University of Nevada, Reno

Robust Methods for UHPC Early-Strength Determination and Quality Control for Accelerated Bridge Construction

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in
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by
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ABSTRACT

Ultra-high performance concrete (UHPC) is an advanced cementitious construction material that has been widely used recently. The significant advantage of UHPC is that it can reach high compression strength about 10-12 ksi after one day and about 21-23 ksi after 28 days of casting. Such advantage is crucial for accelerated construction, especially bridges where the roads are fully closed when traditional construction methods are used. To minimize road closures and enhance construction zones safety, accelerated bridge construction (ABC) techniques are becoming more common. Using advanced materials like UHPC for connecting bridge components is a major aspect of ABC. However, to confidently move from one construction phase to the next or eventually open bridges to traffic, a quality control method is needed to verify the specified strength of connections and other critical materials like UHPC. Therefore, this research focuses on assessing and developing the maturity method for UHPC at early ages as a quality control method to provide accurate strength predictions. For this purpose, more than 900 specimens of 3"×6" cylinders and 4"×4"×4" and 2"×2"×2" cubes from eight different UHPC mixtures were cast and tested.

Overall, this research showed that the maturity method is applicable for UHPC at early ages and can lead to a good strength prediction when proper guidelines as presented in this thesis are adopted. However, the results show that the current existing ASTM C1074 maturity method procedures and recommendations are ineffective in predicting UHPC strength for ages of one day and less. Also, the 4"×4"×4" cubes showed better strength predictions than the 3"×6" cylinders at ages less than one-day. Moreover, the Arrhenius method has slightly better results than the Nurse-Saul. Finally, new maturity constants were proposed, the lab breaking points' ages were determined, and new curve fitting equations were developed and proposed to predict the UHPC strength with minimal errors.

Furthermore, cubes showed better strength predictions than the cylinders, and since cylinders require surface preparation, this consumes time and makes the quality control results sensitive to the specimens’ preparation procedure especially for early age. Thus, the second part of this research focuses on using cubes as an alternative to cylinders. For such, the size effect of the cubes and cylinders with different sizes and various strength levels from less than 1 ksi to over 20 ksi was studied. Furthermore, other factors were considered such as different fiber content and curing regimes. The mentioned factors helped study the size effect effectively and propose robust conversion factors and functions between specimen shapes and sizes.

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CHAPTER 1. INTRODUCTION

1.1. Study Motivation and Literature Review

Ultra-high performance concrete (UHPC) is a cementitious material characterized by durability, long-term stability, and high compressive strength [1]. UHPC can reach a compressive strength of 10 ksi after 24 hours and 22 ksi after 28 days of casting if a specific curing procedure is followed. Compared with conventional concrete, the high compressive strength of UHPC leads to a considerable reduction in the members' cross-sections and thus the geometry of the overall structure. In addition, the fast strength gain of UHPC leads to accelerating the construction phases, which reduces construction time and the direct and indirect costs of the human resources, machinery, road closures, etc. The application of UHPC in bridges varies from small components such as field connections (Figure 1) to big elements like girders, beams, and columns [2]–[15].

Figure 1. UHPC applications: (a) Precast deck panels with transverse and longitudinal joints [16], (b) Precast column and drop bent cap for Laurel Street Overcrossing project in California, USA (courtesy of Dorie Mellon)

One of the reasons that caused the UHPC to have higher strength than conventional concrete is the packing of the material itself and the fine elements that make it. UHPC comprises portland cement, fine sand, silica fume, steel fibers, super plasticizer, and low water to cement ratio. Eliminating the coarse aggregate in the UHPC and replacing it with fine material improve the packing by eliminating the voids that the coarse aggregate could cause. In addition, the strength difference of UHPC comes with a higher price. The proprietary UHPC can reach $2000/yd3, unlike the conventional concrete, which costs $150/yd3. Although there is a big difference in the costs, bridge owners prefer using UHPC because this difference in material cost is not as high as the costs of traffic closure, heavy construction machines, human resources … etc. Due to the mentioned reasons above, UHPC became one of the materials that could be used in the Accelerated bridge(ABC) construction projects. ABC is methods or techniques that are used in construction to reduce the onsite construction time. ABC methods not only is limited to material choice but also to innovative planning and design.

Due to the popularity of the UHPC in the construction market, robust quality control methods are needed to monitor its strength and make the implementation of UHPC more effective. The importance of tracking the strength of UHPC is to verify that the structural strength of the UHPC elements meets the required standards to effectively strip the forms and proceed with the following construction phases. For instance, the bridge can only operate when a UHPC field joint strength reaches a threshold of 8000 psi [17] some projects require 14 ksi [18]. To real-time verify such strength, destructive and non-destructive methods could be used. One of the non-destructive methods is called the maturity method.

The maturity method is well established and widely used quality control method for predicting the strength of the concrete based on its temperature history. The method was initially developed to be applied to the conventional concrete. The American Society for Testing and Materials (ASTM) guides the application of the maturity method on conventional concrete through the technical standard: ASTM C1074 [19]. Two maturity functions are proposed in the ASTM C1074: Nurse-Saul and Arrhenius methods. To predict the strength of a concrete member using the maturity method, a temperature history of that member and at least five compressive strength results of lab-cured specimens of the concrete in question are needed. Then, the strength maturity equation could be established and used to predict the strength of the concrete in question at any age. The maturity equations involve maturity constants; these constants can be determined through an experimental test mentioned in the ASTM C1074. In case of not conducting this experimental test, the ASTM C1074 recommends maturity constant values that are alternative to the experimental tests and could be implemented in the strength maturity equation. Moreover, the ASTM C1074 also recommends the testing ages of the lab-cured specimens under compression, i.e., 1, 3, 7, 14, and 28 days. Although it is not explicitly mentioned in the ASTM C1074 that the maturity methods procedures and the mentioned recommendations could be used for UHPC, construction engineers and researchers are adopting them in the application of the UHPC. Figure 2 how to establish the strength maturity relationship.

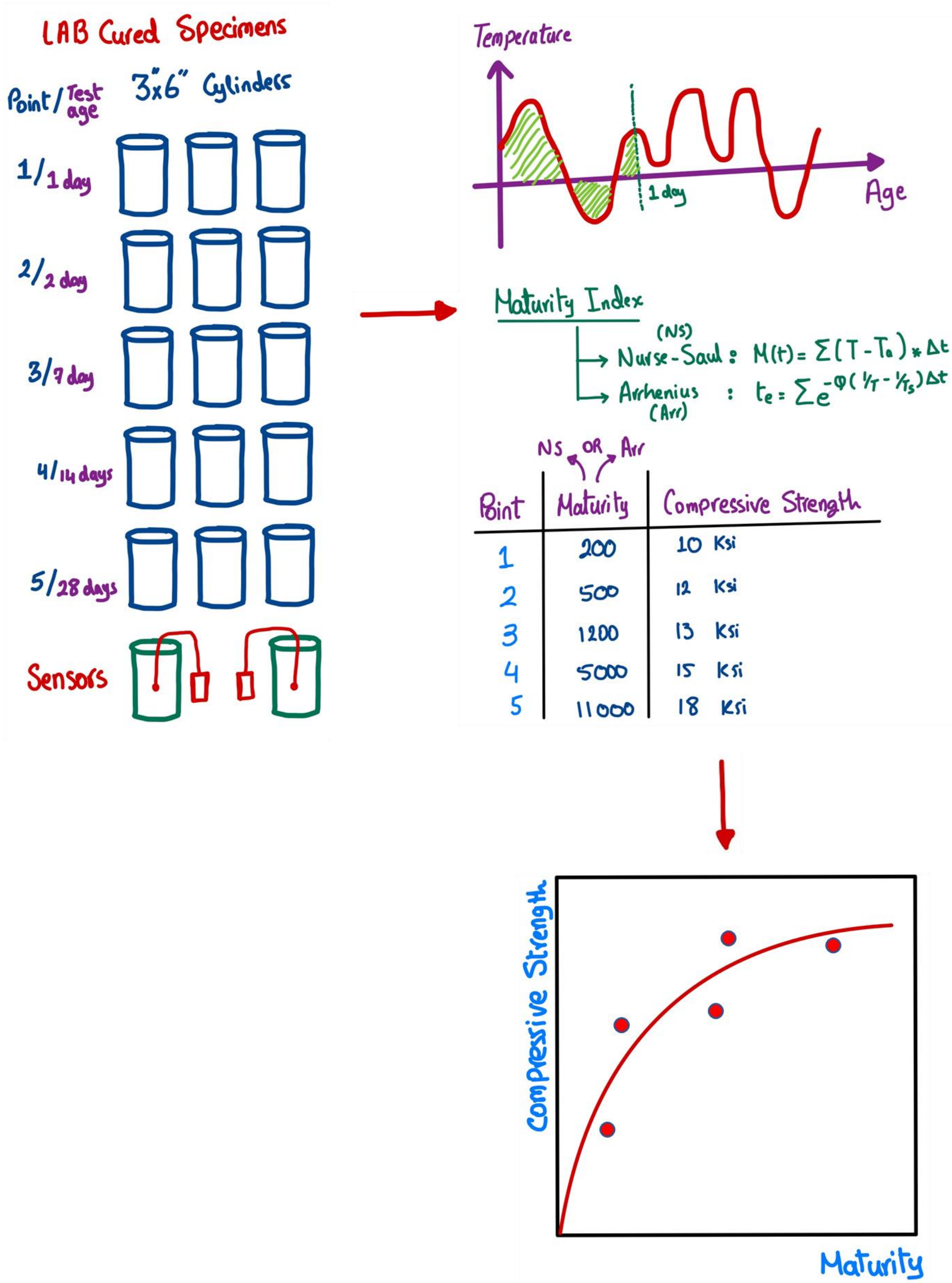

Figure 2. Illustration on establishing the strength maturity method

Carino et al. [20] assessed the applicability of the maturity method on high-performance concrete (HPC), and they found that the maturity method provides good strength predictions for the HPC. Also, they found that the curing temperature did not affect the long-term strength, in contrast to the conventional concrete's known behavior. The difference between UHPC and HPC is that the UHPC has a lower water-cement ratio and has fibers. This gives an insight into the possibility of using the maturity method for UHPC. However, the effect of adding fibers to concrete was studied, and it was found that the addition of fibers slightly delays the hydration reaction [21], [22]. Wang and Kim [23] studied multiple regression fit equations for the strength maturity data points of UHPC with various types of fibers. They used the available maturity constants in the literature for the conventional concrete in the applications of UHPC. They concluded no significant difference between the logarithmic and hyperbolic equations. Such a conclusion indicates that the conventional concrete maturity constant could be used for UHPC in fitting the lab breaking points. Poole and Harrington [24] concluded for the concrete material that if the difference between the lab and in site specimens is more than 15˚C, the maturity constant (Q) needs to be evaluated accurately. At the same time, they also suggested that Q is variable, not constant, unlike what is mentioned in the ASTM C1074, and it changes with time and temperature. Other authors suggested that for UHPC, the maturity constant experimental tests mentioned in the ASTM C1074 provide approximate results [22]. Thus, site specimens with different temperatures, humidity, and overall site conditions are needed to verify the accuracy of the established strength maturity relationships based on lab-cured specimens. Up to now, far too little attention has been paid to validating the UHPC strength maturity relationship with the site specimens; instead, the available literature focused on validating and fitting the strength maturity relationship with the lab cured specimens that were used initially to establish the relationship.

Further, when casting UHPC, cylinders are supposed to be delivered to the labs to be tested in compression as a quality control method to verify the strength of the UHPC [25]. In the United States, the standardized cylinder for UHPC compression testing is 75 mm in diameter × 150 mm in height (3" ×6") [25]. However, cylinders require specific operations before testing in compression, such as cutting and grinding the surfaces as shown in Figure *3*. Such processes consume time in addition to the high costs due to the high expense of the machines used, such as the high-capacity compression machine, grinding machine, and cutting machine. Furthermore, in remote construction sites, construction firms are required to move the lab equipment to the site; thus, more costs are directed towards the machines and the time-consuming operations because of the cylinder preparation process. To save the time consumed in preparing the cylinders, cubes could be used as an alternative to the cylinders. In China. the standard quality control specimen in compression is the 100 mm × 100 mm × 100mm (4" ×4"×4") [26]. The main advantage of using cubes is that they do not require any special operations such as cutting and grinding the faces. Also, smaller specimens could save money in terms of easily finding and buying the normal load capacity compression testing machines instead of the high load capacity ones. To use different specimens other than the standardized 75mm × 150mm cylinders, a study on different specimen shapes and sizes should be performed, and the conversion factors between them should be calculated

Mansur and Islam [27] tested 210 UHPC specimens in compression at 28 days. The specimens were cylinders and cubes with different sizes and aspect ratios. They used 11 UHPC mixes with different compressive strength levels that ranged from 20 MPa to 100 MPa. They found that the ratio of the cube to cylinders changes with changing the concrete strength levels and the aspect ratio of specimens. Graybeal [28] studied the effect of various specimens' shapes and sizes on the compressive strength of one UHPC proprietary mix with 6% fibers by weight. He used: 51-, 76-, and 102-mm (2-, 3-, and 4-inch) diameter cylinders with a height to diameter ratio of 2 and 51- and 100-mm (2- and 4-inch) cubes. He found that the smaller specimen sizes showed larger standard deviations than the bigger specimens; thus, he does not recommend using specimens smaller than 76mm. Graybeal and Davis[29] studied different sizes of cubes and cylinders UHPC specimens. The specimen's sizes were: 76 and 102 mm (2, 3, and 4 in.) cylinders and 51, 70.7, and 100 mm (2, 2.78, and 4 in.) cubes. They used three mixtures: two different mixtures have 2% fibers by volume, and the third one has no fibers. Two different curing conditions were adopted. They tested the cubes and cylinders at the ages of 3, 4, 9, 27, and 28 days after casting to have a different compressive strength levels ranging from 80 to 200 MPa (11.6 to 29.0 ksi). They concluded that the conversion factors of 1.00 and 0.96 between the 100mm cube and 51mm cube to 76mm cylinder, respectively. They recommend using 70.7mm cube and not recommending the 51mm cylinders and cubes due to their large strength variations compared with the other sizes. Zabihi and Eren [30] studied different UHPC specimens with varying strength levels in compression at the age of 28 days. The specimens were 100, 150- and 200-mm cubes and 150×300 and 100×200 mm cylinders. They studied two different strength levels of UHPC and the specimens and used two curing regimes of air and water cured. They reported the conversion factors between the specimens and found that they have different trends at different curing conditions. Fladr et al. [31] investigated the conversion factors between different compressive strength levels of 150mm and 100mm cubes. The testing age was 28 days, and the UHPC mix used was nonproprietary. They found that the conversion factor between the 100mm and 150 mm changes with the strength level. They also found that the ratio of 100mm cubes to 150mm cubes increases with the increase in compressive until it reaches a compressive strength of 140 MPa, after which the ratio becomes independent of the shape. Zhang et al. [32] studied the influence of the fibers' type and content and the water-to-binder ratios in the UHPC mixtures on the different cubes’ sizes of 40, 70.7, 100, and 150mm under compression. They found that increasing the fiber content increase the compressive strength. Also, they found that the fiber type affects the size effect of the compressive strength. Fládr and Bílý[33] studied different UHPC mixtures with varying strength levels ranging from 100 MPa to 175 MPa on different sizes of 40, 100, 150, and 200 mm cubes. They found that with increasing the strength, the size effect reduces. They also found that the size effect varies by varying the UHPC mix compositions and strength levels.

Extensive research has shown that the high compressive strength of 130 MPa and greater diminishes the size effect of the specimens. However, this high compressive strength values only appear at later ages. But that's not the case with the 12hrs or the one-day strength when the bridge owners seek to open the bridge. Thus, the conversion factors in the literature from 51mm and the 100mm cubes to 76mm cylinders were close to 1.00. Such a conversion factor is valid at a late age or when the material has already gained all its strength, but what about the conversion factor at 12 hrs or one day? The bridge can only operate when field joint concrete strength reaches a threshold of 8000 psi (55 MPa) [17] and the factor of 1.00 is not valid to be used at this strength level. So, little published data spotted the light on the conversion factors for lower strength or a conversion function that could be valid for all ages or all strength levels.

1.2. Research, Objectives, and Tasks

The objectives of this project are to:

1. Conduct comparative compression tests for various UHPC mixes and types using cubes and cylinders at early ages (as early as 14 hours).
2. Develop strength maturity curves for various UHPC mixes and assess the reliability of using such curves for estimating UHPC early strength.
3. Collect data from UHPC vendors on UHPC maturity to assemble a larger database.
4. develop guidelines for UHPC quality control and assurance as pertains to early compression strength characterization.

1.3. Thesis Overview

In this thesis, the first aim is to assess the application of the maturity methods for strength predictions of UHPC starting from the early ages of 14 hours by developing the maturity curves using the lab cured specimens, then validate the curve using the site specimens where the ambient conditions are different from the lab and finally calculating the errors. The second aim is to adjust the procedures of the maturity method by assessing a wide range of maturity constants and ages and the number of lab breaking points to reduce errors. The third aim is to apply both Nurse-Saul and Arrhenius functions on different mold shapes: 3" ×6" cylinders and 4" ×4" cubes to assess which maturity function and specimen shape are better in terms of strength prediction and testing process. Finally, the fourth aim is to develop procedures and guidelines based on the conclusions of the previous aims that lead to providing strength prediction results of UHPC with minimal errors.

The aims were achieved by using eight UHPC mixtures that include both proprietary and non-proprietary mixtures, three different temperature/maturity sensors, and two different specimen shapes were used in this paper. More than 900 lab and site cured UHPC specimens were tested at early, middle, and late ages. Finally, the eight UHPC mixtures were cast throughout the year where the specimens were subjected to a wide range of temperatures and site conditions, from being warm and dry in the summer to below freezing and humid in the winter

The thesis also investigated the applicability of using 51mm and 100mm cubes as an alternative to the standardized 76mm cylinders. The reason is that the cubes, unlike cylinders, don’t require surface preparations of cutting and grinding, and the smaller cube size reduces the testing machine capacity requirements. For such an objective, robust conclusions and conversion factors of UHPC with different shapes and sizes were concluded and presented in this thesis.

