ARCHITECTURAL ULTRA HIGH PERFORMANCE CONCRETE

Presented by:

TAKTL®

LEARNING OBJECTIVES

Upon completion of this course the student will be able to:

1. Explain the properties and performance of Ultra High Performance Concrete (UHPC).
2. Describe the history of UHPC and current architectural applications.
3. Examine Architectural UHPC panel and cast facade element applications.
4. Outline manufacturing processes and related design-cost considerations.

CONTINUING EDUCATION

CREDIT: 1 LU

COURSE NUMBER: ARmay2016.5

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Kevin Gannon, LEED AP, Building Enclosure Council

The next generation of concrete technology is changing what is possible for architecture, engineering and construction professionals. Ultra High Performance Concrete (UHPC), along with parametric modeling, rapid prototyping, CNC fabrication, and automated manufacturing are coming together to provide unprecedented possibilities for architectural concrete components and building skins.

WHAT IS ULTRA HIGH PERFORMANCE CONCRETE (UHPC)?

UHPC is a category of concrete characterized by high strength, low water absorption, and high resistance to waterborne and airborne chemical degradation. The compressive strength of UHPC used in architectural applications typically ranges from 17,000 psi to 25,000 psi, with flexural strength ranging from 3,600 psi to 6,000 psi and beyond. Although extremely high compressive strengths can be achieved with UHPC, for thin architectural elements, the mix design favors flexural strength over compressive strength. This high strength matrix is further augmented with a small percentage of alkali resistant (AR) glass fibers, polyvinyl alcohol (PVA) fibers, or steel fibers. For aesthetic and in some cases fire code reasons, AR glass fibers are most common in Architectural UHPC. However, because the base matrix strength is so much higher than conventional GFRC, the concentration of fibers is significantly lower. In fact, glass fiber reinforced UHPC (GFR-UHPC) does not utilize enough glass fibers by percentage of volume to be placed in a GFRC category according to the Precast Concrete Institute (PCI). Therefore, UHPC manufacturing plants producing architectural products are most often certified under the requirements of PCI MNL 117-13, Quality Control for Plants and Production of Architectural Precast Concrete Products. Three-dimensional UHPC elements can also incorporate reinforcement, such as steel bars, glass or carbon fiber rods, as well as be pre-stressed; however, such reinforcements are not typically necessary for most architectural applications.

The basic raw materials of UHPC are familiar to everyone who knows concrete: water, sand, cement, silica fume, and plasticizers. It sounds simple enough, but UHPC is an order of magnitude different from traditional categories of concrete. There are no magic ingredients: resins, cellulose, or special polymers are not used to achieve the outstanding properties of thin Architectural UHPC profiles. The secret lies in extremely small particle size and carefully selected particle chemistry and geometries that combine under exacting mixing, vibration, and curing regimens to form a base matrix with tightly packed particles and very strong molecular bonds. The design and calibration of UHPC formulas and selection of raw materials involves state of the art concrete chemistry and micro/nano-particle engineering to optimize chemical and mechanical bonds.

Because the mixing operation, casting techniques, and curing procedures require highly specialized equipment and controls unique to UHPC, and particularly Architectural UHPC, products are typically delivered as finished, pre-cast elements rather than produced on-site with a UHPC pre-mix. Automated dosing and mixing equipment is required to precisely measure and thoroughly mix the raw materials. UHPC contains significantly less cement and water by volume compared with traditional pre-cast concrete. Because the formula contains so little water, a small amount of specialized plasticizers are needed to allow the material to flow into molds. The process of adding plasticizers is both time and temperature dependent. Once cast, the parts require even and level vibration to eliminate trapped air before moving by conveyor to a level, temperature controlled chamber. The entire casting process from material delivery to the mixer through final vibration, is highly time dependent. This is yet another reason that controlled factory conditions are required. The net effect is maximum compactness and an extremely small, disconnected pore structure.

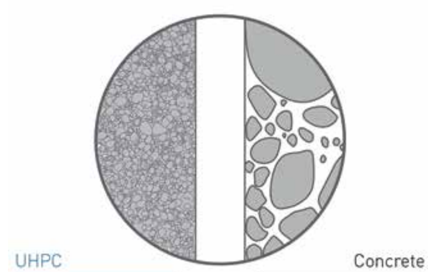
The performance properties of UHPC manufactured in automated, controlled conditions are:

- High compressive and flexural strength
- High impact resistance
- Extremely low coefficient of thermal expansion, shrinkage, and creep
- Very low water absorption and zero water movement
- High resistance chemical degradation (salts and carbonation)
- Excellent freeze/thaw strength and surface appearance retention

