Open-Recipe Ultra-High-Performance Concrete

Busting the cost myth

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

Ultra-high-performance concrete (UHPC) is emerging as a game-changing technology for infrastructure applications. UHPC has self-consolidating properties and is an extremely durable cementitious product that achieves a compressive strength of at least 150 MPa (21.7 ksi). It is comprised of component materials with particle sizes and distributions carefully selected to maximize packing density, which enables the impressive 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 3%) of short steel fibers, which enhance the material's tensile behavior and toughness.[1,2]

UHPC has rapidly grown in popularity in the United States and worldwide. The U.S. Federal Highway Administration (FHWA) and multiple state Departments of Transportation (DOTs) have shown strong interest in UHPC and its application to bridges. For example, the third and fourth rounds of the Every Day Counts (EDC) program (EDC-3 and EDC-4, spanning 2015 through 2018) focused on demonstrating the advantages that UHPC offers for connecting prefabricated bridge elements. The upcoming round of EDC (EDC-6) will address the use of UHPC for bridge repair and rehabilitation.

Although UHPC has shown strong benefits in the targeted FHWA applications, we, the authors, believe that the true potential of UHPC lies in precast technology, where the material's high strength enables light and durable components for accelerated construction. Lightweight UHPC products provide cost savings on multiple fronts, including transportation, substructure design, construction, and, most importantly, maintenance. Yet, in spite of these benefits, UHPC technology has not yet seen widespread adoption in the United States, primarily because most applications to date have used proprietary products that remain extremely expensive.

This article introduces open-recipe UHPC as an alternative to expensive proprietary products and with the potential to disrupt the precast concrete market. It describes the history of UHPC, discusses the components of open-recipe UHPC, and makes the case for broadening the use of this powerful new technology.

The Road to Open-Recipe UHPC: A Brief History

The development of UHPC can be traced back to the early 1980s, when Birchall et al.[3] proposed macro-defect-free (MDF) cement, which had a compressive strength in excess of 300 MPa (43.5 ksi). Densified small-particle (DSP) concrete was introduced at about the same time. DSP employed microsilica spherical particles having an average diameter of 0.1 micron to fill the voids between cement particles. The spherical shape improved workability and led to dense packing. A high-range water-reducing admixture (HRWRA) was used to ensure workability, and it was shown that the material could achieve compressive strengths of up to 250 MPa (36.3 ksi).[4] Richard and Cheyrezy[5,6] used finer and more reactive components to formulate what they called reactive-powder concrete (RPC). RPC is based on the principle of improving homogeneity by eliminating coarse aggregates, optimizing particle-packing density, and applying heat and pressure before and during setting. At about the same time RPC was proposed, de Larrard and Sedran[7] employed optimized particle packing and used a special selection of fine and ultrafine particles to develop a low-porosity, high-durability, and self-compacting concrete. The optimized particle packing was theorized to be the reason behind the material's high compressive strength and durability.

All of the previous efforts represent early versions of a class of materials now known as UHPC. Figure 1 compares the internal structure of regular concrete and UHPC. Note the homogeneity of the internal structure, which is the main reason for its exceptional properties.

UHPC has seen an exponential growth in research

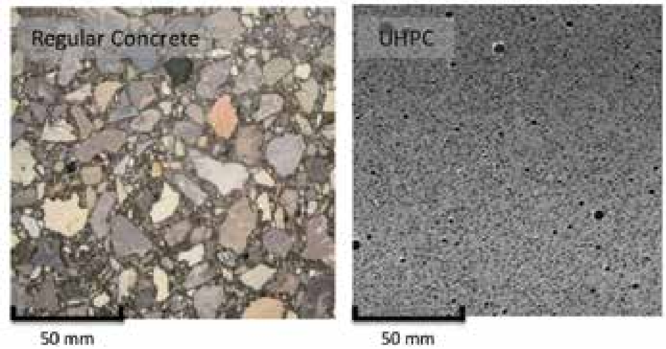

Fig. 1: Comparison between: (a) regular concrete; and (b) UHPC. Note the uniform nature of UHPC