CHAPTER 2. ASSESSMENT OF THE MATURITY METHOD ON UHPC

2.1. The Maturity Method

The maturity method is a non-destructive test used to predict the strength of the concrete based on its temperature history. First, the concrete's temperature is measured and stored using sensors; as shown in Figure *3*(a), the sensors are embedded in the UHPC members. However, in the case of testing specimens, i.e., cylinders and cubes Figure *3*(b) and (c), the sensors are embedded in the center of the specimen and at mid-height. Then, the temperature histories are used to calculate maturity indexes by two main maturity functions proposed in the ASTM C1074: Nurse-Saul function (NS) or time-temperature factor and Arrhenius function or Equivalent age (EQ). The NS maturity function assumes linear relationships between the temperature and rate of strength gain[34] and is presented in Eq.1.

$$M(t) = \sum (T_a - T_o)\Delta t \tag{1}$$

where M(t) is the temperature-time factor at age t, T_a is the average concrete temperature during time interval Δt, and T_o is the datum temperature. On the other hand, the EQ function assumes a non-linear relationship between the temperature and strength gain, as presented in Eq.2.

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

Where t_e is the equivalent age at a specified temperature T_s, Q is activation energy divided by the gas constant 8.13 J/(K.mol), and T_a is the average concrete temperature during time interval Δt. Moreover, special preparations are performed on 3" ×6" cylindrical specimens before axial testing, such as cutting the top 0.5” surface and then grinding both top and bottom surfaces, as shown in Figure *4*(a) and (b), respectively. After preparing the specimens, the 3" ×6" cylinders and 4" ×4" cubes are axially loaded according to ASTM C39 [35], as shown in Figure *4*(c) and (d). However, the loading rates are increased because of the high strength of UHPC and based on the study done by Graybeal [1], he concluded that adjusting the loading rate by increasing it would not affect the results. Furthermore, the maturity index values at the compression testing ages are stored. Eventually, a table could be developed that contains the maturity index values accompanied by the compressive strengths of the specimens.

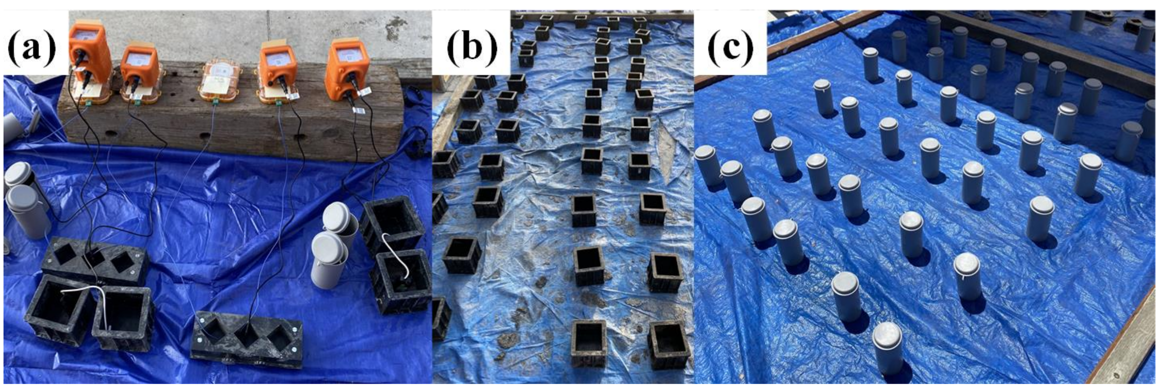

Figure 3. Experiment preparations: (a) specimens with sensors, (b) cube specimens, (c) cylinder specimens

The ASTM C1074 requires breaking specimens in at least five ages: 1, 3, 7, 14, and 28 days. At each breaking age, an average of three specimens is needed. Finally, the maturity curve could be established by fitting the strength and maturity index by a regression curve.

Wang and Kim [23] studied multiple regressions curves, i.e., hyperbolic and logarithmic regressions on different UHPC with various fibers and found a negligible difference. Therefore, in addition to its simplicity, the logarithmic equation was used in this research.

2.2. Experimental Campaign and Research Methodology

Eight UHPC of proprietary and non-proprietary mixtures were used in this research: Accelerated bridge construction (ABC)-Non-proprietary 1% fibers, CeEntek 1% fibers, CeEntek 2% fibers, SteeLike 1% fibers, SteeLike 2% fibers, Cor-Tuf 2% fibers, Lafarge with accelerator 2% fibers and Lafarge without accelerator 2% fibers. The proportions of the eight UHPC mixtures are shown in Table 1. For each UHPC mixture, a set of 3" ×6" cylinders and 4" ×4" cubes molds were used, as shown in Figure *3*(b) and (c). After casting, the specimens were divided into two groups. One group was cured in the lab standard curing room(lab cured specimens) according to ASTM C511 [36], and the other group was left outside the lab, where an ambient atmosphere existed to mimic the construction site conditions(site cured specimens). Temperature/maturity sensors were used to measure and store the temperature of the specimen at time intervals of 30 minutes. Three sensors were placed in two specimens of the same shape for both curing conditions, as shown in Figure *3*(a). These sensors were from three different vendors: LumiCon, Maturix, and Giatec. Furthermore, the lab cured specimens were tested in compression at ages: 0.6, 0.75, 0.85, 1, 2, 3, 7, 14, 28 days. On the other hand, the site cured specimens at 1,2 and 3 days. The compressive strength testing results are shown in Tables 2 to 5.

The research starts with a parametric study in which five UHPC mixtures: ABC non-proprietary 1% fibers, CeEntek 1% and 2% fibers, SteeLike 1%, and 2% fibers, were used to assess the maturity procedures recommended by the ASTM C1074. The stored temperature histories of both lab and site specimens of these five mixtures were used to determine the NS and EQ maturity index values. However, the lab and site temperature histories of all the UHPC mixtures that were used throughout the research are shown in Figure *6*, Figure *7*, Figure *8*, Figure *9*, Figure *10*, and Figure *11*. The specimens were left outside until 12 hours when the molds were removed. Then, a group of specimens was taken to the standard curing room, and the other group was left outside; their temperature histories are shown in Figure *9*, Figure *10*, and Figure *11*. It can be observed that the site specimens were subjected to a wide range of ambient temperatures where some specimens had a max temperature of 45˚C and other specimens had a minimum temperature of -5˚C.

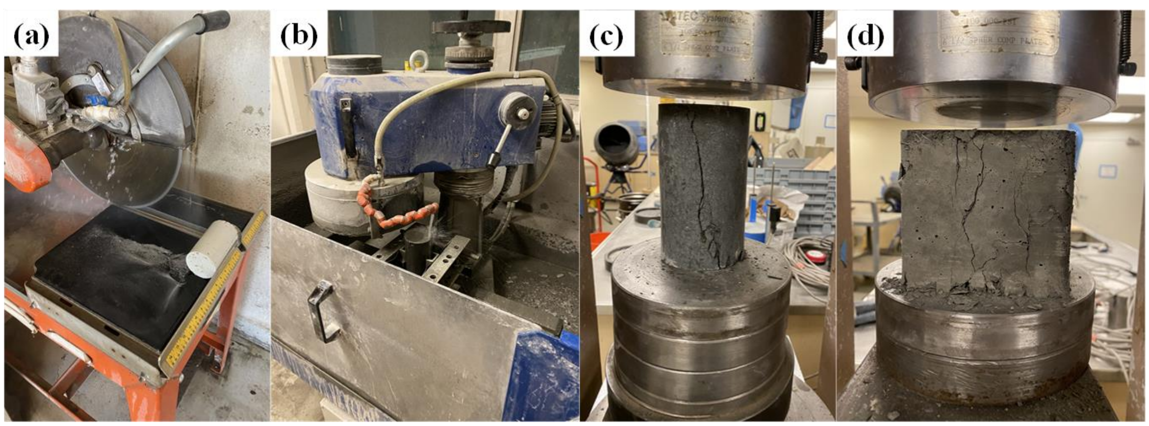

Figure 4. Testing procedure: (a) cutting the cylinder (b) grinding the cylinder (c) testing cylinder specimen (d) testing cube specimen

Table 1 Constituents the different UHPC mixtures used in this research

Constituents (lb/yd^3)		**ABC-NP**	**SteeLike**	**CeEntek 1%**	**CeEntek 2%**	**Cor-Tuf**	**Lafarge***
Type I Cement		1179.6	-	-	-	1269	-
Slag		589.8	-	-	-	-	-
Silica fumes		196.6	-	-	-	-	-
Fine masonry sand		1966	-	-	-	1350	-
Steel fibers**	1%	132.3	132.3	133	-	-	-
	2%	-	264.6	-	264	265	263.8
Superplasticizer		22.12	16.54	-	-	60.75	50.32
Corrosion plasticizer		-	-	-	-	22.82	-
workability plasticizer		-	-	-	-	47.25	-
water		393.2	199.8	274.1	271.4	243	171.8
Premix		-	3600	3916	3876	1080	3681.8
Ice		-	133.2	-	-	-	-
Accelerator		-	-	39.2	38.8	-	12.27
Nano-fibers		-	-	22.5	22.3	-	-

*Lafarge with Accelerator is presented, however, Lafarge without accelerator is has same constituents as the Lafarge with accelerator excepts that there is no added accelerator.
** The presented fibers percentage are by volume

The maturity method recommendations were assessed using five different mixtures with different initial temperatures and site conditions. Then, factors such as best configurations (lab age tests), best maturity constants, and the optimum number and ages of lab axial tested specimens used to establish the strength maturity relationships were determined. Moreover, both specimens’ shapes and maturity functions NS and EQ were assessed to determine which shape and maturity function leads to better predictions with minimal errors.

The error analysis in the following sections is demonstrated in Figure *5*. When the strength maturity equation curve is developed, as shown in Figure *5*(a), it is supposed to predict the strength of the site specimens through their maturity index values. For the same maturity index values, if the strengths of the lab and site specimens were not equal, the errors are calculated and plotted vs. time, as demonstrated in Figure *5*(b). The solid black line in Figure *5*(b) at error = 10% is added to mark a reference for the 10% allowed error tolerance in the ASTM C1074, above which the strength maturity curve has to either modify or not be valid. Theoretically, at the same maturity index, the compressive strength of the lab and site specimens should be equal [19], [34]. However, that is not the case, as it will be explored in the following sections.

After the five UHPC mixtures were used in the parametric study, three more mixtures: Cor-Tuf, and Lafarge with and without the accelerator, were used to validate the conclusions that came out from the parametric study. The lab and site temperature histories of the additional three UHPC mixtures are shown in Figure *6*, Figure *7*, Figure *8*, Figure *9*, Figure *10*, and Figure *11*.

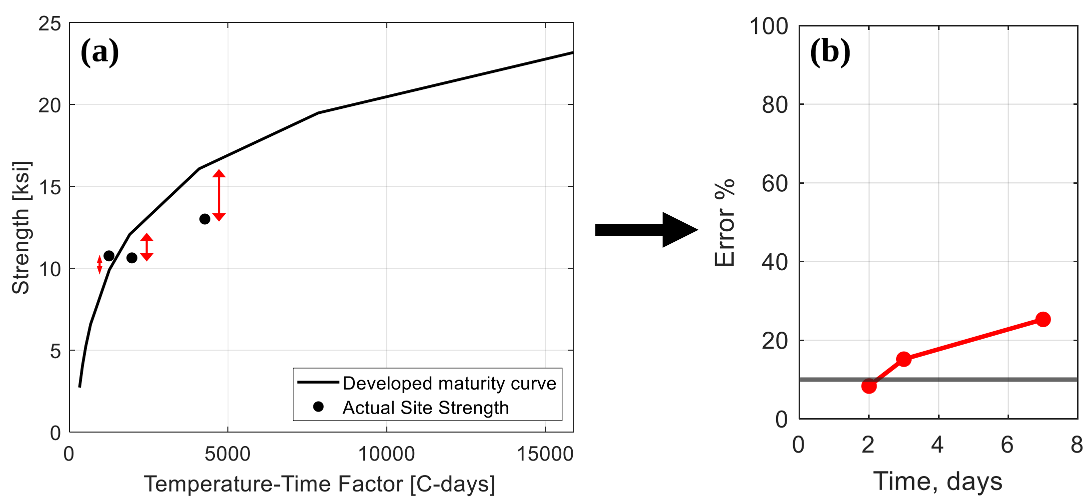

Figure 5. Demonstration of the error analysis: (a) the shown error, (b) calculated error

2.3. The Parametric Study

To establish the strength-maturity relationship, the ASTM C1074 recommends specific maturity constants such as 0˚C for datum temperature in the NS function and a range of values from 38 to 45 KJ/mol for the activation energy in the EQ function. These recommended values were concluded from the lab experiments conducted on conventional concrete[34]. Therefore, these constants are only applicable when applying the maturity method to conventional concrete. Although the UHPC is not mentioned in the ASTM C1074, these recommended constants are popular and were used among researchers [23], [37] and construction engineers when applying the maturity method to UHPC projects. Moreover, the ASTM C1074 requires five compression tests of lab-cured UHPC specimens at five ages. Each age represents a breaking point; in other words, at least five-breaking points are needed to establish the strength-maturity relationship. The ASTM C1074 also recommends the ages for the five breaking points: 1,3,7,14, and 28 days.

Table 2. ABC Non-Proprietary 1% fibers and SteeLike with 2% fibers compressive strength

Mixture	Curing	Time, days	Compressive Strength, MPa			Standard Deviation, MPa			Coefficient of Variation			Conversion Factors		
			76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	102mm cube to 76mm cylinder	51mm cube to 76mm cylinder	51mm cube to 102mm cube
Nonproprietary 1% fibers	Lab cured	0.56	16.04	18.49	13.55	1.007	0.600	0.405	0.0213	0.0076	0.0035	0.867	1.184	1.37
		0.72	29.10	29.40	18.72	1.598	1.383	1.999	0.0537	0.0402	0.0841	0.990	1.555	1.57
		0.86	33.24	27.43	32.20	2.048	1.200	1.211	0.0883	0.0303	0.0308	1.211	1.032	0.85
		1.01	47.28	42.86	44.79	1.253	1.052	1.232	0.0330	0.0233	0.0320	1.103	1.056	0.96
		2.01	68.41	55.06	36.44	0.395	2.277	2.254	0.0033	0.1090	0.1068	1.242	1.877	1.51
		3.16	82.96	67.69	42.55	2.997	1.446	0.780	0.1889	0.0440	0.0128	1.225	1.949	1.59
		7.09	97.43	69.54	66.33	1.370	1.529	0.501	0.0395	0.0492	0.0053	1.401	1.469	1.05
		13.95	104.24	81.20	80.81	0.121	2.615	3.977	0.0003	0.1439	0.3328	1.284	1.290	1.00
		28.20	114.14	89.65	79.83	5.631	1.577	5.045	0.6670	0.0523	0.5354	1.273	1.430	1.12
	Site cured	2.01	74.17	52.61	47.53	2.326	1.374	0.414	0.1138	0.0397	0.0036	1.410	1.561	1.11
		3.16	73.33	70.77	37.88	2.585	0.882	1.629	0.1405	0.0164	0.0558	1.036	1.936	1.87
		7.10	89.68	80.21	69.93	3.094	6.594	4.762	0.2014	0.9146	0.4770	1.118	1.282	1.15
SteeLike 2% fibers	Lab cured	0.62	25.85	48.54	10.59	0.354	0.968	0.430	0.0026	0.0197	0.0039	0.71	0.56	0.79
		0.74	48.69	51.95	29.50	3.569	2.775	1.815	0.2679	0.1620	0.0693	0.83	0.60	0.73
		0.84	61.51	56.21	37.62	3.207	2.437	1.625	0.2164	0.1249	0.0555	1.07	0.95	0.89
		1.03	63.08	65.97	58.57	3.546	0.044	1.024	0.2645	0.0000	0.0221	1.28	1.06	0.83
		2.05	83.95	65.31	81.88	1.400	4.621	4.281	0.0412	0.4493	0.3855	1.38	1.06	0.77
		3.02	90.63	82.69	102.36	3.410	6.195	7.380	0.2447	0.8073	1.1456	1.18	1.03	0.87
		7.12	107.49	79.98	94.78	4.749	1.614	1.666	0.4743	0.0548	0.0584	1.21	1.05	0.87
		14.04	123.45	87.31	83.70	7.914	0.984	1.650	1.3175	0.0204	0.0573	1.20	0.99	0.83
		28.11	133.95	96.57	105.44	3.383	3.290	7.465	0.2407	0.2277	1.1721	1.52	0.85	0.56
	Site cured	1.03	73.14	54.83	53.41	1.782	2.092	3.309	0.0668	0.0921	0.2304	1.32	1.46	1.11
		2.04	76.36	66.42	76.89	4.079	2.981	2.999	0.3500	0.1869	0.1892	1.22	1.40	1.15
		3.03	89.02	74.08	90.83	0.206	5.321	3.710	0.0009	0.5957	0.2896	0.71	0.56	0.79

Table 3. SteeLike 1% and Lafarge without Accelerator with 2% fibers compressive strength