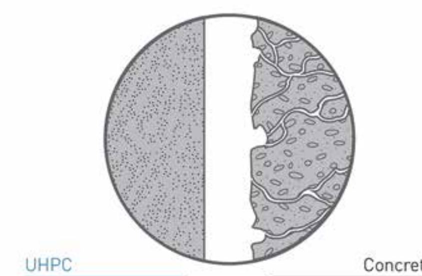
HISTORY OF UHPC—CIVIL APPLICATIONS

UHPC has been in use for more than 30 years, developed initially for large and specialized civil engineering applications that could benefit from

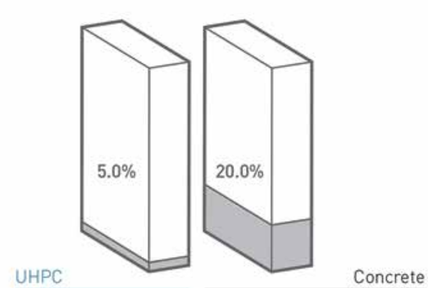
Diag. A | **Matrix Density**



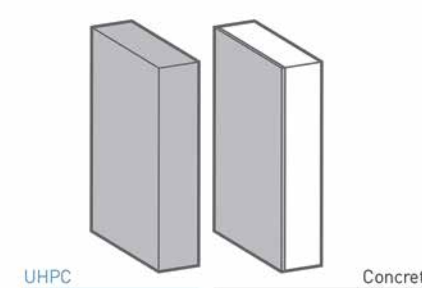
Diag. B | **Surface Quality**



Diag. C | **Water Content**



Diag. D | **Color Integrity**



its high strength and durability under extreme conditions. Such applications—seawall anchors, bridge abutments, super thin arches, bridge decks, pre-cast beams for nuclear power—are still the predominant use cases for UHPC.

However, today a wide variety of formulations are being developed that advance the performance characteristics of this category of concrete and are tailored to requirements of specific applications—everything from cast refractory components and injection-molded complex parts to extruded profiles. Industrial, architectural, and landscape design professionals are now embracing UHPC for its aesthetic potential in addition to its outstanding strength and durability.

HIGH TECH CONCRETE MEETS ARCHITECTURAL DESIGN

All the properties and characteristics of UHPC that are desired in special civil engineering construction are harnessed and molded into high quality Architectural UHPC elements with surfaces, shapes, and assembled systems not possible a few short years ago. If ever there was a material that was imbued with Vitruvius' united triad of architecture values; "firmitas" (solidity, materiality), "utilitas" (function & commodity), and "venustas" (beauty and desire), UHPC is especially qualified.

We now have a material that is not only very strong and durable, but also a material that, when combined with today's advanced manufacturing technology and tooling techniques, can provide for the demands of high performance building requirements, design aspirations, and construction economics. Below are listed just a few of the aspects of the material that make it an exceptional fit for architectural applications:

- Precisely replicates mold surfaces and geometries, creating limitless possibilities for patterns, textures, and shapes
- Natural, mineral-based raw materials afford graceful weathering and aging of material
- Extremely durable and low maintenance, outperforming CIP and many types of stone
- Inherent strength that allows thinner and lighter panels and profiles than stone, conventional pre-cast concrete, and most profiled terracotta
- Higher span to weight ratios that result in fewer attachment points and sub-frame components, reduced installation labor, and lower specialized hardware costs
- The ability to precisely process and finish parts post-casting—CNC cutting, drilling, media-blasting—and assemble parts with high performance adhesive.

ARCHITECTURAL APPLICATIONS

The Architectural UHPC industry is just getting started in the United States and, in fact, there are only a few fully integrated manufacturers of Architectural UHPC in the world. It will be a very long time before we exhaust the potential for the material and its architectural applications. Within the last six years, Architectural UHPC has been installed on government buildings, including foreign consulates and courthouses, university buildings, museums, airports, commercial office buildings, as well as hotel and residential high-rise developments. Applications for Architectural UHPC are varied and include:

- Cladding panels (close cladding and ventilated facades)
- Unitized curtain wall (integrated with glazing assembly or opaque units)
- Cast corners matching the thickness of panels
- Shading devices or light reflectors
- Screens and lattices (hung or self-supporting)
- Acoustical barrier and/or diffusion/ reflection parts
- Fins, copings, sills and headers, water tables, etc. for masonry facades
- Manufactured permanent formwork for high quality finish face of structural elements
- Planters, benches, bollards, and other landscape elements
- Columns, beams, and floor spanning slabs

Additional applications are being developed for manufacture every day. For the purposes of this unit, we will focus on the characteristics and manufacture of facade elements and panels.

DRIVERS FOR FACADE AESTHETICS AND PERFORMANCE

Demands upon building envelopes have intensified within the last 15 years with greater emphasis on light-weight, high-performance facades and the layering of facades to achieve both aesthetic and performance design intent. Simultaneously, building owners and designers are seeking options to "impress" a building with unique identity and appropriate contextual response.

