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QUANTIFYING EARLY-AGE CONCRETE MECHANICAL PROPERTIES AND CURING CONDITIONS UTILIZING AN AUTOMATED SYSTEM

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2019

Dedication

I would love to dedicate my work to my beautiful mother, Guadalupe Arras, through her continuous support helping me finish this milestone of my career. Also, to my beloved grandparents whose love during their life gave me the strength to further my education.

QUANTIFYING EARLY-AGE CONCRETE MECHANICAL PROPERTIES AND CURING CONDITIONS UTILIZING AN AUTOMATED SYSTEM

by

BENJAMIN ARRAS, B.S.C.E

THESIS

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Abstract

The validation of concrete quality based on the 28-day strength is a lengthy process. Predicting concrete mechanical properties through early-age methods can streamline the construction process. Early-age concrete behavior consists of assessing the concrete curing as-related to setting stages, the hydration process, strength and stiffness development, while considering various environmental system parameters. This paper reports on a nondestructive method for observing the early-age strength and modulus development of concrete mixes over seven days in a controlled, laboratory setting. An apparatus was designed and built for continuous acquisition of seismic modulus data (using free-free resonant column) and heat of hydration/maturity information (derived from ambient air temperature and specimen internal temperature).

The experimental design, carried out with the apparatus, represented curing conditions at controlled temperatures (50°F, 70°F, 90°F) and humidity levels (40% and 80%). Two different sources of aggregates, dolomite and gravel, were also considered. An alternative method for quantifying maturity is presented. Concrete samples also underwent compression testing at 1-day, 3-days, and 7-days. The developed apparatus and ensuing analysis method exhibited promising results for predicting the strength from the seismic modulus and maturity over a 7-day period. The heat of hydration, the curing process and the resulting impact on the concrete mechanical properties was also assessed.

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Chapter 1: Introduction

Portland cement concrete (PCC) long life, durability and constructability makes it a vital component of the civil infrastructure. In March 2019, the Portland Cement Association (PCA) envisioned a growth for cement consumption of 2.3% through 2019 into 2020. Approximately 85 million tons of concrete were produced in 2018 in the United States, and 4 billion tons produced throughout the world (U.S. Geological Survey, 2019). In regards to the overall construction and quality-control process, the 28-day period for concrete strength verification (ASTM C39) may result in monetary and time losses associated with facility closure. Expediting facility opening will amount to tremendous cost and time savings, and ultimately, greatly benefit facility users. This study consisted of observing the concrete mechanical properties and curing characteristics throughout the early-strength development phase, considering that the early-strength development varies and is a function of mix proportions, aggregate type and the surrounding environmental conditions.

Early-age concrete characteristics encompass the assessment of the concrete setting, as related to the initial and final set, the intermediary hydration process, and the ensuing strength and stiffness development. Nondestructive testing (NDT) methods, in conjunction with conventional compression testing, can be leveraged to monitor the strength development throughout the curing process (Nazarian et al., 2006). This study focuses on assessing stiffness and strength development through the continuous acquisition of the seismic modulus. The early-age behavior must also be paired with observing curing as a function of heat generation resulting from the hydration process. To that end, concrete maturity should also be assessed. Several studies have observed early-strength development considering seismic methods, while simultaneously monitoring maturity (Nazarian et al., 1997; Yuan et al., 2003/2005; Yi et al., 2005; Nazarian et al., 2006; Lara, 2008; Benaicha et al., 2016; Collier et al., 2017; Wolf, 2018).

Chapter 2: Literature Review

The hydration process of concrete is a significant factor impacting the strength development and is inherently tied to the surrounding environmental conditions. Schindler and Folliard (2005) determined all concrete mixtures have distinct and unique degrees of hydration development that are closely related to the environmental conditions; dealing with the curing temperature of concrete. Neville (1996) and Glisic and Simon (2000) broke down the hydration process into three stages. Stage I (dormant period) is initial hydration composed of a small period, typically 1-2 hours, where chemical reactivity occurs between the chemical admixtures and mix-related components. Stage II (setting period) is when the hydration product layers come in contact with other products. As a result, setting (initial set and final set) occurs in this stage, approximately between 4-10 hours. Lastly, stage III (hardening period) is the process in which reactivity will remain present as long as water and hydration products are available. Stage III is the longest stage, roughly 18-30 hours. Mindess et al. (2003) later broke down the process into five stages. Stage I (initiation) is the process of reactivity occurring due to the presence of water. Interaction occurs between the water and the tricalcium aluminate (C_3A) products. Stage II (dormant period) is where the dissolution of ions continues, and initial set takes place. Initial set occurs when the alite (C_3S) products begin to react, in which the silicate hydrates rapidly. Stage III (acceleration) occurs up to the maximum rate of heat evolution seen in concrete, during which final set can be found. Alite (C_3S) and belite (C_2S) product begin to hydrate and release heat. Stage IV (deceleration) is a diffusion-controlled process where surface area of hydrated particles increases, while those that have not hydrated, decrease. During the later parts of this stage, the ettringite decomposes; converting to the monosulfate phase where all of the gypsum is consumed. Stage V (steady period) is a diffusion controlled stage where the hydration is significantly affected due to the increase of hydrated particle thickness (C-S-H developing from stage III).

2.1 Hydration

The concept of maturity, as a function of time and temperature, has been studied as part of assessing concrete strength gain during curing (Nurse, 1949; McIntosh, 1949; Saul, 1951). McIntosh (1949) assumed the rate of hardening, at any moment, was proportional to the amount of which curing temperature exceeded a datum temperature. Different researchers seem to consider various datum points. Nurse and Saul (1951) derived the Nurse-Saul Maturity Function (**Equation 1**), which gives a maturity index also known as the Time-Temperature Factor (TTF).

$$M = \sum_0^t (T_c - T_o)\, \Delta t \qquad (1)$$

where M = temperature-time factor, T_c = concrete average specimen temperature, T_o = datum temperature and Δt = testing time interval(s). Saul (1951) recommended using a datum temperature of 32ºF (0ºC); however, under lower curing temperatures a lower datum value should be considered. **Equation 1** represents a cumulative method; integrating the temperature-time curve. As a result, strength progression can be plotted with maturity. This method has been specified in ASTM C1074, which also contains the use of an equivalent age equation. The Arrhenius Maturity Function (**Equation 2**) provides a relationship between compresive strength and equivalent age:

$$t_e = \sum e^{-Q(\frac{1}{T_a} - \frac{1}{T_s})\Delta t} \qquad (2)$$

where t_e = equivalent age at specified temperature T_s, Q = activation enery divided by gas constant, T_a = concrete average specimen temperature, T_s = reference temperature and Δt = time interval. The reference temperature is abitary; but usually taken as 68ºF or 73ºF (20ºC or 23ºC).

2.2 Enviromental Impacts

Early-age behavior and the curing of concrete is affected by surrounding environmental conditions, namely, air temperature and humidity level. The early and final strengths of the concrete vary when considering low, moderate and high curing tempertures. Generally, concrete curing at low temperatures will result in slow progression of concrete strength, delays hardening, yet achieves long-term high strength. Conversely, curing at high temperatures results in faster strength development and more rapid hardening, but then results in lower long-term final strength, as compared to curing at a moderate temperature. Humidity plays a role on the setting times, and allows the hydration process to initiate with the presence of moisture in the mix outside the w/c ratio. **Table 1** summarizes the literature in terms of strength development considering varying temperatures.

Table 1 - Literature Discussing Concrete Curing, Hardening and Strength Development

Reference	Key Findings / Comments
Burg, 1996	• As an approximation, setting time will change approximately 50% for each 10ºC change in temperature from a reference temperature. Lower temperatures increase set times; higher temperatures decrease set times • Strength development at low temperatures is lengthy and small change, although later age strength is equal or exceeded that of the reference temperature mix • At high temperatures early strength has a reversed effect after 7 days which the reference temperature mix has a higher strength than the high temperature mix
Neville, 1996	• Typically standard curing temperature ranges from 64°F - 70°F (18°C - 21°C) • Increase in curing temperature speeds up the chemical reactions of hydration, benefiting early strength. Also, reduces length of dormant period • Although, early strength is developed through higher temperatures strength gain after 7 days is compromised as there is an increase pores in the structure
Abel and Hover, 2000	• Analyzed the effect of setting conditions on fresh concrete, inspired by ASTM C403, proposing a penetrometer probe to measure the pressure to embed the concrete surface.
Mindess et al, 2003	• Moisture presence during curing affects the development of concrete strength, rate of strength gain slows down as water is lost from concrete • Increased early strength at higher temperatures is due to cement hydrating faster • Curing at low temperature can result in higher ultimate strength, and the higher the initial temperature will yield a lower later strength
Yi et al., 2005	• The rate of hydration changes as the curing temperature of concrete changes • Increasing curing temperatures generally increase early strength, however it may decrease its later strength development • Water and void volumes within the concrete increase with an increase in curing temperature
Yikici & Chen, 2015	• Higher curing temperatures speed up the hydration process and leads to early strength gain • Larger mass concrete structures have variable concrete temperatures throughout the structure which affect the curing history • High curing temperatures at early-age lead to a lower ultimate strength when compared to lower early-age curing temperatures
Wolf, 2018	• Changing humidity from 80% to 40% had a small effect on the setting conditions when compared to the temperature effects • Setting occurred at early stage with high temperatures, while low temperatures had a lengthy set time that took twice as long

Chapter 3: Experimental Design

This paper describes a method for obtaining empirical relationships to estimate the strength and modulus development over seven days considering the environmental conditions. A laboratory study was carried out on concrete samples casted, observed, and tested in a controlled, laboratory setting. Curing conditions under varying temperature and humidity ranges were followed to gain a better understanding of their impacts on concrete strength and hydration. This study will expand on Wolf (2018) by supplementing case variants representing additional environmental conditions and an additional aggregate type. An alternative approach to standard maturity will be further discussed and presented.

