Assessment and Development of the Maturity Method as a Quality Control Method for Ultra High Performance Concrete

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Abstract

For accelerated bridge construction (ABC), where time plays a vital role in the project, a high strength material such as UHPC is used such that high design strength can be reached as early as 12 hours. To verify that the required strength has been reached, a robust quality control method is needed. For concrete materials, the ASTM C1074 provides procedures and recommendations for a non-destructive quality control method that relates the strength of the material with its temperature history, namely the maturity method. However, such ASTM C1074 procedures and recommendations have not been exclusively established nor yet verified for advanced materials such as UHPC. Nevertheless, the industry has started using the ASTM C1074 maturity method for UHPC assuming it should be valid. To confirm or develop new adjustments for the UHPC strength maturity, this paper assesses the applicability of the ASTM C1074 for UHPC. The assessment included the use of five different UHPC mixtures in addition to variables such as curing regimes, targeted age, fiber content, maturity, different functions, and mold shapes and sizes. The assessment showed that the ASTM C1074 could lead to good results if some modifications are made and certain recommendations are followed. Finally, as a further development to the maturity method for UHPC, the paper presents a new curve fitting procedure to reduce strength prediction errors.

Keywords: UHPC, Strength Maturity, ASTM C1074, Early Age Strength, Quality Control

1. Introduction

Reducing construction time has been an important research topic for both academic and industrial sectors, especially for bridge construction projects which cause traffic delays, congestion, and road closures. Thus, the bridge owners usually use precast members that are cast and ready in the workshops before construction starts. When constructing bridges using the precast members, among other accelerated bridge construction (ABC) methods, connections and field joints are then needed to be poured between the precast members. Such joints need to be cast on site and cannot be prefabricated. Conventional concrete field joints are traditionally used to connect the precast bridge girders, which dictates larger joint dimensions for rebar development and also delay bridge operation until the field joint concrete strength reaches a threshold of 8000 psi for instance (Lee et al. 2014). While conventional concrete might gain this strength after 28 days and cannot help reduce joint dimensions, a more robust material is desired to minimize field joints size and reach high strength in fewer days. As such, ultra-high performance concrete (UHPC), which is a robust cementitious material with compressive strength of up to 25 ksi among other superior mechanical properties, can be ideal for ABC and field joints. UHPC can reach 8000 psi in a day or less if a proper curing regime is followed and a good quality control method is adopted to verify the on-site strength. To verify such strength in real time, both destructive and non-destructive methods could be used. One of the non-destructive methods is the maturity method, which is discussed here.

The maturity method is a 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 for 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. Two strength maturity functions are proposed in the ASTM C1074: Nurse-Saul (indicated herein as NS) and Arrhenius (indicated herein as energy equation or EQ) methods. The NS maturity function assumes linear relationships between the temperature and the rate of strength gain (Carino and Lew 2004) and is presented in Equation (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 which is set by the ASTM that recommends using 0˚C. On the other hand, the EQ function assumes a non-linear relationship between the temperature and strength gain, as presented in Equation (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 taken as 41.55 KJ/mol according to ASTM, and T_a is the average concrete temperature during time interval Δt.

To establish the strength maturity function to predict the strength of concrete, the concrete to be used in the field has to be tested in the laboratory first using 3 in ×6 in (76.2 mm × 152.4 mm) cylinders. The cylinders should be cured in a standard curing room according to ASTM C511 (ASTM C511-21). Next, cylinders should be tested under compression at ages 1, 3, 7, 14, and 28 days. Additionally, from the time of mixing until the testing, the temperature of the specimens needs to be measured and stored so that a table of accumulated temperature history values (maturity index) at each age of the five breaking points, accompanied by the compression tests results at each age. The points in the table can be plotted against compression strength, and a function can be fit using an ASTM suggested logarithmic best-fitting method. It is noted again that although it is not mentioned in the ASTM C1074 that the maturity methods procedures and the mentioned recommendations could be used for UHPC, yet construction engineers and researchers are adopting the method for UHPC assuming its validity.

Carino et al. (1992) assessed the applicability of the maturity method for 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 (Carino et al. 1992). The difference between UHPC and HPC is that the UHPC has a lower water-cement ratio and uses steel fibers. This gives an insight into the possibility of using the maturity method for UHPC. The effect of adding fibers to concrete was studied, and it was found that adding fibers slightly delays the hydration reaction (Govin 2014). Wang and Kim (2020) 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 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 (1996) concluded for the concrete material that if the difference between the lab and in-situ 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 (Allard et al. 2020). 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, which is yet to be done.

