

NPCA WHITE PAPER

**ULTRA HIGH
PERFORMANCE
CONCRETE (UHPC)**

**GUIDE TO MANUFACTURING ARCHITECTURAL
PRECAST UHPC ELEMENTS**



NPCA

Precast... The Concrete Solution

GUIDE TO MANUFACTURING ARCHITECTURAL PRECAST UHPC ELEMENTS

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INTRODUCTION

As a material on the leading edge of concrete innovation, ultra high performance concrete (UHPC) provides a new technology to expand a precaster's business with new products and solutions. The material's combination of superior properties facilitates the ability to design thin, complex shapes, curvatures and highly customized textures – applications which are difficult or impossible to achieve with traditional reinforced concrete elements.

UHPC is a range of formulations which may be used for many different architectural and structural applications. Reinforced with high-carbon metallic fibers, structural UHPC products can achieve compressive strengths up to 29,000 psi (200 MPa) and flexural strengths up to 2,900 psi (20 MPa). For architectural UHPC applications, Polyvinyl Alcohol (PVA) fibers are typically used.

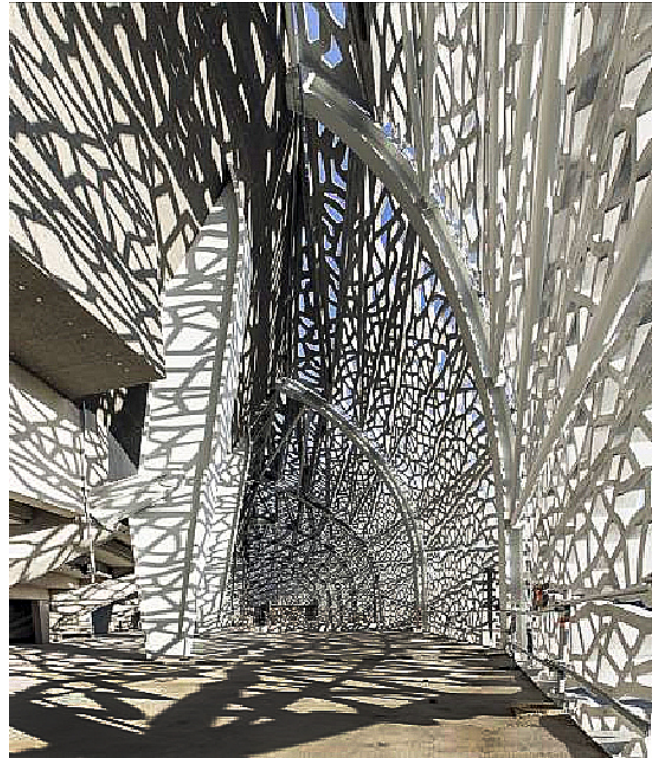
Architectural UHPC can achieve compressive strengths up to 17,000 psi (117 MPa) and flexural strengths up to 2,900 psi (20 MPa). Due to the material's superior compressive and flexural properties, the need for passive reinforcing can be eliminated or greatly reduced (depending on the application). It is also highly moldable and replicates form materials with extreme precision.

Currently, the use of steel fibers in strictly architectural UHPC applications is very limited, however some projects which fall into both architectural and structural categories, such as the MuCEM and Jean Bouin Stadium, have begun using steel fibers.

The advantages of UHPC are numerous and typically include reduced global costs such as formwork, labor, maintenance and speed of construction. For more than a decade, UHPC has been used by innovative precasters worldwide in ways that complement their existing businesses by expanding their product ranges to include new solutions for structural and/or architectural markets. Applications include bridge beams and decks, solid and perforated wall panels/facades, urban furniture, louvers, stairs, large-format floor tiles, pipes and marine structures.

SECTION 1: PURPOSE

The purpose of this report is to provide a guide for the manufacture of architectural precast UHPC elements and educate precasters on the potential opportunities that exist through production of innovative products and solutions that complement their existing businesses. The following report describes the general handling and quality control procedures including the storage, forming, batching and curing of architectural UHPC. In addition, several applications utilizing architectural precast UHPC elements are discussed.



This open lattice facade comprised of UHPC at the Stade Jean-Bouin in Paris allows sunlight to filter through.

(Photo © courtesy of Lisa Ricciotti)

SECTION 2: WHAT IS ARCHITECTURAL UHPC?