Mixture	Curing	Time, days	Compressive Strength, MPa			Standard Deviation, MPa			Coefficient of Variation			Conversion Factors		
			76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	102mm cube to 76mm cylinder	51mm cube to 76mm cylinder	51mm cube to 102mm cube
SteeLike 1% fibers	Lab cured	0.61	16.70	16.71	8.68	0.171	0.072	0.658	0.0006	0.0001	0.0091	0.87	1.18	1.37
		0.70	28.08	33.38	15.14	1.178	1.316	0.323	0.0292	0.0365	0.0022	0.99	1.55	1.57
		0.86	51.94	48.60	47.05	2.326	2.719	2.157	0.1138	0.1555	0.0978	1.21	1.03	0.85
		1.02	60.00	51.99	57.13	0.577	2.918	2.145	0.0070	0.1792	0.0968	1.10	1.06	0.96
		2.04	73.12	72.90	78.53	2.030	0.657	3.555	0.0867	0.0091	0.2659	1.24	1.88	1.51
		2.97	93.12	71.40	83.81	4.192	0.863	6.099	0.3696	0.0157	0.7824	1.23	1.95	1.59
		7.01	107.37	81.45	57.89	1.911	1.640	2.624	0.0768	0.0566	0.1448	1.40	1.47	1.05
		13.98	122.02	93.82	90.89	1.122	4.230	1.719	0.0265	0.3764	0.0622	1.28	1.29	1.00
		28.00	136.59	92.60	113.42	2.183	3.899	1.658	0.1002	0.3198	0.0578	1.27	1.43	1.12
	Site cured	1.03	66.56	63.23	63.60	0.534	2.829	3.551	0.0060	0.1684	0.2653	1.41	1.56	1.11
		2.04	82.34	70.77	78.23	1.431	2.880	4.660	0.0431	0.1744	0.4567	1.04	1.94	1.87
		2.99	89.02	80.96	74.83	0.206	1.643	0.386	0.0009	0.0568	0.0031	1.12	1.28	1.15
Lafarge without Accelerator	Lab cured	1.05	2.90	4.91	7.11	0.244	0.184	0.567	0.0013	0.0007	0.0068	0.59	0.41	0.69
		2.08	59.29	52.25	55.26	0.551	2.804	0.835	0.0064	0.1654	0.0147	1.13	1.07	0.95
		3.28	78.77	70.99	64.78	1.241	0.782	3.852	0.0324	0.0129	0.3122	1.11	1.22	1.10
		7.10	115.40	93.37	107.33	1.424	1.165	0.284	0.0427	0.0286	0.0017	1.24	1.08	0.87
		15.16	124.47	113.93	103.79	2.970	0.058	0.879	0.1855	0.0001	0.0163	1.09	1.20	1.10
		28.12	143.77	123.96	115.58	0.963	4.822	8.208	0.0195	0.4892	1.4172	1.16	1.24	1.07
	Site cured	0.62	6.54	7.00	8.60	0.176	0.455	0.607	0.0006	0.0043	0.0078	0.93	0.76	0.81
		0.82	34.37	38.34	36.43	1.247	1.837	2.444	0.0327	0.0710	0.1256	0.90	0.94	1.05
		1.03	35.78	40.11	40.63	0.085	1.375	0.725	0.0002	0.0398	0.0111	0.89	0.88	0.99
		2.06	47.27	47.68	50.79	1.881	1.613	1.386	0.0744	0.0547	0.0404	0.99	0.93	0.94
		3.27	55.06	59.65	52.92	2.179	0.749	1.280	0.0999	0.0118	0.0345	0.92	1.04	1.13
		7.07	72.03	71.82	61.15	1.222	1.948	3.218	0.0314	0.0798	0.2178	1.00	1.18	1.17

		15.14	84.56	88.79	81.33	2.057	3.310	6.853	0.0890	0.2304	0.9880	0.95	1.04	1.09
		28.11	102.48	93.30	84.70	5.360	5.344	1.856	0.6043	0.6009	0.0725	1.10	1.21	1.10

Table 4. CeEntek 1% and 2% fibers compressive strength

Mixture	Curing	Time, days	Compressive Strength, MPa			Standard Deviation, MPa			Coefficient of Variation			Conversion Factors		
			76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	102mm cube to 76mm cylinder	51mm cube to 76mm cylinder	51mm cube to 102mm cube
CeEntek 1% fibers	Lab cured	0.63	7.24	10.80	4.94	0.449	0.543	0.199	0.0042	0.0062	0.0008	0.67	1.47	2.19
		0.71	11.03	12.24	7.76	0.389	0.740	0.374	0.0032	0.0115	0.0029	0.90	1.42	1.58
		0.85	27.74	22.54	15.73	2.036	0.771	0.443	0.0872	0.0125	0.0041	1.23	1.76	1.43
		1.04	63.59	67.24	48.37	5.150	3.501	3.217	0.5579	0.2578	0.2177	0.95	1.31	1.39
		2.03	105.79	93.51	90.59	3.496	4.812	1.496	0.2571	0.4872	0.0471	1.13	1.17	1.03
		3.08	110.95	87.27	88.03	4.745	6.046	3.190	0.4736	0.7688	0.2141	1.27	1.26	0.99
		7.01	109.04	91.94	78.22	2.572	2.757	4.448	0.1391	0.1599	0.4161	1.19	1.39	1.18
		14.02	122.82	102.43	86.45	3.850	2.405	4.566	0.3118	0.1217	0.4387	1.20	1.42	1.18
		28.07	147.65	119.19	111.48	1.787	5.717	7.270	0.0672	0.6876	1.1118	1.24	1.32	1.07
	Site cured	1.05	42.19	48.16	24.73	3.856	3.726	0.162	0.3128	0.2920	0.0006	0.88	1.71	1.95
		2.04	77.15	75.40	57.85	0.345	1.233	4.230	0.0025	0.0320	0.3764	1.02	1.33	1.30
		3.09	89.95	80.03	73.82	1.463	1.043	5.418	0.0450	0.0229	0.6175	1.12	1.22	1.08
CeEntek 2% fibers	Lab cured	0.63	27.09	34.42	33.56	2.345	2.815	2.646	0.1156	0.1667	0.1473	0.79	0.81	1.03
		0.75	39.28	46.61	37.86	2.974	1.058	2.670	0.1860	0.0235	0.1499	0.84	1.04	1.23
		0.85	65.95	54.79	62.63	3.559	1.453	4.996	0.2664	0.0444	0.5251	1.20	1.05	0.87
		1.05	94.79	63.24	92.77	3.599	2.449	2.287	0.2725	0.1262	0.1101	1.50	1.02	0.68
		2.06	111.76	83.90	102.86	3.018	1.042	4.570	0.1915	0.0229	0.4394	1.33	1.09	0.82
		3.06	112.12	79.58	104.41	2.857	1.332	2.689	0.1717	0.0373	0.1521	1.41	1.07	0.76
		6.99	126.93	96.66	105.76	1.511	4.342	0.985	0.0481	0.3967	0.0204	1.31	1.20	0.91
		14.07	133.96	103.18	117.15	2.370	3.577	3.538	0.1181	0.2692	0.2633	1.30	1.14	0.88
		28.01	140.32	115.76	141.71	4.288	4.492	5.329	0.3867	0.4244	0.5973	1.21	0.99	0.82
	Site cured	1.06	72.23	53.82	62.22	3.238	2.980	3.066	0.2206	0.1868	0.1978	1.34	1.16	0.87
		2.06	91.65	71.10	85.68	1.719	2.088	2.359	0.0622	0.0917	0.1170	1.29	1.07	0.83
		3.07	100.98	72.00	81.93	0.527	5.263	2.536	0.0058	0.5827	0.1353	1.40	1.23	0.88

Table 5. LaFarge 2% fibers with accelerator and Cor-tuf 2% fibers compressive strength

Mixture	Curing	Time, days	Compressive Strength, MPa			Standard Deviation, MPa			Coefficient of Variation			Conversion Factors		
			76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	76mm cylinder	102mm cube	51mm cube	102mm cube to 76mm cylinder	51mm cube to 76mm cylinder	51mm cube to 102mm cube
Lafarge with Accelerator	Lab cured	0.61	7.67	7.02	7.41	0.015	0.005	0.466	0.0000	0.0000	0.0046	1.09	1.03	0.95
		0.78	22.78	18.72	14.18	0.536	1.204	1.020	0.0061	0.0305	0.0219	1.22	1.61	1.32
		0.95	42.30	39.36	36.68	1.828	1.261	1.607	0.0703	0.0334	0.0543	1.07	1.15	1.07
		1.04	53.10	42.06	46.30	0.341	0.013	0.901	0.0025	0.0000	0.0171	1.26	1.15	0.91
		2.14	92.08	70.97	92.70	2.402	0.277	3.185	0.1214	0.0016	0.2134	1.30	0.99	0.77
		3.03	100.01	83.94	103.15	3.272	0.080	3.908	0.2252	0.0001	0.3213	1.19	0.97	0.81
		7.00	128.93	95.90	110.04	0.944	5.946	9.051	0.0187	0.7438	1.7231	1.34	1.17	0.87
		14.14	149.94	118.05	138.13	2.477	8.937	9.171	0.1291	1.6801	1.7693	1.27	1.09	0.85
		29.15	156.81	127.37	113.27	6.461	0.610	8.577	0.8783	0.0078	1.5476	1.23	1.38	1.12
	Site cured	1.02	1.92	1.52	3.41	0.112	0.042	0.302	0.0003	0.0000	0.0019	1.27	0.56	0.44
		2.12	21.17	16.87	25.35	1.368	0.006	1.523	0.0394	0.0000	0.0488	1.25	0.84	0.67
		3.02	47.08	44.34	44.46	2.738	0.367	0.715	0.1578	0.0028	0.0108	1.06	1.06	1.00
		6.98	79.41	68.23	73.09	1.310	4.347	0.138	0.0361	0.3975	0.0004	1.16	1.09	0.93
		14.13	90.48	87.61	87.61	2.382	2.514	6.404	0.1194	0.1329	0.8626	1.03	1.03	1.00
		29.14	95.98	96.34	96.34	0.549	6.618	1.938	0.0063	0.9213	0.0790	1.00	1.00	1.00
Cor-Tuf	Lab cured	0.86	3.11	4.35	5.52	0.061	0.359	0.122	0.0001	0.0027	0.0003	0.714	0.562	0.79
		1.01	9.36	11.32	15.59	0.682	0.600	0.638	0.0098	0.0076	0.0086	0.826	0.600	0.73
		1.54	57.77	54.20	61.10	1.273	0.969	2.034	0.0341	0.0198	0.0870	1.066	0.945	0.89
		2.03	72.27	56.27	68.08	2.648	4.040	3.436	0.1475	0.3433	0.2484	1.284	1.062	0.83
		3.13	86.08	62.40	81.47	3.892	1.072	0.034	0.3186	0.0242	0.0000	1.379	1.057	0.77
		7.18	106.07	90.13	103.31	2.954	6.609	5.122	0.1836	0.9187	0.5518	1.177	1.027	0.87
		14.03	136.21	112.75	129.57	1.601	2.526	2.236	0.0539	0.1343	0.1052	1.208	1.051	0.87
		28.16	141.50	118.36	143.11	5.679	5.173	3.175	0.6784	0.5630	0.2120	1.196	0.989	0.83
	Si te	3.04	8.21	5.39	9.64	0.092	0.574	0.267	0.0002	0.0069	0.0015	1.523	0.852	0.56

		8.17	52.99	40.04	36.23	1.523	1.189	1.523	0.0488	0.0298	0.0488	1.323	1.463	1.11
		28.14	82.37	67.53	58.87	2.311	1.875	2.310	0.1124	0.0739	0.1123	1.220	1.399	1.15

