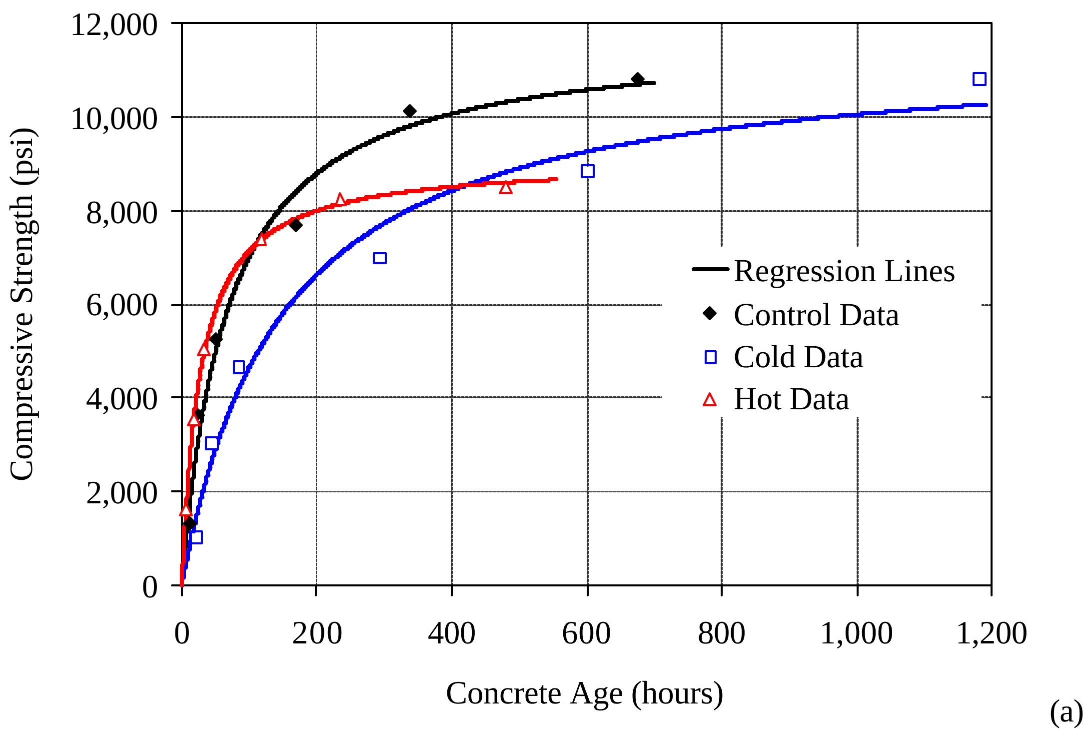


(a)



(b)

Figure B-8: Type III - 0.44 mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method



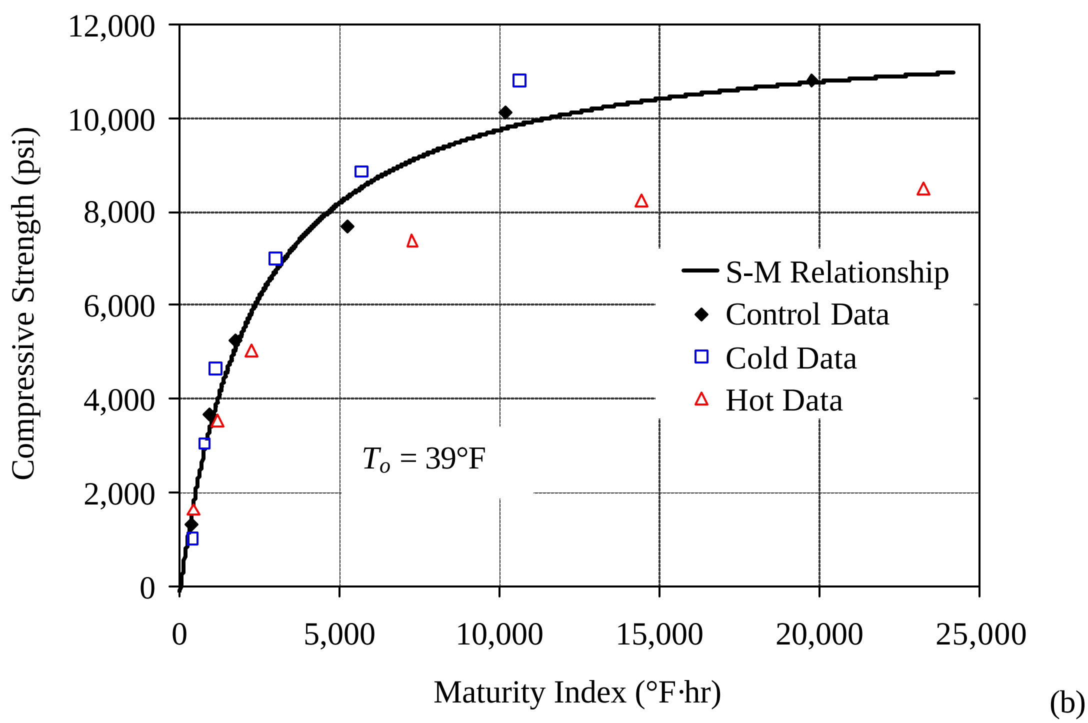
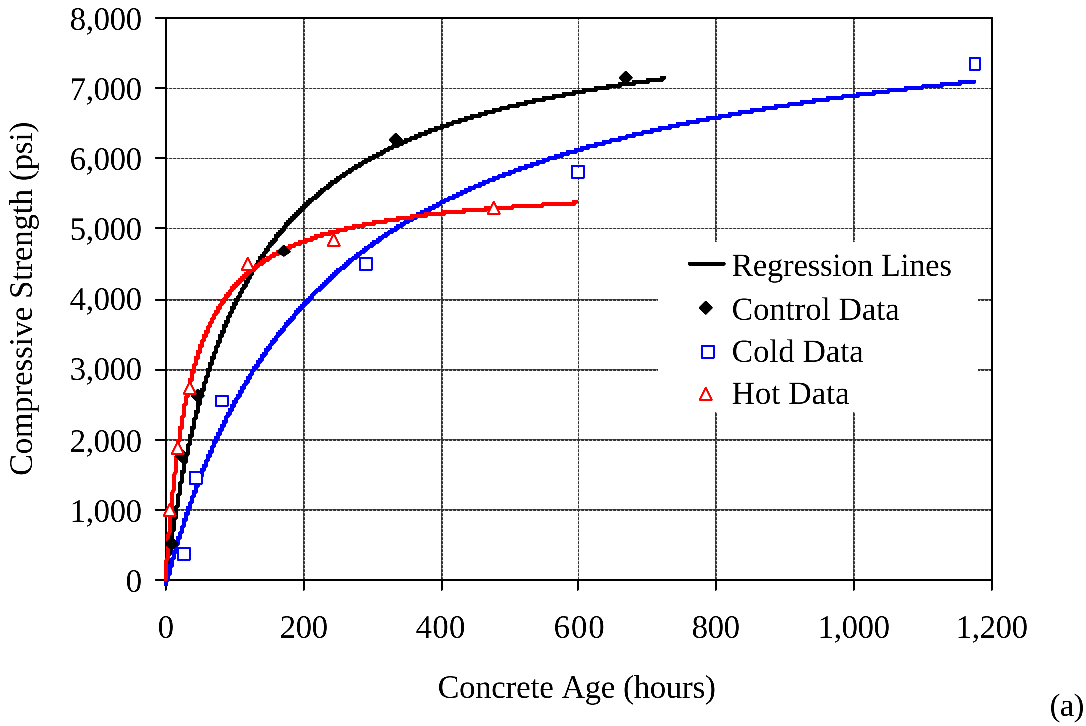


Figure B-9: 70/20/10 - 0.37 mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method



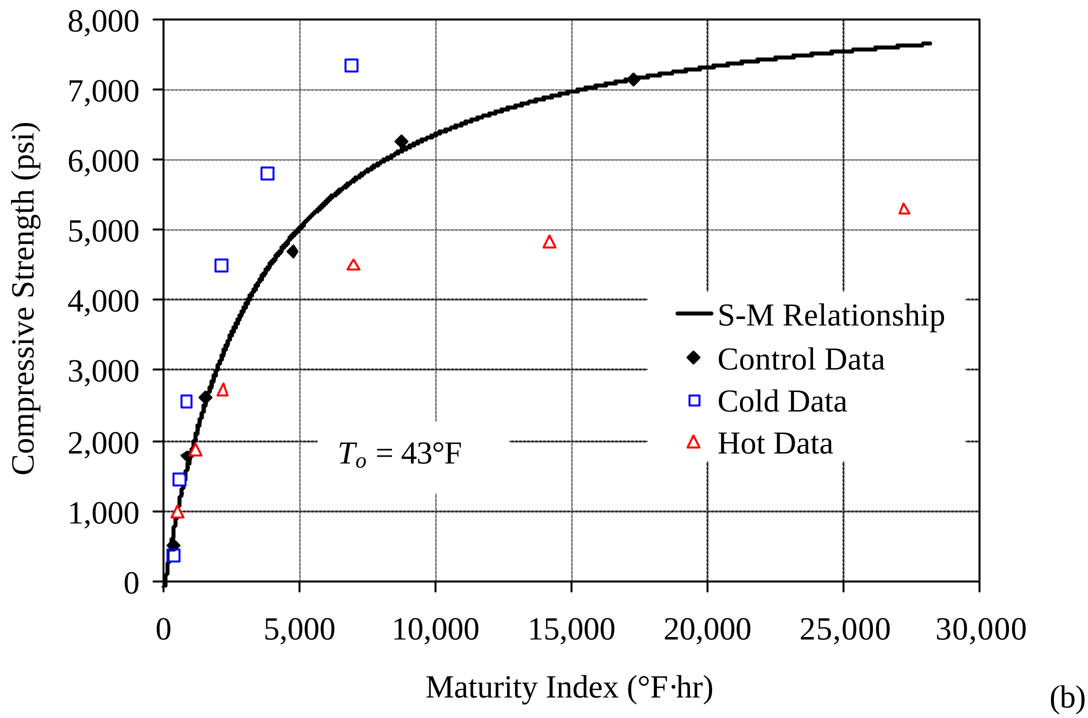


Figure B-10: 70/20/10 - 0.44 mixture, (a) compressive strength vs. age, (b) strength-maturity plot, ASTM C 1074 method

APPENDIX C: STRENGTH-MATURITY RELATIONSHIPS FOR ARRHENIUS MATURITY FUNCTION, ASTM C 1074 METHOD

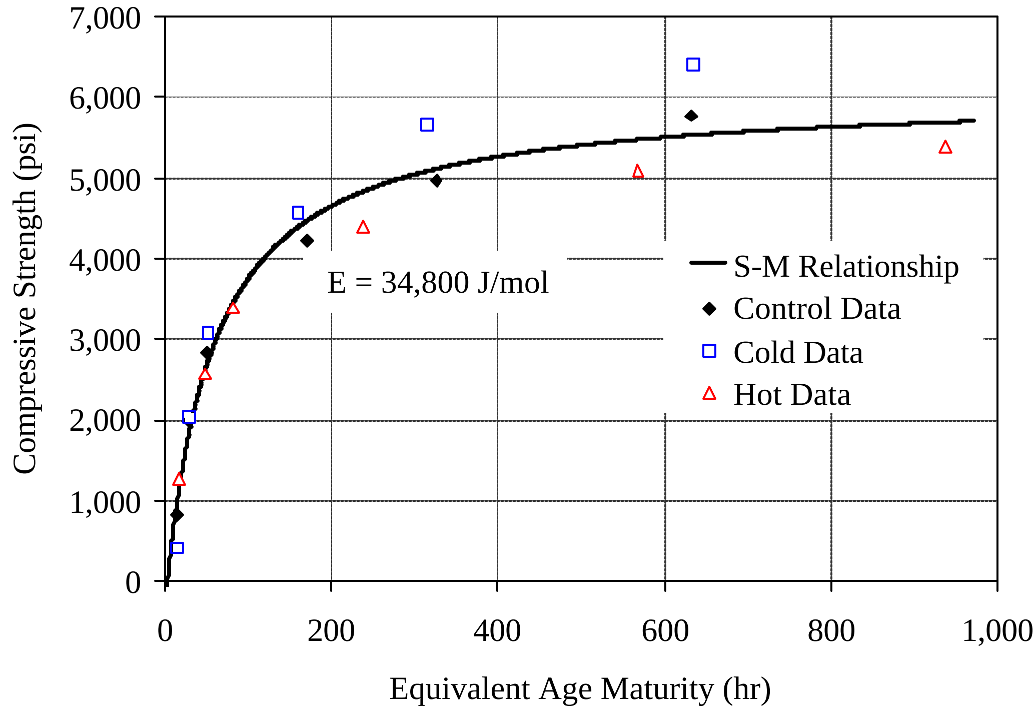


Figure C-1: Strength-maturity plot, ASTM C 1074 method for Type I - 0.44 mixture

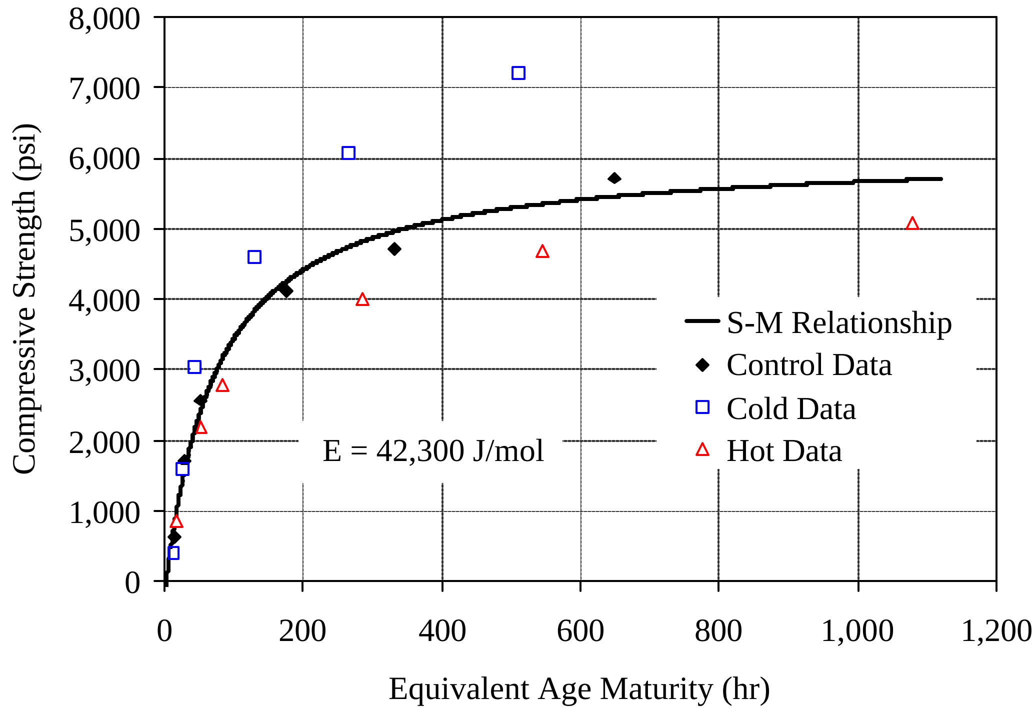


Figure C-2: Strength-maturity plot, ASTM C 1074 method for Type I - 0.48 mixture

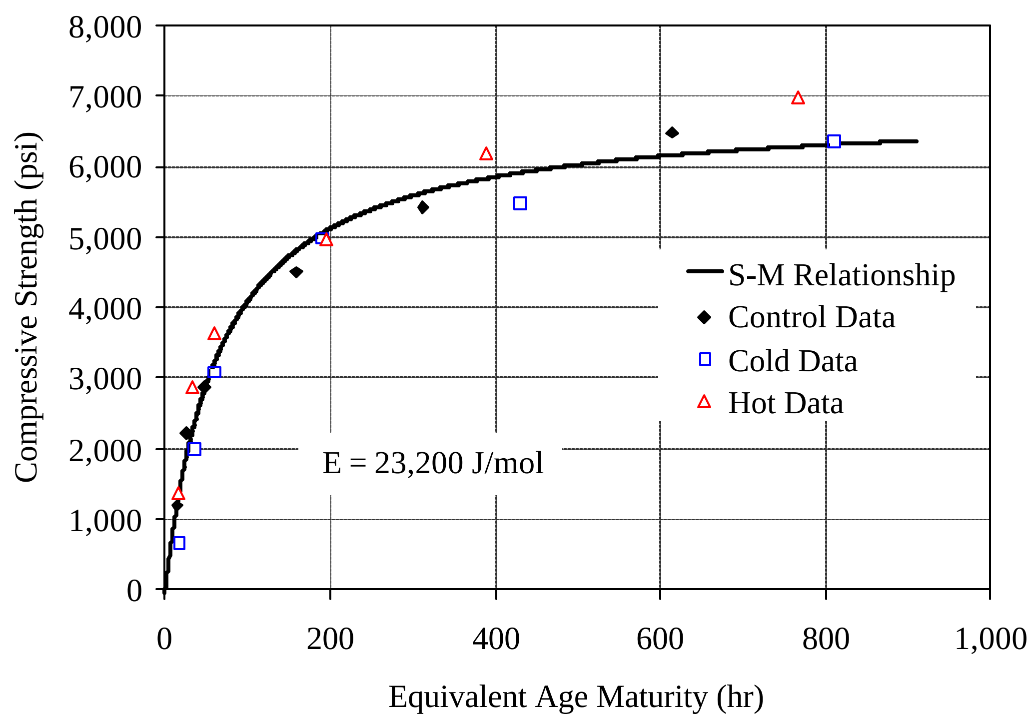


Figure C-3: Strength-maturity plot, ASTM C 1074 method for 30% F mixture

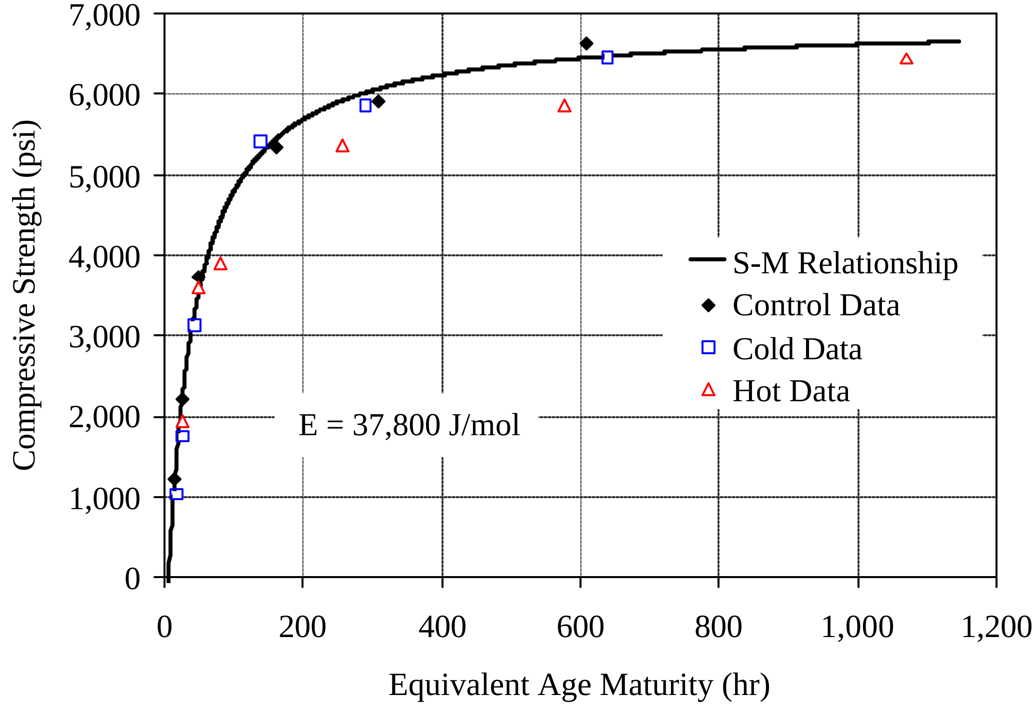


Figure C-4: Strength-maturity plot, ASTM C 1074 method for 20% C mixture

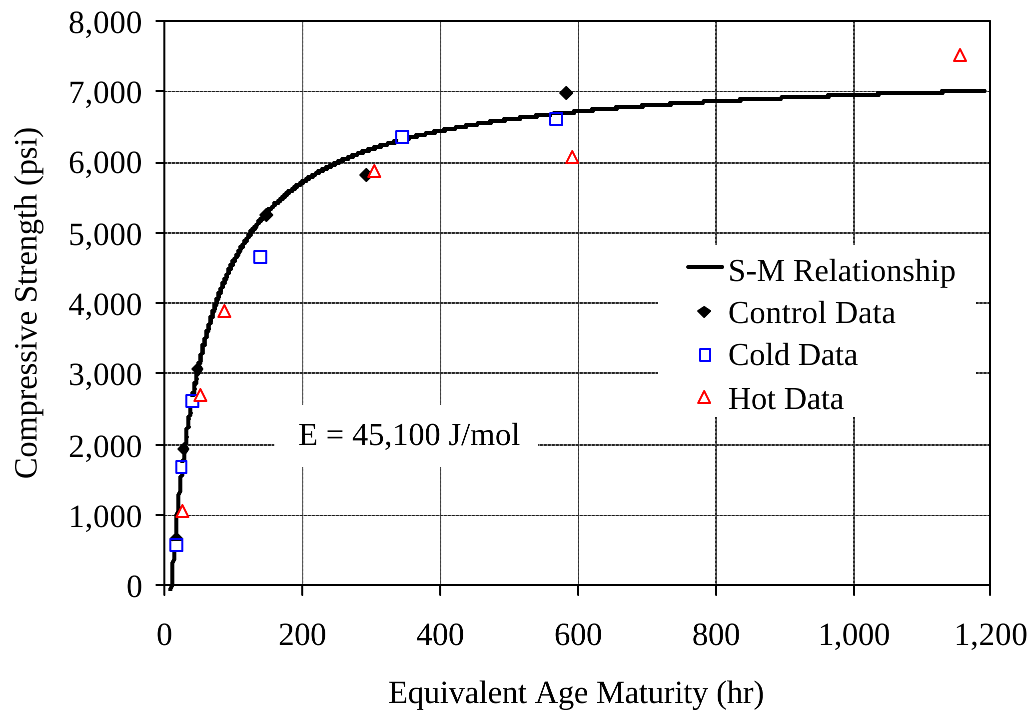


Figure C-5: Strength-maturity plot, ASTM C 1074 method for 30% C mixture

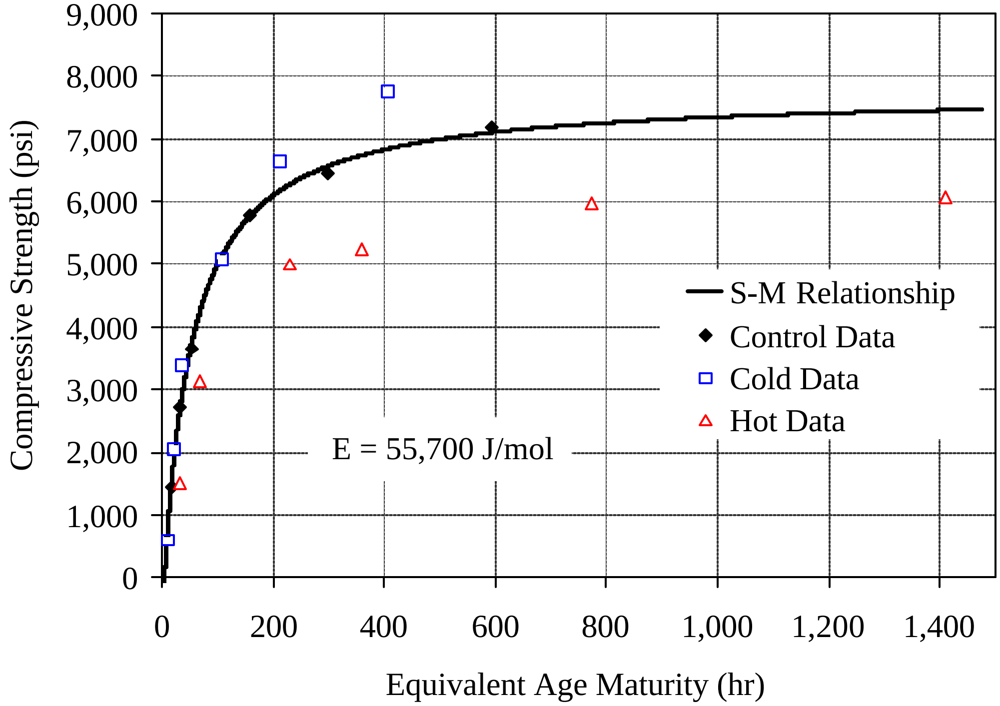


Figure C-6: Strength-maturity plot, ASTM C 1074 method for 30% Slag mixture

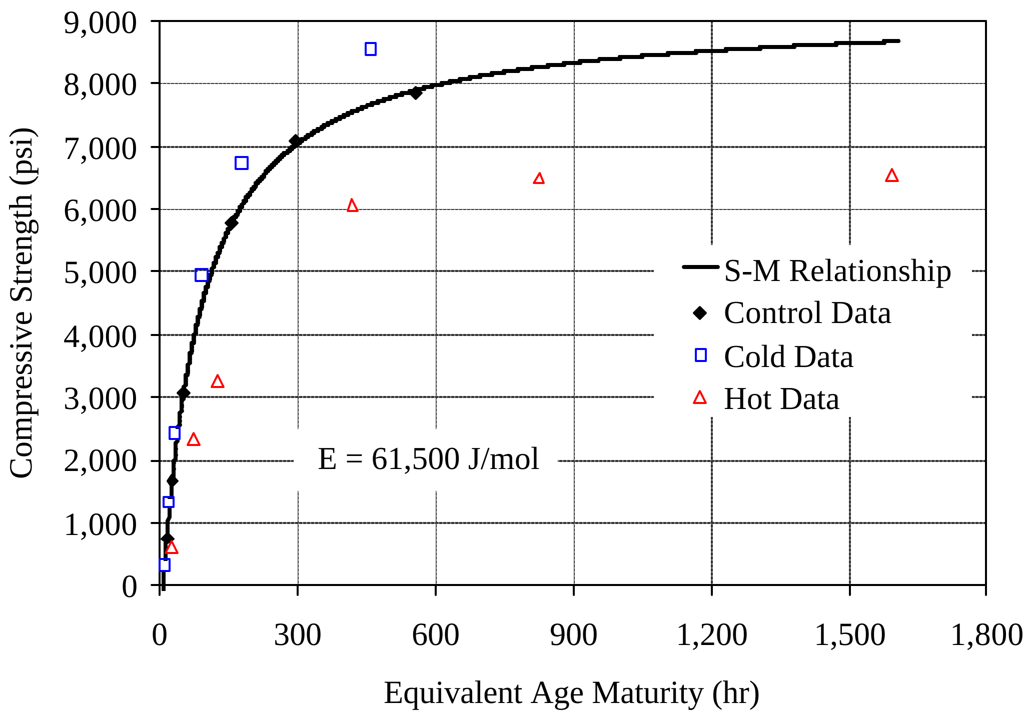


Figure C-7: Strength-maturity plot, ASTM C 1074 method for 50% Slag mixture

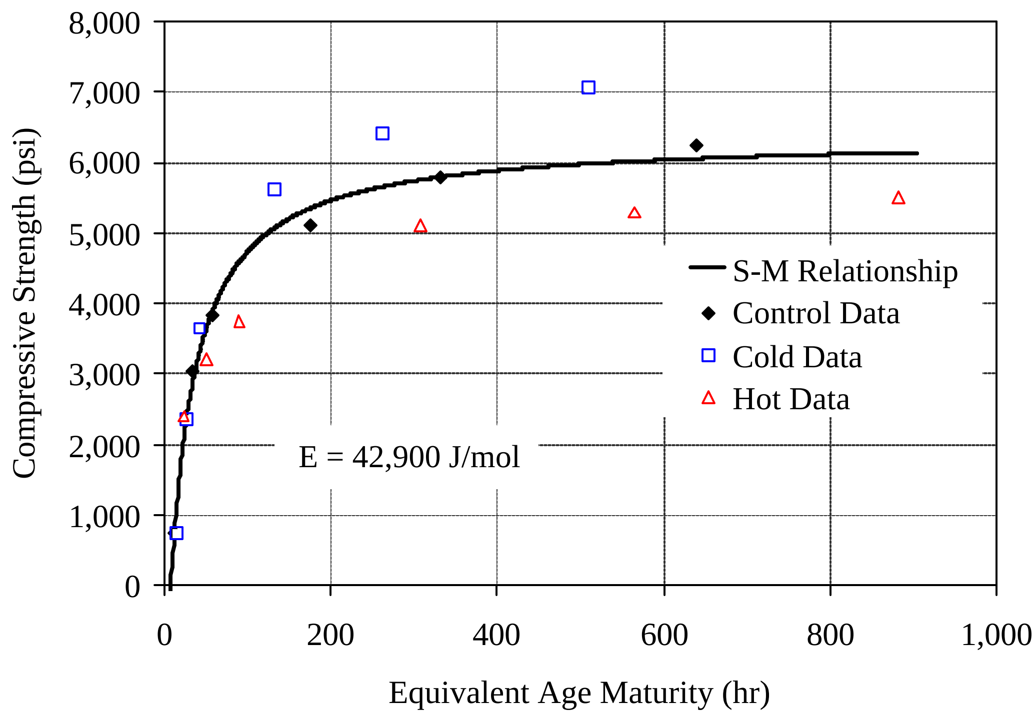


Figure C-8: Strength-maturity plot, ASTM C 1074 method for Type III - 0.44 mixture

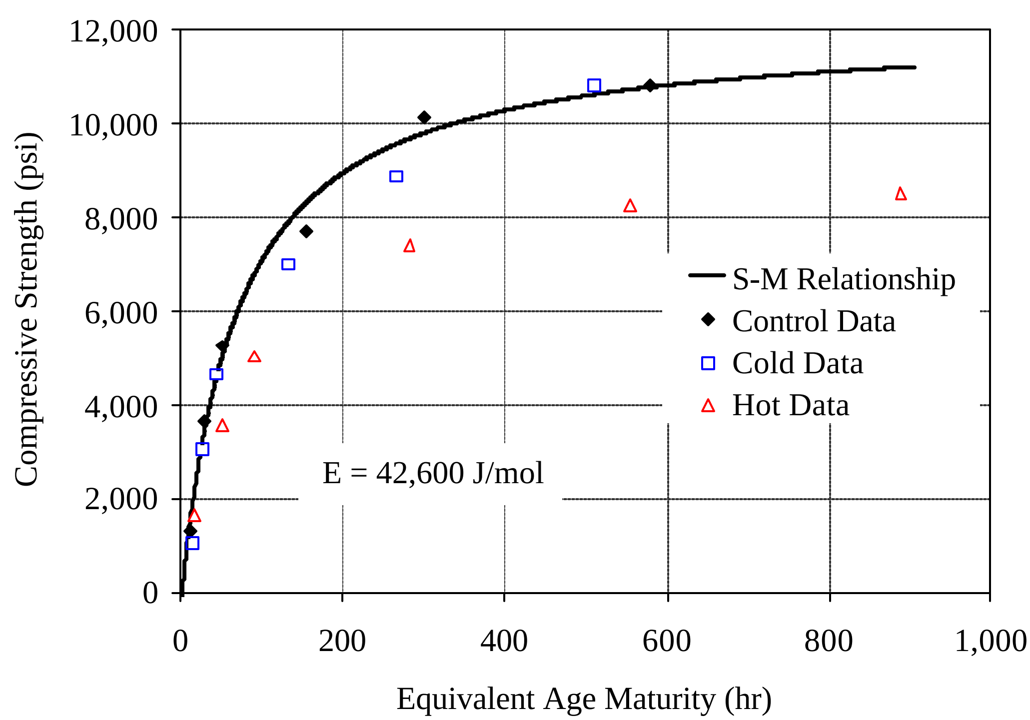


Figure C-9: Strength-maturity plot, ASTM C 1074 method for 70/20/10 - 0.37 mixture

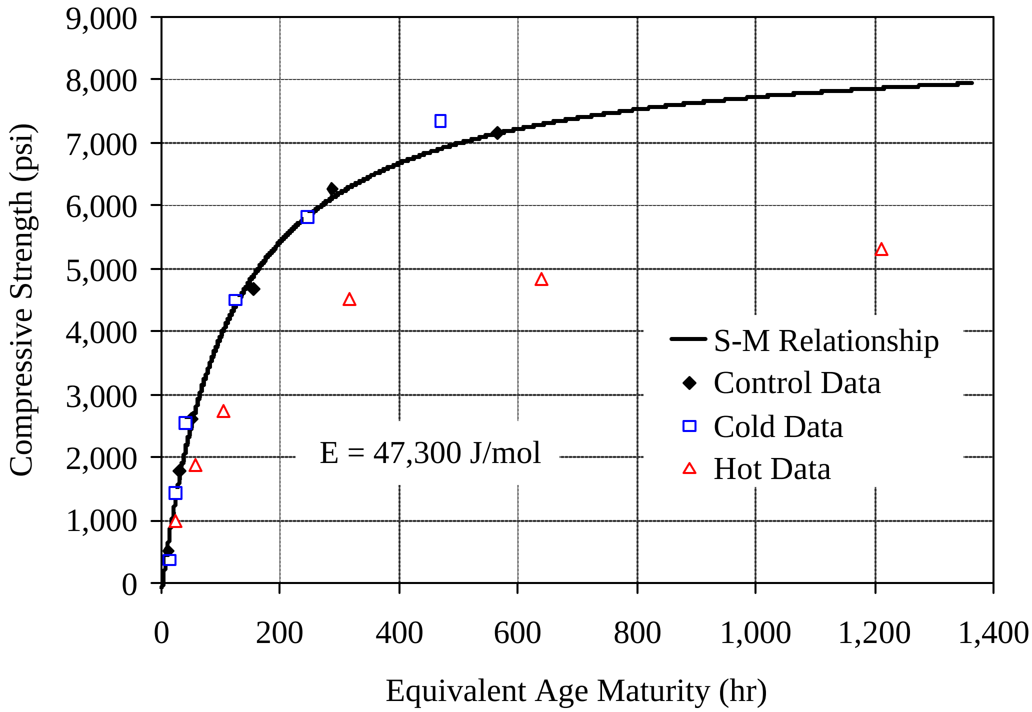


Figure C-10: Strength-maturity plot, ASTM C 1074 method for 70/20/10 - 0.44 mixture

APPENDIX D: ERROR TABLES FOR ASTM C 1074 METHOD

Table D-1: Error using NSM function based on ASTM C 1074 methods for the Type I - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	830	990	160	19	190	8
	1.0	1990	1800	-190	-10		
	2.0	2840	2710	-130	-5		
	7.3	4210	4470	260	6		
	14.2	4970	5110	140	3		
	28.0	5760	5520	-240	-4		
Cold	0.9	420	800	380	90	670	30
	1.9	2050	1660	-390	-19		
	3.5	3090	2410	-680	-22		
	12.4	4580	3980	-600	-13		
	25.0	5670	4760	-910	-16		
	49.2	6410	5360	-1050	-16		
Hot	0.3	1270	930	-340	-27	280	10
	0.9	2570	2300	-270	-11		
	1.5	3390	3160	-230	-7		
	5.0	4380	4680	300	7		
	12.1	5090	5390	300	6		
	20.1	5390	5630	240	4		

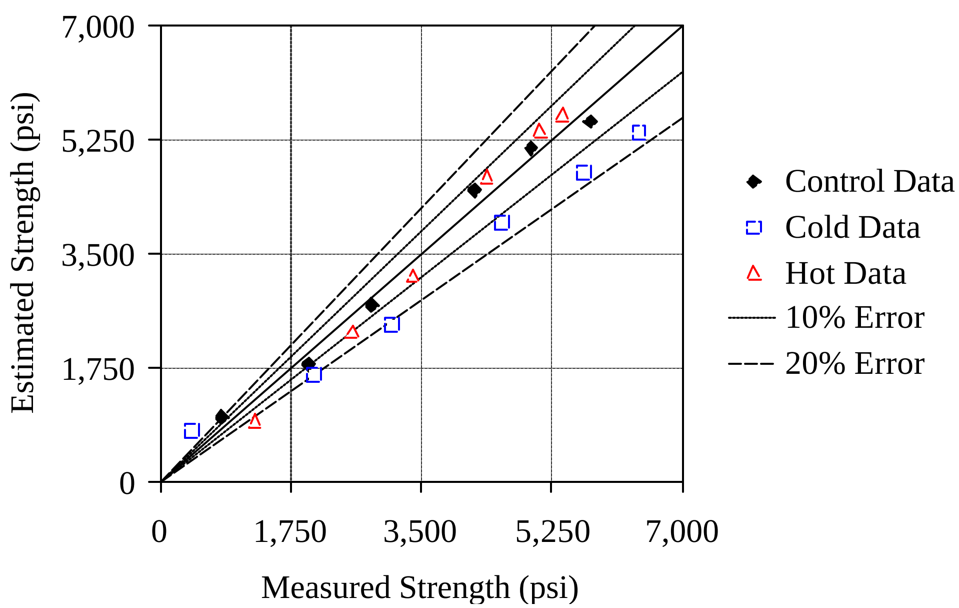


Figure D-1: Estimated strength versus actual strength for Type I - 0.44 mixture

Table D-2: Error using NSM function based on ASTM C 1074 methods for the Type I - 0.48 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	630	780	150	24	190	9
	1.0	1710	1540	-170	-10		
	2.0	2570	2440	-130	-5		
	7.4	4120	4260	140	3		
	14.2	4700	4960	260	6		
	28.3	5710	5450	-260	-5		
Cold	0.9	410	580	170	41	1247	34
	1.9	1600	1210	-390	-24		
	3.6	3040	1770	-1270	-42		
	12.0	4610	3170	-1440	-31		
	25.1	6080	4180	-1900	-31		
	49.1	7210	4900	-2310	-32		
Hot	0.3	850	780	-70	-8	302	9
	0.8	2180	1980	-200	-9		
	1.4	2770	2740	-30	-1		
	5.1	4010	4530	520	13		
	9.8	4670	5160	490	10		
	19.8	5080	5580	500	10		

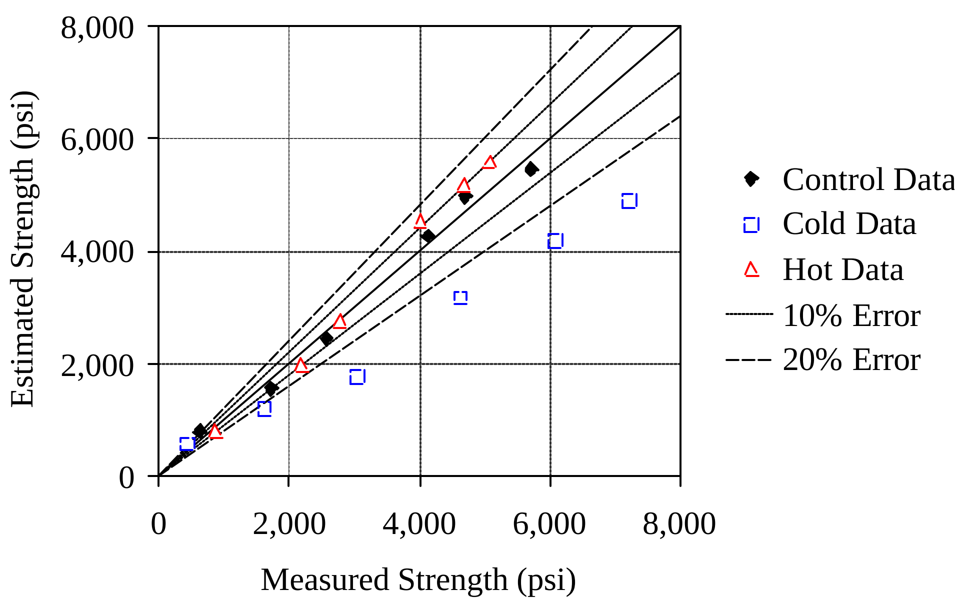


Figure D-2: Estimated strength versus actual strength for Type I - 0.48 mixture

Table D-3: Error using NSM function based on ASTM C 1074 methods for the 30% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1180	1220	40	3	200	6
	1.1	2200	1910	-290	-13		
	2.0	2860	2810	-50	-2		
	7.0	4490	4810	320	7		
	14.1	5420	5620	200	4		
	28.2	6480	6160	-320	-5		
Cold	0.9	670	1250	580	87	240	18
	1.9	1990	2170	180	9		
	3.5	3090	3010	-80	-3		
	12.2	4990	4860	-130	-3		
	25.0	5480	5840	360	7		
	49.0	6350	6250	-100	-2		
Hot	0.4	1350	1220	-130	-10	420	11
	0.8	2860	2180	-680	-24		
	1.5	3620	3080	-540	-15		
	5.0	4960	5000	40	1		
	10.1	6190	5780	-410	-7		
	20.0	6960	6250	-710	-10		

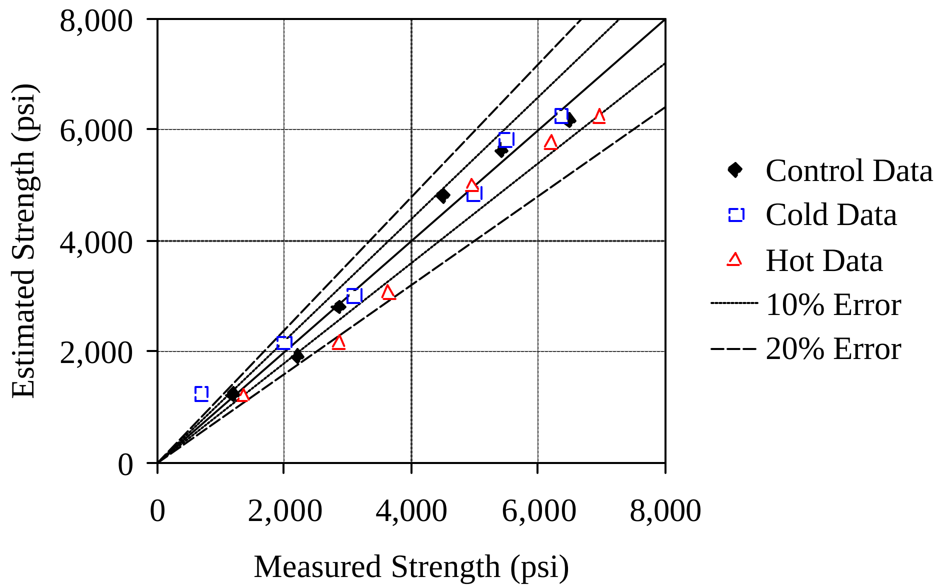


Figure D-3: Estimated strength versus actual strength for 30% F mixture

Table D-4: Error using NSM function based on ASTM C 1074 methods for the 20% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1220	1200	-20	-2	130	3
	1.0	2210	2320	110	5		
	2.0	3730	3540	-190	-5		
	7.0	5330	5440	110	2		
	14.1	5900	6060	160	3		
	28.0	6620	6440	-180	-3		
Cold	1.2	1040	1010	-30	-3	310	8
	1.8	1760	1810	50	3		
	3.4	3140	2610	-530	-17		
	12.0	5410	4590	-820	-15		
	25.9	5870	5560	-310	-5		
	49.0	6460	6330	-130	-2		
Hot	0.5	1930	1780	-150	-8	300	7
	0.8	3600	3040	-560	-16		
	1.4	3900	4030	130	3		
	5.0	5360	5740	380	7		
	10.3	5850	6310	460	8		
	20.0	6440	6570	130	2		