Figure 1 displays a flow chart outlining the scope of work for this study. The analyses are categorized into "Environmental" and "Mix Related." In addition to testing the cylindrical concrete specimens, mortar mixtures samples were also cured under the specified condition to follow ASTM C403 using Humboldt ASME Penetrometer for estimates of setting. The research consisted of 12 testing case variants. Concrete test sets were cured and tested at three temperatures of 50ºF, 70ºF and 90ºF and humidity levels of 40% and 80%. Specimens were cast in accordance to ASTM C470 and tested in laboratory conditions following ASTM C192. Each testing set consisted of twelve 6-in. by 12-in. standard cylinders. Three of those specimens, referred to as the "reference mix" were cured under ideal conditions (70ºF, 100% humidity), to verify that the mix met the local highway agencies requirements/specifications. The remaining nine specimens underwent curing at specified temperature and humidity levels. Three of the nine specimens were continuously monitored for seven-days in order to acquire continuous seismic modulus and maturity (i.e. internal temperature and ambient temperature) data. Data acquisition consisted of the following time intervals and data point frequency:

- 0-12 hours: 12 measurements/hr
- 12-24 hours: 4 measurements/hr
- 24-48 hours: 2 measurements/hr
- 48-168 hours: 1 measurement/hr

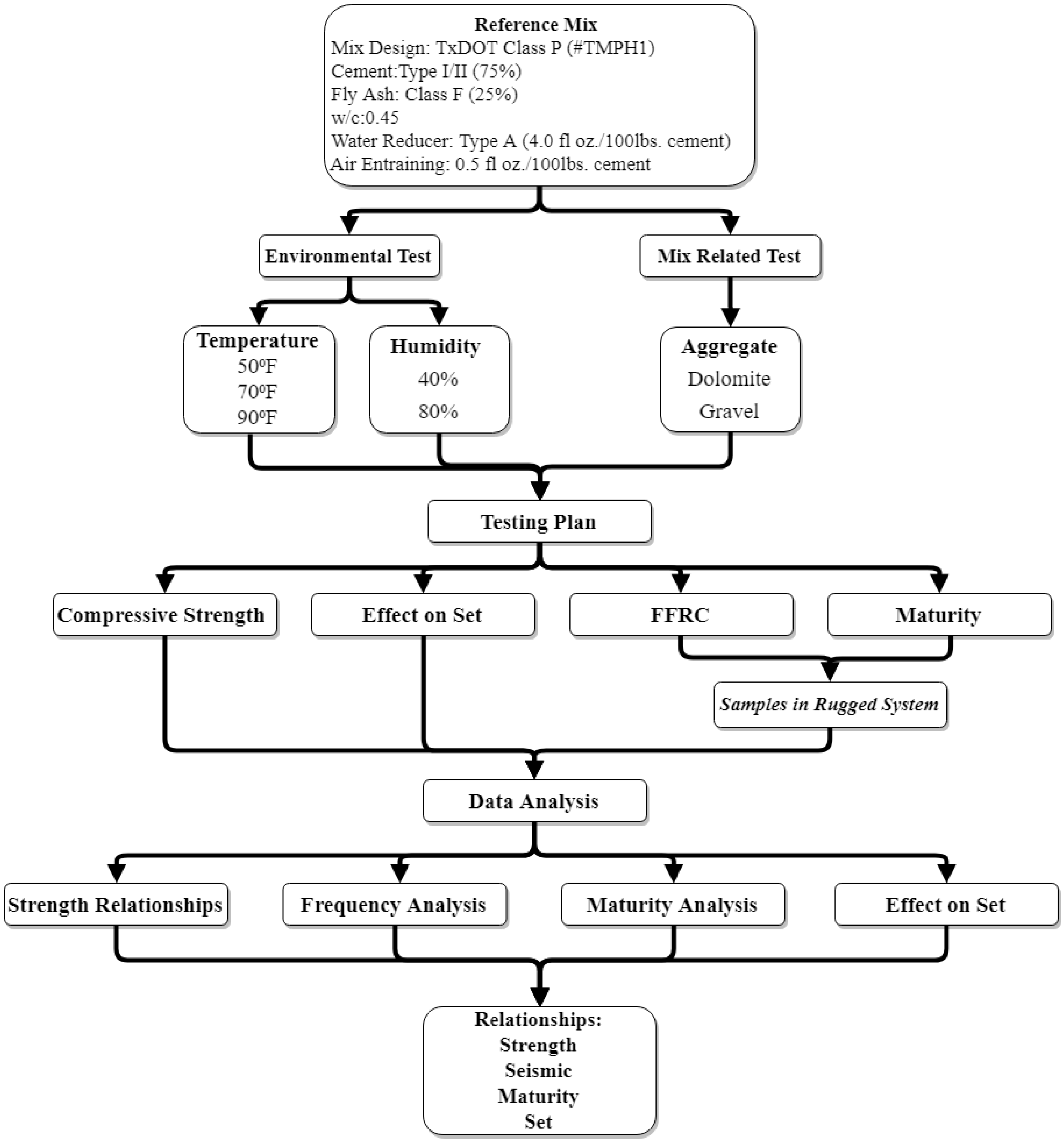

Figure 1 - Overview of work plan

Specimens 1 through 3 underwent compression testing at one-day, followed with Specimens 4 through 6 at three-days, and Specimens 7 through 9 at seven-days. Specimens 7 through 9 were placed in the test apparatus for the seven-day period in order to acquire continuous seismic moduli and maturity information. The internal temperature data captured for each replicate, along with the ambient air temperature, were utilized to observe the hydration and to calculate the maturity metrics. The test matrix described above was applied to a gravel mix from South Texas. Comparative data from Wolf (2018) is included, this comprises a mix from West Texas with dolomite aggregates. Several mixture parameters were maintained as control in the gravel and dolomite mixes in order to provide direct, comparable analyses. These fixed mixture parameters were: gradation, air entraining admixture, water reducer, and Type I/II cement. The 28-day specifications mandate a 4,000 psi compressive strength for the dolomite mix and a 4,200 psi compressive strength for gravel. The mix design was composed of 75% of Type I/II cement and 25% of fly ash Class F. The chemical admixtures included water reducer and air entraining with dosages of 4 and 0.5 fl oz/100 lbs of cement, respectively. The aggregate composition was 60% coarse aggregates and 40% fine aggregates.

An apparatus was designed and built for continuous acquisition of seismic modulus data (as per ASTM C 215) and heat of hydration/maturity information (derived from ambient air temperature and specimen internal temperature) over a 7-day period. As shown in **Figure 2,** the apparatus includes a thermocouple, and an impact source and accelerometer. The thermocouple wire is used to capture the specimen internal temperature, while a separate thermocouple captures ambient air temperature. The impact from the source is applied automatically onto the surface of each concrete specimen at a user-defined time intervals. The signal recorded by the accelerometer is analyzed as discussed by Wolf (2018) to obtain the compression and shear wave velocities. The data collection and analysis are automated by a software residing in a computer that also houses the data acquisition system (not shown). The apparatus can accommodate three 6-in. x 12-in. concrete specimens.

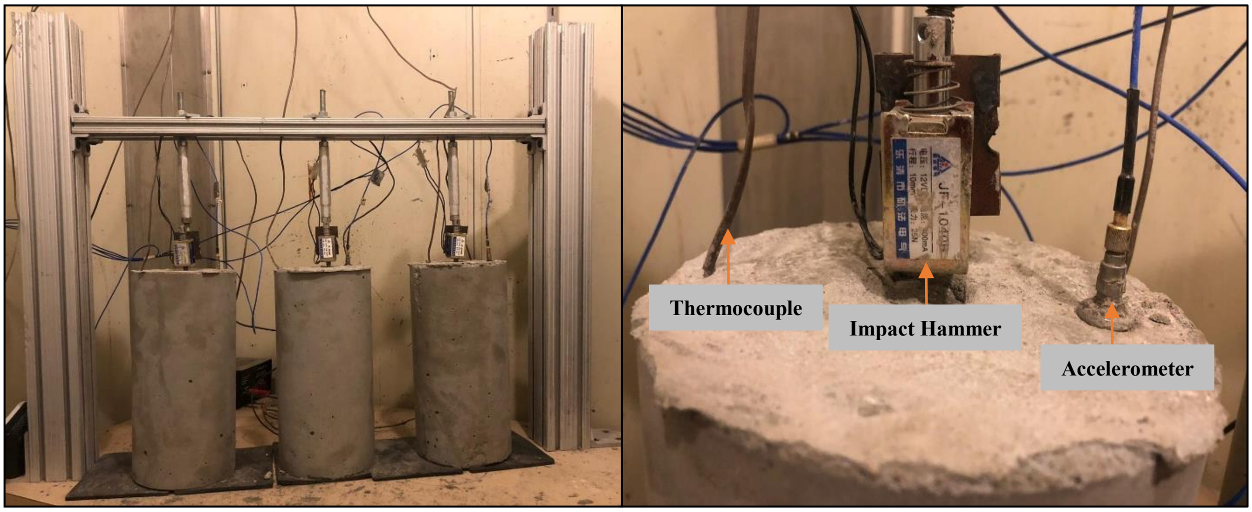

Figure 2 - Automated modulus and maturity apparatus

Chapter 4: Results

ASTM C-215 and Nazarian et al. (2006) thoroughly describe the data analysis associated with the seismic method. The density (ρ) is calculated from the mass (*M*), length (*L*) and cross-sectional area of the specimens:

$$\rho = \frac{M}{LA_s} \tag{3}$$

Seismic modulus (E) is calculated from the longitudinal standing frequencies (f_L) calculated through conducting a fast-Fourier transform on the accelerometer time history through:

$$E = \rho(2f_L L)^2 \tag{4}$$

Figure 3 displays the seismic modulus developments during concrete curing over a seven-day period for the gravel mix subjected to a range of temperature of 50°F, 70°F and 90°F at humidity levels of 40% and 80%. Three distinct regions can be distinguished for each curve. The modulus of the concrete is close to nil for the first few hours when the concrete is essentially in a liquid form. This range is followed by a rapid increase in modulus for the first 24 to 36 hours when the concrete is hardening, and is followed by a period where the modulus increases gradually. At 50°F and 90°F, the specimens cured at 80% humidity showed lower moduli than the 70ºF specimen did over the 7-day period. While a humidity level of 80% led to a higher rate of stiffness development, the specimens cured at 40% humidity yielded higher stiffness in the long-term. In regards to temperature influence, as expected, increasing the curing temperature showed consistently a higher rate of stiffness development. Given that hydration is temperature dependent, the degree of hydration is achieved more rapidly with increasing temperatures.

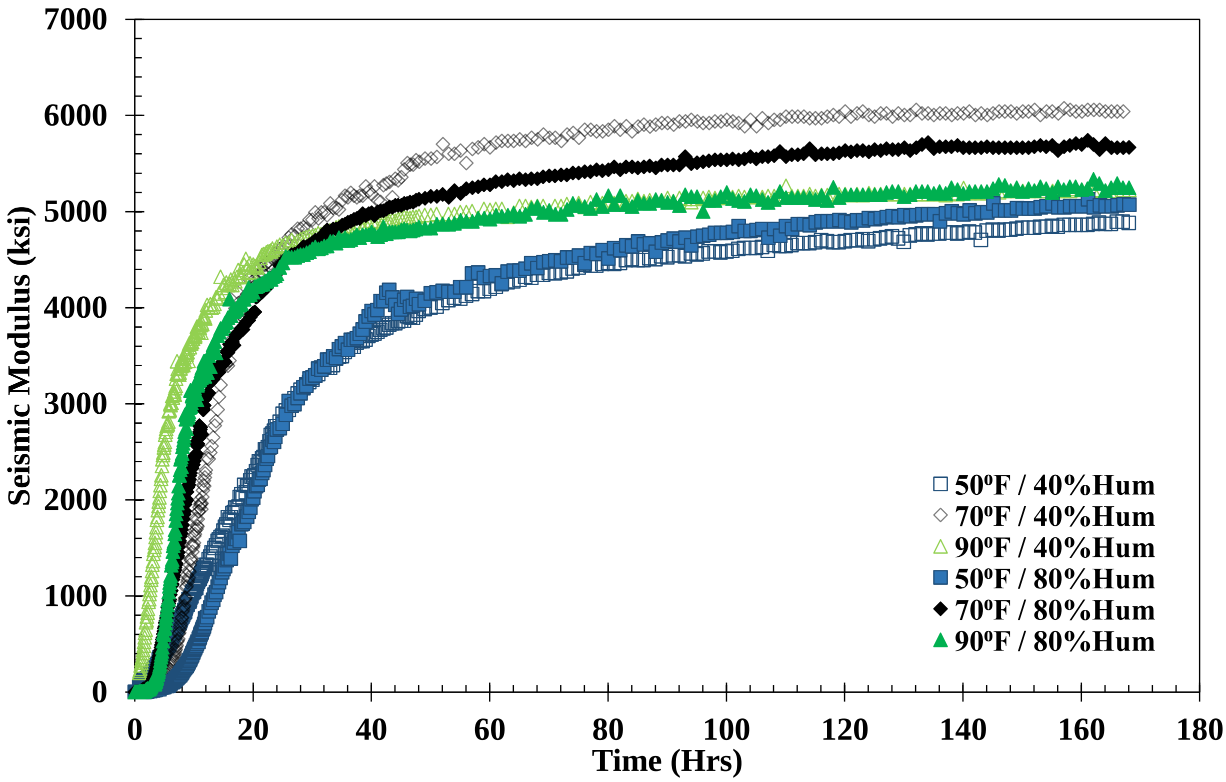

Figure 3 - Continuous FFRC to monitor modulus development

The continuous capture of FFRC data provides a clear, continuous view into the modulus growth over the seven-day period. A constraint to monitoring the curing over a 7-day period is that the long-term stiffness is not captured. As described by Schindler (2004), typical behavior over a 28-day period is that concrete cured at lower temperatures achieves higher compressive strengths over the long term, despite displaying lower rates of strength/stiffness development from initial to final set. Slower hydration results in more dense and uniform microstructures. Curing at relatively higher temperatures results in hydration product forming shells around cement grains, resulting in increased porosity and lower long-term strength. The trends displayed in **Figure 3** indicate this kind of behavior. The concrete specimens cured at 50ºF indicate slow, but continuing increase in stiffness. The specimens cured at 70ºF and 90ºF show to hit asymptotes, or an upper limit in stiffness after 150-hrs.

4.1 Development Mechanical Property Relationships based on FFRC Tests

As described in ASTM C215, the captured FFRC data also enabled the calculation of Poisson's ratio for the gravel and dolomite mixes. **Equation 5** displays the relationship among Poisson's ratio, shear standing frequencies (f_s) and longitudinal standing frequencies (f_L) obtained from the lab tests;

$$\upsilon = \frac{(0.5\lambda - 1)}{(\lambda - 1)} \tag{5}$$

where

$$\lambda = \left[\frac{f_L}{f_S}\right]^2 C_{L/D} \tag{6}$$

$C_{L/D}$ is a correction factor that is used when the length to diameter ratio is not 2 (ASTM C 215).

The measurement of the Poisson's ratio can prove valuable during facility evaluation for predicting the remaining life of the concrete structure and for concrete thickness design. **Table 2** displays the average Poisson's Ratio for the evaluated materials. Poisson's ratio does not seem to be impacted by temperature and humidity changes, at least, during the first 7-days.

Table 2 - Calculated Poisson's Ratio for Gravel and Dolomite Mixes

Controlled Humidity	Curing Temperature	Poisson's Ratio	
		Dolomite (Wolf, 2018)	Gravel
40%	50°F	0.22	0.22
	70°F	0.20	0.21
	90°F	0.23	0.22
80%	50°F	0.23	0.23
	70°F	0.22	0.22
	90°F	0.22	0.23

Wolf (2018) proposed the following generalized relationship to describe the variation of seismic modulus with time:

$$E = e^{\left(a - \left(\frac{b}{(time)^2}\right)\right)} \tag{7}$$

where *a* and *b* are shape parameters obtained from fitting the equation to measured data.

Table 3 displays the shape parameters for each seismic modulus growth development trends. The shape parameters were summarized in order to obtain coefficients that are representative of the collective data. Variable a, which is related to the long-term modulus of the mix is rather insensitive to the humidity and temperature. Variable b, related to the short-term rate of the development in modulus, indicates the increase in arriving to the long-term asymptote. As b value increases, the final set is further delayed.

Table 3 - Seismic Modulus Development Shape Constants

Controlled Humidity	Curing Temperature	Dolomite (Wolf, 2018)			Gravel		
		a	***b***	R^2	***a***	***b***	R^2
40%	50°F	8.5	257	1.00	8.4	331	1.00
	70°F	8.6	124	1.00	8.7	163	1.00
	90°F	8.6	65	1.00	8.6	60	1.00
80%	50°F	8.5	229	1.00	8.5	350	1.00
	70°F	8.6	139	1.00	8.7	129	1.00
	90°F	8.6	88	0.99	8.6	72	1.00

As shown in **Figure 4**, the modulus growth for concrete can also be observed with respect to the standard maturity. To predict the seismic modulus, the following generalized equation can be used:

$$E = c \ln M - d \tag{8}$$

where M = temperature-time factor, c and d= regression coefficients.

