

Field Application of Nonproprietary Ultra-High-Performance Concrete

Experiences gained and lessons learned

by Sherif El-Tawil, Yuh-Shiou Tai, and John A. Belcher II

Ultra-high-performance concrete (UHPC) achieves a compressive strength of at least 150 MPa (21,700 psi) and it has self-consolidating properties. UHPC comprises component materials with particle sizes and distributions carefully selected to maximize packing density^{1,2} (constituent particles arranged as compactly as possible), which is the reason for the extremely high mechanical and durability properties of the material. Another key feature of UHPC is that it is reinforced with a small percentage by volume (typically 1 to 2%) of short steel fibers, which enhance the material's tensile behavior and energy dissipation.^{3,4}

The Federal Highway Administration (FHWA) and multiple state Departments of Transportation (DOTs) have exhibited strong interest in UHPC and its application in bridges. For example, the third round of the Every Day Counts (EDC-3) report included a chapter on UHPC connections for prefabricated bridge elements.⁵ The fourth round of the program, EDC-4, is also expected to include that general topic.

The use of UHPC as a field-cast material is not new, but most experience in Europe and the United States has been gained with proprietary materials,⁶ particularly for field-cast connections as outlined in Reference 7. A common thread in UHPC applications is that the required volume of material is not large, primarily because proprietary UHPC is expensive. UHPC must be purchased from specific suppliers, and the contractors that work with it must be specially trained, certified, and supervised, further increasing the unit cost. In a 2016 Michigan Department of Transportation (MDOT) project that required 8 yd³ (6 m³) of UHPC, the unit cost for the proprietary UHPC material was estimated at \$2500/yd³ (\$3300/m³). Another \$3700/yd³ (\$5000/m³) was spent on the specialized construction and technical services required by the supplier, although this cost is expected to drop substantially as the quantity of material increases and more experience is gained with the product.

Researchers at the University of Michigan, Ann Arbor, MI, developed a family of nonproprietary UHPC mixtures^{1,2} that can be made from off-the-shelf products and do not require onerous placement or special curing processes. The resulting material has similar performance characteristics but is substantially less expensive than proprietary UHPC mixtures. This article describes experience gained with a nonproprietary UHPC mixture optimized for field applications.

Development of Nonproprietary UHPC Mixtures

Component selection

The nonproprietary UHPC mixture was produced using Type I ordinary portland cement (OPC), ground-granulated blast-furnace slag (GGBS or slag cement), silica fume, two types of silica sand, and short steel fibers. To ensure workability, a high-range water-reducing admixture (HRWRA or superplasticizer) was used. Optimum packing density of the particles was based on the material gradations as discussed in previous studies.^{1,2} Four variants of the mixtures described in References 1 and 2 were considered good candidates for field application. The experimental variables were the amount of HRWRA and fiber length. The mixture proportions by weight are shown in Table 1.

White Type I portland cement was used in the initial development of UHPC³ due to its low tricalcium aluminate (C₃A) content and high combined content of di- and tricalcium silicate (C₂S and C₃S), resulting in exceptional performance in the fresh and hardened states. However, white cement is expensive (currently, about \$275/ton). Research in References 1 and 2 has shown that Type I OPC, which is much cheaper (at \$150/ton), can be successfully used. In general, the selected cement must have a C₃A content lower than 8% and a relatively low Blaine fineness to reduce water demand during hydration. Many suppliers in the United States can meet this requirement.

Table 1:
Mixture proportions by weight (portland cement + slag cement = 1.0)

Mixture No.	Water	Type I OPC	Slag cement	Silica fume	HRWRA	Silica sand		Steel fiber	
						Sand A	Sand B	13 mm length	19 mm length
1	0.22	0.5	0.5	0.25	0.02	0.30	1.21	—	0.20
2					0.02		1.21	0.20	—
3					0.03		1.21	0.20	—
4					0.035		1.20	0.20	—

Note: 1 mm = 0.04 in.