Therefore, the design challenge is to meet the high-performance building envelope targets, control the weight and cost (related to the primary, secondary and tertiary structure cost), and to have a durable edifice that defines urban space and delineates the form of the building in a meaningful way. All this is achieved within 3 to 8 inches of a facade assembly depth. It is not by chance that many of today's facade designers are focused on surface pattern and variety, looking for color and value contrast, pushing the boundaries of materials for thin profiles, and reviving the preferences for natural, authentic materials.

BUILDING ENVELOPE PERFORMANCE AND UHPC

In response to new code standards with higher energy conservation requirements and designer and client communities looking to exceed prescribed or minimum energy code compliance, opaque facade designs are on the rise. Continuous insulation wall assemblies, recently adopted by the IBC and ASHRAE 90, support the increased use of opaque facade design. Architectural UHPC panels are a natural fit with ventilated facades offering a variety of cladding panel sizes, reduced weight to area ratio, and the ability to control thicknesses for any facade composition. Regardless of the fire rating of the enclosing wall, non-combustible materials are essential to multi-story wall assemblies. Architectural UHPC is a non-combustible material and has zero flame spread.

Efforts to construct better buildings, delivered faster, and at lower cost, are creating innovations in pre-fabrication and pre-assembly. The reduced weight and efficiency of installing unitized systems, combined with the quality assurance that comes with factory pre-assembly, are attractive options for meeting today's construction schedules. The use of these delivery methods for critical facade components increases every year. Working with an automated manufacturer and its knowledgeable project management staff best leverages the benefits of pre-assembled Architectural UHPC components. Projects also frequently combine curtain wall unitization of UHPC with field installed UHPC elements, requiring the proactive coordination of schedules and communication between the manufacturer's project manager, unitizing processor, and installation contractor.

There is now a greater focus on durable, low maintenance materials, not only for the longevity of building finishes, but also for the durability of products during shipping, handling, and construction processes. Architectural UPHC should outlast the life of the building and weather gracefully. The inherent strength of the material greatly reduces the need for overstock or replacement from shipping or construction site handling.

LOOKING SPECIFICALLY AT ARCHITECTURAL UHPC FACADE PANELS

Pound for pound, Architectural UHPC is more expensive than conventional pre-cast concrete or even high performing concrete; however, far less material is used to achieve the same panel sizes or shapes. Therefore, when properly comparing the cost of full-wall assemblies and installation labor, Architectural UHPC has the potential to produce an integrated solution that is higher performing and less expensive than pre-cast or traditional GFRC.

Although the particles in UHPC are packed more compactly, the density of Architectural UHPC is actually similar to other concrete, averaging 140 pounds per cubic foot. 5/8" thick panels weigh 7.2 pounds per square foot and are easily manufactured in 4’x10’ or 5'x12' panel sizes. This weight and area is only 25–35% of the weight of 1½"–2" thick stone and 10–15% of the weight of 4"–6" pre-cast concrete. Further, stone would likely be divided into smaller panels for the same coverage area. The weight of 5/8" Architectural UHPC is aligned most closely with that of Insulated Glass Units. The ability to manufacture thin panel sizes up to 60"x144" makes Architectural UHPC cladding panels attractive for both ventilated facade and curtain wall applications.

This article continues on http://go.hw.net/AR516Course5. Go online to read the rest of the article and complete the corresponding quiz for credit.

SPONSOR INFORMATION

TAKTL®

TAKTL is the first company to fully integrate Ultra High Performance Concrete (UHPC) formulation, design, mold making, and automated manufacturing to deliver high quality architectural products, made in the USA. TAKTL offers a variety of standard and custom programs to address the needs of projects spanning a wide range of design requirements, budgets, and schedules.

QUIZ

1. UHPC has both high compressive strength and ductility, meaning it has tensile and bending capacity that is not found in concrete. What compressive and flexural strength ranges apply to manufactured thin Architectural UHPC?
   a. Compressive: 3500–5000 psi | Flexural: 500–700 psi
   b. Compressive: 4500–5500 psi | Flexural: 700–900 psi
   c. Compressive: 5500–7500 psi | Flexural: 900–1200 psi
   d. Compressive: 17,000–20,000 psi | Flexural: 3600–6000 psi

2. What contributes to the high strength of Architectural UHPC?
   a. Finely calibrated and automated raw material dosing and high intensity mixing
   b. The range of particle sizes and shapes, extending down to nano scale.
   c. Reduced water in the mix and controlled curing
   d. All of the above
   e. None of the above

3. True or false: Architectural UHPC is sold as a pre-mix and can be mixed on-site with conventional concrete mixing equipment.

