

Shifting Sands: Unlocking Cost-Effective Ultra-High-Performance Concrete with Natural Sand Alternatives

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Ultra-high-performance concrete (UHPC) is specified for demanding bridge and structural applications that require high compressive strength, low permeability, enhanced durability, and improved resilience. In many applications, the structural efficiency of UHPC delivers compounding savings. Lighter sections reduce handling and transportation costs; smaller foundations are required; and the extreme durability of UHPC dramatically lowers long-term maintenance and replacement expenditures. However, the broader adoption of UHPC has long been constrained by initial material cost. A significant driver of that cost is quartz (silica) sand, a precisely graded, processed aggregate that is expensive to source and transport. The research described in this article asked a straightforward question: Could widely available, inexpensive natural sands serve the same purpose? The answer, backed by both laboratory and field data, is a resounding yes!

The Problem with Quartz Sand

Finely graded quartz sand is used in traditional UHPC mixtures because of

its high purity and favorable particle characteristics. However, quartz sand typically requires energy-intensive processing and transportation over long-distance supply chains, and those requirements contribute significantly to material cost and environmental impact. As the use of UHPC transitions from niche applications to broader infrastructure deployment, the high cost of silica sand and the associated sustainability concerns have become increasingly important considerations.

Natural sands such as mason sand, golf course sand, and bunker sand are locally available across the United States, require minimal processing, and cost 95% less than quartz sand. This study, conducted at the University of Michigan using an open-source UHPC mixture developed by El-Tawil et al.,¹ systematically evaluated whether these sands could replace quartz sand without compromising performance.

The Sands Tested

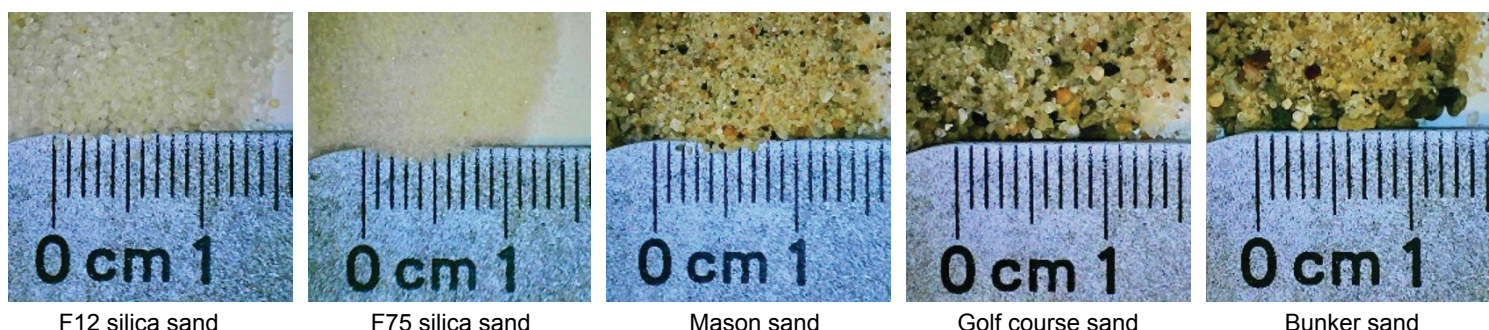
Four natural sands were evaluated alongside two reference quartz sands

(F12 and F75) that are conventionally combined in UHPC production (Fig. 1). Each natural sand candidate has distinct characteristics:

- Mason sand (ASTM C144² and ASTM C33³) is well graded, typically sourced from river deposits or crushed rock, and widely available from masonry suppliers.
- Golf course sand meets United States Golf Association (USGA) topdressing guidelines,⁴ with rounded to subangular particles and tight size control.
- Bunker sand meets the USGA characteristics outlined for golf bunker performance⁵ with a high proportion of medium-sized particles (0.25–1.0 mm [0.01–0.04 in.]) and an angular, gritty texture.
- 3CS (3 Coarse Sand designation), a fine sand found locally in Michigan, was tested only under field conditions in this study.

