Robust Methods for UHPC Early-Strength Determination and Quality Control For ABC

Quarterly Progress Report
For the period ending September 1, 2021

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1. PROJECT ABSTRACT

It is a well-known fact now that UHPC is one of the most commonly used or desired solution for ABC connections nowadays. With large initiatives for developing non-proprietary UHPC mixes (e.g. ABC-UTC ongoing imitative), the applications and use of UHPC for ABC will only continue to increase. Given the ABC nature, many projects considering UHPC for connections and early bridge opening for traffic or following construction phases are hinging on reaching a desired early age strength. For example, bridge owners have recently specified Ductal JS1212 for projects requiring that 12 ksi strength is achieved at 12 hours. While robust mixes can accomplish this requirement, a reliable quality control method to verify such requirement on-site is still lacking. In remote sites, it becomes harder to verify the UHPC early age strength using the current state-of-practice, i.e. preparing cylinders by cutting and grinding the ends then testing them within 10-12 hours. To help address this issue, this project will extend two methods that have been well-established and used for conventional concrete strength characterization to use for UHPC. These are using cubes as opposed to cylinders for compression tests and utilizing previously-developed strength maturity curves for quality control. No documented efforts have yet showed the feasibility of such methods for early strength determination of UHPC. Thus, a comprehensive experimental program that considers 3 different UHPC mixes with wide range of mechanical properties will be conducted in this study to develop guidance for UHPC quality control and early strength characterization.

2. RESEARCH PLAN

2.1. STATEMENT OF PROBLEM

UHPC is one of the most commonly used or desired solution for ABC connections nowadays. With large initiatives for developing non-proprietary UHPC mixes (e.g. ABC-UTC ongoing imitative), the applications and use of UHPC for ABC are further expanding in the US and international markets. Given the ABC nature, many projects considering UHPC for connections and early bridge opening for traffic or following construction phases are hinging on reaching a desired early age strength. For example, bridge owners have recently specified Ductal JS1212 for projects requiring that 12 ksi strength is achieved at 12 hours. While robust mixes can accomplish this requirement, a reliable quality control method to verify such requirement on-site is still lacking. In remote sites, it becomes harder to verify the UHPC early age strength using the current state-of-practice, i.e. preparing cylinders by cutting and grinding the ends then testing them within 10-12 hours. In consultation with Caltrans among UHPC vendors and experts in relevant ACI committees, there is big interest in using two of the well-established methods for conventional concrete strength characterization for UHPC. These are using cubes as opposed to cylinders, and relying on strength maturity for quality control. No documented efforts have yet showed the feasibility of such methods for early strength determination of UHPC, which is the motivation of this project.

2.2. RESEARCH APPROACH AND OBJECTIVES

Proper cylinder preparation (e.g. surface grinding) is crucial for UHPC strength evaluation, but could be hard to apply especially for early age testing at 10-, 12-, 14-hour age, etc. when heat curing is desired or in case of remote sites and lack of near-by well-equipped testing facilities. Meanwhile, other methods such as the strength maturity method (SMM) and using cubes instead of cylinders for strength evaluation are well established but never explored specifically for early age strength of UHPC. Using brass or steel molds for the cubes will likely lead to the desired planeness and orthogonally of cube sides for compression testing. Accordingly, either SMM or the use of cubes, if properly specified and validated using laboratory testing, would eliminate the need for UHPC cylinder grinding and reduce the variability commonly observed in early-strength UHPC cylinder testing.

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 10 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 (e.g. Steelike Inc.) on UHPC maturity to assemble a larger database; and (4) develop guidelines for UHPC quality control and assurance as pertains to early compression strength characterization. It is worth noting that the PI was recently involved in a pilot study through Caltrans (see Figure 1 for some illustrations) to explore feasibility of SMM for UHPC 12-hour strength characterization. Figure 1 shows pictures of sampling and heat curing of UHPC cylinders along with a strength maturity sensor that is embedded in selected cylinders to measure the strength maturity index. The very preliminary results obtained from that effort were very promising in terms of results consistency and such results are presented later in the work plan as a sample of what can be generalized and comprehensively established through this project.