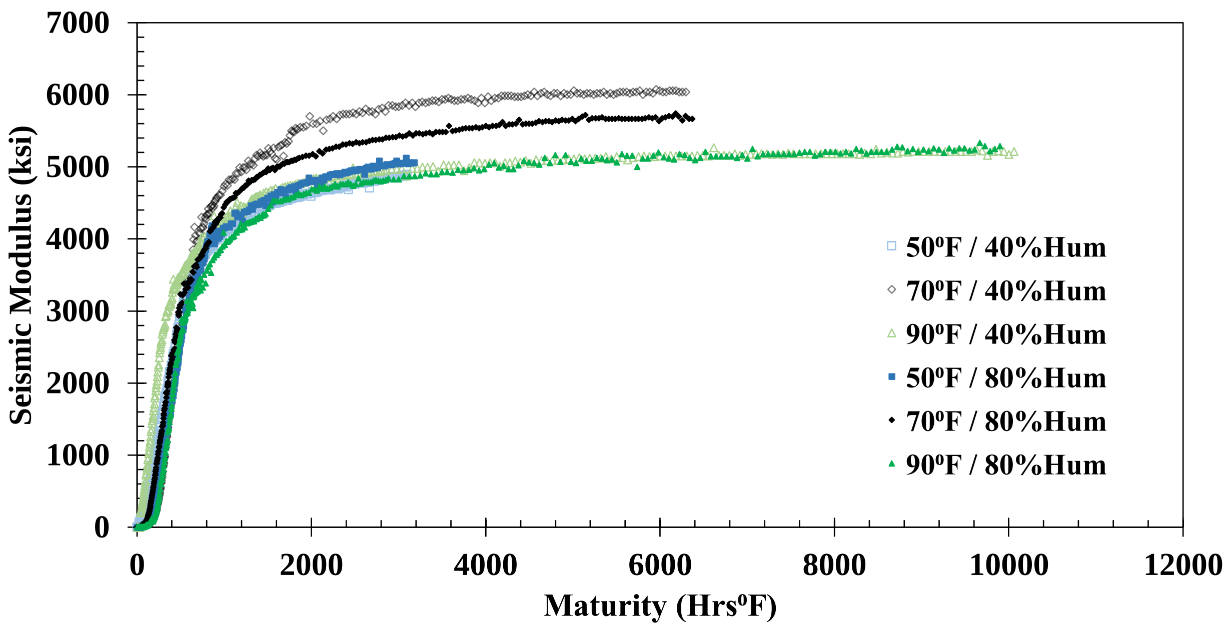

Figure 4 - Seismic modulus development with standard maturity for Gravel Mixes

Table 4 displays the regression function obtained, along with the coefficients of determination (R^2). The regression coefficients (c and d) vary, and are specific to the evaluated, local aggregate and cementitious material. The trends in the data presented in **Figure 3** and **Figure 4** are similar indicating that a near linear relationship may exist between the actual time and TTF.

Table 4 - Relationships between seismic modulus and maturity

Controlled Humidity	Curing Temperature	Dolomite (Wolf, 2018)			Gravel		
		c	***d***	**R^2**	***c***	***d***	**R^2**
40%	50°F	1188.3	7266.4	1.00	966.3	5301.4	0.99
	70°F	984.6	5622.2	0.98	1142.9	6760.8	0.99
	90°F	619.6	2782.9	0.99	557.6	2367.6	0.94
80%	50°F	1230.7	7178.2	1.00	1316.2	7950.6	0.99
	70°F	1008.7	5821.7	1.00	951.5	5208.5	0.99
	90°F	590.7	2554	0.81	537.7	2063.8	0.80

As discussed in Nazarian et al. (2006), the continuous seismic moduli can then be leveraged to obtain empirical relationships between the modulus and concrete compressive strength. The unconfined compressive strengths taken at 1-day, 3-day, and 7-day ages can be plotted with the respective seismic modulus. For demonstration, **Figure 5** displays such analysis being performed on the gravel and dolomite concrete mixtures taken at 70°F and 40% humidity. Compressive strength at any time can be estimated at a given time with the following generalized equation:

$$f_c = je^{k*E_s} \qquad (9)$$

where f_c = compressive strength, j and k are regression coefficients.

Table 5 displays the modulus-strength equations for the analyzed data sets. The j coefficients showed higher variance when compared with the more consistent k coefficients. The regression function obtained exhibit coefficients of determination ranging from 0.87-0.99. The utility in obtaining these relationships for local materials is that they can be leveraged with projects that use a similar mix with material from a consistent source. Concrete modulus obtained through nondestructive methods, such portable seismic pavement analyzer (PSPA), or other simple convenient field-based methods, can be input to the locally developed generalized function to obtain the concrete compressive strength without having to extract core samples or having to mold additional samples on the day of pouring (see Nazarian et al., 2006).

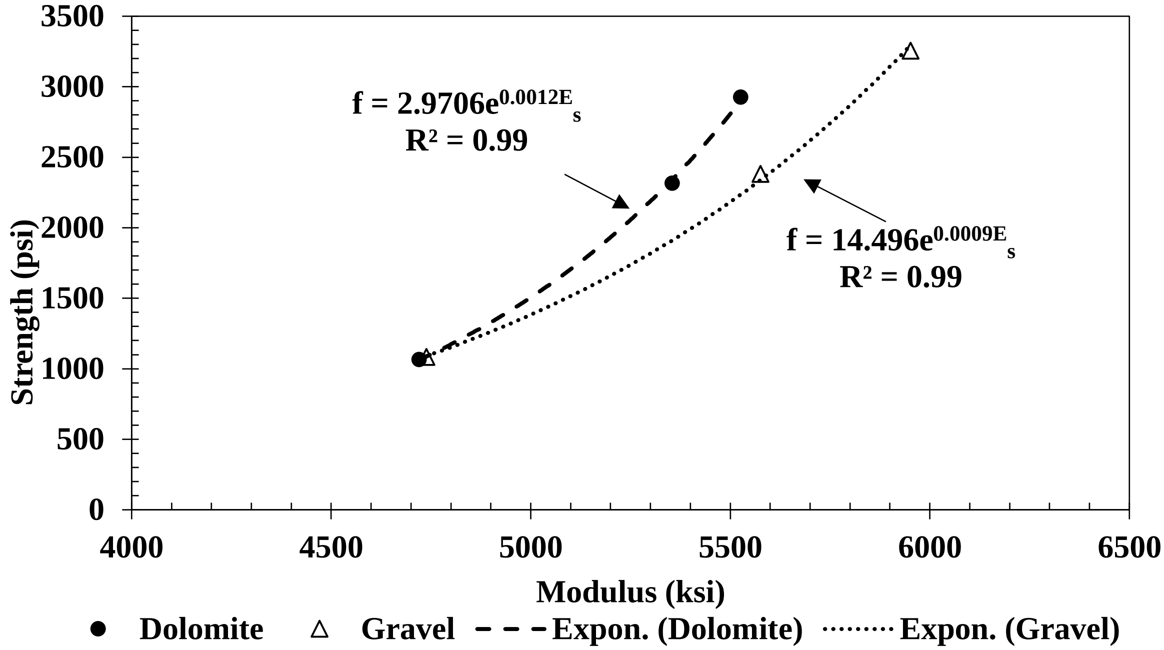

Figure 5 - Variations of compressive strength with modulus (70°F/ 40% humidity)

Table 5 - Seismic Modulus and compressive strength relationships

Controlled Humidity	**Curing Temperature**	**Dolomite (Wolf, 2018)**			**Gravel**		
		j	***k***	**R^2**	***j***	***k***	**R^2**
40%	50°F	5.5005	0.0011	0.99	31.702	0.0009	0.99
	70°F	2.9706	0.0012	0.99	6.0257	0.0011	0.99
	90°F	2.7734	0.0012	0.99	2.9338	0.0013	0.99
80%	50°F	20.748	0.0009	0.99	41.968	0.0008	0.99
	70°F	76.423	0.0006	0.92	78.302	0.0006	0.97
	90°F	74.299	0.0006	0.87	76.267	0.0006	0.90

4.2 Alternative Maturity Method

The conventional method for quantifying the heat of hydration and curing process is to develop and assess the standard maturity plots. Standard maturity is performed in a controlled laboratory setting. While standard maturity employs a datum temperature, commonly taken as 14°F or 32°F, the integration of the time-temperature curve usually yields a piece-wise type of linear function, with changes in slope corresponding to significant variations in internal temperature. While standard maturity has traditionally held useful in assessing heat production during the hydration process, this data visualization method presents limitations in interpretation. The subtle change in slopes can be difficult to interpret in a graphical method, for practical purposes. The method of *Alternative Maturity (Alt TTF)* introduced by Wolf (2018) is further refined in this paper. Alternative maturity employs the ambient air temperature as the datum temperature, as opposed to the constant datum temperature associated with standard maturity. Alternative maturity is calculated as follows:

$$AM = \sum_0^t (T_c - T_o)\, \Delta t \tag{10}$$

where AM = Alternative temperature-time factor (Alternative TTF), T_c = concrete average specimen temperature, T_o = ambient air temperature and Δt = testing time interval(s).

For demonstration, **Figure 6a** displays the Alternative TTF plotted for the gravel data sets at 50°F, 70°F, 90°F at 40% humidity. **Figure 6b** demonstrates data interpretation of this method. The *heat production duration* can be observed as the time period from a) when the concrete specimen equilibrates with the ambient air temperature of the experiment to b) the end of primary concrete hydration. This primary stage of concrete hydration, as defined in this paper, is interpreted as the instances where the internal temperature of the concrete is exceeding the surrounding ambient air temperature. This method of visualizing heat production duration provides a more clear and practical metric for delineating the hydration process. The total area of this curve provides an additional metric of heat generation; it is termed *Maximum Yield in Alternative TTF* (as shown in **Figure 6b**). As primary hydration concludes, the concrete internal temperature again equilibrates with the ambient air temperature; effectively concluding this distinct duration of heat production. As a consistent measure to this study, the concrete specimens are demolded at 24-hrs. The internal temperature of the concrete drops below the ambient air temperature for a period of time, it is termed *Cooling Duration After Demold*.