In summary, very limited and only preliminary studies considered validating UHPC strength maturity relationship with the site specimens, and most of the available literature focused only on validating and fitting the strength maturity relationship with lab cured specimens that are already used to establish the relationship as per ASTM. No comprehensive studies considered different types of UHPCs or varied the experimental settings to capture wide range of construction conditions. Thus, this paper aims to fill such knowledge gaps and assess the maturity method of UHPC and provide guidance on what to consider when ASTM C1974 is applied to UHPC. In addition, we develop and propose here a curve best fitting that shows promising results in predicting the UHPC strength when compared to the default ASTM logarithmic fitting.

2. Experimental Campaign

The experimental campaign includes both proprietary and non-proprietary UHPC mixtures. The UHPC types used in this research are: (1) ABC-UTC non-proprietary with 1% fibers (Abokifa and Moustafa 2021), (2) carbon nano-enhanced UHPC, i.e. CeEntek with 1% and 2% fibers (Cimesa and Moustafa 2022), (3) SteeLike with 1% and 2% fibers, (4) Cor-Tuf with 2% fibers, and (5) Lafarge Ductal with 2% fibers with and without accelerator. The specimens types used in this research included both 75 mm diameter × 150 mm height (3 in × 6 in) cylinders as well as 100 mm × 100 mm × 100 mm (4 in × 4 in × 4 in) cubes. In addition, three different maturity sensors from three different vendors were used to measure and store the concrete samples temperature.

The cast specimens were divided into two groups: the first group was cured in the lab standard curing room (indicated herein as lab cured) according to ASTM C511-21 until testing. The lab-cured specimens were tested in compression at ages of: 0.6, 0.75, 0.85, 1, 2, 3, 7, 14, and 28 days. The second group was left in our fabrication yard until testing to mimic the conditions of construction sites (indicated herein as site cure). The site-cured specimens were tested only at four ages: 0.6, 1, 2, and 3 days, since the focus is mostly on early strength and quality control breaking points. The casting of the UHPC mixtures took place throughout the year in Reno, NV, where the weather varied from hot and dry in the summer to cold, rainy, and snowy in the winter. In addition, some specimens were placed in the oven for 12 hours at a temperature of 104°F (40°C) to represent heat curing. Full details of the proportions of the UHPC mixtures used in this study, temperature histories of the specimens from the sensors, and full compression test results of the tested specimens can be found in Ibrahim (2022) and Ibrahim and Moustafa (2022).

3. Discussion of Validity of ASTM C1074 Configurations and Maturity Constants

The study used three out of the five different UHPC mixtures to evaluate the ASTM procedure and draw conclusions that were then tested on the independent data from other two mixtures. The study begins with testing the accuracy of ASTM recommendations for conventional concrete when applied to UHPC. The accuracy of the established strength maturity functions for each mixture from the lab specimens is tested with the site-cured specimens. The sensors embedded in the site-cured specimens produce maturity index values at a certain age, that theoretically, can be input into the strength maturity function established from the lab specimens to obtain a "real-time" strength of those specimens. Thus, the accuracy of the strength output from the strength maturity equation is tested when comparing calculated values against the actual strength values obtained from site specimens breaking points. The site specimens were tested at four ages: 0.6, 1, 2, and 3 days. The errors are calculated and presented in Figure 1. Figure 1 shows four graphs that combine cases of 3 in × 6 in cylinders or 4 in × 4 in × 4 in cubes along with both NS and EQ functions. In addition, The solid black line in Figure 1 is added at an error value of 10% to mark a reference for the 10% allowed error tolerance in the ASTM C1074; above which the strength maturity curve has to be modified or otherwise it will not be valid. It can be observed from Figure 1 that the errors are acceptable for both specimen shapes and functions for all ages except for the very early strength at one day age or less, where the errors tend to be high. This observation suggests that deviating from the standard ASTM lab breaking ages of 1, 3, 7, 14, and 28 days to consider other age configurations, the errors might be reduced.

