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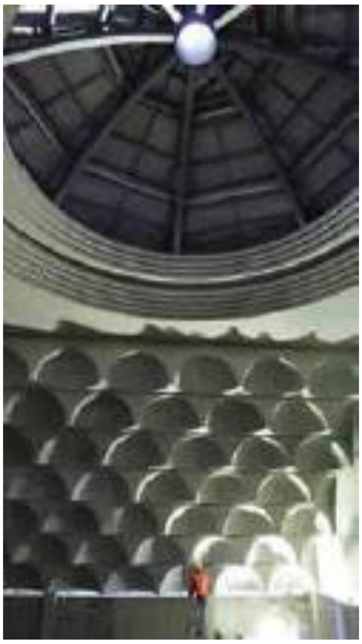

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MyConcrete:
The Bulletin of the American Concrete Institute – Malaysia Chapter

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ARTICLE

Reprint from CI Magazine, Volume 42, No 3, Page 37-40

An Awe-Inspiring Place

Sydney's Punchbowl Mosque showcases the architectural flexibility of concrete.

by Deborah R. Huso

In 2018, the Australian Islamic Mission (AIM) celebrated the completion of its stark yet elegant mosque in the Punchbowl suburb of Sydney, Australia. Named after a nearby circular valley that nineteenth-century settlers called “the punch bowl”, the suburb located in Sydney's southwest and is known for its cultural diversity.

The Punchbowl's Mosque design, the brainchild of Greek-Australian architect Angelo Candalepas of Candalepas Associates in Sydney, features what might call (but Candalepas downplays) a “brutalist” structure with a simplicity of exterior architecture that belies its inspirational interior. Almost the entirety of the structure is rendered in concrete. With no elaborate ornamentation other than gold calligraphy painted on minidomes in the main prayer hall, the combination of formed concrete with wood and stone detailing creates a space that is arresting in its delicate restraint.

Concrete as Sculptural Material

Architecturally as well as spiritually, the design speaks to the efforts of AIM and Candalepas to improve interfaith relations in New South Wales. The main entry doors intentionally open to the street (Fig.1), creating a sense of welcoming and transparency to passerby of all faiths. Adjacent to the entry, a single minaret is subtly incorporated into a wing of the building that frames the mosque's courtyard. (Fig.1)

The architect selected concrete as the primary construction material largely because AIM's construction brief called for a structure that would last 300 years. “Concrete is often mistaken for a material that is only solid and firm” says Angelo Candalepas. “but its ability to be cast in many types of forms gives it a potential that is not often realised.” It is that potential that Candalepas sought to manipulate when selecting concrete as the construction material.

The final set of construction drawings were sent to the builder in the fall of 2014. That package included 1:20 scale detail sections showing the mosque's key elements, including details of the concrete ceiling of the mosque's prayer space. In addition to a concrete ring beam with a stepped soffit evoking a corbelled dome structure, the ceiling comprises seven rows of quarter-sphere muqarnas (ornamented vaulting formed as quarter-sphere minidomes) on the northwestern and southwestern sides of the space (Fig.2). According to Candalepas, the drawings called for Class 2C finish for all visible concrete in accordance with Australian Standard AS 3610. Project construction began in October 2015 with the mosque's basement car park.

Fig. 1: Punchbowl Mosque, Sydney, Australia, with main entry doors facing the street and a single minaret adjacent to the entry (left) (photo by Brett Boardman, courtesy of Candalepas Associates)

Fig. 2: A view from the floor of the main prayer hall, showing the stepped soffit of the concrete ring beam and rows of quarter- sphere muqarnas. Since this photo was taken, Turkish and Iranian calligraphers have inscribed the smooth and seamless concrete surfaces of the minidomes with the 99 names of Allah in gold calligraphy *(photo by Brett Boardman, courtesy of Candalepas Associates.*

The Muqarnas

The sculptural ceiling of the prayer space features 102 muqarnas spread across two faces of the ceiling like a honeycomb (Fig.2). Because the concrete was to serve as the painting surface for calligraphers, Candalepas did not want to use any chemical release agents. He also provided no option for patching damaged surfaces.