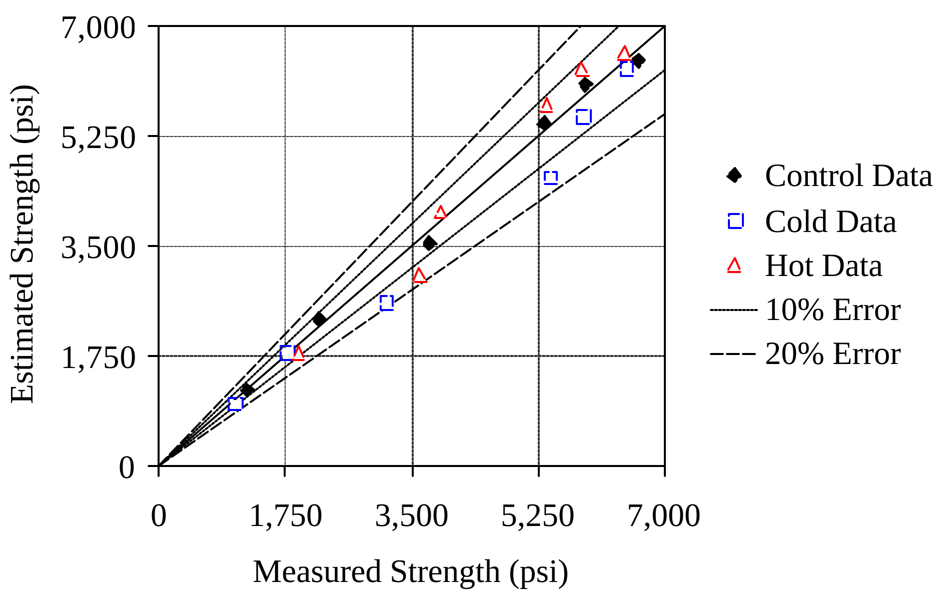


Figure D-4: Estimated strength versus actual strength for 20% C mixture

Table D-5: Error using NSM function based on ASTM C 1074 methods for the 30% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	670	790	120	18	160	6
	1.0	1940	1790	-150	-8		
	2.0	3060	3020	-40	-1		
	7.2	5250	5260	10	0		
	14.1	5820	6160	340	6		
	28.1	6970	6690	-280	-4		
Cold	1.3	570	330	-240	-42	420	22
	1.9	1680	920	-760	-45		
	3.5	2620	1750	-870	-33		
	12.1	4650	4460	-190	-4		
	25.0	6350	6100	-250	-4		
	49.2	6610	6380	-230	-3		
Hot	0.4	1050	1140	90	9	260	6
	0.8	2710	2550	-160	-6		
	1.4	3900	3700	-200	-5		
	5.0	5870	5880	10	0		
	9.9	6070	6520	450	7		
	19.9	7510	6890	-620	-8		

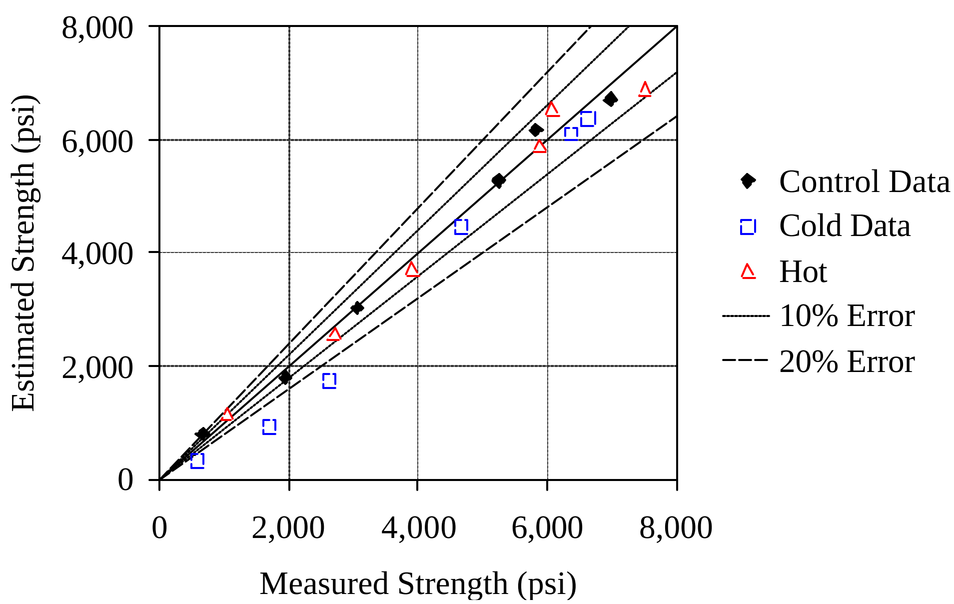


Figure D-5: Estimated strength versus actual strength for 30% C mixture

Table D-6: Error using NSM function based on ASTM C 1074 methods for the 30% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1430	1500	70	5	80	2
	1.0	2730	2580	-150	-5		
	2.0	3650	3700	50	1		
	7.1	5770	5780	10	0		
	14.1	6450	6560	110	2		
	28.0	7180	7090	-90	-1		
Cold	0.9	610	640	30	5	1240	26
	1.9	2050	1450	-600	-29		
	3.6	3400	2040	-1360	-40		
	12.2	5080	3590	-1490	-29		
	25.1	6640	4700	-1940	-29		
	49.4	7750	5750	-2000	-26		
Hot	0.4	1500	1760	260	17	730	15
	0.8	3130	3260	130	4		
	2.9	4990	5640	650	13		
	4.9	5240	6300	1060	20		
	10.8	5960	6990	1030	17		
	19.8	6060	7300	1240	20		

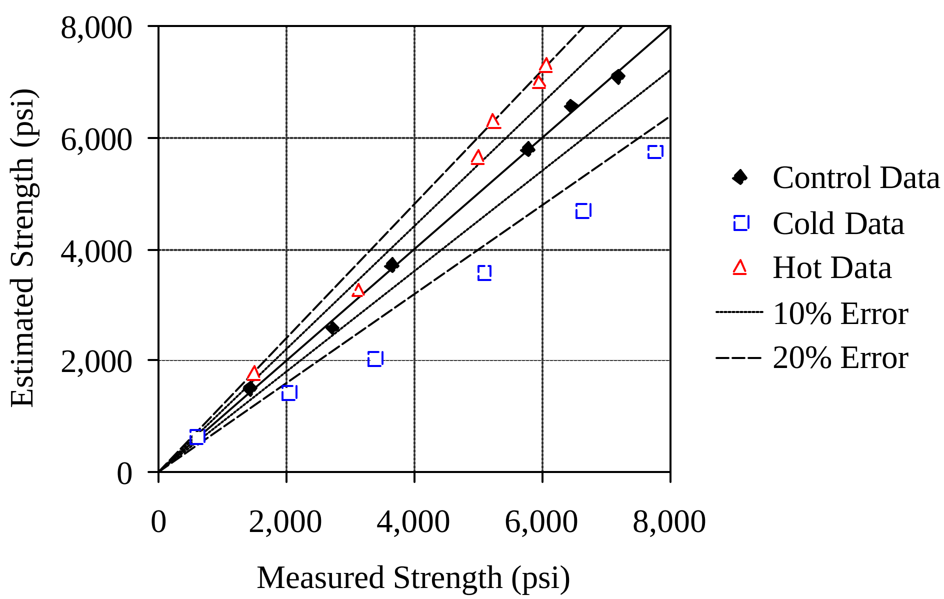


Figure D-6: Estimated strength versus actual strength for 30% Slag mixture

Table D-7: Error using NSM function based on ASTM C 1074 methods for the 50% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	760	740	-20	-3	30	1
	1.0	1680	1690	10	1		
	2.1	3060	3070	10	0		
	7.2	5770	5790	20	0		
	14.2	7090	7020	-70	-1		
	28.1	7840	7880	40	1		
Cold	0.9	330	0	-330	-100	1870	63
	1.9	1340	280	-1060	-79		
	3.4	2450	740	-1710	-70		
	12.3	4960	2010	-2950	-59		
	24.9	6740	3270	-3470	-51		
	49.0	8560	6880	-1680	-20		
Hot	0.3	610	770	160	26	810	20
	0.8	2330	2660	330	14		
	1.4	3240	3900	660	20		
	5.0	6060	6710	650	11		
	10.1	6490	7730	1240	19		
	19.8	6540	8350	1810	28		

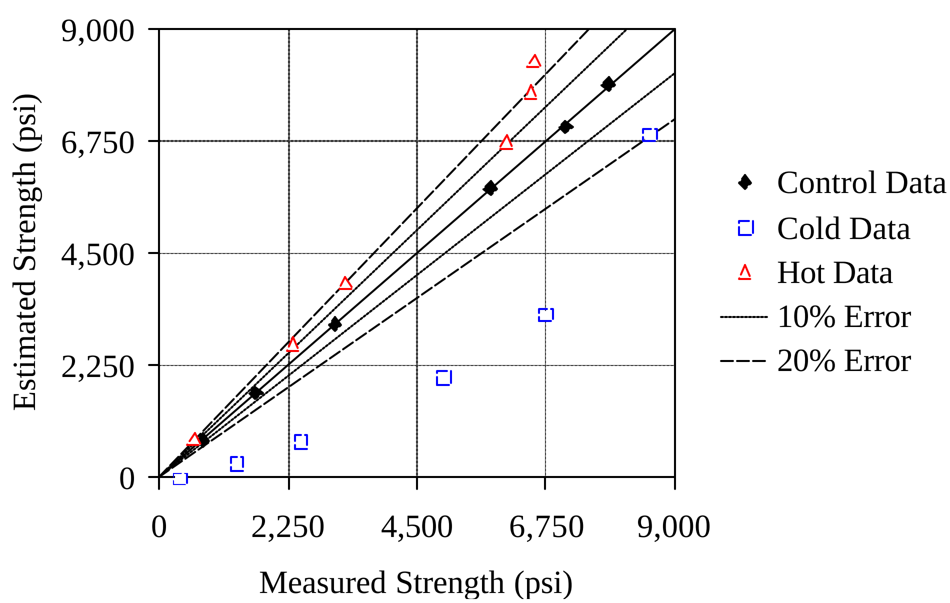


Figure D-7: Estimated strength versus actual strength for 50% Slag mixture

Table D-8: Error using NSM function based on ASTM C 1074 methods for the Type III - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	730	800	70	10	150	5
	1.0	3040	2820	-220	-7		
	2.0	3820	3920	100	3		
	7.2	5100	5370	270	5		
	14.0	5780	5790	10	0		
	28.2	6240	6030	-210	-3		
Cold	1.0	750	980	230	31	660	17
	1.8	2370	2230	-140	-6		
	3.4	3660	3090	-570	-16		
	12.1	5630	4800	-830	-15		
	24.9	6430	5450	-980	-15		
	49.2	7070	5840	-1230	-17		
Hot	0.3	2400	1300	-1100	-46	540	15
	0.7	3210	3020	-190	-6		
	1.4	3740	4110	370	10		
	5.3	5100	5560	460	9		
	10.0	5290	5890	600	11		
	20.2	5500	6040	540	10		

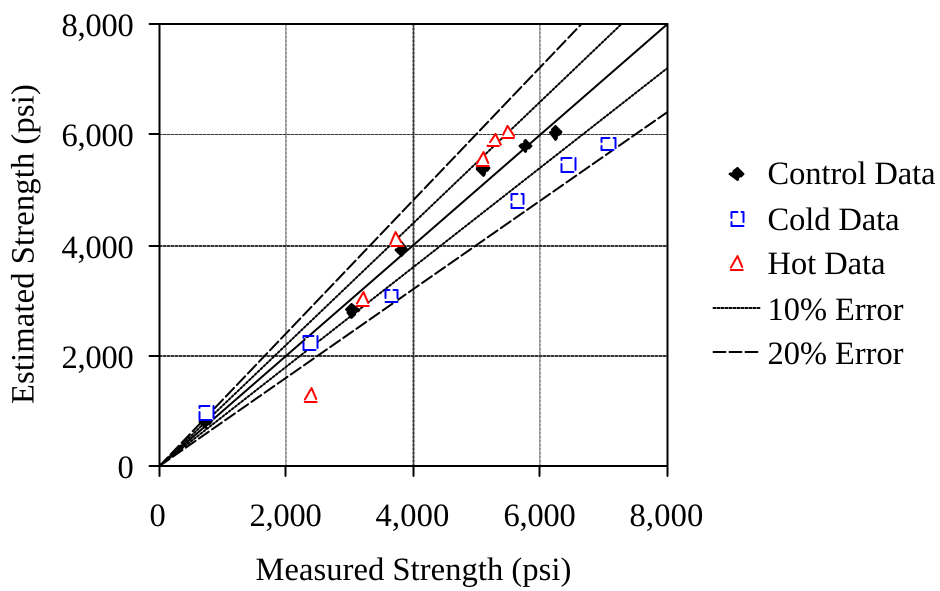


Figure D-8: Estimated strength versus actual strength for Type III - 0.44 mixture

Table D-9: Error using NSM function based on ASTM C 1074 methods for the 70/20/10 - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1300	1550	250	19	300	7
	1.0	3650	3320	-330	-9		
	2.1	5240	5050	-190	-4		
	7.0	7670	8320	650	8		
	14.1	10110	9780	-330	-3		
	28.1	10800	10750	-50	0		
Cold	0.9	1040	1520	480	46	538	15
	1.8	3060	2810	-250	-8		
	3.5	4650	3790	-860	-18		
	12.2	7000	6700	-300	-4		
	25.0	8870	8500	-370	-4		
	49.2	10820	9850	-970	-9		
Hot	0.3	1640	1650	10	1	1255	18
	0.7	3540	4010	470	13		
	1.4	5020	5820	800	16		
	4.9	7390	9090	1700	23		
	9.8	8240	10350	2110	26		
	20.0	8490	10930	2440	29		

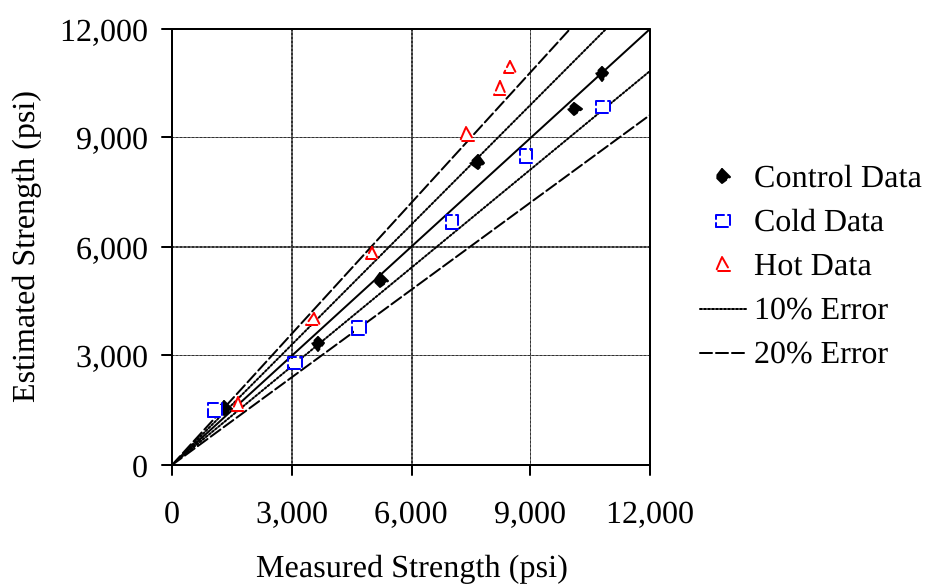


Figure D-9: Estimated strength versus actual strength for 70/20/10 - 0.37 mixture

Table D-10: Error using NSM function based on ASTM C 1074 methods for the 70/20/10 - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	510	650	140	27	120	8
	1.0	1770	1600	-170	-10		
	2.0	2610	2540	-70	-3		
	7.2	4680	4910	230	5		
	13.9	6250	6120	-130	-2		
	27.9	7140	7140	0	0		
Cold	1.0	370	620	250	68	1020	35
	1.8	1450	1070	-380	-26		
	3.4	2560	1500	-1060	-41		
	12.1	4510	3150	-1360	-30		
	24.9	5820	4420	-1400	-24		
	48.9	7360	5680	-1680	-23		
Hot	0.3	980	920	-60	-6	1060	25
	0.8	1860	2050	190	10		
	1.5	2720	3230	510	19		
	5.0	4500	5700	1200	27		
	10.2	4840	6890	2050	42		
	19.9	5300	7620	2320	44		

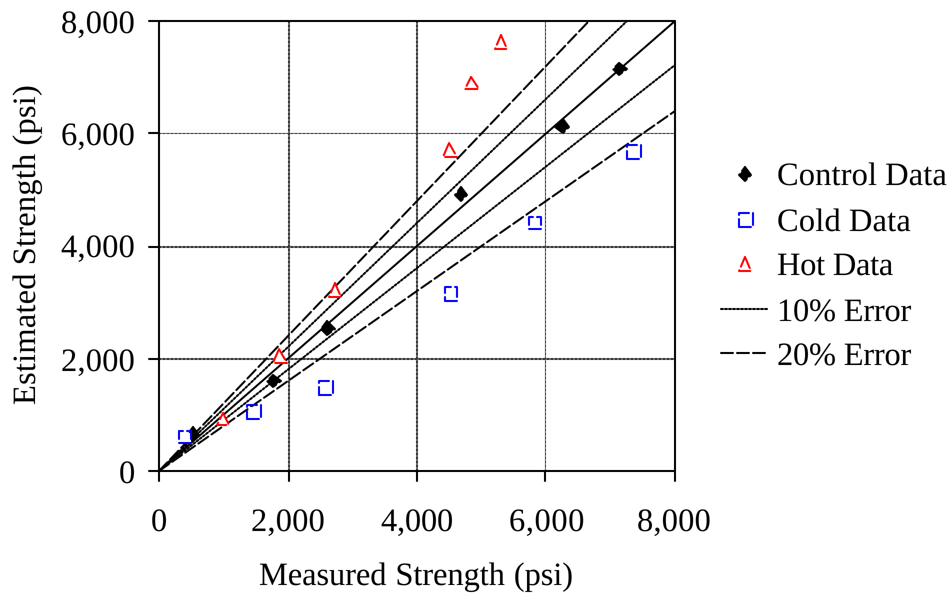


Figure D-10: Estimated strength versus actual strength for 70/20/10 - 0.44 mixture

Table D-11: Error using AM function based on ASTM C 1074 methods for the Type I - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	830	980	150	18	180	7
	1.0	1990	1800	-190	-10		
	2.0	2840	2710	-130	-5		
	7.3	4210	4460	250	6		
	14.2	4970	5110	140	3		
	28.0	5760	5530	-230	-4		
Cold	0.9	420	900	480	114	460	28
	1.9	2050	1830	-220	-11		
	3.5	3090	2690	-400	-13		
	12.4	4580	4380	-200	-4		
	25.0	5670	5080	-590	-10		
	49.2	6410	5530	-880	-14		
Hot	0.3	1270	1150	-120	-9	220	6
	0.9	2570	2610	40	2		
	1.5	3390	3450	60	2		
	5.0	4380	4830	450	10		
	12.1	5090	5470	380	7		
	20.1	5390	5680	290	5		

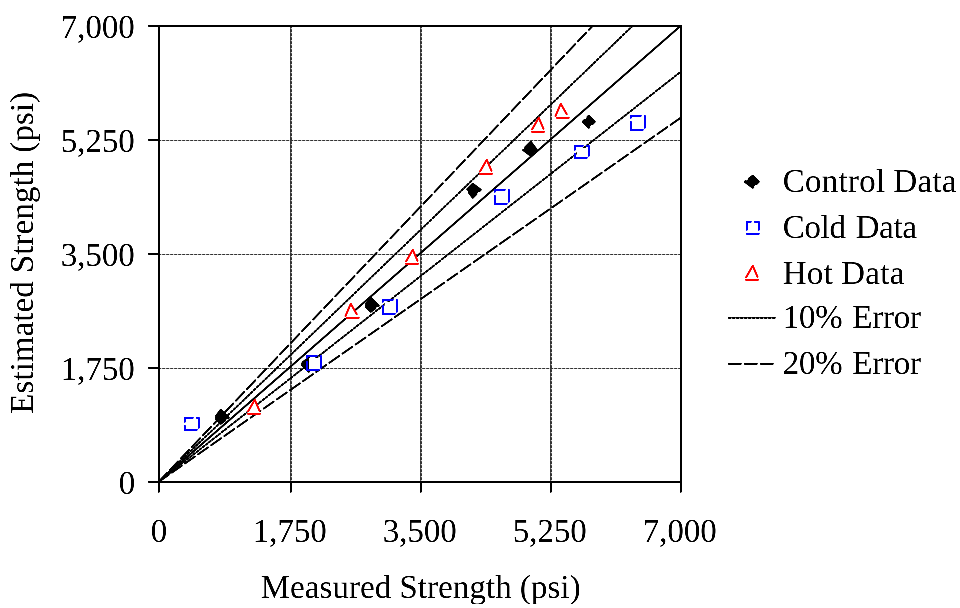


Figure D-11: Estimated strength versus actual strength for Type I - 0.44 mixture

Table D-12: Error using AM function based on ASTM C 1074 methods for the Type I - 0.48 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	630	780	150	24	1820	9
	1.0	1710	1550	-160	-9		
	2.0	2570	2440	-130	-5		
	7.4	4120	4250	130	3		
	14.2	4700	4960	260	6		
	28.3	5710	5450	-260	-5		
Cold	0.9	410	670	260	63	910	29
	1.9	1600	1380	-220	-14		
	3.6	3040	2110	-930	-31		
	12.0	4610	3810	-800	-17		
	25.1	6080	4730	-1350	-22		
	49.1	7210	5300	-1910	-26		
Hot	0.3	850	1000	150	18	490	15
	0.8	2180	2450	270	12		
	1.4	2770	3180	410	15		
	5.1	4010	4810	800	20		
	9.8	4670	5340	670	14		
	19.8	5080	5690	610	12		

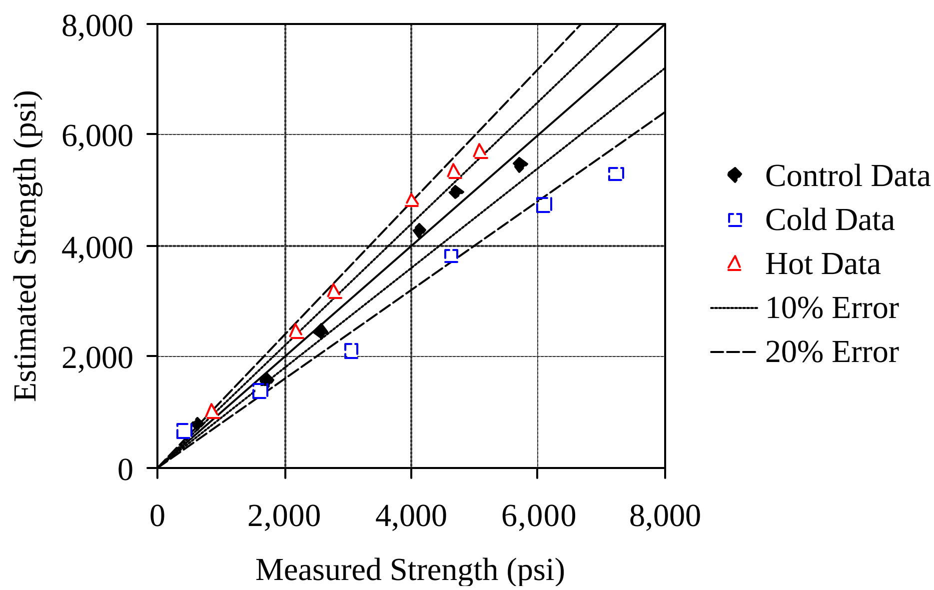


Figure D-12: Estimated strength versus actual strength for Type I - 0.48 mixture

Table D-13: Error using AM function based on ASTM C 1074 methods for the 30% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1180	1220	40	3	200	6
	1.1	2200	1910	-290	-13		
	2.0	2860	2810	-50	-2		
	7.0	4490	4810	320	7		
	14.1	5420	5620	200	4		
	28.2	6480	6160	-320	-5		
Cold	0.9	670	1320	650	97	260	21
	1.9	1990	2280	290	15		
	3.5	3090	3170	80	3		
	12.2	4990	5040	50	1		
	25.0	5480	5900	420	8		
	49.0	6350	6300	-50	-1		
Hot	0.4	1350	1290	-60	-4	370	9
	0.8	2860	2280	-580	-20		
	1.5	3620	3190	-430	-12		
	5.0	4960	5080	120	2		
	10.1	6190	5820	-370	-6		
	20.0	6960	6280	-680	-10		

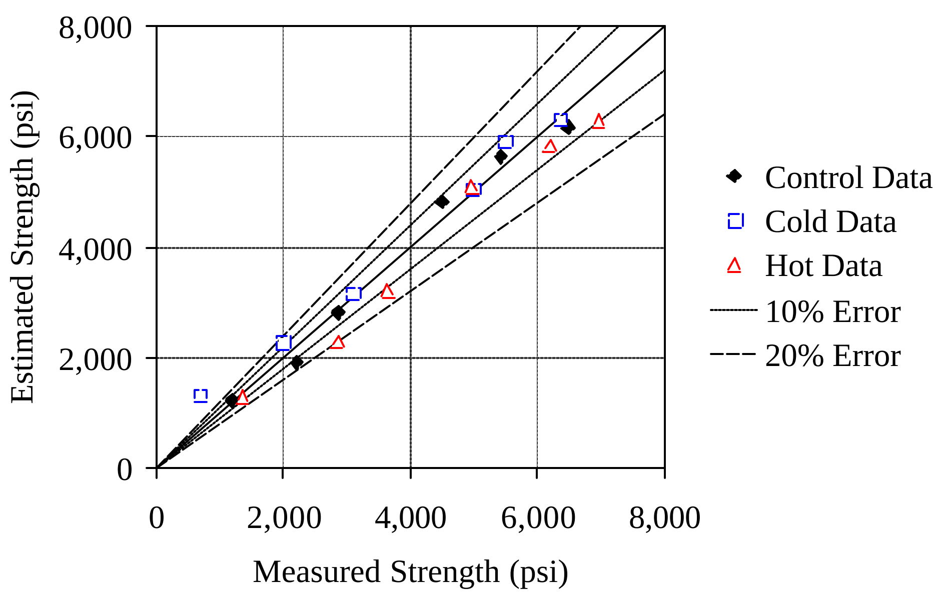


Figure D-13: Estimated strength versus actual strength for 30% F mixture

Table D-14: Error using AM function based on ASTM C 1074 methods for the 20% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1220	1200	-20	-2	130	3
	1.0	2210	2330	120	5		
	2.0	3730	3540	-190	-5		
	7.0	5330	5440	110	2		
	14.1	5900	6060	160	3		
	28.0	6620	6440	-180	-3		
Cold	1.2	1040	1310	270	26	180	9
	1.8	1760	2140	380	22		
	3.4	3140	3230	90	3		
	12.0	5410	5240	-170	-3		
	25.9	5870	6010	140	2		
	49.0	6460	6460	0	0		
Hot	0.5	1930	2210	280	15	360	9
	0.8	3600	3530	-70	-2		
	1.4	3900	4420	520	13		
	5.0	5360	5910	550	10		
	10.3	5850	6420	570	10		
	20.0	6440	6630	190	3		

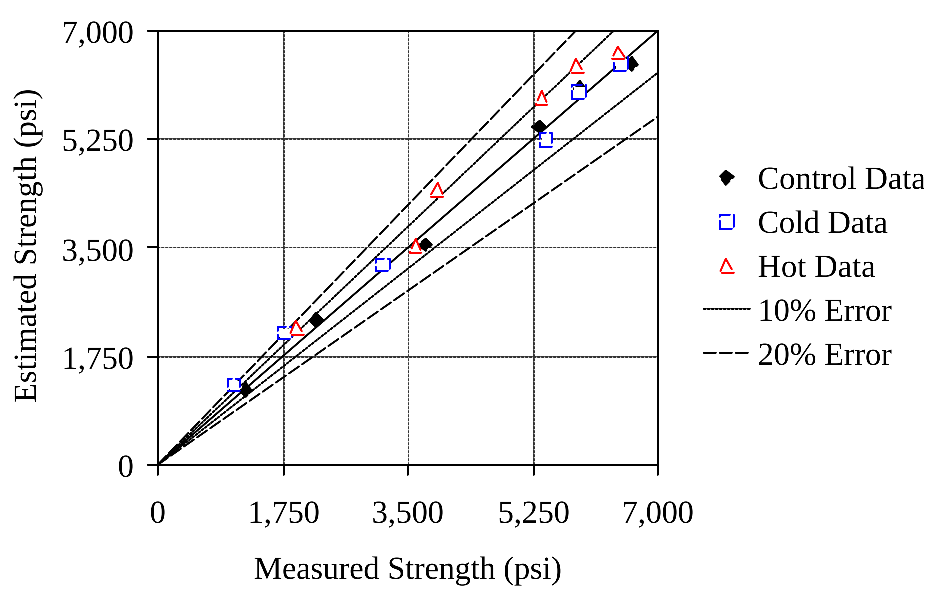


Figure D-14: Estimated strength versus actual strength for 20% C mixture

Table D-15: Error using AM function based on ASTM C 1074 methods for the 30% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	670	780	110	16	150	6
	1.0	1940	1800	-140	-7		
	2.0	3060	3020	-40	-1		
	7.2	5250	5260	10	0		
	14.1	5820	6150	330	6		
	28.1	6970	6690	-280	-4		
Cold	1.3	570	740	170	30	170	9
	1.9	1680	1480	-200	-12		
	3.5	2620	2620	0	0		
	12.1	4650	5160	510	11		
	25.0	6350	6310	-40	-1		
	49.2	6610	6680	70	1		
Hot	0.4	1050	1610	560	53	500	18
	0.8	2710	3250	540	20		
	1.4	3900	4300	400	10		
	5.0	5870	6200	330	6		
	9.9	6070	6700	630	10		
	19.9	7510	6990	-520	-7		

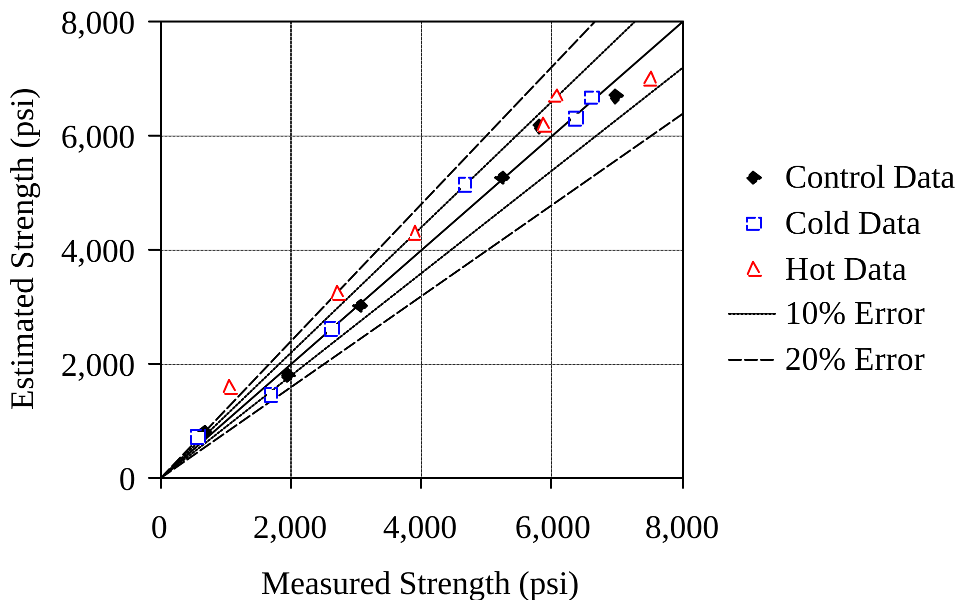


Figure D-15: Estimated strength versus actual strength for 30% C mixture

Table D-16: Error using AM function based on ASTM C 1074 methods for the 30% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1430	1490	60	4	70	2
	1.0	2730	2610	-120	-4		
	2.0	3650	3700	50	1		
	7.1	5770	5770	0	0		
	14.1	6450	6560	110	2		
	28.0	7180	7100	-80	-1		
Cold	0.9	610	840	230	38	380	13
	1.9	2050	1900	-150	-7		
	3.6	3400	2910	-490	-14		
	12.2	5080	5100	20	0		
	25.1	6640	6150	-490	-7		
	49.4	7750	6830	-920	-12		
Hot	0.4	1500	2660	1160	77	1280	25
	0.8	3130	4250	1120	36		
	2.9	4990	6260	1270	25		
	4.9	5240	6730	1490	28		
	10.8	5960	7230	1270	21		
	19.8	6060	7450	1390	23		

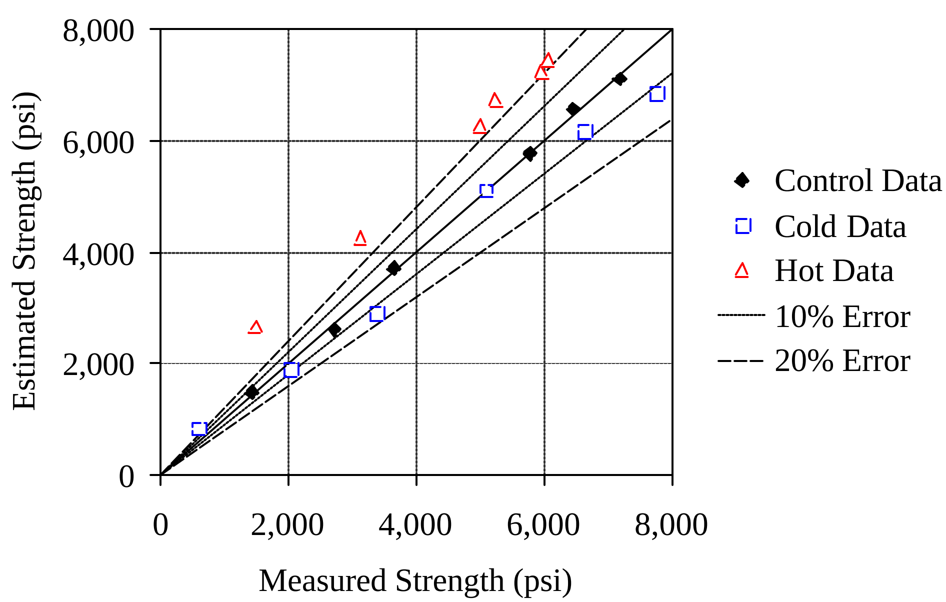


Figure D-16: Estimated strength versus actual strength for 30% Slag mixture

Table D-17: Error using AM function based on ASTM C 1074 methods for the 50% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	760	730	-30	-4	30	1
	1.0	1680	1710	30	2		
	2.1	3060	3070	10	0		
	7.2	5770	5780	10	0		
	14.2	7090	7020	-70	-1		
	28.1	7840	7890	50	1		
Cold	0.9	330	100	-230	-70	550	26
	1.9	1340	950	-390	-29		
	3.4	2450	1870	-580	-24		
	12.3	4960	4470	-490	-10		
	24.9	6740	6050	-690	-10		
	49.0	8560	7660	-900	-11		
Hot	0.3	610	1570	960	157	1660	62
	0.8	2330	3950	1620	70		
	1.4	3240	5250	2010	62		
	5.0	6060	7550	1490	25		
	10.1	6490	8260	1770	27		
	19.8	6540	8660	2120	32		

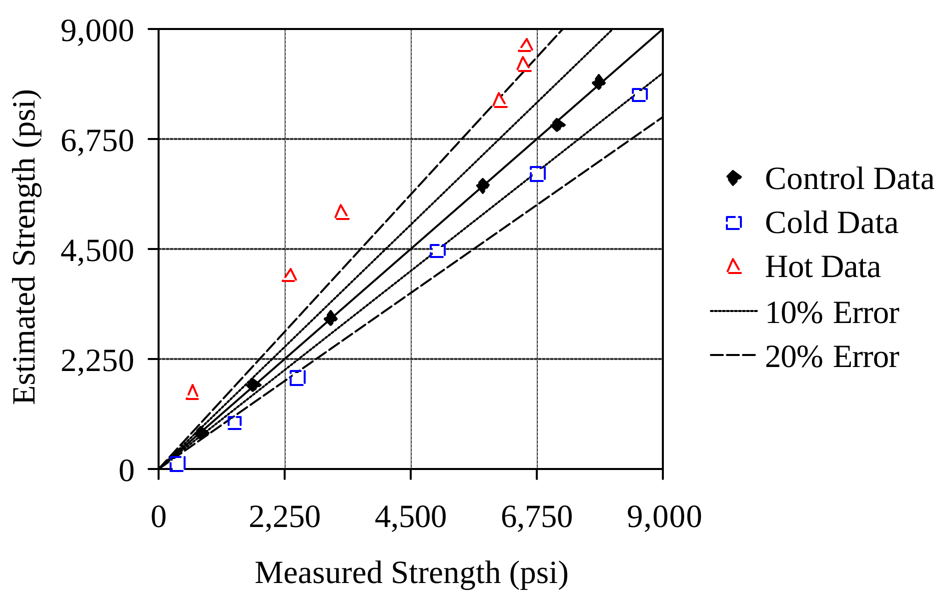


Figure D-17: Estimated strength versus actual strength for 50% Slag mixture

Table D-18: Error using AM function based on ASTM C 1074 methods for the Type III - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	730	790	60	8	130	4
	1.0	3040	2850	-190	-6		
	2.0	3820	3890	70	2		
	7.2	5100	5350	250	5		
	14.0	5780	5790	10	0		
	28.2	6240	6050	-190	-3		
Cold	1.0	750	970	220	29	530	14
	1.8	2370	2230	-140	-6		
	3.4	3660	3270	-390	-11		
	12.1	5630	5050	-580	-10		
	24.9	6430	5650	-780	-12		
	49.2	7070	5980	-1090	-15		
Hot	0.3	2400	2070	-330	-14	610	15
	0.7	3210	3690	480	15		
	1.4	3740	4590	850	23		
	5.3	5100	5750	650	13		
	10.0	5290	6010	720	14		
	20.2	5500	6130	630	11		

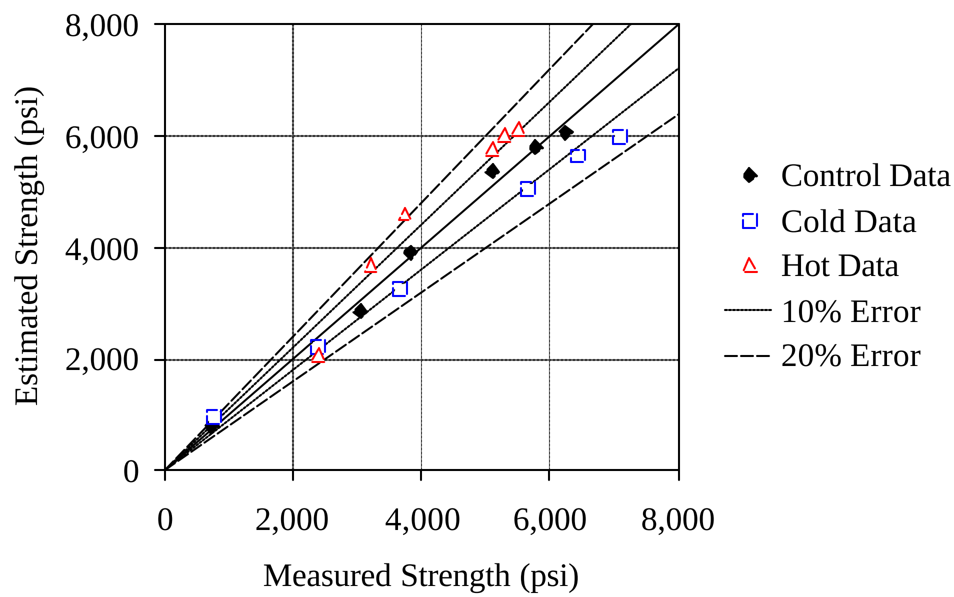


Figure D-18: Estimated strength versus actual strength for Type III - 0.44 mixture

Table D-19: Error using AM function based on ASTM C 1074 methods for the 70/20/10 - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1300	1530	230	18	290	7
	1.0	3650	3340	-310	-8		
	2.1	5240	5050	-190	-4		
	7.0	7670	8310	640	8		
	14.1	10110	9780	-330	-3		
	28.1	10800	10760	-40	0		
Cold	0.9	1040	1650	610	59	430	14
	1.8	3060	3100	40	1		
	3.5	4650	4480	-170	-4		
	12.2	7000	7870	870	12		
	25.0	8870	9540	670	8		
	49.2	10820	10600	-220	-2		
Hot	0.3	1640	2290	650	40	1880	35
	0.7	3540	4980	1440	41		
	1.4	5020	6800	1780	35		
	4.9	7390	9660	2270	31		
	9.8	8240	10710	2470	30		
	20.0	8490	11180	2690	32		

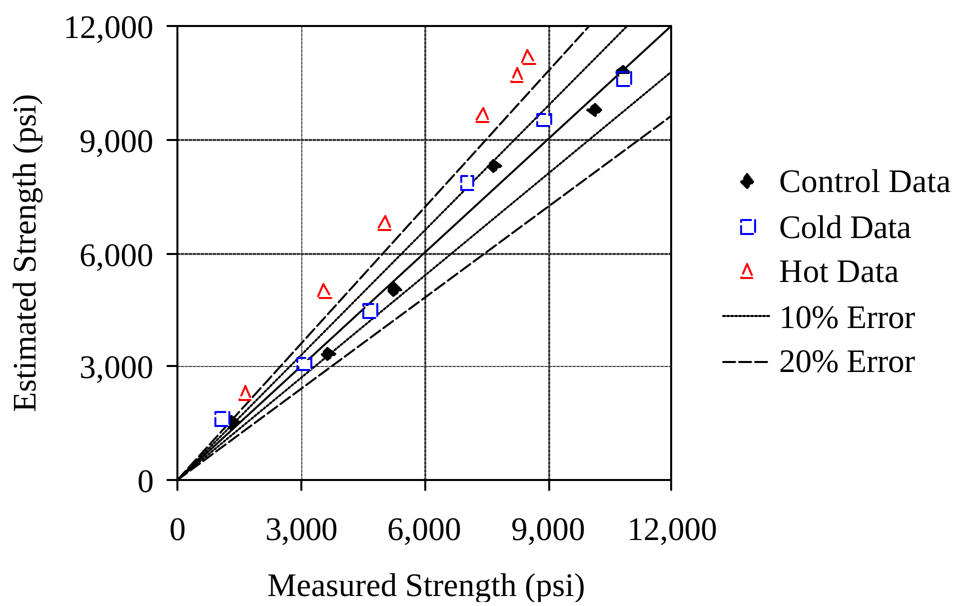


Figure D-19: Estimated strength versus actual strength for 70/20/10 - 0.37 mixture