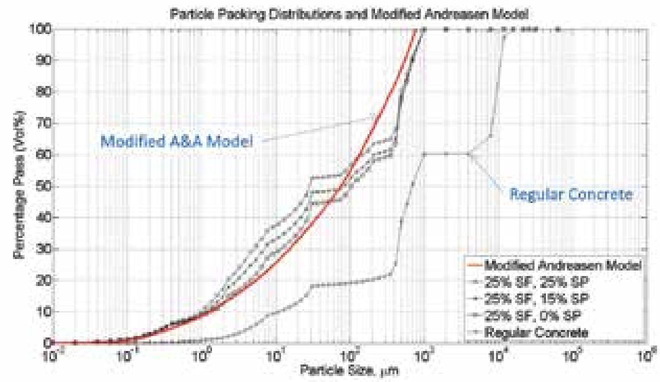

Fig. 2: Achieving high packing density in UHPC

activities over the past decade with a focus on developing nonproprietary products that are optimized for cost and use in structural applications. Notable examples include Hirshi and Wombacher[8]; Alkaysi and El-Tawil[9]; Meng et al.[10]; and Zhong et al.[11] To differentiate these efforts from proprietary products (which are closed or have protected formulas), the term "open-recipe UHPC" is employed by the authors. The formula and mixing method for an open-recipe UHPC are published (known) and conducive to further development by others. The concept of open development is well known in software engineering and has led to rapid and broad innovations that would have otherwise been stymied if development had been closed to generic users and coders.

Achieving High Packing Density

The packing theory developed by Andreasen and Andersen[12] (A&A) is the basic method used for designing open-recipe UHPC. Proper application of packing theory can control the fresh and hardened properties of UHPC because the improved particulate packing leads to more usable water as a lubricant. According to A&A theory, optimal packing can be achieved when the cumulative particle size distribution (PSD) obeys the following equation:

$$P(D) = \left(\frac{D}{D_{\max}}\right)^q \times 100\%$$

where $P(D)$ is the percentage of the material that can pass through a sieve with opening D, and D_{max} is the maximum particle size of the mixture. The distribution modulus q has a value between 0 and 1. The A&A model does not contain a minimum particle size. To account for that, a modified version of the model suggested by Funk and Dinger[13] is commonly used:

$$P(D) = \left(\frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q}\right) \times 100\%$$

where D_{min} is the minimum particle size in the mixture. Andreasen and Andersen[12] found that optimum packing is obtained when $q = 0.37$. However, for mixtures with a high amount of powders ($D < 250$ μm), a smaller q value in the range of 0.22 to 0.25 is recommended. Figure 2 shows a plot of various UHPC mixtures in El-Tawil et al.[14] as compared to an optimum particle distribution in regular concrete. It is clear from the figure that regular concrete has a far from optimal packing density as opposed to various UHPC mixtures (note that the horizontal axis is logarithmic).

Ingredients of Open-Recipe UHPC

Open-recipe UHPC is made from common, off-the-shelf ingredients. Mixing them as reported in Alkaysi and El-Tawil,[9] without heat or pressure treatment, results in UHPC with properties that are comparable to proprietary products. For example, the mixture derived in Alkaysi and El-Tawil[9] reached a compressive strength of 192.7 MPa (28 ksi), peak tensile strength (direct tension) of 10.9 MPa (1580 psi), strain at peak stress of 0.64%, and energy absorption capacity of 57.2 kJ/m^3. Samples prepared with these mixtures also had negligible mass loss after 60 cycles of freezing and thawing, and they passed negligible to very low total charge[15] when tested per ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."

Main ingredients

The cement used in open-recipe UHPC is a 50-50 mixture of ordinary portland cement (OPC) Type I and slag cement. In general, OPC must have a tricalcium aluminate (C3A) content lower than 8% and a relatively low Blaine fineness to reduce water demand during the hydration. Many suppliers in the United States can meet this requirement. The use of slag cement decreases the cost and environmental and ecological burdens of using only OPC, and it has a positive influence on durability.