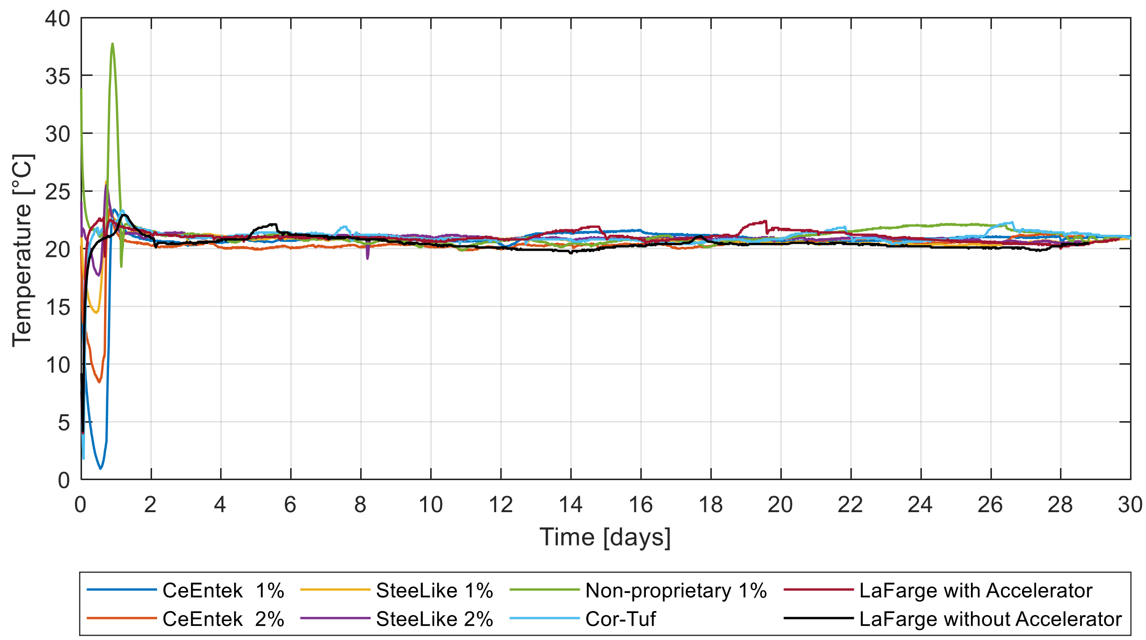

Figure 6. Temperature history of the lab cured 3" ×6" cylinders specimens

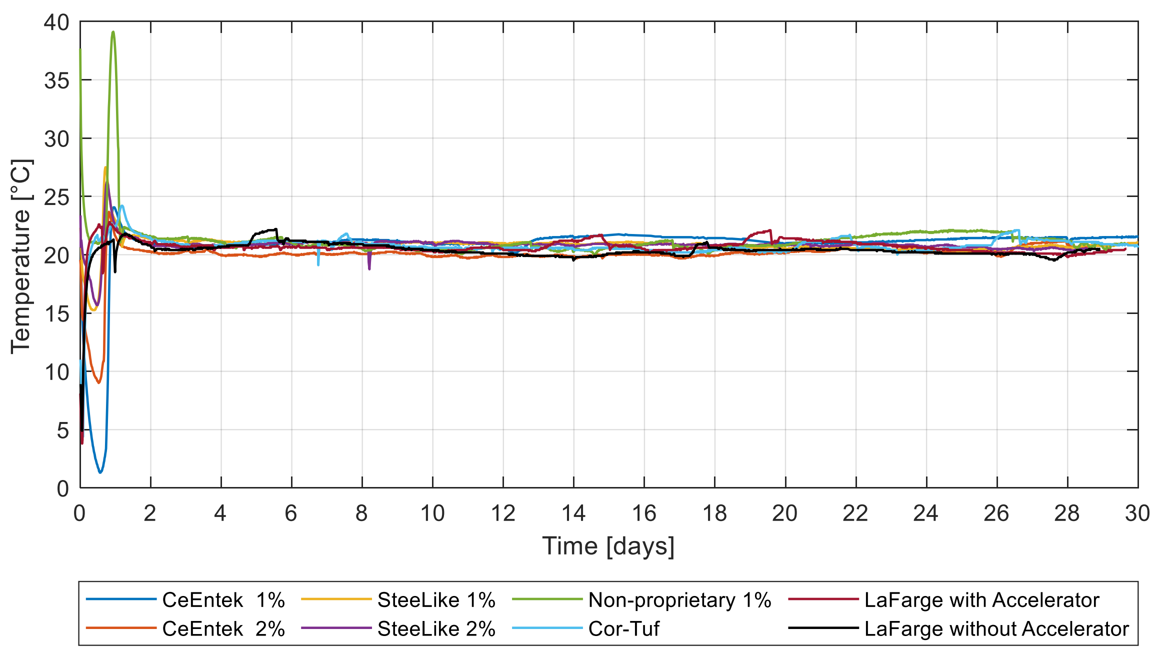

Figure 7. Temperature history of the lab cured 4" ×4"×4" cubes specimens

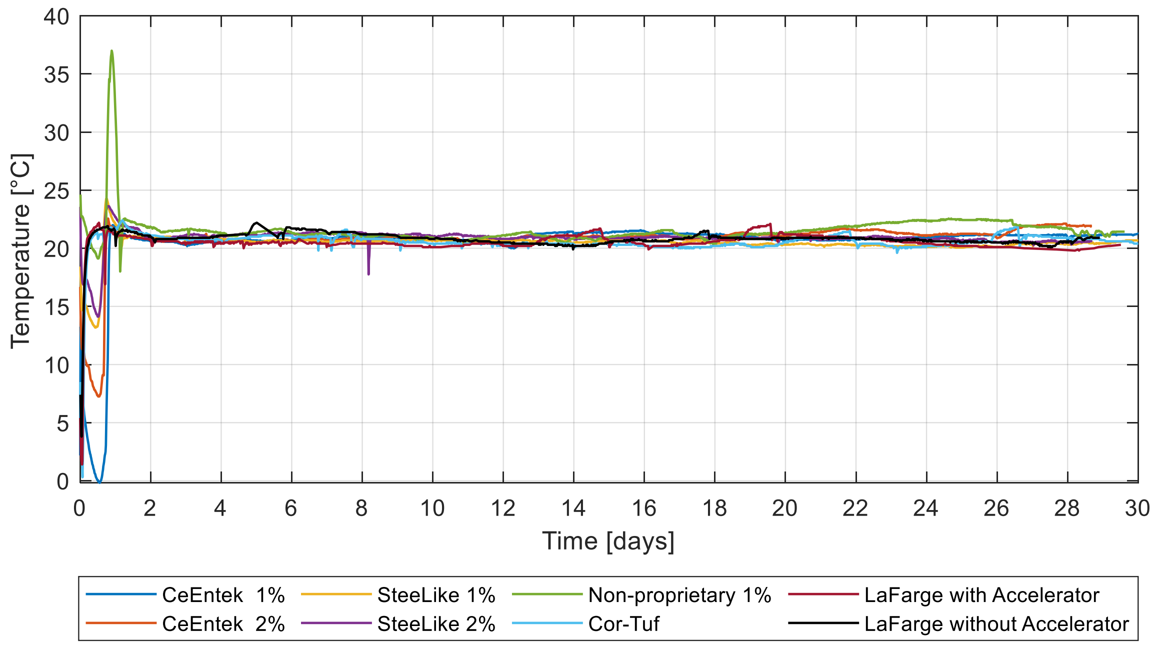

Figure 8. Temperature history of the lab cured 2" ×2"×2" cubes specimens

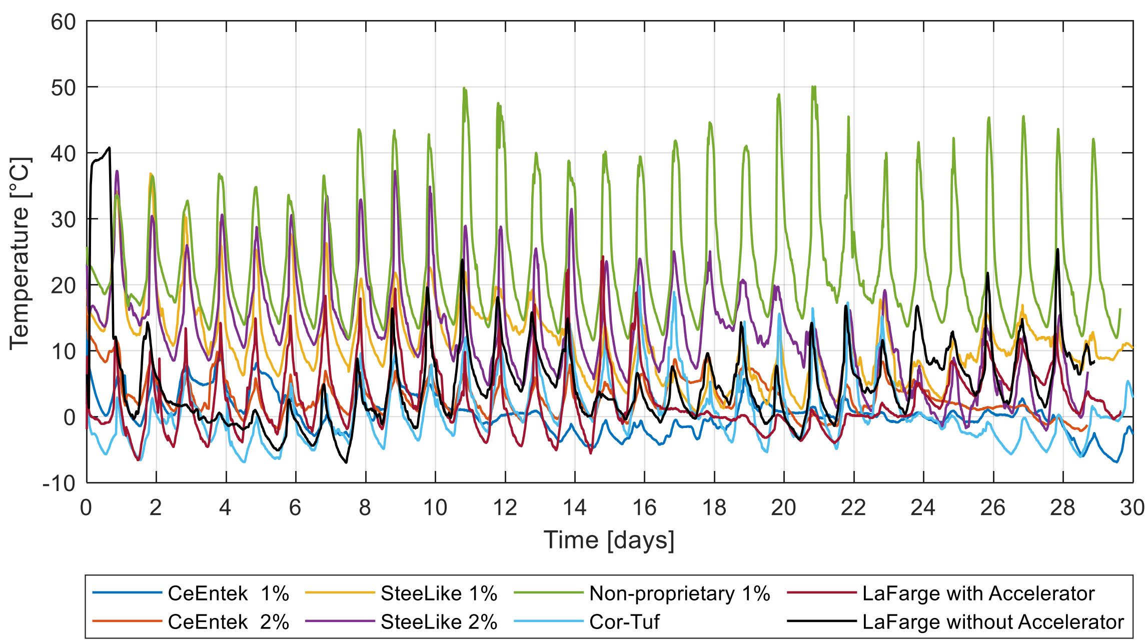

Figure 9. Temperature history of the site cured 3" ×6" cylinders specimens

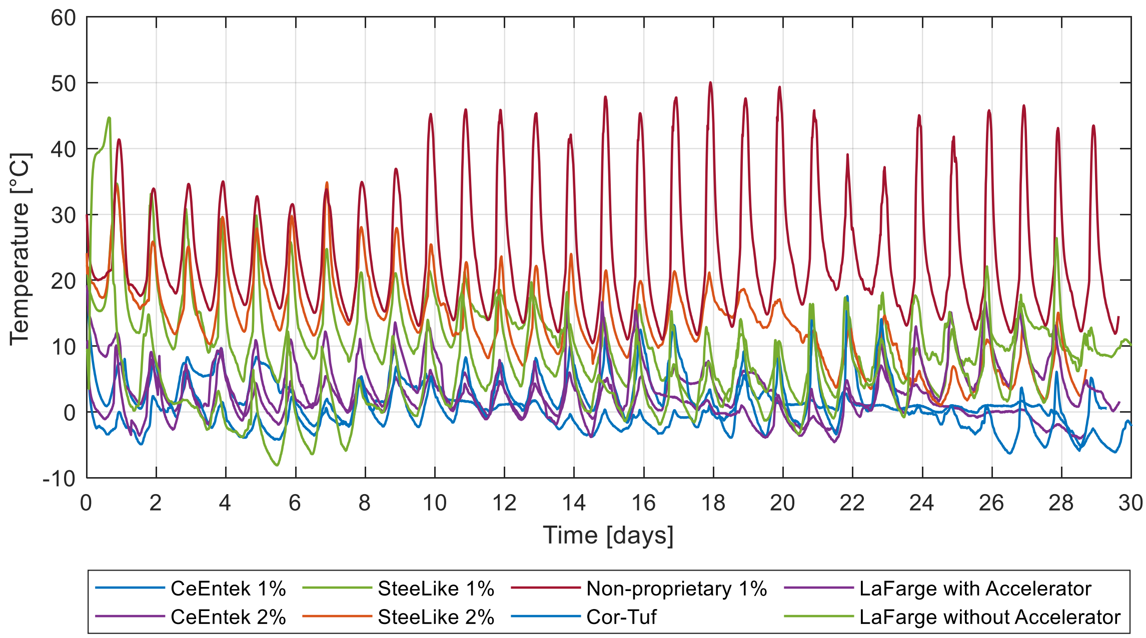

Figure 10. Temperature history of the site cured 4" ×4"×4" cubes specimens

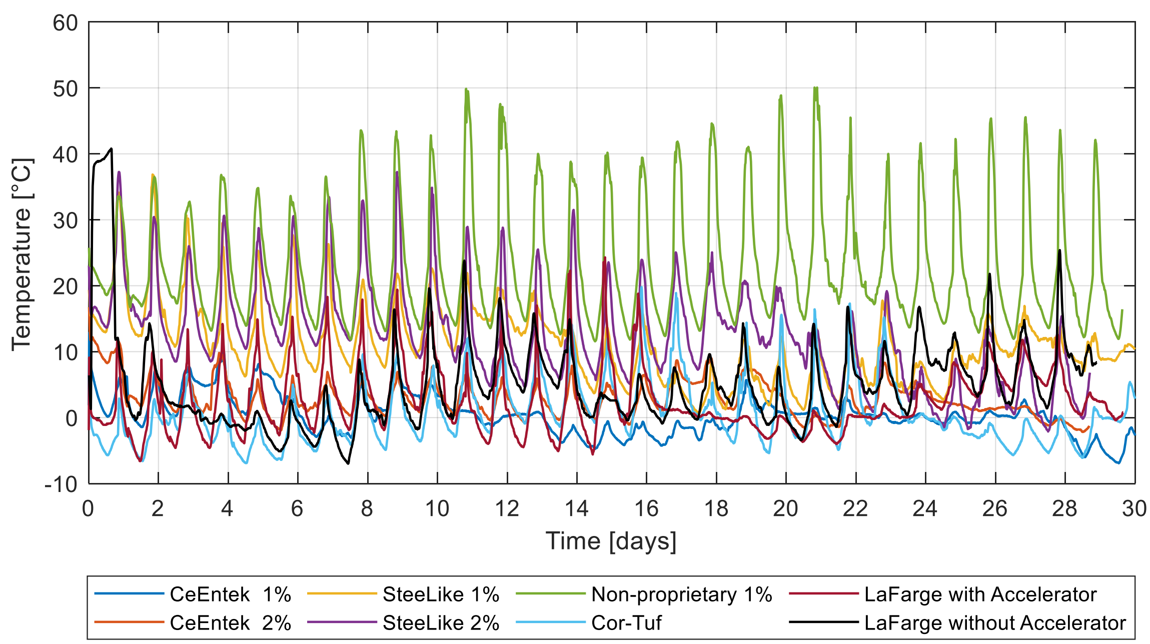

Figure 11. Temperature history of the site cured 2" ×2"×2" cubes specimens

In this study, the lab- and site-cured 3" ×6" cylinders and 4" ×4" cubes specimens were taken from five UHPC mixtures: ABC non-proprietary 1% fibers, CeEntek 1% and 2% fibers, SteeLike 1%, and 2% fibers. The lab-cured specimens were tested at nine ages: 0.6, 0.75, 1, 2, 3, 7, 14, and 28 days and the site-cured specimens were tested at four ages: 0.6, 1, 2, and 3 days. The 0.6-day specimen is the same for the lab cured and the site cured because, at this age, the molds were stripped off, and the specimens were divided and placed in their curing group whether it's lab cured or site cured. Using the nine lab-breaking points for each UHPC mixture, the parametric study was performed to develop multiple strength-maturity relationships that can estimate the compressive strengths of the site-cured specimens based on their maturity indexes. Next, the differences in the form of percentage error were calculated between the estimated compressive strength values and the measured compressive strength values, as demonstrated in Figure *5*. Finally, the resulted percentage error values were used to judge the different variables used in this parametric study. The variables used in this parametric study were the chosen five lab breaking points out of nine, the number and the ages of breaking points, and finally, different maturity constants. The goals of this parametric study were:

- To investigate the applicability of using the maturity method for UHPC using the ASTM C1074 recommended lab breaking points number and ages and the recommended maturity constants,
- To come up with the best age breaking point choices(configurations) and maturity constants that reduce the errors of the estimated compressive strengths to 10%,

- To investigate the influence of cylinders and cubes on the accuracy of the predictions,
- To investigate the influence of different maturity functions, i.e., NS and EQ, on the accuracy of the predictions,
- And finally, to provide engineers and researchers with thorough guidelines on using the maturity method for UHPC to estimate the compressive strength with minimal errors.

2.3.1. The Influence of the ASTM C1074 recommended configuration and maturity constants on the accuracy of the strength estimation.

In this section, the strength-maturity relationships were established using the ASTM recommended configuration and maturity constants for each UHPC mixture. The specimens used for establishing the relationships were lab-cured 3" ×6" cylinders and 4" ×4" cubes specimens. For each mixture, four strength-maturity relationships were established:

- A relationship for 3" ×6" cylinders using the NS function,
- A relationship for 3" ×6" cylinders using the EQ function,
- A relationship for 4" ×4" cubes using the NS function,
- And a relationship for 4" ×4" cubes using the EQ function.

The ages of the lab-breaking points of the lab 3" ×6" cylinders and 4" ×4" cubes specimens used to establish the strength-maturity relationships were 1, 3, 7, 14, and 28 days. The chosen lab-breaking points ages are the configuration that the ASTM recommends. Using this configuration, the strength-maturity relationships were established. The ASTM recommended constants: 0˚C for datum temperature and 41.55 KJ/mol for the activation energy. To estimate the compressive strength of the site-cured 3" ×6" cylinders and 4" ×4" cubes specimens, the measured site maturity indexes values were used in the developed equations to get the predicted site compressive strengths. The compressive strength of the site cured 3" ×6" cylinders and 4" ×4" cubes specimens were measured by breaking them at 14-hours, 1, 2, and 3 days. The difference between the site-measured and -predicted compressive strengths inform of percentage errors was calculated and plotted with the breaking time as shown in Figure *12*. Figure *12*contains plots of the percentage error vs. site breaking age. The black horizontal solid line indicated the 10% error tolerance that the ASTM states. Moreover, the percentage error is calculated by taking the difference between the predicted site strengths from the established strength maturity relationships and the measured site strength from axially testing the site cylinders and -cubes specimens.

As shown in Figure *12*, the two-and three-day errors were less than 10% when using the EQ maturity functions on the 3x6 specimens. And for the NS function using the cylinders, the two-and three-day errors were less than 10% for all mixtures except for CeEntek 1%, which was less than 20%. Similarly, the two-and three-day errors for the 4x4 specimens using the EQ function were relatively lower than the NS function, but both were below the 20% error. On the other hand, the 14-hours error for both cylinders and cubes using NS and EQ functions was higher than 10%. However, the 4" ×4" cubes showed less errors compared with the 3" ×6" cylinders which exceeded 100% and were cut from the plot. Also, the average error for both specimen shapes and maturity function the one-day points exceeded 10%.

To sum, it is observed that the cubes are superior over the cylinders at ages less than one-day. The reason might be that the specimen preparation of cutting and grinding performed on the cylinders, specifically for the specimens that were tested at ages less than one-day, may have affected the strength of the cylinders and thus negatively affected the results. The cylinders at that time might not be strong enough for such operations; however, for one day strength and later, the cylinders might be strong enough not to be affected by the cutting and the grinding operations. Furthermore, there was no significant difference between the cylinders and cubes at later ages of two- and three days. Moreover, it is observed that there was no significant difference between NS and EQ maturity functions which makes no method superior over the other. Finally, based on the observation that the ASTM configuration led to less than 10% errors for days two and three but high errors for one day and even higher for less than one-day, such observation suggests that the ASTM recommended age testing configuration is not suitable for both one-day strength prediction and less. Thus, it is possible to hypothesize that there are other age testing configurations that might lead to better prediction for one-day strength and less. Therefore, since there may be a relation between the age testing configuration and the targeted strength prediction age, we will divide the ages in this thesis into categories, a category for configurations that leads to estimating the strengths of ages less than one day, similarly, a category for one-day strength estimation and a category for the two-and three-days strength estimations.

On the other hand, the discrepancy of the error among the strength ages might be because of the maturity constant that is recommended by the ASTM that is believed to not be valid for UHPC, and there might be other maturity constants that will lead to better prediction for all ages and all UHPC mixtures.

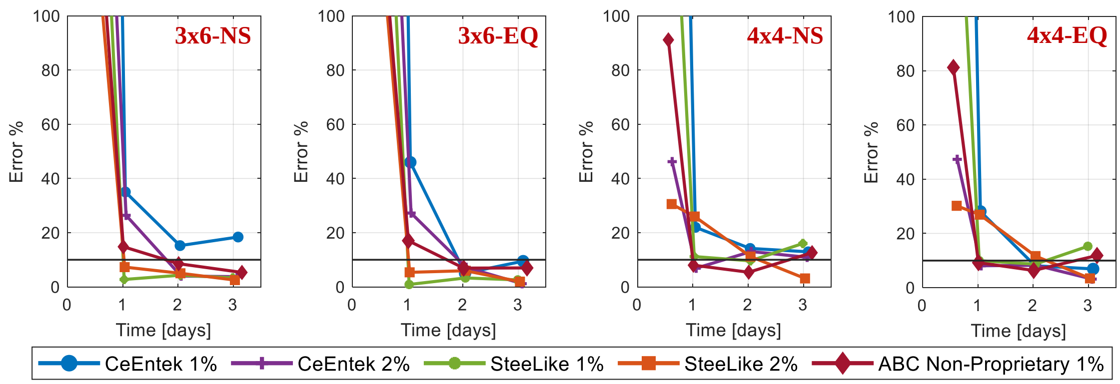

Figure 12. percentage error vs. age of the difference between the predicted and measured site strength when using the ASTM age configuration for both specimens' shapes and maturity functions

The two previous hypotheses are studied in the following sections to develop better age testing configuration choices and determine maturity constants that enhance strength predictions. Therefore, the following sections will explore different strength-maturity configurations and study the influence of the different maturity constants on strength prediction.

2.3.2. The effect of using different configurations established using ASTM recommended maturity constants on the accuracy of the predictions.

In this section, different five-breaking points configurations were picked from nine-lab breaking points to establish different strength-maturity relationships. Although the ASTM configuration was not selected, the ASTM recommended maturity constants were still used to develop the relationships. The influence of these different configurations on the accuracy of the strength estimation of five UHPC mixtures was investigated. Table 1 shows the configurations that were used. The colored highlighted cells for each configuration in Table 1 indicate the chosen five points for each configuration. For instance, in configuration 1 in Table 6, the orange color highlighted cells are 0.6, 0.7, 0.8, 3, and 28 days which indicates that these are the five lab breaking points of configuration 1 that were used along with their maturity index values to develop the strength-maturity relationship. Then, using the site specimens' maturity index values as maturity index input in this relationship, the compressive strength values of the site specimens were predicted. Finally, the difference between the predicted and the measured strengths was calculated inform of percentage error.

Configuration 1 in Table 6 is a randomly picked five-points used to develop the

strength-maturity relationship for each UHPC mixture. It is shown in Figure *13* that most of the error percentages points were higher than 10%. Since we couldn't manually pick the best five-point configuration that would lead to minimum error, a MATLAB program was written to loop through the five UHPC mixtures' temperature and compressive strength results data of both the lab and site specimens. Then for each mixture, maturity function, and specimen shape, the maturity index tables were developed using the ASTM recommended maturity constants. Next, the program will loop through all nine lab breaking points and pick all possible five-point configurations to get the best configurations with less errors. Finally, the resulted configurations for each age category from this iteration search method(ISM) were filtered based on the minimum errors values and presented in Table 6. Although the ISM objective was to search for configurations that lead to site strength predictions errors of less than 10% for all ages, however, it was not possible to find a configuration that limits the errors to 10% for all ages; what was possible that each age has a specific pattern of configurations that will reduce the error. Such observations strengthen the use of age categories.

Using ISM, a pattern of configurations was observed for each age category to reduce the strength estimation errors, as shown in Table 6, where configurations are displayed for each age. It is observed that a pattern needs to be followed to predict the compressive strength for each age. For instance, to estimate the strength of the 14-hours (0.6-day), the lab breaking points configuration to develop the strength maturity relationship need to be taken around the 0.6-day as shown in ISM-1. It was impossible to break the specimen before that age because it had not reached the final setting. Similarly, for the one-day and two-and-three days categories, the points are recommended to be taken around those ages to obtain strength estimations with minimal errors. No configurations were found that led to accurate predictions for all the 14-hours, one, two- and three-day points combined; however, the presented configurations in Table 6 were the best configurations that will lead to minimal errors.

Figure *14* shows plots of the error percentages with the breaking time of different strength maturity relationships developed using the ISM configurations presented in Table 6. Not all the configurations shown in Table 6 were plotted; instead, one configuration per category was selected and plotted. The plots show the error percentages calculated from the difference between the actual measured compressive strength for the site specimens and predicted strength using the strength maturity relationship in the configuration in question. The strength maturity relationship of each configuration was developed for all maturity functions(NS and EQ) and specimen shapes(3" ×6" and 4" ×4").