Table D-20: Error using AM function based on ASTM C 1074 methods for the 70/20/10 - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	510	630	120	24	120	7
	1.0	1770	1620	-150	-8		
	2.0	2610	2540	-70	-3		
	7.2	4680	4900	220	5		
	13.9	6250	6120	-130	-2		
	27.9	7140	7150	10	0		
Cold	1.0	370	730	360	97	280	23
	1.8	1450	1260	-190	-13		
	3.4	2560	2020	-540	-21		
	12.1	4510	4380	-130	-3		
	24.9	5820	5810	-10	0		
	48.9	7360	6900	-460	-6		
Hot	0.3	980	1400	420	43	1580	47
	0.8	1860	2780	920	49		
	1.5	2720	4030	1310	48		
	5.0	4500	6290	1790	40		
	10.2	4840	7290	2450	51		
	19.9	5300	7860	2560	48		

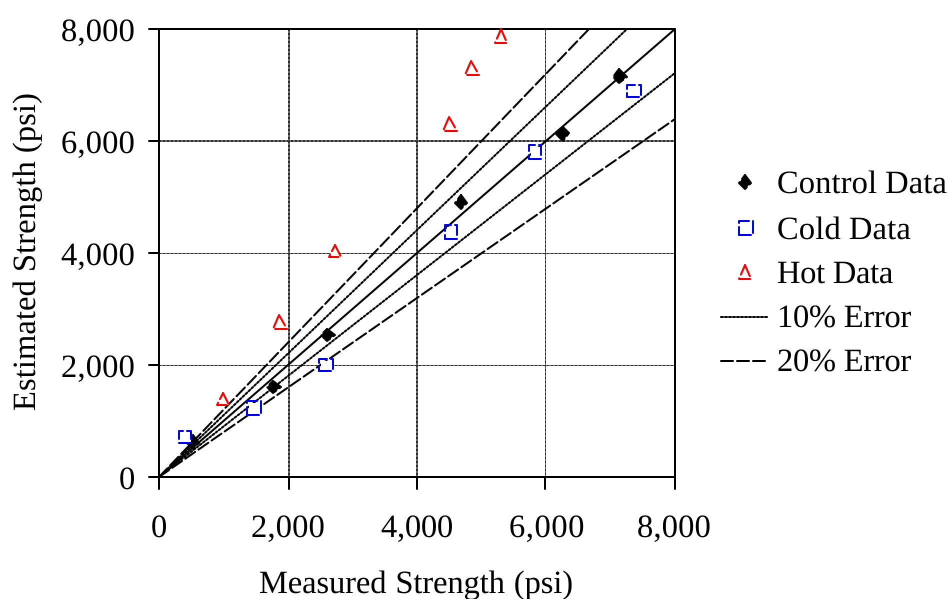


Figure D-20: Estimated strength versus actual strength for 70/20/10 - 0.44 mixture

APPENDIX E: STRENGTH-MATURITY RELATIONSHIPS FOR NURSE-SAUL MATURITY FUNCTION, MODIFIED ASTM METHOD

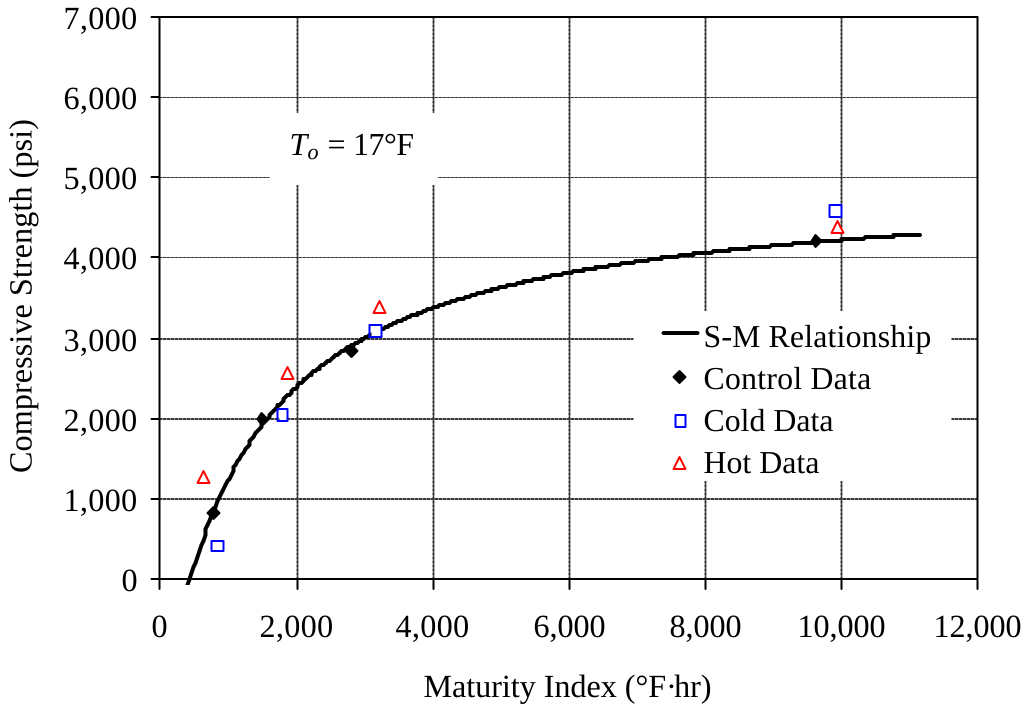


Figure E-1: Strength-maturity plot, Modified ASTM method for Type I - 0.44

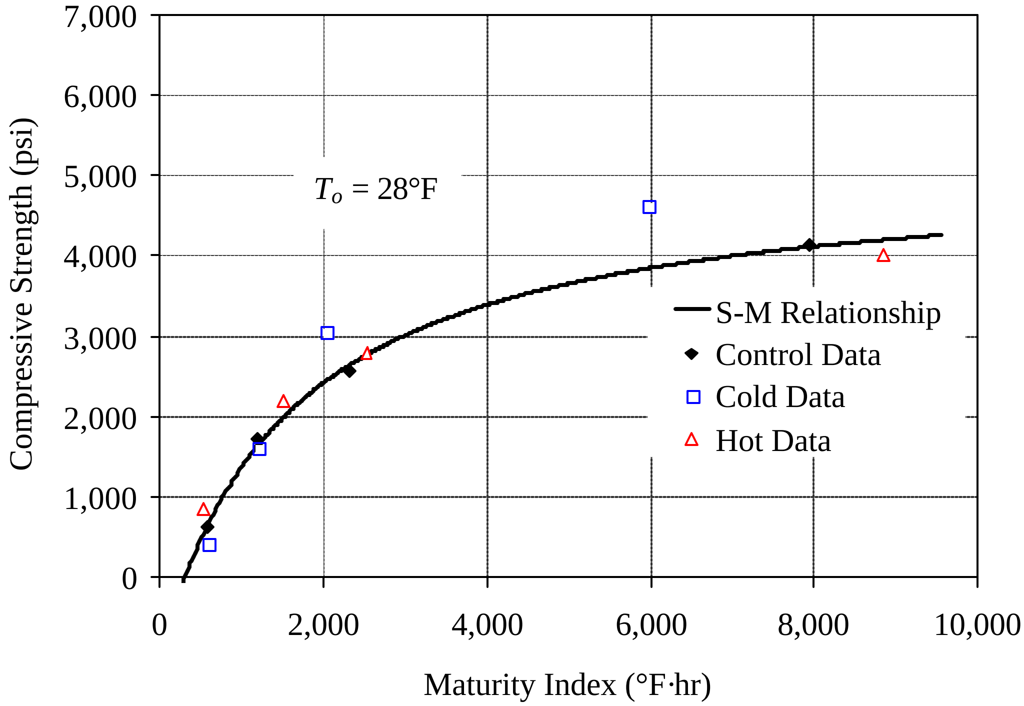


Figure E-2: Strength-maturity plot, Modified ASTM method for Type I - 0.48 mixture

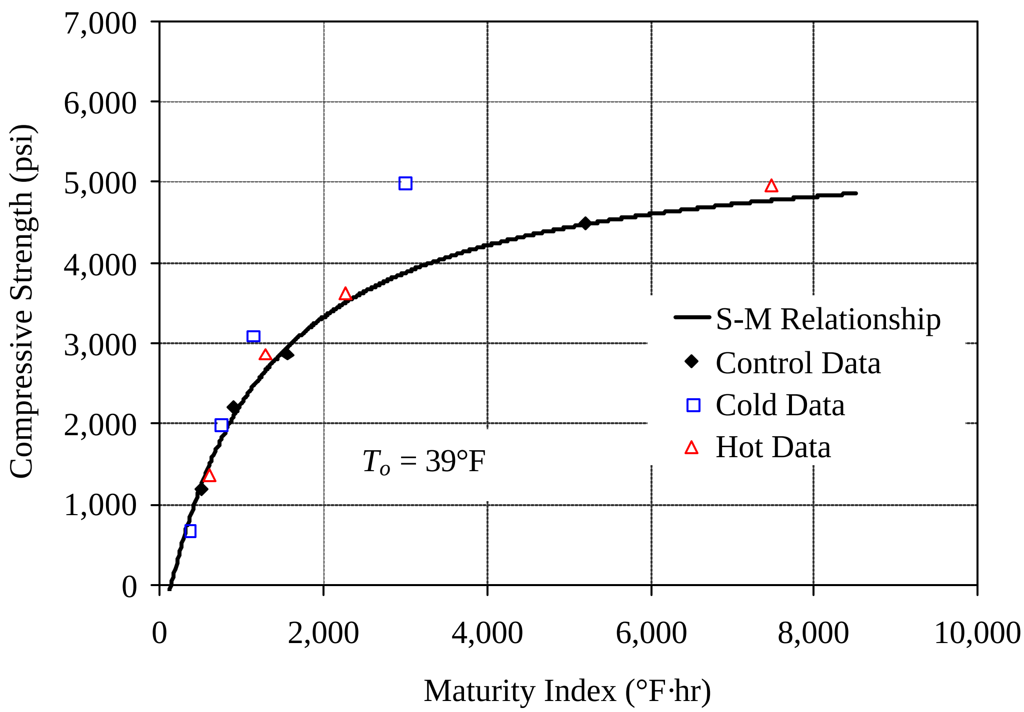


Figure E-3: Strength-maturity plot, Modified ASTM method for 30% F mixture

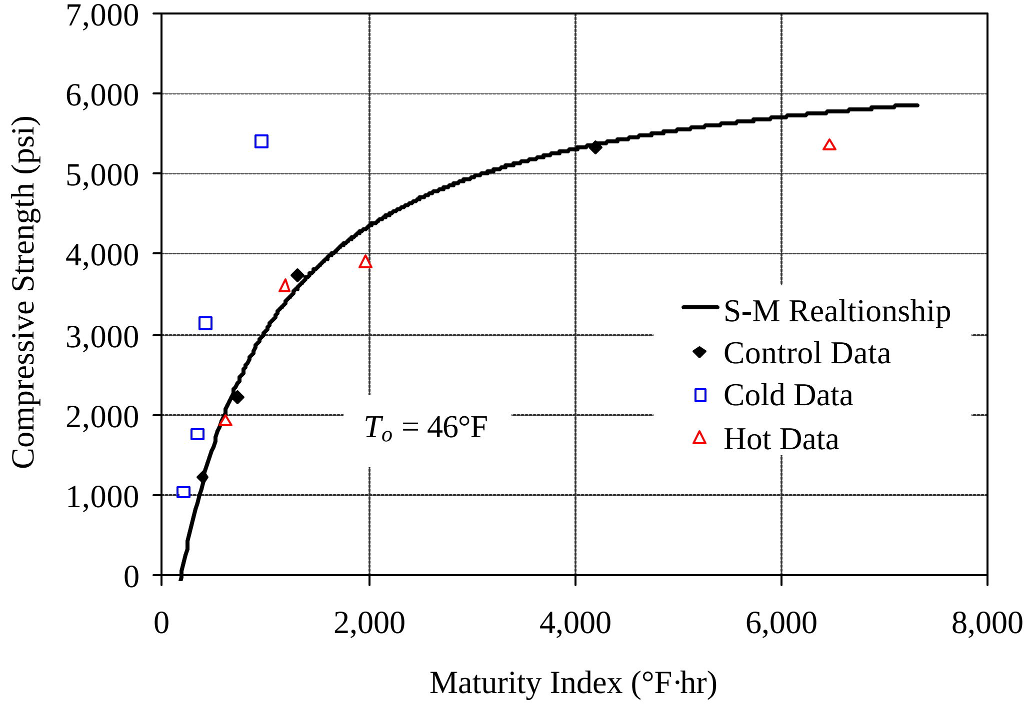


Figure E-4: Strength-maturity plot, Modified ASTM method for 20% C mixture

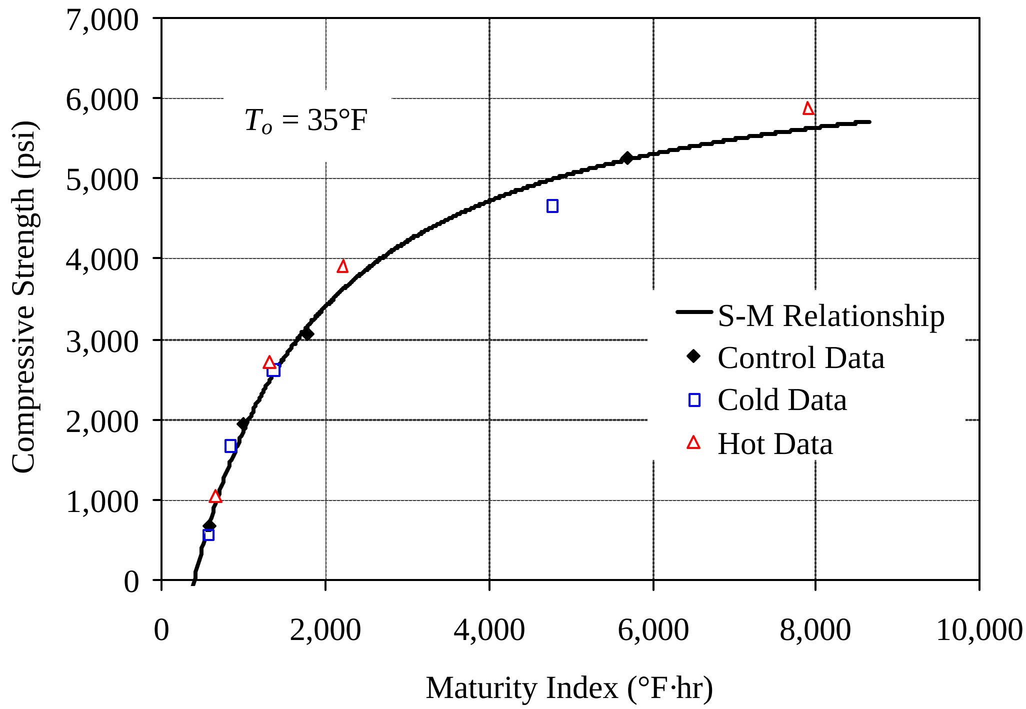


Figure E-5: Strength-maturity plot, Modified ASTM method for 30% C mixture

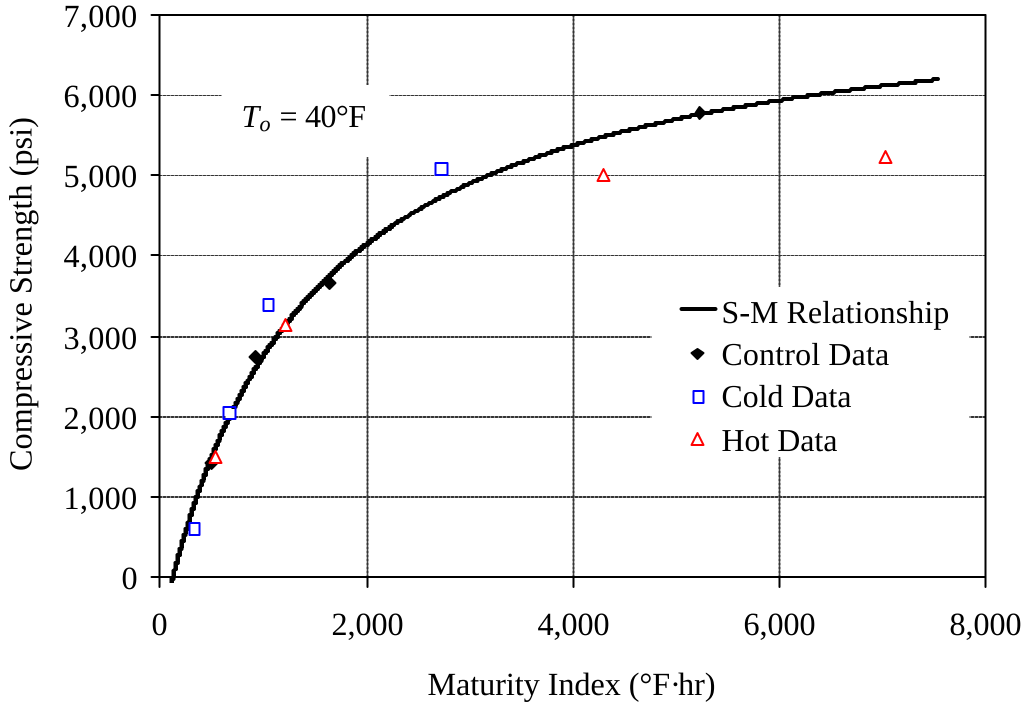


Figure E-6: Strength-maturity plot, Modified ASTM method for 30% Slag mixture

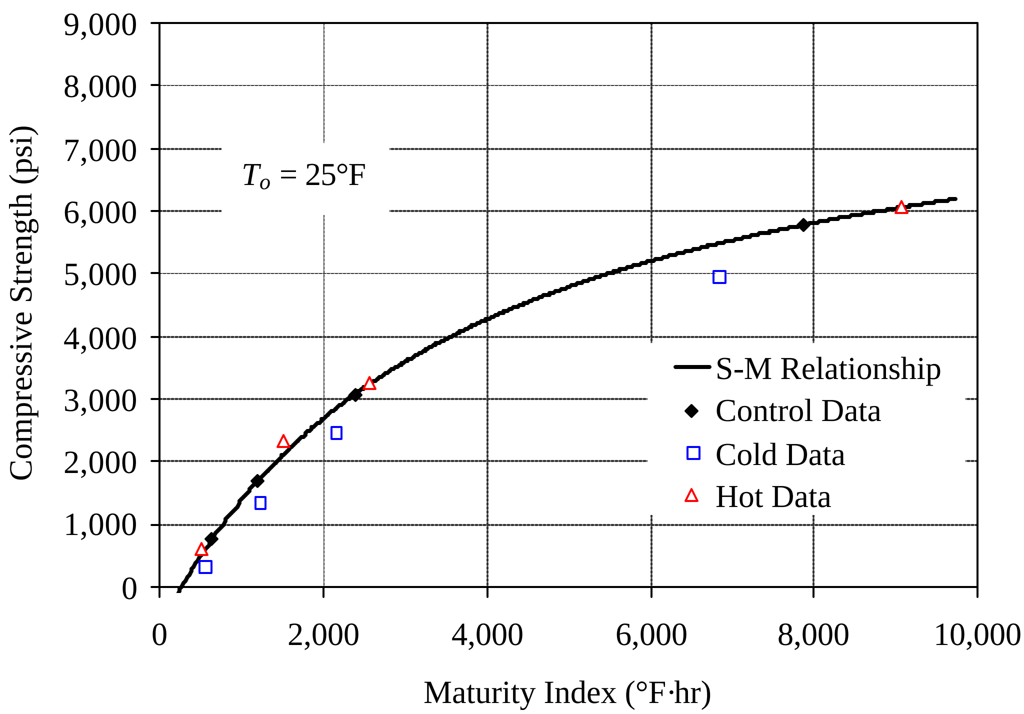


Figure E-7: Strength-maturity plot, Modified ASTM method for 50% Slag mixture

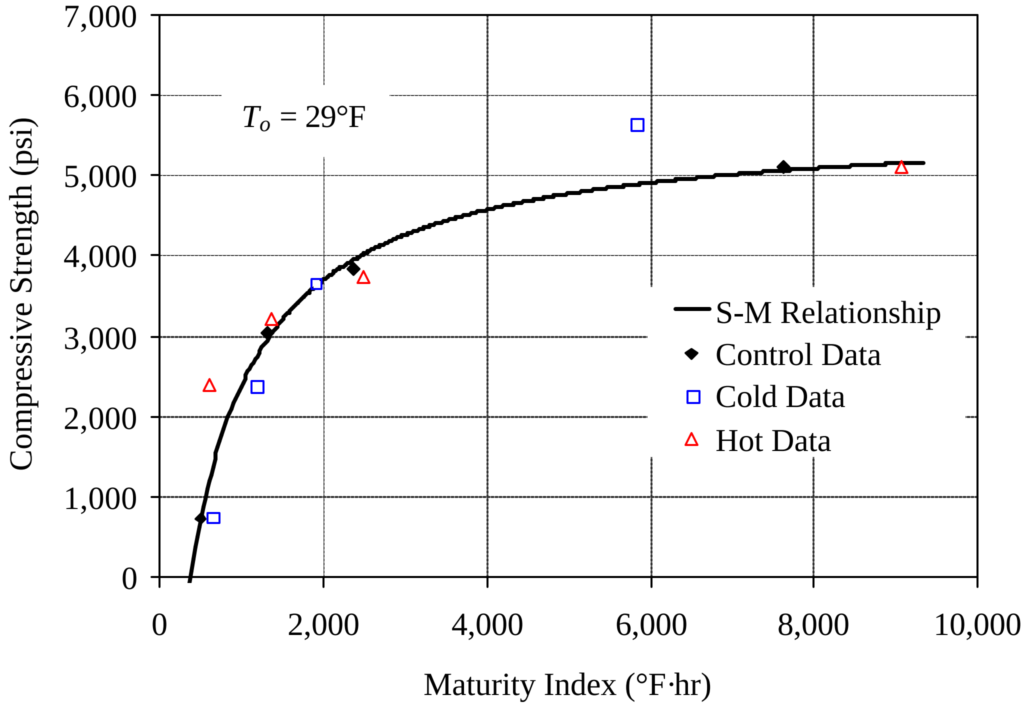


Figure E-8: Strength-maturity plot, Modified ASTM method for Type III - 0.44 mixture

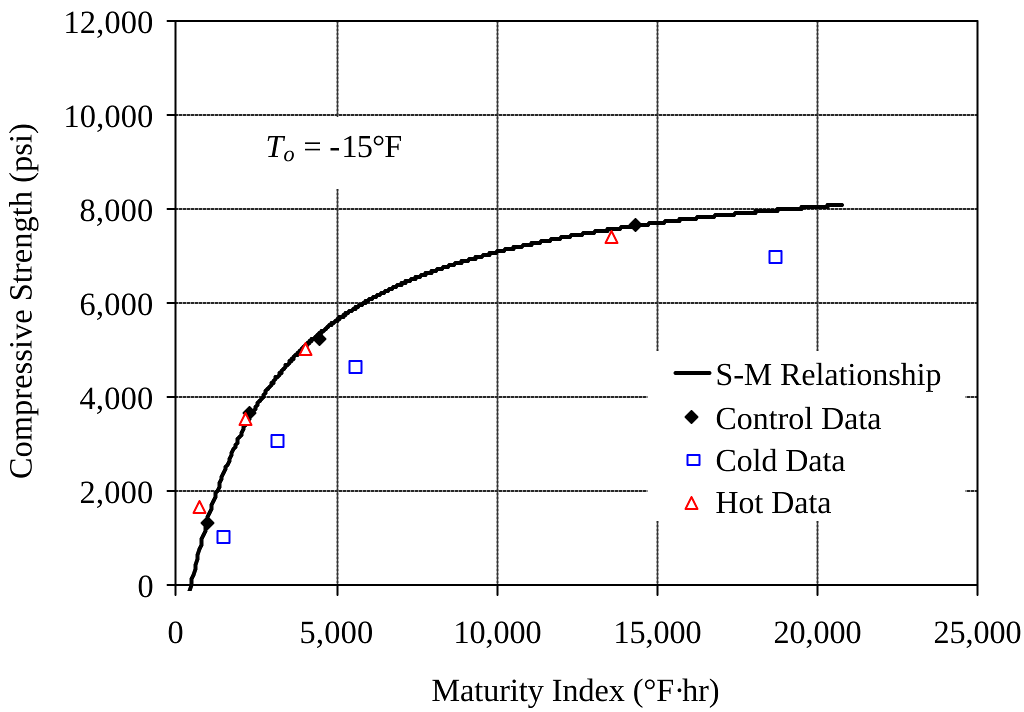


Figure E-9: Strength-maturity plot, Modified ASTM method for 70/20/10 - 0.37 mixture

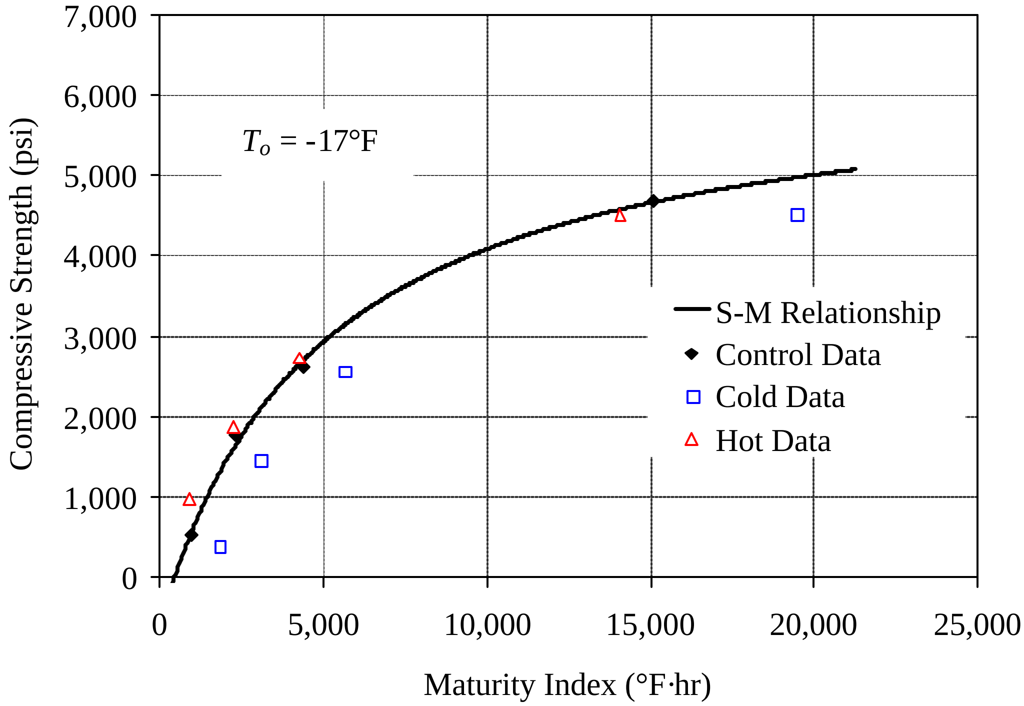


Figure E-10: Strength-maturity plot, Modified ASTM method for 70/20/10-0.44 mixture

APPENDIX F: STRENGTH-MATURITY RELATIONSHIPS FOR ARRHENIUS MATURITY FUNCTION, MODIFIED ASTM METHOD

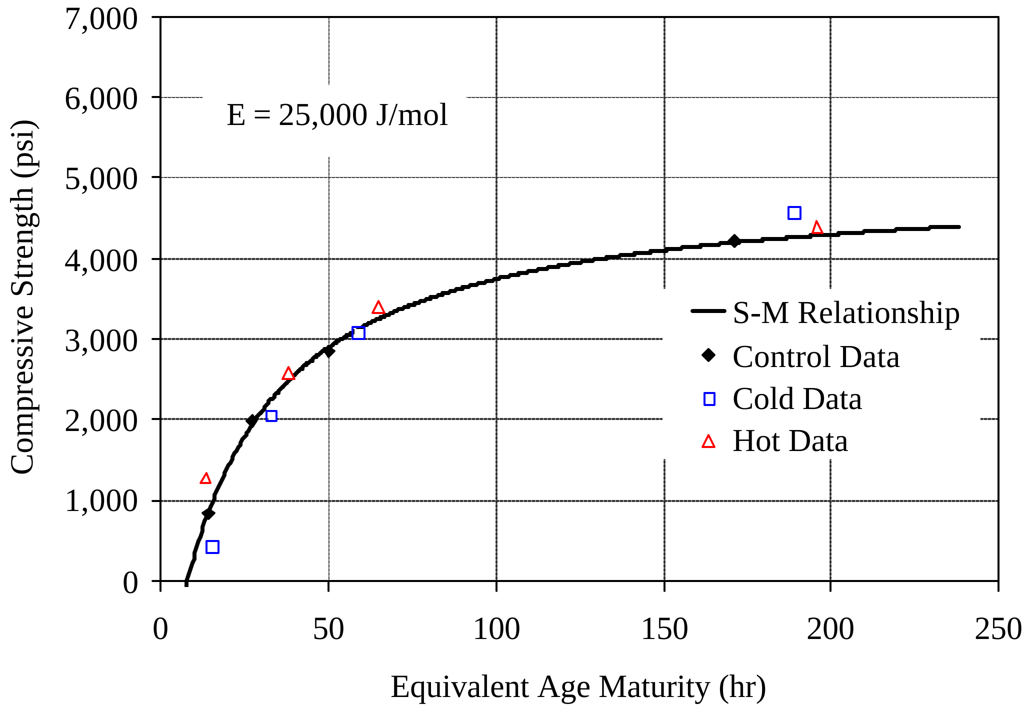


Figure F-1: Strength-maturity plot, Modified ASTM method for Type I - 0.44 mixture

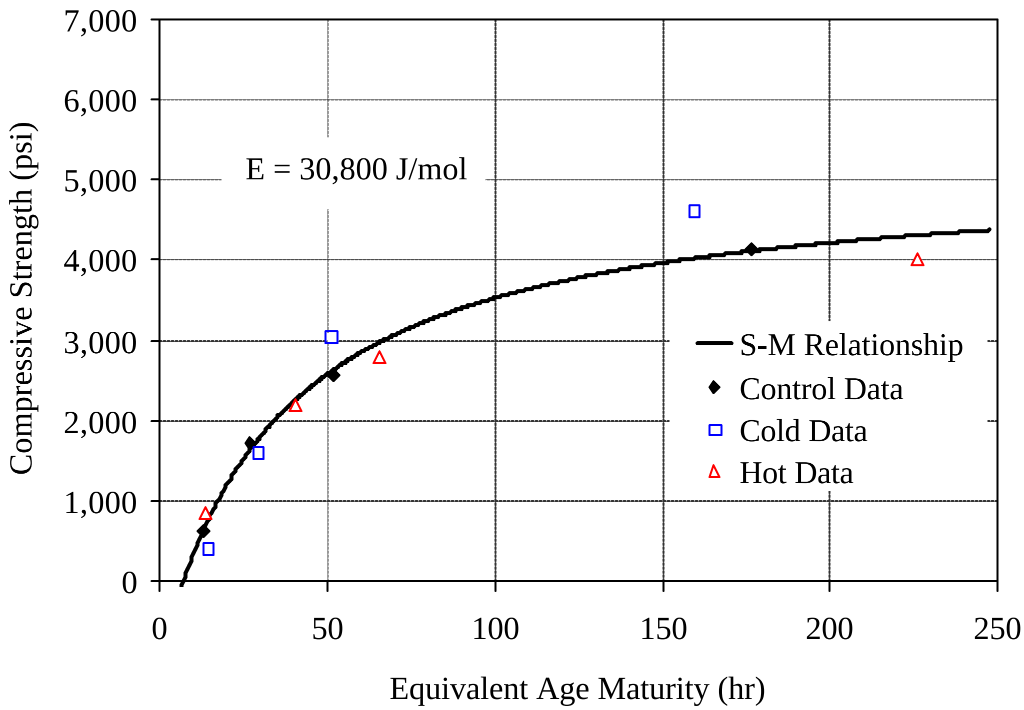


Figure F-2: Strength-maturity plot, Modified ASTM method for Type I - 0.48 mixture

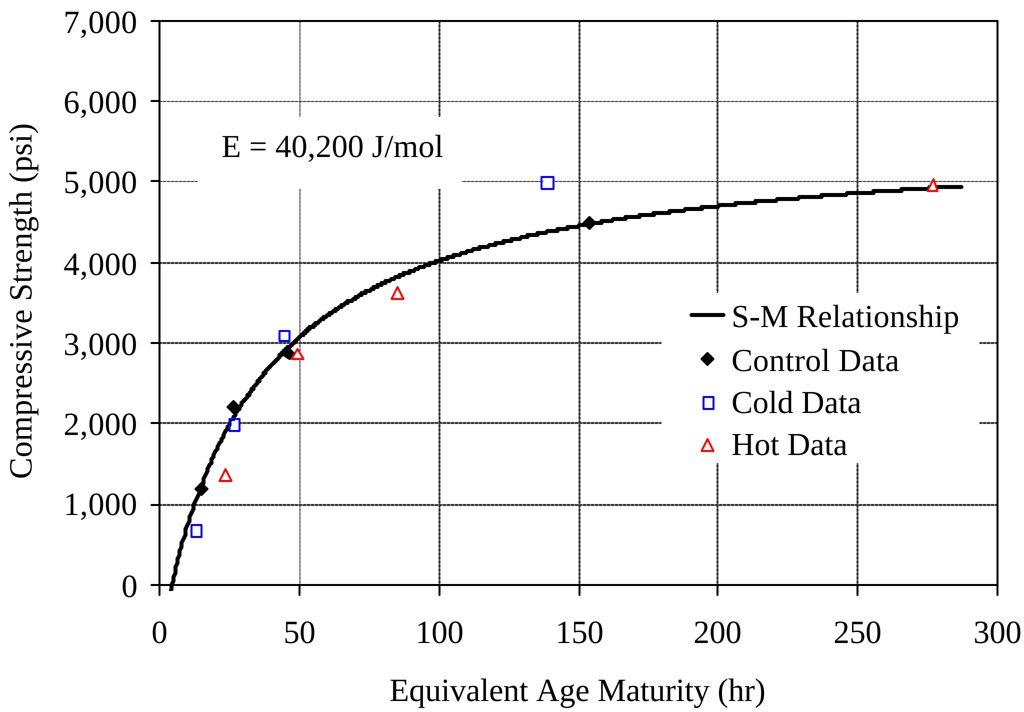


Figure F-3: Strength-maturity plot, Modified ASTM method for 30% F mixture

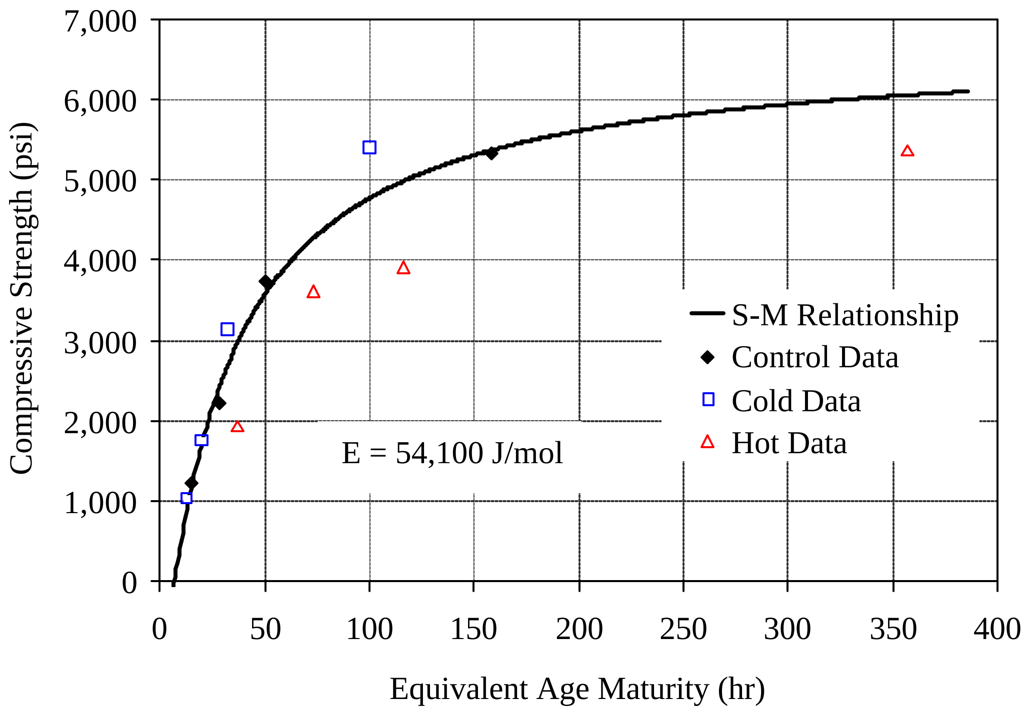


Figure F-4: Strength-maturity plot, Modified ASTM method for 20% C mixture

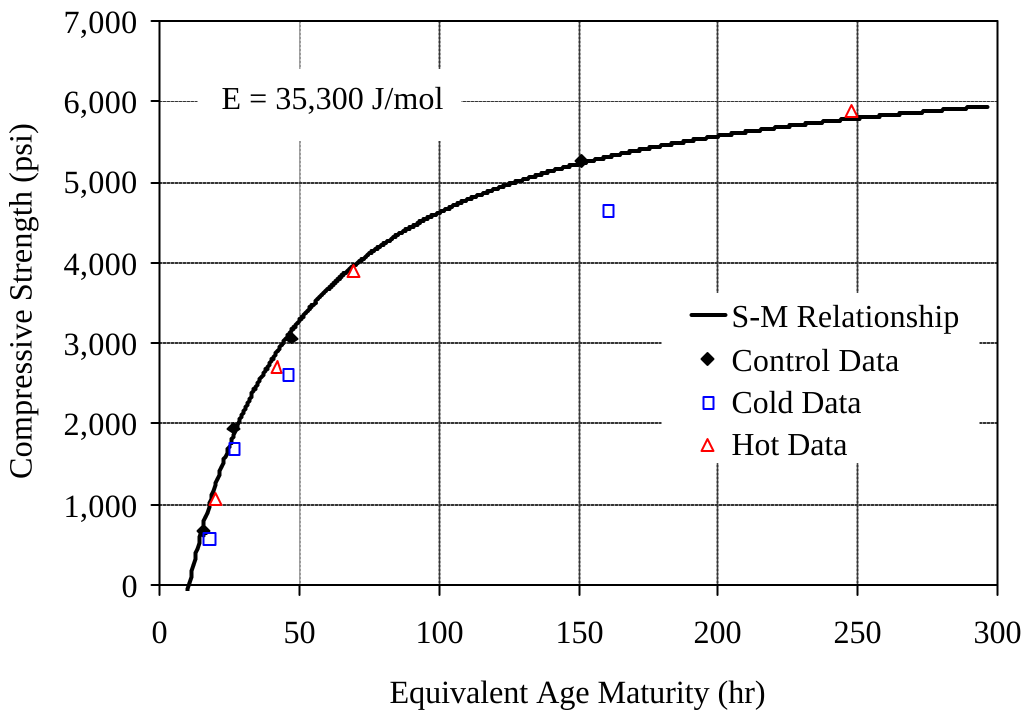


Figure F-5: Strength-maturity plot, Modified ASTM method for 30% C mixture

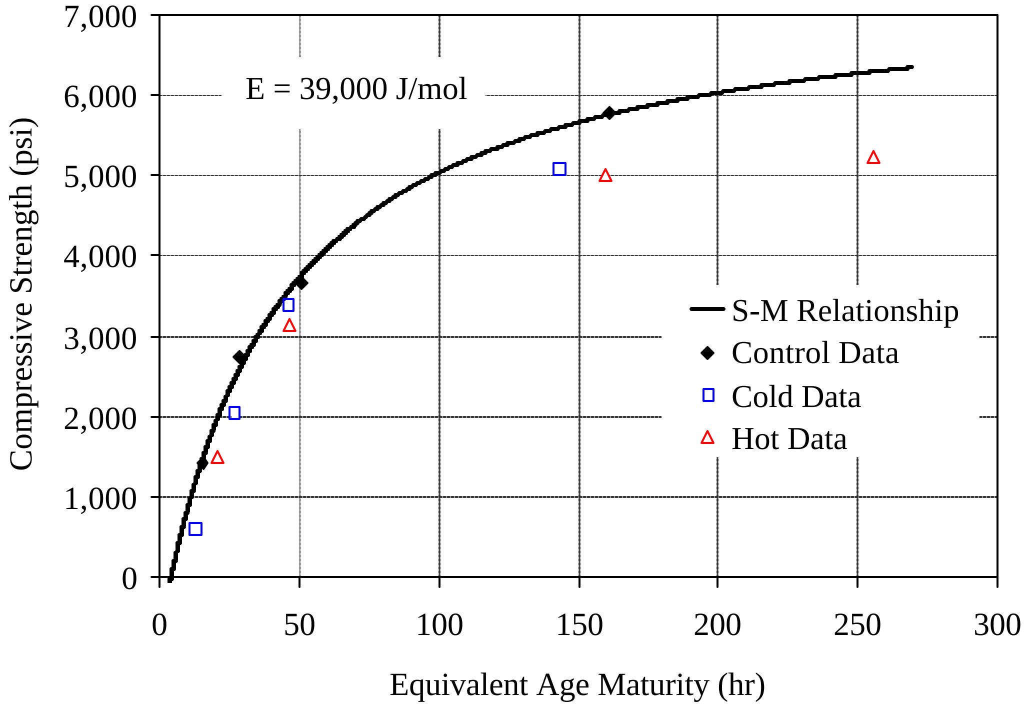


Figure F-6: Strength-maturity plot, Modified ASTM method for 30% Slag mixture

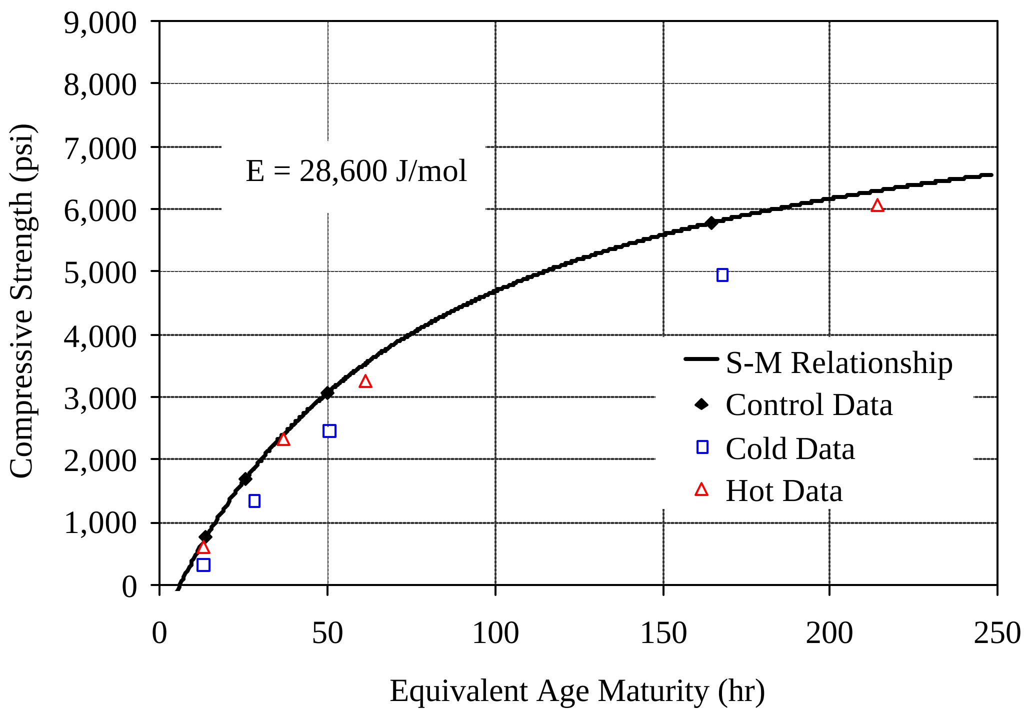


Figure F-7: Strength-maturity plot, Modified ASTM method for 50% Slag mixture

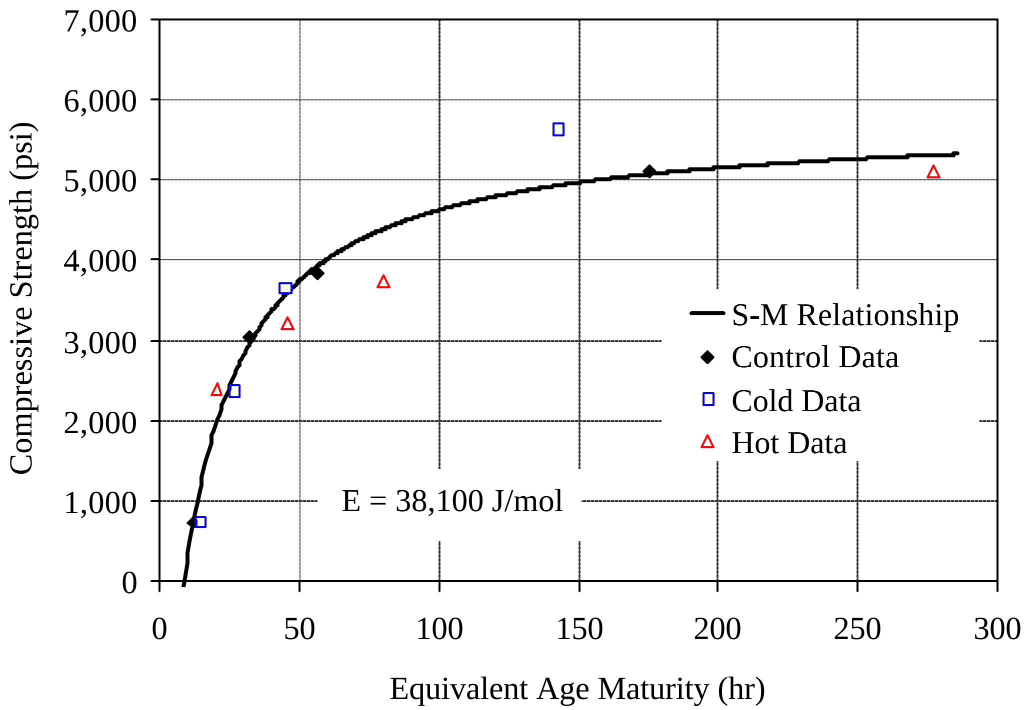


Figure F-8: Strength-maturity plot, Modified ASTM method for Type III - 0.44 mixture