Silica fume is a by-product of the manufacture of silicon alloys. Its superfine spherical particles and pozzolanic reactivity densify the microstructure and significantly improve the compressive strength of UHPC. The median particle size is in the range of 0.1 to 10 μm . Silica fume with a lower carbon content is preferred because it decreases the water demand while promoting high flowability.

Eliminating the coarse aggregate promotes high compressive strength. Instead of coarse aggregate, two types of quartz silica sand were used, with grain sizes of 70 to 200 μm and 400 to 800 μm . These grain sizes were optimized to enhance packing density.

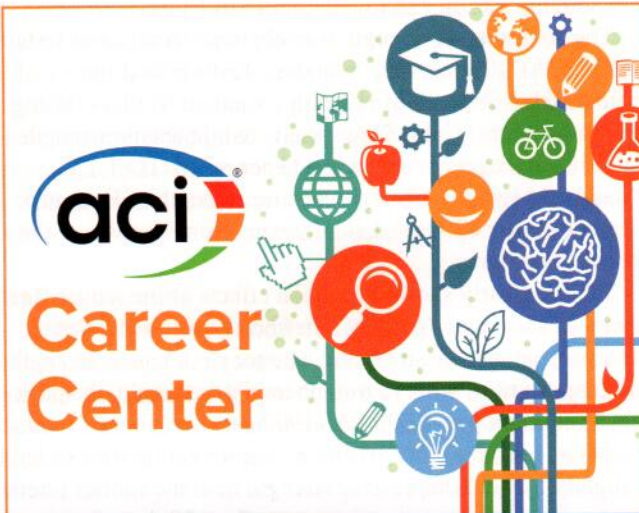
Unlike regular concrete, UHPC comprises a lot of cement, which increases costs and has environmental and ecological burdens. It also has a negative impact on the heat of hydration, which can lead to shrinkage problems. Therefore, slag cement was added to make the mixtures more environmentally friendly (because GGBS is a by-product of the steelmaking industry). Slag cement is a beneficial mineral admixture for concrete because of its pozzolanic properties and its positive influence on the durability of concrete.⁸

A polycarboxylate-based HRWRA was also used in the UHPC mixtures. In the previous study, 1.35% of HRWRA by weight of cement was used.¹ However, because of its sensitivity to the composition of silica fume (especially carbon content) and the activity of cement, larger dosages were explored in this study to ensure suitable workability for field applications. Hence, three dosages of HRWRA were considered. The most effective dosage was selected based on optimal combinations of turnover time measured after the addition of water and HRWRA, the spread (as explained next), and compressive strength. Lastly, fibers with high yield strength (2000 MPa [290,000 psi]) were selected. The fiber lengths were 19 mm (0.75 in.) in Mixture 1 and 13 mm (0.50 in.) in the remaining three mixtures. The volume fraction of fibers was 2% in all mixtures.

Laboratory trial batches

Laboratory mixing was done using a Hobart-type laboratory mixer according to the procedure described in Reference 3. First, the silica sand and silica fume were dry-mixed for about 5 minutes. Cement and slag cement were

then added to the mixture and dry-mixed for another 5 minutes. Next, water and HRWRA were separately mixed together and the mixture was added gradually to the dry materials. Premixing the HRWRA and water aided in a more uniform distribution of the HRWRA in the batch. The UHPC mixture showed appropriate workability (turnover) approximately 5 to 7 minutes after the addition of water and HRWRA. Once an adequate mixture consistency was achieved, the steel fibers were added into the mixer and allowed to mix at 60 rpm until they were well dispersed.