Table 6. Different configurations using the ASTM recommended maturity constants

Ages, days/ Configurations	0.6	0.7	0.8	1	2	3	7	14	28
Randomly picked point configuration									
Configuration 1	■	■	■			■			■
Best configurations for 0.6-day strength predictions									
ISM-1	■	■	■	■	■				
Best configurations for one-day strength prediction									
ISM-2			■	■	■	■	■		
ISM-3			■	■		■	■	■	
ISM-4			■		■	■		■	■
ISM-5			■	■			■	■	■
Best configurations for two- and three--days strength predictions									
ISM-6				■	■	■		■	■
ISM-7				■	■	■	■	■	
ISM-8				■	■	■	■		■
ISM-9				■	■		■	■	■
Best configurations for one-, two-, and three--days strength predictions									
ISM-10			■	■	■	■			■
ISM-11			■	■	■			■	■

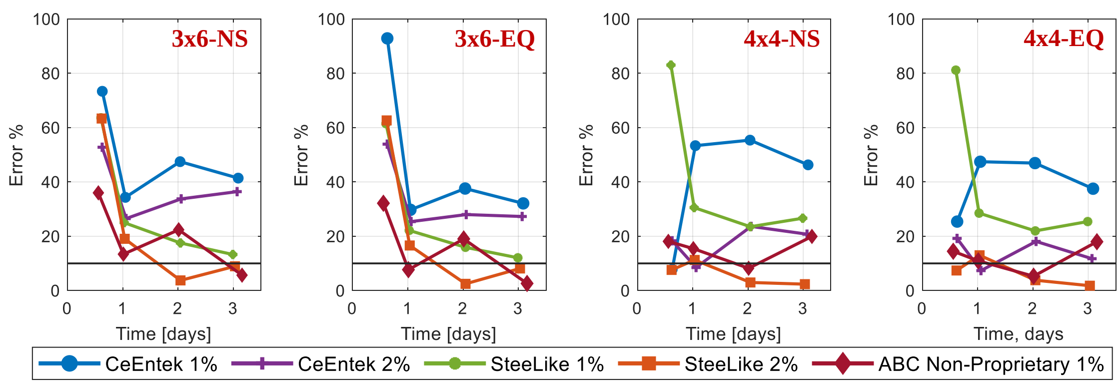

Figure 13. percentage error vs. age of the difference between the predicted and measured site strength when using random ages configuration for both specimens' shapes and maturity functions

ISM-1 in Figure *14* had the lowest percentage errors for the 14-hours age compared with the other ISMs in Figure *14* and the ASTM configuration in Figure *12*. Also, the percentage errors for the 4" ×4" cubes were lower than the 3" ×6" cylinders. The reason for the cubes being better was discussed in the previous section. In addition, the 4" ×4" cubes using the EQ function showed lower percentage errors than the NS function. On the other hand, there is no significant difference between the specimen shapes and maturity functions for both the one-day strength presented in ISM-2 and the two-and three-days strength presented in ISM-6. Furthermore, the cylinders showed similar results to the cubes because they were strong enough not to have the cutting and grinding operations affecting them. Finally, ISM-10 is the best configuration, leading to less errors for all ages combined. Yet, the errors for all points combined cannot be limited to 10%, which also strengthens the age categories concept.

In conclusion, it is possible using the ASTM recommended maturity constants to estimate the compressive strength with a limited error of 10% if the configurations adopted to develop strength maturity relationships align with the ISM configurations shown in Table 6. Moreover, this section showed the configurations that limit the errors to 10% for the 14-hours, one-day, and two-and three-days strength categories. However, for all ages combined is still challenging to reduce their errors. As a trial to solve this challenge, the influence of increasing the number of breaking points of the configurations from five to six points on the compressive strength estimations will be investigated in the next section.

2.3.3. The influence of choosing six points configurations with the ASTM C1074 recommended maturity constants on the accuracy of the predictions.

This section investigates the influence of adding an extra breaking point in the strength maturity configurations on the accuracy of the compressive strength predictions. The maturity functions used were the NS and EQ maturity functions, and the maturity constants adopted in this section were the ASTM recommended values. In addition, the specimens used were both the 3" ×6" cylinders and 4" ×4" cubes. So, instead of randomly picking six breaking points, ISM was used to iterate through all possible six points out of the total available nine points and report the configuration. Then, the configurations were filtered by the lowest percentage errors and are presented in Table 7.

The names of the ISM configurations presented in Table 7 and Figure *15* end with (*) to differentiate between them and the five-point ISM configurations presented in Table 6. One ISM configuration per age category was plotted in Figure *15*. Figure *15* shows different ISM configurations, and for each configuration, the percentage errors were plotted with the breaking age for NS and EQ maturity functions and 3" ×6" cylinders and 4" ×4" cubes specimens. From Figure *15*, it can be observed that the percentages errors of the plotted ISMs are similar to the plotted ISMs in Figure *14*. Therefore, it can be concluded that the ISM's six-point configurations are as good as the five-points, and no significant differences were found. Both methods would lead to low percentages errors if the configurations followed to estimate the compressive strength were taken from Table 6 and Table 7.

It is worth mentioning that the authors performed a similar study on the effect of adding an extra point on the accuracy of the predictions[38]. However, the methodology of the judgment was different. The authors compared establishing the strength maturity equation using five and six lab points out of the nine lab points, and the accuracy of the equation was tested based on the other lab points that were not used to form the equation. It was found that using six points is better than using five points in case the point to be predicted is lab point(strength) which was subjected to a similar curing regime (lab curing room) as the points where the equation was established in the first place. However, next section, the influence of changing the maturity constants on the strength estimation will be investigated to check whether changing the constants might lead to an enhanced strength estimation for each age specifically and for all ages combined generally.

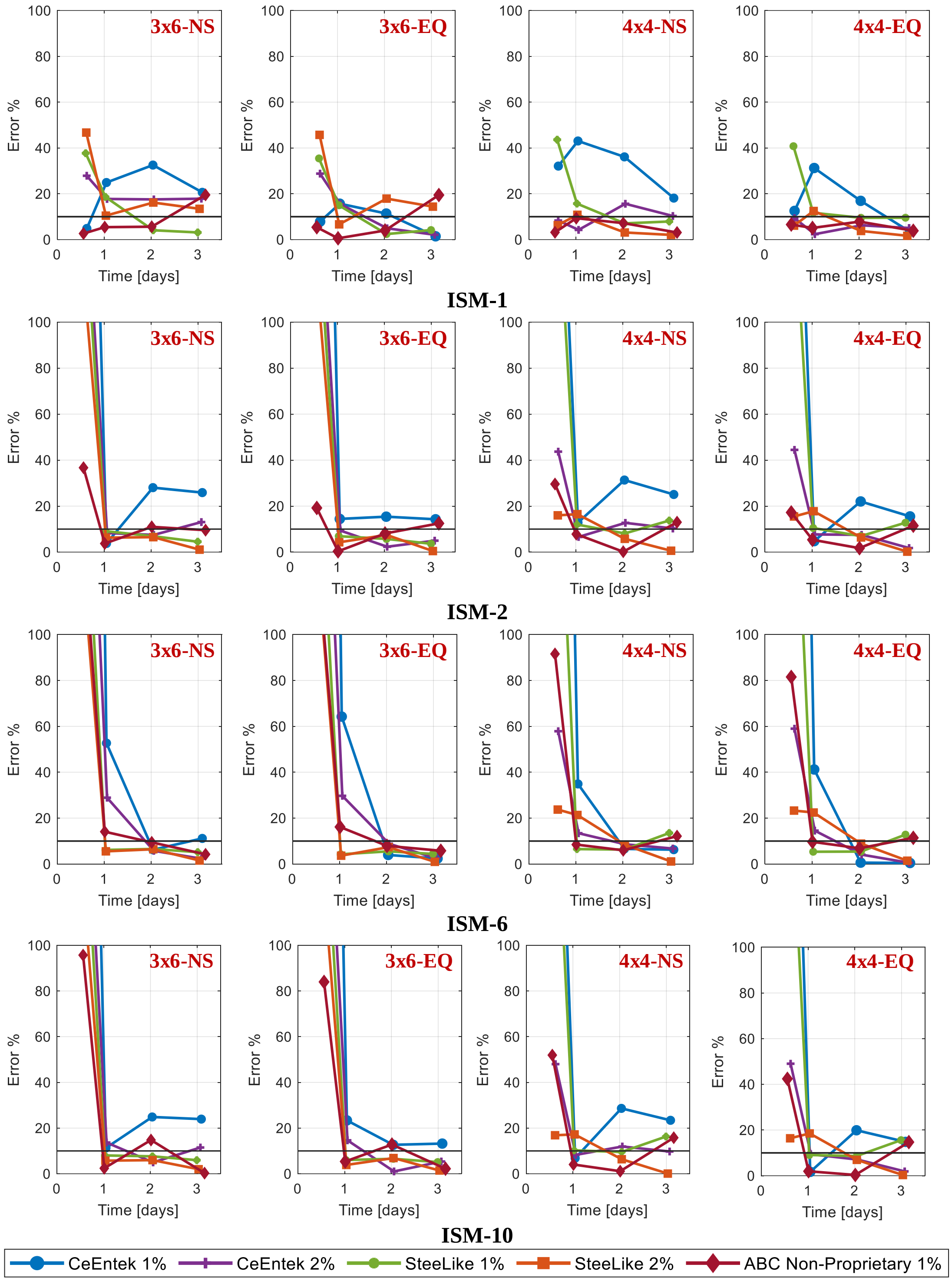

Figure 14. The error percentages vs. breaking time for different ISM strength-maturity relationships

Table 7. Different ISM configurations using the ASTM recommended maturity constants

Ages, days/ Configurations	0.6		0.7	0.8	1	2	3	7	14	28
	Best configurations for 0.6-day strength predictions									
ISM-1*										
	Best configurations for one-day strength prediction									
ISM-2*										
ISM-3*										
	Best configurations for two- and three--days strength predictions									
ISM-4*										
	Best configurations for one-, two-, and three--days strength predictions									
ISM-5*										
ISM-6*										
ISM-7*										
ISM-8*										

2.3.4. The influence of the different maturity constants on the compressive strength estimation

This section aims to study a range of maturity constants to enhance strength predictions. Instead of obtaining the maturity constants experimentally, the maturity constants for NS and EQ functions were treated as regression coefficients in the maturity equations. A similar study was performed before on the maturity constants for conventional concrete, where the maturity constants were treated as regression coefficients instead of experimentally determining them[39]. For datum temperature, the selected range of values was: -15, -10, -5, -2, 0, 2, 5, and 10°C, and for Q, which is the activation energy divided by the gas constant, the selected range was: 3000, 5000, 7000, 9000, 13000 and 17000 K. Each constant was used to obtain the maturity indexes for NS and EQ maturity functions and 3" ×6" cylinders and 4" ×4" cubes specimens for all the five UHPC mixtures. Then by accompanying a specific five-point configuration of lab maturity indexes with the lab breaking points using the logarithmic equation, the strength maturity relationships were developed.

Furthermore, the five breaking points configurations used to develop these relationships were: ISM 1, 2, 6, and 7 from Table 6, along with the ASTM recommended configuration. Following that, using the temperature histories of the site specimens as an input in the developed strength maturity relationship, the site-specimen strengths were predicted. Next, the difference between the site's predicted strength and the measured strength was calculated in the form of percentage error. Then, the average error percentages of the five UHPC mixtures for each maturity constant was calculated and plotted.

The selected range of maturity constants was applied in the strength maturity equations developed using the ASTM configuration, and the percentage errors were calculated and plotted in Figure *16* and Figure *17*. Figure *16* is for the NS maturity functions, and Figure *17* is for the EQ maturity function. Both Figure *16* and Figure *17* show that no single constant could achieve a percentage error of 10% or lower for the strength predictions at all ages combined when using the ASTM configuration. However, it can be observed that the maturity constants are not constants; instead, they are variables, and these variables depend on the age category. For instance, for both 3" ×6" cylinders and 4" ×4" cubes:

- To achieve a percentage error of 10%, the DT in the NS maturity function could be taken equal to 5˚C for the one-day strength estimation, while for the two and three-days strength estimation, the DT could be taken equal to any value in a range between -2˚C and -15 ˚C.

- To achieve a percentage error of 15%, which is the lowest possible for one-day strength using the EQ maturity function, The Q could be taken equal to any value in a range between 9000 to 13000 K for the one-day strength estimation, while to achieve a percentage error of 10% for the two and three-days strength estimation, the Q could be taken equals to any value in a range between 3000 to 9000 K.

Figure *18* and Figure *19* show the average percentage errors of the strength maturity relationships developed using the ISM configurations that are presented in Table 8. A range of maturity constants was used in the maturity equations. The maturity functions used were the NS and EQ functions. Based on Figure *18* and Figure *19*, the maturity constants that led to minimal errors for both maturity functions and specimen shapes are summarized in Table 8. This section aimed to investigate the maturity constants used for the UHPC. The ASTM configuration could be used to achieve better strength predictions if the maturity constant were variable, and the variability depends on the age when the predictions are required. However, it is not practical to have dynamic values for maturity constants. Therefore, the ISM configurations targeted for specific ages strength prediction showed a fixed maturity constant. Table 8 shows the maturity constants that could be used for the different ISM configurations to get a strength prediction of an error of about 10% or less, except for the strength estimations of ages less than one-day, which had an error percentage of about 15% to 18%. The common DT values found for all ISMs for both specimen's shapes were -5 to -2˚C. On the other hand, the common Q value found for all ISMs for both specimen shapes was 5000 K.

2.3.5. The Piecewise linear method(PWLM): New method for predicting the UHPC compressive strength

Based on the previous parametric study, the main two conclusions were:

1. To be able to predict the compressive strength of UHPC with minimal errors, the lab breaking points ages need to be close to the age of the required site predictions. In other words, if the site strength is required to be predicted at an early age, the ages of the lab breaking points should be early as well. However, due to the difference in temperature between the site and the lab, the early age of the site specimens might align with the late age of the lab specimen(maturity concept). Therefore, the lab breaking points and site breaking points will be addressed by the maturity index values instead of the ages.
2. The strength maturity relationship is sensitive to the maturity constants, especially the datum temperature that is used in the NS equation. However, the Q value used in the Arrhenius equation is less sensitive. In other words, a large range of Q was concluded to be valid for various UHPC mixtures, as shown in Table 3.

Table 8. Maturity Constant for different ISMs

Maturity constant / Configurations	t_0, ˚C		Q, K	
	3" ×6" cylinders	4" ×4" cubes	3" ×6" cylinders	4" ×4" cubes
ISM 1	-15 to 2		9000 to 13000	3000 to 9000
ISM 2	-5 to -2		3000 to 5000	
ISM 6	-15 to 2		3000 to 9000	
ISM 10	-5 to -2		5000 to 7000	

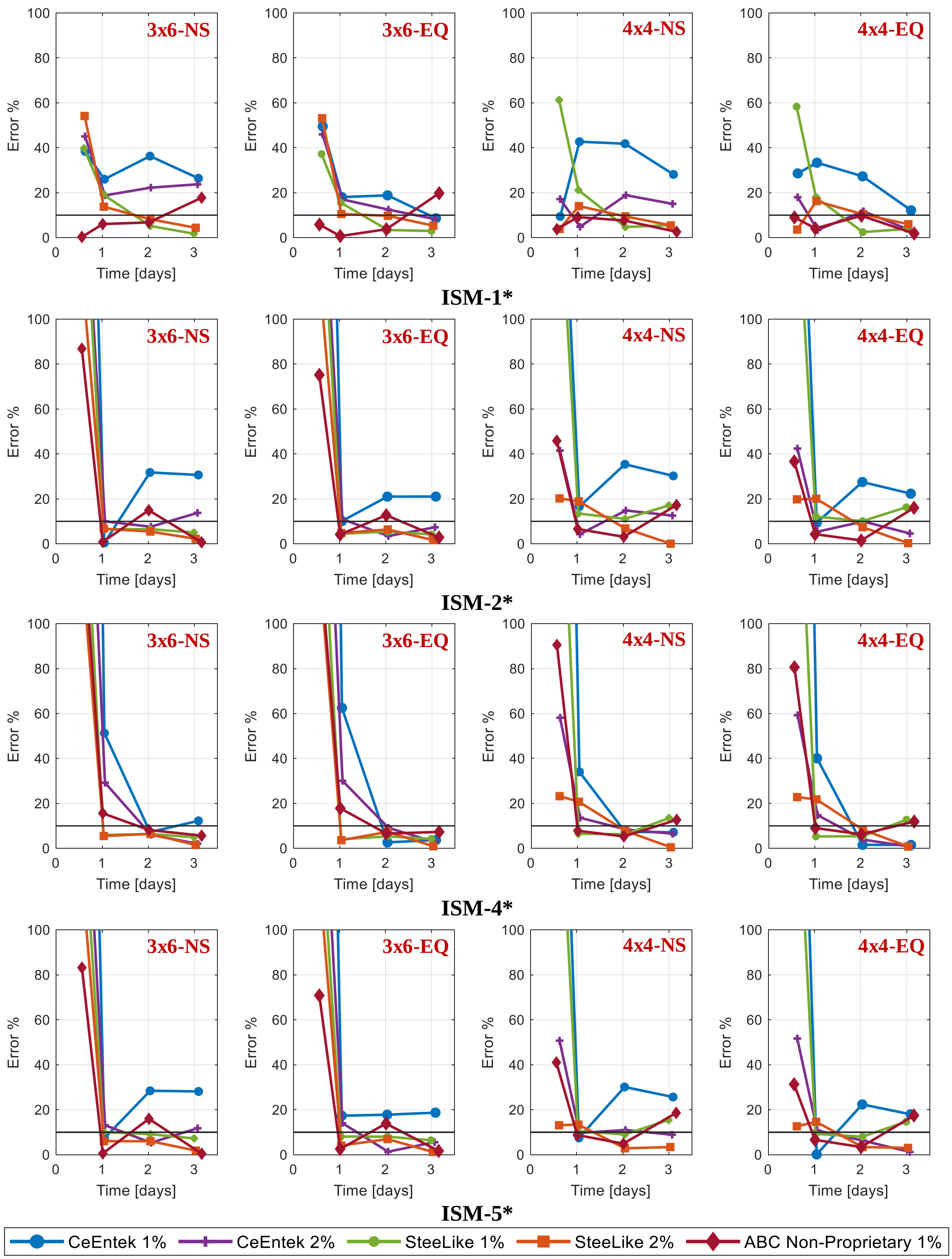

Figure 15. The error percentages vs. breaking time for six-points configurations that were developed using ISM