4. How does Architectural UHPC have less of an environmental impact compared to conventional concrete?
   a. 75% less water by volume
   b. Reduced weight: less fuel/sf area transported
   c. Reduced Carbon footprint—less cement/sf area
   d. Bulk materials are sourced locally
   e. All of the above

5. Architectural UHPC can be produced in thin panels or profiled shapes. How does this advantage compare to conventional pre-cast 4"–6" thickness (50–70 lbs./sf) for a 5'x10' panel: what would the thickness and weight be for the same size panel in UHPC?
   a. 2" and 22.5 lbs./sf
   b. 5/8" and 7.2 lbs/sf
   c. 1 1/2" and 17 lbs/sf
   d. 3/4" and 8.4 lbs/sf

6. For thin facade panels what are the two most critical structural performance factors for wind load?
   a. Thermal expansion and anchor shear
   b. Compressive strength and anchor shear strength
   c. Flexural strength and anchor tensile strength
   d. Joints width and floor deflection

7. The tight packing of particles in architectural UHPC results in very low water absorption. Which performance characteristic below is NOT also the result of the densely packed material matrix.
   a. Excellent freeze thaw performance
   b. Resistance to chemical degradation
   c. High compressive and flexural strength
   d. Faster cure time
   e. Replication of fine detail of molds

8. Automated media blasting of Architectural UHPC is a low environmental impact way to reveal decorative aggregates or change the surface of the cast part because__________.
   a. It utilizes plant based compounds
   b. It is human powered
   c. It changes the chemistry of the concrete
   d. It does not use harmful chemicals and is a fully contained process that recycles the media

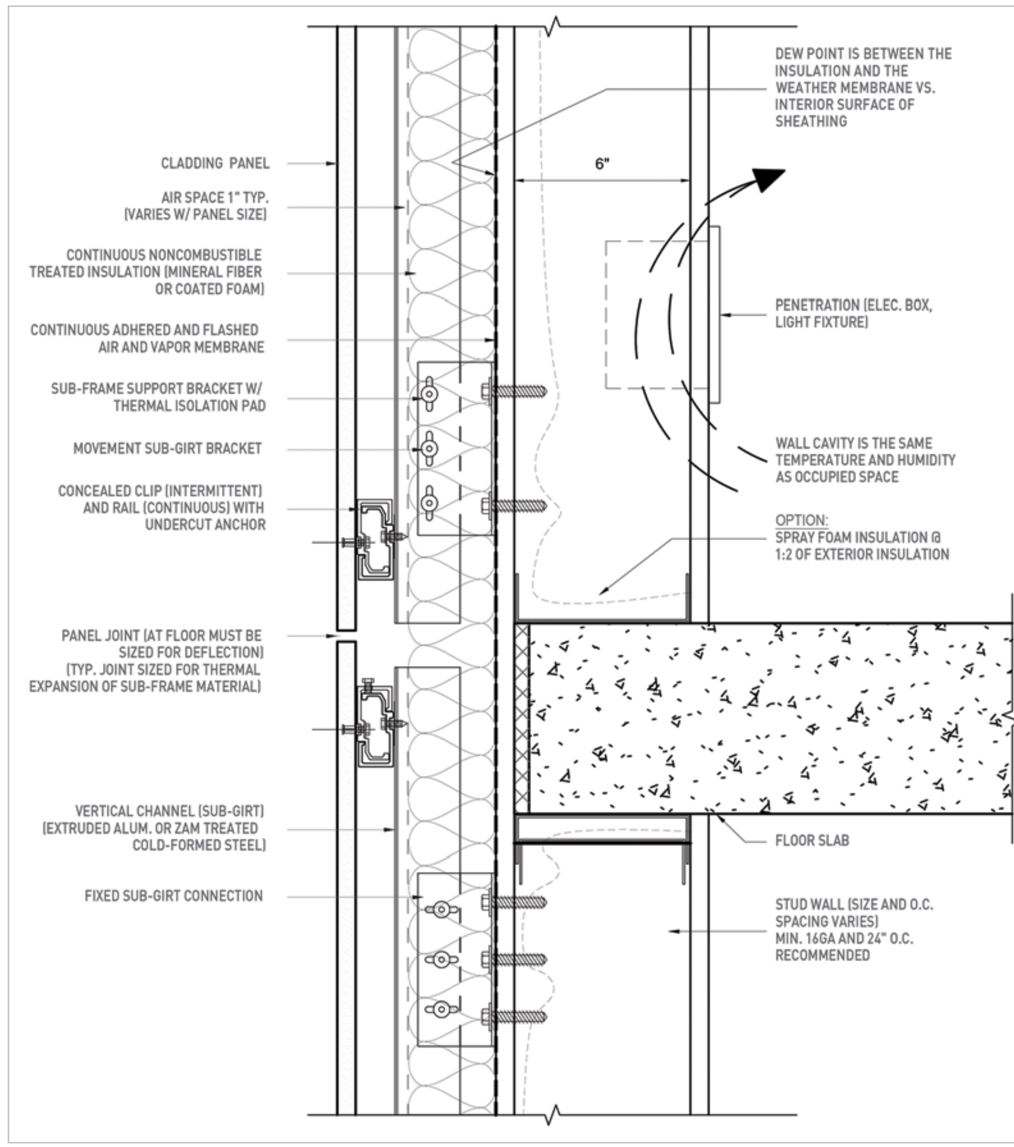
9. Architectural UHPC panels are an excellent cladding for ventilated facades assemblies. For what other applications is the material well suited?
   a. Integration into unitized curtain-walls
   b. Pier and column finish
   c. Perforated screen walls
   d. Fins and masonry trim
   e. Urban and landscape elements
   f. All of the above

