Manufacturing of Architectural Ultra-High-Performance Panels with Complex Geometry and Features Using Non-Metallic Fibers

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Abstract

This paper is a presentation of the process used for the manufacture of ultra-high-performance concrete (UHPC) Cladding Panel with Complex Geometry. It discusses the basic principles, mixing proportions, mixing techniques, molding materials, and pouring techniques to produce high-quality UHPC. The high proportion of ultrafine particles used in UHPC enables optimal packing to minimize composite porosity using a very low water-binder ratio. Molding materials used successfully in the manufacture of UHPC precast elements are steel, silicone, polyurethane, lexan, glass, epoxy-painted wood, and Teflon. UHPC, also known as [1]reactive powder concrete, is characterized by its high strength and ductility due to the presence of metallic or non-metallic fiber reinforcement. The manufacturing process followed in this paper aims to optimize the mix for the most appropriate water:cement ratio and superplasticizer:cement ratio to achieve the target strength and workability. UHPC is a material that is currently gaining momentum in terms of research and implementation due to its outstanding qualities and superiority in comparison with conventional and high-strength concrete.

Keywords: UHPC Panel, Architectural UHPC, UHPC Mix Design, Compressive Strength, UHPC ASTM Testing Standards, Steel Fiber Reinforcement, Non Metallic Fiber Reinforcement

1. Development of Mix Design Category

1.1. Basic Principles of UHPC Design

Concrete has made remarkable progress over the past few decades especially UHPC with some mix designs reaching compressive strengths up to 200 MPa (30,000 psi). The development of super-plasticizers enables the production of easy-flowing concrete with a high proportion of ultrafine particles optimally packed to minimize the composite porosity using a very low water-binder ratio. The aim is to achieve a densely compacted cementitious matrix having adequate strength and good workability. The [2]basic principles used in the design of UHPC are:

- Optimizing the granular mixture to minimize composite porosity achieved by a wide distribution of powder size classes and reducing the water-to-binder ratio
- Using post-set heat treatment to enhance the microstructure as it speeds up the pozzolanic reaction of silica flour and improves the mechanical properties
- Eliminating coarse aggregates to improve homogeneity resulting in a reduction in the mechanical effects caused by heterogeneity

- Adding adequate volume fraction of metallic or non-metallic fibers to increase the ductile behavior and tensile strength.

1.2. Raw Materials used in the UHPC Mixture

The typical constituents of UHPC formulations include a combination of Portland cement, fine sand, small aggregates, silica fume (or other cementitious material), high-range water-reducing admixture, chemical admixtures, fibers, and water. Depending on the application of a particular UHPC mix design, the materials are used in different combinations. The different raw materials used in UHPC design include

- **Dry Materials –** Type I, II OR V cement (C_3A< 8%), silica fume (SiO_2 >95%), Supplemental material (up to 2- Fly ash, slag, ground silica, or metakaolin), Sand (Fine<0.03 inch preferred)
- **Fibers -** Architectural UHPC utilizes fibers with a minimum tensile strength of 140 ksi and a diameter of upto 300 microns. For architectural applications, organic fibers and inorganic fibers are typically used. However, when very thin sections are desired and the UHPC members are expected to experience excessive wind pressure and tensile load, steel fibers may be specified in architectural UHPC applications. [3]Some types of fibers used are
  - Metallic fibers – steel fibers having a minimum tensile strength of 310 ksi and diameter of upto 200 microns
  - Natural fibers – carbon fibers, glass fibers, basalt fibers and plant fibers
  - Synthetic fibers – polyvinyl alcohol fibers, polyethylene fibers and polypropylene fibers
- **Chemicals –**High range water reducers (HRWR) or super-plasticizers that help attain required flowability and are required for concrete mixes having very low water-to-powder ratio and Concrete setting accelerators that help accelerate the setting process of concrete.
- **Accelerators -** Set accelerators to shorten the time taken for the concrete to set AND Strength accelerators to speed up early strength gain
- **Water -** Water used for mixing is usually potable water but if not they must be free from contaminants that can harm the concrete like oil, salts, acids, chlorides, etc.
- **Color Pigments**
  - Solid pigment – Ensure there are no changes in flow properties if volume exceeds 1% of total dry material. Additional water may be required to compensate for its addition
  - Liquid pigment – Care has to be taken not to exceed the water content. If the dose exceeds 3% by mass of dry materials, it can cause adverse effects

