Lab-Mixed versus Truck-Mixed UHPC—What's the Difference?

by Sherif El-Tawil, M.A. Saqif, Dewayne Rogers, and Yuh-Shiou Tai

Ultra-high-performance concrete (UHPC) is a major innovation in concrete technology.[1,2] Intrigued by its unique properties, engineers have increasingly explored the characteristics of UHPC and the performance of structures made from it. This is demonstrated by the increased number of publications with keywords "ultra-high-performance concrete" as documented in Google Scholar (Fig. 1).[3] The quantity of UHPC publications has grown from only 92 in 2005 to almost 5000 in 2021. Given that 36,500 publications had the keywords "reinforced concrete" in 2021, it's clear that UHPC has come to represent a sizeable portion of the worldwide concrete research portfolio.

Recognizing its potential, the Federal Highway Administration (FHWA) has aggressively promoted UHPC technology through its Everyday Counts (EDC) Programs 3, 4, and 6 spanning 2015 through 2022.[4] ASTM International and ACI recently released guidelines for testing and designing structures made of UHPC.[5,6] These codification efforts have culminated in recommended provisions for adoption into the AASHTO bridge specifications. The provisions are currently under review by AASHTO committees.

One of the hurdles to adoption of UHPC technology is the widespread belief that UHPC is difficult to mix. Many believe that high shear mixers, which are expensive to purchase or rent, are needed to adequately mix UHPC. Recent evidence, however, suggests that the use of such specialized mixers is not necessary. For example, El-Tawil et al.[7] successfully used a forced-action mixer (a commonly used mortar pan mixer) to mix UHPC in the field. The problem is that such mixers have small capacity, typically 1/3 to 1/2 yd^3 (0.25 to 0.38 m^3), hindering large scale application of UHPC.

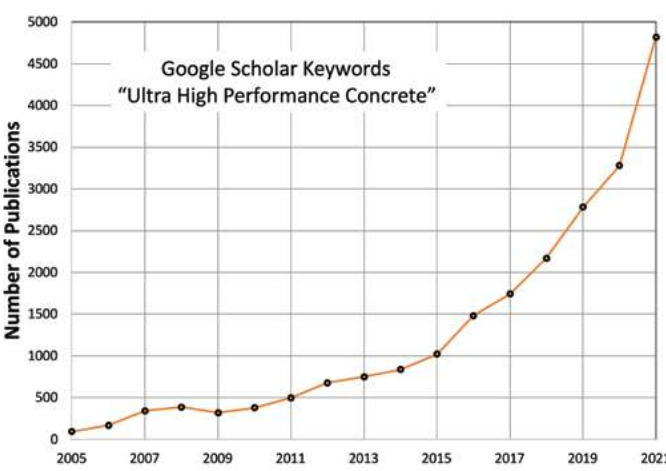

Fig. 1: Since 2005, the number of research papers focused on ultra-high-performance concrete has exhibited exponential growth

This article documents our recent efforts to mix UHPC in common concrete field mixers and ready mixed concrete trucks, and it compares the fresh and hardened properties of UHPC produced using these systems with UHPC produced using a laboratory mixer. Our work shows that UHPC is not as difficult to mix as is commonly believed, and it is possible to achieve a high-quality mixture with common mixing equipment.

Mixture Design and Components

The authors developed a family of open recipe UHPC mixtures made from off-the-shelf ingredients as outlined in Table 1.[7-10] The mixtures differ in the amount of high-range water-reducing admixture (HRWRA) used. Ideally, trial mixtures should be performed to select the lowest HRWRA dose (and hence lowest cost) that permits adequate mixing as judged by the UHPC mixture's workability. In this work, Mixture D, with the highest HRWRA dose, was used to provide the best chance for successful mixing with minimal upfront experimentation costs. Mixture components included:

- **Cement**—The cement was a 50-50 blend of ordinary portland cement (OPC) Type I and slag cement Grade 100 cement;
- **Silica fume**—The silica fume was of the undensified kind, and two types (SF1 and SF2) were used (shown in Fig. 2). Although a lower carbon content is preferred because that decreases the water demand while promoting high flowability, SF1 was deliberately chosen to be higher in carbon content (hence its dark gray color) to determine if field mixing with such a material can be achieved;
- **Sand**—Two types of quartz silica sand were used, with grain sizes of 70 to 200 μm and 400 to 800 μm. These grain sizes are optimized to enhance packing density as outlined in El-Tawil et al.[9];

- **HRWRA**—A polycarboxylate-based admixture was used, as our previous research showed that this was the most effective HRWRA;
- **Steel fibers**—The mixture was reinforced with short, straight, steel fibers dosed at 2% by volume (265 lb/yd^3 [157 kg/m^3]). The properties of the steel fibers are provided in Table 2; and
- **Defoaming agent**—A defoaming agent (at the rate of 0.5 lb/yd^3 [0.3 kg/m^3]) was used.

Table 1:
Mixture proportions (from Reference 7)

Material	Quantity, lb/yd^3			
	Mixture A[*]	Mixture B[*]	Mixture C[*]	Mixture D[*]
Type I cement	653			
Slag cement	653			
Fine sand[†]	398	396	395	394
Coarse sand[‡]	1590	1586	1582	1577
Silica fume	327			
Water	276	272	268	264
HRWRA[§,‖]	20	26	33	39
Steel fibers[#]	265			

[*]Mixtures A, B, C, and D have HRWRA dosages of 1.5%, 2%, 2.5%, and 3%, respectively

[†]Grain sizes: 80 to 200 μm

[‡]Grain sizes: 400 to 800 μm

[§]Polycarboxylate ether-based high-range water reducer

[‖]HRWRA dosage can be adjusted to meet the paste flowability requirements. Dosages vary with the type of silica fume and range from 1.5% to 3.0% by weight of cement

[#]Steel fibers comprise 2% by volume

Note: A defoaming agent (at the rate of 0.5 lb/yd^3) is recommended for concrete truck mixing to reduce the formation of bubbles

Note: 1 lb/yd^3 = 0.6 kg/m^3

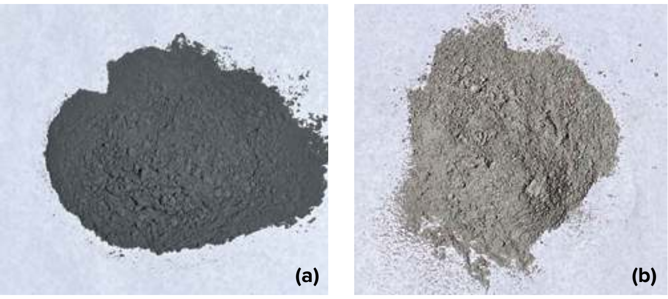

Fig. 2: Types of silica fume used in this work: (a) SF1; and (b) SF2

Acceptance Criterion for Workability

The workability for freshly mixed UHPC was determined by measuring the spread value in accordance with ASTM C1437.[11] After mixing, the fresh paste mixture was placed into a spread cone (Fig. 3). Special care was taken to keep the spread cone and the base plate at the same humidity level prior to testing. Due to the inherent high flowability of the paste, there was no need to compact the UHPC in the mold and no vibration was used. The spread cone was filled to the rim, lifted at a fixed speed, and the material remaining on the wall of the cone was scraped off into the material on the base plate. The material was allowed to spread undisturbed for 2 min ± 5 sec, when the diameter of the spread UHPC paste was measured along two perpendicular directions. The average diameter was calculated and recorded as the spread value. A spread between 7 and 12 in. (180 to 305 mm), as seen Fig. 4, indicated an acceptable mixture.

