NON-PROPRIETARY ULTRA-HIGH PERFORMANCE CONCRETE MIX DESIGN FOR ABC APPLICATIONS

Quarterly Progress Report
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1. Background and Introduction

Ultra-High Performance Concrete (UHPC) has received a significant attention for bridge applications, especially where superior strength and durability characteristics are critical (e.g., in joints). Although the high strength and durability of UHPC permits the production of thinner/lighter elements with a longer service life and less maintenance needs, use of UHPC in many of bridge projects is found cost prohibitive because commercially available/proprietary mixes can cost up to 20 times of conventional concrete mixes. This has motivated research efforts to develop cost-effective UHPC mixes through optimizing the cement content, replacing a portion of cement with supplementary cementitious materials, relying on less expensive granular materials, and removing special curing conditions (such as steam curing) from the production process. El-Tawil et al. [1] successfully developed cost-effective UHPC by replacing cement with ground granulated blast furnace slag and without use of silica powder and post-placement treatment. Ghafari et al. [2] provided an analytical model for developing a UHPC mixture with minimum cement content based on statistical mixture design. They succeeded in attaining a strength of 22 ksi without using steam curing and optimized minimum cement content. Yu et al. [3] successfully replaced a portion of cement with filler materials like limestone and quartz powder without any significant effect on strength of UHPC. Shi et al. [4] replaced a portion of cement with fly ash or slag; with proper particle size distribution, they developed UHPC with strength exceeding 22 ksi, even with normal curing. Soliman and Tagnit-Hamou [5,6] successfully replaced half of quartz with a less expensive glass powder [5] and 70% of silica fume with fine glass powder [6] producing similar compressive strength. Wille and Boisvert-Cotulio [7] used a range of readily available materials to find the least expensive combination for UHPC preparation. This study concluded that the UHPC exceeding 22 ksi can be developed without any special curing and use of ordinary mixers. The UHPC developed costs \$516/yd^3 without fibers and costs \$1029/yd^3 with steel fibers. Yail [8] developed non-proprietary UHPC for Colorado Department of Transportation using locally available materials and mentioned up to 74% cost reduction. Although this value was for when they compared their minimum non-proprietary UHPC cost (\$1535/yd^3 for no fiber UHPC) to the highest cost of proprietary UHPC (\$5886/yd^3) [8], so their cost still seems really high. Berry et al. [9], used masonry sand as replacement of filler and fly ash as supplementary cementitious materials in development of non-proprietary UHPC. Using Anderson- Andreason model, they were able to develop non-proprietary UHPC with a compressive strength of exceeding

20 ksi, with price as low as \$500/ yd^3. A study completed by FHWA [10] outlined promising advances made in the development of non-proprietary UHPC mixes with a material cost ranging from \$355 to \$500/yd^3, excluding the cost of fibers [10]. Addition of fibers was reported to increase the total costs by up to \$470/yd^3. The cost analysis showed that almost half of the total cost is to purchase of steel fibers. As steel fibers are the main contributor to the unit cost of UHPC and they are also prone to chloride-induced corrosion, there is a need to look for alternative fibers and optimize fiber contents in UHPC.

2. Problem Statement

Despite superior strength and durability, the use of UHPC in conventional concrete applications has been limited mainly due to cost considerations. This has motivated research efforts to develop cost-effective UHPC mixes through optimizing the cement content, replacing a portion of cement with supplementary cementitious materials, and relying on less expensive granular materials. As steel fibers are the main contributor to the unit cost of UHPC and they are also prone to chloride-induced corrosion, the two main objectives of this research project are (1) to identify the most optimal dosage(s), size(s), and shape(s) of steel fibers in practical applications, and (2) to explore the possibility of replacing part of steel fibers with alternative non-metallic fibers that are commonly less expensive and more available than their steel counterparts.

3. Objectives and Research Approach

This project will follow a systematic research plan to assess the strength and durability of UHPC mixes with (1) a range of dosages, sizes, and shapes of steel fibers, and (2) a hybrid of steel and non-metallic fibers. For this purpose, fresh and hardened properties of non-proprietary UHPC mixes will be investigated at ISU through a set of laboratory experiments.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Literature Review.