Figure 1. UHPC cylinders sampling, heat curing, and application of strength maturity sensors at a contractor's site in Sparks, NV for characterizing Ductal JS1212

2.2.1. Summary of Project Activities

An experimental approach will be used and several research activities will be executed to accomplish the objective of this study. A summary of the proposed research tasks is as follows:

- Task 1 – Conduct literature search on maturity method for concrete strength evaluation
- Task 2 – Comparative assessment of cubes and cylinders for UHPC early strength
- Task 3 – Establishing strength maturity datasets using experimental testing
- Task 4 – Develop quality control guidelines for UHPC early strength characterization
- Task 5 – Summarize the results in a final report

2.2.2. Progress of Research Tasks

An overview of each research task and progress-to-date is presented in this section.

Task 1 – Conduct literature search on strength maturity

For the cube vs. cylinder, (Graybeal & Davis, 2008) and (Kusumawardaningsih et al., 2015) presented the conversion factors for different UHPC specimen sizes; they presented only one conversion factor between all two different sizes. In contrast, it was found that the conversion factor is not constant for two different sizes, which will be discussed later in this report.
On the other hand, the strength maturity relationship, its procedures, and the equations for developing the strength-maturity relation for UHPC are the same for normal concrete and are mentioned in (ASTM C1856, 2017)However, later in this report, we found out that the strength-maturity relation needs to be adjusted to predict the early strength of UHPC starting from 12 hours.

Task 2 – Comparative assessment of cubes and cylinders for UHPC early strength

The objective of this task is to conduct large number of UHPC cube and cylinder tests with various sizes, that ranges from 2 to 4 inches in diameter or cube side length, and at different ages (10-, 12-, 14-, 18-, and 24-hours, as well as 3-, 7-, 14-, and 28-days). Moreover, at least three different UHPC mixes will be considered to cover a wide range of strength and mechanical properties. To establish accurate reference strength, careful cylinder preparation (surface cutting, grinding, and polishing) will be considered. So far, two non-proprietary UHPC mixes with 1% and 2% have been used to develop the conversion factors. It is found out that the conversion factor between two different sizes is not constant; for example, two different sizes can have multiple conversion factors, as shown in Table 1 along with figure 2 of one of the two mixes. On the other hand, conversion factors close to factors presented in the table and the figure appeared in the other mix. Such findings will be confirmed and adjusted statistically after studying more mixes of both proprietary and not proprietary. Further, it is still under study, however, whether the conversion factors depend on the curing history (maturity) or the specimen's age.

	Conversion Factors	
Time, days	4x4 to 3x6	2x2 to 3x6
0.47	0.47	0.70
0.52	0.79	1.12
0.61	0.97	1.16
0.78	0.86	0.94
0.90	0.84	0.88
1.01	0.75	0.84
2.03	0.94	0.82
3.01	0.73	0.80
6.71	0.89	0.77
28.02	1.33	1.06

Table 1: Strength conversion factors between both 4inx4in and 2inx2in cubes to 3inx6in cylinder