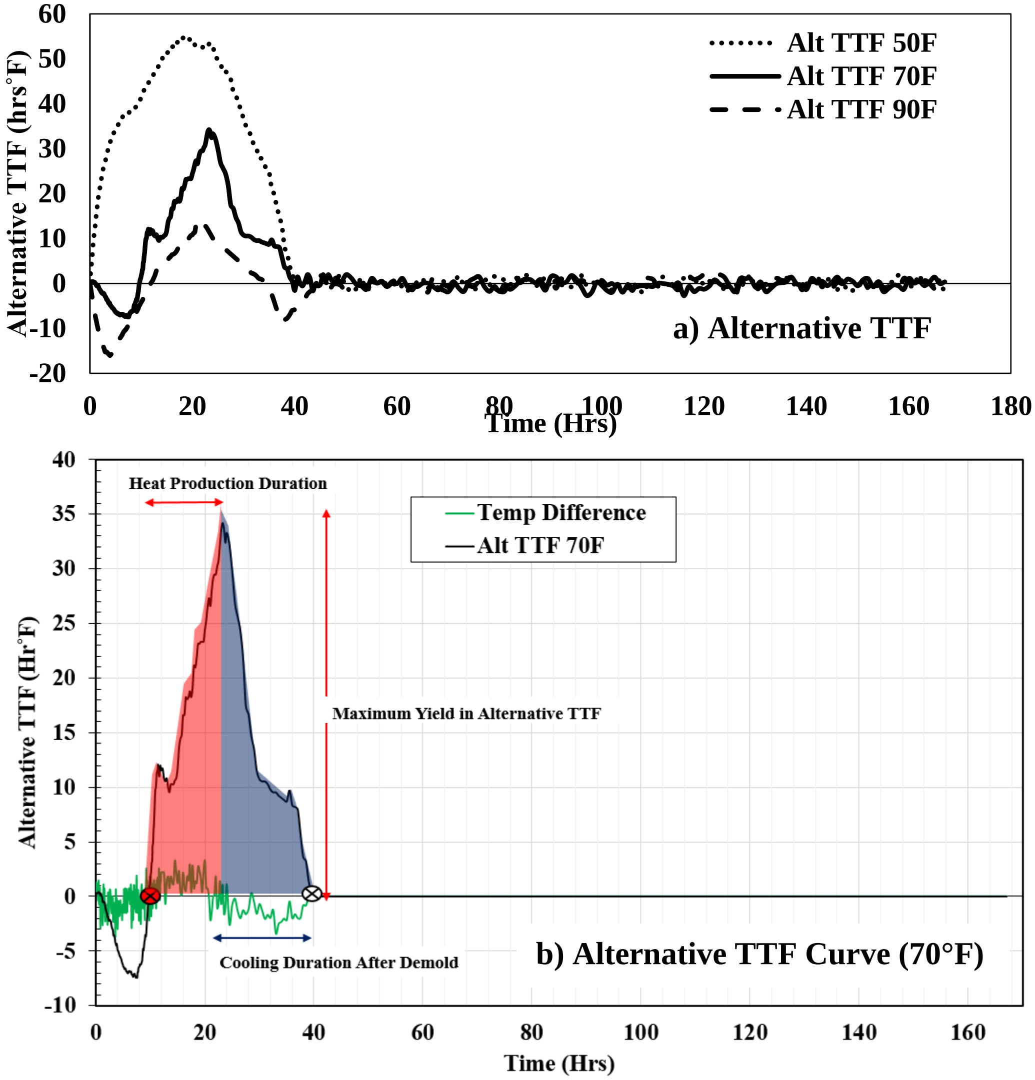

Figure 6 - Alternative maturity of concrete concept

For demonstration of comparative analysis, **Table 6** displays the heat production durations and the maximum yields in alternative TTF for both mixes at 50ºF, 70ºF, 90ºF and 40% and 80% humidity. Employing this alternative maturity (Alt TTF) method provides clearly discernable metrics for assessing the effects of temperature and humidity on the hydration process of local concrete materials.

Table 6 - Alternative TTF Heat Production Characteristics

Controlled Humidity	Curing Temperature	Dolomite (Wolf, 2018)		Gravel	
		Heat Production Duration (Hrs.)	Maximum Yield in Alternative TTF (Hr˚F)	Heat Production Duration (Hrs.)	Maximum Yield in Alternative TTF (Hr˚F)
40%	50°F	10.9	58.7	11.7	18.5
	70°F	15.9	64.4	13.6	34.2
	90°F	16.3	46.8	17.0	30.1
80%	50°F	19.8	52.8	19.8	35.3
	70°F	18.2	53.6	22.9	57.9
	90°F	16.3	49.8	19.5	48.3

Chapter 5: Summary and Conclusions

Concrete strength development and monitoring of concrete curing are indispensable processes of ensuring that the placed slabs meet contract specifications, and that they will meet or exceed long-term performance expectations. Early-strength prediction methodologies can prove useful in field applications in that their implementation can curtail facility closure; effectively benefiting the contractor, owner, and facility users.

This study provides a methodology for estimating the concrete strength and modulus throughout the initial and final curing stages; significantly before the 28-day conventional practice. The proposed method can be emulated by engineers as an effective, empirical method for implementation on use of local materials, when utilizing standard mix designs. An apparatus was designed and developed to capture the continuous modulus and maturity data. This data can then be processed to obtain concrete maturity over time, and continuous modulus and strength development. The proposed methodology provides a means to assess stiffness and strength development with setting, while observing concrete hydration. FFRC data was also employed to estimate the Poisson's Ratio of the material; a parameter useful for concrete evaluation and design applications.

The study employs the Alternative TTF concept (Wolf, 2018) for assessing hydration in proposed terms of *heat production duration*, and *maximum yield in Alternative TTF*. These metrics provide a clear mode for delineating heat generation during concrete hydration, considering the influence from ambient air temperature and humidity. The following are the conclusions obtained from the study:

- An apparatus was developed that can be utilized to observe continuous strength and stiffness development. The temperature data can be processed to observe standard maturity and Alternative TTF

- High fidelity, empirical relationships were obtained that allow for prediction of modulus development as a function of time and standard maturity. The analysis also provides insight to concrete early-age behavior at the different temperatures (50ºF, 70ºF, 90ºF) and humidity levels (40%, 80%, 95%).

- A method for developing empirical relationships between modulus and concrete strength are presented. A method for obtaining the Poisson's Ratio based on FFRC response is also presented.

- *Alternative Maturity (Alternative TTF)* is an unconventional method that was implemented for this study. This metric enables the delineation of heat of hydration as related to concrete setting.

- Largely, stiffness development of the evaluated concrete yielded typical behavior given the temperature and system humidity levels. There were outliers observed.

- There is existing potential for future research; the inclusion of additional mixture variants accounting for additional variables, such as: chemical admixtures, cement types, fly ash class, mix design parameters and expanding on curing temperature and humidity ranges.

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Glossary

Absorption - the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body; also, the increase in mass of a porous solid body resulting from the penetration of a liquid into its permeable pores (ASTM C125, R2008).

Admixture - a material other than water, aggregates, cementitious material, and fiber reinforcement that is used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing (ASTM C125R2015).

- Air-entraining admixture - admixture that causes the development of a system of microscopic air bubbles in concrete or mortar during mixing (ASTM C125, R2008).
- Chemical admixture - an admixture in the form of a liquid, suspension, or water-soluble solid (ASTM C125, 2014).
- Extended set-control admixture - an admixture that can predictably reduce the hydration rate of cement for applications requiring extended time of setting followed by normal strength development. (ASTM C125, 2019).
- Retarding admixture - an admixture that decreases the rate of reaction of cementitious materials thus increasing time of setting of a cementitious mixture (ASTM C125, 2015)
- Water-reducing admixture - admixture that either increases the slump of freshly mixed mortar or concrete without increasing the water content or that maintains the slump with a reduced amount of water due to factors other than air entrainment (ASTM C125, R2008).
- Water-reducing admixture, high-range - a water-reducing admixture capable of producing at least 12 % reduction of water content when tested in accordance with Specification C494/C494M and meeting the other relevant requirements of Specification C494/C494M (ASTM C125, R2008).

Aggregate - granular material, such as sand, gravel, crushed stone, or iron blast-furnace slag, used with a cementing medium to form hydraulic-cement concrete or mortar (ASTM C125, R2008).

- Coarse aggregate - aggregate predominantly retained on the 4.75-mm (No. 4) sieve; or (2) that portion of an aggregate retained on the 4.75-mm (No. 4) sieve (ASTM C125, R2008).
- Fine aggregate - aggregate passing the 9.5-mm (3⁄8-in.) sieve and almost entirely passing the 4.75-mm (No. 4) sieve and predominantly retained on the 75-µm (No. 200) sieve; or (2) that portion of an aggregate passing the 4.75-mm (No. 4) sieve and retained on the 75-µm (No. 200) sieve (ASTM C125, R2008).

Air entrained - air voids, typically between 10 and 1000 µm (1 mm) in diameter and spherical or nearly so, that are incorporated intentionally into a cementitious mixture during mixing by use of an air entraining admixture (ASTM C125, 2012).

Cement, *hydraulic* - cement that sets and hardens by chemical reaction with water and is capable of doing so under water (ASTM C125, R2015).

Cementitious material (hydraulic) - an inorganic material or a mixture of inorganic materials that sets and develops strength by chemical reaction with water by formation of hydrates and is capable of doing so under water (ASTM C125, R2015).

