TECH**BRIEF**

# Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector

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## Objective

The long-term goals of this study are to facilitate the use of ultra-high performance concrete (UHPC) among U.S. suppliers and contractors, accelerate its application in U.S. construction, and promote a more resilient and sustainable future U.S. infrastructure. In pursuit of these goals, the objective of this research was to develop a non-proprietary cost effective UHPC characterized by compressive strength exceeding 20 ksi (138 MPa), pre- and post-cracking tensile strength above 0.72 ksi (5 MPa), and sufficient durability properties. The mix designs were optimized in their efficiency considering workability, mechanical performance, and cost effectiveness. In support of cost effectiveness, locally available materials were used from selected areas in the United States. The results of the research effort are summarized herein, and mix designs are suggested for the following three regions: the Northeast area in the vicinity of New York, Connecticut, and New Jersey; the upper Midwest area in the vicinity of Iowa, Minnesota, and Michigan; and the Northwest area in the vicinity of Washington and Oregon.

## Introduction

UHPC has attracted the growing interest of researchers in academia, engineers in the public and private sectors, and contractors across the world due to its highly enhanced mechanical and durability properties in comparison to conventional

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concrete. It is generally understood that UHPC is a concrete that uses a relatively high binder ratio, has a water-to-cement (w/c) ratio of 0.24 and lower, and has a compressive strength in excess of 22 ksi (150 MPa). Low matrix porosity and high particle packing density leads to significantly higher durability at a similar unit weight compared to conventional concrete. The addition of discontinuous fibers leads to significantly higher ductility and durability of the cracked matrix. Although there are many advantages of UHPC over conventional concrete, there is currently only one commercial supplier to the transportation infrastructure market in the United States. The commercially available product is a proprietary blend and is sold for about $2,000/yd$^3$ ($2,600/m$^3$). This price includes the material costs of the proprietary blend and the fiber reinforcement, as well as costs associated with the development and delivery of said material. Commercially available UHPC is about 20 times more expensive than conventional concrete, which is about $100/yd$^3$ ($130/m$^3$). The proprietary nature, increased quality control, and high material costs are some factors that have limited the wide spread use of UHPC in the U.S. infrastructure.

Previous research efforts by Wille et al. show that non-proprietary UHPC can be designed to achieve a compressive strength in excess of 29 ksi (200 MPa) by using materials available in the United States under ambient curing conditions without the need of special treatment such as heat, steam, or pressure. (See references 1–4.) The basic principles of UHPC design include high particle packing density, high-quality materials, cement hydration, pozzolanic reactions and filler effect of supplemental materials, high particle dispersion quality, and optimized particle to high-range water reducer interaction. Based on these principles and on the experimental results of prior research, the material constituents for designing UHPC are predefined, and their approximated median particle size (50 percent) as well as their range of particle size distribution (10 and 90 percent) are recommended in table 1. (See references 1–4.)

Prior research results suggest the following mix proportions for designing UHPC by weight ratios as follows:

- Cement : silica fume : supplemental material = 1.0 : 0.25 : 0.25.
- w/c ratio = 0.2–0.3.
- Aggregate : cement ratio = 1.0–2.0.
- Fiber volume fraction = 1.0–2.0 percent.

## Research Approach

Based on prior experimental UHPC material development, the material constituents

Table 1. Recommended material constituents for UHPC matrix design.

| Type | Particle Size | | | Comments |
|---|---|---|---|---|
| | Median | 10 Percent | 90 Percent | |
| Water | N/A | N/A | N/A | N/A |
| High-range water reducer (HRWR) | N/A | N/A | N/A | Best in workability and air release |
| Silica fume | 0.2–1 µm | 0.1 µm | 2 µm | Low carbon content |
| Supplemental material | 2–5 µm | 1 µm | 10 µm | Filler effect, spherical shape, and pozzolanic reaction preferred |
| Cement | 10–20 µm | 3 µm | 40 µm | Low tricalcium aluminate and high combination of tri- and dicalcium silicate |
| Fine aggregate 1 | 100 µm | > 50 µm | < 300 µm | High quality, high strength, low water absorption, and optimized particle packing |
| Fine aggregate 2 | 500 µm | > 300 µm | < 1,000 µm | |
| Coarse aggregate | N/A | > 1,000 µm | < 9 mm | |

1 inch = 25,400 µm
1 inch = 25.4 mm
N/A = Not applicable.

necessary for UHPC were defined, and lists of locally available materials in the three regions previously specified were created. This included a list of cements, silica fumes, supplemental materials, HRWRs, aggregates, and fibers. Next, these materials were preselected based on availability, cost, region, particle size distribution, and chemical and physical composition. Finally, 12 types of cement, 5 silica fumes, 13 supplemental materials, 8 high-range water reducers, 10 aggregate variations, and 5 different fiber reinforcements were ordered for experimental investigation and included in the research program.