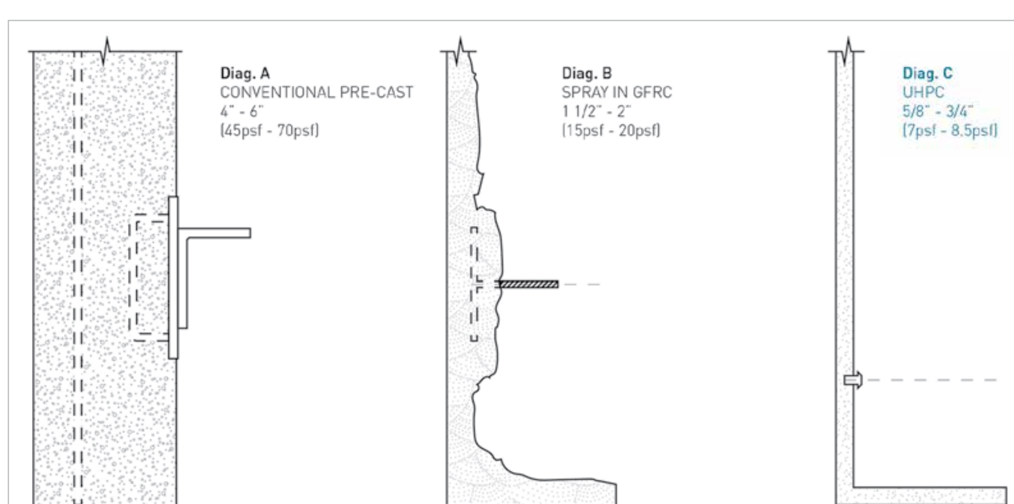
10. Although many factors are considered and combined to generate a budget for production of Architectural UHPC panels and shapes, which two cost factors are Architectural UHPC panel manufacturers most sensitive to?
    a. Color and texture
    b. Wall assembly and sub-frame material
    c. Panel utilization and mold reusability
    d. Thickness and wall assembly

For the same area of facade, the difference in weight dramatically changes not only the wall assembly options and the type of structure required to hang such panels/parts, it also trades thickness and weight for insulation and rentable floor area. For multi-story and high-rise buildings with large areas of opaque facade surface, the differences can be on the order of magnitude of millions of pounds of weight and either an increase in wall insulation or thousands of square feet moved onto the rentable area side of the ledger. The reduced weight of the facade can drive reductions in the size of the foundation and the size of primary structural framing at the perimeter of the building. In addition, thinner, lighter panels give installing contractors a multitude of choices with regard to the means and methods employed on-site to take best advantage of their resources and skill sets. In the case of cladding, this means the ability to hand-set from scaffolding and booms or mast climbers versus the necessity of cranes for pre-cast and spray-in GFRC.

Thin Architectural UHPC panels have higher strength than most composite panels. This is critical for the impact resistance and flexural strength needed by thin cladding. The supporting assembly or sub-frame for the cladding system can be similar or equal in cost to the panels themselves. Panel strength has a role in the requirements for attachment. Anchor capacity and flexural strength are not only the important structural performance factors for thin panels under wind and seismic loads, they can affect the distribution and density of attachment components. Aluminum extrusions and stainless steel hardware are most commonly specified for attachment systems. Given the costs of these types of non-corrosive metals, the use of Architectural UHPC cladding significantly reduces the frequency of anchor points and sub-frame components and thus, the associated cost of material and the installation labor required.

Because UHPC has such high strength in thin profiles, designers are often looking to push the panel/part size to the limits of manufacturing, which is actually quite large. It is worth noting that the increased handling costs of moving large, thin pieces in manufacture, transport, and installation should be carefully considered. Because something is possible does not always mean it is the best choice when looking holistically at the facade assembly and constructability.