Proposed task description: The research team has conducted a preliminary review of relevant studies and projects completed to date in the United States and beyond. As the first task of this project, the research team will compile all related information available in journals, conference proceedings, and technical reports in a concise summary usable by the involved researchers and engineers. The main objective of this task is to obtain a comprehensive understanding of the studies that have investigated fibers for concrete applications with a focus on UHPC materials.

Description of work performed up to this period: *A literature review has been completed covering the studies on the development of non-proprietary UHPC and use of fibers (of various types and dosages) in UHPC. Additionally, effects of fibers of various types in fiber-reinforced concrete have been reviewed.*

Task 2 – Experimental Tests on UHPC Mixes with Steel Fibers.

Proposed task description: There are several factors that affect the performance of fibers in concrete mixes, including dosage, size, and shape. A set of criteria will be employed to evaluate the adequacy of the developed UHPC mixes and optimize the use of steel fibers. The criteria of interest will examine early-age shrinkage cracking, transportation of aggressive ions, freeze/thaw cycles, and abrasion resistance, while maintaining proper workability, strength, and toughness characteristics.

Description of work performed up to this period: For the purpose of this task, the developed non-proprietary UHPC mixes in ISU were optimized using various combinations of ingredients and changing the maximum size of solid particles. Investigation on the effect of steel fiber dosage (0 to 3%) and steel fiber type on the properties of optimized non-proprietary UHPC has been completed. In addition to the straight steel fibers, two more types of fiber, namely, steel hooked and twisted wire fibers, have been tested.

Details of material:

The materials used for the production of non-proprietary UHPC included cement, silica fume, regular sand, masonry sand, steel fiber, high range water reducer (HRWR) and water. The ASTM Type I cement was used in this study. The specific density of cement was 3.10. The list of this cement's chemical oxides can be found in Table 1. The regular laboratory fine aggregate (0 - 4.75 mm (0.1850 in)) was used. This was modified in such a way that the maximum size remaining is 2.38 mm (0.0937 in). The specific density of fine aggregate was 2.72. The masonry sand used was 15% of the total sand to obtain the maximum particle packing in accordance to the Anderson-Andreason particle packing. The particle size distribution of laboratory sand, masonry sand, cement and silica fume is shown in Figure 1(a). The steel fibers had a diameter of 0.2 mm (0.00788 in) and a length of 13 mm (0.5120 in).

Table 1 Chemical oxides of cement and silica fume.

Type of Binder	CaO	SiO_2	SO_3	Fe_2O_3	Al_2O_3	MgO	K_2O	Na_2O	TiO_2
Portland cement	62.94	20.10	3.18	3.09	4.44	2.88	0.61	0.10	0.24
Silica fume	0.3	94.3	-	0.1	0.09	0.43	0.83	0.27	-

Mix proportions:

The mixture proportioning of non-proprietary UHPC was developed by using the modified Anderson-Andreason curve to ensure maximum particle packing. The mixtures were made by selecting a range of 1.2 to 1.4 for sand-to-cement ratio. Using this range, three non-proprietary mixtures were prepared. The mix designs showed in Figure 1(b) were developed by fixing the sand-to-cement ratio at 1.2 for mix M2 and 1.4 for mix M1. For these two mixtures, sands passing 2.38 mm (0.0937 in) sieve were used. On the other hand, Mix M3 was prepared with an especial preparation of sand. For this mixture, sand was sieved and separated. Then, the exact amount of sand fitting the target curve was used.