Architectural precast UHPC products reach a minimum compressive strength of 17,000 psi (117 MPa) after 28 days. They are blended with fibers in order to achieve ductile behavior under tension, which may eliminate the need for passive (non-prestressed) reinforcement. Appropriate batching, casting, finishing and curing procedures are of the utmost importance in order to ensure the highest level of quality, appearance and performance.

The main principle of this technology is based on systematic elimination of inherent weaknesses associated with conventional concrete. The ductile behavior of this material is a first for concrete, with the capacity to deform and support flexural and tensile loads, even after initial cracking. These superior performance characteristics are the result of improved microstructural properties of the mineral matrix and control of the bond between the matrix and the fiber.

The optimization of granulars, fibers and admixtures provide a very low porosity in a cement-based mineral granulometric matrix. The premix components consist of granular material with a diameter less than 1 mm, and a highly reduced water-cement ratio (less than 0.25, depending on the type of UHPC

formulation). Elimination of coarse aggregates, along with the granular gradation and fiber aspect ratio, facilitates a high fiber content and isotropic dispersion.

Due to UHPC's plastic and hardened properties, plus the elimination of rebar, precasters can achieve complex shapes that are extremely durable and cost effective, and require little maintenance. The material replicates textures, form and shape with high precision and can be produced in a range of long-lasting colors. It works well for new, innovative concrete applications and supports new trends in architecture: purity of line, delicacy, enhancement of texture and mineral bias.

With UHPC, precasters can offer new, innovative building envelope solutions for creative architects; for example: structural, decorative perforated facades in mesh or lattice-style designs; ultra thin, lightweight panels with large surface areas and perforation rates that exceed 50%; and full facades with complex shapes, curvatures and textures.

UHPC has also been used in a variety of urban furnishings. Because of its strength, impact resistance, durability and low maintenance requirements, it is an excellent alternative to traditional materials. A range of elements, such as sculptures, benches, bollards and street furnishings, have been added to the product offerings of traditional precast manufacturers. Also, interior designers and precasters may create new, contemporary, lightweight, colored and textured products such as chairs, stairs and tiles for floors and walls.

SECTION 3: RAW MATERIALS

Dry Materials

The dry materials in UHPC are cement, silica fume, ground quartz and silica sand. These materials conform to the Mill Certificate specifications; a copy of each is kept on file.

Fiber Reinforcement

Architectural UHPC precast products are fiber reinforced with fibers having a minimum tensile strength of 140 ksi and a diameter of up to 300 microns. Steel fibers may also be specified in architectural UHPC applications, particularly when very thin sections are desired and the UHPC members are projected to experience excessive wind pressures and tensile loads. Steel fibers used in architectural UHPC have a minimum tensile strength of 310 ksi and diameter of up to 200 microns. The fibers conform to the Mill Certificate specifications. A copy of each Mill Certificate is kept on file.

Water

Water should be potable (drinkable), but if not potable it must be free of contaminations such as oils, acids, salts, chlorides or other compounds that may be harmful to concrete.

Chemicals

Admixtures for concrete are used to enhance and/or obtain certain properties of fresh and hardened UHPC. High-range water reducers are essential to UHPC for providing the plasticizing effects, allowing the concrete to flow to self consolidation. Air-entraining admixtures are not used in UHPC.

Accelerators

There are two types of accelerators that alter the early strength characteristics of concrete in distinct ways. Set accelerators shorten the set time, whereas strength accelerators speed up early strength gain but do little to alter the initial set characteristics. The dosage rate varies by supplier. Consult the supplier for product details and mix time prior to incorporating an accelerator. Calcium chloride accelerators are not recommended, as the additional chlorides promote degradation of reinforcement and may promote drying shrinkage. The 28-day strength of concrete with the incorporation of accelerating admixtures may be slightly lower than mixes without them.

Color Pigments

Solid or liquid pigments can be utilized for architectural UHPC.

Solid Pigment: When using a solid pigment, the flow properties start to change once the volume surpasses 1% of total dry materials. In order to maintain similar flow, water will have to be added to compensate for the additional dry material. The only way to know the exact impact of this change on the UHPC properties is through testing.

Liquid Pigment: When using liquid pigment, one must be aware of the water being added to the concrete mix. If the liquid pigment dose surpasses the maximum of 3% mass of dry materials, the user could cause negative effects on the UHPC matrix, which must be validated using appropriate laboratory testing methods.