1.3. Proportioning of Materials to Make the Right Mixture

Following are the [4]recommendations for mix proportions developed for use with commercially available constituent materials:

- Moderately fine cement with C_3A content significantly lower than 8%
- Sand-cement ratio of 1.40 for a maximum grain size of 0.8 mm (0.3 inch)
- Silica fume with very low carbon content at 25% of cement weight
- Supplemental material at 15%- 25% of cement weight
- High-range water-reducing (HRWR) admixture

- Water-cement ratio of about 0.22
- Fibers at 2.50% by volume

1.4. Correct Mixing Techniques

Once all the component materials for UHPC have been gathered in their right proportions, mixing begins. UHPC mixing time ranges from 7 to 18 minutes, which is much longer than the time required for mixing conventional concrete. For energy efficiency, batch sizes are often reduced from 40 to 75% of the batch size recommended by the mixer manufacturer. To remove entrapped air from the mixture, the mixer is slowed down prior to placing as entrapped air can lead to a weak matrix and poor surface finish in the element. Mixing time can be reduced in two ways:

- By optimizing the particle size distribution, replacing cement and quartz flour with silica fume, matching the type of HRWR and cement, and increasing the speed of the mixer
- Dividing the mixing process into two stages – high speed mixing for 40 seconds followed by low speed mixing for 70 seconds for a total time of about 2 minutes

2. Manufacturing of Mockup Panel

2.1. Correct Material for Mold Work Selection for UHPC Pour

Mold technology can help achieve a [6]great deal of embodied energy reduction without impacting the characteristics of the end product. Self-leveling UHPC formulations have no internal shear in the plastic state, creating challenges for developing formworks with tight tolerances and complete enclosure. For the precise design of the mold, it is important to consider initial UHPC shrinkage and potential deflections.

Molding materials used successfully in the manufacture of UHPC precast elements are steel, silicone, polyurethane, lexan, glass, epoxy-painted wood, and Teflon. As UHPC replicates surfaces with high precision, specific molding details critical in its design, construction and use of formworks are: molding material, release agents, methods of release during initial shrinkage, orientation and mold support, and expected surface outcome.

2.2. Setup of Molds and Pouring Techniques

Architectural UHPC precast elements must be cast in a proper sequence to achieve the desired orientation of reinforcement fibers. The [7]two important factors of fiber dispersion are fiber orientation and distribution, which are influenced by the pouring method, mold size, shape and size of fibers, and paste bonding strength. Molds must be filled slowly so as to prevent air entrapment. Internal vibration must not be done due to fiber reinforcement but limited external vibration can be done to release any entrapped air.

Mold filling is completed in a continuous casting process by following behind the leading edge of the UHPC pour. The discharge point is moved at a rate that it always stays behind the leading edge of the flow allowing the mold to be filled in one continuous motion. Where UHPC flows meet each other probability of forming a weak plane exists as there is minimal fibers bridging the junction. After placement, the exposed surface is covered to prevent dehydration.

2.3. Special Casting Techniques

- **Injection casting technique** – The flow properties of UHPC allow injection techniques to be used to create sophisticated forms and shapes that cannot be achieved by conventional techniques. The complex canopy roof system for the Shawnessy LRT Station in Calgary, Alberta, Canada, was completed using this technique.
- **Displacement casting technique** –Exact volume of material needed is deposited and the top portion of the mold is introduced, which displaces the mixture into the shape of the casting. By controlling the entry points of the secondary form, the plastic UHPC can be moved in a direction that will influence the orientation of the fibers and help release entrapped air. However, this method requires alignment guides to control the exact positioning of the top form and also requires a considerable force of displacement.

3. Flow Analysis through the Molds

The flow is tested for the final UHPC mix after all adjustments for the constituents have been made. The flow is measured using ASTM C230 - Standard specification for flow table for use in tests of hydraulic cement, and ASTM C1437 - Standard test for flow of hydraulic cement mortar.