Thus, casting the muqarnas was the most challenging aspect of the construction. “There was a high level of concern [about] the finish that could be achieved for the exposed concrete surfaces, especially the muqarnas”, says Paul Moore, Structural and Section Manager and Principal at Wood & Grieve Engineers, the firm that prepared detailed project designs and documentation and supervised structural work during the mosque’s construction. To address this, Wood & Grieve documented reinforcing bars for these elements in three dimensions in Autodesk Revit, producing perspective views as well as the typical plans, sections and elevations.

To ensure the finish could be achieved, Sydney based builder Infinity Constructions Group made several test placements, including the construction of a mock-up of the walls and lower muqarnas at the west corner of the building (Fig. 3). In addition to using the same formwork system and reinforcing layout as required for the actual structure, the mock-up was constructed using the concrete mixture and curing techniques that were to be used in the final construction.

Fig. 3: A mockup was used to verify methods and materials for construction of the muqarnas: (a) formwork with molded and coated fiberglass domes; and (b) finished surface after stripping the molds *(photos by Adrian Curtin, courtesy of Boral Australia)*

Each minidome is a quarter sphere, 1500 mm (59 in.) wide and 750 mm (29.5 in.) high, with a 30 mm (1-1.8 in.) diameter hole created at the centre using a tube and a form tie. To allow light yet prevent water from penetrating the ceiling, the tubes were subsequently plugged with clear polymethyl methacrylate caps where they pierce the roof sheathing. The curved surfaces were formed using molded fibreglass domes with a smooth polymer coating. The dome forms were separated by 120 mm (5 in.) to create vertical, semicircular flat planes between the curved surfaces; the flat surfaces between the minidomes were cast against galvanized-steel sheets backed by plywood (shown in Fig.4).

During construction, each fibreglass dome was penetrated at its centre point by a single large form tie that extended to the sloped framework for the roof of the building. The concrete thickness at this point was 350 mm (13-3/4 in.). “I had imagined we would be able to have large ties since I had desired the entire ceiling to have many skylights”, Candalepas notes. “In ancient Turkish mosques, the night sky was replicated within the domes. I found that the juxtaposition between the eternal values of the form-giving sphere (the dome) above the space was able to be enhanced with the mosque ceiling describing the night sky below it.” He also noted that the concave surfaces “showcase the subtle gradation of light at different intensities and concurrently.”

The formwork for the mosque ceiling was constructed and scaffolded to progressively step up and out by 810 mm (32 in.) vertically and horizontally with each row of muqarnas. According to Candalepas, “Stripping the lowest levels of formwork after the first concrete pours would, therefore, not be possible until all the remaining concrete pours for the mosque’s ceiling and ring beam had been completed.” The builder created flat shelves of formwork to set out the stepping profile of the raked ceiling to two sides of the mosque and then cut rectangular slots into these shelves at intervals that matched the set-out of the muqarnas.

“Fibre glass molds placed on the inside face of each formwork slot created the quarter-spherical domes [of the muqarnas],” Candalepas adds, noting that the concrete placements for the main prayer space took up to a full day to pump, given the complex geometry for the interior formwork. Candalepas says the builder cleaned and polished formwork each day before the next day’s concrete placement.

Concrete for Sculptural Finish

During the production of the tender documents, Candalepas collaborated closely on concrete specifications with Sydney-based structural engineering firm Taylor Thomson & Whitting and concrete manufacturer Boral Australia. The team selected a white concrete mixture based on Boral’s patented Envisia® System. Envisia mixtures contain a high supplementary cementitious material content and thus have a lower CO_2 footprint than conventional concrete mixtures.

Aesthetics and long-term performance were also major considerations. As Candalepas notes, "Low-shrinkage performance, in particular, was a significant consideration given the complexity and volume of the concrete pours proposed for the main prayer space." Envisia concrete consumes much of the mixing water while it is setting, resulting in reduced volume loss from water evaporation. This results in 50% lower shrinkage than conventional concrete mixtures, yet the proprietary mixture can also achieve the same setting times and strength gain as more conventional mixtures.