WHO INSTALLS ARCHITECTURAL UHPC?

To date, Architectural UHPC has been installed by many different trades. In recent years, construction firms and sub-contracting companies have established specialization in facade installations. This emergence is in response to the new products and wall assemblies being designed and the intensified focus on a single-source of responsibility for the weather tightness and thermal performance of the building envelope. Some of these sub-contracting specialists are outgrowths of metal panel installers and some have combined the resources of several companies to provide the experience and skill sets required to tackle today's complex facade assemblies. Most frequently, carpenters with experience in setting lightweight sub-frames and composite panels install Architectural UHPC. However, ironworkers, masons, and glazing contractors have also successfully installed Architectural UHPC. The critical factors for installation are as much about the handling and competence with the occasional field cutting and drilling requirements as they are about the installation of the weather barrier and the accuracy of the mounting system.

TYPES OF ARCHITECTURAL UHPC MANUFACTURE

With the many new opportunities for design and performance Architectural UHPC provides, there are also new challenges. Manufacturing Architectural UHPC is fundamentally different than conventional pre-cast and GFRC. Everything from dosing measurement, mixer technology, batching sizes and timing, casting techniques, mold design and management, and material handling systems needs to be properly designed and calibrated to achieve the characteristics of Architectural UHPC. With the high volume production necessary for facade cladding, it is very important that designers and contractors are working with suppliers experienced in Architectural UHPC production and operating in a facility with a certified Quality Management System (QMS).

Architects obtain the best results for projects through early engagement with the manufacturer. What may seem to be small variables in the facade design can result in significant differences in manufacturability or cost. Clarity in documentation of the design and installation priorities and sequence are the necessary foundation for good collaboration with manufacturers. When project documents are clear and complete, the manufacturer will be able to provide better feedback, more accurate schedules, and tighter pricing.

If a manufacturer has standard patterns and colors, samples may be available within a short period of time. Custom sample creation for pattern, shape or color or production of prototypes require the same steps as final manufacturing: 1) custom molds, if required, are designed and constructed; 2) parts are cast and cured; 3) cured parts are cut, drilled, and sealed. Factoring in a cure time of approximately 28 days before design strength and surface stability have been attained, the minimum turnaround for custom samples and prototypes is six weeks, increasing with the complexity and scale of mold design requirements.

There are two stages in the manufacture of Architectural UHPC products. The first stage includes mold design and fabrication, mold preparation, raw material dosing, mixing, casting, de-molding, and curing. Precise molds, extremely accurate raw material measurement, and high intensity mixing are critical to attaining a high quality mix. Then, the delivery method to molds, ranging from fully automated continuous sheet casting to off-line casting of individual three-dimensional parts, ensures compaction, fiber orientation, and the elimination of trapped air. Close control of temperature and humidity throughout production and curing are also essential to attaining not only the highest strength, but also the best surface quality and color consistency. The second stage of manufacturing is finishing. Similar to high volume stone processing, Architectural UHPC finishing utilizes CNC equipment and tools. This stage includes surface treatments, cutting, drilling, sub-assembly work (bonding and/or attachment of hardware), and crating for shipment to the project site or unitizing facility.

Given the variety of sizes, patterns, and colors the unique design criteria for each facade project, and the costs and risks associated with managing an inventory of stock, Architectural UHPC is typically made to order. Even "standard" products are made to order. Standard products maintain panel sizes within reasonable sheet utilization from 4'x10' blanks and are made from an established color mix design using an inventory of mold sets that have a known manufacturing history. The exception to made-to-order panels is a product line that has a fixed set of sizes and attachment patterns. In this case, the inherent efficiencies of sheet utilization, fully loading casting sessions to stock inventory, and the repeatability of part size and drilling patterns, allow the manufacturer to offer products at a lower price point with a shorter lead time. To take full advantage of the pre-determined panels, designers should delineate their facades in disciplined modules both horizontally and vertically, similar to the approach with dimensioned stone or masonry. The variety of sizes, colors, and textures available in the TAKTLSELECT program, for instance, enables the designer to accommodate a range of fenestration and building massing dimensions while achieving richness in pattern and surface.

The most prevalent type of Architectural UHPC products are facade panels in a variety of thicknesses, surfaces, and profiles. Among the advantages of Architectural UHPC cast panels over extruded composite panels are: the opportunity to cast non-linear patterns and to easily change thicknesses for structural and/or aesthetic reasons. The base thickness of patterned panel is not less than 5/8" thickness of a non-textured panel. For example: 1-1/8" thick overall with 1/2" maximum depth of pattern or reveals.