UHPC uses two kinds of silica products: silica fume and silica sand. The former is a by-product of the production of silicon alloys, and its superfine spherical particles (the median particle size is in the range of 0.1 to 10 microns) and pozzolanic reactivity densify the microstructure and significantly improve the compressive strength of UHPC. Two types of quartz silica sand are also used, with grain sizes of 70 to 200 μm and 400 to 800 μm. These grain sizes are optimized to enhance packing density.

Steel fibers are added to enhance the tensile properties of

Fig. 3: Fractured surface of a UHPC structural member with visible fiber pullout

Table 1:
Mixture proportions by weight of cement (OPC + GGBS = 1.0) for a family of UHPC mixtures

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

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

[†]Grain sizes 80 to 200 microns

[‡]Grain sizes 400 to 800 microns

[§]Polycarboxylate ether-based HRWRA

[‖]HRWRA dosage rates 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 the cement

[#]Steel fibers are 2% by volume

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

UHPC. Once a crack occurs, fibers bridge the crack, resisting further crack growth and propagation. This type of behavior promotes multiple cracking prior to crack localization, leads to strain hardening response, and is directly responsible for the material's high energy absorption capacity. The behavior of UHPC in tension, particularly its postcracking response, is directly dependent on the fiber-matrix interaction that occurs during fiber pullout (refer to Fig. 3). The most commonly used fibers are made from high-strength steel (yield strength greater than 2000 MPa [290 ksi]) and are 0.2 mm (0.008 in.) in diameter and 13 to 19 mm (1/2 to 3/4 in.) in length.

Mixture design

There are several published mixture designs. Table 1 shows a family of four UHPC mixtures. The difference between them is the amount of HRWRA used. Due to the extremely low water-cement ratio (*w/c*), users may have to experiment to achieve an optimal amount of HRWRA to ensure that the material passes the spread test (described next). Depending on its source, silica fume may have high levels of carbon content, which will increase the water demand, reduce the flowability, and adversely affect mixability, as noted by El-Tawil et al.[16] A lower carbon content is preferred. Silica fume with high carbon content is usually quite dark in color. Interpolation between the quantities in Table 1 can be done if different levels of HRWRA are needed.

Spread test

The spread test is a versatile test for checking the quality of the freshly mixed UHPC. The test is based on ASTM C1437, "Standard Test Method for Flow of Hydraulic Cement Mortar." After mixing the paste, the fresh mixture is placed into a spread cone. Special care should be 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 is no need to compact the UHPC in the mold. The spread cone is filled up to the rim and then lifted at a fixed speed. The leftover material sticking to the wall of the cone is scraped off and added to the material on the base plate as it spreads. After 2 minutes ± 5 seconds has elapsed, the diameter of the spread is measured along two orthogonal directions, and the average diameter is calculated and recorded as the spread value. The spread should be between 175 and 300 mm (7 and 12 in). Spread values outside this range indicate that the mixture should be rejected.

Busting the Cost Myth

One of the biggest impediments to using UHPC is the perceived high cost. On a unit volume basis, UHPC is indeed expensive when compared to traditional concrete. Per HiPer Fiber,[17] the cost of open-recipe UHPC ranged from \$567 to \$697/yd^3 USD in 2019. When the fibers were domestically sourced, the cost ranged from \$726 to \$856/yd^3 USD in 2019. If a high-quality, highway construction-grade concrete costs X = \$120/yd^3, then open-recipe UHPC costs about $6X$.

But a unit of concrete does not exist in isolation. For concrete to be placed in its final location, design and construction costs must also be expended. For example, a commonly cited highway construction cost is \$1 × 10^6/lane-mile in 2019 dollars. This translates into roughly \$500/yd^3 of placed concrete, suggesting that construction costs exclusive of the concrete itself are about \$380/yd^3. If the unit cost of a prestressed concrete girder was about \$1000/yd^3 USD in 2019, other costs (such as formwork, reinforcing, labor, overhead, and transportation) would be about \$880/yd^3.