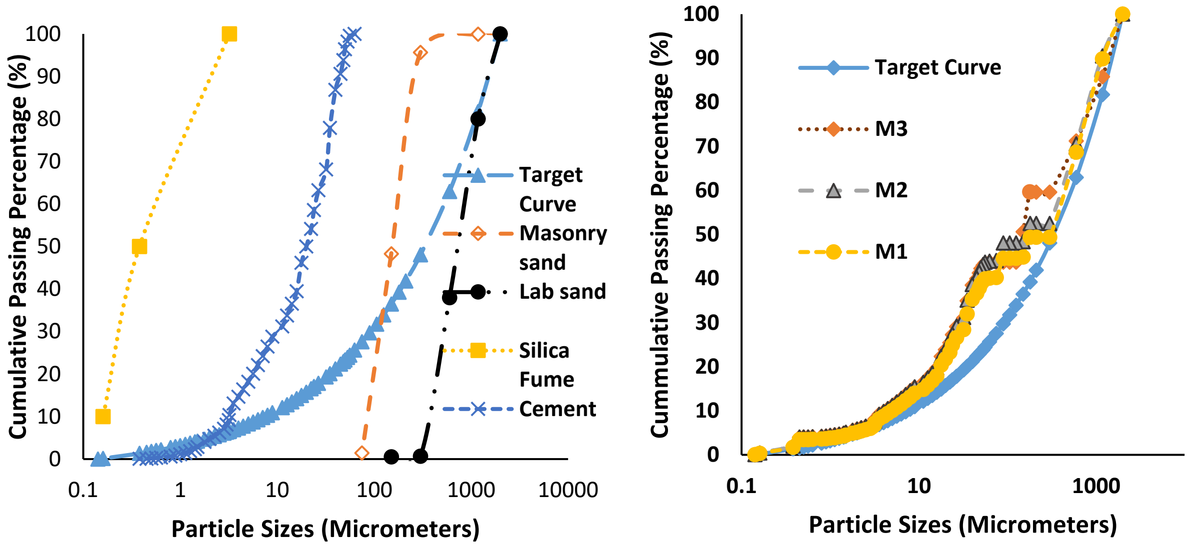


Figure 1 (a) Particle size distribution of materials used in non-proprietary UHPC mixtures, (b) Anderson- Andreason curves for mixtures M1, M2, and M3

Testing procedure:

The samples of the prepared mixtures were tested for flow, compressive strength, rapid chloride penetration, rapid chloride migration, and surface resistivity. The flow was measured using the flow table modified by ASTM C143 for testing flow of mortars. This was measured in accordance with the standard, except that 25 drops of flow table was removed as the developed UHPCs were self-consolidating. The compressive test was done in accordance to ASTM C39 on three 100×200 mm (4×8 in) cylinders. The ends of cylinders were grinded before testing for compressive test, as the strength of UHPC samples is usually higher than the capping materials used for testing normal concrete samples. The rapid chloride penetration test (RCPT) was performed according to ASTM C1202 on 50×100 mm (2×4 in) disks. The rapid chloride migration test (RMT) was conducted in accordance to NT BUILD 492 on 50×100 mm (2×4 in) disks. The surface resistivity was measured in accordance with ASTM WK37880 using 100×200 mm (4×8 in) cylinders. The results from these tests are shown in the Table 2.

Table 2 Flow, Compressive strength, Resistivity, Chloride Migration Depth, and Chloride Migration Coefficient of UHPC Mixes

Mix	**P1**	**P2**	**M1**	**M2**	**M3**
Flow (in)	8.5	8.5	8.5	8.5	8.0
Compressive strength (ksi)	17.0	14.6	14.1	14.2	14.7
Resistivity (kohm.cm)	60.0	23.5	8.0	8.5	20.2
Migration depth (mm)	4.71	3.90	5.64	5.98	6.24
Migration Coefficient (×E-12 m^2/s)	1.90	1.51	2.32	2.48	2.62

Results and discussion:

The flow of UHPC mixtures were measured similar to mortars by using a flow table, except that 25 drops of the flow table was removed. The mix was allowed to spread and the flow was measured after the mix stopped. The results of flow test are reported in Table 2. It can be seen that all the mixtures had a similar flow of 203 mm (8.0 in) to 216 mm (8.5 in). This confirms that they can all be consolidated properly. The compression test was conducted on three cylinders of each mixture at the age of 7 days and their average values are tabulated in Table 2. Among the developed non-proprietary mixtures, the compressive strengths for mix M3, i.e., the mix with modified sand, showed the highest strength followed by mixtures M2 and M1. The compressive strength of these mixtures were almost in the same range of the compressive strength of proprietary mix P2, while compressive strength of all mixes were lower than the compressive strength of proprietary mix P1. The compressive strength of all mixtures were sufficient to be used as UHPC. It should be noted that there have been debates on the strength required for a concrete to be considered UHPC, whether considerably high strength is needed when an exceptional durability performance is provided, or if strength is the critical aspect for a UHPC mixture. The surface resistivity was measured on three cylinders of each mixture and their average values are provided in Table 2. The surface resistivity for the proprietary mix P1 was the highest followed by the proprietary mix P2. The resistivity for Mix 3 was almost equal to the resistivity of proprietary mix P2, however, mixes M1 and M2 showed lower values for resistivity. This observation raised the question if the developed non-proprietary mixtures can provide similar resistance against chloride penetration *to proprietary mixtures. The samples were tested for chloride penetration with both RCPT and RMT. The results from RCPT showed surprisingly high current values in the range of 3000 to 10000 Coulombs in different non-proprietary mixtures, as expected based on the surface resistivity values. To understand if the mixtures are vulnerable to chloride attack or if resistivity and RCPT are proper tests for such an evaluation, a rapid chloride migration test was devised. While RCPT measures the charge passed through the concrete sample and relates it to chloride ion penetration, the measurement in RMT is by spraying silver nitrate on the split sample and observing the depth of penetrated chloride ions through the formation of silver chloride (white silver chloride forms when silver nitrate reaches and reacts with penetrated chloride). The results of RMT, documented in Table 2, showed that the chloride migration in non-proprietary and proprietary UHPC mixtures were almost in the same ranges*

Optimization of base mix

The base mix M2 developed in the results presented above was further modified by changing the maximum particle size, the sand to cement ratio and the silica fume to cement ratio in the UHPC mixtures. The modified Anderson-Andreason curve depends on two major aspects, the distribution modulus and the maximum particle size. To explore the effect of these two factors on the strength development of UHPC, six mixes were developed using the proportioning of mix M2. The maximum particle size of sand was reduced from 2.38 mm to 0.6 mm. The distribution modulus was also varied from the initial selection of 0.37. Two further values 0.23 and 0.30 were evaluated for the distribution modulus. Three additional sand to cement ratios 0.8, 0.9 and 1.0 were evaluated. The change in the particle sizes resulted an increase in the compressive strength, as smaller particle sizes result in reduced pore volumes. The compressive strength increased to 15.2 ksi for maximum particle size of 0.6 mm from 14.1 ksi for maximum particle size of 2.38 mm. The results for the change in distribution modulus are shown in Figure 2. The distribution modulus of 0.37 resulted in the highest compressive strength.