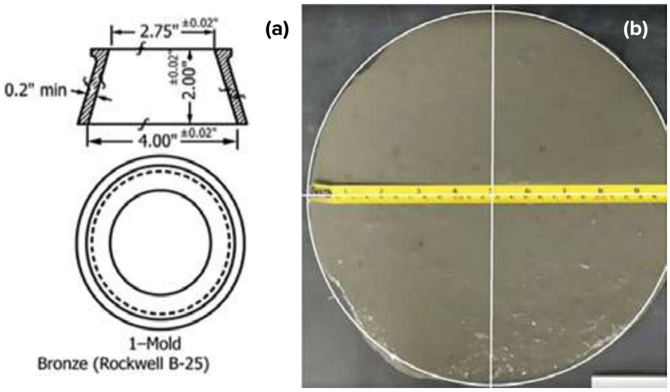

Fig. 3: Spread test: (a) conical mold for flow test; and (b) spread test

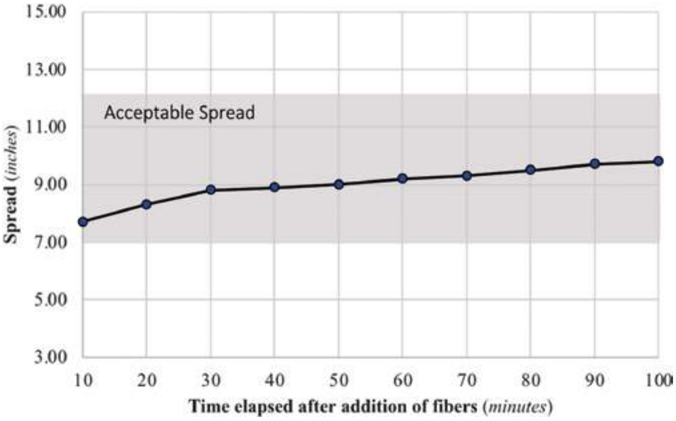

Fig. 4: Spread versus mixing time for Mixture F2 (Note: 1 in. = 25 mm)

Table 2:
Properties of steel fibers used in this study

Type of fiber	Density, kg/m^3	Tensile strength, MPa	Fiber length l_f, mm	Fiber diameter d_f, mm	Fiber aspect ratio l_f / d_f
Straight, brass coated	7800	2850	13.0	0.20	65.0

Note: 1 kg/m^3 = 1.7 lb/yd^3; 1 MPa = 145 psi; 1 mm = 0.04 in.

Mixing Protocol

The following mixing protocol was used in the lab and field experiments:

- Add dry components and mix for 10 minutes;
- Mix the water and HRWRA and then gradually add it to the mixture over a 2-minute period;
- Wait for turnover (fluidity), which usually occurs within 5 minutes;
- Mix another 5 minutes after turnover;
- Add steel fibers gradually over a 2-minute period; and
- Mix for another 5 minutes before casting specimens.

Trial Mixtures

Table 3 lists various mixtures made for this research. Four types of mixing equipment were used. Lab mixing was conducted using a Hobart planetary mixer (designated H mixer) as in El-Tawil et al.[9] Mixing was also done using two types of mixers that are commonly used in the field for smaller jobs: a rotating pan mixer, designated F1 (Fig. 5(a)), and a rotating drum mixer, designated F2 (Fig. 5(b)). Field mixing was done using a concrete truck, designated T (Fig. 5(c)).

Figure 6(a) shows that the F1 mixer has full reach of all parts of the mixing pan through a high-speed whirler as well as a wall scraper. The F2 mixer is quite basic, revolves slowly (less than 30 revolutions per minute) and the mixing blades only plow through the mixture when it's still powdery and then lifts and drops the wet mixture when it turns over (Fig. 6(b)). Figure 6(c) shows the inside of the concrete truck with a spiral blade that works like the blades of the F2 mixer. Clearly, the F2 and T mixers do not have the ability to mix as thoroughly as the F1 and H mixers, which can generate high levels of shear mixing.

The H and F mixtures were prepared at room temperature of 70°F (21°C). The T mixtures were prepared in wintertime in a warehouse that was heated but still relatively colder with temperatures ranging from 52 to 67°F (11 to 19°C) for mixtures T1 through T6. The sizes of the mixtures varied greatly. As shown in Table 3, the F mixtures were an order of magnitude greater than the H mixture, and the T mixtures where two orders of magnitude greater than the F mixtures.