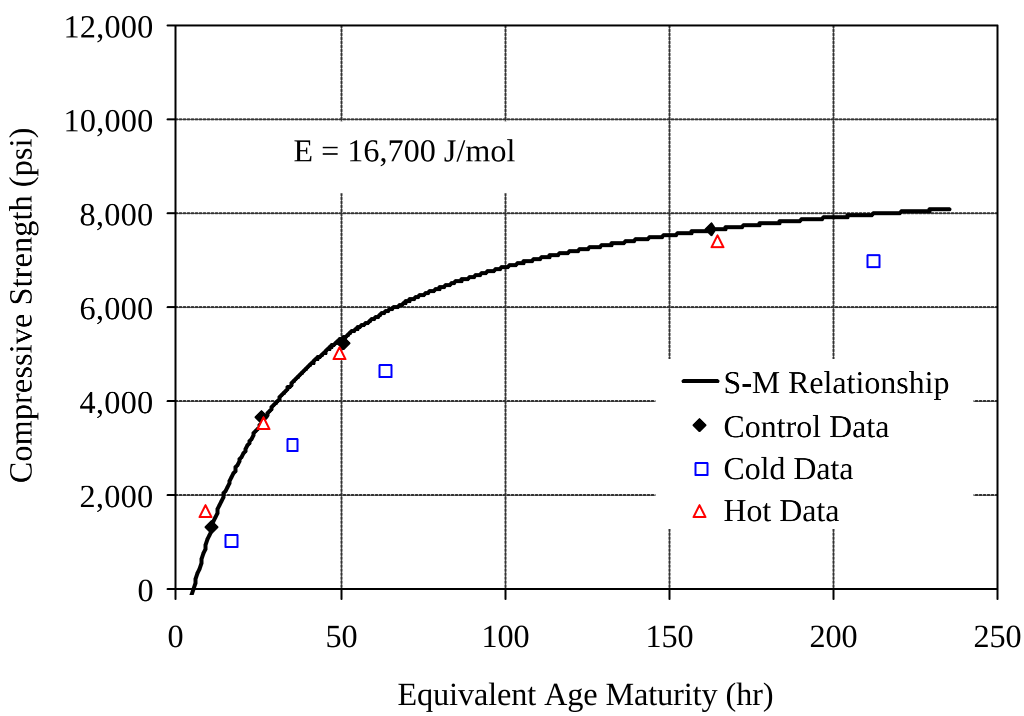


Figure F-9: Strength-maturity plot, Modified ASTM method for 70/20/10 - 0.37 mixture

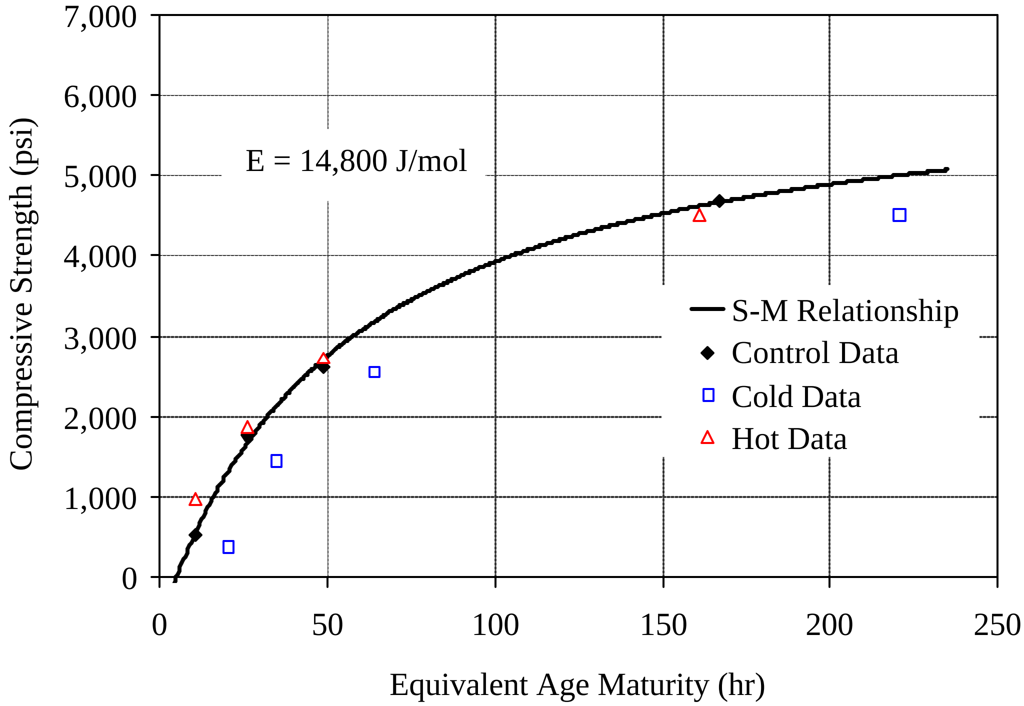


Figure F-10: Strength-maturity plot, Modified ASTM method for 70/20/10-0.44 mixture

APPENDIX G: ERROR TABLES FOR MODIFIED ASTM METHOD

Table G-1: Error using NSM function based on Modified ASTM method for Type I - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	830	990	160	19	190	10	850	20	2	40	2
	1.0	1,990	1,800	-190	-10			1,920	-70	-4		
	2.0	2,840	2,710	-130	-5			2,900	60	2		
	7.3	4,210	4,470	260	6			4,190	-20	0		
Cold	0.9	420	800	380	90	510	36	940	520	124	270	35
	1.9	2,050	1,660	-390	-19			2,210	160	8		
	3.5	3,090	2,410	-680	-22			3,070	-20	-1		
	12.4	4,580	3,980	-600	-13			4,210	-370	-8		
Hot	0.3	1,270	930	-340	-27	290	13	540	-730	-57	380	20
	0.9	2,570	2,300	-270	-11			2,270	-300	-12		
	1.5	3,390	3,160	-230	-7			3,090	-300	-9		
	5.0	4,380	4,680	300	7			4,210	-170	-4		

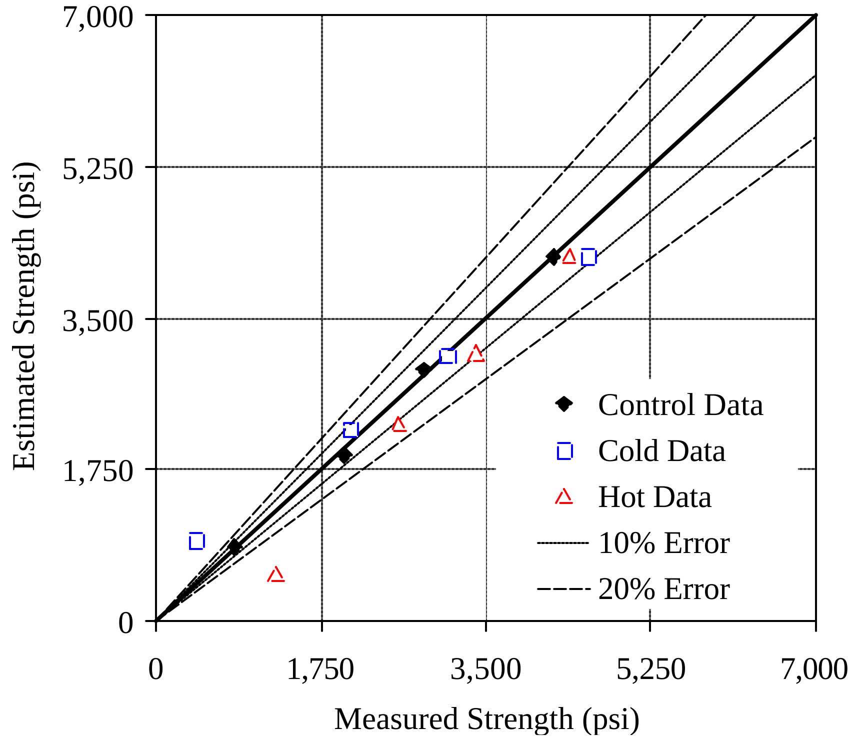


Figure G-1: Error plot for the Type I - 0.44 mixture, Modified method, NSM

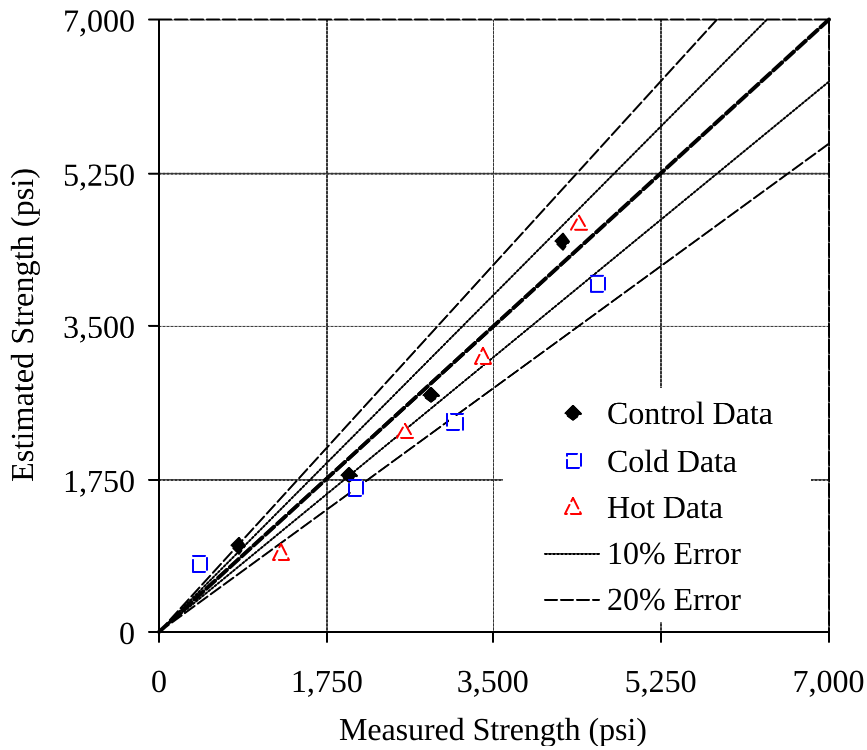


Figure G-2: Error plot for the Type I - 0.44 mixture, ASTM C 1074 method, NSM

Table G-2: Error using NSM function based on Modified ASTM method for Type I - 0.48 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	630	780	150	24	150	11	660	30	5	50	3
	1.0	1,710	1,540	-170	-10			1,630	-80	-5		
	2.0	2,570	2,440	-130	-5			2,630	60	2		
	7.4	4,120	4,260	140	3			4,110	-10	0		
Cold	0.9	410	580	170	41	820	35	670	260	63	420	26
	1.9	1,600	1,210	-390	-24			1,650	50	3		
	3.6	3,040	1,770	-1,270	-42			2,450	-590	-19		
	12.0	4,610	3,170	-1,440	-31			3,840	-770	-17		
Hot	0.3	850	780	-70	-8	210	8	550	-300	-35	170	12
	0.8	2,180	1,980	-200	-9			1,990	-190	-9		
	1.4	2,770	2,740	-30	-1			2,760	-10	0		
	5.1	4,010	4,530	520	13			4,190	180	4		

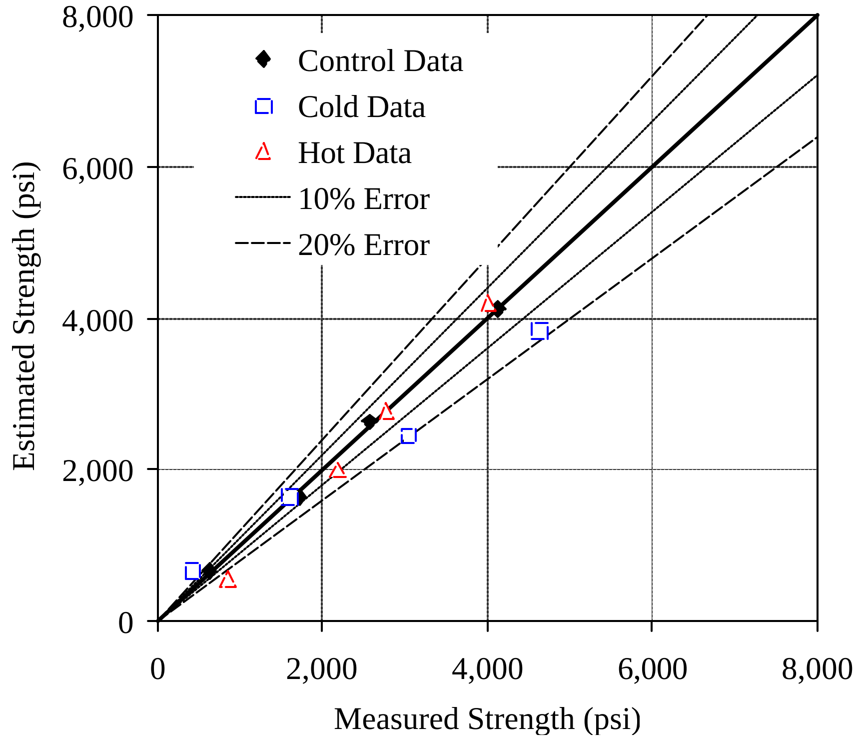


Figure G-3: Error plot for the Type I - 0.48 mixture, Modified method, NSM

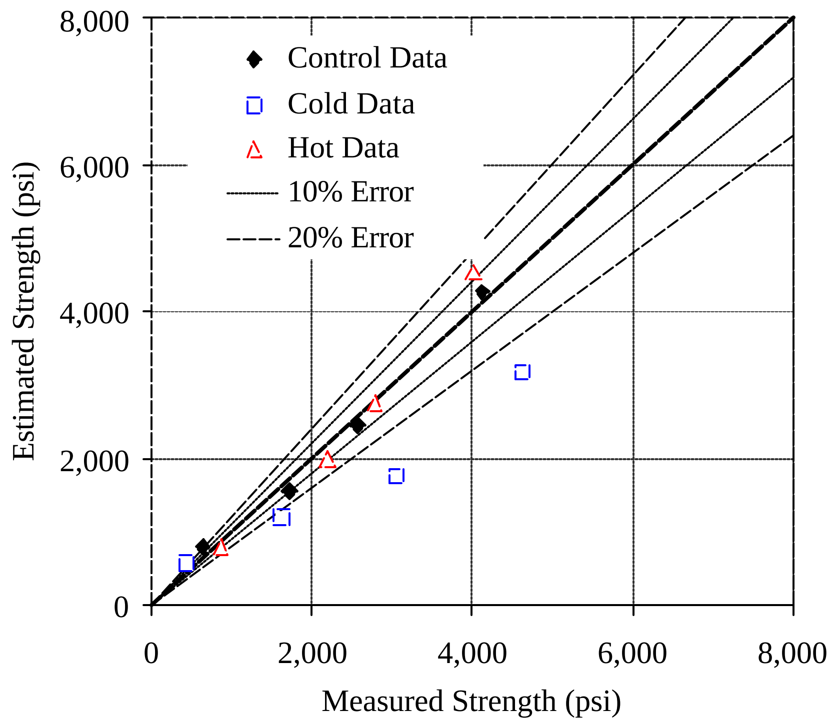


Figure G-4: Error plot for the Type I - 0.48 mixture, ASTM C 1074 method, NSM

Table G-3: Error using NSM function based on Modified ASTM method for 30% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,180	1,220	40	3	180	6	1,230	50	4	70	3
	1.1	2,200	1,910	-290	-13			2,080	-120	-5		
	2.0	2,860	2,810	-50	-2			2,960	100	3		
	7.0	4,490	4,810	320	7			4,470	-20	0		
Cold	0.9	670	1,250	580	87	240	25	840	170	25	530	19
	1.9	1,990	2,170	180	9			1,800	-190	-10		
	3.5	3,090	3,010	-80	-3			2,470	-620	-20		
	12.2	4,990	4,860	-130	-3			3,870	-1,120	-22		
Hot	0.4	1,350	1,220	-130	-10	350	12	1,500	150	11	160	6
	0.8	2,860	2,180	-680	-24			2,670	-190	-7		
	1.5	3,620	3,080	-540	-15			3,500	-120	-3		
	5.0	4,960	5,000	40	1			4,770	-190	-4		

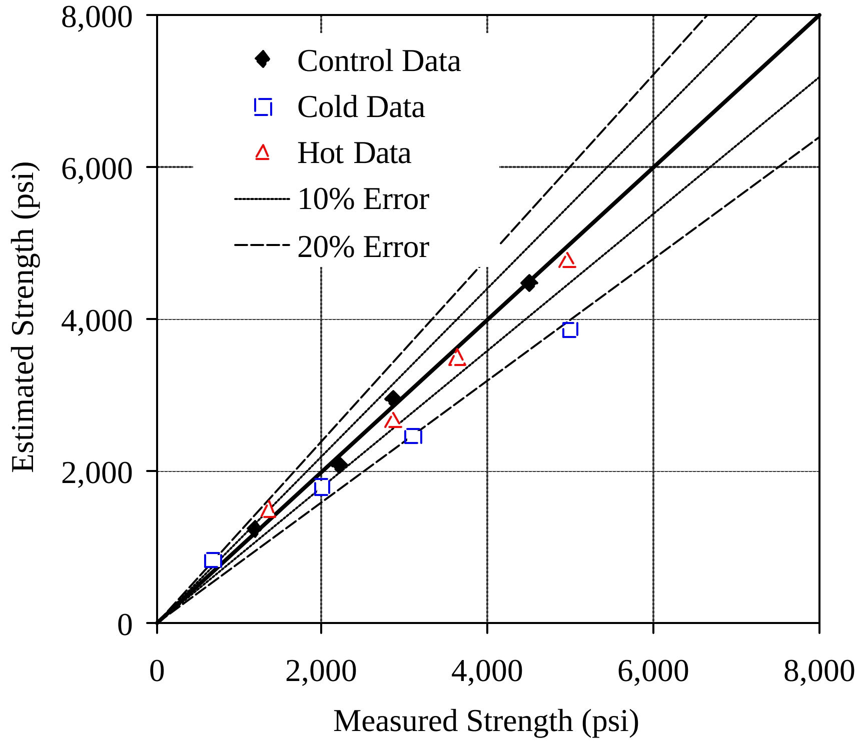


Figure G-5: Error plot for the 30% F mixture, Modified method, NSM

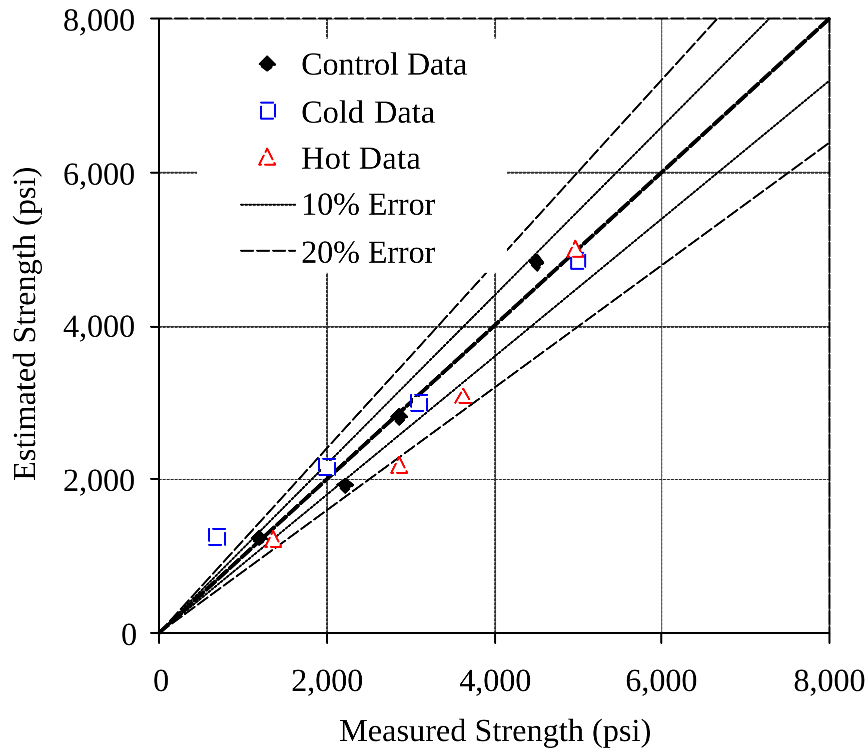


Figure G-6: Error plot for the 30% F mixture, ASTM C 1074 method, NSM

Table G-4: Error using NSM function based on Modified ASTM method for 20% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,220	1,200	-20	-2	110	3	1,160	-60	-5	100	4
	1.0	2,210	2,320	110	5			2,390	180	8		
	2.0	3,730	3,540	-190	-5			3,590	-140	-4		
	7.0	5,330	5,440	110	2			5,360	30	1		
Cold	1.2	1,040	1,010	-30	-3	360	9	110	-930	-89	1540	61
	1.8	1,760	1,810	50	3			900	-860	-49		
	3.4	3,140	2,610	-530	-17			1,260	-1,880	-60		
	12.0	5,410	4,590	-820	-15			2,930	-2,480	-46		
Hot	0.5	1,930	1,780	-150	-8	310	8	2,060	130	7	290	8
	0.8	3,600	3,040	-560	-16			3,380	-220	-6		
	1.4	3,900	4,030	130	3			4,310	410	11		
	5.0	5,360	5,740	380	7			5,760	400	7		

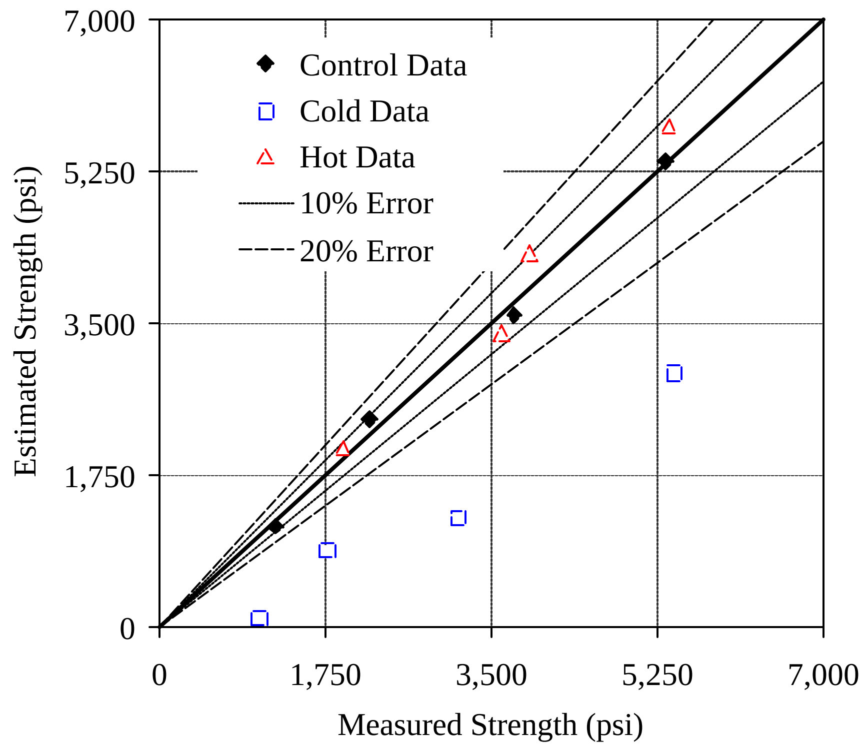


Figure G-7: Error plot for the 20% C mixture, Modified method, NSM

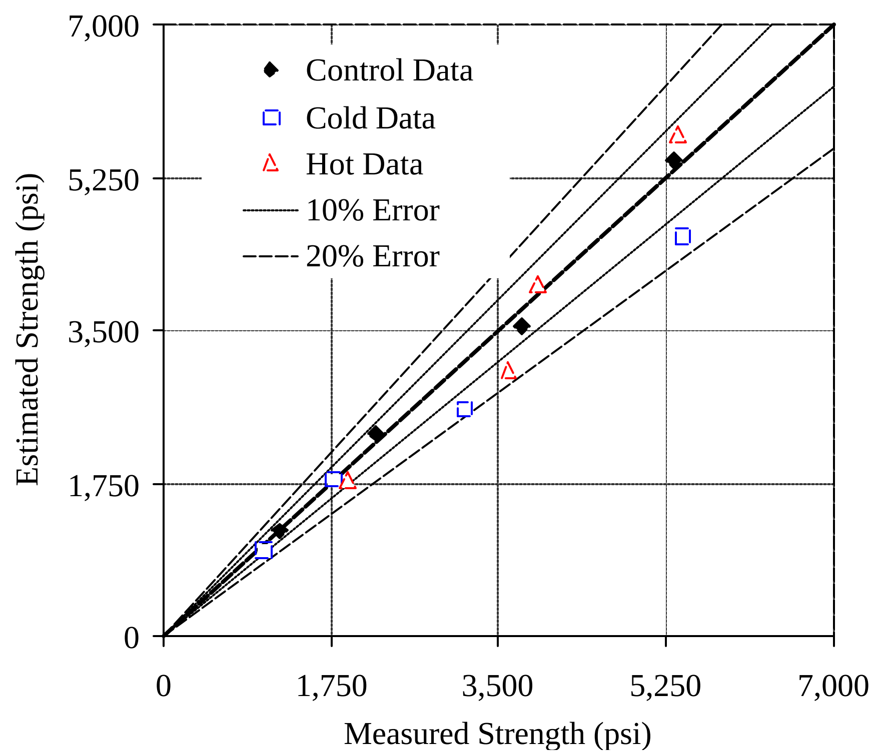


Figure G-8: Error plot for the 20% C mixture, ASTM C 1074 method, NSM

Table G-5: Error using NSM function based on Modified ASTM method for 30% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	670	790	120	18	80	7	720	50	7	70	4
	1.0	1,940	1,790	-150	-8			1,830	-110	-6		
	2.0	3,060	3,020	-40	-1			3,140	80	3		
	7.2	5,250	5,260	10	0			5,230	-20	0		
Cold	1.3	570	330	-240	-42	520	31	640	70	12	170	9
	1.9	1,680	920	-760	-45			1,450	-230	-14		
	3.5	2,620	1,750	-870	-33			2,560	-60	-2		
	12.1	4,650	4,460	-190	-4			4,980	330	7		
Hot	0.4	1,050	1,140	90	9	120	5	970	-80	-8	220	7
	0.8	2,710	2,550	-160	-6			2,460	-250	-9		
	1.4	3,900	3,700	-200	-5			3,610	-290	-7		
	5.0	5,870	5,880	10	0			5,620	-250	-4		

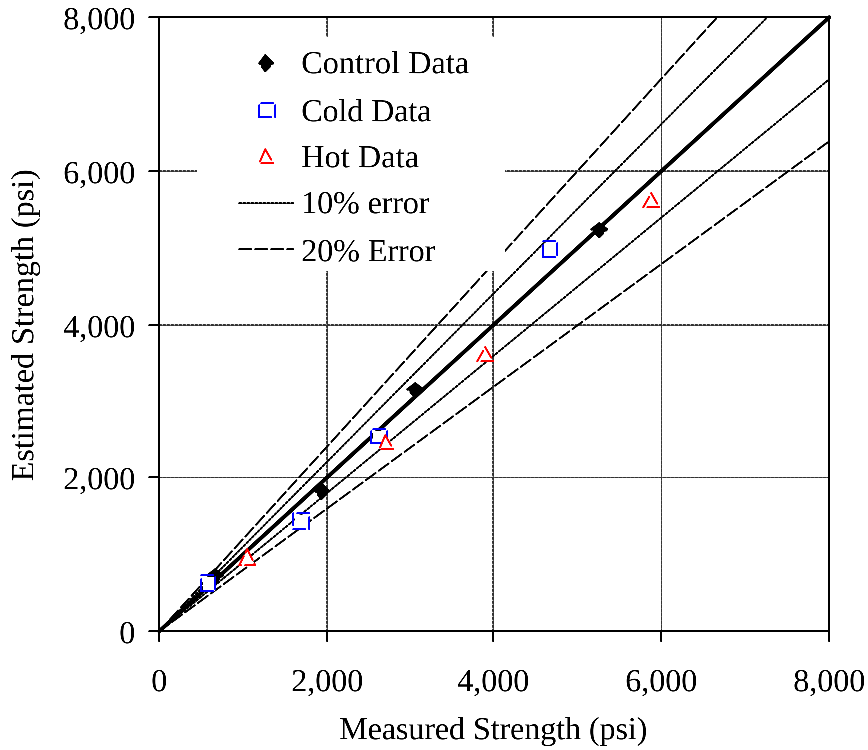


Figure G-9: Error plot for the 30% C mixture, Modified method, NSM

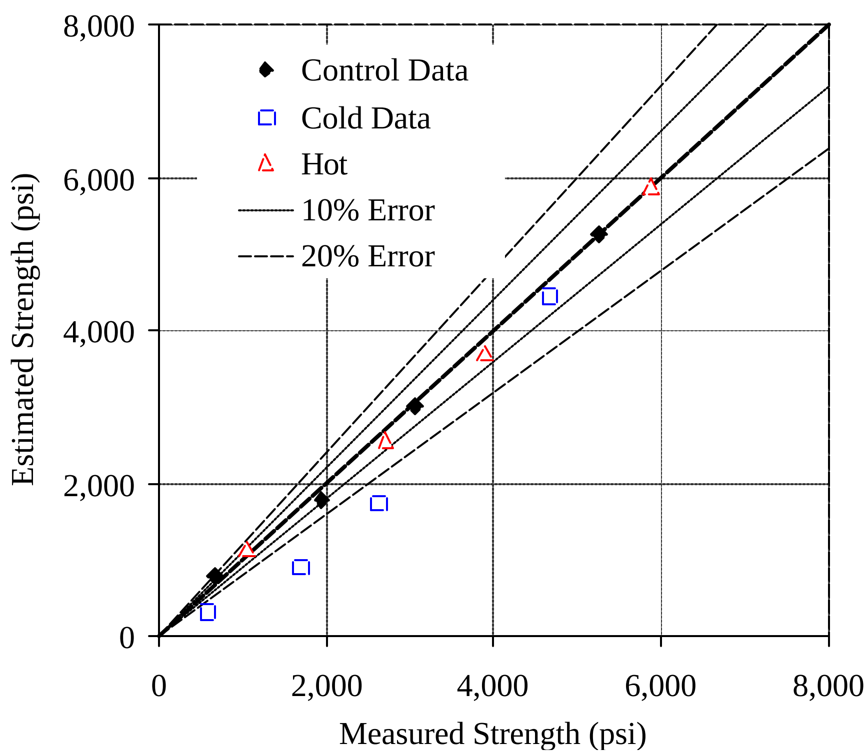


Figure G-10: Error plot for the 30% C mixture, ASTM C 1074 method, NSM

Table G-6: Error using NSM function based on Modified ASTM method for 30% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,430	1,500	70	5	70	3	1,470	40	3	70	3
	1.0	2,730	2,580	-150	-5			2,600	-130	-5		
	2.0	3,650	3,700	50	1			3,750	100	3		
	7.1	5,770	5,780	10	0			5,760	-10	0		
Cold	0.9	610	640	30	5	870	26	890	280	46	320	18
	1.9	2,050	1,450	-600	-29			1,980	-70	-3		
	3.6	3,400	2,040	-1,360	-40			2,840	-560	-16		
	12.2	5,080	3,590	-1,490	-29			4,720	-360	-7		
Hot	0.4	1,500	1,760	260	17	530	14	1,620	120	8	370	9
	0.8	3,130	3,260	130	4			3,140	10	0		
	2.9	4,990	5,640	650	13			5,480	490	10		
	4.9	5,240	6,300	1,060	20			6,110	870	17		

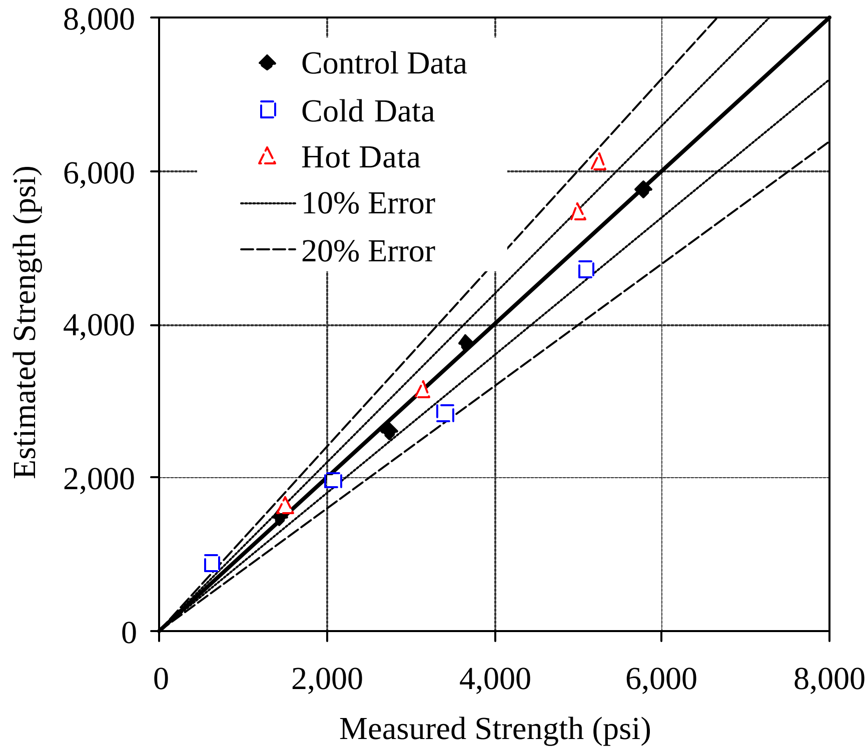


Figure G-11: Error plot for the 30% Slag mixture, Modified method, NSM

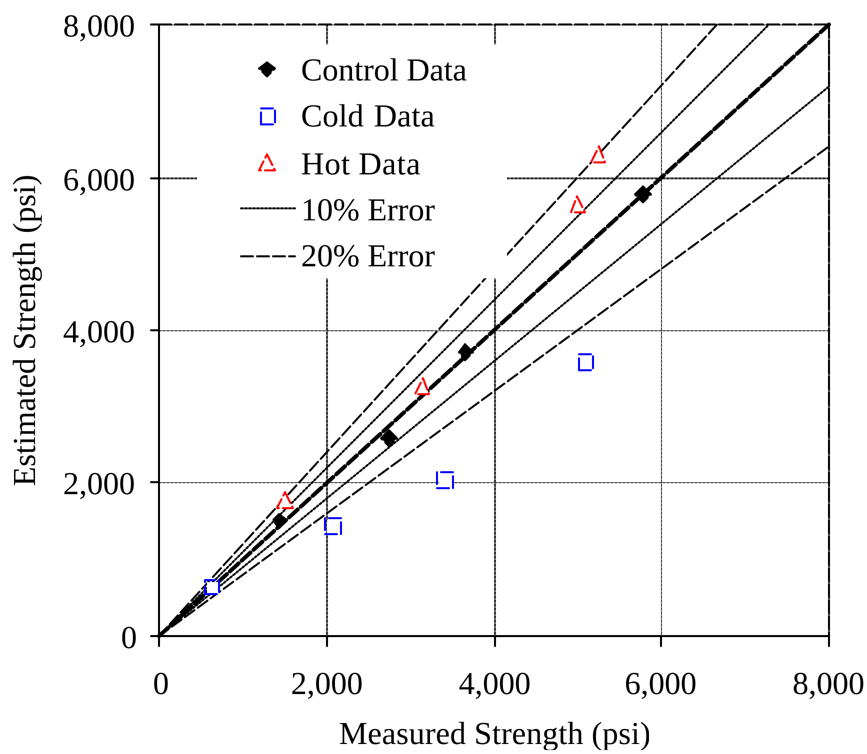


Figure G-12: Error plot for the 30% Slag mixture, ASTM C 1074 method, NSM

Table G-7: Error using NSM function based on Modified ASTM method for 50% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	760	740	-20	-3	20	1	760	0	0	10	0
	1.0	1,680	1,690	10	1			1,670	-10	-1		
	2.1	3,060	3,070	10	0			3,070	10	0		
	7.2	5,770	5,790	20	0			5,770	0	0		
Cold	0.9	330	0	-330	-100	1510	77	600	270	82	390	34
	1.9	1,340	280	-1,060	-79			1,710	370	28		
	3.4	2,450	740	-1,710	-70			2,840	390	16		
	12.3	4,960	2,010	-2,950	-59			5,480	520	10		
Hot	0.3	610	770	160	26	450	18	500	-110	-18	90	7
	0.8	2,330	2,660	330	14			2,100	-230	-10		
	1.4	3,240	3,900	660	20			3,230	-10	0		
	5.0	6,060	6,710	650	11			6,050	-10	0		

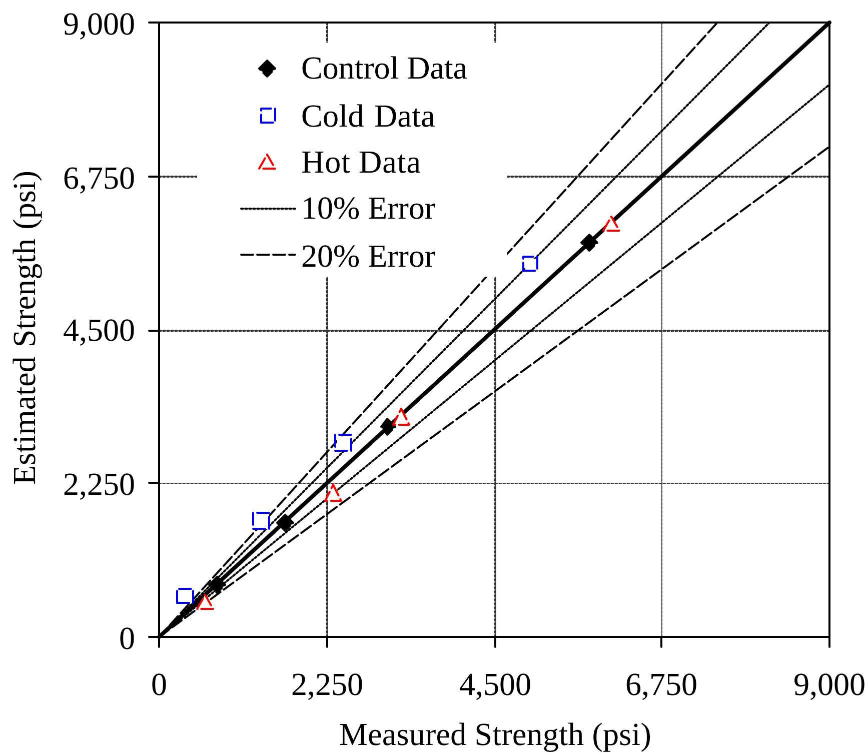


Figure G-13: Error plot for the 50% Slag mixture, Modified method, NSM

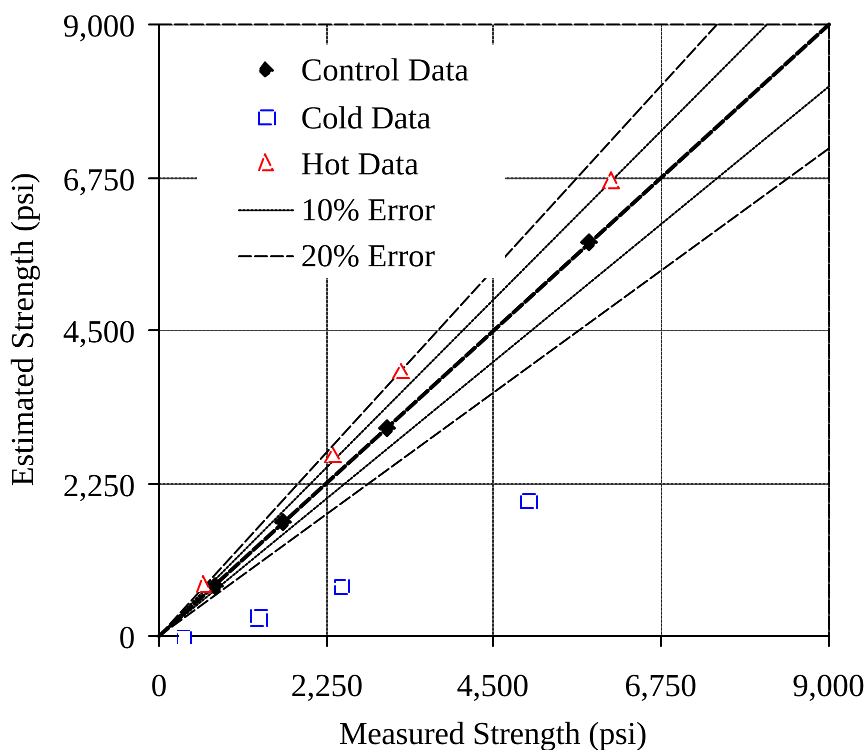


Figure G-14: Error plot for the 50% Slag mixture, ASTM C 1074 method, NSM

Table G-8: Error using NSM function based on Modified ASTM method for Type III - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	730	800	70	10	170	6	750	20	3	70	2
	1.0	3,040	2,820	-220	-7			2,950	-90	-3		
	2.0	3,820	3,920	100	3			3,950	130	3		
	7.2	5,100	5,370	270	5			5,060	-40	-1		
Cold	1.0	750	980	230	31	440	17	1,360	610	81	440	28
	1.8	2,370	2,230	-140	-6			2,730	360	15		
	3.4	3,660	3,090	-570	-16			3,610	-50	-1		
	12.1	5,630	4,800	-830	-15			4,890	-740	-13		
Hot	0.3	2,400	1,300	-1,100	-46	530	18	1,210	-1,190	-50	420	16
	0.7	3,210	3,020	-190	-6			3,040	-170	-5		
	1.4	3,740	4,110	370	10			4,010	270	7		
	5.3	5,100	5,560	460	9			5,150	50	1		