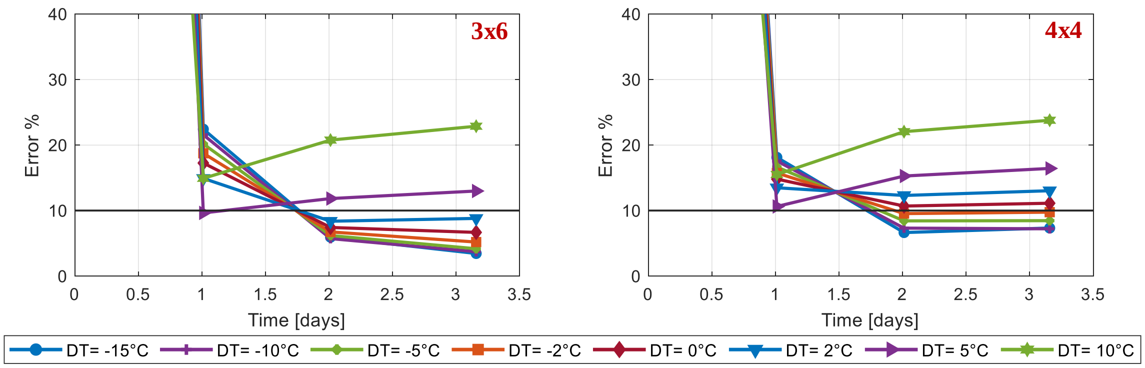

Figure 16. Average percentage error vs. breaking time for ASTM configuration strength maturity relationships of five UHPC mixtures developed using NS functions with a range of maturity constants for both 3" ×6" cylinders and 4" ×4" cubes

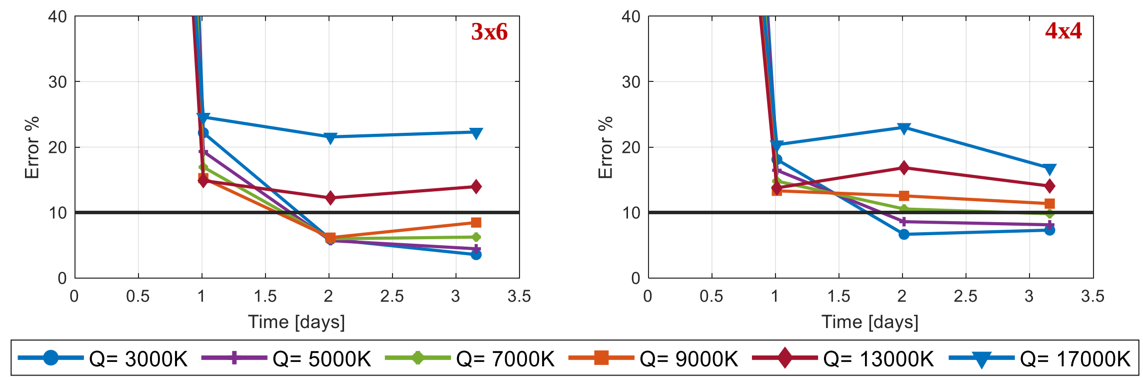

Figure 17. Average percentage error vs. breaking time for ASTM configuration strength maturity relationships of five UHPC mixtures developed using EQ functions with a range of maturity constants for both 3" ×6" cylinders and 4" ×4" cubes

Therefore, based on the mentioned two points, a new method PWLM is proposed to provide better strength predictions. The method is made for 3" ×6" cylinders using the Arrhenius maturity method. Moreover, the previous conclusions were based on the five UHPC mixtures. In this section, where the new method is proposed based on the five UHPPC mixtures, the additional three mixtures: Cor-tuf, and Lafarge, with and without the accelerator, will be used to validate the newly proposed method.

2.3.5.1. Developing the PWLM equation

To start with, as mentioned in point 1, the five UHPC mixtures showed that to predict the site compressive strength accurately, the maturity index values of the lab breaking points that are used in the development of the strength-maturity equation should be close to the maturity index values of the site specimens that need to be predicted. However, it is inaccurate to address the breaking points with age (i.e., break the lab specimen at days 1,2,3,7,14, and 28 days) because the site temperature and curing methods are different from the lab curing rooms.

Therefore, in this newly proposed method, maturity index values are addressed instead of the ages of the lab breaking points. However, to address the lab breaking points by maturity index values, the maturity constants need to be fixed because different maturity constants will lead to different maturity index values. Therefore, the maturity constant used in the newly proposed method is Q: the Arrhenius equation maturity constant. The Arrhenius is used in this method because it showed slightly better results than Nurse-Saul in the parametric study and because of the less sensitivity of its maturity constant Q. Moreover, the reference temperature is taken as 23˚C, and the Q value of the Arrhenius equation that will be fixed in this method equals 5000 K because it showed good predictions for different UHPC mixtures, as concluded in Table 8.

The findings of the previous parametric study gave an insight into the effect of lab breaking points' ages on the accuracy of the predictions. Therefore, the additional three UHPC mixtures are used to verify the previous conclusions and the newly proposed method. The strength maturity relationships of all the eight UHPC mixtures were plotted and showed a pattern of four slopes, as shown in Figure *20*. Figure *20* is a strength-maturity relationship of eight UHPC mixtures. The three added mixtures were with different curing conditions. It was observed that when developing the equation using points from different slopes or different age categories, high errors were reported. Thus, the previous sections concluded the ISM configurations to provide better strength predictions because they combined the lab breaking point ages that were close together in one category and thus one equation. This developed equation could give accurate results for certain ages but not a wide range of ages. Therefore, the development of the PWLM combines specific lab breaking points in one equation, and this equation is only valid for a particular range of maturity index values.

The PWLM is a developed ISM that instead of having one equation of the strength maturity relationship created using lab breaking points from different slopes to predict all the strength ages, it uses two lab breaking points from each slope. The PWLM divides the strength maturity curve into four zones based on the slopes, and for each zone, one equation is developed by using two points, and these two lab breaking points are the points that define the slope. The maturity curves for all eight tested UHPC mixtures follow the same pattern, where the slope of the maturity lines changes four times. The slopes of six mixtures out of eight change at maturity index values of approximately 18, 60, and 300 hours. Therefore, the maturity curves were divided into four zones. The zones of the Cor-Tuf and Lafarge with no accelerator were different from the other six mixtures due to the low ambient temperature, and no accelerator was added to both materials. However, the slopes did change four times but at different maturity index values. Thus, it is recommended to increase the ambient temperature for the lab specimens or add an accelerator. Although Lafarge with accelerator was cast at low temperature, the presence of the accelerator made the mixture follow the pattern.

So, the first step of this method is to capture where the slope changes by breaking five lab specimens at maturity index values equal to a point before 18 hours (i.e., 10 hours), then 18, 60, 300, and 600 hours. These maturity values could be determined by using maturity devices embedded in the specimens and will notify the engineer at the required equivalent ages. Next, these maturity devices need to be adjusted to Arrhenius function, and the reference temperature is adjusted to 23 ˚C, and Q is adjusted to 5000 K. After breaking the lab specimens at the mentioned maturity index values, four strength maturity equations are to be developed by the logarithmic function:

- Equitation using the two breaking points at 10 and 18 equivalent age hours
- Equitation using the two breaking points at 18 and 60 equivalent age hours
- Equitation using the two breaking points at 60 and 300 equivalent age hours
- Equitation using the two breaking points at 300 and 600 equivalent age hours

Based on the maturity index value of the site specimen, an equation out of the four could be used. For instance, if the equivalent age of the site specimen was equal to 50, that means to predict the strength, the second equation developed in the range of 18 to 60 hours will be used.

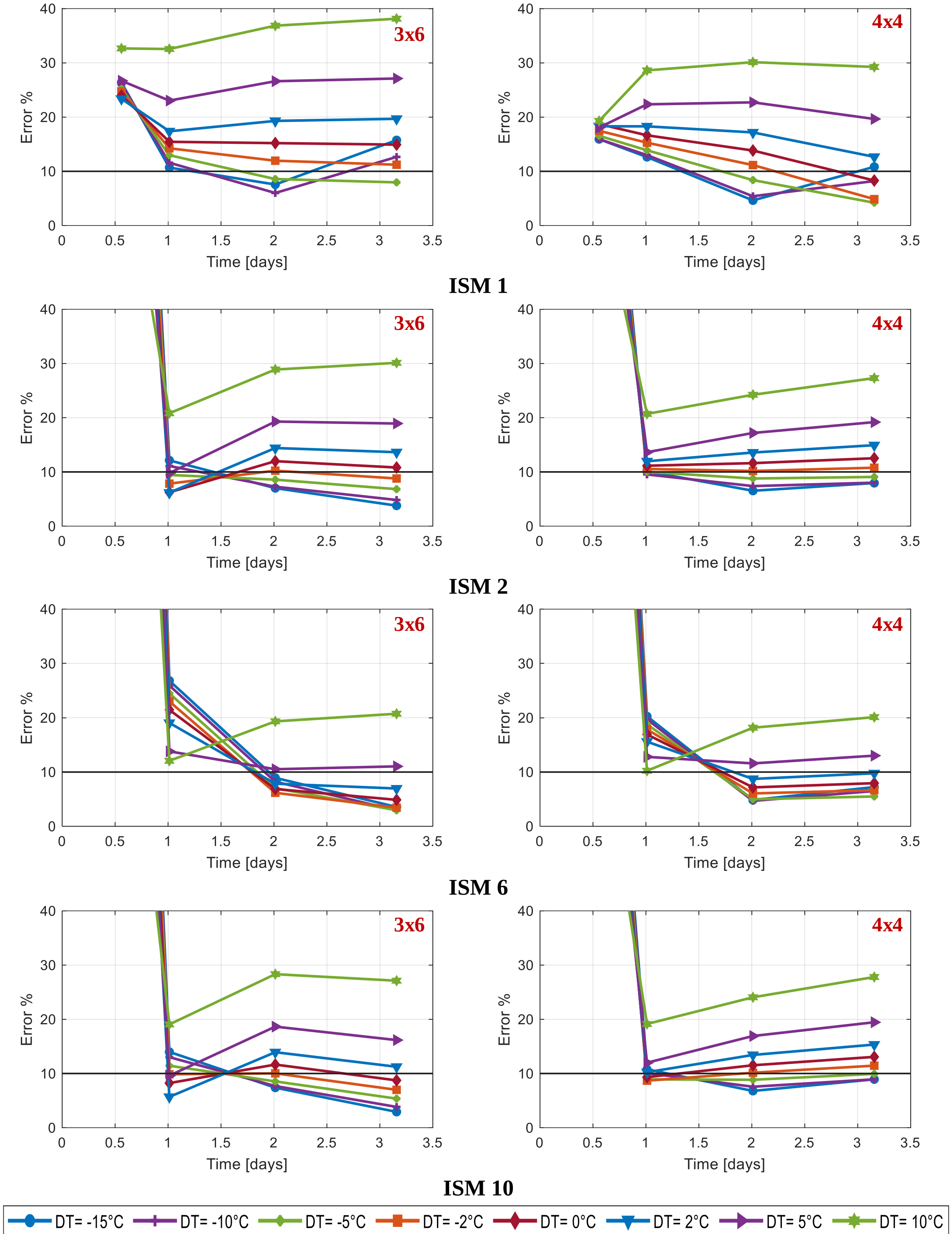

Figure 18. NS maturity function for both 3" ×6" cylinders and 4" ×4" cubes using different ISM configurations

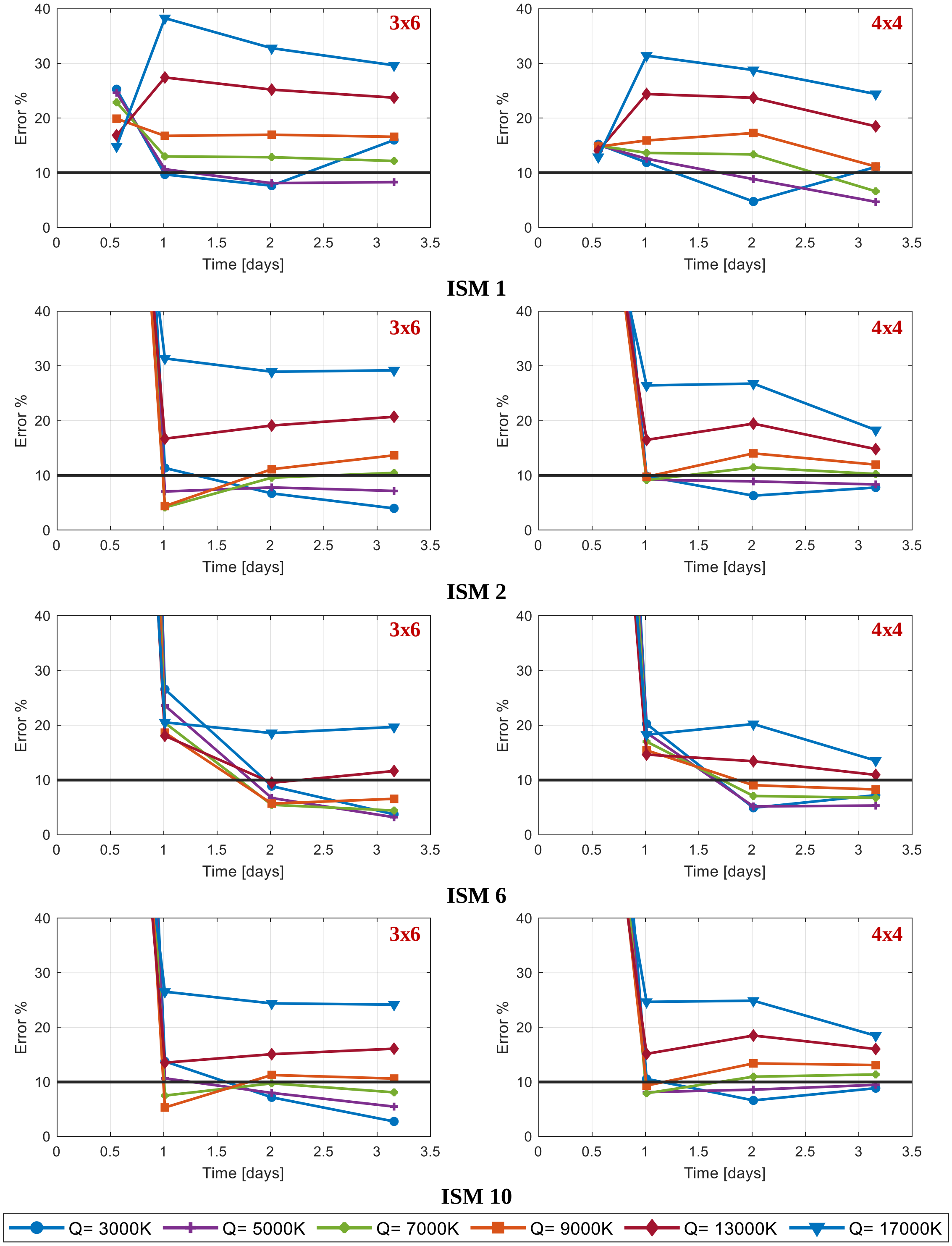

Figure 19. EQ maturity function for both 3" ×6" cylinders and 4" ×4" cubes using different ISM configurations

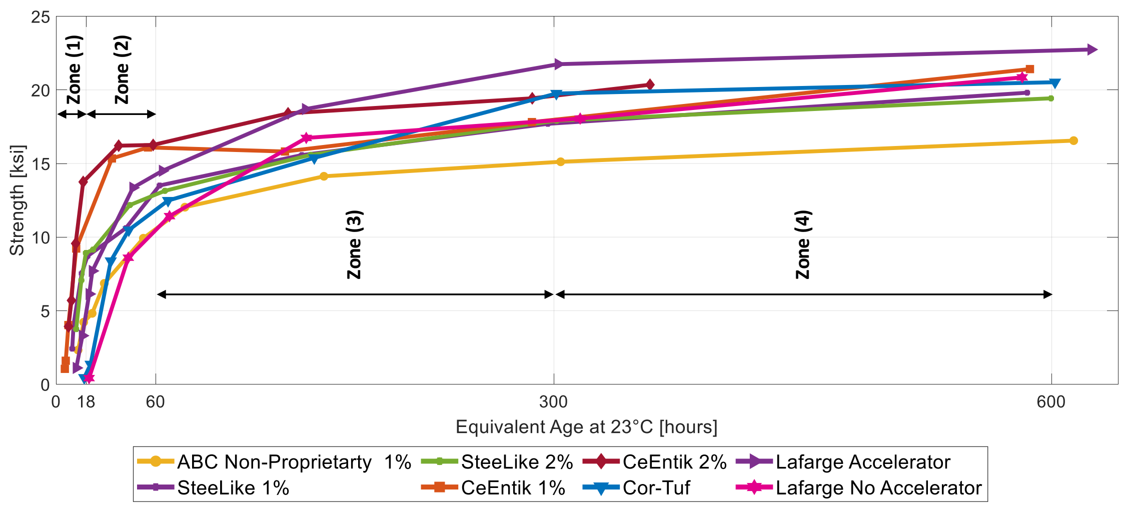

Figure 20. Strength-Maturity curves for the eight UHPC mixtures

2.3.5.2. Validating the PWLM with eight UHPC mixtures

Even though the ISM categories were proposed earlier in this paper to predict the strength at certain ages based on the age categories of the lab breaking points, the ISM has disadvantages. First, although the method itself showed better results than the ASTM in predicting the UHPC compressive strength, it is not practical for predicting multiple different ages because it requires many lab breaking points to cover early, middle, and late ages. Unless the engineer is consistent about the age predictions, that is when the method is practical. The second disadvantage is that the method is based on if the lab breaking points were at early ages, for example, then the method will be effective for the site specimens at an early age; such assumption is based on that the site temperature is similar to the lab temperature. But suppose the temperature at the site was higher than at the lab. In that case, the early ages strengths of the site specimens will be similar to the middle or late ages strengths of the lab specimens(maturity concept), and errors will be more significant. Therefore, the maturity index values were addressed instead of the ages to generalize the method more.