The H mixture was typically ready in about 25 minutes. The F1 and F2 mixtures took a bit longer, about 45 and

Table 3:
Test results for trial mixtures

Mixture designation	Equipment used	SF type	Volume, yd^3	Spread per ASTM C1437, in.	Compressive strength at 28 days, ksi	Tensile strength at 28 days, ksi
H	Hobart planetary mixer	SF2	0.0065	9.8	27.6	1.64
F1	Rotating pan mixer	SF1	0.03	8.8	26.45	1.61
F2	Rotating drum mixer	SF2	0.07	9.0	25.4	1.57
T1	Concrete truck mixer	SF2	3	29.0*	18.4	Not measured
T2		SF1		8.5	25.2	1.50
T3				9.5	25.8	1.59
T4				9.0	25.9	1.65
T5			3.5	8.5	23.7	1.82
T6				10.25	24.0	1.74

*Measured by mistake using ASTM C1611/C1611M[12] not C1437

Note: 1 yd^3 = 0.76 m^3; 1 in. = 25 mm; 1 ksi = 6.9 MPa

Fig. 5: Types of mixing equipment used in this study: (a) rotating pan mixer (F1); (b) rotating drum mixer (F2); and (c) concrete truck (T)

Fig. 6: Details of mixing equipment: (a) F1 mixer with side scrapers and high-shear “whirler” blades; (b) F2 mixer with fixed blades; and (c) T mixer with the spiral blade

Table 4:
Compressive strength gain with time

Days	Mixture T1	Mixture T2	Mixture T3[*]	Mixture T4[*]	Mixture T5[*]	Mixture T6[*]
4	9.1	12.6[†]	–	–	–	–
7	11.2[†]	24.9	25.7	17.4	–	25.0
11	22.3	–	–	–	–	–
28	18.4	25.2	25.8	25.9	23.7	24.0
56	–	–	–	–	23.8	25.1

[*]Heat curing started after 1 day

[†]Heat curing started on day shown

30 minutes, respectively, whereas the T mixtures required at least 30 minutes or were sometimes left to mix longer (up to 90 minutes) as the forms were being prepared for placing. Aside from this practical consideration, as indicated in Fig. 4, the longer mixing time can help the mixture to meet the spread acceptance criterion. This suggests that mixtures that do not initially meet the acceptance criteria could be mixed for a longer period to meet the requirements.

Properties of Trial Mixtures

Table 3 summarizes the fresh and hardened properties of the mixtures, while Table 4 shows the gain in compressive strength with time for the concrete truck mixed mixtures evaluated in this study. Based on the strength results, the H mixture was the most successful, albeit not by much over the other mixture types. The spread was 9.8 in. (250 mm) and the compressive and tensile strengths were 27.6 ksi and 1.64 ksi (190 MPa and 11.3 MPa), respectively. The F1 mixture had a spread of 8.8 in. (225 mm) and compressive and tensile strengths of 26.45 ksi and 1.61 ksi (182 MPa and 11.1 MPa), respectively. The F2 mixture had a similar performance to F1. The T mixtures had a spread that ranged from 8.5 to 10.25 in. (215 to 260 mm). The 28-day compressive strengths for the T mixtures ranged from 18.4 to 25.9 ksi (127 to 177 MPa). The lowest strength for the T mixtures was determined for Mixture T1, which was the first concrete truck mixed mixture conducted in this research program. The reason for the low strength for this mixture is discussed next.

Fig. 7: UHPC cured slowly in a cold temperature environment (picture taken 24 hours after placement). Ambient curing temperature was estimated to be 55°F (13°C)

The ambient temperature for Mixture T1 was not measured, but it was estimated to be about 55°F (13°C). The temperature was measured for the remaining T mixtures. Once mixing concluded and the UHPC was placed into the forms, samples were taken and left to cure next to the member. After 1 day, it was clear that the UHPC had failed to fully cure. Figure 7 shows that demolded specimens at 24 hours were only partially hardened as compared to the tested cubes shown