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Table 2:
Mechanical properties of laboratory and field batches

Mixture no. or ID	Spread, mm (in.)	Compressive strength, MPa (psi)				Tensile strength, MPa (psi)	Strain at peak tensile stress, %
		7-day	14-day	28-day	56-day		
1	214 (8.4)	121.3 (17,600)	149.1 (21,600)	175.7 (25,500)	196.2 (28,500)	12.9 (1900)	0.41
2	215 (8.5)	118.2 (17,100)	147.8 (21,400)	169.2 (24,500)	187.4 (27,200)	11.1 (1600)	0.17
3	235 (9.3)	118.8 (17,200)	143.5 (20,800)	159.0 (23,100)	176.4 (25,600)	9.5 (1400)	0.18
4	238 (9.4)	113.4 (16,500)	137.1 (19,900)	151.9 (22,100)	—*	9.6 (1400)	0.14
Field	238 (9.4)	108.9 (15,800)	127.0 (18,400)	148.1 (21,500)	—*	8.3 (1200)	0.13

*Specimens not tested. Not enough were made due to an oversight

After mixing was completed, the rheology of the UHPC mixture was assessed by measuring spread. The spread test method was based on ASTM C1437, "Standard Test Method for Flow of Hydraulic Cement Mortar," with one modification—the fresh UHPC was allowed to spread freely on a plexiglass plate instead of being dropped on a flow table as specified in the standard. When the mixture stopped spreading, the diameter of the spread was measured. Based on previous experience and research documented in References 1 and 2, a mixture was considered appropriate for use if its spread ranged from 175 to 300 mm (7 to 12 in.).

The compressive strength was obtained from cubes tested per ASTM C109/C109M, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)," while tensile strength was obtained using coupons tested per AASHTO T 132, "Standard Method of Test for Tensile Strength of Hydraulic Cement Mortars." Table 2 summarizes the properties of the four trial mixtures.

Table 2 clearly shows beneficial effects of the longer steel fibers, as Mixture 1 (with 19 mm fibers) exhibited a larger strain at peak tensile stress and a larger peak tensile strength than the mixtures with 13 mm fibers. For example, the peak tensile strength was 12.9 MPa (1900 psi) for Mixture 1 versus 9.5 MPa (1400 psi) for Mixture 3. The longer fibers also led to a slightly higher compressive strength than the shorter fibers. For example, the compressive strength at 28 days for Mixture 1 was 175.7 MPa (25,500 psi) versus 169.2 MPa (24,600 psi) for Mixture 2.

The 28-day compressive strength decreased with increasing amount of HRWRA. For example, the 28-day strength was 169.2 MPa (24,600 psi) for Mixture 2 and 151.9 MPa (22,100 psi) for Mixture 4, representing a 10% drop (Table 2). This was also true for tensile strength. The effects of using slag cement were also evident, as the strength kept rising substantially beyond 28 days. The 56-day compressive strength was 17 to 20 MPa (2500 to 3000 psi) higher. Comparing all the results, Mixture 3 provided a good compromise between flowability and strength, and it was selected for the field placement.

Field Application of UHPC

The bridge repair project was located on Kilgore Road over the Pine River (Structure No. 10091), Kenockee Township, MI, shown in Fig. 1(a). The bridge is 13.6 m (44.7 ft) long and 6.5 m (21.4 ft) wide (Fig. 1(b)). The repair effort entailed replacing the joints connecting the reinforced concrete beams with UHPC (Fig. 2).