Table 2:
Effect of *Y* and *Z* on change in short-term cost of UHPC (highlighted area corresponds to reduction)

	Case 1					
Y \ Z	0.1	0.2	0.3	0.4	0.5	0.6
0.4	57.5%	50.0%	42.5%	35.0%	27.5%	20.0%
0.5	42.5%	35.0%	27.5%	20.0%	12.5%	5.0%
0.6	27.5%	20.0%	12.5%	5.0%	−2.5%	−10.0%
0.7	12.5%	5.0%	−2.5%	−10.0%	−17.5%	−25.0%
	Case 2					
Y \ Z	0.1	0.2	0.3	0.4	0.5	0.6
0.4	23.8%	15.0%	6.3%	−2.5%	−11.3%	−20.0%
0.5	16.3%	7.5%	−1.3%	−10.0%	−18.8%	−27.5%
0.6	8.7%	0.0%	−8.8%	−17.5%	−26.3%	−35.0%
0.7	1.3%	−7.5%	−16.3%	−25.0%	−33.8%	−42.5%

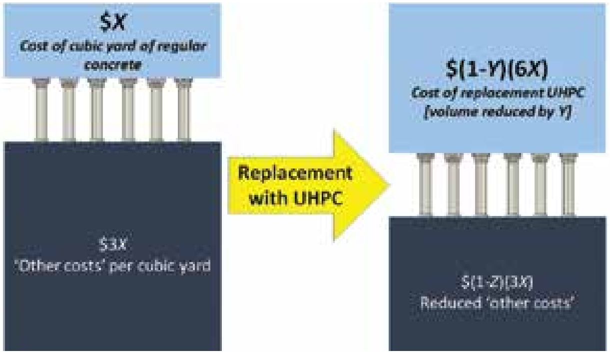

Fig. 4: Schematic representation of cost benefits of replacing regular concrete with UHPC

As such, the other costs for 1 yd^3 of placed regular concrete range from about 3*X* to 7*X*.

The extreme strength of UHPC allows for a significant reduction in the amount of material used, leading to lower weight of concrete material. Let *Y* be the reduction in weight of a structurally competitive UHPC element, expressed as a percentage of the weight of the original concrete element. For example, a regular concrete deck replaced with a same-depth UHPC waffle-slab alternative will have $Y = 45\%$.[18] Aaleti et al.[18] noted that a substantially higher *Y* could be achieved because the replacement deck was much stronger than the original one. This significant reduction will certainly lead to a reduction in the other costs due to lower dead weight and reduced transportation cost. Let the reduction in other costs for the replaced product be *Z*, expressed as a percentage of the costs for the replaced product. Because *Y* and *Z* are not precisely known and would, moreover, depend on the specific application, their effect on the cost of a placed 1 yd^3 of UHPC as a function of *X* is bracketed in Table 2 for feasible ranges of *Y* and *Z*.

For example, when the other costs are at the low end (that is, 3*X*), and assuming $Y = 60\%$ and $Z = 40\%$, the cost of replacing regular concrete with UHPC is:

Case 1:

$((100 - Y)/100) \times 6X$ [cost of open-recipe UHPC] + $3X$ [other costs] $\times ((100 - Z)/100) = 4.2X$

Compared to the original cost of 4*X* (original *X* plus 3*X* in other costs), this implies a 5% premium to use open-recipe UHPC, which indicates that it is just slightly more expensive than normal concrete.

At the other end of the spectrum, when the other costs are high (that is, 7*X*) and again assuming $Y = 60\%$ and $Z = 40\%$, the cost of replacement is:

Case 2:

$((100 - Y)/100) \times 6X$ [cost of open-recipe UHPC] + $7X$ [other costs] $\times ((100 - Z)/100) = 6.6X$

Compared to the original total cost of 8*X* (original *X* plus 7*X* in other costs), using open-recipe UHPC results in a 17.5% savings in costs. The shaded regions in Table 2 represent zones where replacing regular concrete with open-recipe UHPC results in cost savings, while Fig. 4 shows the comparison in a schematic manner.