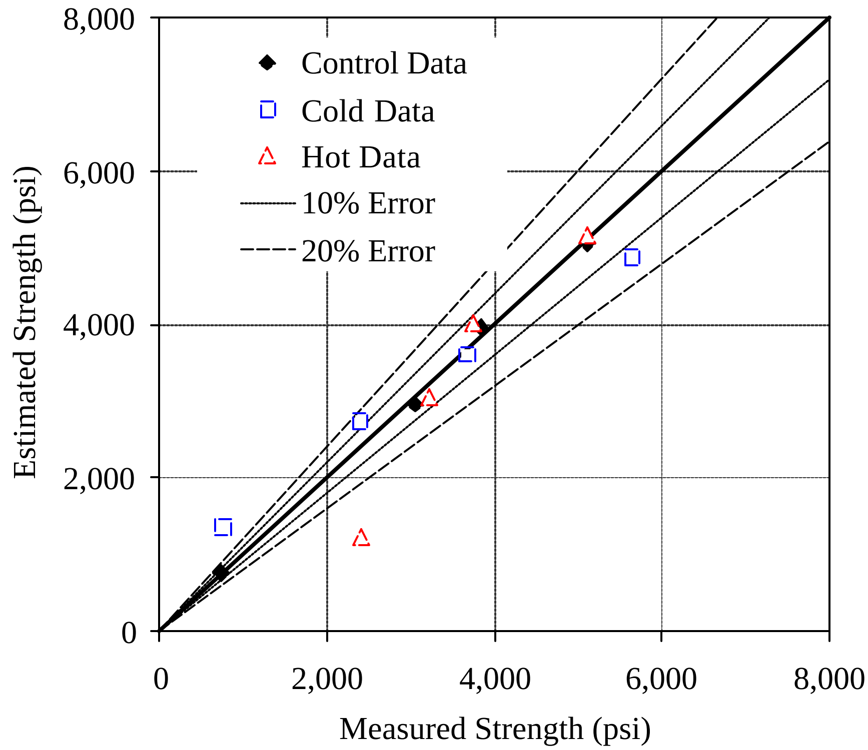


Figure G-15: Error plot for the Type III - 0.44 mixture, Modified method, NSM

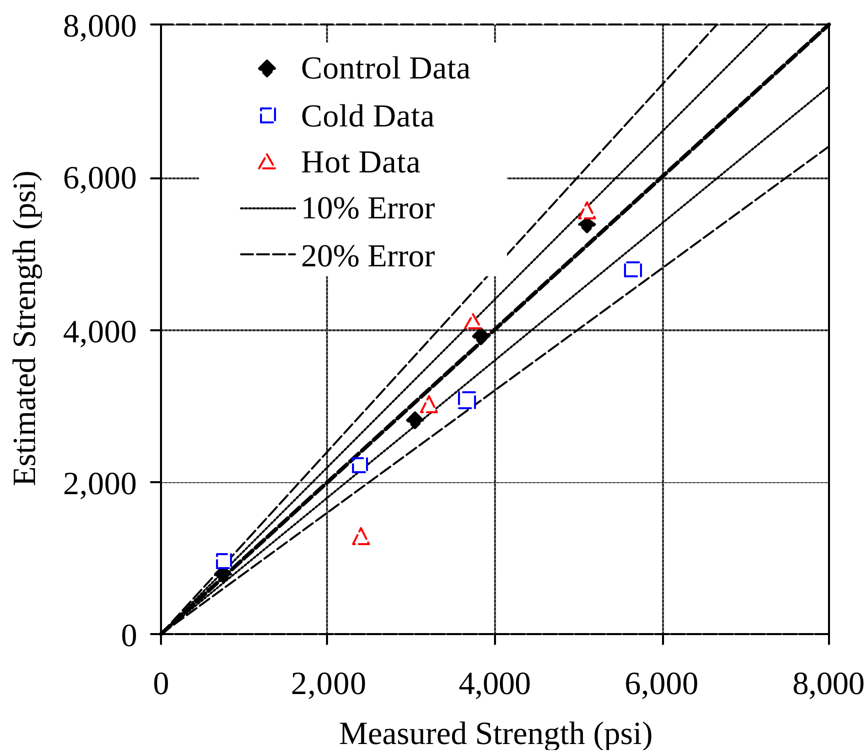


Figure G-16: Error plot for the Type III - 0.44 mixture, ASTM C 1074 method, NSM

Table G-9: Error using NSM function based on Modified ASTM method for 70/20/10 - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**ASTM C 1074**					**Modified ASTM**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,300	1,550	250	19	360	10	1,340	40	3	80	2
	1.0	3,650	3,320	-330	-9			3,530	-120	-3		
	2.1	5,240	5,050	-190	-4			5,350	110	2		
	7.0	7,670	8,320	650	8			7,640	-30	0		
Cold	0.9	1,040	1,520	480	46	470	19	2,330	1,290	124	1210	52
	1.8	3,060	2,810	-250	-8			4,400	1,340	44		
	3.5	4,650	3,790	-860	-18			5,890	1,240	27		
	12.2	7,000	6,700	-300	-4			7,970	970	14		
Hot	0.3	1,640	1,650	10	1	750	13	740	-900	-55	320	16
	0.7	3,540	4,010	470	13			3,400	-140	-4		
	1.4	5,020	5,820	800	16			5,080	60	1		
	4.9	7,390	9,090	1,700	23			7,560	170	2		

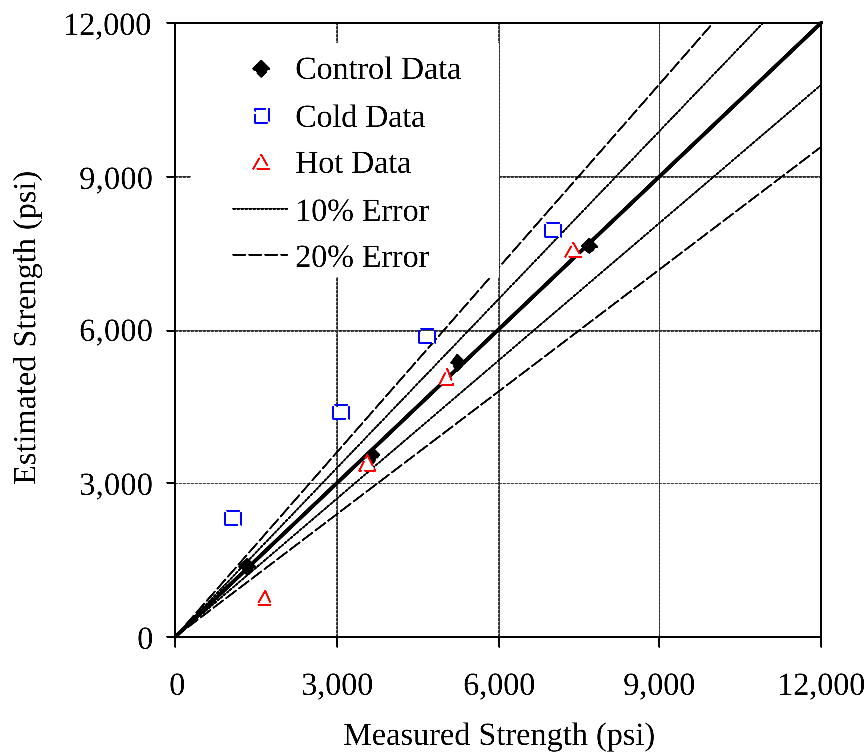


Figure G-17: Error plot for the 70/20/10 - 0.37 mixture, Modified method, NSM

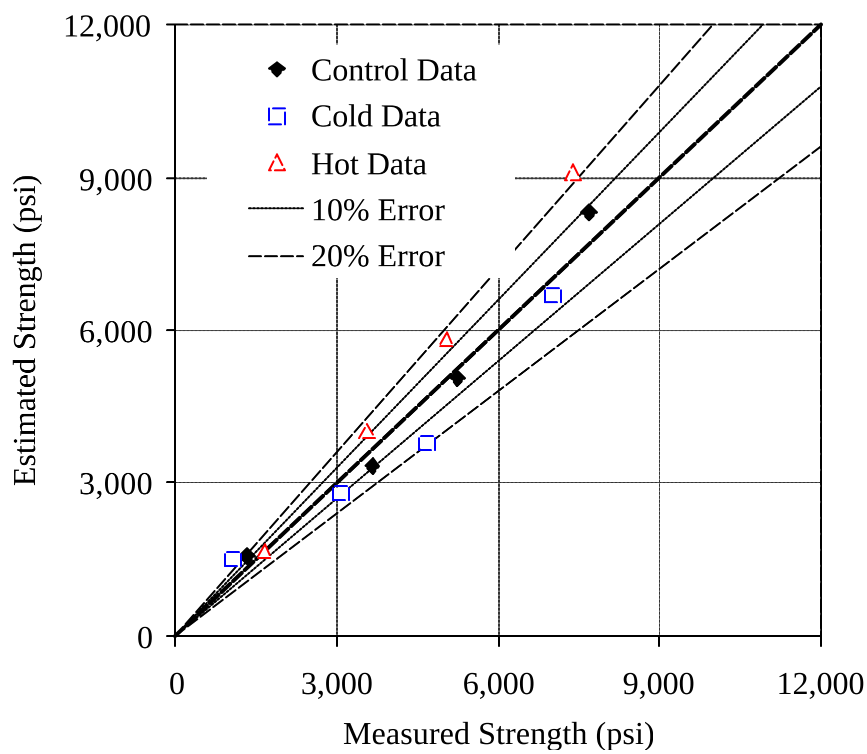


Figure G-18: Error plot for the 70/20/10 - 0.37 mixture, ASTM C 1074 method, NSM

Table G-10: Error using NSM function based on Modified ASTM method for the 70/20/10 - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	510	650	140	27	150	11	560	50	10	70	5
	1.0	1,770	1,600	-170	-10			1,650	-120	-7		
	2.0	2,610	2,540	-70	-3			2,700	90	3		
	7.2	4,680	4,910	230	5			4,660	-20	0		
Cold	1.0	370	620	250	68	760	41	1,300	930	251	660	82
	1.8	1,450	1,070	-380	-26			2,100	650	45		
	3.4	2,560	1,500	-1,060	-41			3,140	580	23		
	12.1	4,510	3,150	-1,360	-30			4,970	460	10		
Hot	0.3	980	920	-60	-6	490	15	520	-460	-47	220	16
	0.8	1,860	2,050	190	10			1,600	-260	-14		
	1.5	2,720	3,230	510	19			2,640	-80	-3		
	5.0	4,500	5,700	1,200	27			4,570	70	2		

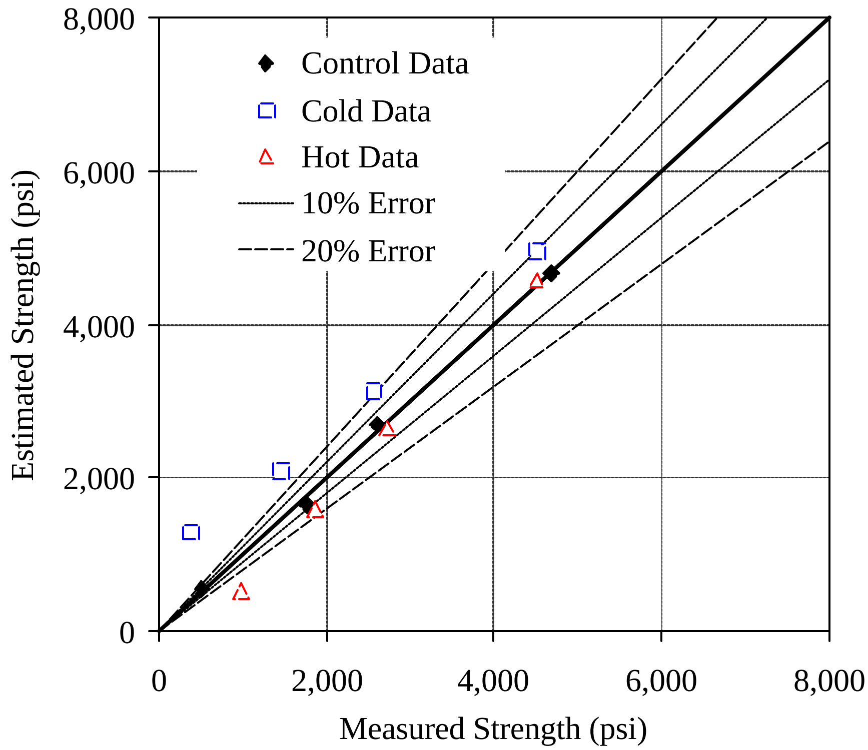


Figure G-19: Error plot for the 70/20/10 - 0.44 mixture, Modified method, NSM

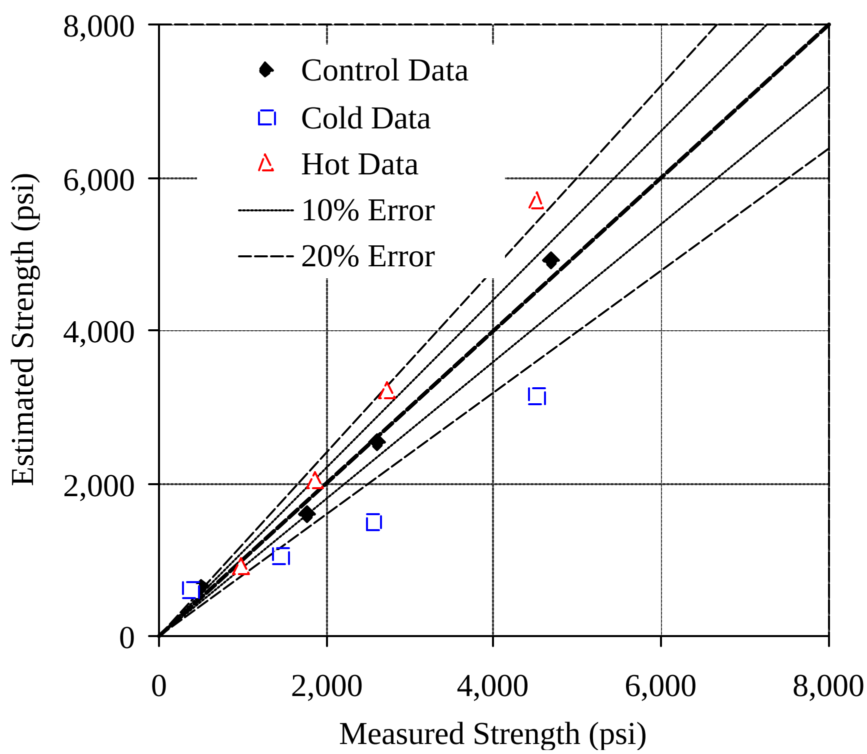


Figure G-20: Error plot for the 70/20/10 - 0.44 mixture, ASTM C 1074 method, NSM

Table G-11: Error using AM function based on Modified ASTM method for Type I - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	830	980	150	18	180	10	850	20	2	40	2
	1.0	1,990	1,800	-190	-10			1,920	-70	-4		
	2.0	2,840	2,710	-130	-5			2,900	60	2		
	7.3	4,210	4,460	250	6			4,190	-20	0		
Cold	0.9	420	900	480	114	330	36	950	530	126	260	36
	1.9	2,050	1,830	-220	-11			2,230	180	9		
	3.5	3,090	2,690	-400	-13			3,110	20	1		
	12.4	4,580	4,380	-200	-4			4,260	-320	-7		
Hot	0.3	1,270	1,150	-120	-9	170	6	740	-530	-42	220	13
	0.9	2,570	2,610	40	2			2,470	-100	-4		
	1.5	3,390	3,450	60	2			3,250	-140	-4		
	5.0	4,380	4,830	450	10			4,280	-100	-2		

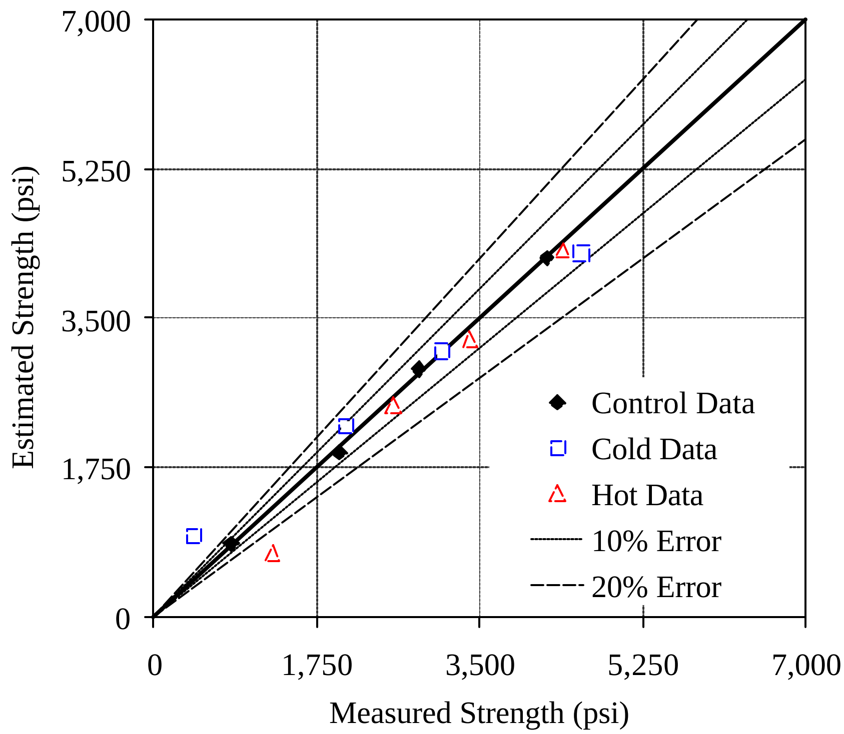


Figure G-21: Error plot for the Type I - 0.44 mixture, Modified method, AM

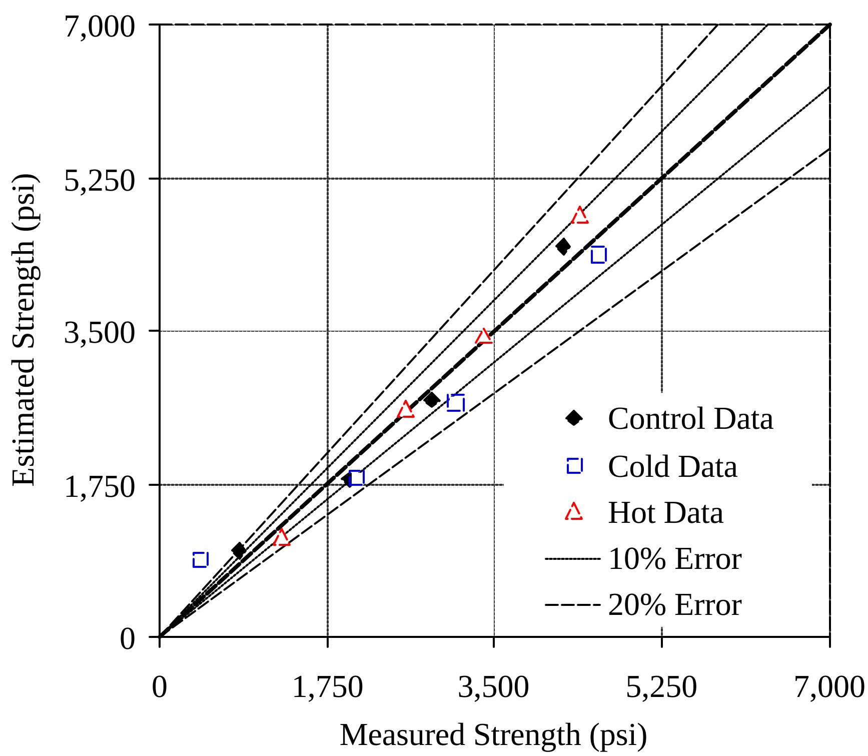


Figure G-22: Error plot for the Type I - 0.44 mixture, ASTM C 1074 method, AM

Table 6.12: Error using AM function based on Modified ASTM method for Type I - 0.48 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	630	780	150	24	140	10	650	20	3	40	2
	1.0	1,710	1,550	-160	-9			1,640	-70	-4		
	2.0	2,570	2,440	-130	-5			2,630	60	2		
	7.4	4,120	4,250	130	3			4,110	-10	0		
Cold	0.9	410	670	260	63	550	31	740	330	80	380	29
	1.9	1,600	1,380	-220	-14			1,760	160	10		
	3.6	3,040	2,110	-930	-31			2,610	-430	-14		
	12.0	4,610	3,810	-800	-17			4,010	-600	-13		
Hot	0.3	850	1,000	150	18	410	16	710	-140	-16	180	9
	0.8	2,180	2,450	270	12			2,250	70	3		
	1.4	2,770	3,180	410	15			2,970	200	7		
	5.1	4,010	4,810	800	20			4,300	290	7		

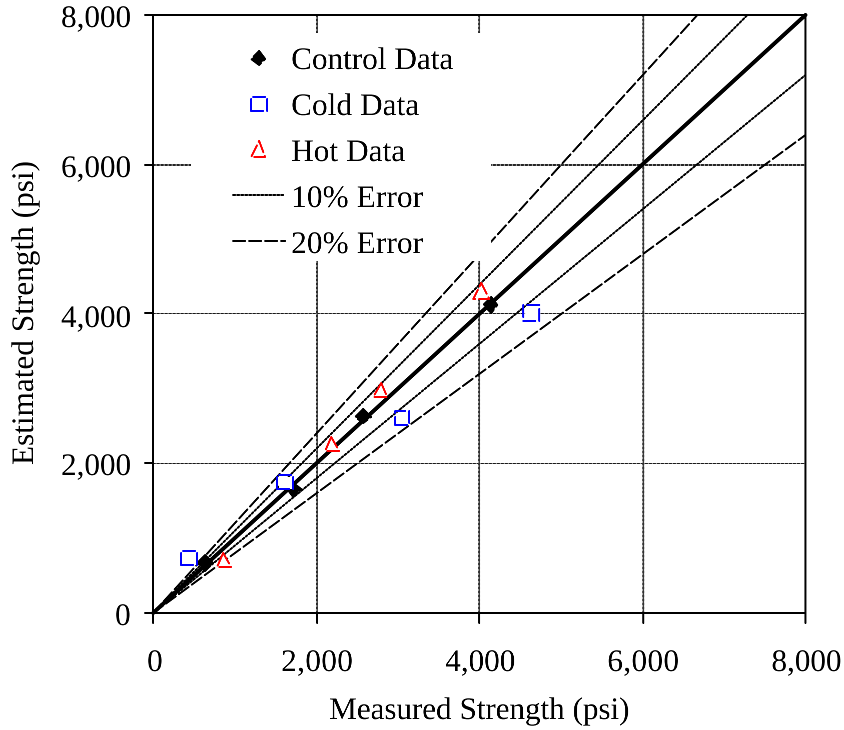


Figure G-23: Error plot for the Type I - 0.48 mixture, Modified method, AM

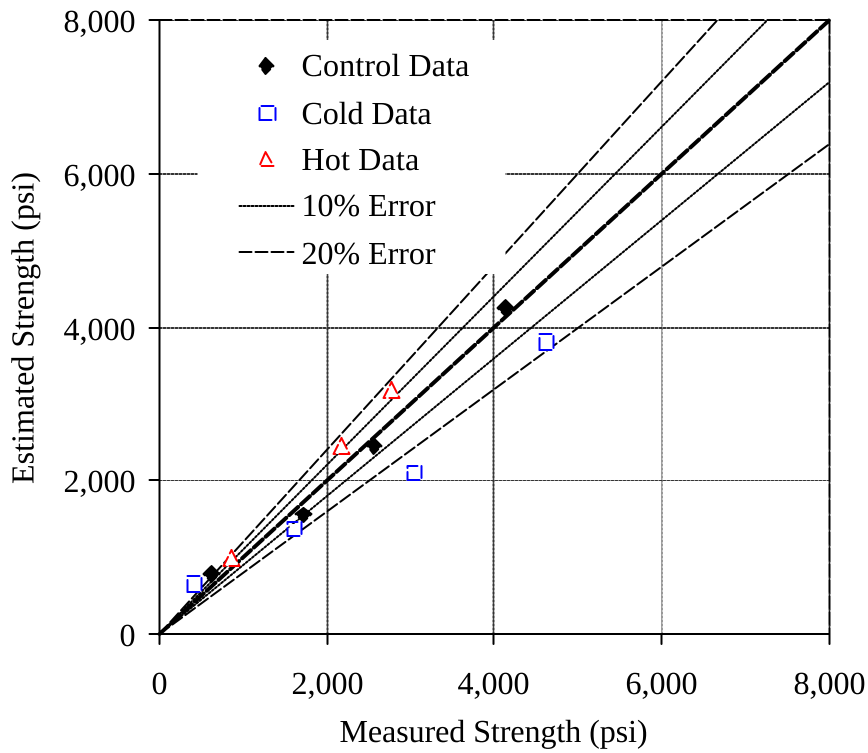


Figure G-24: Error plot for the Type I - 0.48 mixture, ASTM C 1074 method, AM

Table G-13: Error using AM function based on Modified ASTM method for 30% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,180	1,220	40	3	180	6	1,230	50	4	70	3
	1.1	2,200	1,910	-290	-13			2,080	-120	-5		
	2.0	2,860	2,810	-50	-2			2,950	90	3		
	7.0	4,490	4,810	320	7			4,470	-20	0		
Cold	0.9	670	1,320	650	97	270	29	1,040	370	55	320	20
	1.9	1,990	2,280	290	15			2,080	90	5		
	3.5	3,090	3,170	80	3			2,890	-200	-6		
	12.2	4,990	5,040	50	1			4,370	-620	-12		
Hot	0.4	1,350	1,290	-60	-4	300	10	1,870	520	39	238	13
	0.8	2,860	2,280	-580	-20			3,050	190	7		
	1.5	3,620	3,190	-430	-12			3,820	200	6		
	5.0	4,960	5,080	120	2			4,920	-40	-1		

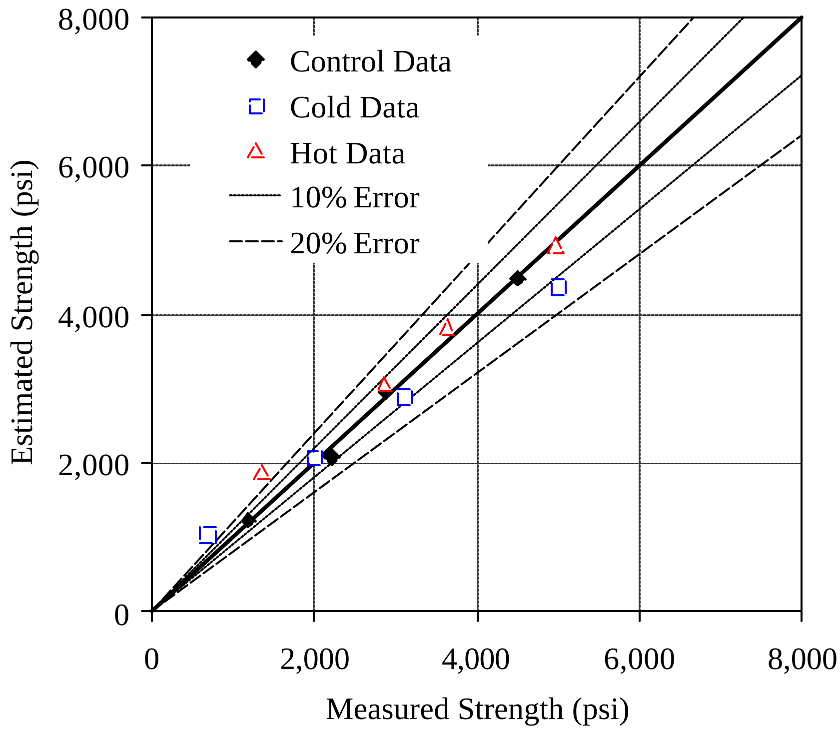


Figure G-25: Error plot for the 30% F mixture, Modified method, AM

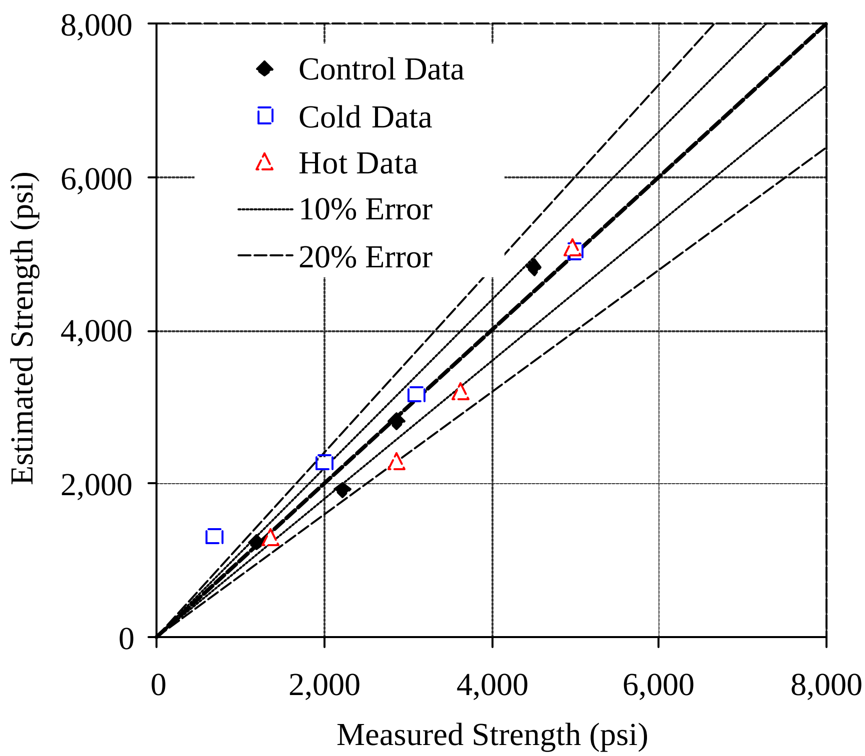


Figure G-26: Error plot for the 30% F mixture, ASTM C 1074 method, AM

Table G-14: Error using AM function based on Modified ASTM method for 20% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,220	1,200	-20	-2	110	4	1,150	-70	-6	110	5
	1.0	2,210	2,330	120	5			2,400	190	9		
	2.0	3,730	3,540	-190	-5			3,570	-160	-4		
	7.0	5,330	5,440	110	2			5,360	30	1		
Cold	1.2	1,040	1,310	270	26	230	13	800	-240	-23	370	14
	1.8	1,760	2,140	380	22			1,630	-130	-7		
	3.4	3,140	3,230	90	3			2,660	-480	-15		
	12.0	5,410	5,240	-170	-3			4,770	-640	-12		
Hot	0.5	1,930	2,210	280	15	360	10	2,970	1,040	54	870	28
	0.8	3,600	3,530	-70	-2			4,280	680	19		
	1.4	3,900	4,420	520	13			4,980	1,080	28		
	5.0	5,360	5,910	550	10			6,050	690	13		

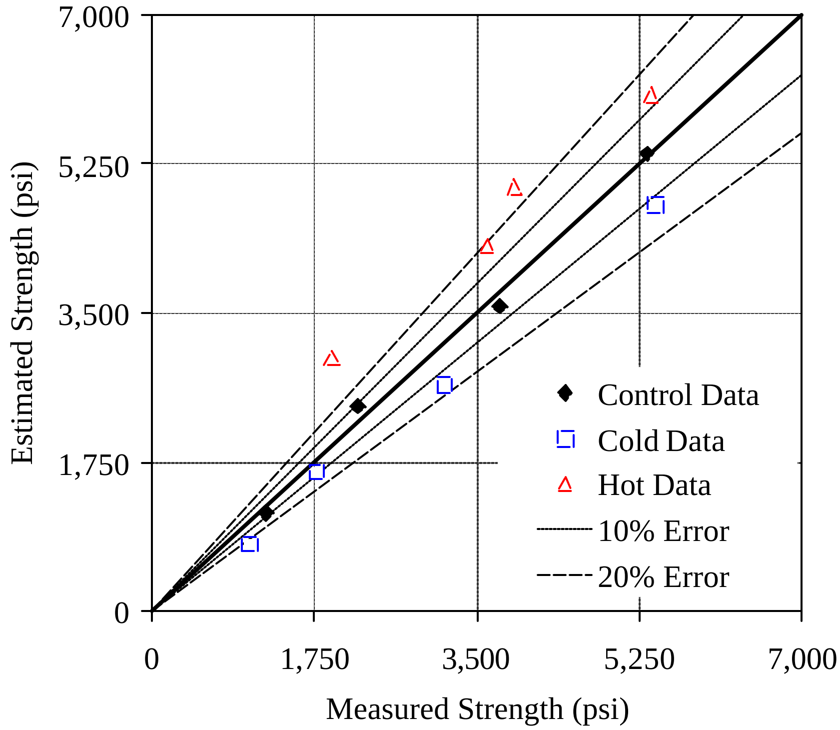


Figure G-27: Error plot for the 20% C mixture, Modified method, AM

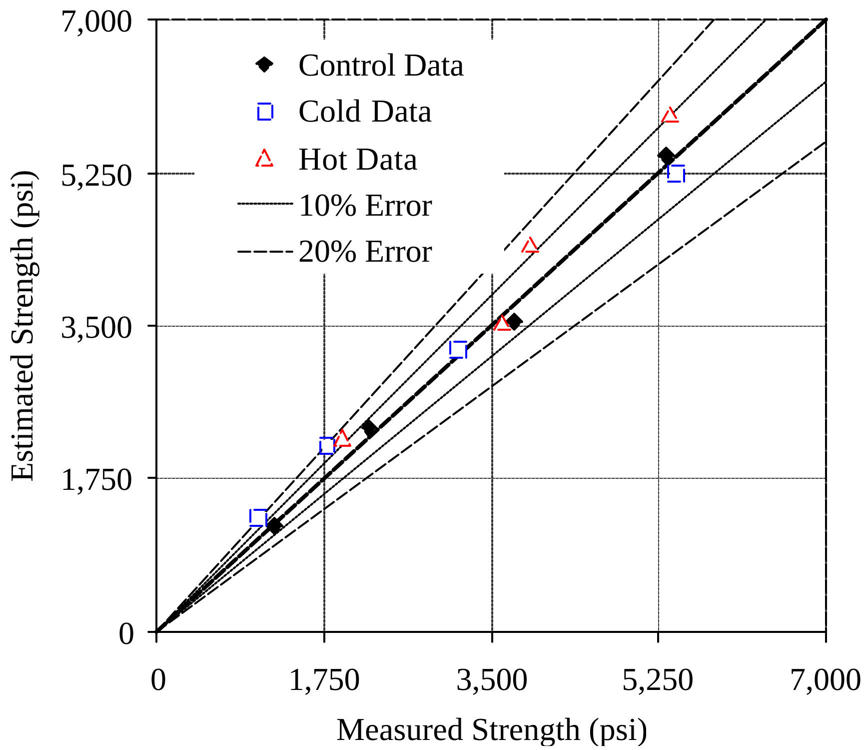


Figure G-28: Error plot for the 20% C mixture, ASTM C 1074 method, AM

Table G-15: Error using AM function based on Modified ASTM method for 30% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	670	780	110	16	80	6	720	50	7	70	4
	1.0	1,940	1,800	-140	-7			1,830	-110	-6		
	2.0	3,060	3,020	-40	-1			3,140	80	3		
	7.2	5,250	5,260	10	0			5,230	-20	0		
Cold	1.3	570	740	170	30	220	13	980	410	72	430	29
	1.9	1,680	1,480	-200	-12			1,860	180	11		
	3.5	2,620	2,620	0	0			3,090	470	18		
	12.1	4,650	5,160	510	11			5,310	660	14		
Hot	0.4	1,050	1,610	560	53	460	22	1,270	220	21	140	8
	0.8	2,710	3,250	540	20			2,880	170	6		
	1.4	3,900	4,300	400	10			3,960	60	2		
	5.0	5,870	6,200	330	6			5,780	-90	-2		

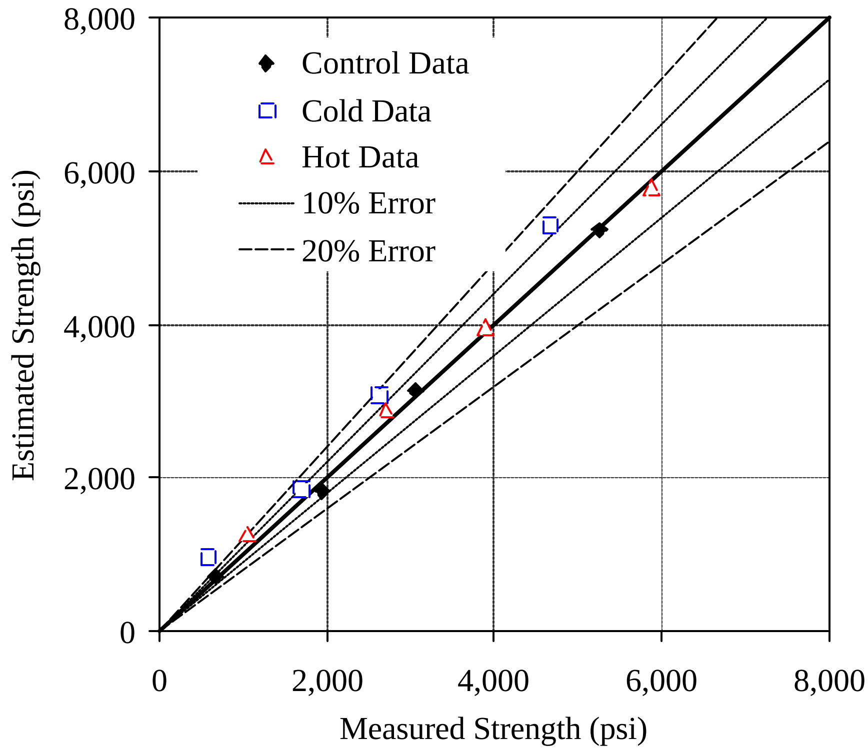


Figure G-29: Error plot for the 30% C mixture, Modified method, AM

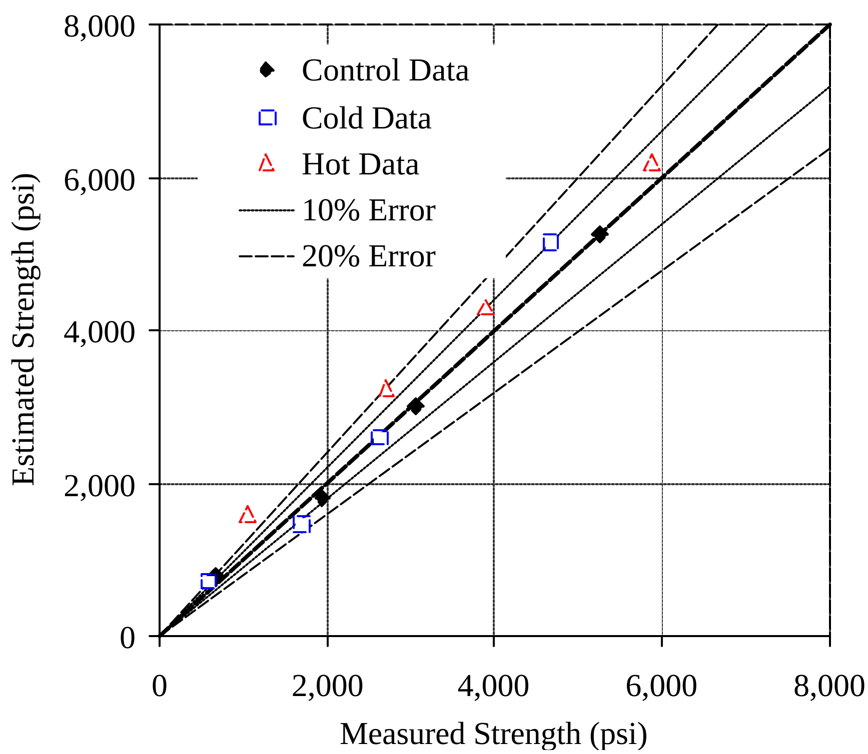


Figure G-30: Error plot for the 30% C mixture, ASTM C 1074 method, AM

Table G-16: Error using AM function based on Modified ASTM method for 30% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,430	1,490	60	4	60	2	1,470	40	3	70	3
	1.0	2,730	2,610	-120	-4			2,600	-130	-5		
	2.0	3,650	3,700	50	1			3,750	100	3		
	7.1	5,770	5,770	0	0			5,760	-10	0		
Cold	0.9	610	840	230	38	220	15	1,180	570	93	410	32
	1.9	2,050	1,900	-150	-7			2,440	390	19		
	3.6	3,400	2,910	-490	-14			3,550	150	4		
	12.2	5,080	5,100	20	0			5,590	510	10		
Hot	0.4	1,500	2,660	1,160	77	1260	42	2,010	510	34	690	21
	0.8	3,130	4,250	1,120	36			3,560	430	14		
	2.9	4,990	6,260	1,270	25			5,740	750	15		
	4.9	5,240	6,730	1,490	28			6,290	1,050	20		