3.1. Arranging the Mold and Formwork

Once the mold material is selected, the next step is to put together a mold using a combination of GFRC, wood, rubber and PVC. Figure 1 shows the different mold materials

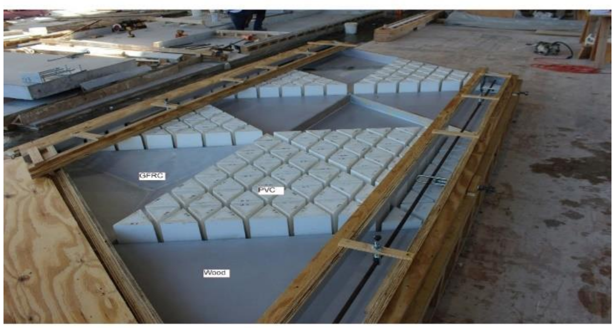

Figure 1. GFRC, wood, rubber and PVC mold material

Figure 2. The ¾” rib spacing in the mold work

The next challenge was to get the right flow that would allow the mix to flow through the ¾” ribs. Multiple iterations were performed for fiber dosage, water-cement ratio, and water content. Parameters were changed based on strength requirements and an 8 in. (20.32 cm) spread was finally decided. The 8 in. (20.32 cm) spread allowed the UHPC mix to flow through the ¾ in. (1.90 cm) rib space. Another important parameter while pouring the UHPC mix is vibration. The tendency of UHPC to exhibit rheological behavior necessitates additional form preparation but reduces the efforts required during casting.

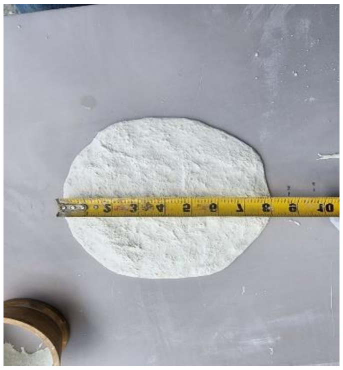

Figure 3. The 8” spread for the right flow

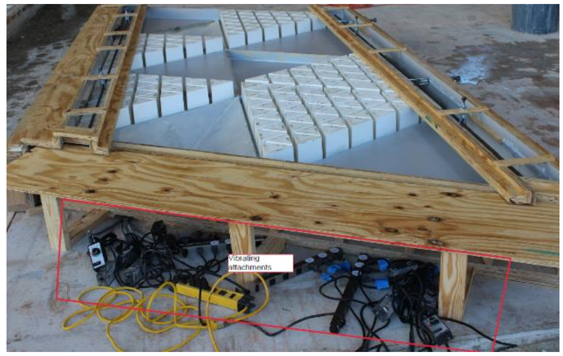

Figure 4. Vibrating attachments under the mold

Due to the presence of fiber reinforcement, [8]internal vibration is not recommended but limited external vibration can be performed to facilitate entrapped air to come out. We had to place vibrating devices beneath the mold, which were connected to electrical output, to provide external vibration while pouring to remove trapped air. A uniform duration of vibration is maintained. When the concrete surface becomes relatively smooth and air bubbles stop breaking through, it is usually sufficient. Care should be taken not to over vibrate as it can cause segregation. According to ASTM C 192/C192M-02, there are two types of external vibrators - table or plank. The required frequency of external vibration is 3600 vibrations per minute, i.e. 60 Hz or higher. The mold must be clamped securely to the table or plank to prevent movement.

3.2. Mixing of the UHPC Constituents

The UHPC mix has low water content and reduced or eliminated coarse aggregates compared to conventional concrete. A regular concrete mixer can mix UHPC but requires greater energy input, which can cause overheating of the mixture. To prevent this a [8]high-energy mixer can be used or the temperature can be lowered by using ice either fully or partially as water content. High shear mixers, especially counter-current pan mixers are considered to provide the most efficient and consistent mixing of UHPC and also reduce mix time. They disperse water and admixtures onto the cement particles without heating the mix through kinetic energy generated by mixing. We used an existing traditional precast concrete mixer.