Cementitious material, (SCM) - an inorganic material that contributes to the properties of a cementitious mixture through hydraulic or pozzolanic activity, or both (ASTM C125, R2015).
Concrete - a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate; in hydraulic-cement concrete, the binder is formed from a mixture of hydraulic cement and water (ASTM C125, R2015).
Concrete, *fresh* - concrete that possesses enough of its original workability so that it can be placed and consolidated by the intended methods (ASTM C125, 2016).
Concrete, *hardened* - concrete that has developed sufficient strength to serve some defined purpose or resist a stipulated loading without failure (ASTM C125, R2015).
Curing - action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop (ASTM C125, R2015).
Equivalent Age - the number of days or hours of curing of a concrete mixture at a specified temperature required to produce a maturity equal to the maturity achieved by a given curing period at concrete temperatures different from the specified temperature (ASTM C125, 2015).
Factor, *temperature-time* - the maturity index computed as the area between the concrete temperature and the datum temperature from the plot of measured concrete temperature versus time, expressed in units of degree-days or degree-hours (ASTM C125, 2015).
Fly ash - finely divided residue that results from the process of combustion of ground or powdered coal and that is transported by flue gases (ASTM C125, R2016).
Gravel - coarse aggregate resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate (ASTM C125, R2016).
Hardening - of strength and other properties of a cementitious mixture after final setting (ASTM C125, 2018).
Maturity - the extent of the development of a property of a cementitious mixture (ASTM C125, 2018).
Maturity function - a mathematical expression that uses the measured temperature history of a cementitious mixture during a curing period to calculate an index that is indicative of the maturity at the end of that period (ASTM C125, 2018).
Maturity index - an indicator of maturity calculated from the temperature history of the cementitious mixture by using a maturity function (ASTM C125, 2018).
Setting - the process, due to chemical reactions, occurring after the addition of mixing water, that results in a gradual development of rigidity of a cementitious mixture (ASTM C125, R2018).
Temperature, ***datum*** - the temperature value that is used for calculating the temperature-time factor (ASTM C125, 2015).
Time of setting - the elapsed time from the addition of mixing water to a cementitious mixture until the mixture reaches a specified degree of rigidity as measured by a specific procedure (ASTM C125, R2012).
Water-cement ratio - the ratio of the mass of water, excluding water absorbed by the aggregates, to the mass of portland cement in a cementitious mixture, stated as a decimal (ASTM C125, 2015).
Workability - of concrete, that property of freshly mixed concrete that affects the ease with which it can be mixed, placed, consolidated, and struck off (ASTM C125, 2014).

Appendix A: Internal Temperature Trends

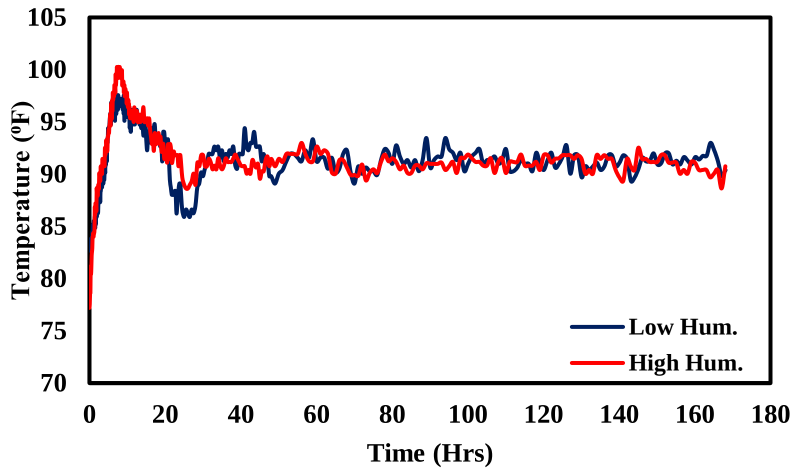

Figure A.1 - Internal Temperature Development Curing at 90ºF

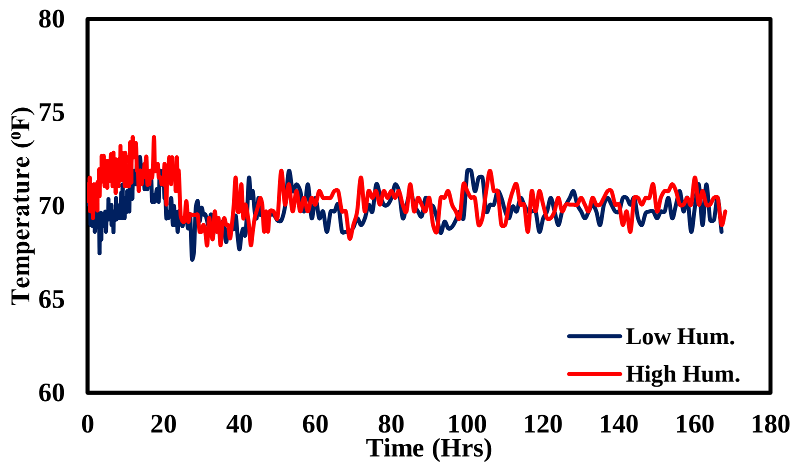

Figure A.2 - Internal Temperature Development Curing at 70ºF

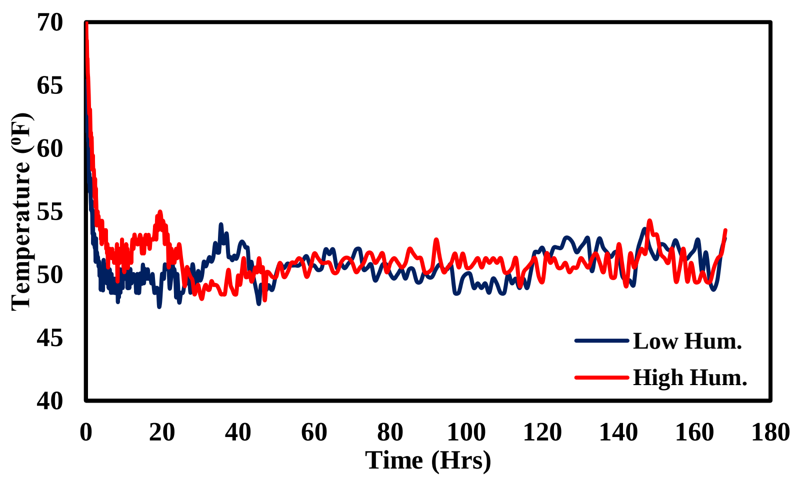

Figure A.3 - Internal Temperature Development Curing at 50ºF

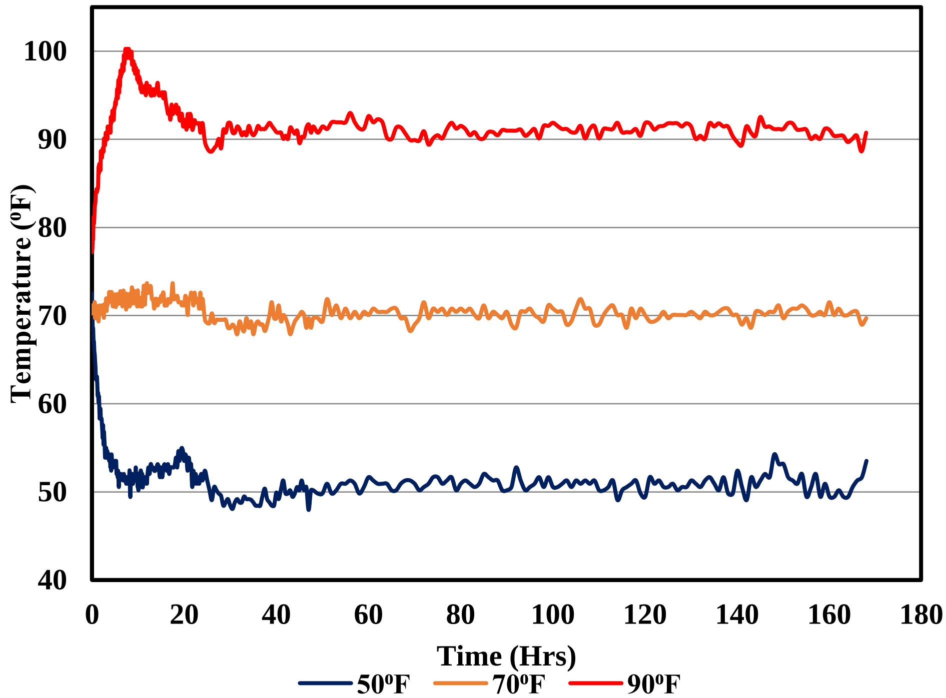

Figure A.4 - Internal Temperature Trends Curing at 80% Hum.