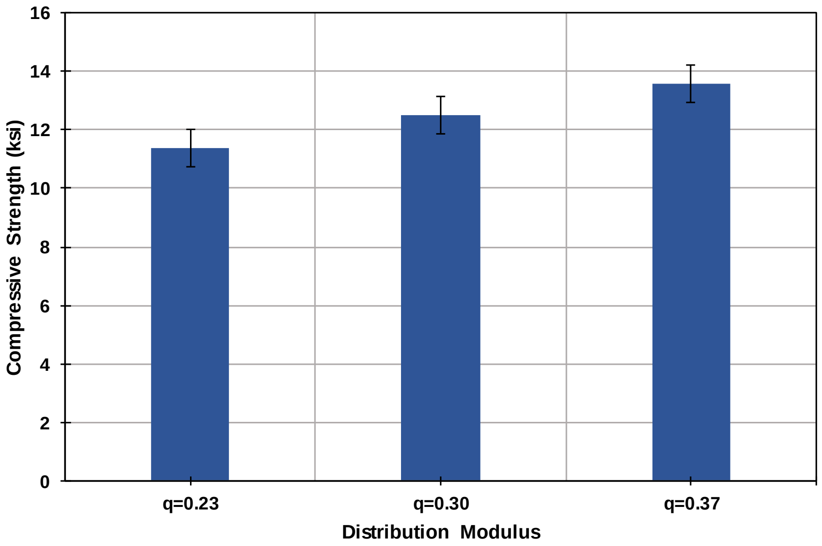


Figure 2 Effect of distribution modulus on compressive strength

The sand to cement ratio plays an important role in the strength gain of UHPC, as more cement is available for hydration and filling the voids produced between coarser sand particles. To further understand this effect, three additional sand to cement ratios were evaluated in addition to the base mix of M1. The results presented in Table 3 show that the mix with sand to cement ratio of 1 resulted in the highest compressive strength. The surface resistivity increased with lower sand to cement ratio, however, the same trend was not observed in the absorption values of the samples.

Table 3 Results for varying sand to cement ratio

S/C ratio	7-Day Compressive Strength (ksi)		Resistivity (kΩ-cm)	Absorption (%)
	Cylinders	Cubes		
0.8	11.35	14.02	13.6	6.4
0.9	12.68	13.91	13.3	5.11
1.0	12.35	15.15	9.4	5.58
1.2	11.13	14.30	9.6	6.04

Evaluation of effects of types of steel fibers

For all the mix proportions discussed above, the fiber percentage was kept at 2% by volume of concrete. The literature review shows that the dosage as well as the size and types of fiber has a significant effect on the properties of resulting UHPC mixtures. A range of steel fiber dosages and types were used to understand their effects on the performance of UHPC mixes. The dosage of steel fibers was considered from 1% to 3% by volume of total UHPC mix. Five different mixtures (S1, S1.5, S2, S2.5 and S3) were prepared for different dosages of steel fibers. Two mixes were prepared using 2% of wire and 2% of hooked fibers. Additionally, four more mixtures were prepared utilizing a combination of straight steel fibers with twisted wire fibers (S1T1 and S0.5T1.5), and hooked fibers (S1H1 and S0.5H1.5). The entire mixing matrix is shown in Table 4.

Table 4 Testing matrix for evaluating effects of variation in dosage and type of steel fibers

	S1	**S1.5**	**S2**	**S2.5**	**S3**	**S1T1**	**S0.5T1.5**	**T2**	**S1H1**	**S0.5H1.5**	**H2**
Steel (S)	1.0	1.5	2.0	2.5	3.0	1.0	0.5	-	1.0	0.5	-
Twisted Wire fibers (T)	-	-	-	-	-	1.0	1.5	2.0	-	-	-
Hooked fibers (H)	-	-	-	-	-	-	-	-	1.0	1.5	2.0

Test Plan and results

The testing for these mixes is focused on determining the fresh properties and mechanical strength of the proposed mixtures. Since, the fibers vary in length and geometry they result in variation in workability and bond strength within the matrix. Upon completing the planned tests, an in-depth insight will be provided on how these fibers are affecting the fresh properties as well as the mechanical properties of the developed UHPC mixes. The testing and data processing activities have been completed. The fresh and mechanical properties of the mixes have been evaluated. A preliminary processing of the results shows that an increase in both compressive and flexural strengths with an increase in the percentage of fibers. The increase in fiber content, however, has adverse effect on the flow. In particular, the high steel percentages required an increase in high range water reducer.

The combination of different fiber types (twisted wire steel fibers and hooked steel fibers) with the straight type resulted in variation in flow, compressive strength, and flexural strength. These properties differed depending on the types of fibers, as well as the percentage of the fibers. From the combination of different fiber combinations shown in Table 4, the S0.5T1.5 combination resulted in highest compressive strength, while the S1T1 combination resulted in the highest flexural strength.

Task 3 – Experimental Tests on UHPC Mixes with Hybrid Fibers.