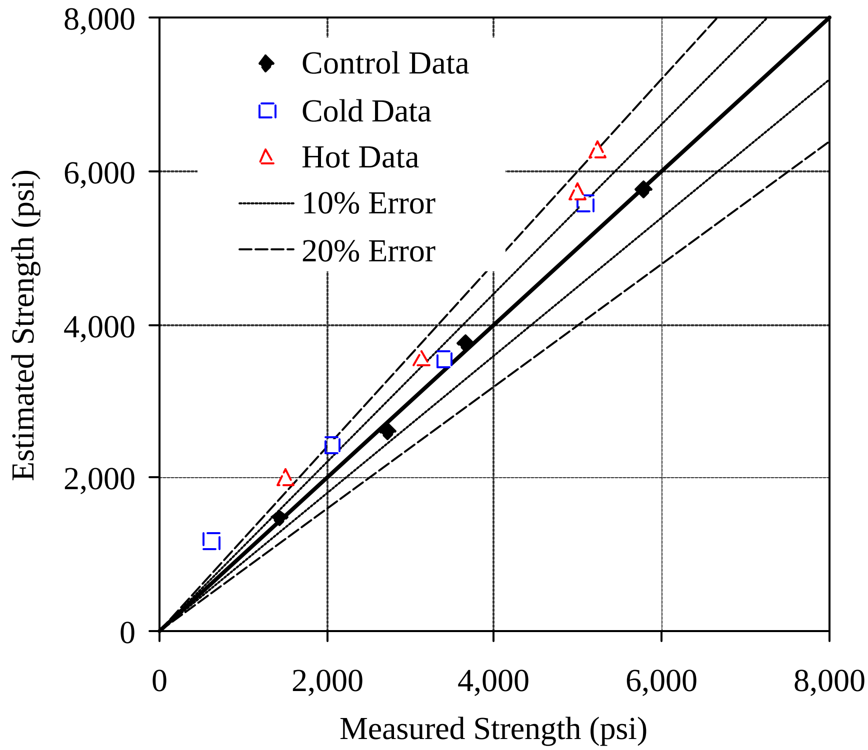


Figure G-31: Error plot for the 30% Slag mixture, Modified method, AM

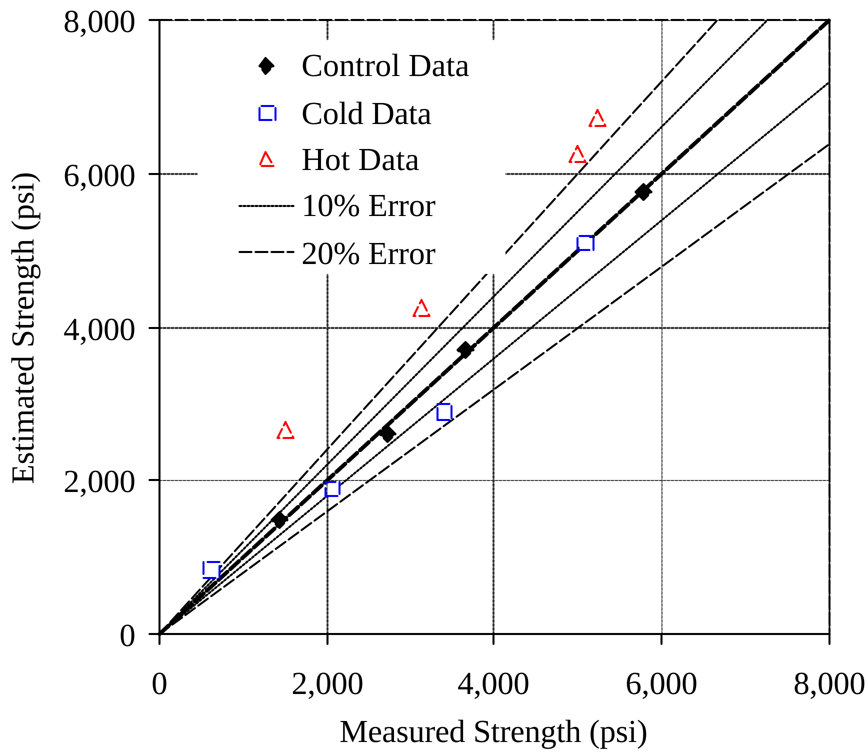


Figure G-32: Error plot for the 30% Slag mixture, ASTM C 1074 method, AM

Table G-17: Error using AM function based on Modified ASTM method for 50% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	760	730	-30	-4	20	2	760	0	0	10	0
	1.0	1,680	1,710	30	2			1,670	-10	-1		
	2.1	3,060	3,070	10	0			3,070	10	0		
	7.2	5,770	5,780	10	0			5,770	0	0		
Cold	0.9	330	100	-230	-70	420	33	670	340	103	580	46
	1.9	1,340	950	-390	-29			1,850	510	38		
	3.4	2,450	1,870	-580	-24			3,070	620	25		
	12.3	4,960	4,470	-490	-10			5,810	850	17		
Hot	0.3	610	1,570	960	157	1520	78	670	60	10	160	6
	0.8	2,330	3,950	1,620	70			2,380	50	2		
	1.4	3,240	5,250	2,010	62			3,540	300	9		
	5.0	6,060	7,550	1,490	25			6,280	220	4		

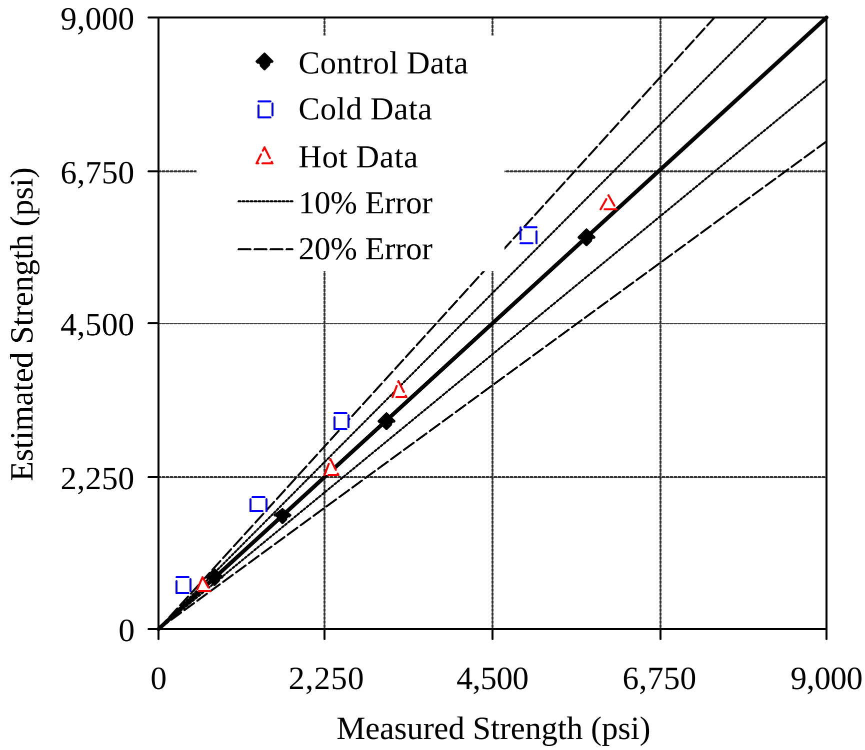


Figure G-33: Error plot for the 50% Slag mixture, Modified method, AM

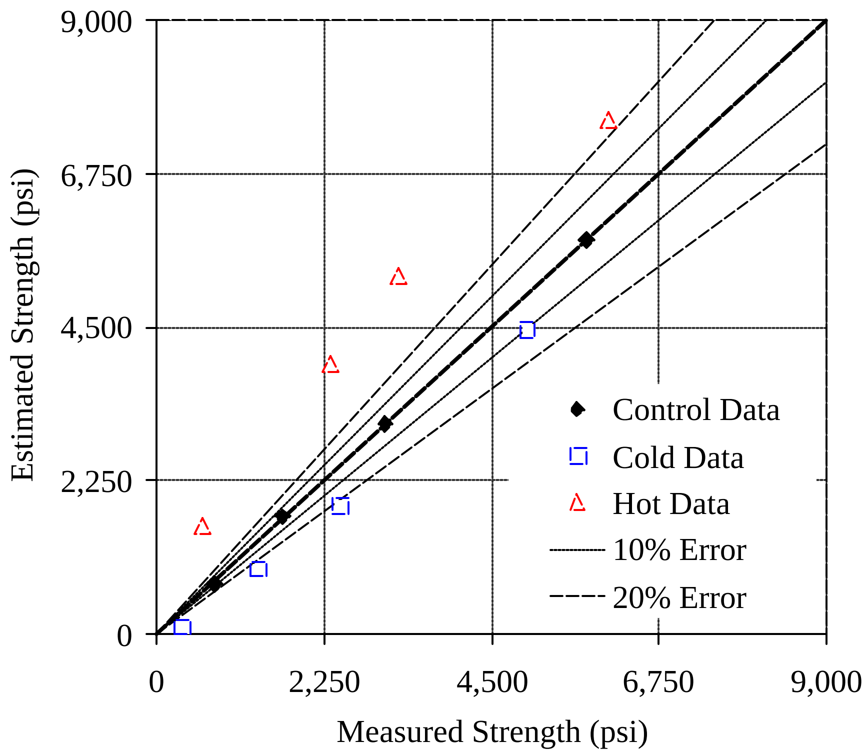


Figure G-34: Error plot for the 50% Slag mixture, ASTM C 1074 method, AM

Table G-18: Error using AM function based on Modified ASTM method for Type III - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	730	790	60	8	140	5	740	10	1	60	2
	1.0	3,040	2,850	-190	-6			2,960	-80	-3		
	2.0	3,820	3,890	70	2			3,930	110	3		
	7.2	5,100	5,350	250	5			5,070	-30	-1		
Cold	1.0	750	970	220	29	330	14	1,170	420	56	360	20
	1.8	2,370	2,230	-140	-6			2,560	190	8		
	3.4	3,660	3,270	-390	-11			3,550	-110	-3		
	12.1	5,630	5,050	-580	-10			4,920	-710	-13		
Hot	0.3	2,400	2,070	-330	-14	580	16	1,980	-420	-18	410	13
	0.7	3,210	3,690	480	15			3,590	380	12		
	1.4	3,740	4,590	850	23			4,380	640	17		
	5.3	5,100	5,750	650	13			5,300	200	4		

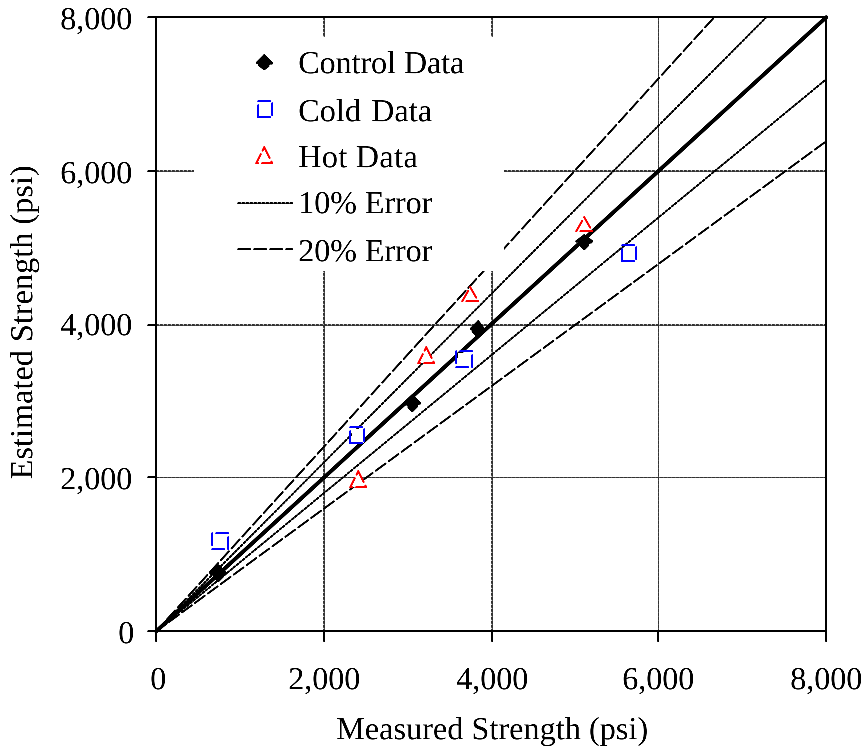


Figure G-35: Error plot for the Type III - 0.44 mixture, Modified method, AM

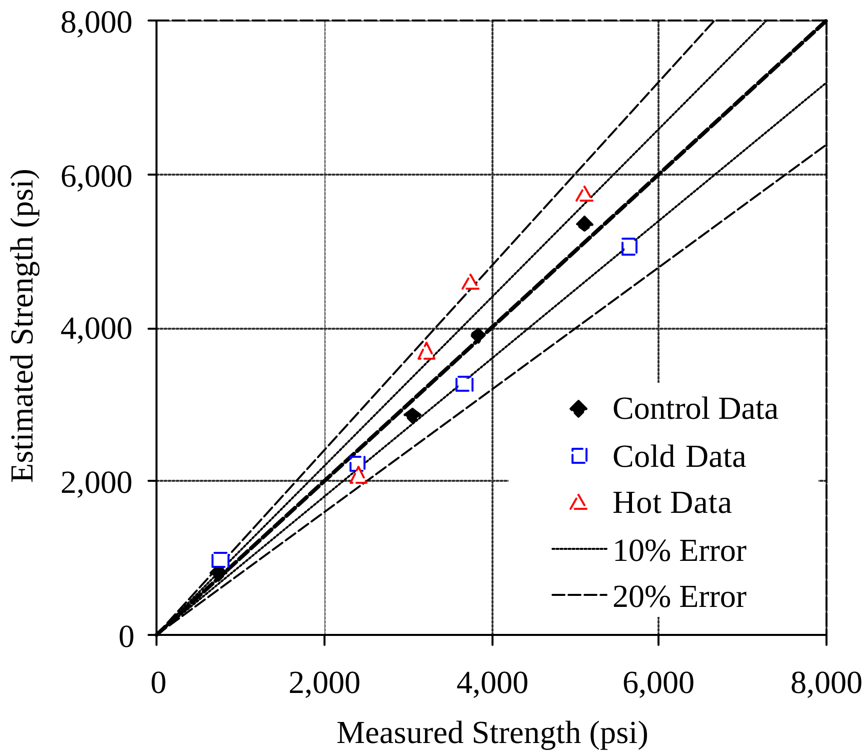


Figure G-36: Error plot for the Type III - 0.44 mixture, ASTM C 1074 method, AM

Table G-19: Error using AM function based on Modified ASTM method for 70/20/10 - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,300	1,530	230	18	340	10	1,340	40	3	80	2
	1.0	3,650	3,340	-310	-8			3,530	-120	-3		
	2.1	5,240	5,050	-190	-4			5,350	110	2		
	7.0	7,670	8,310	640	8			7,640	-30	0		
Cold	0.9	1,040	1,650	610	59	420	19	2,300	1,260	121	1190	51
	1.8	3,060	3,100	40	1			4,370	1,310	43		
	3.5	4,650	4,480	-170	-4			5,870	1,220	26		
	12.2	7,000	7,870	870	12			7,970	970	14		
Hot	0.3	1,640	2,290	650	40	1540	37	910	-730	-45	330	14
	0.7	3,540	4,980	1,440	41			3,610	70	2		
	1.4	5,020	6,800	1,780	35			5,270	250	5		
	4.9	7,390	9,660	2,270	31			7,660	270	4		

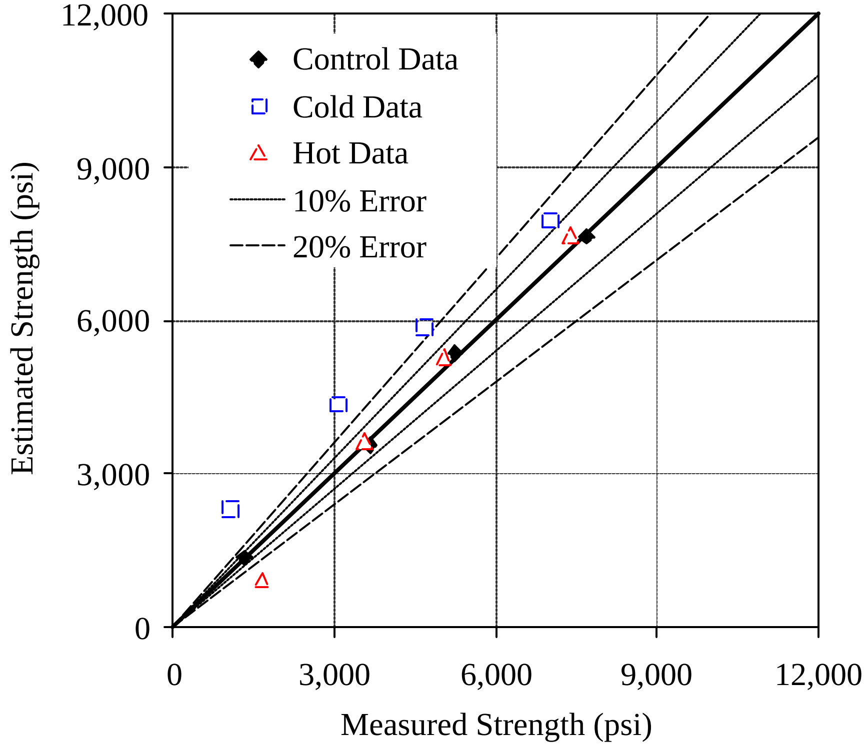


Figure G-37: Error plot for the 70/20/10 - 0.37 mixture, Modified method, AM

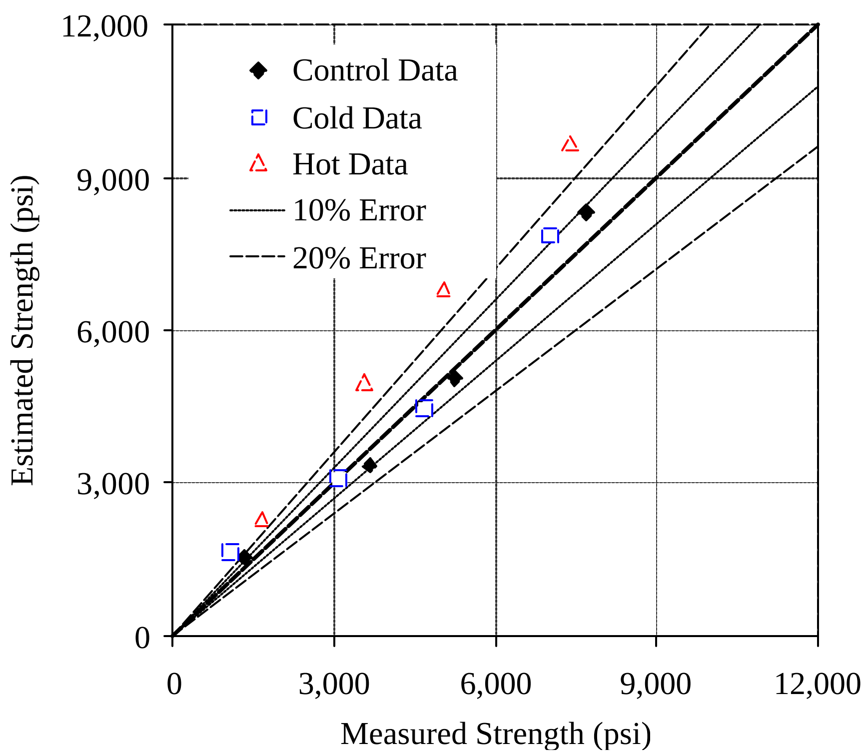


Figure G-38: Error plot for the 70/20/10 - 0.37 mixture, ASTM C 1074 method, AM

Table G-20: Error using AM function based on Modified ASTM method for 70/20/10 - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	ASTM C 1074					Modified ASTM				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	510	630	120	24	140	10	560	50	10	70	5
	1.0	1,770	1,620	-150	-8			1,650	-120	-7		
	2.0	2,610	2,540	-70	-3			2,700	90	3		
	7.2	4,680	4,900	220	5			4,660	-20	0		
Cold	1.0	370	730	360	97	310	34	1,310	940	254	680	84
	1.8	1,450	1,260	-190	-13			2,110	660	46		
	3.4	2,560	2,020	-540	-21			3,170	610	24		
	12.1	4,510	4,380	-130	-3			5,000	490	11		
Hot	0.3	980	1,400	420	43	1110	45	560	-420	-43	190	14
	0.8	1,860	2,780	920	49			1,660	-200	-11		
	1.5	2,720	4,030	1,310	48			2,710	-10	0		
	5.0	4,500	6,290	1,790	40			4,620	120	3		

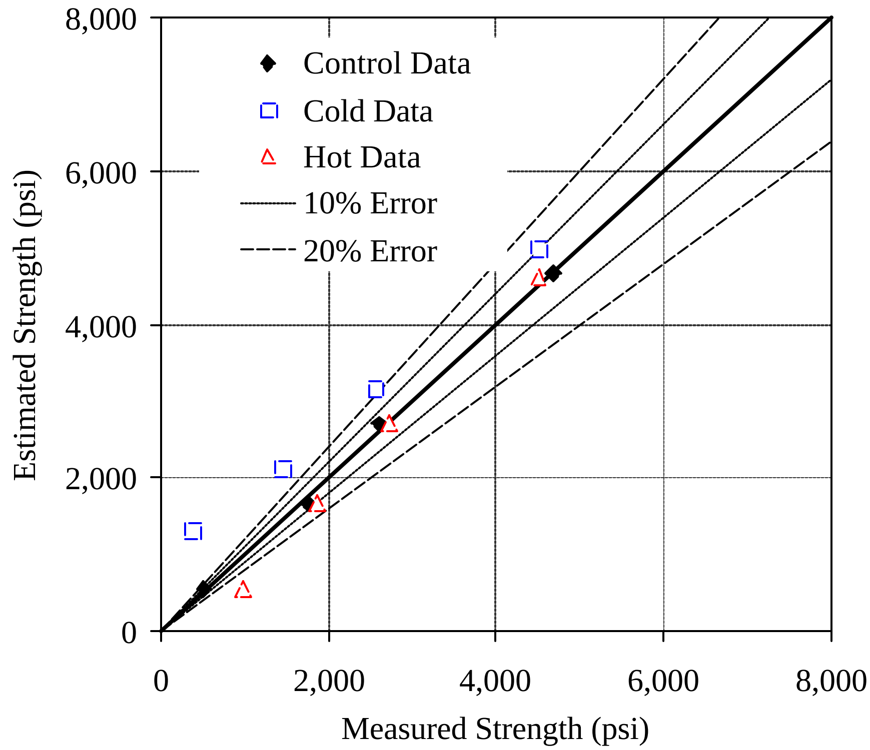


Figure G-39: Error plot for the 70/20/10 - 0.44 mixture, Modified method, AM

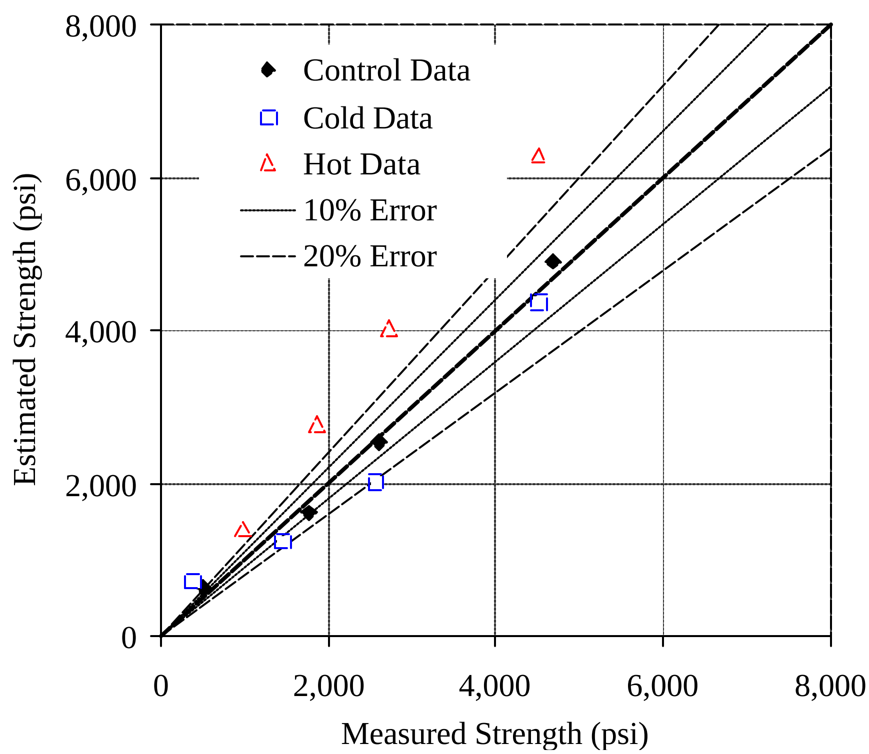


Figure G-40: Error plot for the 70/20/10 - 0.44 mixture, ASTM C 1074 method, AM

APPENDIX H: ERROR TABLES FOR NURSE-SAUL MATURITY FUNCTION, SIMPLIFIED METHOD

Table H-1: Error using NSM function based on simplified method for Type I - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	830	850	20	2	40	2	840	10	1	30	2
	1.0	1,990	1,920	-70	-4			1,930	-60	-3		
	2.0	2,840	2,900	60	2			2,890	50	2		
	7.3	4,210	4,190	-20	0			4,200	-10	0		
Cold	0.9	420	970	550	131	280	37	650	230	55	330	22
	1.9	2,050	2,240	190	9			1,890	-160	-8		
	3.5	3,090	3,100	10	0			2,740	-350	-11		
	12.4	4,580	4,230	-350	-8			3,990	-590	-13		
Hot	0.3	1,270	520	-750	-59	390	21	700	-570	-45	240	14
	0.9	2,570	2,250	-320	-12			2,440	-130	-5		
	1.5	3,390	3,070	-320	-9			3,230	-160	-5		
	5.0	4,380	4,200	-180	-4			4,300	-80	-2		

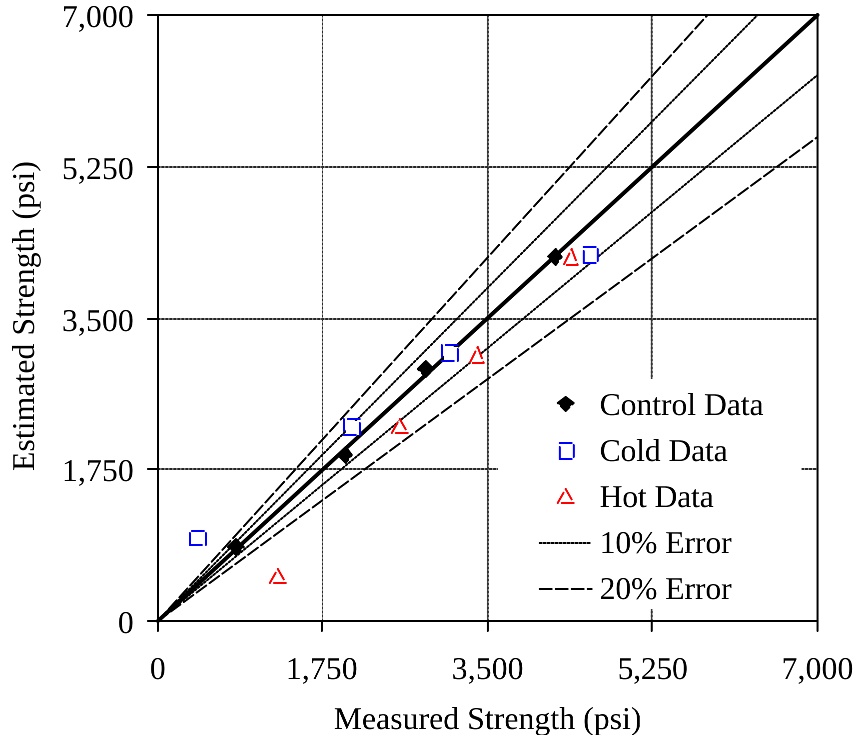


Figure H-1: Error plot for the Type I - 0.44 mixture, simplified method, T_o = 14°F

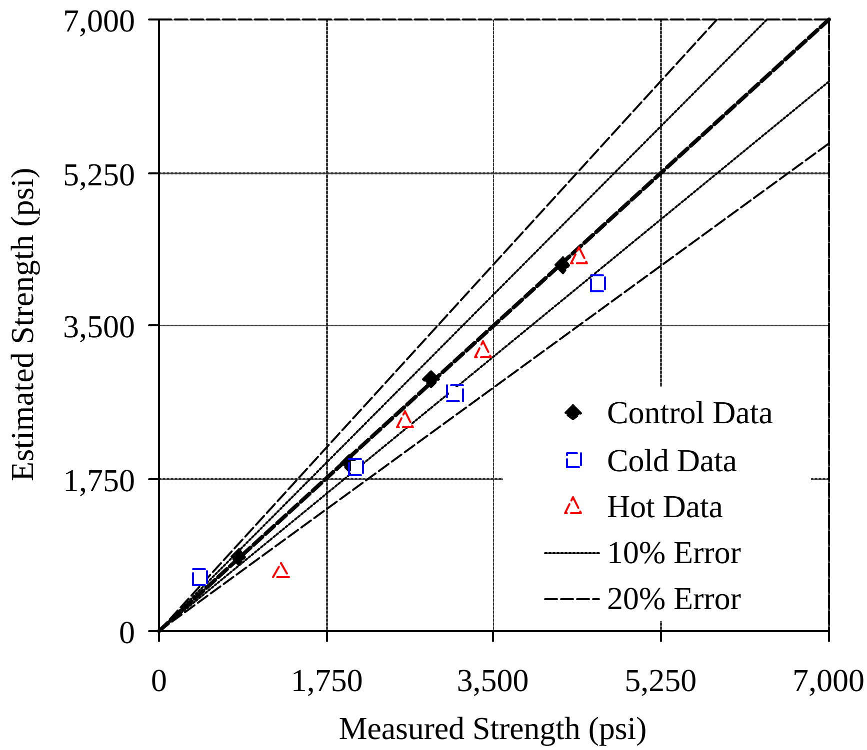


Figure H-2: Error plot for the Type I - 0.44 mixture, simplified method, T_o = 32°F

Table H-2: Error using NSM function based on simplified method for Type I - 0.48 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	630	660	30	5	50	3	650	20	3	40	2
	1.0	1,710	1,630	-80	-5			1,640	-70	-4		
	2.0	2,570	2,640	70	3			2,630	60	2		
	7.4	4,120	4,100	-20	0			4,110	-10	0		
Cold	0.9	410	880	470	115	410	39	570	160	39	468	22
	1.9	1,600	1,920	320	20			1,530	-70	-4		
	3.6	3,040	2,750	-290	-10			2,300	-740	-24		
	12.0	4,610	4,070	-540	-12			3,710	-900	-20		
Hot	0.3	850	470	-380	-45	240	17	580	-270	-32	168	11
	0.8	2,180	1,860	-320	-15			2,040	-140	-6		
	1.4	2,770	2,640	-130	-5			2,810	40	1		
	5.1	4,010	4,120	110	3			4,230	220	5		

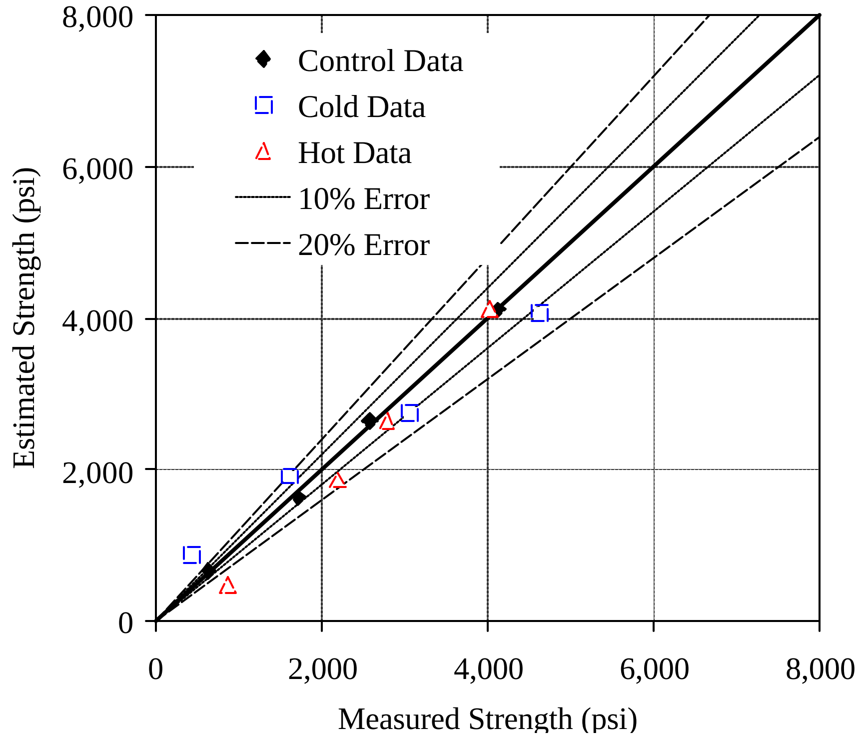


Figure H-3: Error plot for the Type I - 0.48 mixture, simplified method, T_o = 14°F

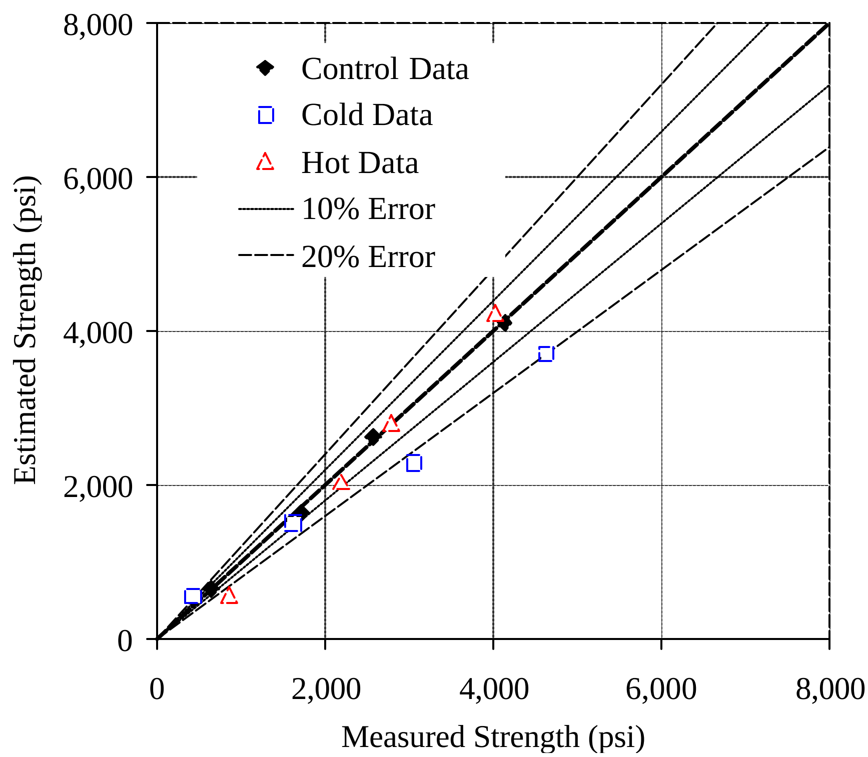


Figure H-4: Error plot for the Type I - 0.48 mixture, simplified method, T_o = 32°F

Table H-3: Error using NSM function based on simplified method for 30% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**T_o = 14°F (-10°C)**					**T_o = 32°F (0°C)**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,180	1,240	60	5	80	4	1,230	50	4	80	4
	1.1	2,200	2,060	-140	-6			2,070	-130	-6		
	2.0	2,860	2,970	110	4			2,960	100	3		
	7.0	4,490	4,470	-20	0			4,470	-20	0		
Cold	0.9	670	1,320	650	97	410	33	1,040	370	55	370	21
	1.9	1,990	2,410	420	21			2,070	80	4		
	3.5	3,090	3,210	120	4			2,820	-270	-9		
	12.2	4,990	4,550	-440	-9			4,250	-740	-15		
Hot	0.4	1,350	1,190	-160	-12	390	13	1,380	30	2	220	7
	0.8	2,860	2,310	-550	-19			2,530	-330	-12		
	1.5	3,620	3,170	-450	-12			3,370	-250	-7		
	5.0	4,960	4,570	-390	-8			4,690	-270	-5		

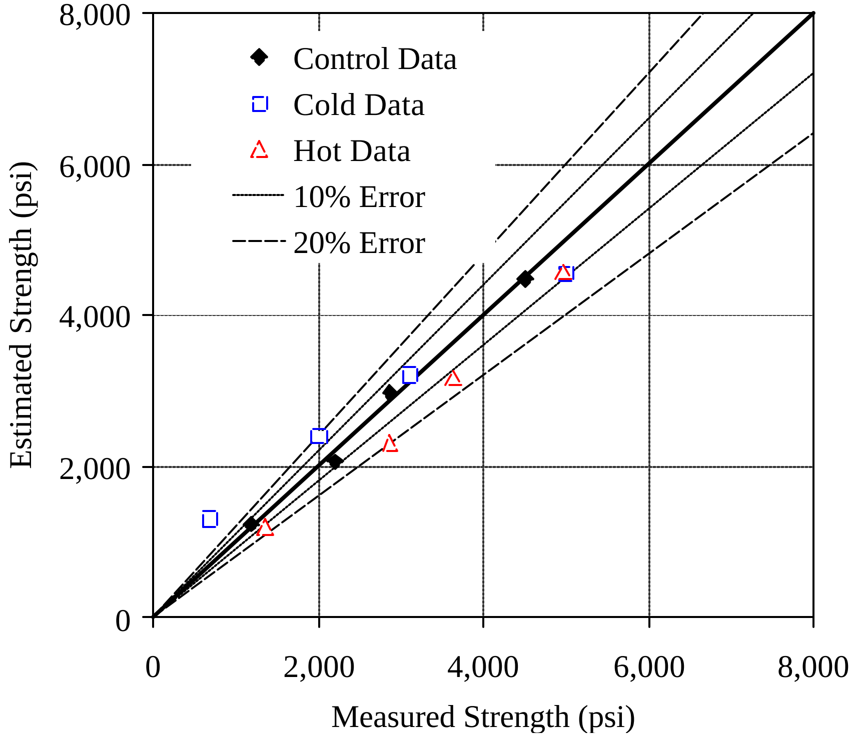


Figure H-5: Error plot for the 30% F mixture, simplified method, T_o = 14°F

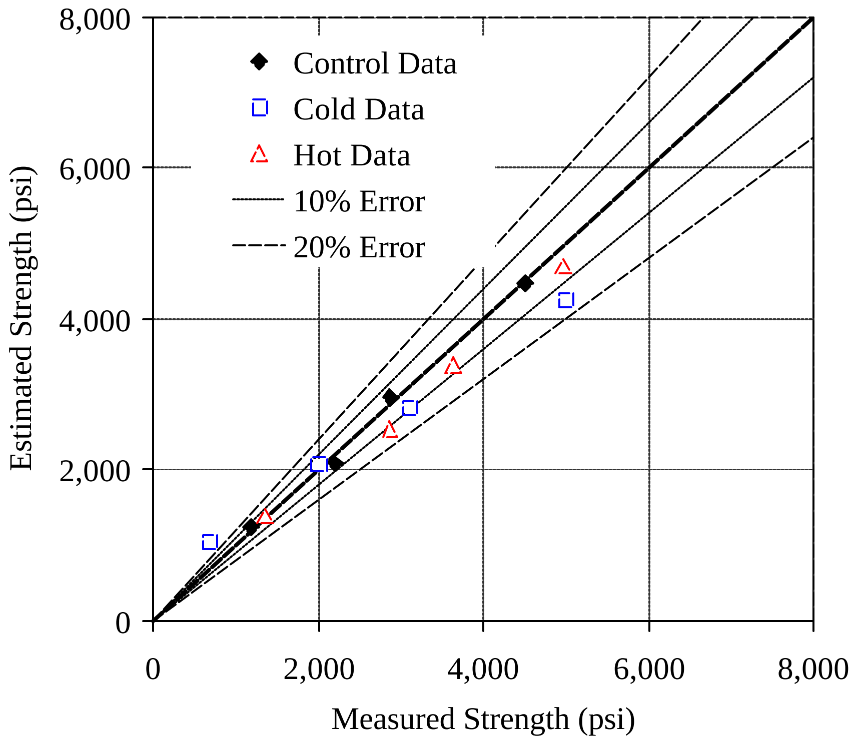


Figure H-6: Error plot for the 30% F mixture, simplified method, T_o = 32°F

Table H-4: Error using NSM function based on simplified method for 20% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,220	1,170	-50	-4	80	3	1,160	-60	-5	90	4
	1.0	2,210	2,350	140	6			2,360	150	7		
	2.0	3,730	3,620	-110	-3			3,610	-120	-3		
	7.0	5,330	5,350	20	0			5,360	30	1		
Cold	1.2	1,040	1,670	630	61	520	32	1,190	150	14	260	11
	1.8	1,760	2,590	830	47			2,100	340	19		
	3.4	3,140	3,700	560	18			3,070	-70	-2		
	12.0	5,410	5,370	-40	-1			4,940	-470	-9		
Hot	0.5	1,930	1,440	-490	-25	390	14	1,690	-240	-12	280	9
	0.8	3,600	2,730	-870	-24			3,000	-600	-17		
	1.4	3,900	3,750	-150	-4			3,980	80	2		
	5.0	5,360	5,420	60	1			5,560	200	4		