Figure *21* compares the application of the PWLM, ASTM, and ISM 1 methods on the eight UHPC mixtures. ISM 1 was developed initially for use at early ages. The ISM 1 was used for 3" ×6" cylinders using the Arrhenius maturity method. As shown in Figure *15*, ISM 1 developed using the earliest five lab breaking points showed better results than the ASTM at ages one day and less except for Lafarge without accelerator. However, as can be observed, at later ages, more than three days, the error was getting bigger as seen in ABC Non-proprietary 1%, Lafarge with an accelerator, Lafarge without the accelerator, and Cor-tuf. On the other hand, in the PWLM method, all early, middle, and later ages were better than the ASTM and ISM methods except for Lafarge without accelerator and Cor-Tuf. Finally, the terms to use the PWLM are either adding an accelerator to the mixture, increasing the lab specimens' early temperature if the ambient temperature is below 0˚C, or both.

Using the logarithmic function in the strength maturity relationships and applying modification is simpler than the linear hyperbolic or the parabolic hyperbolic functions. However, although the ASTM C1074 recommends the logarithmic function, it has shown that it is not a good representation for both low and high values of the maturity index[34]. This may be because of the curve fitting of the strength maturity points on multiple slopes. Therefore, the PWLM is introduced to fix the high and low maturity index issues by using the piecewise linear method. Furthermore, since this paper focuses more on the early maturity index values, thus PWLM is effective not only for the low/early maturity index values but also for late/high maturity index values.

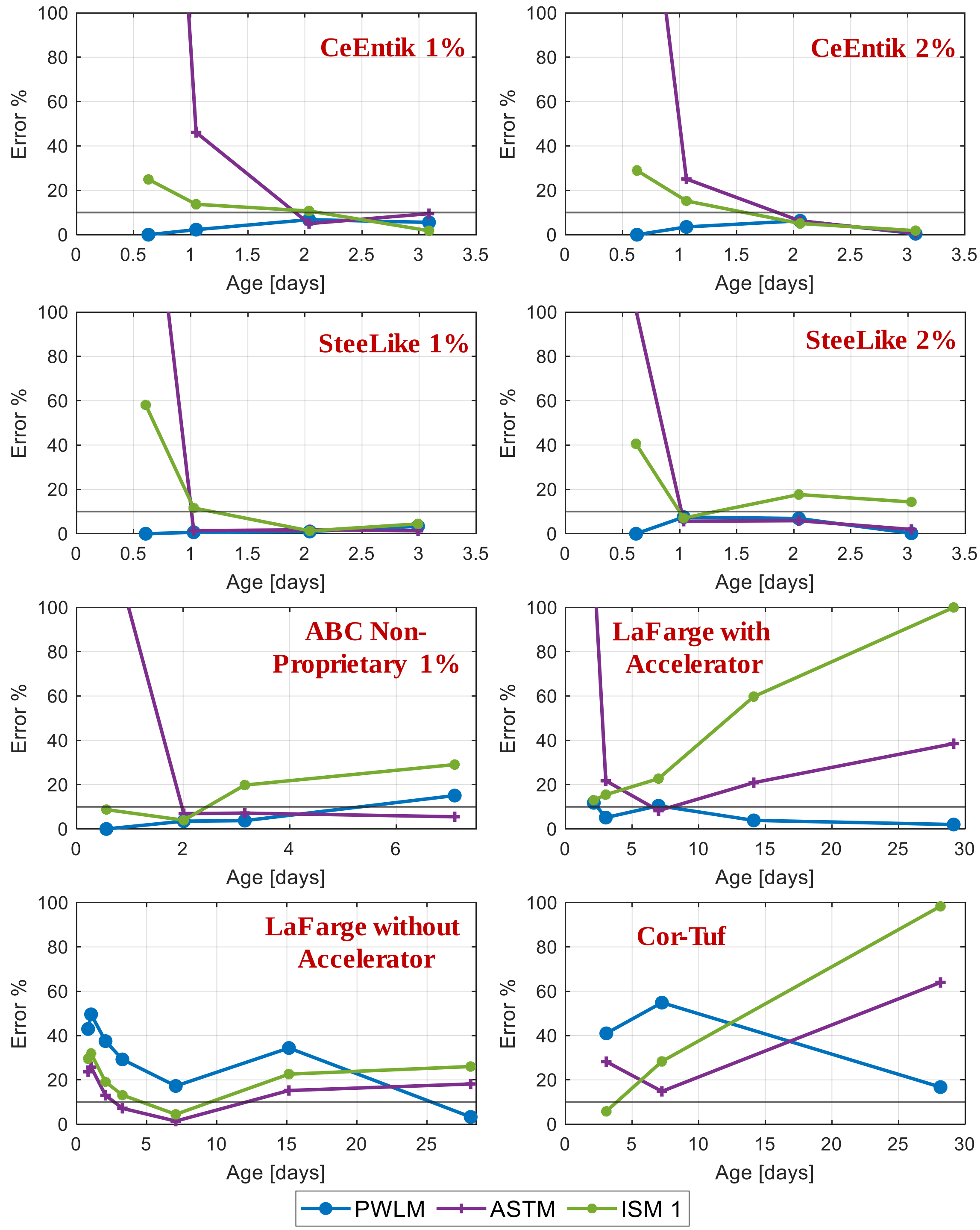

Figure 21. Age vs. Error% for different methods for predicting the strength

CHAPTER 3. ROBUST SIZE EFFECT STUDY OF MULTIPLE UHPC MIXTURES OF DIFFERENT SPECIMENS' SHAPES AND SIZES

3.1. Experimental program

The experimental campaign includes both proprietary and nonproprietary UHPC mixtures. The proprietary UHPC mixtures used are the most popular and available in the United States and international UHPC market. The proprietary UHPC mixtures used were: SteeLike and CeEntek with 2% and 1% fibers (ST1%, ST2%, CeE1% and CeE2%) in addition to Ductal with and without accelerator and Cor-tuf with 2% fibers(LfA2%, LfNa 2% and CTF2%). On the other hand, the nonproprietary mixture used was the ABC-UTC mixture with 1% fibers. The proportions of the proprietary and nonproprietary UHPC mixtures are shown in Table 1. The specimens' shapes and sizes that were studied in this research are 75mm in diameter × 150mm in height (3" ×6") cylinders denoted herein as 75mm cylinder, 100×100×100mm (4" ×4"×4") cubes indicated herein by 100mm cube and, 51×51×51mm (2" ×2"×2") cubes denoted herein by 51mm cubes as shown in Figure *22*. For each UHPC cast, around 117 specimens of all mold sizes were taken, as shown in Figure *3*a. The casted specimens were divided into two groups; the first group was cured in the lab standard curing room (lab cured) according to ASTM C511[36] until testing. The second group was left outside the lab to mimic the conditions of the construction site (site cured) until testing. The casting of the UHPC mixtures took place throughout the whole year in Reno, Nevada, where weather conditions varied from hot and dry in the summer to cold rainy, and snowy in the winter. As stated in the literature, temperature and curing conditions might affect the conversion factors; thus, a wide range of temperatures was considered. In addition, some specimens were placed in the oven for 12 hours at a temperature of 40°C. To measure and track the temperature of the specimens, different maturity sensors which measure both temperature and strengths were used, as shown in Figure *3*. The sensors used were: LumiCon, Maturix, and Giatec. The temperature histories of the lab and site cured specimens are shown in Figure *6*, Figure *7*, Figure *8*, Figure *9*, and Figure *11*.

Figure 22. Compressive strength test of 2" cube

Before testing cylinder specimens, flat surfaces needed to be formed through special preparations such as cutting the top surface and then grinding both the top and bottom surfaces, as shown in Figure *4*(a) and Figure *4*(b.) Then all specimens were tested axially, as shown in Figure *4*c. Figure *4*d, and Figure *22*. The cylinder specimen was tested according to ASTM C39 [40] and the cubes specimens were tested according to ASTM C109 [41]. The loading rates were modified because of the high strength of UHPC that could take a long time to break, and according to Graybeal [1] studied the influence of increasing the loading rates on the compressive strength results and found that it did not influence them.

3.2. Conversion factors of the compressive strength between cubes and cylinders

The cylinders and cubes specimens were tested from 14 hours to 28 days. The compressive strength range covered from less than 7 MPa to over 140Mpa. Such range widens the data covered in the literature. This section aims to study the factors affecting the conversion factors, such as UHPC mixture type and the strength level. Moreover, the conversion factors between the 76mm cylinders, the 51mm, and the 100mm cubes were reported. At each age and at each age, at least three specimens were tested in compression. The average of the three values, standard deviation, and variance was calculated and reported in Tables 2 to 5.

3.3. The influence of different UHPC mixtures on the conversion factor

This section shows the different trends of the different UHPC mixtures. Figure *23* shows the compressive strength level vs. the conversion factors of cubes vs. cylinders and small cubes vs. big cubes. Figure *23* generally indicates that the conversion factors change with the change of UHPC type and the level of strength. Significant discrepancies at low strength levels were observed in Figure *23*b and Figure *23*c when converting the 51mm cube to 76mm cylinders and 100mm cube. However, the discrepancies were reduced by increasing the strength level to 60 MPa. Few discrepancies were observed in the conversion between the 100mmcubes to 76mm cylinders.

3.4. The influence of strength level on the size effect of UHPC

In this section, all the compressive strength data were plotted for all UHPC mixtures with the conversion factors to study the strength level's effect on the conversion factor, as shown in Figure *24*. As observed in Figure *23*, Figure *24* also shows the discrepancies in the conversion factors between the 51mm cubes with both the 76mm cylinders and100mm cubes. However, the discrepancies reduce with increasing the level of the strength of 60 MPa.

3.5. Conversion factors of the specimens

The least-squares method was used to calculate the conversion factors and functions. Three functions were calculated; the first function is a linear regression that included an intercept, the second is a linear regression function without an intercept(zero intercepts), and the third function was the power function. All three functions were calculated and plotted in Figure *25*, Figure *26*, Figure *27* and are presented along with their R^2 in Table 9. As presented in Table 9, the power function showed a higher R^2 then the linear regressions functions for all three conversions. The conversion of both cubes to cylinders showed good R^2 value which encourages the use of cubes as an alternative to cylinders in terms of quality control, especially at an early age when the cylinder preparations affect the compressive strength of the specimens and the easy handling of the cubes relative to cylinders.

3.6. Application of Conversion factors: Strength maturity

The owners of accelerated construction projects seek to utilize the structural element as early as 12 hours after casting the UHPC if a specific strength has been reached. Thus, the maturity method is one of the quality control methods to ensure the element has reached such strength. The maturity method is non-destructive testing that predicts the concrete's strength based on its temperature history. It is a well-established quality control method for conventional concrete. For UHPC, on the other hand, it was proved that it could be a quality control method, and the guidelines for using this method on UHPC, especially at an early age, as presented in chapter 2. The American Society for Testing and Materials (ASTM), which guides the application of the maturity method on conventional concrete through the technical standard: ASTM C1074 [19] requires to use the of 76mm cylinders; however, due to the cylinder preparations needed, that might consume time and affect the strength of the cylinders at early ages, the authors recommend to use the cubes instead. However, the design standards require the strength of the cylinder; that's when the conversion factors come into place. The cubes can be used in the whole maturity method of temperature and strength monitoring. Then, a robust conversion factor could be utilized to get the cylinder strength for the design purposes.

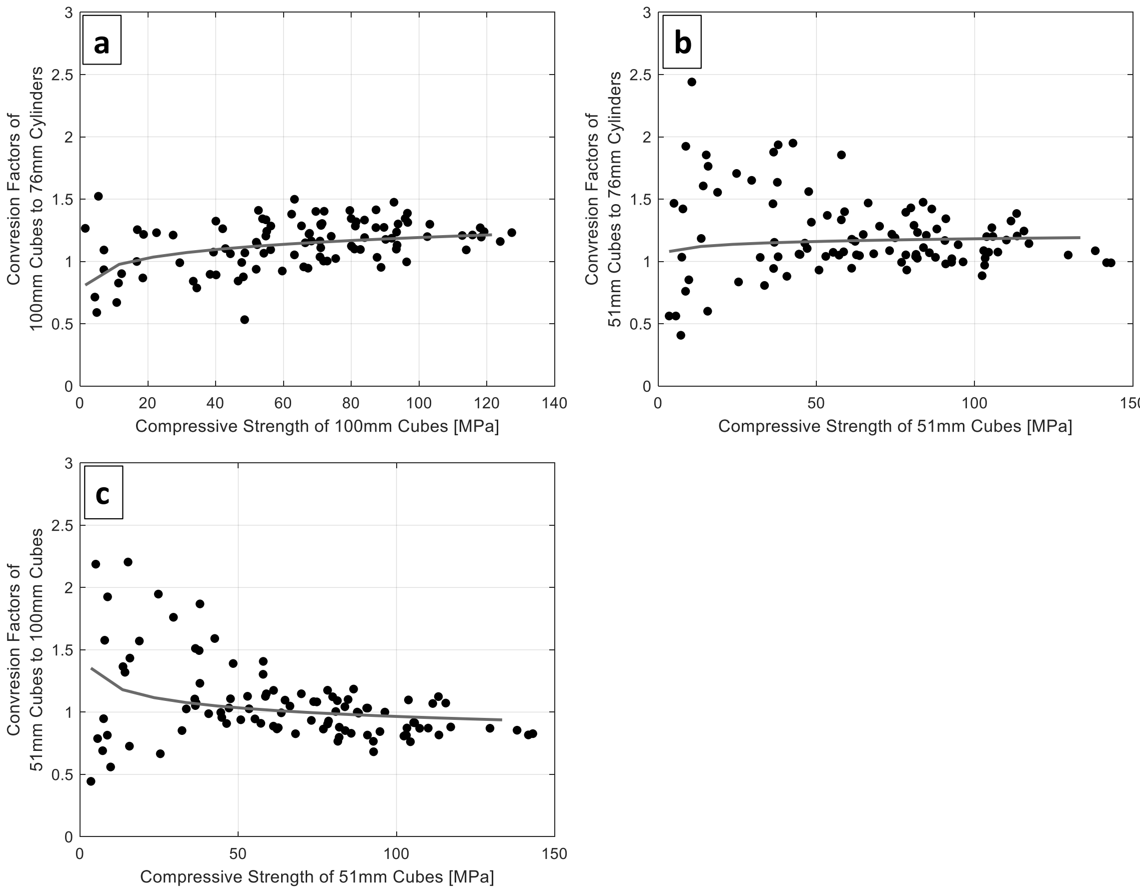

Figure 23 the influence of the strength levels on the conversion factors between a) 100mmcubes to 76mm cylinders, b) 51mm cubes to76mm cylinders, and c) the 51mm cubes and the 100mm cylinders

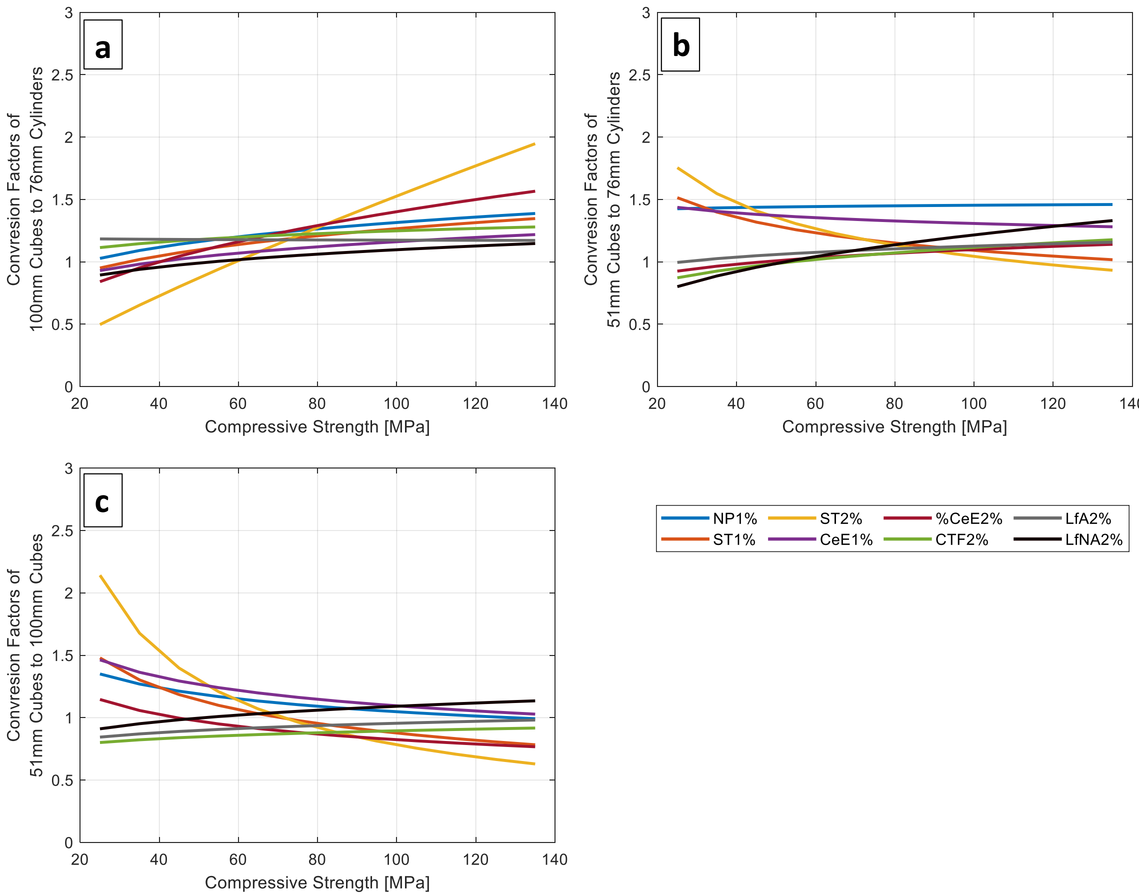

Figure 24. Strength vs. conversion factors of all used UHPC mixtures and specimen shapes and sizes: a) between 100mm cubes ad 76mm cylinders, b) between 51mm cubes and 76mm cylinders, c) between 51mm cubes and 100mm cubes

A detailed study on the maturity method included both the 76mm cylinders and 100mm cubes. It was found that the 100mm cubes led to better strength prediction at early ages. A possible explanation for this might be that the operations performed on the cylinders influence the strength of the cylinders. In this section, an application of the conversion factors is presented. For example, the strength maturity relationship could be established for the 100mm or the 51 mm cubes for better strength prediction at an early age and then converted to the 76mm cylinders for designing and quality control purposes.