Fig. 4: Muqarnas were formed using molded fiberglass minidomes spaced 120 mm (5 in.) apart, and the flat surfaces between minidomes were formed using galvanized steel on plywood panels: (a) view of minidome forms installed on scaffolding; (b) view of exterior formwork for the sloping roof; and (c) view of minidomes during stripping *operations* *(photos by Adrian Curtin, courtesy of Boral Australia)*

Fig. 5: The dome is a structural steel structure that includes a clerestory base: (a) a view during construction, showing the steel structure above the concrete ring beam; and (b) a view after completion, showing the visual drama created by the diffuse lighting of the stepped ring beam and veneer ceiling *(photos by Adrian Curtin, courtesy of Boral Australia)*

The Main Prayer Hall

The walls within the mosque's main prayer hall are typically 200 mm (8 in.) thick and include 300 x 600 mm (12 x 24 in.) pilasters. The walls stop short of the lower level of muqarnas, allowing outside light filtered through translucent glass to illuminate the minidomes from below. To meet thermal and aesthetic requirements, the wall areas between pilasters also have interior insulation as well as granite and hoop pine veneer plywood finishes. The concrete used to construct the wall had an 80 mm (3-1/4 in.) slump and a maximum aggregate size of 20 mm (3/4 in.) . The concrete used to construct the muqarnas had a 120 mm (4-3/4 in.) slump.

The Dome

The designer initially envisioned the dome to be constructed in stone. However, after a series of prototypes were considered, a structural steel dome supported by a concrete ring beam was selected. The ceiling of the dome is finished with sheets of marine plywood with hoop pine veneer (Fig. 5). The stepped concentric circles of the ceiling and ring beam, along with the diffuse light provided by the dome's oculus and clerestory, create an ethereal aesthetic in the main prayer hall.

The builder cast a 100 x 100 mm (4 x 4 in.) rebate into the top of the mosque walls and muqarnas to recess the construction joint for the flat concrete ceiling and profiled ring beam. Then the construction team fashioned a construction deck above the flat ceiling and placed the form for the ring beam, constructing it in two concrete placements (Fig.6). Candalepas says the construction deck remained in place as the formwork for the muqarnas was stripped below it in December 2016. After that, the builder began working on the steel structure of the dome, clerestory, glazing, and oculus. By the end of January 2017, the formwork of the muqarnas as well as the scaffolding had been stripped away to reveal the main prayer space's finished interior.

Appreciation

Punchbowl Mosque won the 2018 Sulman Medal for Public Architecture before it was completed in December 2018. The mosque opened for worship in the summer of 2019.

Note : Additional information on the Australian Standard discussed in this article can be found at www.standards.org.au

Fig.6: Ring beam construction: (a) before the first concrete placement; and (b) before the second placement *(photos by Adrian Curtin, courtesy of Boral Australia)*

Deborah R. Huso is Creative Director and Founding Partner of WWM, Charlottesville, VA. Her publication credits include positions as contributing editor with the *Progressive Farmer* and as a monthly columnist for *HousingWire* magazine. She has contributed articles to many other publications, including *Precast Solutions, U.S. News and World Report, USA Today*, and *Business Insider*, and she has provided website development and content strategy for several Fortune 500 companies.

Selected for reader interest by the editors

TECHNICAL REPORT

Reprint from CI Magazine, Volume 40, No 1, Page 36-42

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 density1,2 (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 mixtures1,2 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 MixturesComponent 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.

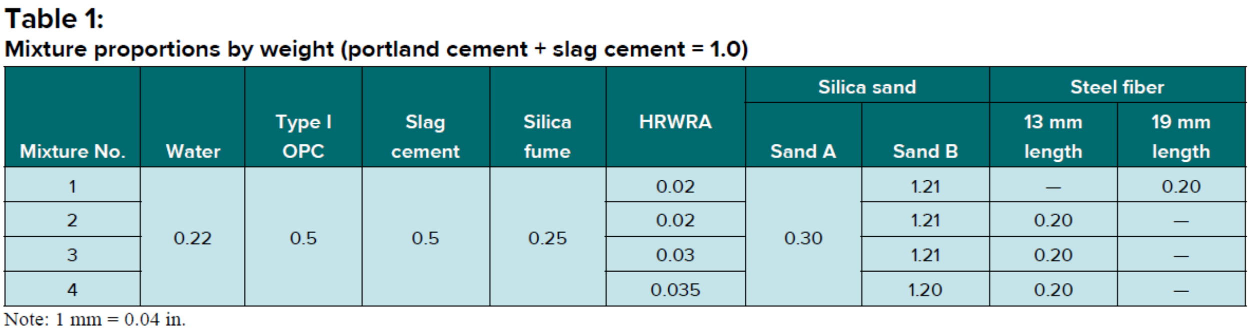

Table 1:
Mixture proportions by weight (portland cement + slag cement = 1.0)

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.