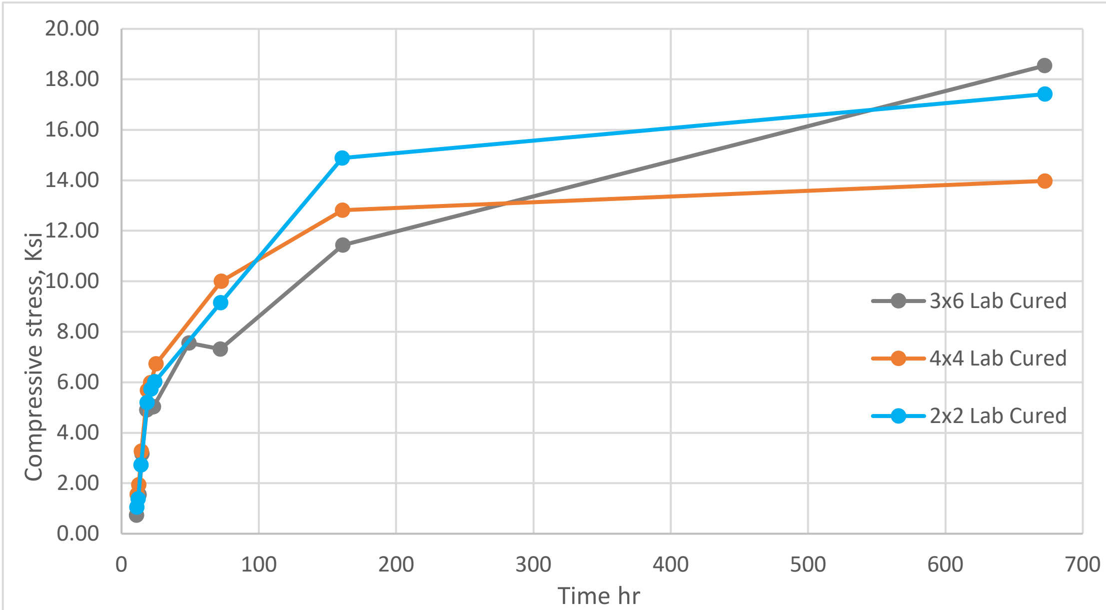

Figure 2: Strength gain for three different sizes

Task 3 – Establishing strength maturity large datasets using experimental testing.

Multiple maturity curves have been generated using the technology of three vendors: LumiCon, Giatec, and Maturix. All three sensors from the three vendors were implemented in both UHPC mixes that have been studied. Moreover, this task is divided into two parts, the first part is to assess the maturity equation and the curve, and the second part is meant to study the maturity constants (to and Q). what will be discussed here is part 1. However, part 2 is yet to be studied and discussed in the following quarter report.

To start with, since the primary focus in this research project is the early strength of UHPC as early as 10 hours to, for example, be able to confidently open the traffic after 10 – 12 hours of closure due to pouring the UHPC. So, the maturity curves for different specimen sizes and mixes were noticed to have a linear relationship at an early age, not logarithmic. However, after approximately 24 hours, the relationship turns to be logarithmic. Figure 2 shows the relation of both actual strength vs. maturity and estimated strength vs. maturity. Besides, the maturity equation for figure 2 was built using 10 points instead of 5, which is recommended by (ASTM C1856, 2017) to get an accurate equation to base it as a reference. However, the early age strength error for the time less than 24 hours was as high as 65%, which was why we turned our focus into using a linear equation for the early age.

Further, figure 2 shows two curves: the estimated strength vs. maturity and real strength vs. maturity, and both are similar. However, even though there is a similarity, the error is high at an early age (Table 2).

Finally, this behavior is repeated in the second mix as well. To confirm such behavior and further explore it, the other mixes that will be studied will provide more data to drive the equation with its terms statistically.