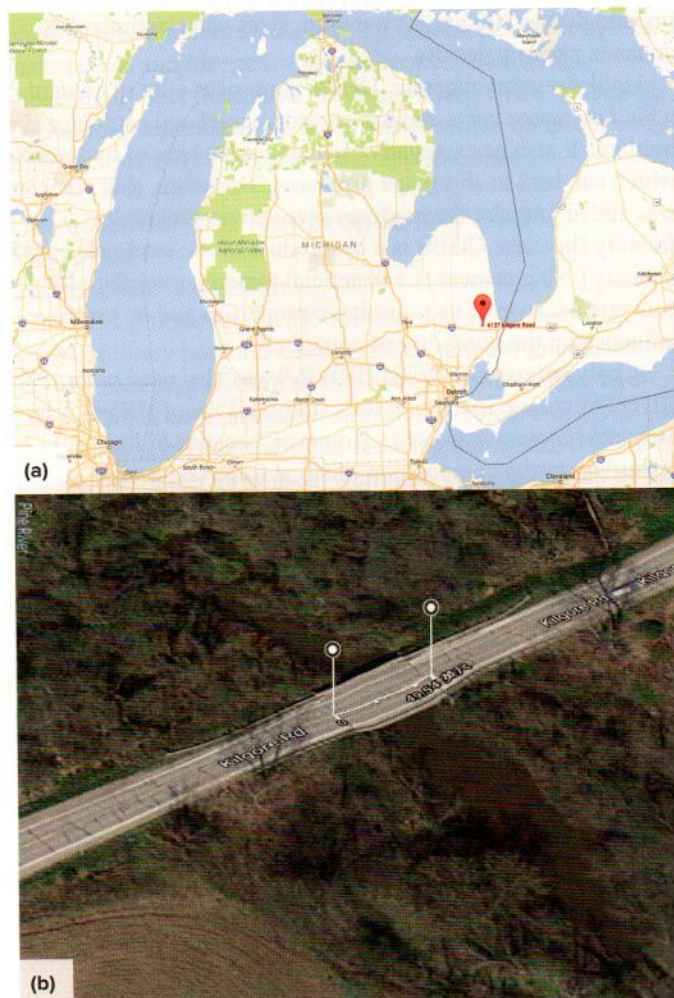


Fig. 1: Bridge repair site: (a) location in Michigan; and (b) aerial view



Fig. 2: Joints between reinforced concrete beams were replaced with UHPC. Dimension lumber portals and threaded rods held the bottom formwork tight against the beam flanges to prevent leakage of the UHPC

Mixing equipment

Mixing was carried out by a Michigan-based contractor employing the mixture protocol developed in the lab. The contractor used two Mortarman 360 MBP pan mixers, each with a capacity of 8 ft³ (0.23 m³). Mixing volume was limited to 5.5 ft³ (0.16 m³) because early trials showed that greater loads led to mixing difficulties—the material’s viscosity increased dramatically at turnover, which caused the mixer’s engine to labor noticeably and even stall. Once successfully mixed, the material was discharged into wheelbarrows and transported to the placement location.

Mixing process

Construction took place on a summer day with temperatures forecasted between 23 and 32°C (73 and 90°F). The high temperature prompted concerns about water evaporation during mixing. Because UHPC has a low water content, moisture loss due to evaporation could result in a degradation in the fresh and hardened properties of UHPC. The ambient temperatures during preparation of a few batches are summarized in Table 3, along with the measured mixture temperatures. The latter are generally higher than the former due to the mixing energy imparted to the mixture and heat of hydration.

The first batch was mixed at an ambient temperature of 23.9°C (75°F). The mixture temperature peaked at 26.7°C (80°F), and the spread was 238 mm (9.4 in.). The ambient temperature for the second batch was 25.0°C (77°F), but the mixture temperature rose to 35.0°C (95°F). The increased mixture temperature caused a marked reduction in spread, decreasing to 200 mm (8 in.) for the second batch from 238 mm for the first batch.

Table 3 shows that, in general, the turnover time is substantially less than that observed with the Hobart mixer in the lab. It is not clear why that is the case, especially because the field mixer was slower than the lab mixer. However, it is possible that the field mixing attachments are more effective than the lab mixer in inducing shear into the

Table 3:
UHPC fresh test results

Batch no.	Turnover time	Ambient temperature, °C (°F)	Mixture temperature, °C (°F)	Spread, mm (in.)
1	1 minute 30 seconds	23.9 (75)	26.7 (80)	238 (9.4)
3	2 minutes 5 seconds	25.0 (77)	35.0 (95)	200 (8.0)
4	2 minutes 30 seconds	25.6 (78)	30.0 (86)	231 (9.1)
7	2 minutes 45 seconds	26.7 (80)	29.4 (85)	220 (8.7)

mixture. The general trend of faster turnover time with larger mixer was also observed in the lab, although not to the extent seen in the field mixture. Two other observations are evident from Table 3. First, turnover time increased somewhat with increasing ambient and mixture temperatures; and second, the spread dropped significantly as the mixture temperature increased.