UHPC material development is based on a multilevel material approach that emphasizes the optimization of the cementitious paste (phase I), the optimization of the cementitious matrix (phase II), and the optimization of the cementitious composite (phase III). The progressive development of paste, matrix, and composite was chosen to reduce the effort in developing a cost effective UHPC over a short time frame.

The most critical component in UHPC design is developing an ultra-high strength paste to bind aggregates and fibers together. This can be achieved by optimizing the paste's particle packing density. The optimization of the paste is typically focused on its flow characteristic and its compressive strength to expedite the development process. By optimizing the two material properties, it is hypothesized that a basic material will be developed, which will lead to sufficient strength and durability of the UHPC.

In this study, first a reference mix was created. Then, other mixtures were created by replacing only the material in question by volume (e.g., the type of cement). Air content of each specimen, differences in the w/c ratio, and variation in the testing age were taken into account to satisfy comparability between the mixtures and to be able to draw adequate conclusions about the effect of the investigated parameter.

Based on the workability, the compressive strengths, and the material costs, the efficiency parameter *E* can be calculated, which determines performance versus cost. Each component of the paste is evaluated in this regard, and the component with the best efficiency out of each series is chosen to form the optimized paste, which is used for the UHPC matrix design in phase II and the fiber-reinforced UHPC composite design in phase III.

The efficiency parameter *E* is unitless and is defined as shown in figure 1.

Figure 1. Efficiency parameter *E*.

$$E = \frac{0.7 \times \dfrac{f'_{c,N}}{f'_{c,N,\emptyset}} + 0.3 \times \dfrac{spread_N}{spread_{N,\emptyset}}}{\dfrac{cost_p}{cost_{p,\emptyset}}}$$

Where:

$f'_{c,N}$ = 28-day compressive strength normalized at w/c ratio = 0.25 and at an air content = 3 percent.
$f'_{c,N,\Phi}$ = Average normalized 28-day compressive strength over all pastes of one series.
$spread_N$ = Spread value normalized at w/c ratio = 0.25.
$spread_{N,\Phi}$ = Average normalized spread value over all pastes of one series.
$cost_p$ = Cost of the paste per $yd^3$ ($m^3$).
$cost_{p,\Phi}$ = Average cost over all pastes of one series per $yd^3$ ($m^3$).

The factors 0.7 and 0.3 were chosen to consider strength with higher priority over workability.

Phase II focused on the effect of incorporating different types of aggregates into the mix design. Aggregates were primarily selected based on locality, type of material, size, and cost. Four types of aggregates were selected including quartz (Q), basalt (B), limestone (L), and volcanic rock (VR). High-purity Q was selected from a major supplier and can be ordered in different regions of the United States. B was chosen from the Northeast, L was chosen from the upper Midwest, and VR was chosen from the Northwest. At least one type of fine aggregate (smaller than 0.047 inch (1.2 mm)) and one type of coarse aggregate (smaller than 0.5 inch (12.5 mm)) was selected for each material based on gradation tables. Particle packing density of the aggregates is an important parameter to control workability, strength, and durability. Optimization in particle size distribution leads to high particle packing density.

In this study, the selected particle size distribution follows the modified Andreasen and Andersen curve.(5) The optimization of the UHPC matrix is focused on compressive strength, workability, and cost effectiveness in accordance to the paste development. Optimization parameters include the type and form of aggregate, the maximum aggregate size, the particle size distribution, and the aggregate-to-cement ratio.

Phase III focused on the effect of fiber reinforcement to enhance ductility and achieve a sufficient tensile strength. Since the types of fiber commonly used in UHPC design are primarily supplied by companies outside the United States, special emphasis is placed on the selection of appropriate types of fibers available in the United States.

## Mixing, Preparing, and Testing

Aside from a well-graded particle distribution, particle dispersion is important in creating a high particle packing density. Because UHPC has particles much smaller than those in conventional concrete, the mixing procedure has to be adjusted to ensure that agglomerations of these small particles are being broken and that the particles will be homogenously dispersed. In pursuit of this goal, the materials are first mixed dry according to the mixing proportions and procedure in Wille et al.(1) Depending on the materials being used, the mixture becomes fluid within 5 to 10 min. An open, ½ horsepower rotary bench top mixer with a 3-gal (11-L) bowl was used at low to medium speeds for dry mixing and at a high speed once turnover was achieved.