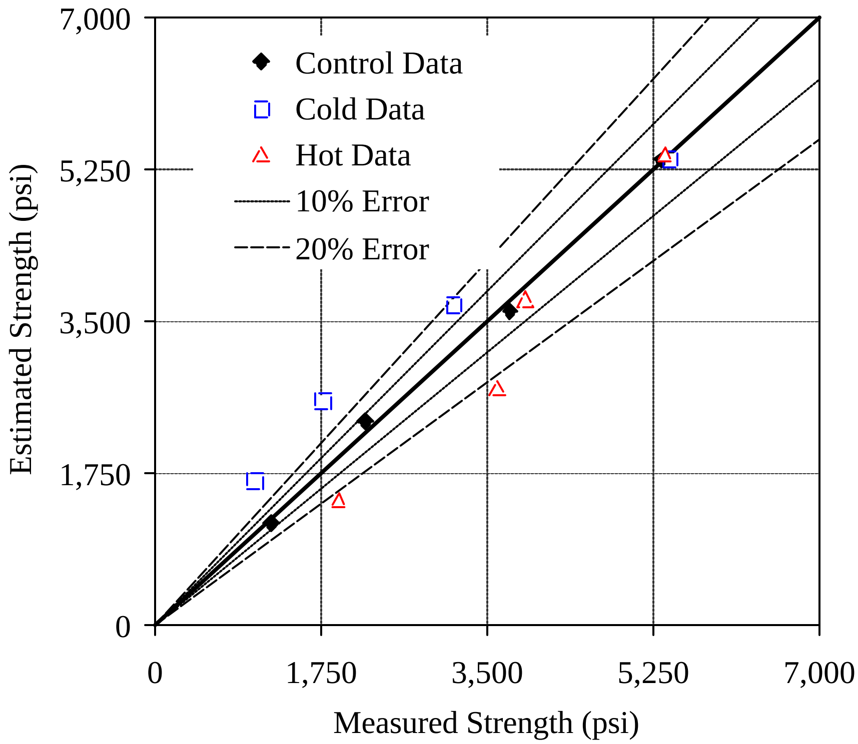


Figure H-7: Error plot for the 20% C mixture, simplified method, T_o = 14°F

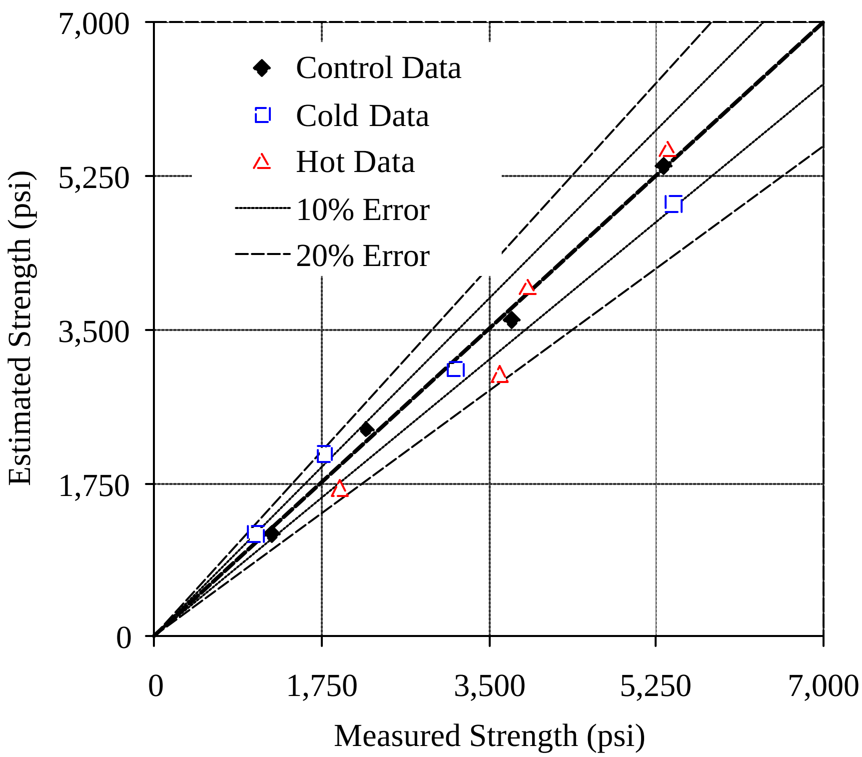


Figure H-8: Error plot for the 20% C mixture, simplified method, T_o = 32°F

Table H-5: Error using NSM function based on simplified method for 30% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	670	730	60	9	80	5	720	50	7	70	4
	1.0	1,940	1,800	-140	-7			1,830	-110	-6		
	2.0	3,060	3,160	100	3			3,150	90	3		
	7.2	5,250	5,230	-20	0			5,230	-20	0		
Cold	1.3	570	1,310	740	130	700	52	790	220	39	220	14
	1.9	1,680	2,200	520	31			1,620	-60	-4		
	3.5	2,620	3,400	780	30			2,770	150	6		
	12.1	4,650	5,410	760	16			5,100	450	10		
Hot	0.4	1,050	690	-360	-34	540	21	920	-130	-12	280	10
	0.8	2,710	2,090	-620	-23			2,390	-320	-12		
	1.4	3,900	3,250	-650	-17			3,540	-360	-9		
	5.0	5,870	5,360	-510	-9			5,570	-300	-5		

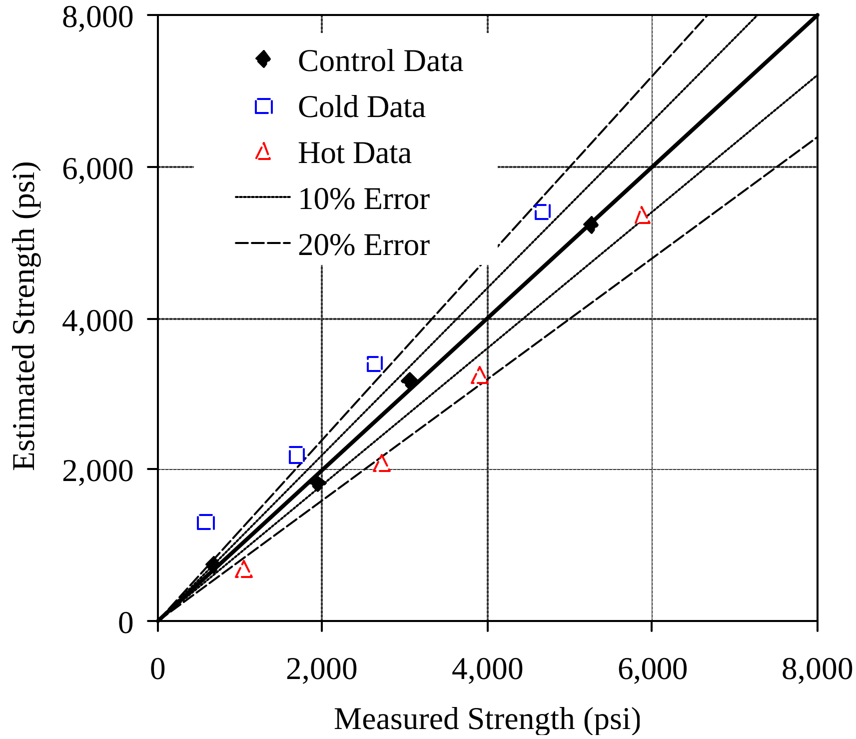


Figure H-9: Error plot for the 30% C mixture, simplified method, T_o = 14°F

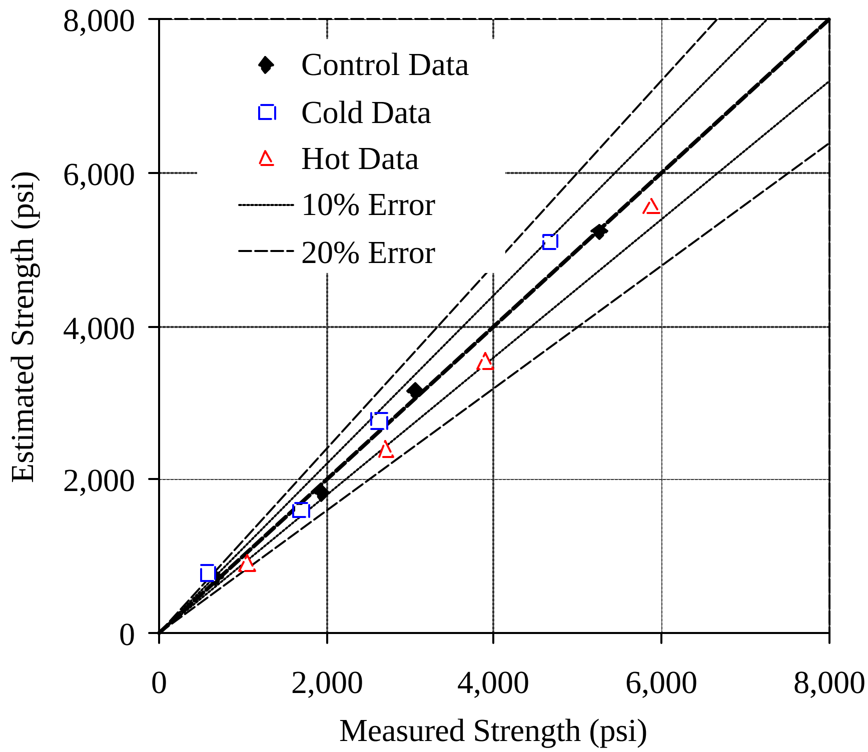


Figure H-10: Error plot for the 30% C mixture, simplified method, T_o = 32°F

Table H-6: Error using NSM function based on simplified method for 30% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,430	1,490	60	4	90	3	1,480	50	3	80	3
	1.0	2,730	2,570	-160	-6			2,590	-140	-5		
	2.0	3,650	3,770	120	3			3,760	110	3		
	7.1	5,770	5,750	-20	0			5,750	-20	0		
Cold	0.9	610	1,560	950	156	790	58	1,210	600	98	340	31
	1.9	2,050	2,900	850	41			2,430	380	19		
	3.6	3,400	4,010	610	18			3,460	60	2		
	12.2	5,080	5,840	760	15			5,400	320	6		
Hot	0.4	1,500	1,320	-180	-12	320	9	1,490	-10	-1	310	7
	0.8	3,130	2,730	-400	-13			2,960	-170	-5		
	2.9	4,990	5,110	120	2			5,320	330	7		
	4.9	5,240	5,800	560	11			5,980	740	14		

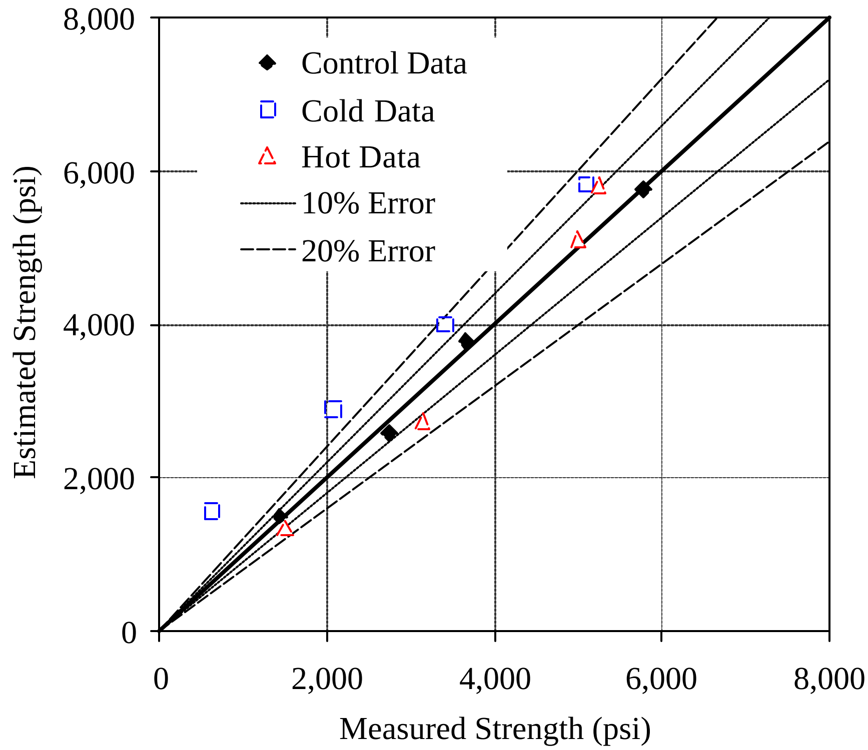


Figure H-11: Error plot for the 30% Slag mixture, simplified method, T_o = 14°F

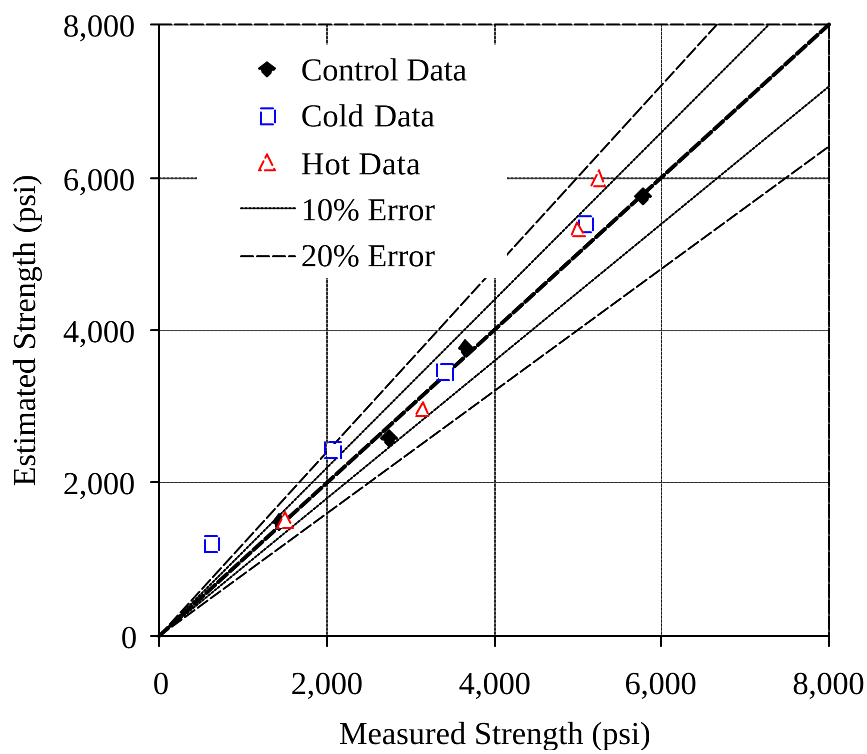


Figure H-12: Error plot for the 30% Slag mixture, simplified method, T_o = 32°F

Table H-7: Error using NSM function based on simplified method for 50% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	760	760	0	0	10	0	760	0	0	0	0
	1.0	1,680	1,660	-20	-1			1,670	-10	-1		
	2.1	3,060	3,070	10	0			3,060	0	0		
	7.2	5,770	5,770	0	0			5,770	0	0		
Cold	0.9	330	760	430	130	660	56	450	120	36	100	12
	1.9	1,340	1,960	620	46			1,470	130	10		
	3.4	2,450	3,170	720	29			2,500	50	2		
	12.3	4,960	5,830	870	18			5,050	90	2		
Hot	0.3	610	440	-170	-28	220	13	560	-50	-8	110	5
	0.8	2,330	1,970	-360	-15			2,210	-120	-5		
	1.4	3,240	3,060	-180	-6			3,370	130	4		
	5.0	6,060	5,890	-170	-3			6,190	130	2		

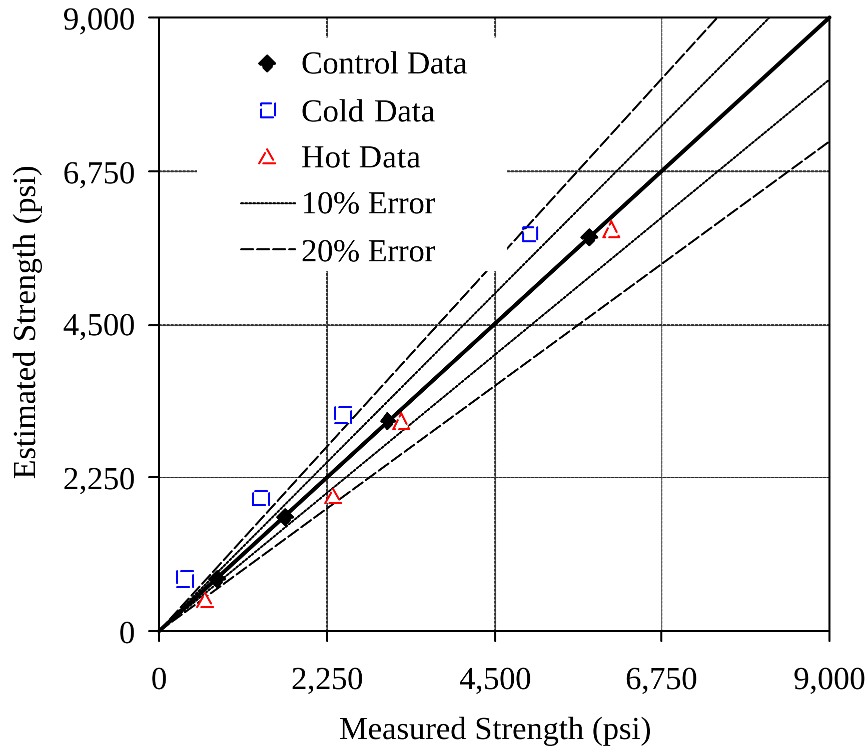


Figure H-13: Error plot for the 50% Sla g mixture, simplified method, T_o = 14°F

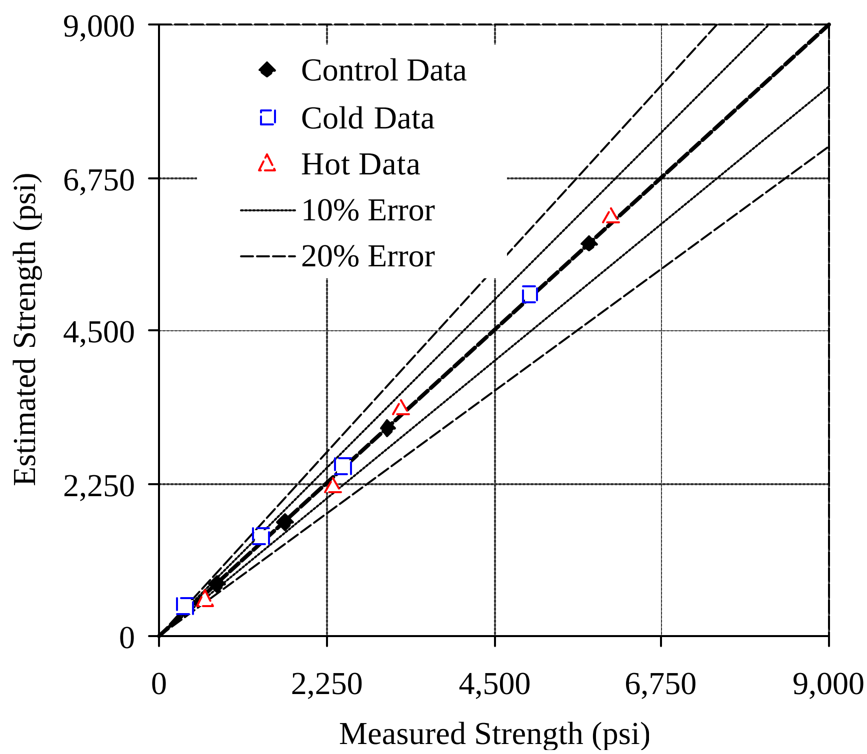


Figure H-14: Error plot for the 50% Slag mixture, simplified method, T_o = 32°F

Table H-8: Error using NSM function based on simplified method for Type III - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	T_o = 14°F (-10°C)					T_o = 32°F (0°C)				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	730	750	20	3	80	3	750	20	3	70	2
	1.0	3,040	2,940	-100	-3			2,950	-90	-3		
	2.0	3,820	3,960	140	4			3,940	120	3		
	7.2	5,100	5,050	-50	-1			5,060	-40	-1		
Cold	1.0	750	1,780	1,030	137	660	47	1,240	490	65	430	24
	1.8	2,370	3,100	730	31			2,620	250	11		
	3.4	3,660	3,970	310	8			3,490	-170	-5		
	12.1	5,630	5,050	-580	-10			4,820	-810	-14		
Hot	0.3	2,400	1,000	-1,400	-58	470	18	1,250	-1,150	-48	410	15
	0.7	3,210	2,890	-320	-10			3,080	-130	-4		
	1.4	3,740	3,900	160	4			4,040	300	8		
	5.3	5,100	5,090	-10	0			5,170	70	1		

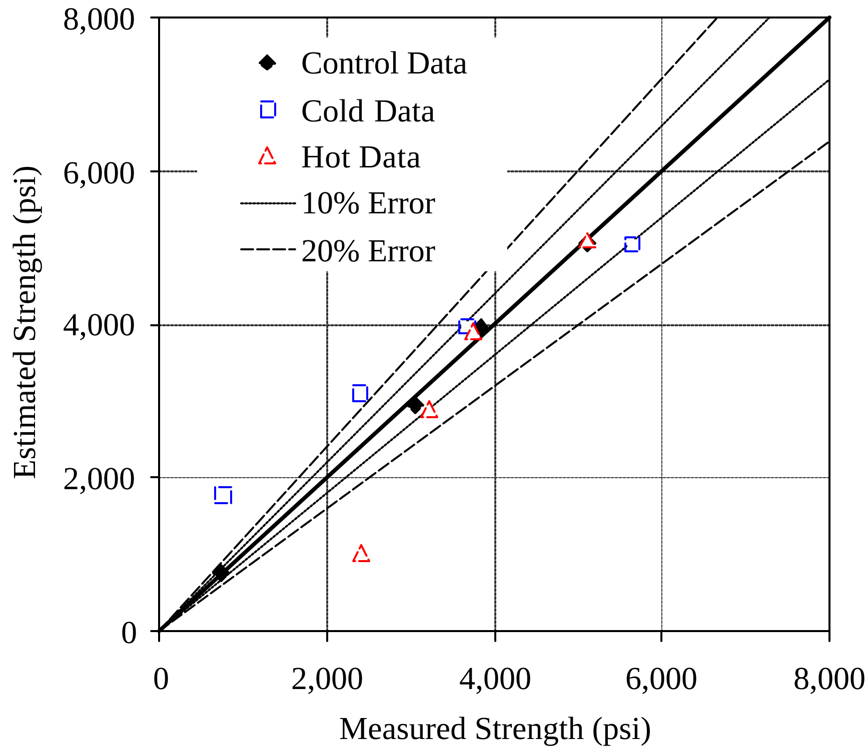


Figure H-15: Error plot for the Type III - 0.44 mixture, simplified method, T_o = 14°F

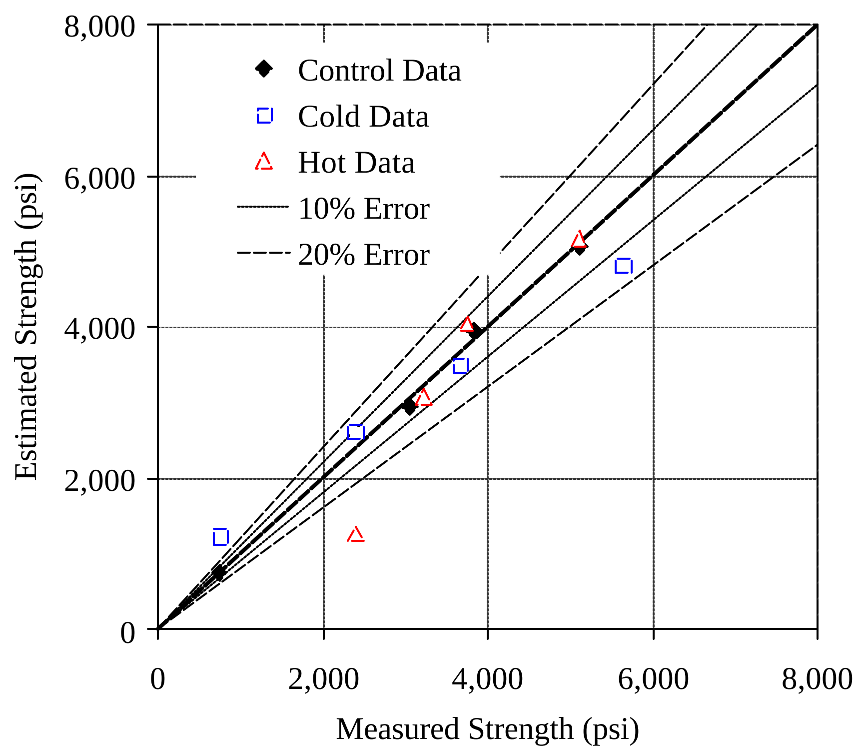


Figure H-16: Error plot for the Type III - 0.44 mixture, simplified method, T_o = 32°F

Table H-9: Error using NSM function based on simplified method for 70/20/10 - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**T_o = 14°F (-10°C)**					**T_o = 32°F (0°C)**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,300	1,330	30	2	70	2	1,330	30	2	50	2
	1.0	3,650	3,550	-100	-3			3,570	-80	-2		
	2.1	5,240	5,340	100	2			5,310	70	1		
	7.0	7,670	7,640	-30	0			7,650	-20	0		
Cold	0.9	1,040	2,030	990	95	890	39	1,600	560	54	330	18
	1.8	3,060	4,040	980	32			3,460	400	13		
	3.5	4,650	5,480	830	18			4,760	110	2		
	12.2	7,000	7,750	750	11			7,240	240	3		
Hot	0.3	1,640	990	-650	-40	390	14	1,290	-350	-21	550	15
	0.7	3,540	3,720	180	5			4,090	550	16		
	1.4	5,020	5,380	360	7			5,730	710	14		
	4.9	7,390	7,740	350	5			7,960	570	8		

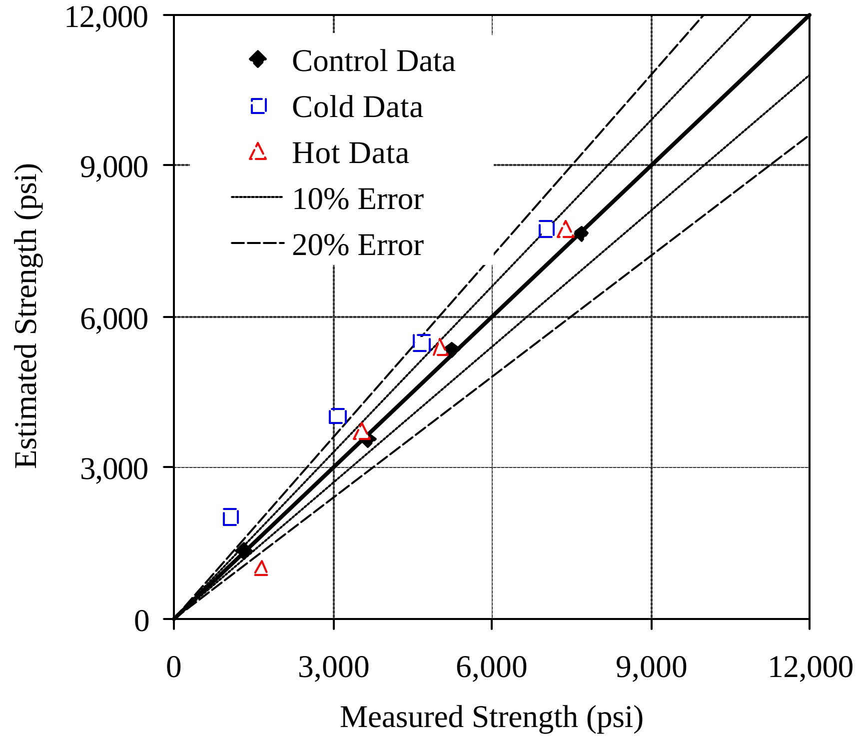


Figure H-17: Error plot for the 70/20/10 - 0.37 mixture, simplified method, T_o = 14°F

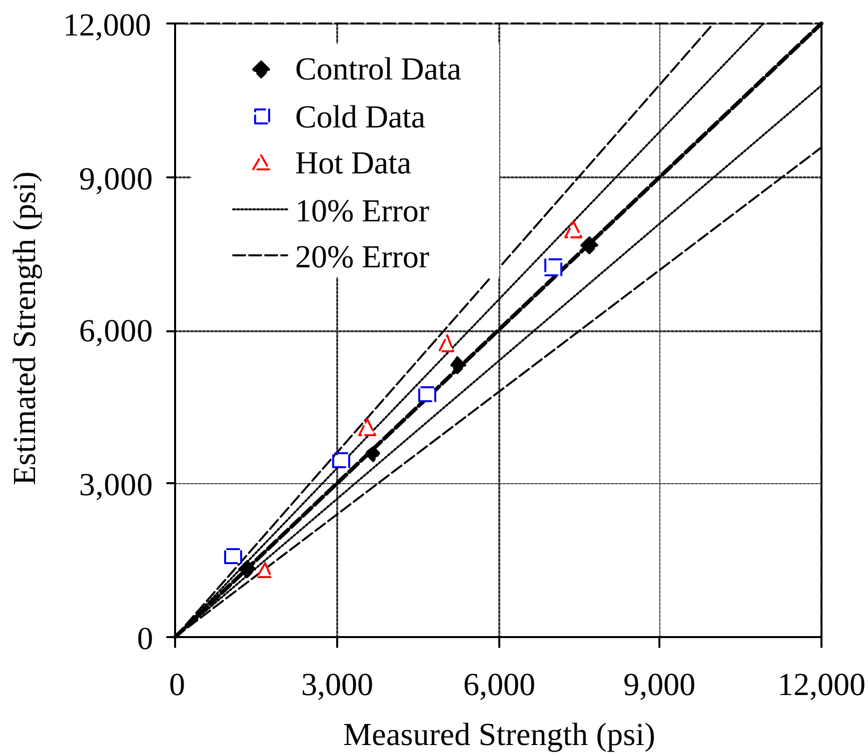


Figure H-18: Error plot for the 70/20/10 - 0.37 mixture, simplified method, T_o = 32°F

Table H-10: Error using NSM function based on simplified method for the 70/20/10 - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**T_o = 14°F (-10°C)**					**T_o = 32°F (0°C)**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	510	550	40	8	60	4	550	40	8	50	4
	1.0	1,770	1,660	-110	-6			1,680	-90	-5		
	2.0	2,610	2,690	80	3			2,680	70	3		
	7.2	4,680	4,660	-20	0			4,670	-10	0		
Cold	1.0	370	1,090	720	195	410	59	820	450	122	240	35
	1.8	1,450	1,850	400	28			1,510	60	4		
	3.4	2,560	2,820	260	10			2,320	-240	-9		
	12.1	4,510	4,760	250	6			4,300	-210	-5		
Hot	0.3	980	630	-350	-36	210	13	750	-230	-23	290	13
	0.8	1,860	1,780	-80	-4			1,970	110	6		
	1.5	2,720	2,850	130	5			3,080	360	13		
	5.0	4,500	4,760	260	6			4,970	470	10		

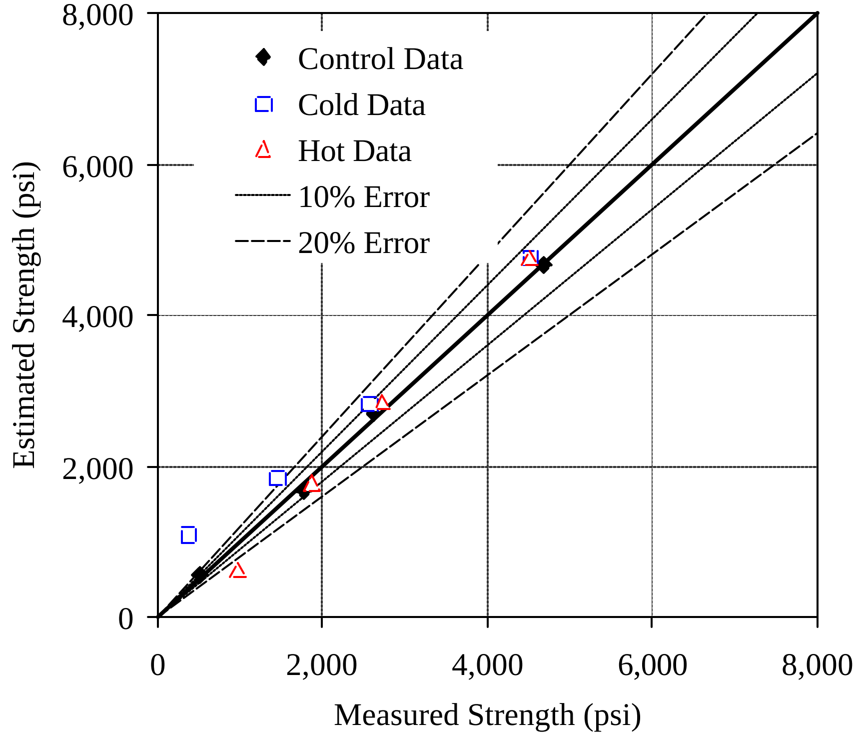


Figure H-19: Error plot for the 70/20/10 - 0.44 mixture, simplified method, T_o = 14°F

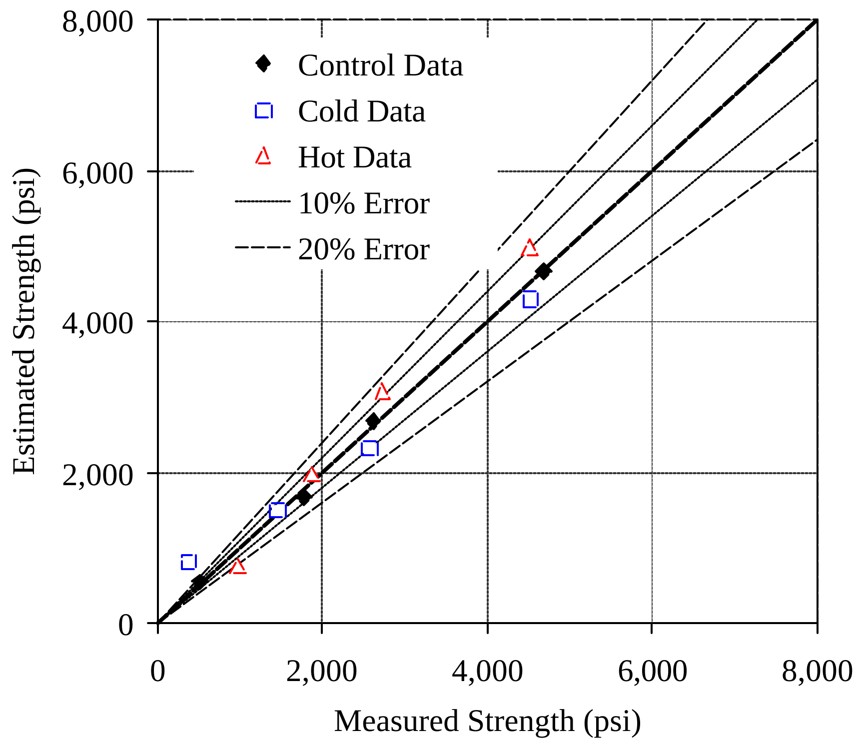


Figure H-20: Error plot for the 70/20/10 - 0.44 mixture, simplified method, T_o = 32°F

APPENDIX I: ERROR TABLES FOR ARRHENIUS MATURITY FUNCTION, SIMPLIFIED METHOD

Table I-1: Error using NSM function based on simplified method for Type I - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**E = 40,000 J/mol**					**E = 25,000 J/mol**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	830	840	10	1	30	1	850	20	2	40	2
	1.0	1,990	1,940	-50	-3			1,920	-70	-4		
	2.0	2,840	2,880	40	1			2,900	60	2		
	7.3	4,210	4,200	-10	0			4,190	-20	0		
Cold	0.9	420	580	160	38	310	18	950	530	126	260	36
	1.9	2,050	1,820	-230	-11			2,230	180	9		
	3.5	3,090	2,730	-360	-12			3,110	20	1		
	12.4	4,580	4,080	-500	-11			4,260	-320	-7		
Hot	0.3	1,270	1,270	0	0	180	6	750	-520	-41	220	13
	0.9	2,570	2,960	390	15			2,470	-100	-4		
	1.5	3,390	3,630	240	7			3,250	-140	-4		
	5.0	4,380	4,480	100	2			4,280	-100	-2		

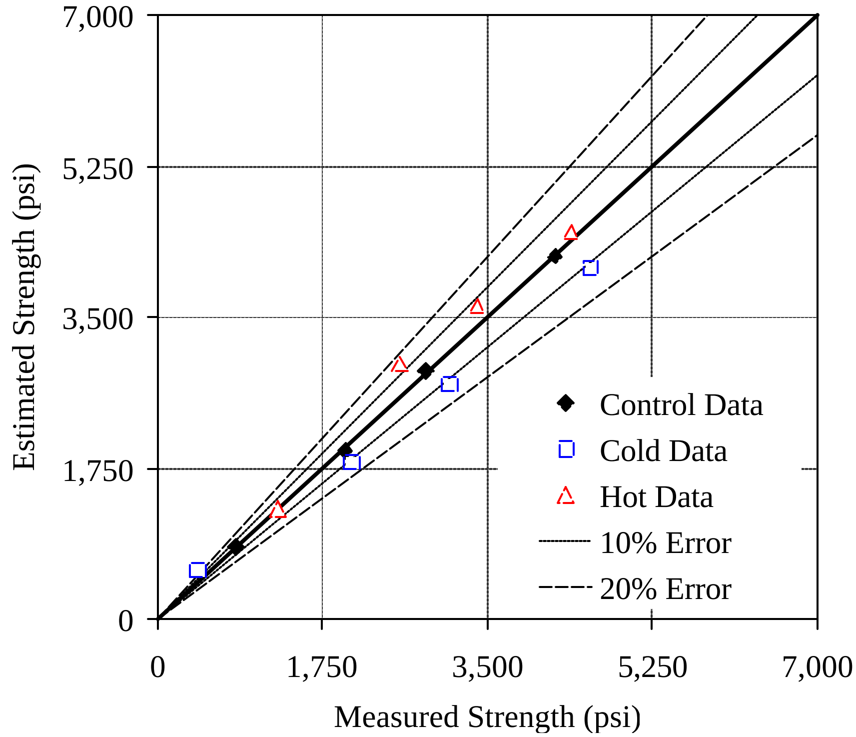


Figure I-1: Error plot for the Type I - 0.44 mixture, simplified method, *E*= 40 kJ/mol

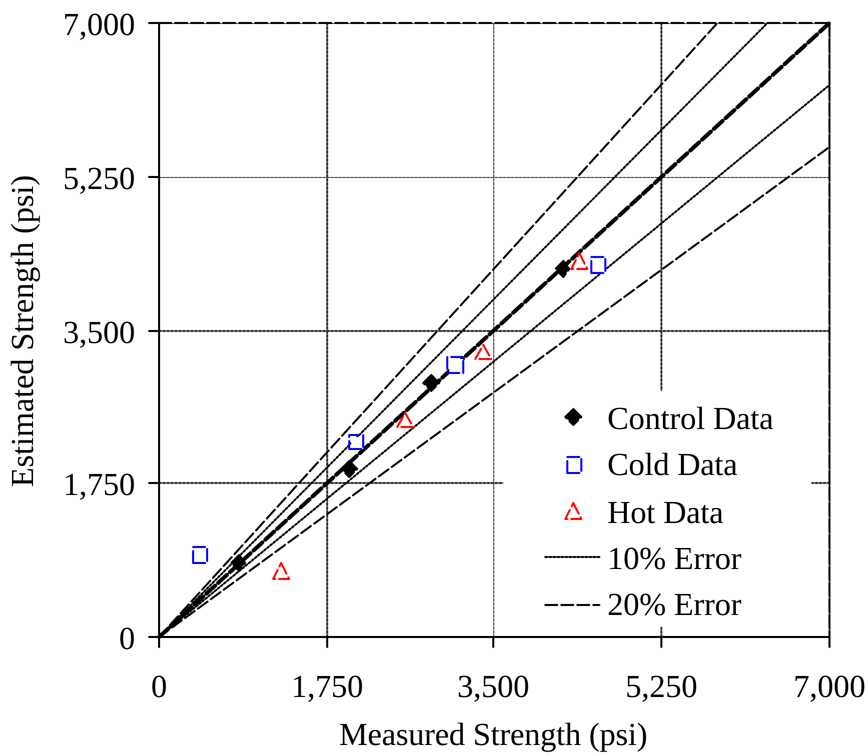


Figure I-2: Error plot for the Type I - 0.44 mixture, simplified method, *E* = 25 kJ/mol

Table I-2: Error using NSM function based on simplified method for Type I - 0.48 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	630	650	20	3	40	2	660	30	5	50	3
	1.0	1,710	1,650	-60	-4			1,630	-80	-5		
	2.0	2,570	2,620	50	2			2,630	60	2		
	7.4	4,120	4,110	-10	0			4,110	-10	0		
Cold	0.9	410	540	130	32	420	19	880	470	115	390	39
	1.9	1,600	1,510	-90	-6			1,920	320	20		
	3.6	3,040	2,340	-700	-23			2,770	-270	-9		
	12.0	4,610	3,840	-770	-17			4,110	-500	-11		
Hot	0.3	850	900	50	6	330	13	590	-260	-31	160	11
	0.8	2,180	2,550	370	17			2,070	-110	-5		
	1.4	2,770	3,220	450	16			2,820	50	2		
	5.1	4,010	4,450	440	11			4,210	200	5		

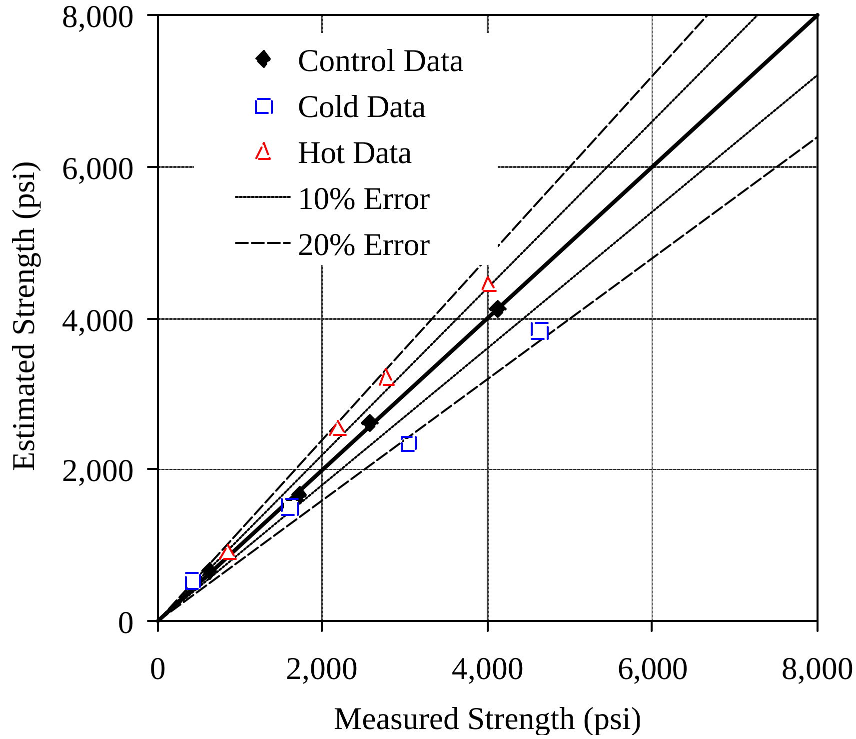


Figure I-3: Error plot for the Type I - 0.48 mixture, simplified method, *E*= 40 kJ/mol