Panels are usually cast in lots of 60 to 100 panels per casting session. The number of

Thickness		Weight		Size	
5/8 in	16mm	7.2 lbs/ft²	35.1 kg/m²	min. 0.5' X 4.0'	max size 5' x 12'
3/4 in	19mm	8.4 lbs/ft²	41.0 kg/m²	min. 0.5' X 4.0'	max size 5' x 14'
1 in	25mm	11.2 lbs/ft²	54.6 kg/m²	*Refer to manufacturer's technical support for sizing*	

Note: Increasing thickness increases the tensile and shear performance of anchors.

castings for a project and the lead-time for casting and post-processing are factors in determining the number of molds needed to meet the requirements of a project. A manufacturer will assess the number of typical part sizes and the quantity of unique sizes and shapes to determine mold and casting strategies. Panel yield, also known as sheet utilization, will be optimized around either available molds or a new set of custom molds. The most important cost factors for a manufacturer are panel yield, ability to reuse molds, and the number of unique molds (pattern or size) that will need to be made.

MOLD DEVELOPMENT

Castings are kept in the molds for a period of a few days to allow the material to cure to handling strength. Therefore, casting for a project is scheduled for mold rotation based upon this cure period. After the initial cure, the cast blanks are cured for approximately 3–4 weeks, depending upon color, thickness, and panel size. At each phase of curing, dedicated rooms or chambers are used with specific temperature and humidity controls to manage panel hydration and color development.

New materials, CNC milling equipment, automated fabrication techniques, and even 3D printing make virtually anything possible for mold development and casting techniques. Mold technologies, combined with the sensitivity of Architectural UHPC to the surface on which it is cast, provide for excellent replication of bold forms and geometries and/or subtle surface variations captured on facade components for the life of the building. A variety of mold materials can be used. Flexible mold materials will provide the best results in capturing detail and allowing de-mold without damage to the cast material or the mold. Many flexible mold materials, for example: silicone and urethane, can be cycled repeatedly for more than one hundred castings, assuming proper cleaning, handling, storage, and environmental conditions in the production facility. Mold materials have their own cure period. Mold making as part of the manufacturer's lead-time is determined by the number, complexity, size, and thickness of the molds needed for the project.

Surfaces that were once only achieved through post-casting operations, such as bush hammering, bead-blasting, and etching, can be captured in molds and cast into Architectural UHPC surfaces more economically with shorter lead-time. Cast surface effects can also eliminate environmentally damaging post-processing processes such as acid etching, open air sandblasting, and surface grinding.

The primary steps in mold development are:

1. Building a Model: The model is the positive object or replication of the final cast form. Models are made from a variety of materials, including pressed metal, milled/CNC-cut high-density foam, plastics, wood based fiber board, composite wood, and vacuum formed plastics. Handcrafted work in concert with the latest additive fabrication technologies are employed, and because Architectural UHPC can be cast against fine textures and patterns, even fabrics, etched metal, and hand-sculpted surfaces can be used to make a model. Whatever the method, producing a dimensionally precise model that factors in the minimal shrinkage of subsequent mold materials as they cure is critical. The model is the starting point for multi-step reproductions, so tolerances in this step are tight and unforgiving
2. Casting a Master: The master is the negative of the final cast form used to create tooling. Typically, rubber is used to cast the master. The type of rubber is determined by the materiality of the model.
3. Creating a Set of Tools: Tools are the positive of the final cast form used as the templates to create the mold set, or the number of tools required to make the quantity of molds needed to produce the project.
4. Casting the Production Mold Set: Production molds are negatives of the final cast forms and are the vessels into which the Architectural UHPC is poured. Generally, 8 to 10 tools are used to cast sets of 40 to 120 molds. Each mold is attached to a supportive carrier for line casting.

Documented quality control specifications for mold-making processes are an essential component of Architectural UHPC product manufacturing and must be part the certified Quality Management System (QMS) of any Architectural UHPC supplier. If the molds are not level and dimensionally true or if there are surface defects, these issues will literally be cast in concrete and replicated throughout the entire project's production. This is why the best Architectural UHPC manufacturers keep mold development as a vertically integrated component of their operation.

COLOR AND DECORATIVE AGGREGATES

In addition to mineral-based raw materials, the Architectural UHPC matrix is colored by UV-stable synthetic oxide pigments. There are limits to color saturation and how deep the hue and value of concrete can be. Most manufacturers set limits on the types of colors offered because high pigment loads can affect other characteristics of the concrete such as strength, surface finish, and weathering. The range for the percentage of pigment relative to the overall volume of raw materials can be between 1.5% at the low end and a maximum of 8% at the high. Some colors, such as red and yellow, are more prone to fading over time and darker colors typically exhibit more color variation. Variation is a necessary and often desired feature of Architectural UHPC since it is formulated from quarried raw materials. Design choices relating to combinations of color, panels size and layout, texture, and finish should be made with the expectation of color variation in mind.