Each mix was evaluated for workability by testing the spread value in accordance with ASTM C230/C230M.(6) After mixing the paste, the UHPC matrix or the fiber-reinforced UHPC material was filled into three cylinders 3 inches (76.2 mm) in diameter and 6 inches (152.4 mm) in nominal length for compression testing and into the spread cone for workability testing. Special emphasis was placed on keeping the spread cone and the base plate at similar humidity prior to testing. After mixing and casting the specimens on a vibration table, the specimens were covered with plastic sheets for one day, de-molded, and placed in a temperature-controlled water bath of ambient temperature for 28 days until compression testing. No heat, steam, or pressure treatment was applied. In addition to consistency in curing conditions, special emphasis was placed on achieving planeness and perpendicularity of the load-faced cylinder ends by using a combination of a cylinder end grinder, a rotary grinding/polishing machine, and a dilatometer to achieve high consistency in compressive strength testing.

Once the specimens were prepared for testing, they were centrically placed in a deformation-controlled hydraulic compression load frame with a capacity of 400,000 lbf (1780 kN). The load platen of the machine displaced at a rate of 0.02 inch/min (0.5 mm/min) to load the specimen leading to failure within 3 to 5 min, which equates to an approximate load rate of 150 psi/s (1.0 MPa/s).

In addition to compression tests, fiber-reinforced UHPC was tested in direct tension. For each series, three prism-shaped specimens with a geometry of 2 × 1 × 14 inches (51 × 25 × 356 mm) were cast and tested at 28 days. Once the specimens had been prepared for testing, they were centrically placed in a displacement controlled hydraulic tensile load frame with a capacity of 60,000 lbf (267 kN). The specimens' ends were gripped with self-aligning, self-tightening mechanical jaws. Two displacement transducers were attached to the specimens' side with a gage length of 5.5 inches (140 mm).

The degradation of UHPC to freezing and thawing cycles was quantified according to ASTM C666.(7) UHPC prisms with a geometry of 3 × 4 × 16 inches (76 × 102 × 406 mm) were cast for this test. After 7 days of curing in a temperature-controlled water bath of 68 °F (20 °C), the specimens were subjected to freezing and thawing while submerged in a water bath. The apparatus used was set for four freeze-thaw cycles per day. The lower and upper temperature values were set to -9 and 37 °F (-23 and 3 °C), respectively.

## Results

Table 2 summarizes the costs for each material used in this research. The cost ranges highlight the potential of successfully developing a cost effective UHPC.

Table 2. Costs of materials used in the research.

| Material | Cost |
|---|---|
| Cement | $92–$250/T |
| Silica fume | $350–$1100/T |
| Supplemental material | $46–$879/T |
| HRWR | $13–$20/gal |
| Fine aggregate | $8.5–$162.5/T |
| Coarse aggregate | $8.25–$19/T |
| Fibers | $2,800–$13,300/T |

1 T = 0.907 Mg
1 gal = 3.785 L

Based on the material efficiency and availability, seven mix proportions are recommended in the following section, including their workability, strengths, and costs.

The results of workability and strength of the pastes with the selected cements led to the conclusion that all investigated white cements type I (~$250/T (~$275/Mg)), oil well cements (~$130/T (~$140/Mg)), and portland cements type II/V (~$110/T (~$120/Mg)) performed suitably for UHPC design with compressive strength in excess of 23 ksi (160 MPa). Pastes with portland cement type III (~$100/T (~$110/Mg)) performed somewhat less suitably. The highest efficiency was achieved by portland cements type II/V. The preferable silica fume ($550/T ($605/Mg)) is a silica fume of light grey color, low carbon content (< 0.7 percent), and a median particle size of about 0.000016 inch (0.4 micrometer). The group of supplemental materials consisted of silica powder, fly ash, metakaolin, ground granulated blast furnace slag, and lime stone powder. All selected supplemental materials performed suitably for UHPC design with compressive strengths from 23 to 29 ksi (160 to 200 MPa). The most efficient supplemental material was fly ash due to its low cost of about $50 to $60/T ($55 to $65/Mg), spherical particle shape for enhanced flowability of the paste, acceptable median particle size of about 0.0004 inch (10 micrometers), potential to pozzolanicly react with the byproducts of the cement hydration, its availability, and positive environmental impact. All selected HRWR performed suitably in terms of compressive strength. HRWR with best workability and air release was chosen for final consideration.