The numbers cited have substantial assumptions in them, but Table 2 brackets them and allows for engineers to explore variations. The possibility for saving is, however, quite real. Engineers in Malaysia and Australia have reported cost savings of 17% in a bridge application.[19] Also, cost savings may come in other ways. For example, if used to remove a load rating posting for a bridge, a deck replacement based on UHPC may lead to substantial, ongoing benefits for nearby communities.

The Real Opportunity for Cost Savings

The previous section suggests that the incremental cost of using open-recipe UHPC to replace regular concrete may be relatively small and that some savings in certain applications could be realized. The real opportunity to save on costs is in long-term maintenance. The extreme durability of UHPC is well documented. The results in Alkaysi and El-Tawil[9] suggest that open-recipe UHPC can be several times as durable as regular concrete. Also, the strain-hardening capacity of UHPC allows designers to ensure that the main steel reinforcement will yield before cracks localize. The ability to protect the main steel reinforcement and remain impervious to harsh environments implies that long-term maintenance costs will be significantly reduced.

It is likely, given current experimental research results, that UHPC structures will deliver at least a 100-year lifespan with minimal maintenance. Compared to regular concrete structures that may need to be extensively maintained during such a period (and possibly replaced at least once), the cost savings could be quite high as depicted schematically in Fig. 5. The longevity of UHPC may, however, lead to future challenges. For example, it may be wise to consider reconfigurability in the design of future UHPC structures so that components from decommissioned structures can be reused.

Conclusion

Open-recipe UHPC is a material with high disruptive potential. Its unique properties enable novel applications in infrastructure design and construction. The open nature of its composition will promote future innovation, including even greater reduction in the cost of the raw material itself and new opportunities for application.

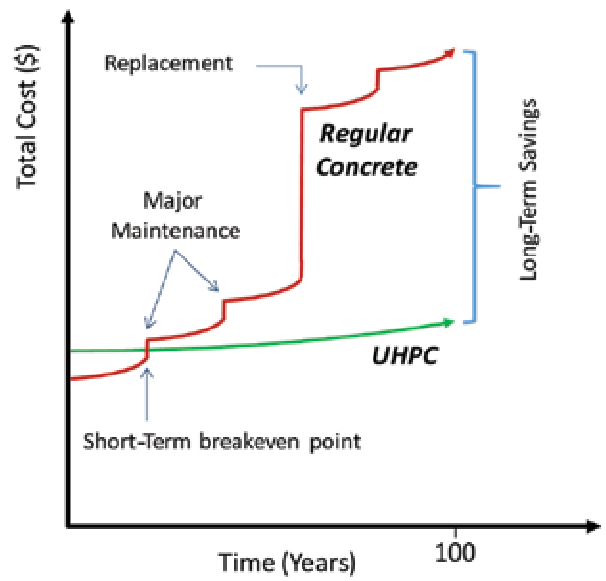

Fig. 5: Schematic diagram of life-cycle cost of UHPC and regular concrete

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

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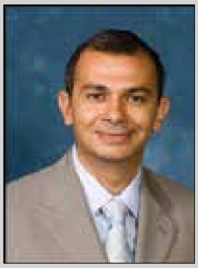

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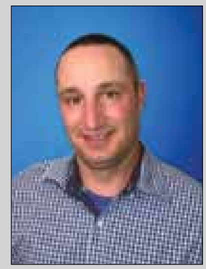

Dewayne Rogers is the Managing Director for the Clare County Road Commission in Michigan. He has implemented the use of open-recipe UHPC on several bridge maintenance projects. He is particularly interested in replacing existing bridge decks with lighter precast panels made entirely of open-recipe UHPC to remove load-rating restrictions or to reduce superstructure weight to lessen foundation needs in new construction.