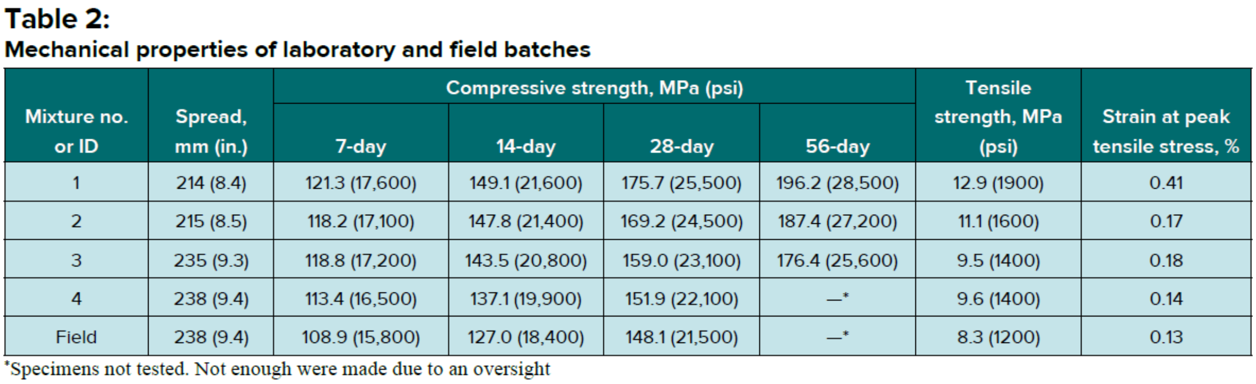

Table 2:
Mechanical properties of laboratory and field batches

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

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)

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 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 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.

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

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.

Table 4:
Cost of Mixture 3 components

Component	Quantity, lb/yd³	Cost per yd³, % 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

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. 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 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.

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CASE STUDY

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Specifying for Performance

Case studies show that cooperative efforts lead to success

by Karthik H. Obla, Daniel J. Gancarz, William R. (Rusty) Owings III, Fouad H. Yazbeck, and David G. Tepke

A design professional's essential responsibility is to ensure that a completed project will attain the level of performance required by the owner. Globally imposing overly conservative requirements (for example, using the harshest environment to set the durability requirements for an entire project) will add needless cost and detract from sustainability goals. Rather, design professionals should define performance-based requirements for the concrete used in the project based on the use and exposure for specific portions. This could be accomplished using a performance specification in lieu of stating prescriptive requirements. For example, Provision 1.10.1 of ACI 318-141 states: "Sponsors of any system of design, construction, or alternative construction materials within the scope of this Code, the adequacy of which has been shown by successful use or by analysis or test, but which does not conform to or is not covered by this Code, shall have the right to present the data on which their design is based to the building official, or to a board of examiners appointed by the building official. This board shall be composed of competent engineers and shall have authority to investigate the data so submitted, require tests, and formulate rules governing design and construction of such systems to meet the intent of this Code. These rules, when approved by the building official and promulgated, shall be of the same force and effect as the provisions of this Code."

Performance is Fundamental

Performance-based specifications that meet explicit durability goals can be successfully used on different types of projects. The following sections describe four examples.

Pavement

Since 2008, the Illinois Tollway has been using performance-based specifications for concrete mixture proportions to ensure durability and sustainability while minimizing cost. A recent example, completed in 2016, was a portion of the $2.5 billion Jane Addams Memorial Tollway (I-90) Rebuilding and Widening Project, from Roselle Road to Illinois Route 53/I-290 in Schaumburg, IL.