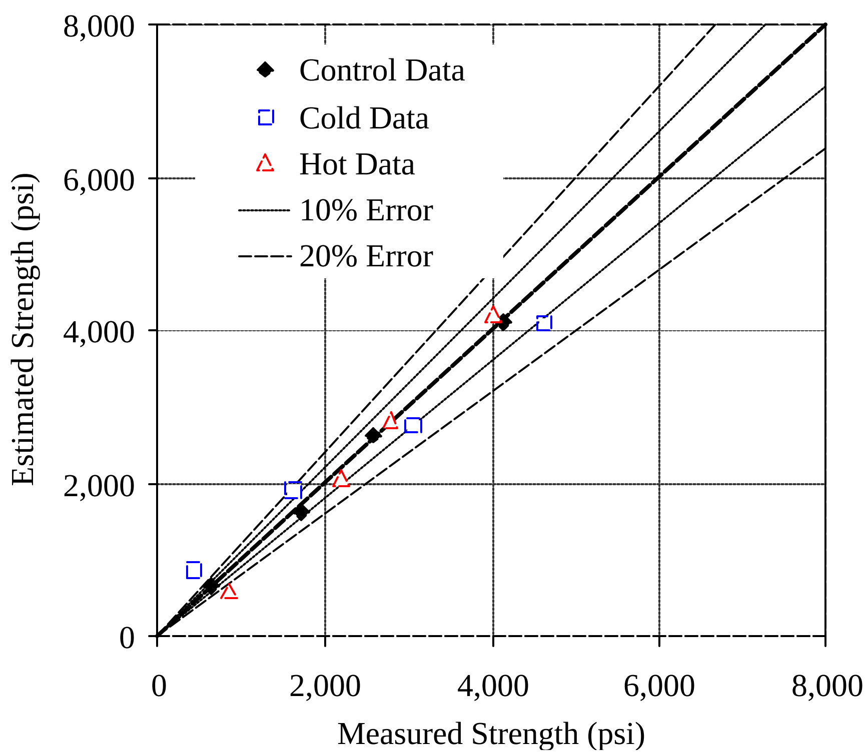


Figure I-4: Error plot for the Type I - 0.48 mixture, simplified method, *E* = 25 kJ/mol

Table I-3: Error using NSM function based on simplified method for 30% F mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,180	1,230	50	4	70	3	1,230	50	4	80	4
	1.1	2,200	2,080	-120	-5			2,060	-140	-6		
	2.0	2,860	2,950	90	3			2,970	110	4		
	7.0	4,490	4,470	-20	0			4,470	-20	0		
Cold	0.9	670	1,040	370	55	320	20	1,320	650	97	410	33
	1.9	1,990	2,080	90	5			2,420	430	22		
	3.5	3,090	2,890	-200	-6			3,240	150	5		
	12.2	4,990	4,380	-610	-12			4,590	-400	-8		
Hot	0.4	1,350	1,870	520	39	240	13	1,380	30	2	230	7
	0.8	2,860	3,050	190	7			2,520	-340	-12		
	1.5	3,620	3,820	200	6			3,360	-260	-7		
	5.0	4,960	4,920	-40	-1			4,670	-290	-6		

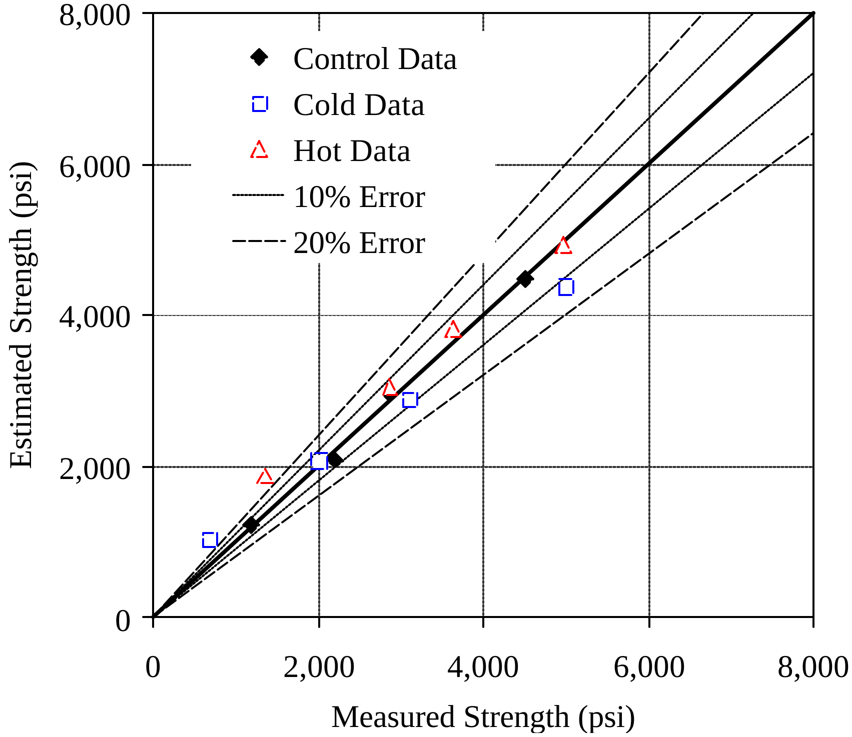


Figure I-5: Error plot for the 30% F mixture, simplified method, *E*= 40 kJ/mol

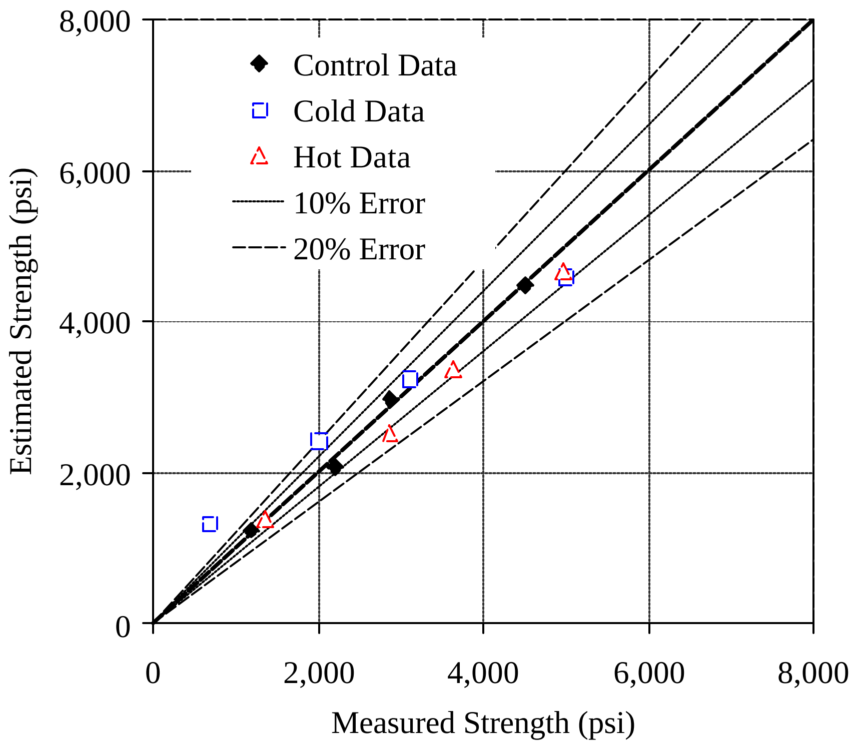


Figure I-6: Error plot for the 30% F mixture, simplified method, *E* = 25 kJ/mol

Table I-4: Error using NSM function based on simplified method for 20% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**E = 40,000 J/mol**					**E = 25,000 J/mol**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,220	1,160	-60	-5	100	4	1,170	-50	-4	90	4
	1.0	2,210	2,380	170	8			2,360	150	7		
	2.0	3,730	3,590	-140	-4			3,610	-120	-3		
	7.0	5,330	5,360	30	1			5,350	20	0		
Cold	1.2	1,040	1,210	170	16	220	11	1,690	650	63	530	32
	1.8	1,760	2,100	340	19			2,600	840	48		
	3.4	3,140	3,210	70	2			3,750	610	19		
	12.0	5,410	5,130	-280	-5			5,420	10	0		
Hot	0.5	1,930	2,350	420	22	400	12	1,710	-220	-11	260	8
	0.8	3,600	3,690	90	3			3,030	-570	-16		
	1.4	3,900	4,520	620	16			3,990	90	2		
	5.0	5,360	5,810	450	8			5,530	170	3		

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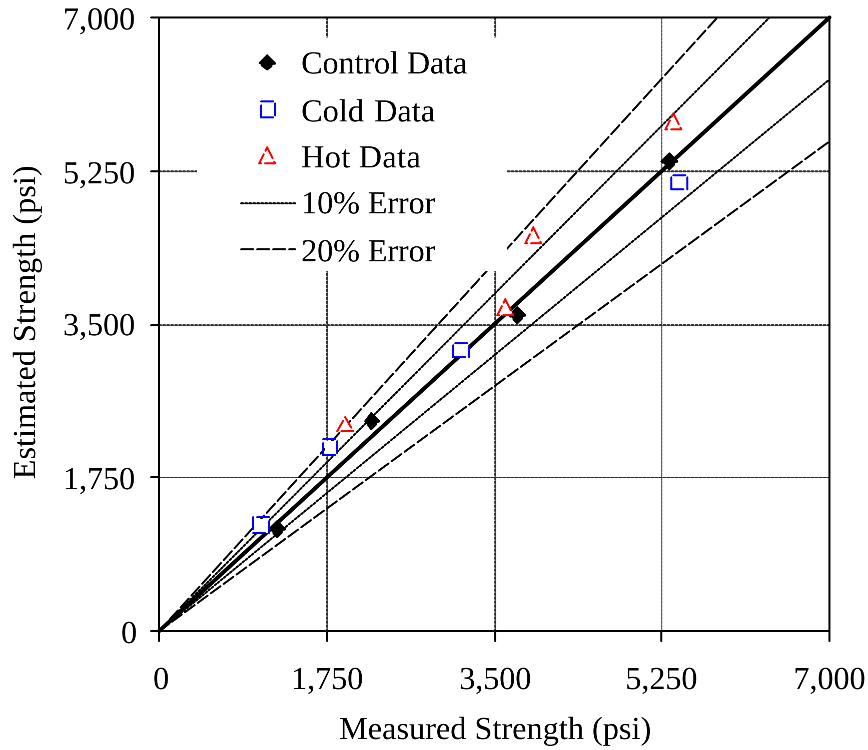

Figure I-7: Error plot for the 20% C mixture, simplified method, *E*= 40 kJ/mol

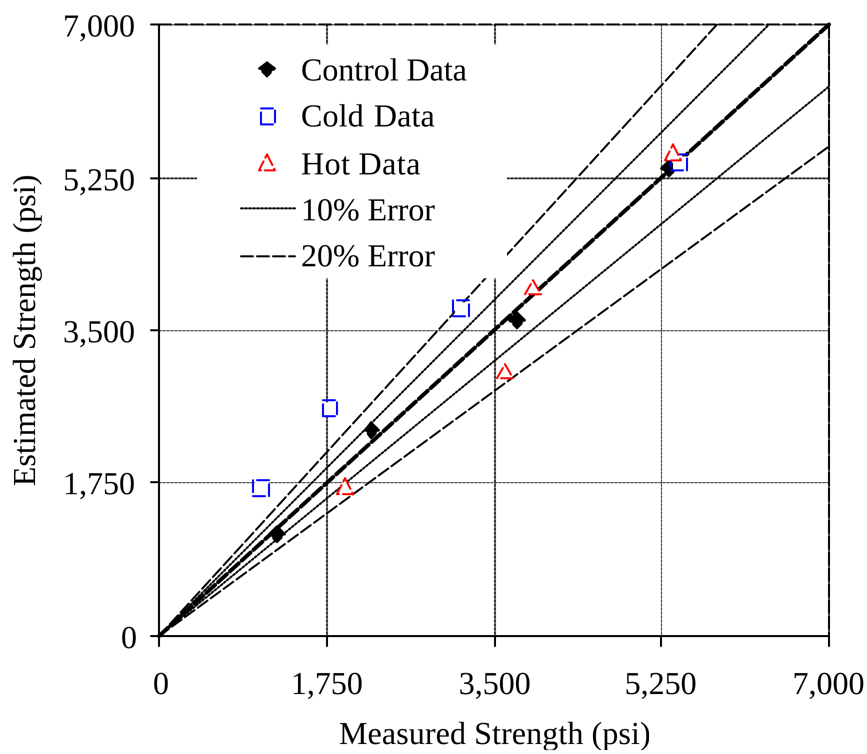

Figure I-8: Error plot for the 20% C mixture, simplified method, *E* = 25 kJ/mol

Table I-5: Error using NSM function based on simplified method for 30% C mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	670	710	40	6	60	3	730	60	9	80	5
	1.0	1,940	1,840	-100	-5			1,810	-130	-7		
	2.0	3,060	3,130	70	2			3,160	100	3		
	7.2	5,250	5,230	-20	0			5,230	-20	0		
Cold	1.3	570	820	250	44	290	17	1,330	760	133	740	54
	1.9	1,680	1,690	10	1			2,240	560	33		
	3.5	2,620	2,920	300	11			3,460	840	32		
	12.1	4,650	5,230	580	12			5,450	800	17		
Hot	0.4	1,050	1,440	390	37	270	15	890	-160	-15	310	11
	0.8	2,710	3,110	400	15			2,380	-330	-12		
	1.4	3,900	4,160	260	7			3,510	-390	-10		
	5.0	5,870	5,900	30	1			5,500	-370	-6		

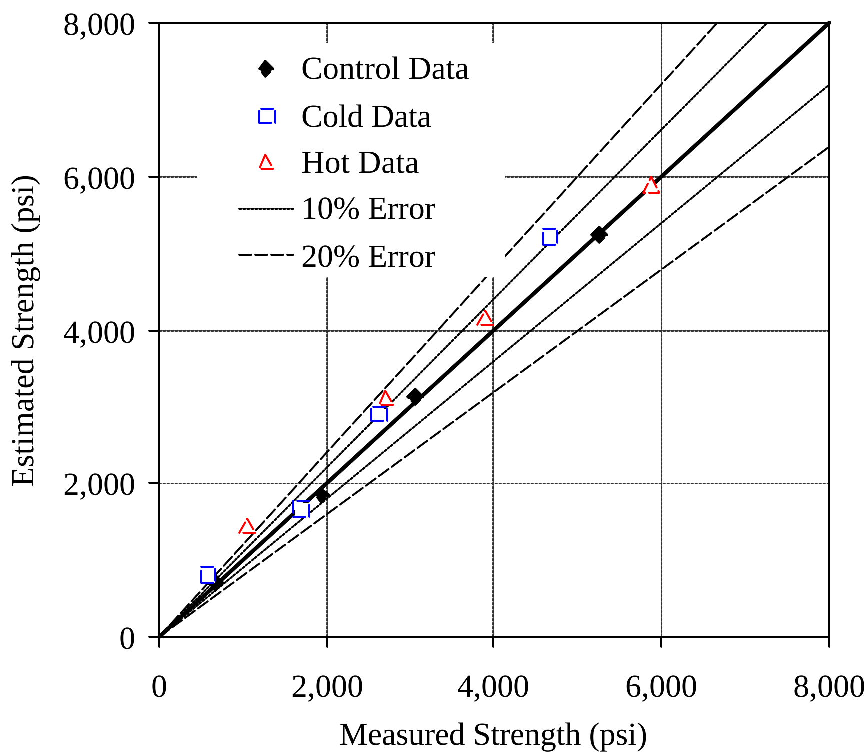

Figure I-9: Error plot for the 30% C mixture, simplified method, *E*= 40 kJ/mol

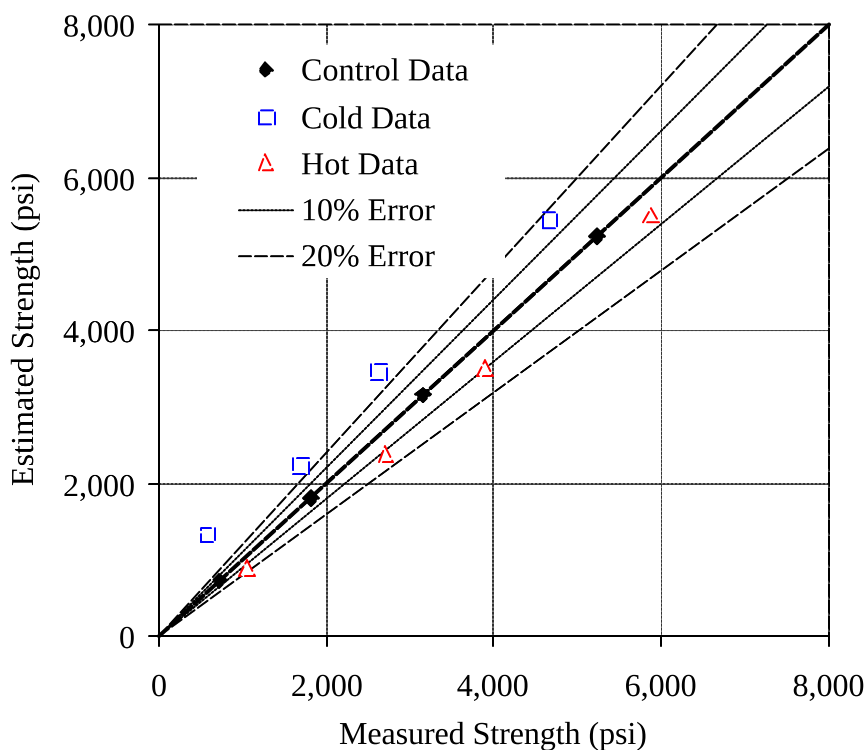

Figure I-10: Error plot for the 30% C mixture, simplified method, *E* = 25 kJ/mol

Table I-6: Error using NSM function based on simplified method for 30% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	**E = 40,000 J/mol**					**E = 25,000 J/mol**				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.6	1,430	1,470	40	3	70	3	1,480	50	3	90	3
	1.0	2,730	2,600	-130	-5			2,580	-150	-5		
	2.0	3,650	3,750	100	3			3,770	120	3		
	7.1	5,770	5,760	-10	0			5,750	-20	0		
Cold	0.9	610	1,150	540	89	370	30	1,550	940	154	810	58
	1.9	2,050	2,410	360	18			2,910	860	42		
	3.6	3,400	3,510	110	3			4,040	640	19		
	12.2	5,080	5,560	480	9			5,890	810	16		
Hot	0.4	1,500	2,040	540	36	720	22	1,530	30	2	300	7
	0.8	3,130	3,610	480	15			2,990	-140	-4		
	2.9	4,990	5,770	780	16			5,300	310	6		
	4.9	5,240	6,310	1,070	20			5,950	710	14		

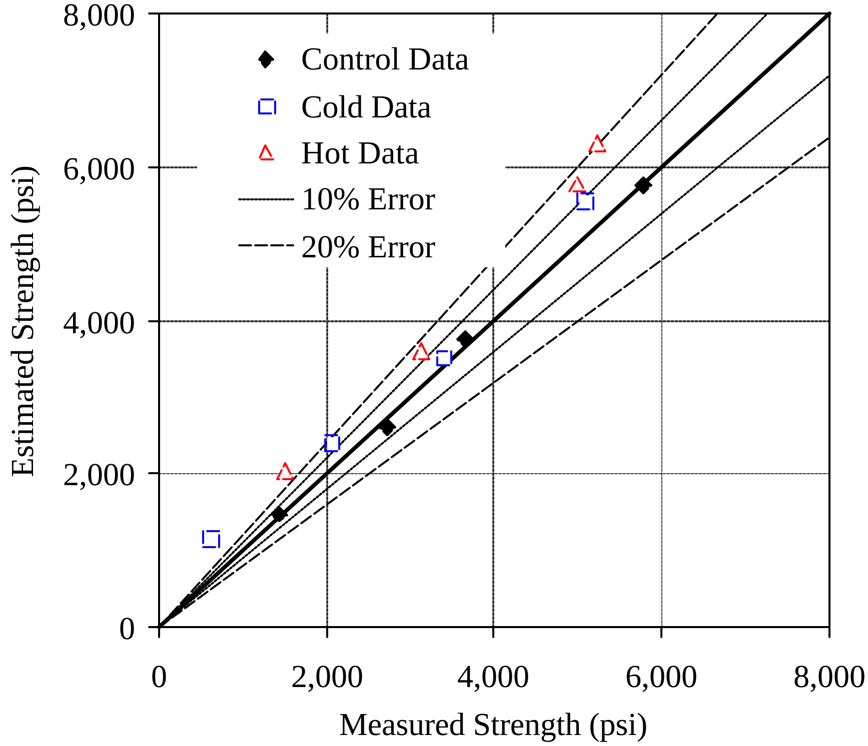

Figure I-11: Error plot for the 30% Slag mixture, simplified method, *E*= 40 kJ/mol

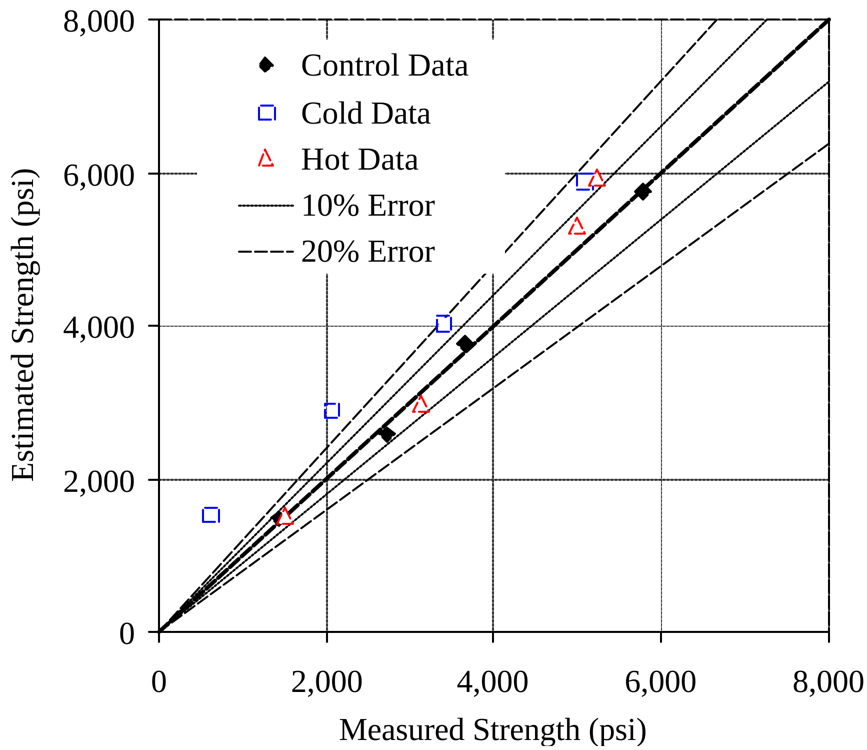

Figure I-12: Error plot for the 30% Slag mixture, simplified method, *E* = 25 kJ/mol

Table I-7: Error using NSM function based on simplified method for 50% Slag mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	760	750	-10	-1	0	0	760	0	0	10	0
	1.0	1,680	1,680	0	0			1,670	-10	-1		
	2.1	3,060	3,060	0	0			3,070	10	0		
	7.2	5,770	5,770	0	0			5,770	0	0		
Cold	0.9	330	480	150	45	240	19	780	450	136	720	59
	1.9	1,340	1,530	190	14			1,990	650	49		
	3.4	2,450	2,640	190	8			3,230	780	32		
	12.3	4,960	5,380	420	8			5,940	980	20		
Hot	0.3	610	910	300	49	600	27	560	-50	-8	90	4
	0.8	2,330	2,860	530	23			2,210	-120	-5		
	1.4	3,240	4,100	860	27			3,350	110	3		
	5.0	6,060	6,750	690	11			6,130	70	1		

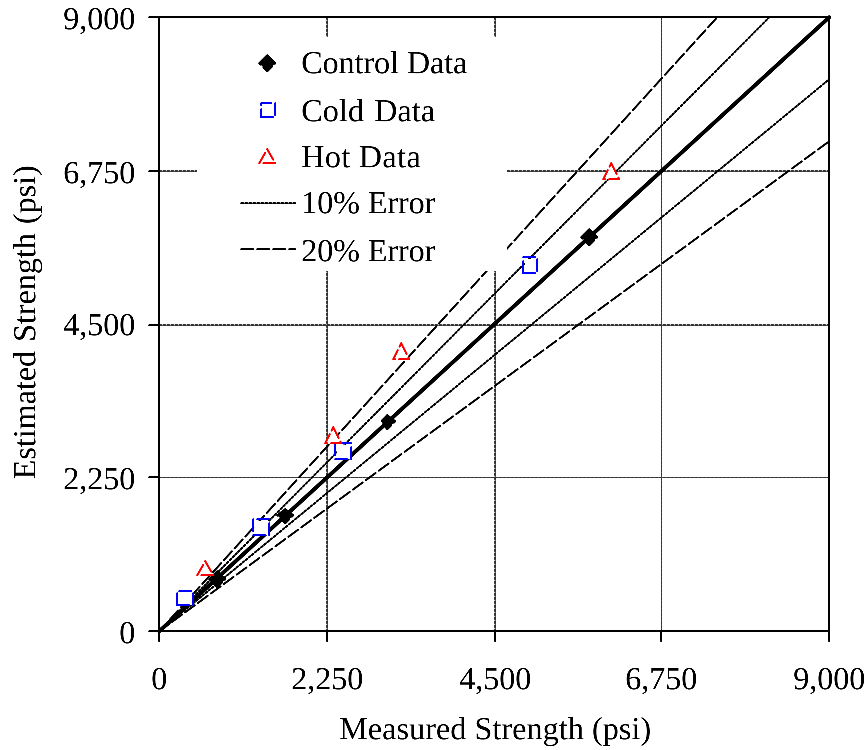

Figure I-13: Error plot for the 50% Slag mixture, simplified method, *E*= 40 kJ/mol

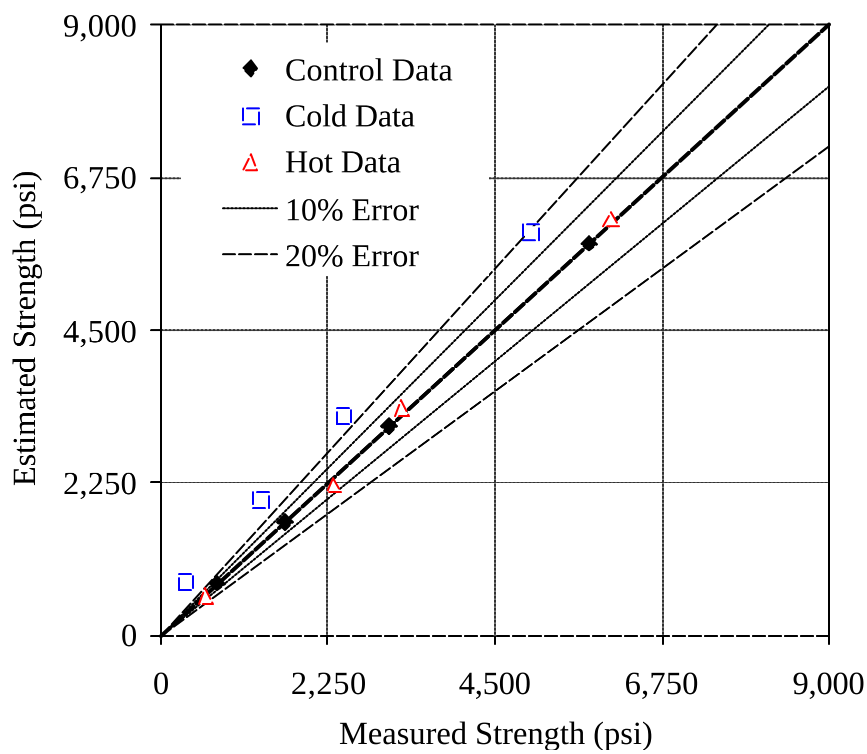

Figure I-14: Error plot for the 50% Slag mixture, simplified method, *E* = 25 kJ/mol

Table I-8: Error using NSM function based on simplified method for Type III - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	730	740	10	1	50	2	750	20	3	70	2
	1.0	3,040	2,970	-70	-2			2,950	-90	-3		
	2.0	3,820	3,920	100	3			3,950	130	3		
	7.2	5,100	5,070	-30	-1			5,060	-40	-1		
Cold	1.0	750	1,090	340	45	340	17	1,730	980	131	640	45
	1.8	2,370	2,480	110	5			3,060	690	29		
	3.4	3,660	3,480	-180	-5			3,980	320	9		
	12.1	5,630	4,900	-730	-13			5,080	-550	-10		
Hot	0.3	2,400	2,060	-340	-14	420	13	1,360	-1,040	-43	370	14
	0.7	3,210	3,650	440	14			3,150	-60	-2		
	1.4	3,740	4,430	690	18			4,080	340	9		
	5.3	5,100	5,320	220	4			5,150	50	1		

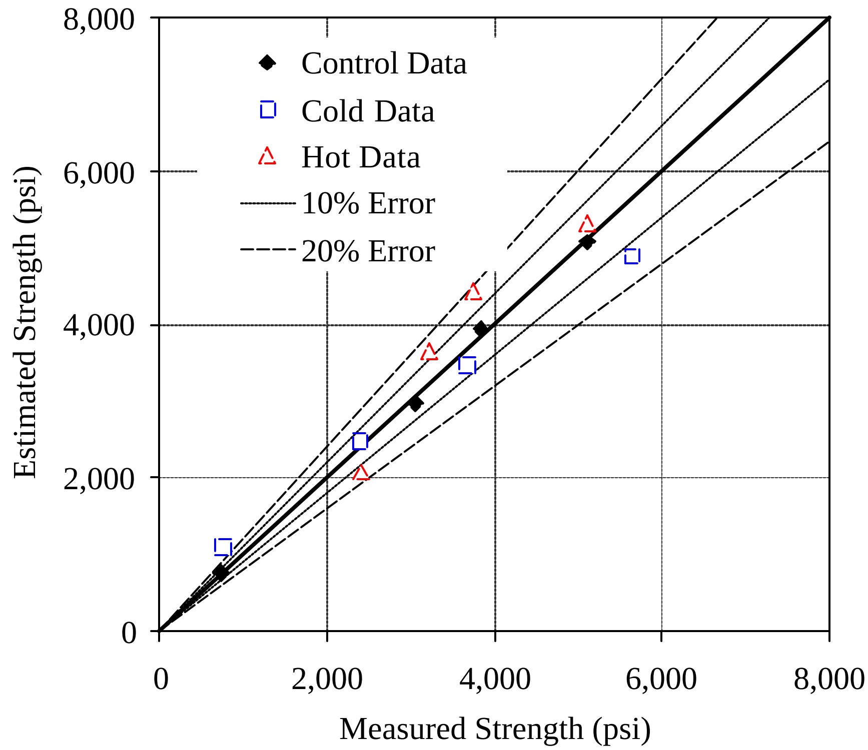

Figure I-15: Error plot for the Type III - 0.44 mixture, simplified method, *E*= 40 kJ/mol

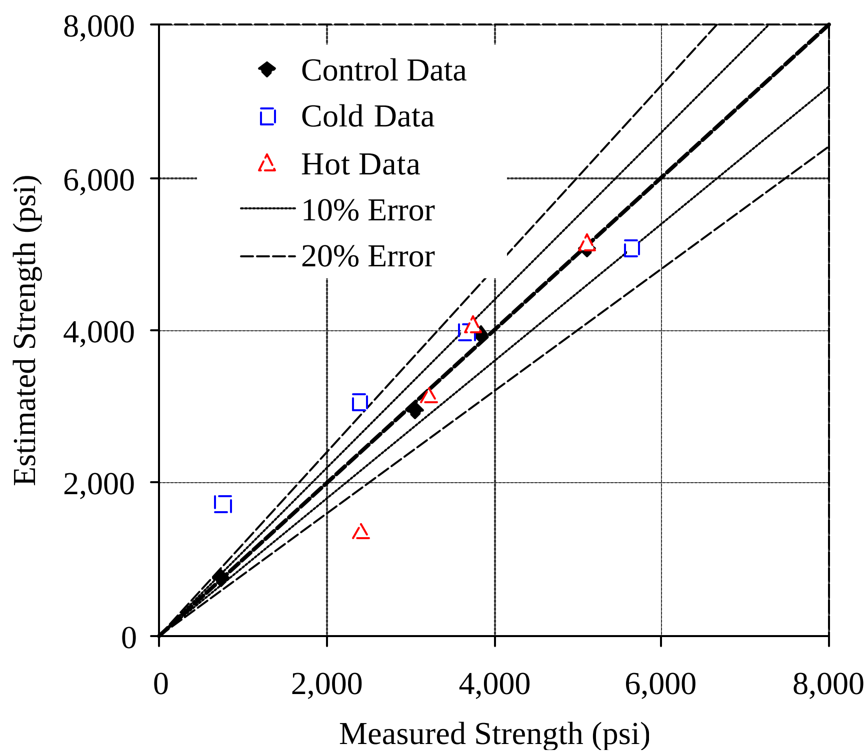

Figure I-16: Error plot for the Type III - 0.44 mixture, simplified method, *E* = 25 kJ/mol

Table I-9: Error using NSM function based on simplified method for 70/20/10 - 0.37 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.5	1,300	1,320	20	2	40	1	1,330	30	2	60	2
	1.0	3,650	3,590	-60	-2			3,560	-90	-2		
	2.1	5,240	5,290	50	1			5,330	90	2		
	7.0	7,670	7,650	-20	0			7,640	-30	0		
Cold	0.9	1,040	1,560	520	50	400	14	2,030	990	95	920	25
	1.8	3,060	3,430	370	12			4,040	980	32		
	3.5	4,650	4,880	230	5			5,540	890	19		
	12.2	7,000	7,460	460	7			7,820	820	12		
Hot	0.3	1,640	2,190	550	34	1140	23	1,330	-310	-19	530	13
	0.7	3,540	5,070	1,530	43			4,130	590	17		
	1.4	5,020	6,540	1,520	30			5,730	710	14		
	4.9	7,390	8,350	960	13			7,910	520	7		

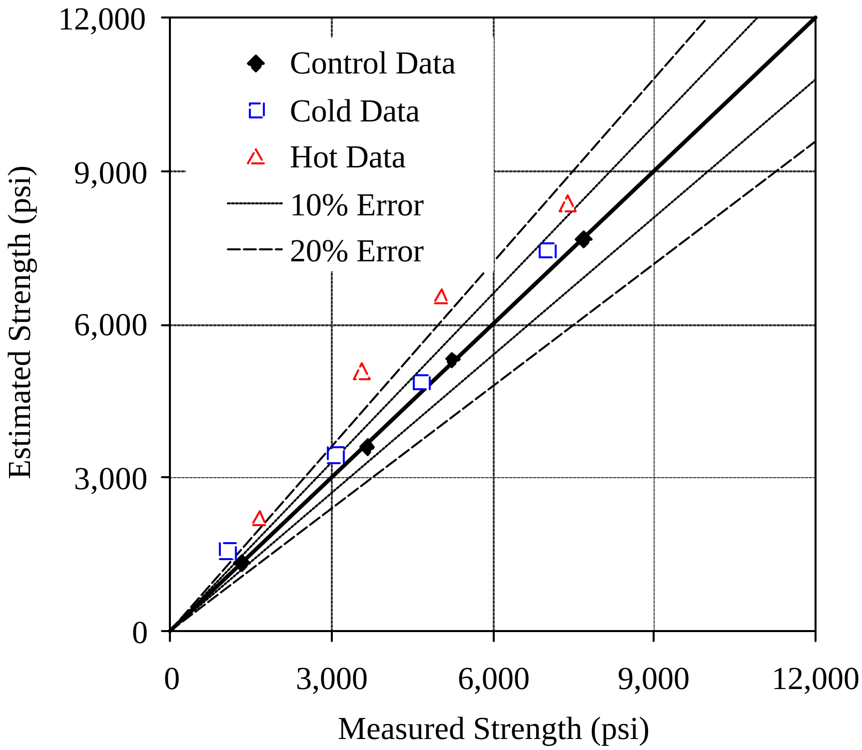

Figure I-17: Error plot for the 70/20/10 - 0.37 mixture, simplified method, *E*= 40 kJ/mol

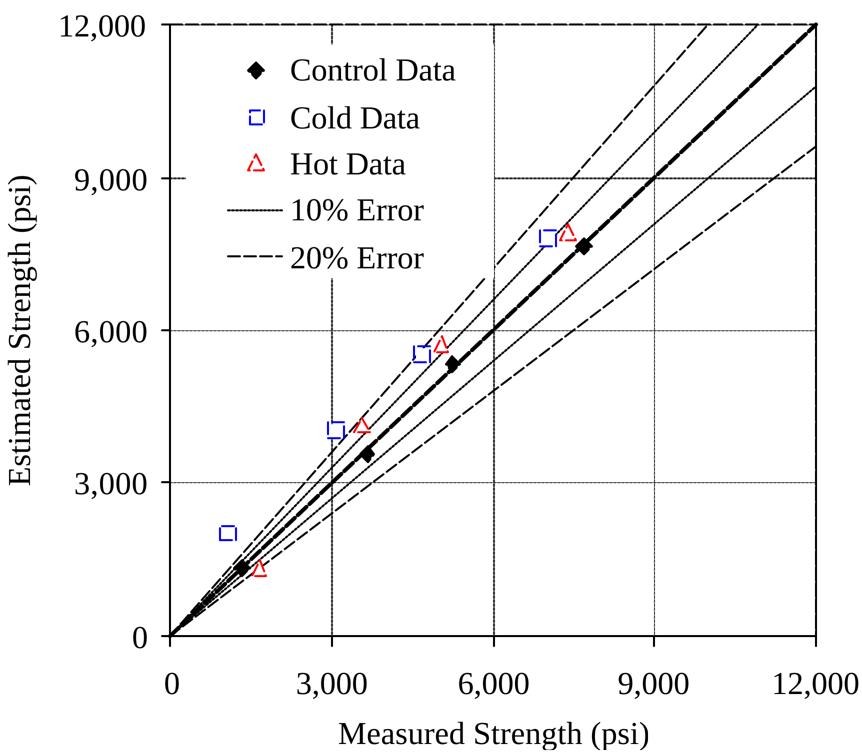

Figure I-18: Error plot for the 70/20/10 - 0.37 mixture, simplified method, *E* = 25 kJ/mol

Table I-10: Error using NSM function based on simplified method for the 70/20/10 - 0.44 mixture

Batch ID	Concrete Age (days)	Compressive Strength Test Result (psi)	E = 40,000 J/mol					E = 25,000 J/mol				
			Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)	Estimated Strength (psi)	Error (psi)	EoE (%)	AAE (psi)	Abs. EoE (%)
Control	0.4	510	540	30	6	50	3	550	40	8	60	4
	1.0	1,770	1,690	-80	-5			1,670	-100	-6		
	2.0	2,610	2,670	60	2			2,690	80	3		
	7.2	4,680	4,670	-10	0			4,660	-20	0		
Cold	1.0	370	790	420	114	170	31	1,090	720	195	430	60
	1.8	1,450	1,470	20	1			1,850	400	28		
	3.4	2,560	2,370	-190	-7			2,850	290	11		
	12.1	4,510	4,480	-30	-1			4,820	310	7		
Hot	0.3	980	1,220	240	24	710	30	790	-190	-19	280	13
	0.8	1,860	2,590	730	39			2,010	150	8		
	1.5	2,720	3,690	970	36			3,090	370	14		
	5.0	4,500	5,390	890	20			4,920	420	9		

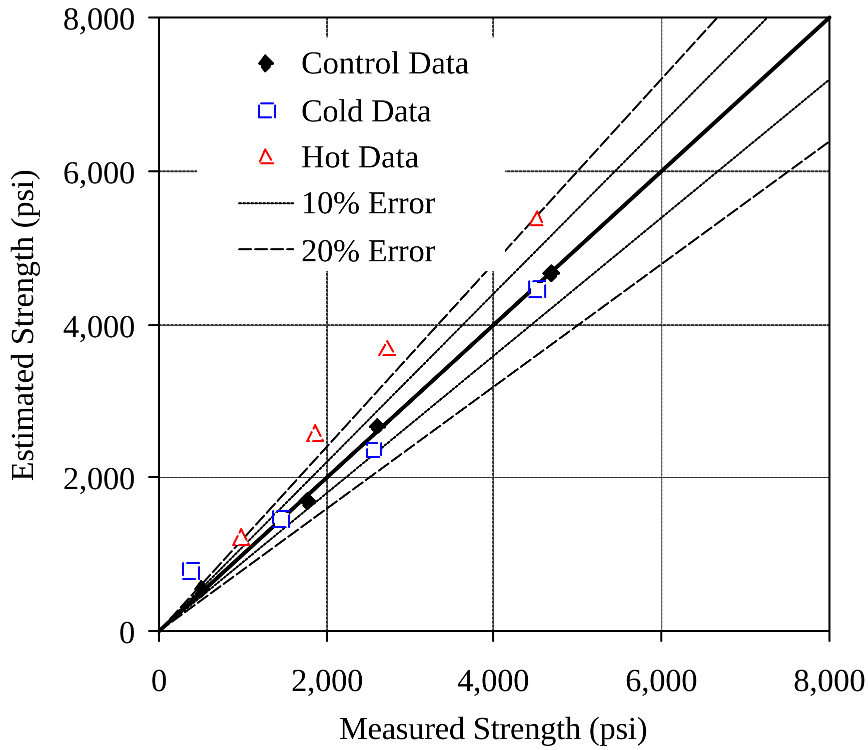

Figure I-19: Error plot for the 70/20/10 - 0.44 mixture, simplified method, *E*= 40 kJ/mol

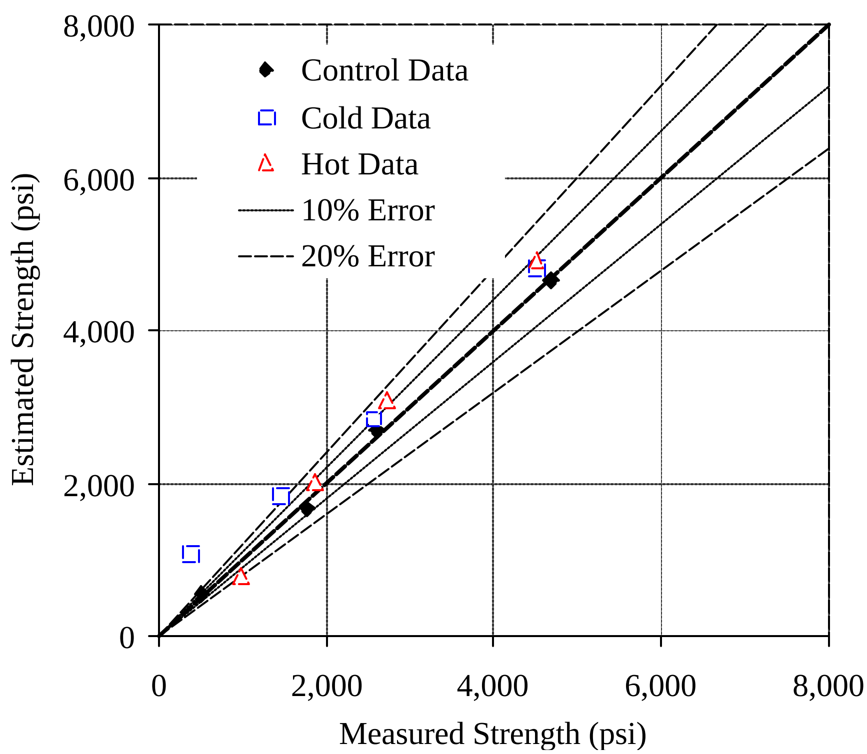

Figure I-20: Error plot for the 70/20/10 - 0.44 mixture, simplified method, *E* = 25 kJ/mol