To address the adverse effects of the high mixture temperature and with the knowledge that the temperature would rise as the day progressed, cubed ice was added as a replacement for some of the mixing water as recommended in Reference 7. On-site experimentation showed that a 40% replacement yielded good results and kept the mixture temperature below about 29.4°C (85°F), a point beyond which the test showed that the spread drops quickly. Figure 3 shows the steps of the field-mixing procedure and testing.

Casting process

UHPC was cast at a rate that did not allow it to flow too far during placement to minimize preferential alignment of the fibers in the direction of flow. This was done by starting the casting process at one end of the joint and proceeding to the other end at a speed comparable to the flow speed of the fresh mixture. Initially, the UHPC was poured into hoppers that directed the flow of the UHPC into the joints. However, after about half of the placement was completed, the hoppers were deemed not useful and abandoned.

The forms can be coated or pre-wetted to ensure that they do not absorb water. The latter route was selected as the more practical solution. The surface of the existing concrete and the reinforcing bars were also pre-wetted to prevent the mixture from losing water to the dry surfaces (Fig. 4(a)). Once casting was carried out, top forms were installed to reduce surface dehydration (Fig. 4(b)).

Post-curing inspection

After the formwork was stripped (1 day after placement), some small holes and shrinkage cracks were visible on the top



Fig. 3: Field mixing procedure and testing of UHPC mixture: (a) addition of dry ingredients; (b) dry mixing; (c) addition of water, HRWRA, and cubed ice; (d) mixture dispersion and homogenization; (e) addition of steel fibers; and (f) flow test



Fig. 4: Casting of UHPC into a joint between beams: (a) pre-wetting and placement; and (b) top forms installed



Fig. 5: Field placement after 1 day: (a) view of a UHPC connection; and (b) shrinkage cracks visible on the surface

surface of the UHPC joints (Fig. 5). These defects were attributed primarily to two factors: dehydration of the top layer associated with the hot weather during construction and entrapped air rising during curing. Nevertheless, a close examination showed that the underlying material was sound.

Comparison of Field and Lab Properties

Cubes and coupons were made during field mixing to compare field properties to lab values. As with the lab program, compressive strength of the field mixture was determined according to ASTM C109/C109M and tensile strength according to AASHTO T 132. The results are listed in Table 2.

The 28-day compressive strength of the field mixture was about 10 MPa (1500 psi) lower than the lab Mixture 3. The tensile properties of the field mixture were also lower than those of Mixture 3. We have two hypotheses for the discrepancy between the lab and field properties. The first is that the hot weather caused mixing water to evaporate rapidly, thereby compromising hydration. The second is that the mixer, while efficient at turning over the mixture quickly, did not provide sufficiently uniform mixing, causing irregular dispersal of the mixture constituents.

A Note About Cost

To satisfy the requirements of MDOT, the material used on this project comprised components that were produced or sold on the U.S. open market. The steel fibers were the most expensive component (refer to Table 4 for total cost and % of total cost). Fiber costs are expected to drop with increasing demand for UHPC, so the overall price should also decrease. If the origin of the fibers is not a constraint, steel fibers sourced from outside the United States could be used instead to reduce the UHPC cost. Another cost-reducing step would be to decrease the amount of steel fibers from 2 to 1.5% by volume. Research documented in Reference 1 shows that this lower level of fiber dosage still yields UHPC with good short- and long-term properties. However, even with a reduced cost of steel fibers, UHPC is still a relatively

Table 4:
Cost of Mixture 3 components

Component	Quantity, lb/yd ³	Cost per yd ³ , % of total
Type I OPC	650	5.0
Slag cement	650	4.3
Silica fume	327	8
HRWRA	39	6.3
Sand A	395	1.2
Sand B	1580	4.8
Steel fibers	265	70.4
Total cost: \$892.70		

Note: 1 lb/yd³ = 0.59 kg/m³

expensive material, although its extremely high durability has the potential to significantly reduce life-cycle costs. Research is needed to fully evaluate the long-term benefits.

