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 22ksi 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. While the former efforts have made advances in the development of non-proprietary UHPC mixes [1-9], the cost of the final product has still remained too high for an immediate implementation. A study completed by FHWA (2013) 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. In a very recent study completed at Iowa State University (ISU) by the proposing team, it was proven that the total material cost can be reduced to \$450/yd^3 if non-proprietary mixes with local materials are developed [11]. 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, 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: To prepare the current proposal, 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.

<u>Description of work performed up to this period</u>: *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 further 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%) on the properties of optimized non-proprietary UHPC is almost completed. The remaining work includes investigation of the effect of steel fiber type and length on the properties of optimized non-proprietary UHPC. For this purpose, different types of steel fiber have been prepared (coated and uncoated high carbon steel wire in two different sizes of 13 and 25 mm). The results of this fiber can be compared with round straight, 13 mm steel fiber used in this investigation.

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.

Description of work performed up to this period: Two types of fibers have been selected and ordered including micro- and macro-fibers. These fibers will be tested with the type of steel fiber chosen from the results of Task 2.

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: This task has been started and general mix design recommendation for steel fiber contained UHPC mix is ready. For hybrid mix design, however, it is in need of more information from the results of third task.

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: Not started.

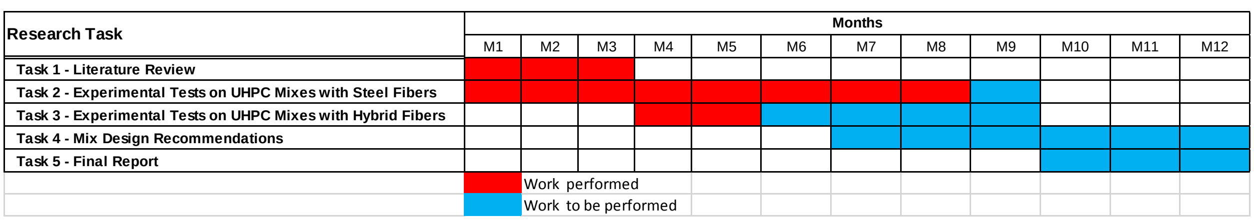
5. Expected Results and Specific Deliverables

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	55%



7. References

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