Storage of Raw Materials

A dry, separate storage area for UHPC raw materials must be provided, as raw materials should not be exposed to moisture. Chemical admixtures must not be exposed to freezing temperatures.



Figure 1 (top left) – High shear mixer; **Figure 2** (left) – Small (14-50 bags mixer); **Figure 3** (above) – UHPC batching facility. (Photos courtesy of Lafarge)

SECTION 4: MANUFACTURING ARCHITECTURAL UHPC PRECAST ELEMENTS

The manufacture of precast UHPC elements presents the industry with new challenges and opportunities. Recognizing that production methods must be reassessed for UHPC production, it is a fundamental change to conventional manufacturing processes. For instance, precasters are required to review their current batching methods, casting techniques, molding expertise and handling techniques.

Batching

To date, many different UHPC product formulations have been successfully batched in various mixers, ranging from a small two-bag mixer to a fully automated batching plant. The mixing efficiency and mixing performance depends on: the type and speed of the mixer; requested mixing time by the precaster; and the required UHPC volume for precast production. When setting up the batch plant for UHPC at a

precast facility, the introduction of raw materials into the mixer must be considered. The key to producing high-quality UHPC products is very precise proportion control of raw materials, temperature control and optimization of the mixer's performance requirements.

For the most efficient and consistent mixing of UHPC, high shear mixers (Figure 1) have been used successfully, especially counter-current pan mixers, which can provide accelerated mixing times. These high shear mixers disperse water and admixtures onto the cement particles without heating the mix through kinetic energy generated by the mixing process. Others, such as mortar, horizontal shaft or pan mixers (Figure 2) have also been used, but they are generally slower. The precaster should therefore consider the tradeoffs of mixing time, batch volume and material placement. Prior to dedicating a mixer for UHPC production, it is recommended to calibrate the mixer by measuring mixing time and flow characteristics of UHPC and comparing the compressive strength to reference strength. For projects requiring larger volumes, mixing procedures have been



Figure 4 – Placing UHPC behind the leading edge.
(Photo courtesy of Lafarge)

perfected to allow batching of UHPC in ready mix concrete trucks.

When setting up the batching facility (Figure 3) for UHPC manufacturing, precasters must consider how each of the materials is weighed and proportioned prior to mixing. Accurate proportioning is essential in successful batching of UHPC (see Table 1). The dry material is added first to the mixer, then the water and liquid superplasticizers are introduced. Once the batch is fluid, the weighed fibers are added to the mixer. When turning the UHPC formulation from dry to liquid stage, significant energy is required by the mixer. Therefore, batch sizes are often reduced, from 40% to 75% of the recommended size by the mixer manufacturer. Prior to placing of UHPC, the mixer may be slowed down in order to allow entrapped air to escape due to the high-speed mixing. Entrapped air may lead to a weaker matrix and poor surface finish of the precast element.

Self-leveling or dry-casting formulations are possible, depending on the casting technique and performance requirements.

Forming

Successful execution of a precast UHPC project depends on the design of the molds and the procedures developed to use them. Traditional hand screeding and finishing of UHPC is not normally used due to its high flow and fiber content of the plastic matrix. Self-leveling UHPC formulations have no internal shear in the plastic state and behave similar to self-consolidating concrete. This creates challenges when developing formworks that are completely enclosed with tight tolerances, as well as opportunities for the precaster to offer a



Figure 5 – Injection casting.
(Photo courtesy of Lafarge)

new range of products with almost any surface texture on all sides of the element.

For accurate mold design, any potential deflections and initial UHPC shrinkage must be considered. Specific molding details are all critical success factors to consider when designing, building and using formworks. Some of these specific details include:

- Release agents
- Type of molding materials
- Methods of release during initial shrinkage
- Orientation
- Mold support

Since UHPC replicates surfaces with great precision, the selection of the mold material is based on the expected surface outcome. The following molding materials have been used successfully in the manufacture of various UHPC precast elements: steel, silicone, lexan, polyurethane, Teflon, glass and wood (with epoxy painted surfaces).

Placing

The casting sequence of architectural UHPC precast elements should be planned in order to achieve an appropriate preferential fiber orientation. Molds are filled slowly to prevent entrapped air. No internal vibration is permitted. Limited external vibration can be used to aid in air removal. Do not allow excessive external vibration, as PVA fibers may float to the surface. Filling of the molds should be completed in a continuous casting process by following behind the leading edge of the UHPC.