Adding aggregates to the paste led to the development of the UHPC matrix. The following two types of UHPC matrices were defined:

- UHPC with fine aggregates only up to a maximum particle size of 0.047 inch (1.2 mm).
- UHPC with fine and coarse aggregates up to a maximum particle size of 0.37 inch (9.5 mm).

Each UHPC matrix consisted of the constituents of the chosen paste and different type of aggregates optimized in their particle size distribution. An aggregate-to-cement ratio of 1.5 was selected for all fine and all coarse UHPC. All matrices were characterized by excellent workability by using a w/c ratio in the range of 0.21 to 0.24. All matrices with coarse aggregates demanded less water to achieve comparable spread values in comparison to matrices with only fine aggregates. Despite a slightly increased w/c ratio, all fine UHPC matrices achieved higher compressive strengths than the coarse UHPC matrices with the same type of aggregate (see table 3 and table 4).

In terms of type of aggregates, the highest compressive strength values were achieved by matrices with Q, followed by B, VR, and L. Based on availability, performance, and costs, it is recommended to use fine B and fine L in the Northeast and the upper Midwest, respectively. Both matrices with fine B and fine L achieved compressive strength above the minimum of 20 ksi (138 MPa), and both type of aggregates are low cost (< $14/T ($15/Mg)). Fine VR can be used as fine aggregates in UHPC in the Northwest. The matrix with fine VR had a compressive strength of 23.5 ksi (162 MPa), which exceeded the minimum required compressive strength of 20 ksi (138 MPa). Coarse L is a suitable option to be used as coarse aggregate in the UHPC matrix design for the upper Midwest. L is reasonably priced ($8.25/T ($9.10/Mg)), and the matrix had a compressive strength of 22.5 ksi (155 MPa), which exceeded the required compressive strength of 20 ksi (138 MPa). Coarse B and coarse VR are the most suitable aggregates for the Northeast and the Northwest, respectively. Q is more expensive ($163/T ($179/Mg)) than the local aggregates discussed, but it is widely available in the United States and outperformed all other aggregates in workability and strength.

By using portland cement type II/V and less expensive silica fume, the costs for UHPC with acceptable performance can be decreased to $260/yd$^3$ (340/m$^3$).

Table 3. UHPC mixtures with fine aggregates only and no fibers.

| Material/Topic | UHPC-1 (B; Northeast) | UHPC-2 (L; Upper Midwest) | UHPC-3 (VR; Northwest) | UHPC-4 (Q; United States) |
|---|---|---|---|---|
| White cement (lb/yd$^3$) | 1,311 | 1,268 | 1,256 | 1,248 |
| Silica fume (lb/yd$^3$) | 328 | 317 | 314 | 312 |
| Fly ash (lb/yd$^3$) | 318 | 308 | 305 | 303 |
| HRWR (lb/yd$^3$) | 48 | 46 | 45 | 45 |
| Fine aggregate (75µm–1.2 mm) (lb/yd$^3$) | 1,966 | 1,903 | 1,884 | 1,871 |
| Aggregate-to-cement ratio | 1.5 | 1.5 | 1.5 | 1.5 |
| w/c ratio | 0.23 | 0.24 | 0.23 | 0.23 |
| Spread (inch) | 11.4 | 10.4 | 11.3 | 12.4 |
| Average compressive strength at 28 days (ksi) | 26.9 | 24.1 | 23.5 | 29.0 |
| Cost ($/yd$^3$) | 494 | 472 | 496 | 652 |

1 lb/yd$^3$ = 0.593 kg/m$^3$
1 inch = 25,400 µm
1 inch = 25.4 mm
1 ksi = 6.89 MPa
1 yd$^3$ = 0.765 m$^3$

Table 4. UHPC mixtures with fine and coarse aggregates and no fibers.