The material's temperature history needs to be measured and stored to establish the strength maturity relationship. Therefore, special maturity sensors (LumiCon, Maturix, and Giatec used in this research) were embedded in the center of the specimen and at mid-height, as shown in Figure *3*a. Then, using the temperature history, the maturity index was calculated. To calculate the maturity index, The ASTM C1074 provides two main maturity index functions Nurse-Saul function (NS) or time-temperature factor and Arrhenius function or Equivalent age(EQ). The NS maturity function assumes linear relationships between the temperature and rate of strength gain[34] and is presented in Eq.1.

The NS equation is used in this section for its simplicity. The maturity index will be calculated based on the lab temperature history and the compressive strength results of SteeLike with 2% fibers. The datum temperature constant of the NS function is taken to be -2 °C as concluded by authors in Chapter 2. The maturity index was calculated using the lab temperature histories of the 76mm cylinders, 100mm cubes, and 51 mm cubes. The ASTM recommends using only five lab breaking points results at ages: 1.3.7.14 and 28 days. Finally, the maturity curve was established by fitting the strength and maturity index by a logarithmic regression curve, as shown in Figure *28*. As shown in Figure *28*, thus the cubes could be used for the whole maturity process and then converted to cylinders.

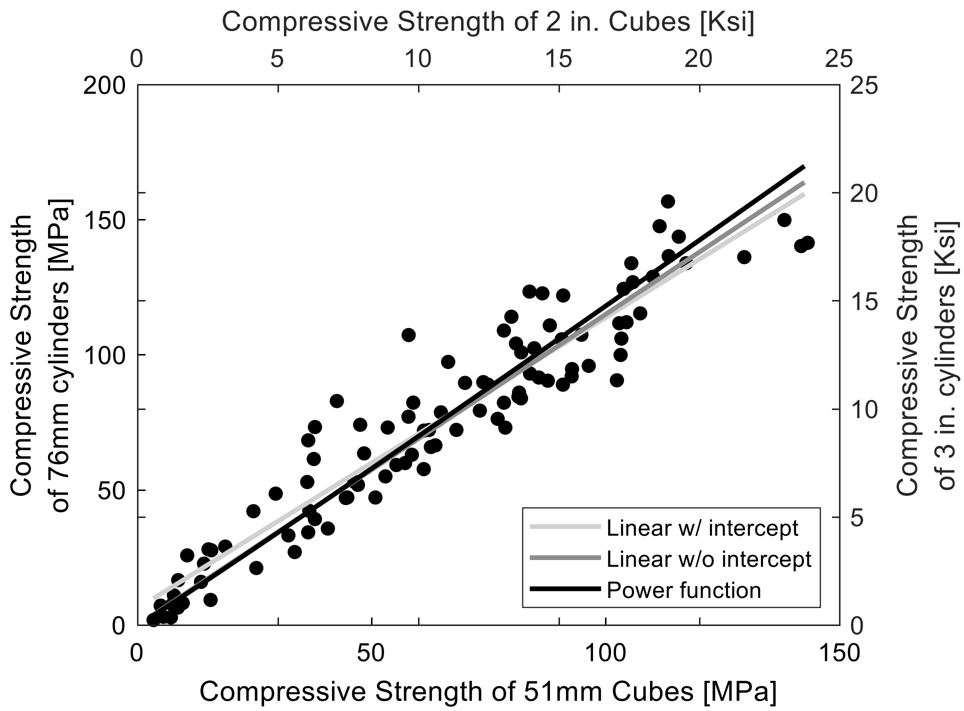

Figure 25. Compressive strength of 51mm (2 in.) cube vs. 76mm (3 in.) cylinder

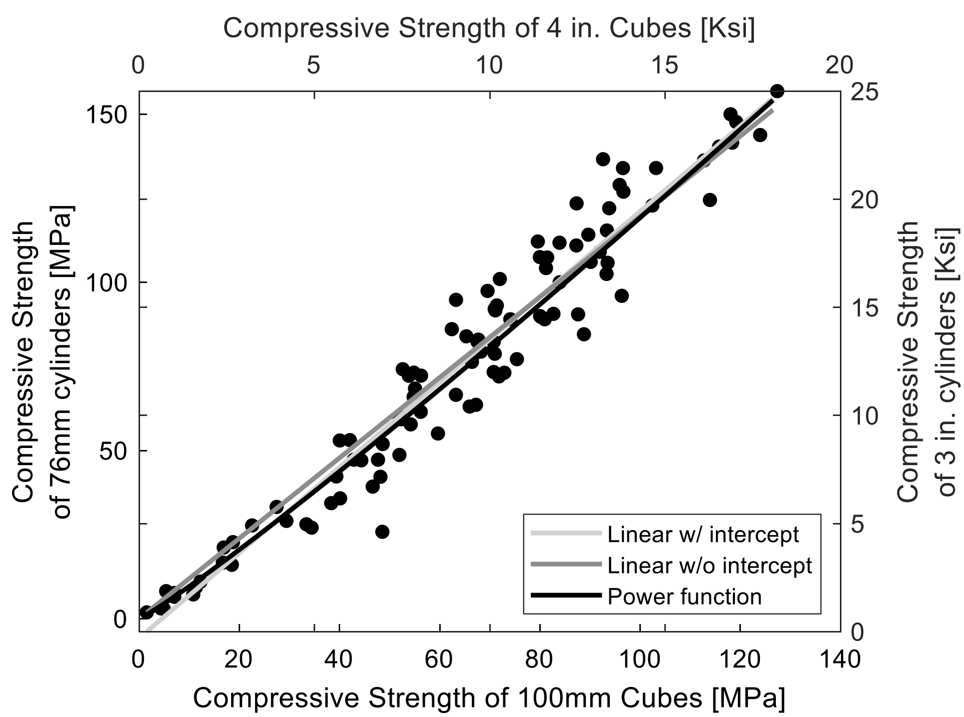

Figure 26. Compressive strength of 102mm (4 in.) cube vs. 76mm (3 in.) cylinder

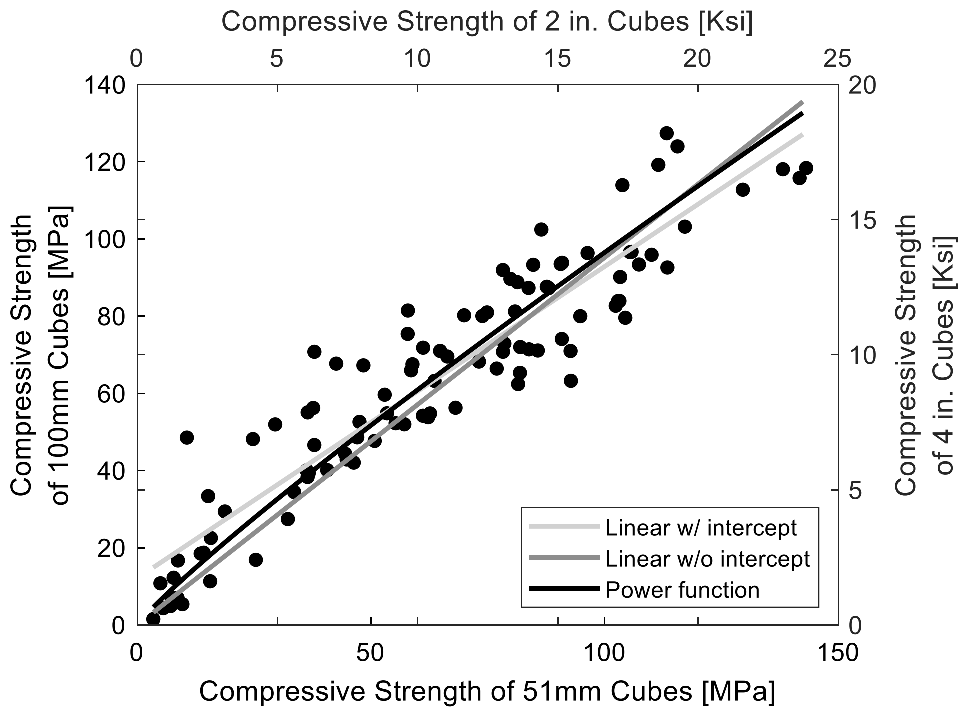

Figure 27. Compressive strength of 51mm (2 in.) cube vs. 102mm (4 in.) cube

Table 9. Conversion factors and functions of compressive strength

	100mm cubes to 76mm cylinders		51mm cubes to 76mm cylinders		51mm cubes to 100mm cubes	
	Function	R^2	Function	R^2	Function	R^2
Linear without intercept	1.1954x	0.94	1.1509x	0.89	0.9519x	0.83
Linear with intercept [MPa]	1.2682x - 5.7417	0.94	1.0767x + 6.2225	0.90	0.8072x + 12.135	0.86
Power function [MPa]	$0.7796x^{1.0922}$	0.96	$1.045x^{1.0267}$	0.91	$1.5295x^{0.9}$	0.87

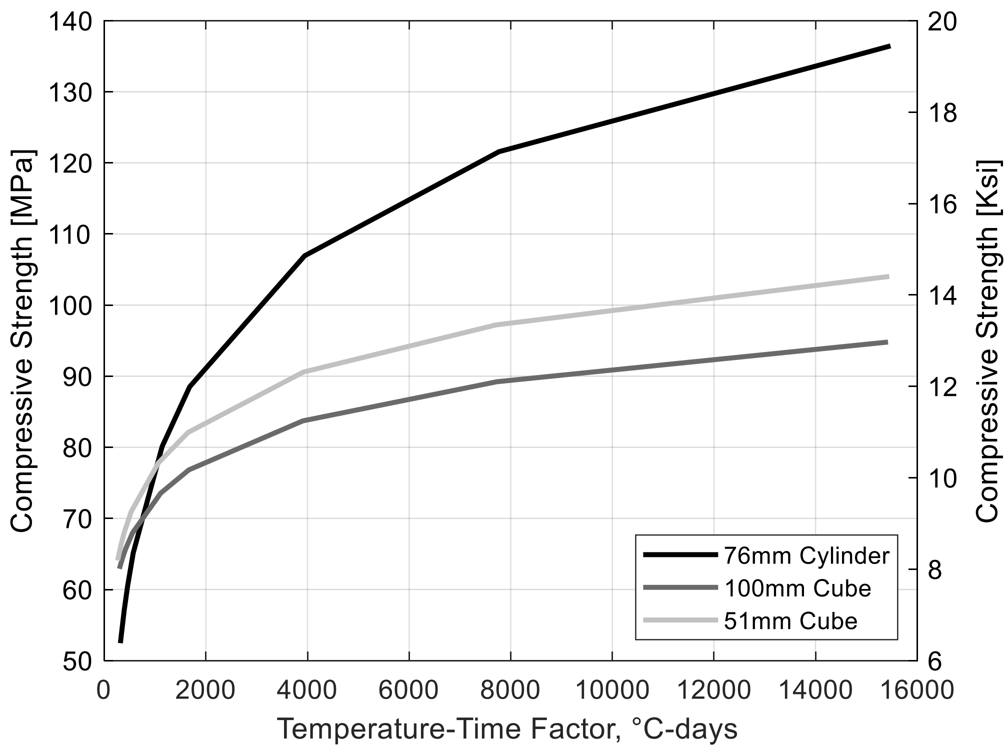

Figure 28. Strength maturity curves for 76mm cylinders, 100mm cubes, and 51mm cubes

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Maturity Assessment

The first part of this thesis aimed to assess the recommended ASTM C1074 maturity methods, procedures, and constants for predicting the compressive strength of UHPC. Eight UHPC mixtures, three different temperature/maturity sensors, and two different specimen shapes were used in this part of the study. About 620 UHPC specimens were tested at early, middle, and late ages. These specimens were divided into two groups. One group was cured in the lab curing room, and the other group was left outside the lab, where an ambient atmosphere existed to mimic the construction site conditions. Finally, the eight UHPC mixtures were cast throughout the year, where they were subjected to a wide range of temperatures and site conditions, from being warm and dry in the summer to below freezing and humid in the winter.

A parametric study was conducted to assess a wide range of maturity constant values that are implemented in the strength maturity equations to find suitable maturity constant values for all UHPC mixtures that lead to better predictions. Different strength-maturity equations were developed using different five and six ages of lab breaking points specimens to check the effect of the lab specimen ages and their number that are used to develop the strength maturity relationship on the accuracy of the predictions. Furthermore, both Nurse-Saul and Arrhenius methods were assessed in the parametric study along with the two specimens' shapes: 3"×6" cylinders and 4"×4" cubes, to find which maturity method and specimen shape would lead to better predictions. Finally, based on the parametric study's observations and conclusions, a piecewise linear method (PWLM) was developed as a curve fitting for the strength maturity points. The method was validated and tested on eight UHPC mixtures. The following points are the major conclusions from the maturity method assessment part of the study:

- The study has found that the accuracy of the compressive strength predictions of the site specimens depends on the ages of the lab breaking points used to develop the strength maturity relationship. Thus, to reduce the error of the predictions, the lab breaking points used to develop the strength maturity equations need to be tested at the ages when the site specimens need to be predicted. As a result, the age categories concept of the lab configuration was introduced. Also, the recommended configurations were proposed for each age category shown in Table 6.
- It is possible using the ASTM recommended maturity constants to estimate the compressive strength with a limited error of around 10% if the configurations adopted to develop strength maturity relationships align with the ISM configurations shown in Table 6.
- The ASTM recommended configuration of the lab breaking points ages were assessed for all the eight UHPC mixtures, and it was found that the configurations lead to inaccurate results for the one-day strength and less. However, the predictions were within the acceptable error range for two days and later.
- The effect of using a wide range of maturity constants: t_0 and Q, on the predictions was investigated. The values that showed good results for the five UHPC mixtures and

on the two specimen shapes, 3" ×6" cylinders and 4" ×4" cubes, were -2 ˚C for t_0 and 5000 K for Q.

- The study investigated the effect of using five and six lab breaking points configuration on the accuracy of the strength predictions, and it was found that no significant differences were reported.
- The different specimen shapes: 3" ×6" cylinders and 4" ×4" cubes, were studied to find if using any of the shapes was superior to the other in terms of the strength predictions; it was found that the cubes at ages less than one-day showed better strength predictions than the cylinders.
- Both Nurse-Saul’s and Arrhenius's maturity methods were assessed, and it was found that the Arrhenius method led to slightly better results than the Nurse-Saul method.
- The strength maturity relationship for eight mixtures was plotted, and a pattern was observed where the slope changes four times. Thus, as a development of the age category proposed method (ISM) which was multiple equations were required to predict the UHPC strength for different ages. A newly proposed method focuses on capturing the strength maturity points that define the slope of the strength maturity curve. Five lab breaking points were needed to capture the slopes of the strength maturity curve, and their maturity index values were reported. Then, two maturity strength points for each slope are used to develop a strength maturity relationship. Eventually, four equations are needed to effectively predict the UHPC strength for all early, middle, and late ages. The method was tested on the eight mixtures and showed good results on six. The guidelines of this method were proposed in the paper.

4.2. Cubes versus Cylinders Assessment

The second part of this thesis aimed at studying the size effects of different specimen shapes and sizes and to determine robust conversion factors and functions between all three 3" ×6" (76 mm) cylinders and both the 2"×2"×2" cubes (51mm side) and 4"×4"×4" cubes (100 mm sides). This part of research used around 900 tested specimens of a wide range of UHPC mixtures at different ages that varied the strength levels. Furthermore, other factors considered, such as different fiber content and curing regimes, were adopted. The mentioned factors helped to effectively study the size effect and calculate robust conversion factors and functions, as presented in Table 9. This second part of the thesis study presented herein resulted in the following conclusions:

- The 2” (51 mm) cubes showed a high discrepancy at low strength levels (early ages) when converting to 4” (100 mm) cubes and 3”×6” (76 mm × 150 mm) cylinders. However, the discrepancies were reduced by increasing the strength level above 60 MPa. Thus, we do not recommend using 51 mm cubes at a strength level of less than 60 MPa.
- Low discrepancies were observed when converting from the 100mm cubes to 76mm cylinders at all strength levels (all ages); thus, we recommend using the 100 mm cubes at all strength levels.
- The conversion factors trend for different shapes and sizes of specimens was not the same for the different UHPC mixtures; thus, a statistical study was performed to calculate the conversion factors.

- The conversion factors vary with varying the UHPC strength level; thus, the presented conversion factors cover the lacking ranges in the literature to make the proposed conversion factors and function in the research valid for all strength levels at all ages.
- Three functions were studied for converting between 100 mm cubes and 51 mm cubes to 76 mm cylinders and 51 mm cubes to 100 mm cubes. The power function showed a high R^2 compared with the other two functions.

4.3. Future Research

This study recommends using cubes at ages less than one-day. Therefore, robust conversion factors for UHPC materials are needed to convert the early age cube strength with the early age cylinders strength because some countries like the United States are using the cylinder's compressive strength to design the structural elements. Moreover, this paper suggested the maturity constant values that could be used for each age and each specimen shape, as shown in Table 3. Thus, from the findings, the maturity constants used in the maturity equation seemed to be variable and are a factor of the age at which the strength needs to be determined and specimen shape, so it will be beneficial if the maturity constants method in the ASTM be updated so that it can include the mentioned factors.

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