All UHPC mixtures used the same binder system: Type IL cement, Grade 100 ground-granulated blast-furnace

Figure 1. Particle shape of the sands (shown from left to right): F12 silica sand, F75 silica sand, mason sand, golf course sand, and bunker sand. All Figures and Photos: University of Michigan.



slag, and undensified silica fume with a polycarboxylate-based water-reducing admixture. Each mixture was reinforced with 13-mm-long (0.5-in.), 0.20-mm-diameter (0.01-in.) brass-coated striated steel fibers at 1.5% by volume. That fiber dosage, which is less than the typical U.S. dosage of 2%, is consistent with prior work on this fiber type.⁶ Figure 2 depicts the particle size distributions of the six different sand types used in the study.

Laboratory Results

Table 1 summarizes the compressive strength and flowability results achieved in the laboratory. All four mixtures that included natural sands far exceeded the 120 MPa (17.5 ksi) compressive threshold required for UHPC classification in the American Association of State Highway and Transportation Officials' *Guide Specifications for Structural Design with Ultra-High Performance Concrete*.⁷ The silica sand reference mixture (SS) reached 191.6 MPa (27.8 ksi), whereas the mason sand (MS), golf sand (GS), and bunker sand (BS) mixtures achieved compressive strengths of 183.8, 178.6, and 176.5 MPa (26.7, 25.9, and 25.6 ksi),

respectively. The lowest strength of the alternate sand mixtures is within 8% of the silica sand reference.

The tensile strength results were equally compelling, and, in some cases, the natural sands outperformed the SS reference (Fig. 3). The GS mixture achieved the highest peak tensile strength at 10.50 MPa (1.52 ksi), compared with 9.80 MPa (1.42 ksi) for the SS reference. The MS and BS mixtures reached tensile strengths of 10.19 and 10.35 MPa (1.48 and 1.50 ksi), respectively. All mixtures exhibited pronounced strain hardening after cracking, a hallmark of effective fiber bridging and a key characteristic of UHPC.

Tensile and compressive strength performance do not always trend together. The BS mixture ranked lowest in compressive strength yet delivered outstanding tensile performance. This difference in performance is because compressive strength depends primarily on particle packing efficiency, whereas tensile behavior is governed by matrix quality and fiber-matrix bonding. The angular texture of bunker sand seems to enhance interfacial bonding with the fiber surface, enabling superior post-cracking resistance.

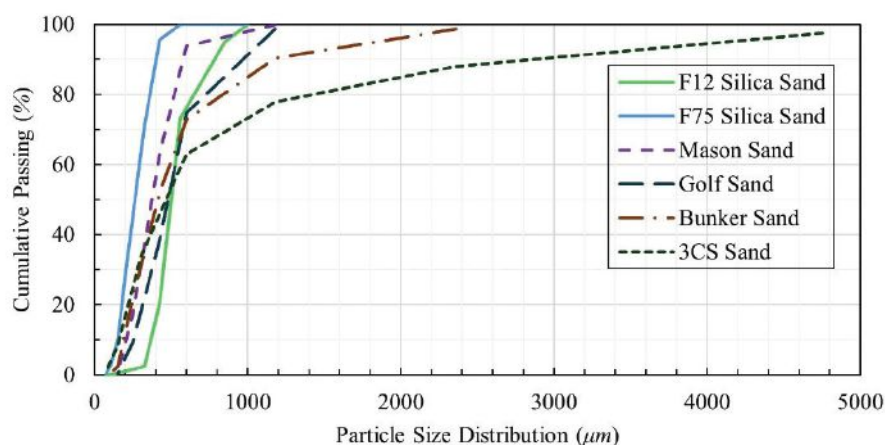


Figure 2. Particle size distributions of various sands.

Table 1. Compressive strength, tensile strength, and flowability of laboratory specimens

Series	Sand type	Flowability, mm	Compressive strength, MPa	Tensile strength, MPa
SS	Silica (F12/F75)	254	191.6 ± 4.36	9.80
MS	Mason	227	183.8 ± 4.40	10.19
GS	Golf	225	178.6 ± 5.19	10.50
BS	Bunker	232	176.5 ± 4.51	10.35

Note: Series 3 Coarse Sand (3CS) was not tested in the laboratory. 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi.