| Material/Topic | UHPC-5 (B; Northeast) | UHPC-6 (L; Upper Midwest) | UHPC-7 (VR; Northwest) |
|---|---|---|---|
| White cement (lb/yd$^3$) | 1,311 | 1,278 | 1,256 |
| Silica fume (lb/yd$^3$) | 328 | 320 | 314 |
| Fly ash (lb/yd$^3$) | 318 | 310 | 305 |
| HRWR (lb/yd$^3$) | 47 | 46 | 45 |
| Fine aggregate (75µm–9.5 mm) (lb/yd$^3$) | 1,966 | 1,917 | 1,884 |
| Aggregate-to-cement ratio | 1.5 | 1.5 | 1.5 |
| w/c ratio | 0.23 | 0.22 | 0.23 |
| Spread (inch) | 10.8 | 10.4 | 10.9 |
| Average compressive strength at 28 days (ksi) | 26.3 | 22.5 | 23.1 |
| Cost ($/yd$^3$) | 494 | 475 | 463 |

1 lb/yd$^3$ = 0.593 kg/m$^3$
1 inch = 25,400 µm
1 inch = 25.4 mm
1 ksi = 6.89 MPa
1 yd$^3$ = 0.765 m$^3$

In order to exceed the required sustained tensile strength of 0.72 ksi (5 MPa), fibers were added by 1.5 volume percent and replaced by the same volumetric amount of aggregate. The best performance was achieved by straight high-strength steel fibers (0.0078 inch (0.2 mm) in diameter and 0.51 inch (13 mm) in length). Table 5 shows that the cost of fiber reinforcement represents about half the cost of the UHPC fiber composite.

Table 5. Cost of material per volume of low cost UHPC.

| Material | Cost ($/yd$^3$) |
|---|---:|
| Portland cement II/V | 73.66 |
| Silica fume | 82.57 |
| Fly ash | 7.54 |
| HRWR | 103.60 |
| Fine aggregate | 12.82 |
| Fibers | 472.39 |
| Total | 751.59 |

1 yd$^3$ = 0.765 m$^3$

UHPC-4 and UHPC-5 (see table 3 and table 4) with and without fibers were further investigated in their freeze-thaw resistance. All four specimens showed no indication of damage after more than 100 freeze-thaw cycles. This was evaluated visually as well as by measuring the resonance frequency.

## Conclusions

This research project emphasized the development of non-proprietary cost effective UHPC using locally available materials in the United States. Based on a progressive UHPC development, the paste, the matrix, and the fiber-reinforced concrete composite were analyzed and optimized in their performance. An efficiency factor *E* was defined to consider the performance in workability, compressive strength, and costs in order to facilitate the selection of the most effective materials. Based on the research, the following conclusions were made:

- Four UHPC matrices with fine aggregates only and three UHPC matrices including coarse aggregates were recommended using locally available materials from three different regions. The three regions included the Northeast, the upper Midwest, and the Northwest. Their material costs without fiber reinforcement ranged between about \$360 and \$500/yd$^3$ (\$470 and \$650/m$^3$) and \$355 to \$380/yd$^3$ (\$460 and \$500/m$^3$) for fine and course UHPC, respectively. The workability of these mixes can facilitate the use of these UHPCs in many structural applications. The compressive strength of the recommended UHPC matrix mixes ranged from 22.5 to 29 ksi (155 to 200 MPa) and exceeded the minimum required compressive strength of 20 ksi (138 MPa).

- Future research efforts are suggested to tailor the weight ratio of cement to silica fume to supplemental material of 1:0.25:0.25 in terms of performance versus cost ratio. A reduction in the amount of the most expensive material and an increase in the amount of the least expensive material might lead to a further improvement in performance versus cost. This optimization was not the scope of this research project and has been left for future research efforts.

- Adding fiber reinforcement of 1.5 percent by volume to the UHPC matrix increases the costs by about \$470/yd$^3$ (\$615/m$^3$). This value, when combined with the cost of the cementitious matrix, results in a total material cost for a fiber-reinforced UHPC of about \$850/yd$^3$ (\$1,110/m$^3$). More research effort is needed to find an alternative cost effective solution to provide sustained tensile strength and enhanced ductility due to the high costs of fiber reinforcement. This can be achieved by finding an alternative fiber reinforcement of lower cost and by reducing the required amount of fiber reinforcement through improved material utilization. A more effective fiber material utilization could be obtained by tailored matrix fiber bond and by combining continuous reinforcement with discontinuous fiber reinforcement.

- Durability properties, such as chloride ion penetration, scaling resistance to deicing chemicals, and other tests, such as strength development, early age strength, early age high-stress creep and long-term creep behavior, shrinkage behavior, abrasion resistance, alkali-silica reaction, and bond behavior between reinforcement bars and composite should be completed so as to facilitate the consideration of non-proprietary UHPC in the U.S. highway bridge sector.

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