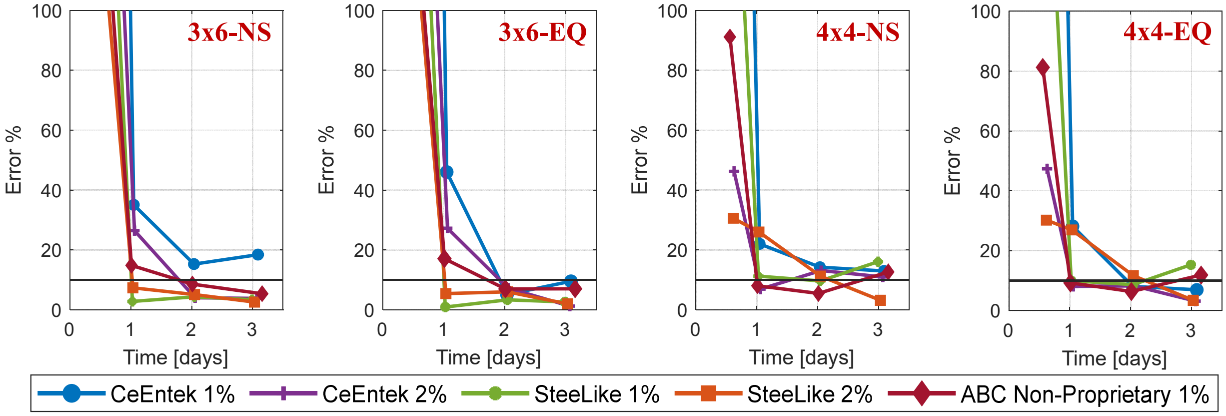


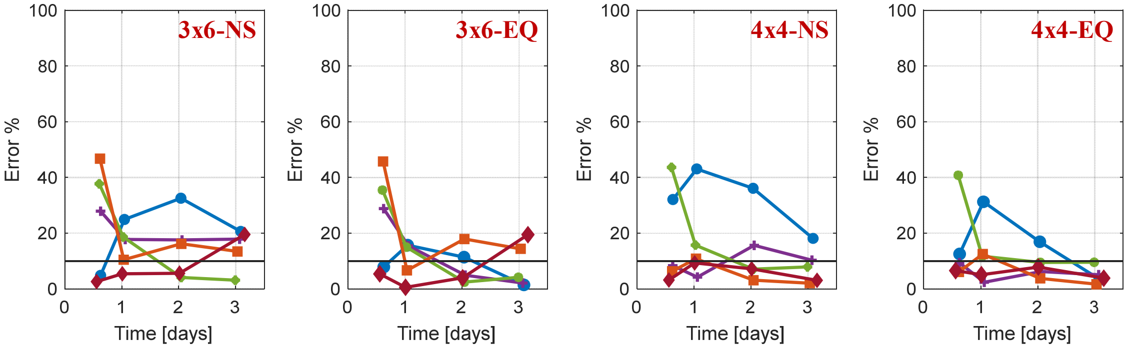
Figure 1. Error (%) in strength prediction against measured strength from breaking points versus age when using the ASTM age configuration for different specimens shapes and maturity functions

Since the authors initially obtained lab specimens breaking points at nine different ages, we developed a simple MATLAB code to loop through the nine lab breaking points and pick all possible combinations of five breaking points and establish a function for each group. The function and the outputs of the function would be then tested against the actual results. Table 1 shows the best age configuration combinations corresponding to the lowest possible error at certain ages. This approach and resulting age combinations or configurations is referred to as the iteration search method (ISM). The errors of ISM configurations were calculated and plotted in Figure 2. It was not possible to find a specific configuration that was valid for all ages. Also, it can be observed that to predict strength at a certain age, the age of the lab breaking point needs to be close to the age that is desired to be accurately predicted.