Field Results

Although the laboratory results in this study were encouraging, field conditions are where materials face the real test. Field specimens were made using mason sand and 3CS sand, mixed by workers with no prior UHPC experience, using an IMER-750 pan mixer, a deliberately practical scenario (Fig. 4).

Two challenges emerged. First, the natural sands arrived wet from washing, so on-site moisture measurement was required to adjust water content in the mixtures. Because UHPC is sensitive to water dosing, accurate adjustment is essential. Second, the mixer lacked sufficient power and nearly stalled when the mixture turned over (became fluid). A slight increase in water content (from 0.24 to 0.25 of the cementitious weight) was needed to keep the mixer running. An uncalibrated moisture meter on site added further uncertainty.

Despite these complications, both field mixtures produced viable UHPC. The MS field mixture reached 152.4 MPa (22.1 ksi) in compression (Table 2). That result is well above the 120 MPa (17.5 ksi) minimum, although it is lower than the laboratory value of 183.8 MPa (26.65 ksi); the difference in results is primarily due to the higher effective water content used in the field. The peak tensile strength in the field was 8.81 MPa (1.28 ksi), about 13% below the laboratory value, whereas the localization strain was 10% higher in the field than in the laboratory, indicating good ductility.

Experience from other projects has shown that truck mixers eliminate many of these field challenges, producing results closer to those obtained in the laboratory without the need for water adjustments during the mixing process.⁸

The Cost Case

The financial argument for UHPC made with natural sand is clear. When golf course sand (representative of all natural sand alternatives tested) is used, the total material cost is approximately \$753/yd³ (Table 3). The equivalent mixture using silica sand would cost \$1068/yd³, 42% more than the golf course sand mixture. In comparison, proprietary UHPC products can cost more than \$2000/yd³.⁹ The dominant cost driver in UHPC products is steel fiber. In this study,