Performance-related mixture and construction special provisions were incorporated into the contract documents, and an outreach program was implemented at the beginning of the project to ensure that the stakeholders (Tollway representatives, contractor, and concrete producer) understood and properly implemented the provisions. The performance criteria for mixture qualification included compressive strength, flexural strength, and plastic and hardened air contents. Jobsite acceptance tests for the concrete included compressive strength and plastic air

The mission of ACI Committee 329, Performance Criteria for Ready Mixed Concrete, is to develop and report information on performance criteria for ready mixed concrete. This article provides summaries of four projects discussed at a session, Case Studies of Performance-Based Specifications, sponsored by Committee 329 at The ACI Concrete Convention and Exposition – Spring 2017 in Detroit, MI.

content. Jobsite acceptance criteria also included edge-slump of the slip-formed pavement, pavement thickness and smoothness, and dowel alignment. Bulk resistivity testing was performed as a research effort to determine the formation factor. The formation factor may be included in future versions of the special provisions.

By using performance criteria, the Tollway allowed greater use of cementitious materials cementitious materials and eliminated restrictions on water-cementitious material ratio (w/cm). It also allowed the implementation of nonstandard aggregate gradations, thus encouraging the use of local materials. To ensure a high-quality mixture, however, prescriptive limits were still placed on specific supplementary cementitious material (SCM) contents, aggregate grading, and aggregate susceptibility to alkali-silica reaction (ASR).
The contractor chose to use a ternary cementitious material mixture with an optimized aggregate gradation. Because the selected mixture had 24% less portland cement and 15% less total cementitious material than a typical Illinois pavement mixture, the Tollway realized a lower bid price. The mixture exceeded the performance criteria and, as a result, the contractor received a bonus.

Jane Addams Memorial Tollway (I-90) Rebuilding and Widening project credits: Illinois Tollway, Owner/Engineer; Walsh Construction Company, Contractor; and Terrell Materials Corporation, Concrete Supplier

Christopher S. Bond Bridge project credits: MoDOT, Owner; Parsons Corp., Engineer; Paseo Corridor Constructors (a partnership of Massman Construction Co, Clarkson Construction Co, and Kiewit Construction Co), Contractor; and Fordyce Concrete, A Division of Ashgrove Materials Corp, Concrete Supplier

Bridge

The Christopher S. Bond Bridge was completed in 2010 in Kansas City, MO. Parsons, the engineer for the project, worked with Missouri Department of Transportation (MoDOT) officials to develop the project using design-build project delivery and a performance-based specification. To achieve the specified performance requirements, the concrete producer used mixture proportions with optimized aggregate gradations and ternary blends of cement and SCMs.

Performance criteria on the project included:

- Drilled shaft foundations—specified compressive strength of 4000 psi (28 MPa) at 56 days, low heat of hydration(158°F [<70°C] maximum per ASTM C150/C150M,“Standard Specification for Portland Cement”), and slump of 8 ± 1 in. (200 ± 25 mm) or spread flow of 26 ± 4 in.(660 ± 100 mm);
- Pylon (center vertical structure)—specified compressive strength of 7000 psi (48 MPa) at 56 days, moderate permeability (<2000 coulombs per ASTM C1202,“Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration”), ASR expansion below 0.08% at 16 and 30 days (ASTM C1567, “Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)”), and slump of 8 ± 1 in. or spread flow of 26 ± 4 in.; and

- Bridge deck—structural pour strips between precast panels and the deck topping with specified compressive strength of 8000 psi (55 MPa) at 56 days, low permeability (<1000 coulombs per ASTM C1202), ASR expansion below 0.08%at 16 and 30 days (ASTM C1567), pass scaling resistance (visual rating of 0-1 per ASTM C672/C672M, “Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals”), microwave oven water content test (AASHTO TP 23, “Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying”) on each day of placement, and slump of 8 ± 1 in. or spread flow of 26 ± 4 in.

Each concrete mixture design was prequalified using laboratory tests and tested as required per the project specification from concrete placed for the structure (ASTM C1202 and C672/C672M testing every 30 days, and ASR testing every 6 months). The microwave test was required on the first load for every placement for the deck structure concrete mixture and had to be completed prior to allowing the concrete to be placed. Testing was done at the plant and the results were communicated to the team on site.