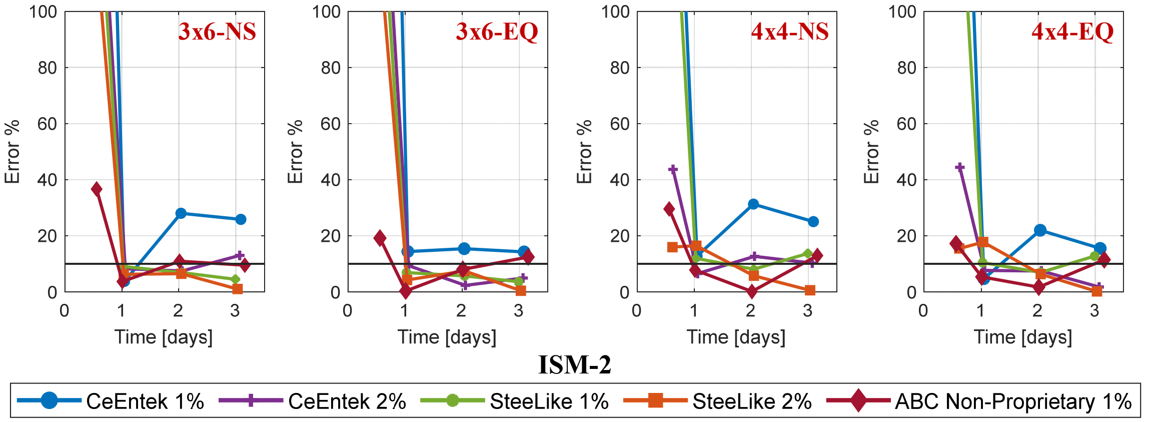
As observed, it was not possible to get an accuracy of less than 10% for all site ages, even after changing the age configuration. The authors then used MATLAB codes again, but this time to loop a wide range of maturity constants, but once again, we could not find constants values that would be applicable for all ages. Nevertheless, the best maturity constants for the ISM configurations are reported in Table 2. In addition, Table 2 provided a range of constants that reduced the errors at specific ages. Overall, we conclude that the ISM configurations provide better strength predictions because they combine the lab breaking point ages that were close together in one category and, hence one equation. Furthermore, this developed equation could give relatively less error results for certain ages but not a wide range of ages. Therefore, these findings gave an insight into the effect of lab breaking points' ages on the accuracy of the predictions.

Table 1. Different configurations based ISM but using the ASTM recommended maturity constants

Age [days]	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			🟨	🟨		🟨	🟨	🟨	
ISM-4			🟦		🟦	🟦		🟦	🟦
Best configurations for two- and three--days strength predictions									
ISM-6				🟧	🟧	🟧		🟧	🟧
ISM-7				🟨	🟨	🟨	🟨	🟨	
ISM-8				🟦	🟦	🟦	🟦		🟦



ISM-1



ISM-2

Figure 2. Error (%) in strength prediction versus age when using ISM configurations

Table 2. Maturity Constant for different ISMs

Maturity constants	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	

To observe the overall picture, the strength maturity curves were plotted without best fitting using all the nine breaking points from the 3 in × 6 in cylinders for all five UHPC mixtures, and the EQ function with a Q value equals 5000K as shown in Figure 3. Figure 3 explains why there is no perfect age configuration that capture strength at all age ranges because the slopes change. In turn, when establishing a relation using all points in zone 1 (first slope), a high error margin should be expected in the other zones and the same for the other zones and so on. Based on this key observation, the authors propose a piecewise linear method (PWLM) to establish the maturity curve as opposed to the standard logarithmic fit suggested by the ASTM. Our proposed PWLM divides the strength maturity curve into four zones based on the slopes, and for each zone, one linear 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 five tested UHPC mixtures follow the same pattern, where the slope of the maturity lines changes four times. The slopes of six out of eight curves change at maturity index values of approximately 18, 60, and 300 equivalent age hours. This how the maturity curves are proposed to be precisely divided into four zones.

In order to apply the PWLM, the first step is to capture where the slope changes by breaking five lab specimens at maturity index values equal to: a point before 18 hours (maybe 10 or 12 hours), then 18, 60, 300, and 600 equivalent age hours. These maturity values could be determined using maturity sensors embedded in the specimens and will send automatic notifications at the required equivalent ages. Next, if the sensors come with applications that directly output maturity values, such built-in applications will then need to be adjusted to the Arrhenius function (EQ), and the reference temperature need to be adjusted to 23 ˚C, and Q is adjusted to 5000K. After breaking the lab specimens at the identified maturity index values, four strength maturity linear equations are established:

- 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, which is meant to predict the strength, the second equation developed in the range of 18 to 60 hours can use this breaking point. The proposed PWLM was used for all different five UHPC mixtures and showed promising results for all ages when compared to both the ASTM recommendations and the ISM configuration #1 which was meant for the early age as shown in Figure 4.