When placing the self-leveling UHPC material into formworks,



Figure 6 – The Shawnessy LRT Station, Calgary, Alberta.
(Photo courtesy of Lafarge)

it is important to take advantage of its fluid characteristics. When discharged from a concrete bucket onto flat-surface molds, UHPC will create a mass of material that will spread itself throughout the form. By moving the discharge point at a rate such that it always stays behind the “leading edge” of the flow (Figure 4), the mold can be filled in one continuous motion. This is important, because if UHPC flows meet each other, there will be minimal fibers bridging the junction, resulting in a weak plane. Due to the material’s fluid characteristics and fiber dispersion, it cannot be finished the same way as traditional concrete (such as raking, troweling or brooming). After placement, any exposed surfaces must be covered in order to prevent dehydration.

UHPC’s high flow properties also permit special casting techniques such as injection (Figure 5) and displacement methods to create sophisticated forms and shapes that cannot be achieved with conventional casting techniques. For instance, an innovative injection technique was successfully used to produce a complex canopy roof system for the Shawnessy LRT Station (Figure 6) in Calgary, Alberta. For this project, the UHPC material was forced into a complex steel mold through a piping system by applying air pressure above the plastic material.

Displacement casting (Figure 7) is another method that offers new opportunities for precasters. This process is completed by depositing the precise volume of material needed, and then introducing the top portion of the mold. This will displace the plastic material into the shape of the casting. If the entry points of the secondary form are controlled, it is possible to move the plastic UHPC in directions that will influence fiber orientation and facilitate the release of entrapped air. For this casting method, alignment guides to control the



Figure 7 – Displacement casting.
(Photo courtesy of Lafarge)

exact positioning of the top form and considerable force of displacement are required. For a high-quality surface appearance, molds must be filled slowly to prevent entrapped air; also, control of the fluid’s rheology minimizes segregation of the fibers.

Curing

Architectural precast UHPC elements are typically removed from the mold after final set has been reached (11,000 psi). If the elements have structural requirements, they can be thermally treated after setting and demolding. This process requires the UHPC precast element to be exposed to 140 F at 95% relative humidity for 72 hours. This allows the hardened architectural UHPC element to reach its ultimate strength and durability characteristics by hydrating all of the free water within the matrix. Thermal treatment also provides improved dimensional stability of the product.

Surface Treatment

Different sealers can be used with architectural UHPC products. The type of sealer depends on the application. For instance, vertical elements do not typically require much abrasion resistance but could be exposed to substantial heat, UV light and staining. Horizontal precast applications could be exposed to the same conditions as vertical applications as well as abrasion. Topical sealers generally repel staining but perform poorly with respect to abrasion. Penetrating sealers tend to bond well into the micro surface of UHPC and perform well in abrasive conditions but do not perform well with staining. It is therefore recommended that the precaster test small samples to determine whether the desired result

Table 1

| Batch Size | < 5 L (0.2 ft ³) | < 30 L (1.1 ft ³) | < 150 L (5.3 ft ³) | < 1 m ³ (1.3 yd ³) | > 1 m ³ (1.3 yd ³) |
|-----------------------|---------------------------------|----------------------------------|-----------------------------------|--|--|
| Scale Accuracy | 0.1 g | 1.0 g | 10 g (1/3 oz) | 100 g (0.2 lbs) | 1000 g (2.2 lbs) |

can be achieved.

Mock-ups

UHPC architectural projects typically require production of precast samples and/or mock-ups for evaluation. The samples must represent the desired color, texture and special shapes (if applicable) of the finished product. To achieve successful completion of any UHPC project, it is recommended that this is a Best Practice procedure.

SECTION 5: QUALITY CONTROL

The most important quality control measures for architectural precast elements are performed during production. The quality control measures during the plastic and hardened states of UHPC must be followed for the successful production of architectural UHPC.

Batching

The key to producing high-quality UHPC products is very precise proportion control of raw materials, temperature control and optimization of the mixer's performance requirements.

For accurate proportioning of the raw materials, the weigh scales have the following accuracies (Table 1). Note that all liquid and dry raw materials must be weighed for successful batching of UHPC.

The temperature of all raw materials must be controlled prior to and during batching. The chemical admixtures must not be exposed to freezing, and dry materials cannot be exposed to moisture. During warm weather batching (77 °F), ice cubes are added to the mixture. Ice cubes are used instead of cool water to aid in mixing, and they ensure that final batch temperatures are within standards.