Initially, the contractor conducted quality control tests and MoDOT conducted random quality assurance (QA) tests in the field. This resulted in a lot of testing of concrete mixtures. Effective communication and sharing of information was important to keep on schedule and address any issues. The QA testing program was relaxed after passing QA test results were consistently reported. The performance specification led to significant cost savings, as the contractor was able to use lower cementitious material contents in comparison to prescriptive mixtures from MoDOT’s standard specification.

Development

The 2012 project, Al Raha Beach Development – Phase 1, Abu Dhabi, UAE, involved several types of structures (infrastructure, seawalls, bridges, residential buildings, and services and utilities). The project’s wide range of exposures led to the use of performance specifications to streamline production, testing, and acceptance of concrete. Another motivation was the potential for reduction of waste due to over-ordering or on-site breakdowns.

The performance requirements were two-fold, with stringent testing for mixture qualification and identity testing (mainly strength and some durability) at the time of supply. All prescriptive requirements (minimum and maximum cement contents, maximum w/cm, SCM types and dosage limits, and aggregate grading limits) were removed to allow mixtures to be designed as “fit for purpose.” The resulting mixtures had elevated cement replacement levels to enhance service life and reduce the carbon footprint. Multiple subproject specifications were replaced with a single document that was enforced sitewide.

There was some reluctance to remove prescriptive elements completely from the specification. This was recognized early on, and some requirements (especially durability testing on site) were incorporated into the performance specifications to alleviate the concerns.

Many advantages were realized, including reduction of waste, better consistency of concrete due to the reduction of number of mixtures produced, and lower CO2 emissions due to a high SCM content.

Steel column encasement

Lower-level columns of Hyperion Towers, North Myrtle Beach, SC, were heavily corroded. The columns support a seven-story condominium, so rehabilitation was urgent. Concrete jacketing was selected as a practical method for addressing structural concerns, and the engineer decided to use a performance specification to obtain the necessary concrete characteristics.

Al Raha Beach Development – Phase 1 project credits: ALDAR Properties, Owner/Engineer; ALDAR Laing O'Rourke, Main Contractor; and ALDAR Readymix, Concrete Supplier

Hyperion Towers project credits: Hyperion Towers Homeowners Association, Owner; SKA Consulting Engineers, Inc., Engineer; Heard Ratzlaff Construction, Inc., Contractor; and Ready Mixed Concrete Company, Concrete Supplier

Concrete that could adequately protect and supplement steel, while providing durability for the severe coastal environment, was needed. A team approach was used—the engineer worked with the contractor to define the QA process, including small batch testing, full-scale trials, and mockup placements.

A self-consolidating concrete (SCC) was used on the project. Some of the key mixture qualification requirements included:

- Minimum compressive strength of 5000 psi (35 MPa);
- Minimum 28-day to 7-day compressive strength ratio of 1.3;
- Maximum rapid indication of chloride-ion penetrability(RCP) of 1200 coulombs (7-day standard cure followed by 21 days at 100°F [38°C]), per ASTM C1202;
- Maximum shrinkage of 300 microstrain (7-day cure followed by 28-day drying) per ASTM C157/C157M,"Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete";
- Maximum ASR expansion of 0.10% at 14 days per ASTM C1260, "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)";
- Maximum column static segregation of 10% per ASTM C1610/C1610M, "Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique";
- Maximum Visual Stability Index (VSI) value of 1 per ASTM C1611/C1611M, "Standard Test Method for Slump Flow of Self-Consolidating Concrete"; and
- Minimum air content of 5% per ASTM C231/C231M,"Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method."

A level of training was required to provide relevance for the types, implementation, importance, and execution of specifications and tests. Specifications were set up such that performance characteristics were required, but prescriptive provisions were included to provide guidance on meeting performance. This allowed the construction team to price the work adequately and consult with the engineer during the mixture development phase. The SCC mixture meeting specifications included 30% Class F fly ash, 5% silica fume, optimized gradation of locally available aggregates, and shrinkage-reducing admixture, with a slump flow of approximately 25 to 28 in. (640 to 710 mm).

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