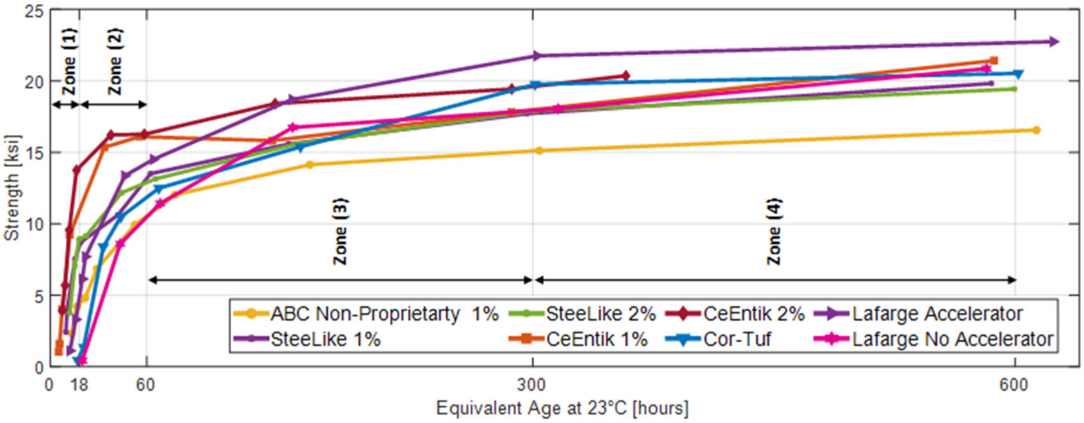


Figure 3. Strength-maturity curves for eight UHPC mixtures

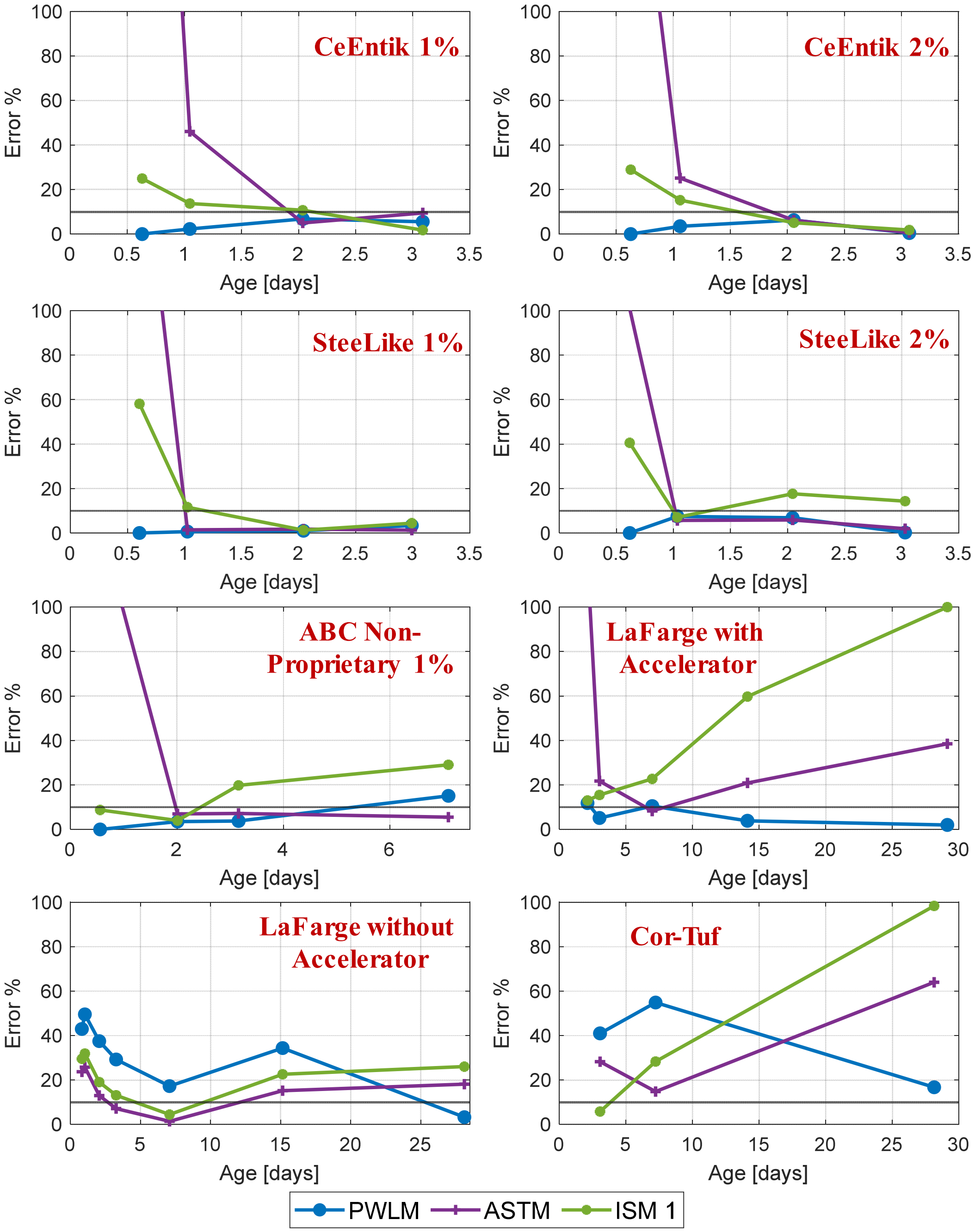


Figure 4. Error (%) versus age for the different methods used and proposed for predicting UHPC strength

4. Conclusions

This paper aimed at assessing the ASTM maturity method for UHPC. It was found that ASTM C1074 recommendations meant for conventional concrete could lead to good strength prediction for UHPC at ages more than one day; however, it is not accurate for early ages of one day and less. An iterative search method was developed to define best ISM breaking age configurations for establishing maturity strength prediction of UHPC at a certain age. In general, it is recommended to break the lab-cured specimens for generating the strength maturity functions at ages similar to when it is desired to be predicted in site. Further, the maturity constants that provided less errors at certain ages were determined and summarized in this paper. Finally, the paper presents also the PWLM for establishing maturity curves over four zones, which is shown to be a more accurate way than ASTM suggested logarithmic curve fitting that usually leads to larger errors at early ages.

5. Acknowledgments

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6. References

- Abokifa, M., & Moustafa, M. A. (2021). Mechanical characterization and material variability effects of emerging non-proprietary UHPC mixes for accelerated bridge construction field joints. Construction and Building Materials, 308, 125064.
- Allard, Thomas E., et al. “Isothermal Strength Development Models of Ultra-High-Performance Concrete.” ACI Materials Journal, vol. 117, no. 1, 2020, pp. 175–85.
- ASTM C511-21. Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes.