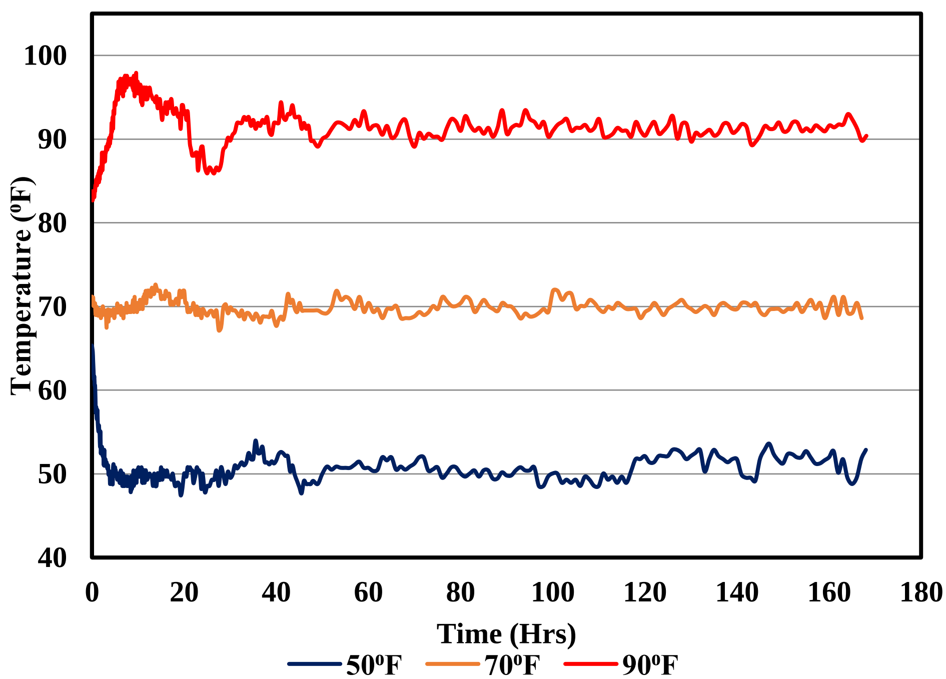

Figure A.5 - Internal Temperature Trends Curing at 40% Hum.