Summary and Conclusions

This article describes a field construction project using a nonproprietary blend of UHPC. Casting UHPC on a warm day led to a reduction in the spread (flowability) as the high temperature compromised the effectiveness of the HRWRA and increased the potential for evaporation of water during mixing and placement. On-site experimentation showed that replacement of 40% of the mixing water with ice kept the mixture temperature at less than 30°C, thus ensuring the effectiveness of the HRWRA. Substantially hotter days will require greater ice quantities, which can be determined by trial and error. Minimizing evaporation can be resolved only by speeding up the mixing and placing processes.

The 28-day compressive strength of the field-mixed material was 148.1 MPa (21,500 psi), which is about 1% less than the 150 MPa needed to define the material as UHPC.

However, the material is expected to continue to gain substantial strength at later ages due to the use of slag cement. Lab tests showed that the 56-day compressive strength was 17 to 20 MPa (2500 to 3000 psi) higher than the 28-day strength. The 150 MPa value is somewhat arbitrary. For example, the FHWA recommends that UHPC is defined using a minimum strength of 145 MPa (21,000 psi) at 28 days, a criterion that the field mixture meets.

Although the cost of nonproprietary UHPC is much less than proprietary UHPC, it is still relatively high compared to regular concrete. It is expected that this cost will come down as increasing demand drives up production of steel fibers and reduces their cost, or as lower-priced imported fibers become available in the United States. Given its great strength, durability, and other exceptional properties, it is expected that UHPC will play a key role in building the next generation infrastructure—one that is significantly more robust, resilient, and sustainable than in the past.

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Disclaimer

The opinions stated in this paper are the authors' and not necessarily those of MDOT or the individuals mentioned.

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Note: Additional information on the ASTM and AASHTO standards discussed in this article can be found at www.astm.org and www.transportation.org, respectively.

Selected for reader interest by the editors.



Sherif El-Tawil is a Professor of civil and environmental engineering at the University of Michigan, Ann Arbor, MI. He has had a long-sustained interest in the development of nonproprietary UHPC and characterization of its short- and long-term properties. El-Tawil is particularly interested in the effects of extreme loading on structural systems and how UHPC, with its unique properties, can be used to mitigate those effects. He is a licensed professional engineer in Michigan.



Yuh-Shiou Tai is a Professor in the Civil Engineering Department at the ROC Military Academy, Taiwan, ROC. He has been a Visiting Research Scientist at the University of Michigan since 2013. His research interests include interfacial bonding properties between steel fiber and the cementitious material; and experimental testing, analysis, and modeling of UHPC under quasi-static and high strain rate loading.

John A. Belcher II has been with the Michigan Department of Transportation (MDOT) for 16 years, during which he served as the Concrete Construction Engineer. He is currently the Bridge Construction Engineer for MDOT.

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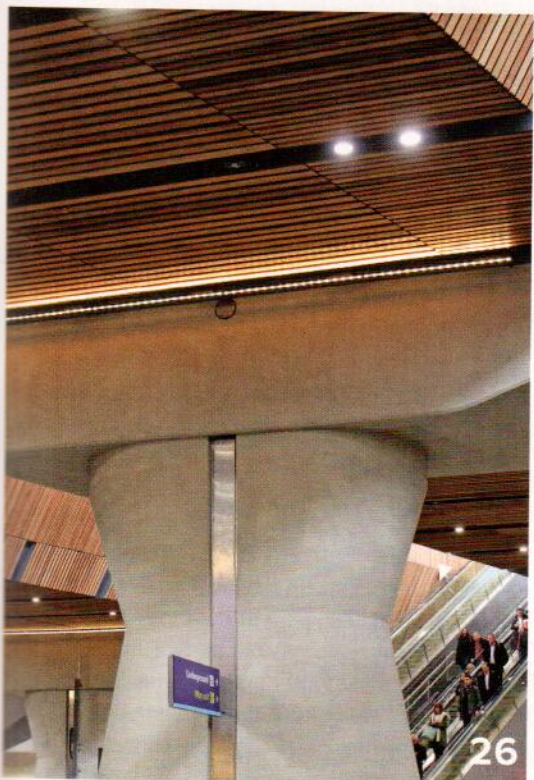
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