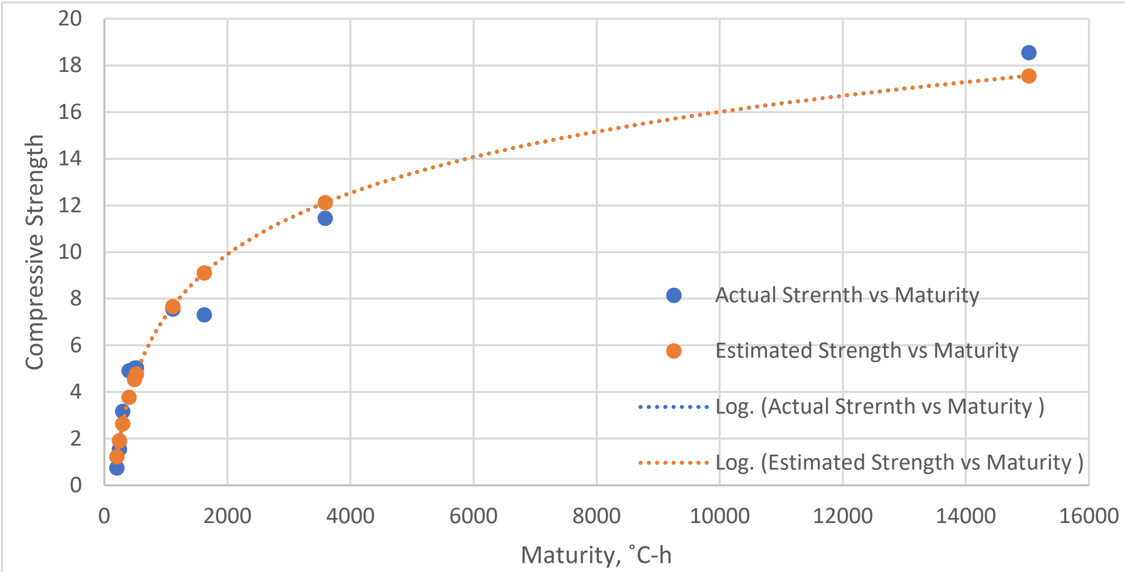

Figure 3: Strength Maturity relationship

Time, days	Actual Strength, Ksi	Estimated Strength, Ksi	Error %
0.46	0.74	1.23	65.52
0.53	1.55	1.90	23.08
0.62	3.17	2.64	16.75
0.77	4.91	3.77	23.23
0.92	5.02	4.54	9.65
0.98	5.04	4.77	5.38
2.05	7.55	7.66	1.48
3.00	7.31	9.10	24.47
6.72	11.44	12.11	5.88
28.01	18.54	17.55	5.34

Table 2: Error between the estimated and the actual strength

TASK 4 – Develop quality control guidelines for UHPC early strength characterization

This task is intended to properly complement the extensive experimental works done in Tasks 2 and 3 to develop some sort of construction specifications and guidelines for UHPC early strength characterization using cubes and the SMM. This effort will be presented as a means of quality control and assurance as opposed to strength characterization for design purposes. Thus, this task is expected to summarize and generalize correlation or conversion factors as well maturity curves for various range of UHPC mixes and sample sizes.

TASK 5 – Results dissemination and Final report

A final report will be prepared and submitted first to the advisory panel for review and comments then a revised version will be widely disseminated through the ABC-UTC. The report will be complemented with ABC-UTC guide for the quality control guidelines. Two journal papers are also expected to be produced from this project and will be submitted for potential publication in peer-reviewed journals.

2.3. ANTICIPATED RESEARCH RESULTS AND DELIVERABLES

- Final Report and ABC-UTC guide on early strength characterization and quality control for UHPC
- Two comprehensive manuscripts that assess the use of cubes versus cylinders for early strength characterization of UHPC and establishing strength maturity methods for UHPC
- Five-minute video summarizing research study and findings

2.4. APPLICABILITY OF RESULTS TO PRACTICE

The results from this project are expected to immediately benefit different states DOTs that have already implemented UHPC for ABC field joints and other applications.

3. TIME REQUIREMENTS (GANT CHART)

To allow for the completion of all the project tasks, the study will be conducted over a period of 15 months (5 quarters) following the schedule in Table 1.

Table 1 – Gantt schedule of major project tasks

Task	2021										2022				
	Mar	Ap	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1. Literature search															
2. Comparative UHPC cubes vs. cylinders															
3. Establish maturity curves															
4. Quality control guide															
5. Final report & dissemination															

	Completed or work in progress		Remaining

Percentage of completed work: 50%

Percentage of remaining work: 50%

4. REFERENCES

ASTM C1856. (2017). Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete. *ASTM International*, *i*, 4. https://doi.org/10.1520/C1856

Graybeal, B., & Davis, M. (2008). Cylinder or cube: Strength testing of 80 to 200 MPa (11.6 to 29 ksi) ultra-high-performance fiber-reinforced concrete. *ACI Materials Journal*, *105*(6), 603–609. https://doi.org/10.14359/20202

Kusumawardaningsih, Y., Fehling, E., & Ismail, M. (2015). UHPC compressive strength test specimens: Cylinder or cube? *Procedia Engineering*, *125*, 1076–1080. https://doi.org/10.1016/j.proeng.2015.11.165