- ASTM C1074-19e1. “Standard Practice for Estimating Concrete Strength by the Maturity Method Maturity Index and Maturity Method.” ASTM International, 2019, pp. 1–11.
- Carino, N. J., et al. “Applicability of the Maturity Method to High-Performance Concrete.” Nistir-4819, 1992.
- Carino, Nicholas J., and H. S. Lew. “The Maturity Method: From Theory to Application.” Structures - A Structural Engineering Odyssey, Structures 2001 - Proceedings of the 2001 Structures Congress and Exposition, vol. 109, 2004, pp. 1–19.
- Cimesa, M., & Moustafa, M. A. (2022). Experimental characterization and analytical assessment of compressive behavior of carbon nanofibers enhanced UHPC. Case Studies in Construction Materials, 17, e01487.
- Govin, Alexandre. Aspects Physico-Chimiques de l ’ Interaction Bois - Ciment Modification de l ’ Hydratation Du Ciment Par Le Bois. 2004, p. 216.
- Ibrahim, M.S. Robust Methods for UHPC Early-Strength Determination and Quality Control for Accelerated Bridge Construction. 2022, MS Thesis, University of Nevada, Reno
- Ibrahim, M.S., & Moustafa, M.A. (2022). Strength Maturity Method for Quality Control of Field-Cast UHPC Seismic Accelerated Bridge Construction Connections, 12NCEE, Salt Lake City, UT
- Lee, George, et al. (2014). Seismic Performance Evaluation of Precast Girders with Field-Cast Ultra High Performance Concrete (UHPC) Connections - MCEER: University at Buffalo.
- Poole, Toy S., and Patrick J. Harrington. An Evaluation of the Maturity Method (ASTM C 1074) for Use in Mass Concrete 19970203 003 OTIC QUALITY HTBPSOi’iäS &. 1996.
- Wang, Jun, and Yail J. Kim. “Functional Characteristics of Ultra-High-Performance Concrete Comprising Various Fibers.” ACI Materials Journal, vol. 117, no. 5, 2020, pp. 179–91.