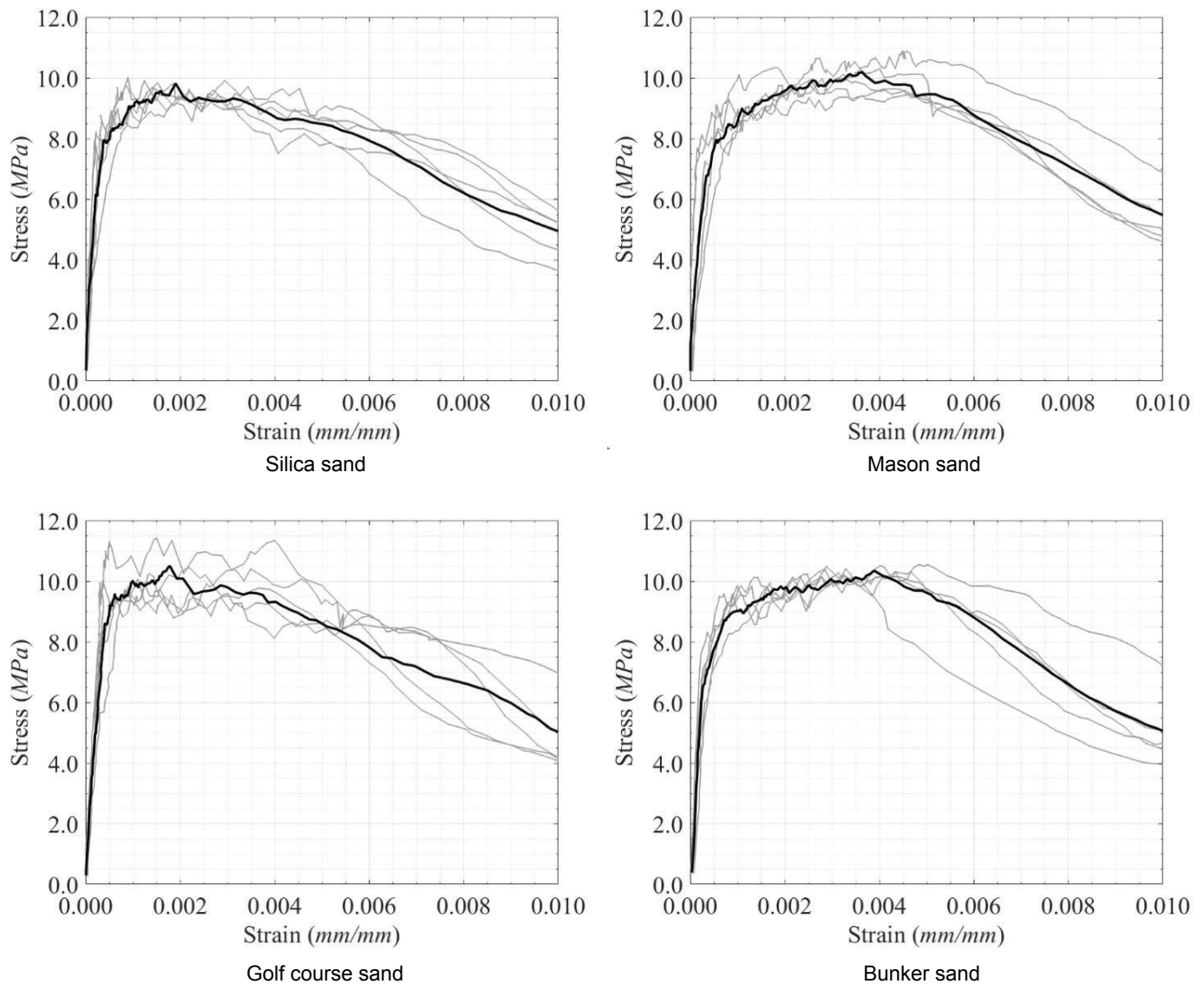


Figure 3. Tensile stress and strain curves of laboratory-mixed ultra-high-performance concrete using silica sand, mason sand, golf course sand, and bunker sand.
Note: 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi.

Table 2. Compressive strength of field-mixed specimens

Series	Sand type	Flowability, mm	Compressive strength, MPa
MS	Mason	254	152.4 ± 5.17
3CS	3CS local	227	149.3 ± 3.00

Note: 3CS = 3 Coarse Sand. 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi.

Table 3. Component unit prices and costs in 2023/2024 dollars

Component	Price	Amount per yd ³	Cost per yd ³
Quartz (silica) sand	\$0.165/lb	—	—
Golf course sand	\$0.005/lb	1971 lb	\$9.86
Cement	\$0.11/lb	653 lb	\$71.83
Slag cement	\$0.09/lb	653 lb	\$58.77
Water-reducing admixture	\$5.45/gal.	4.7 gal.	\$25.62
Silica fume	\$0.45/lb	326 lb	\$146.70
Steel fiber (1.5% by volume)	\$2.20/lb	200 lb	\$440.00
Total			\$752.78

the steel fiber cost \$440/yd³ (58% of total cost) at the 1.5% dosage used. Depending on fiber type and supplier, conventional steel fibers at the standard 2% dosage would cost in the range of \$500/yd³ to \$600/yd³, for a total mixture cost that would be far less than that of the silica sand alternative or proprietary products. At less than \$10/yd³, natural sand represents a fraction of overall UHPC cost regardless of fiber selection, making a compelling case for its use as a lower-cost alternative.

Conclusion

This study demonstrates that mason, golf, bunker, and 3CS sands can fully replace quartz sand in nonproprietary UHPC mixtures without reducing structural performance and may improve tensile behavior. At a small



Figure 4. Field-mixing process: (a) Worker loads steel fiber into IMER-750 mixer; (b) molds for making specimens in the field; (c) flow testing to ensure viability of the ultra-high-performance concrete mixtures.

fraction of the cost of silica sand, these locally available materials offer a practical path to making UHPC more accessible for bridge rehabilitation, accelerated construction, and demanding infrastructure applications.

Two practical lessons from field implementation deserve emphasis. First, moisture management of natural sands is critical and requires calibrated meters and an experienced site engineer. Second, mixer capacity must be sufficient to handle the UHPC mixing process without stalling. Truck mixers are preferred where feasible.

With properties matching those of commercial UHPC, nonproprietary natural sand UHPC offers comparable performance at substantially lower cost, supporting its potential for wider use in the industry. Further technical details about this research may be found in Tang et al.¹⁰ and Pyo et al.¹¹

Acknowledgments

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