Proposed task description: Despite several research studies on UHPC aiming at establishing various applications where superior strength and durability characteristics are required, the research on replacing steel fibers in UHPC with non-metallic fibers is limited. This is, however, important as steel fibers are expensive, heavy, and face the issue of chloride-induced corrosion (although claimed to be minimal by proprietary UHPC mix producers). With recent advances in the development of inexpensive, low-density, corrosion-free, high-tenacity, non-metallic fibers, it is believed to be a promise to use synthetic and glass fibers in UHPC mixes. This promise will be explored through this research task in a systematic way through a test plan similar to the one described in Task 2. To improve the post-cracking tensile properties of UHPC, hybrid fiber reinforcing systems have been introduced by some studies. In the proposed project, blended macro- and micro-fibers will be tested for a hybrid mix to benefit from macro-fibers to efficiently improve post-cracking ductility and micro-fibers to increase the tensile strength.

<u>Description of work performed up to this period</u>*: A detailed literature review on the effect of synthetic fibers and hybrid fibers has been completed. Three types of fibers namely Polyvinyl Alcohol (PVA), Nylon, and Polypropylene fibers were evaluated in combination with steel fibers. The performance of the mixtures was evaluated with a main focus on workability and flexural strength. The tests have been completed and the research team is now working to prepare the report, including supporting discussions and details.*

Task 4 – Mix Design Recommendations.

Proposed task description: Based on the original results of Tasks 2 and 3, different combinations of steel and non-metallic fibers will be selected and mix design recommendations will be made for future use. This will be in a close collaboration with the other ABC UTC partner institutions.

Description of work performed up to this period: The results obtained from Task 1 will be used to recommend a set of mixes that can be designed by utilizing micro steel fibers only. The information from the investigations performed in Task 2 will also be used to recommend optimum combinations of steel micro and macro fibers. The Task 3 results will then be finally utilized to provide mix recommendations regarding the best non-metallic fiber replacement for steel fibers. The criteria for the selection of a hybrid combination of fibers will be mechanical performance and workability.

Task 5 – Final Report.

Proposed task description: A detailed final report will be prepared to document the activities of the project further to the main observations and findings.

Description of work performed up to this period: The research team has made a good progress in preparing the draft final report. This draft will be submitted to the project's advisory panel members for their review and feedback.

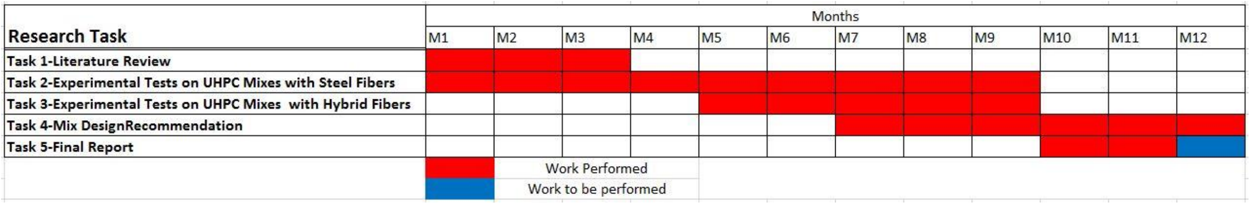
5. Expected Results and Specific Deliverables

This research project directly contributes to expanding the use of UHPC materials for ABC projects. Further to addressing the issues associated with the strength and durability of non-proprietary UHPC mixes, the cost of the final product is minimized by optimizing the use of steel fibers and also exploring the possibility of replacing them with other less expensive choices of fiber. Through a joint effort with other ABC UTC institutions, the promise of time and cost saving will be realized in a variety of practical applications. This can greatly help transportation agencies benefit from UHPC as a superior material for high-quality bridge elements and systems.

6. Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	96%



	Months											
Research Task	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Task 1-Literature Review	🟥	🟥	🟥									
Task 2-Experimental Tests on UHPC Mixes with Steel Fibers	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
Task 3-Experimental Tests on UHPC Mixes with Hybrid Fibers					🟥	🟥	🟥	🟥	🟥			
Task 4-Mix DesignRecommendation							🟥	🟥	🟥	🟥	🟥	🟥
Task 5-Final Report										🟥	🟥	🟦

🟥 Work Performed
🟦 Work to be performed

7. References

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