Appendix B: Comparison of Strength, Modulus and Setting Development

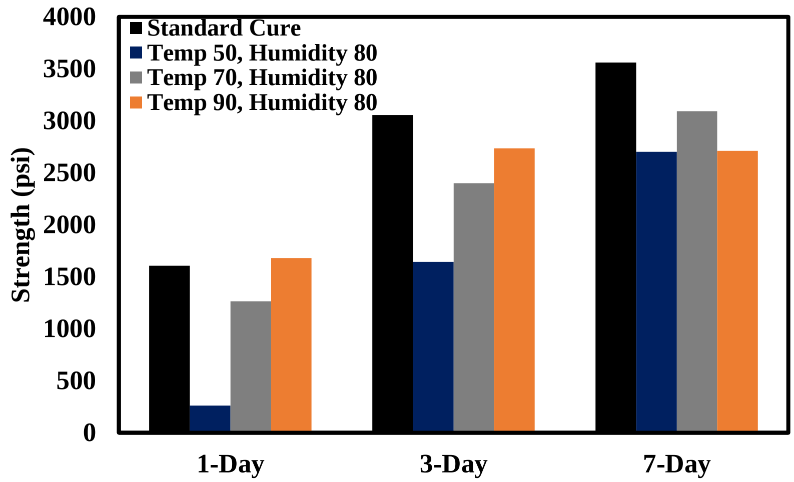

Figure B.1 - Comparison of High Humidity Strength Development

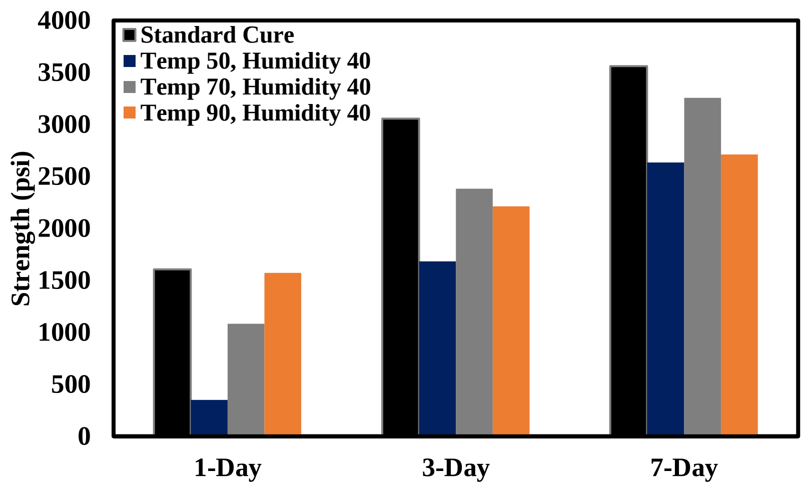

Figure B.2 - Comparison of Low Humidity Strength Development

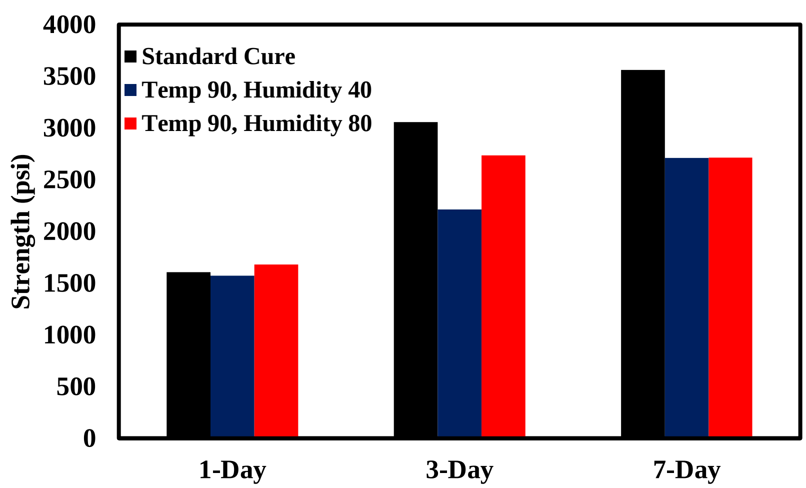

Figure B.3 - Comparison of Strength Development

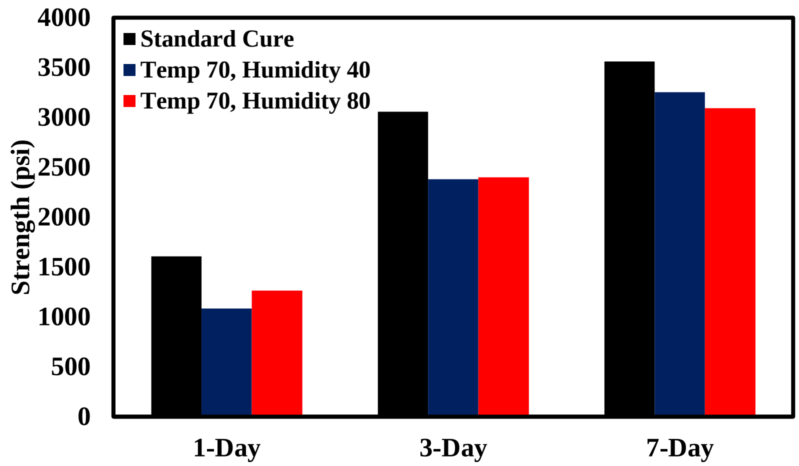

Figure B.4 - Comparison of Strength Development

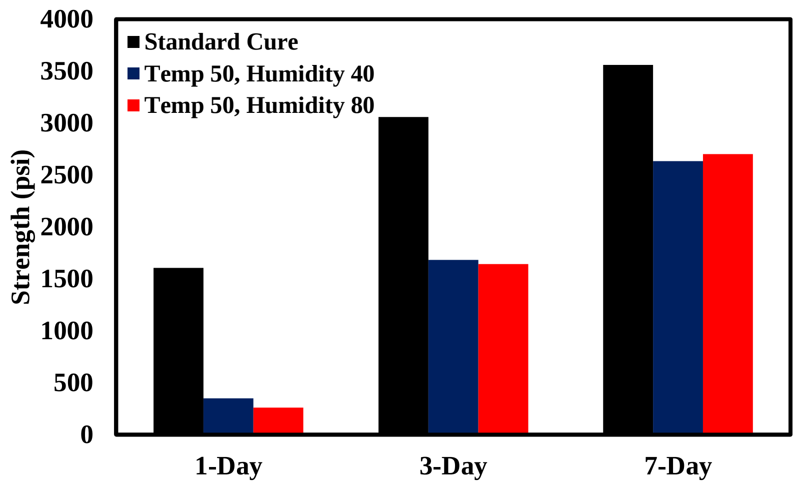

Figure B.5 - Comparison of Strength Development

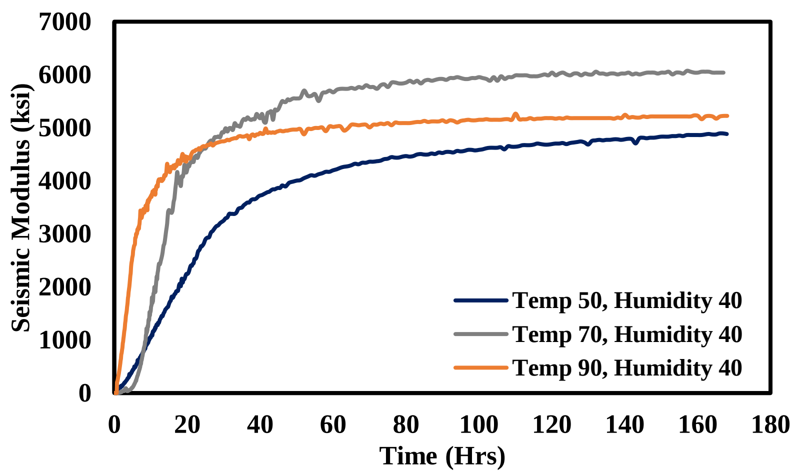

Figure B.6 - Modulus Development of Low Humidity

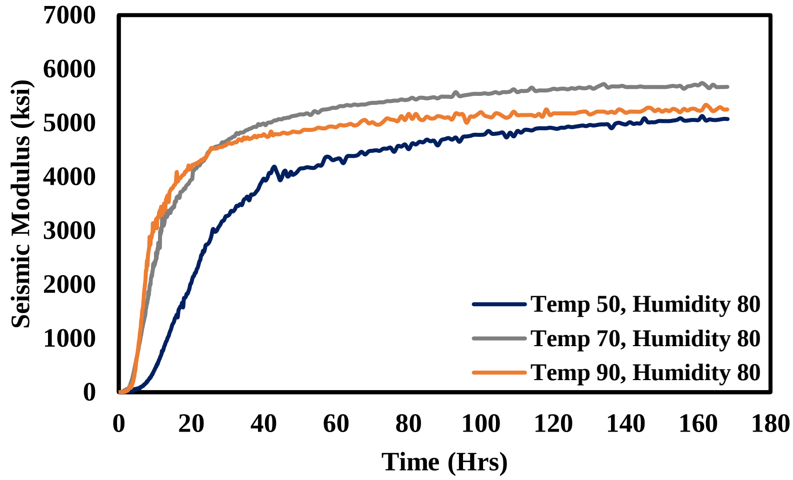

Figure B.7 - Modulus Development of High Humidity

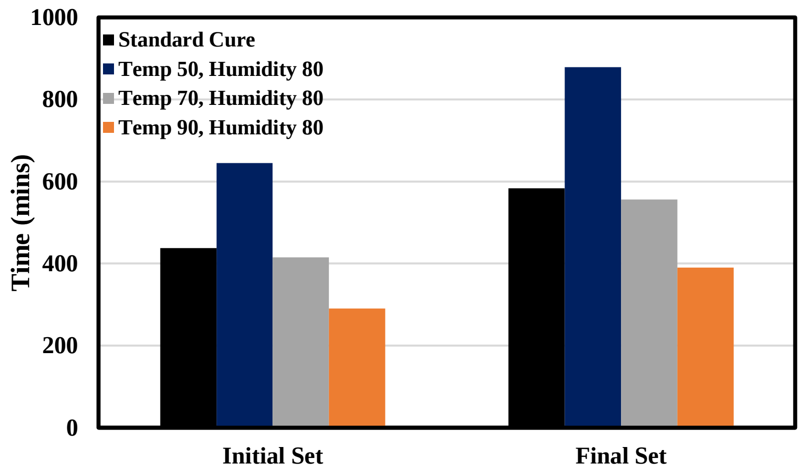

Figure B.8 - Comparison of Setting Times for High Humidity

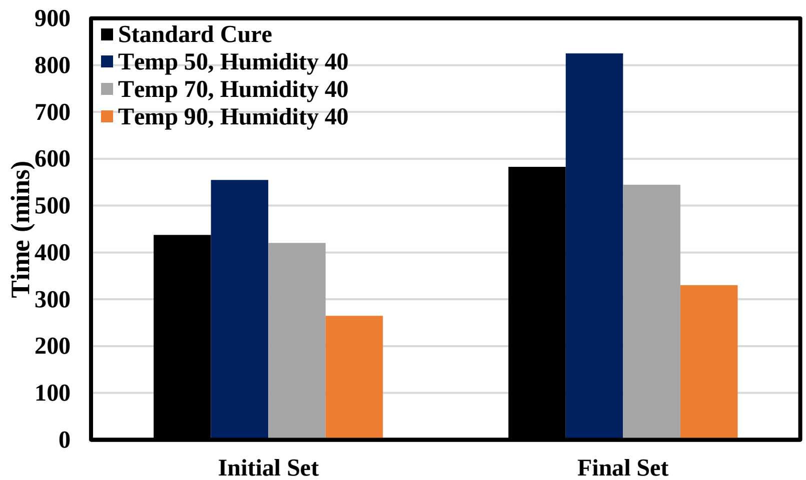

Figure B.9 - Comparison of Setting Times for Low Humidity

Appendix C: Alternative TTF Trends

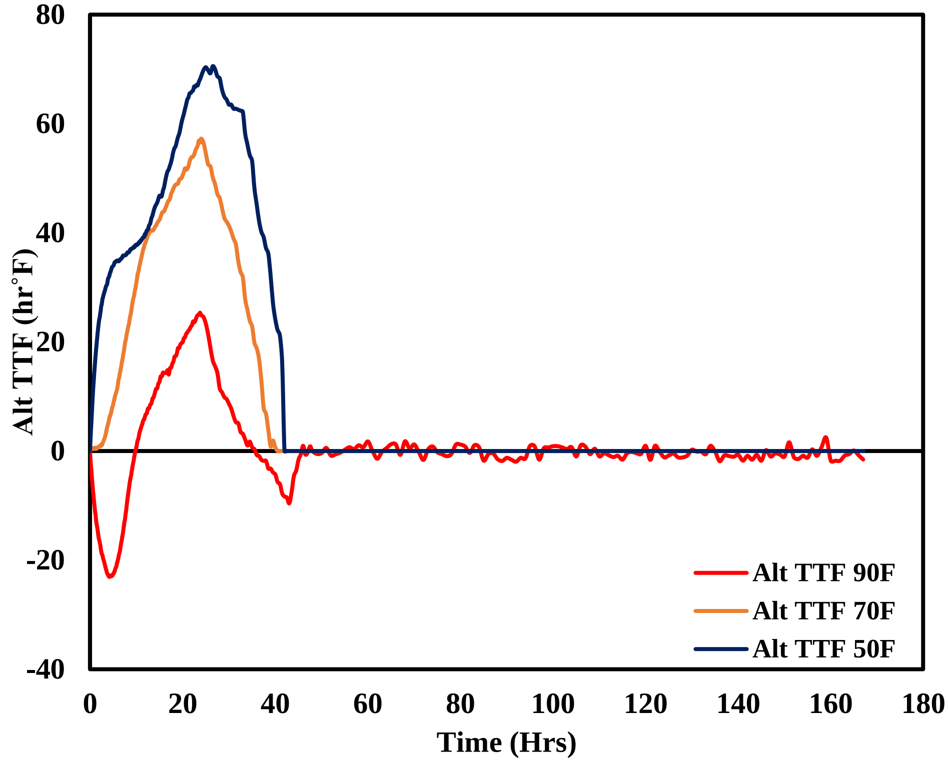

Figure C.1 - Comparison of Alt-Maturity cured at 80% Humidity

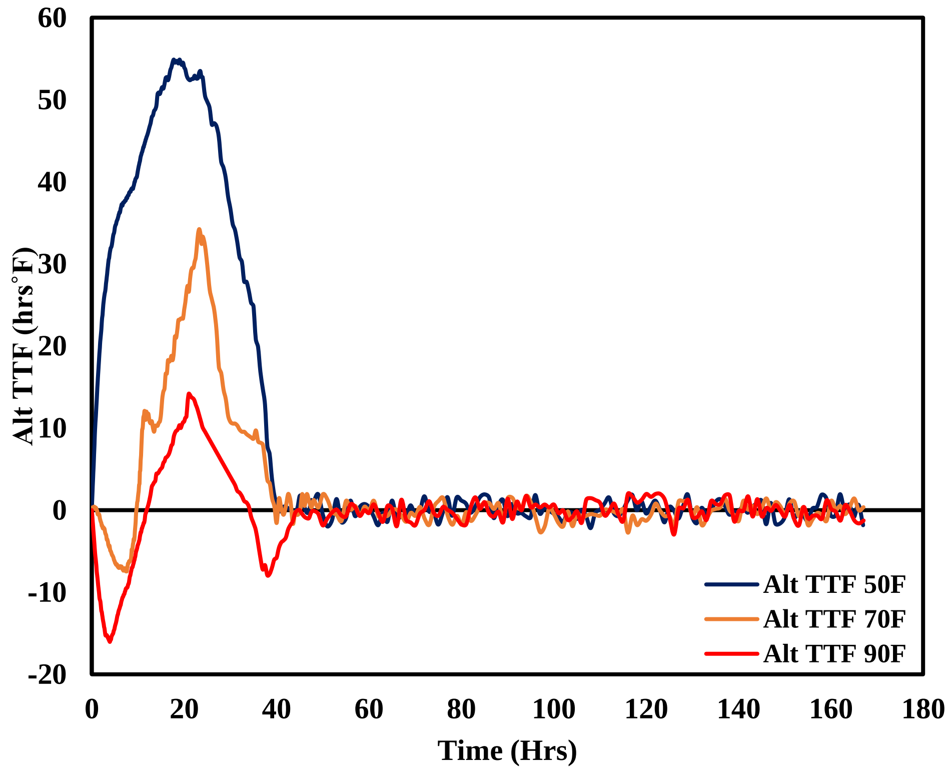

Figure C.2 - Comparison of Alt-Maturity cured at 40% Humidity

Vita

Benjamin Arras is a native of El Paso, Texas, is from humble roots and was raised in the border community. The second son of Guadalupe Arras, he graduated from Coronado High School in 2012. He then followed to enroll in the Civil Engineering program at El Paso Community College where he graduated with his Associate Degree in Civil Engineering in 2015. Transferred over to the University of Texas at El Paso (UTEP) where he received his Bachelor's in Civil Engineering in 2018, and enrolled into the civil engineering master's program thereafter.

Benjamin Arras was involved in nondestructive testing and evaluation research at UTEP during his undergraduate studies, later expanding his research in the early-age behavior of concrete. He worked at the Center for Transportation Infrastructure Systems (CTIS) under the mentorship of Dr. Soheil Nazarian and Dr. Danniel D. Rodriguez. His professional aspirations are to improve and contribute to innovation of our transportation infrastructure that will help bridge diversified communities.

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