Decorative aggregates are typically either cast as surface-layer mix or broadcast onto a mold before casting. Both strategies differentiate the aggregate from the base mix in particle size, shape and often color, in order to limit the degree to which: (1) the mix and the reliable strength profile of the panels is affected and (2) the aggregate may interfere with fiber and mesh reinforcement placement in the panel. This is why the aggregate size often determines the overall thickness of a panel. For example, inclusion of a 1/4" diameter aggregate may require a panel thickness of 3/4" for the same cladding-load engineering of a 5/8" panel without decorative surface aggregates.

Aggregates can be used to create surface effects and intentional variations, serve as the primary coloring component for the panels, and/or to enhance the base mix color. Decorative aggregates can be crushed granite, glass, or a number of other natural and synthetic materials from industrial processes. Aggregates must be clean, free of salt, and checked for chemical compatibility with concrete formulas. Petrographic tests often need to be performed by the purchaser because many aggregate suppliers do not certify their material.

Cure-resist solutions used on molds or acid-etching the material post-cure are established techniques to expose the aggregate. However, a lower environmental impact and more consistent finish can be achieved through automated media blasting that fully contains dust and recycles the "media" employed. The term "media blasting" is used rather than "sand blasting" to generalize the "media" utilized in the process, which can be changed to achieve different surface effects. Once a panel is cured to design strength, it can be blasted to the selected finish.

Controlling decorative aggregates is not feasible for many 3-dimensional shapes cast in enclosed molds. Designers should verify the feasibility of including aggregates and various pigments with the manufacturer before settling on finish choices for their facade designs.

SEALERS AND STAINS

Architectural UHPC is always made with pigments added during initial mixing and integral to the matrix. Therefore, finish color and quality is not dependent upon a coating, nor are coatings required to resist freeze/thaw, chlorine, or carbonation degradation. A hydrophobic sealer may be applied to create an environmental barrier while the material cures. Invisible, saline-based sealers will form a chemical bond with the surface of the concrete. This seal will help to manage color development, as well as provide some protection against graffiti or evidence of handling. Sealing stains are also sometimes used to mitigate the naturally occurring color variation inherent in a mineral-based product.

TOLERANCES/ACCEPTANCE CRITERIA

Architectural UHPC manufacturers can deliver extremely precise surfaces and forms; however, designers and contractors must have realistic expectations for tolerances and acceptance criteria for an entire project scope. Although there can be significantly tighter tolerances for Architectural UHPC compared to thick, pre-cast products, Architectural UHPC is still concrete and there will be dimensional and thickness variations that should be anticipated and accommodated in the installation tolerances. The dimensional tolerances for the parts scale with the size of the parts, and the larger the elements are, the larger the joints for movement of the sub-structure will need to be. This is important when thinking about the module of a building in conjunction with the wall assembly and the performance criteria for the building envelope.

Architectural UHPC manufacturers will outline acceptance criteria in their Quality Management Systems (QMS) and provide guidance to installers for developing installation tolerances within wall assemblies. Manufacturers can provide methods for successful installation such as using trims to capture panel edges. This strategy will save the cost of fabricating returns to match the surface and also will hide the variation in alignment of panels that is most visible at the panel edges. Continuous flush conditions often present challenges to the installer and may result in negative long-term weathering effects. For example, un-checked water washing can result in unsightly deposits on any material. Architectural UHPC manufacturers will recommend drip edges, overhangs, projected head, and sill elements to control water on the facade.

THE FUTURE OF ARCHITECTURAL ULTRA HIGH PERFORMANCE CONCRETE

The challenge and focus of research and development by the leaders in Architectural UHPC manufacture are threefold: (1) further automation of manufacturing processes, (2) new molding techniques, and (3) the development of new formulations. To keep pace with today's design aspirations and support today's construction budgets and schedules solutions for manufacturing surfaces and shapes economically and in higher volumes are necessary. Since Architectural UHPC is initially a liquid, capabilities for creating parts are only limited by the ability to mold material with repeatability and consistent quality. Current formulation research initiatives include efforts to introduce recycled content, create mix designs that can be sprayed or shaped through hybrid extrusion processes rather than casting, and incorporating nano-fiber reinforcement to achieve greater ductility and even higher compressive strength.

The goal for each of these research and development areas is to bring architectural product solutions to market at appropriate prices that provide for new design directions. Whether it be is unite aesthetic character and blast resistance within the same cladding material or combine supporting wall elements with high quality finishes in single components, Architectural UHPC is expanding its participation in design, construction, and materials technology. ■