Placing

The casting sequence of architectural precast UHPC elements should be planned in order to achieve appropriate preferential fiber orientation. Molds are filled slowly to prevent entrapped air. No internal vibration is permitted. Limited external vibration can be used to aid in air removal. Do not allow excessive external vibration, as it causes PVA fibers to float to the surface. Filling of the molds requires one continuous casting by following behind the leading edge of UHPC.

Finishing

Hand tools may be used to control excess material near the edges of the form or to push the material into areas where the flow is not effective. Avoid tearing UHPC with hand tools. Avoid using rakes or any tools that may disrupt the fiber orientation of UHPC. Exposed surfaces must be covered or treated with a curing compound to prevent dehydration of UHPC.

Curing and Demolding

Curing temperatures and time should be recorded until a minimum required demolding strength 75 MPa (11,000 psi) or a minimum percentage of degree of hydration is achieved. It is recommended that curing temperatures of the UHPC product remain between 40 °F and 105 °F. Depending on the raw material selections and curing temperatures, UHPC elements can be demolded between 24 and 48 hours. Appropriate lifting equipment and systems are required to ensure the safe movement of architectural UHPC elements without cracking.

Thermal Treatment

Thermal treatment of architectural UHPC elements is not required. If thermal treatment is applied, the hardened UHPC elements (minimum strength of 11,000 psi) are exposed to a 72-hour heat treatment cycle at 140° +/- 5° F at 95% +/- 3% relative humidity. The temperature change rate of the precast elements must not exceed 20 F per hour.



Figure 8 – The plastic flow of each batch is determined in accordance with ASTM C230.

| | Domain A Stiff mixture | Domain B Fluid mixture | Domain C Highly fluid mixture |
|---------------------------------|----------------------------------|--|---|
| 20-impact spreading test | < 200 mm (8 in) | Between 200 mm (8 in) and 250 mm (10 in) | > 250 mm (10 in) |

Plant Requirements

Workers should be trained on casting, finishing, curing, demolding and thermal treatment procedures prior to using UHPC. The QC inspector then observes, records and ensures proper production practices for the UHPC.

Plastic Properties

Flow Test: The plastic flow of each batch is determined in accordance with ASTM C230 (see Figure 8). The static and dynamic flows after 20 shocks are measured to the nearest in (3 mm).

Temperature Control: During warm weather batching and casting (77 °F), ice cubes may need to be added to the mixture. Ice cubes are used instead of cool water to aid in mixing and ensure that final batch temperatures are within standards. For each batch, the starting and placing temperatures should be measured and recorded.

Hardened Properties

Cylinder Casting Preparation: Rigid cylinder molds (3 in x 6 in [75 x 165 mm]) are cast for compressive strength testing (see Figure 9). Depending on the flow characteristics, measured using a flow test (in accordance with ASTM C1437) of UHPC being sampled, the casting method for the test specimen will change.

Cylinder End Preparation: The top ¼ - ½ in of the top cylinder is removed. Both ends of the cylinders are ground until a length of 6 in. is reached. The angle of plainness is recorded and should not exceed 0.5 degrees. The flatness of the cylinder ends will affect the results. It is important that the preparation is consistent for all cylinders. The casting method for UHPC cylinders (3 in x 6 in) is described in the chart on the next page.

Testing for Compressive Strength: Compressive strength specimens are tested at 145 psi/second. For each daily production run, six compressive cylinders can be made: three specimens to confirm the minimum stripping strength and three specimens for 28-day testing. If thermal treatment is used, extra cylinders should be tested after completion of the



Figures 9, 10 – UHPC compressive strength cylinders (left); vibration of UHPC compressive strength cylinders (right).

| | Domain A Stiff mixture | Domain B Fluid mixture | Domain C Highly fluid mixture |
|---------------------------------|--|--|---|
| 20-impact spreading test | < 200 mm (8 in) | Between 200 mm (8 in) and 250 mm (10 in) | > 250 mm (10 in) |
| Filling | During vibration (Figure 10) – Vibration table adjusted for a 1/64" (0.5 mm) amplitude | | |
| | In several layers (approx. 4), ensuring that no cavities are formed | | |
| Consolidation | On the impact table (ASTM): 100 impacts | Simple cast | Simple cast |

thermal treatment cycle.