Table 1. Mixing sequence and timing at each step

Step	Description	Duration (min.)
1	Dry mix sand and powders	5
2	Add mix water, ice, HRWR	5
3	When flowable, add sealant	1
4	Stop Mixer, spread fluffed fibers and mix	5
5	Test for spread using a small sample	2
6	If acceptable, discharge UHPC or add admixtures as needed to get the right flow	2

Step 1: Add in all the dry ingredients such as sand, cement, and other materials (Figure 5)

Figure 5. Dry ingredients in mixer

Figure 6. Wet ingredients added

Step 2: Add in the wet ingredients - water, ice, and admixtures (Figure 6)
Step 3: Check for flow and add in the fibers. Fluff it up to avoid forming balls. (Figure 7)
Step 4: Test for spread as described in ASTM C 230/ C 230M
Step 5: If the spread test is acceptable, discharge UHPC, else add admixtures for desired flow.

Figure 7. Fibers after dispersing (right)

Figure 8. The final UHPC mix

3.3. Pouring the UHPC Mix

UHPC can be placed immediately after mixing or delayed while additional mixes are being completed. Even though temperature and chemical accelerators can influence the dwell time, UHPC requires multiple hours before it begins to set and care should be taken to prevent self-desiccation. Casting procedures can affect the long-term mechanical and durability properties of UHPC as it influences the dispersion and orientation of the fiber reinforcement. It has a tendency to align in the direction of flow during casting, which must be considered when developing the casting sequence for an element.

Also, the tendency of the fibers to remain in suspension depends on the rheology of the concrete. Care must therefore be taken while modifying rheology or relying excessively on form vibration. For this project, once the UHPC constituents were properly mixed, it was discharged and poured into the prepared mold (Figure 10). The mix was allowed to flow within the ribs by slowly moving the bucket to the other areas of the mold to get a level spread. The externally attached vibrators beneath the molds were turned on to provide the necessary external vibration to remove the trapped air. The mix was allowed to flow within the ribs by slowly moving the bucket to the other areas of the mold to get a level spread throughout the mold. Mold filling was completed in a continuous casting process (Figure 11).

Figure 10. Discharging the UHPC mix

Figure 11. Pouring behind the leading edge

3.4. Covering the Mold

UHPC requires very little additional water due to its special mix proportions. However, this also necessitates careful attention to curing methods so as to prevent the water in the UHPC matrix from escaping before hydration takes place. The exposed surface of any freshly cast UHPC element must be sealed with an impermeable layer such as metal, plastic, plastic-coated wood, etc. The seal must not allow any space between the covering material and the freshly laid UHPC. This eliminates the problem of surface dehydration that can cause cracking and loss of desired material properties of the final product. A compressive strength of 8 ksi (55 MPa) is used as a surrogate value to indicate that the concrete has attained an acceptable level of hydration. For this project, after the placement of concrete, the exposed surface was covered to prevent dehydration. Typically, at this step, thermal treatment is applied per ASTM C1856 section 7.4, but we skipped this step and instead just covered the fresh UHPC mix with plastic.

Figure 12. The filled and covered mold

Figure 13. Stripping the panel

3.5. Striping the Mold

After 24 hrs, typical cylinder breaks are tested to check for stripping strength. If the required stripping strength is achieved, the stripping of the entire panel can be done. Demolding time can vary between 24 and 48 hours. After demolding, the elements must be moved using appropriate lifting equipment and systems. Figure 15 shows our final UHPC product.

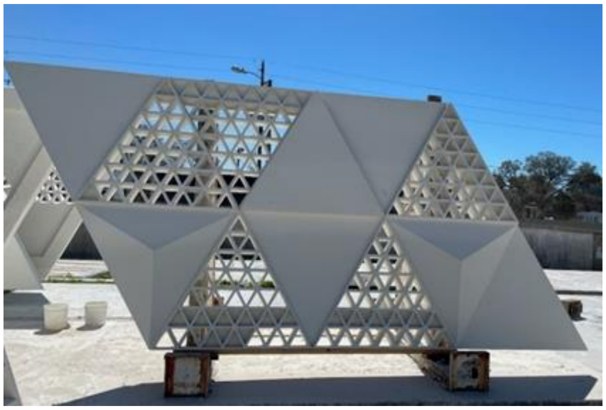

Figure 15. Final UHPC product

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