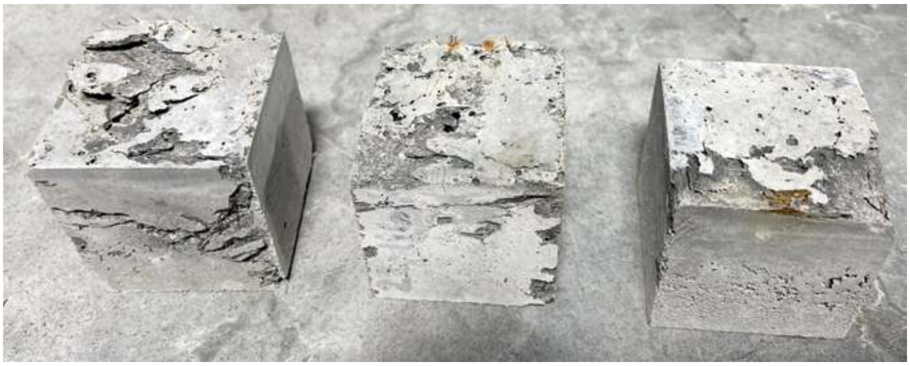

Fig. 8: Cubes after testing

Fig. 9: Composite steel/UHPC girder covered in plastic sheet with heat source to promote curing of UHPC

in Fig. 8. As listed in Table 4, the strength of the UHPC cubes for Mixture T1 reached 9.1 ksi (63 MPa) at 4 days and 11.2 ksi (77 MPa) after 7 days. Because it was well known that colder temperatures slow down curing,[13,14] the decision was made to accelerate curing by applying heat. An enclosure made of heavy plastic sheets was built to cover the entire beam, much like a tent (Fig. 9). The enclosure was heated to between 90 and 110°F (32 and 43°C). After the UHPC set, it was covered with wet burlap supplied by a soaker hose to keep it wet. The heat was applied on the beam for 4 days. Testing at 11 days showed that the UHPC picked up strength quickly, reaching 22.3 ksi (154 MPa). Subsequent testing showed that the strength dropped to 18.4 ksi (127 MPa) at 28 days. It is not clear why the strength decreased. However, there was not significant concern about this test result because it exceeded the design strength and, further, the use of slag cement is known to cause the strength to increase for several months after casting due to its slow pozzolanic reaction.[15]

With the experience gained from Mixture T1, subsequent T mixtures were all heat cured. This resulted in an effective and predictable increase in strength as shown in Table 4. In the lab, the H and F mixtures were cured inside a water bath at 195°F (91°C) for 72 hours. Although samples were submerged in water, the strength at 28 days shows the strategy used for curing Mixture T2 through T6 was just as effective.

Lessons Learned and Observations

The main lessons learned from this research include:

- Mixing open recipe UHPC can be conveniently achieved in a range of common mixer types, including rotating pan, rotating drum, and concrete truck. Successful mixing was achieved between 30 and 45 minutes, depending on the type of mixer used;
- The spread test is a quick and convenient means for judging the quality of a mixture. If a mixture does not pass the initial test, additional mixing may help to achieve the necessary fluidity to pass the test; and
- Placing UHPC in cold weather will lead to slow curing. However, the curing can be greatly accelerated through the application of heat. Heating the beams in this work allowed the mixtures to reach more than 22 ksi (152 MPa) in 72 hours.

Although the raw materials of UHPC are more expensive than that of regular concrete, there is a range of applications where the savings achieved using UHPC make the material competitive with conventional concrete. As outlined in El-Tawil et al.,[16] this is due to the weight savings achieved through slimmer sections, which in turn are cheaper to handle and transport and require smaller foundations systems. In the project outlined in this article, the use of UHPC removed the need to camber the steel tub girders, which were composite with the lightweight UHPC deck, leading to further cost savings. Ultimately, the cost savings associated with the reduction in maintenance and replacement costs due to the extreme durability of UHPC make a compelling case for using this unique material. In addition, UHPC opens the door to new construction applications and structural rehabilitation options that are not feasible with regular concrete. It is hoped that the experience documented in this article will alleviate the reputation that UHCP is difficult to mix and encourage broader experimentation with and usage of this highly beneficial material.

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Selected for reader interest by the editors.

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