Plant Requirements

Persons conducting the QC procedures as per Section 5 must be properly trained to perform all additional tests required for architectural precast UHPC elements. Proper end grinding machines and compressive resistance machines should be used. Neoprene pads are not allowed for compressive resistance testing.

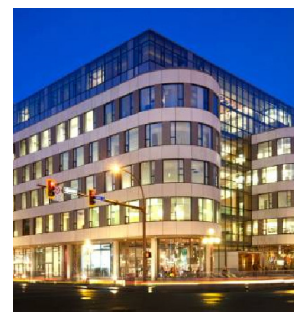
SECTION 6: PRECAST UHPC APPLICATION

Architectural UHPC Applications

UHPC's superior mechanical performances can result in a reduced number of sections, eliminate the need for passive reinforcing, and allow for the design of cantilevered structures that are not possible with conventional concrete. Furthermore, UHPC enables the design and production of ultra-thin elements that are highly durable and sustainable. Its resistance to corrosion, abrasion, carbonation, impact and fire makes it well-suited for structures in harsh environments (i.e., marine or industrial sites) and public buildings that have strict requirements for safety, maintenance and seismic ratings. Examples of architectural UHPC precast elements with complex curves, textures and shapes are illustrated within the following sections.

Curves

Curved UHPC panels allow for the development of tighter radii that would not be efficient with a flat panel system. For "The Atrium" project in Victoria, British Columbia, the architect (D'Ambrosio Architecture + Urbanism) chose UHPC for the spandrel panel section because of its ability to form monolithically tight radial curves (see Figures 11 and 12). A conventional flat panel system would have to be cut to make the turn and result in numerous unattractive seams and openings, which could also reduce energy efficiency. In 2013, this project achieved a LEED Gold rating and won a Royal Architectural Institute of Canada (RAIC) Award for Excellence in the Green Building Category.

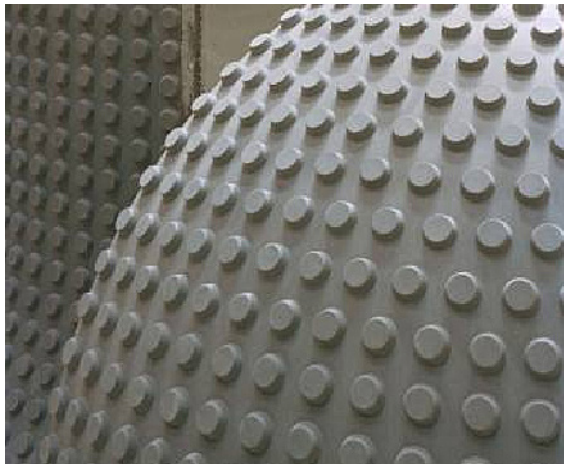


Figures 11, 12 – The Atrium, Victoria, B.C. features an ultra-thin, unitized curtain wall system.

(Photo credits: D'Ambrosio Architecture + Urbanism (top) and Lafarge Canada Inc.)

Texture

The RATP bus center in Thiais, France (designed by ECDM [Emmanuel Combarel Dominique Marrec] architects), is covered with a unique "LEGO® style" textured skin made with UHPC (see Figures 13 and 14). The 1½ in (30 mm) thick skin is curved



Figures 13, 14 – Unique LEGO®-style textured UHPC cladding in France

where it meets the ground and rises gracefully upward toward the sky. Apart from being an anti-slip surface, the shell and ground elements provide a moiré pattern that reflects in the mirrored surface of the colored structural glazing. The project collaborators invested significant time studying, building prototypes, performing tests and creating molds that fulfilled all requirements in terms of durability and economy of resources. The material's fluidity enables it to reproduce the texture of the molds with extreme precision. UHPC was the key element in this project, providing the envelope, skin and ground wall connection.

Perforated and Lattice Panel Systems

Traditional perforated panels are made of metal, painted steel, cast iron, stainless steel or cast aluminum. UHPC offers an alternative for creating original precast decorative elements that are durable, and require less energy consumption to create and less maintenance over time. For example, the Community Center in Sedan, France, was built with a double skin facade in order to provide privacy and protection of the glass fascia behind. The west and south walls consist of UHPC perforated light blue panels, 13 ft by 6.5 ft and 1.5 in (2 m by 4 m and 45 mm) thick that permit sunlight to stream through to the interior spaces (see Figures 15 and 16).

With rounded perforations of various diameters, the panels act as a sunshade. A set of oblong holes in the metal plates (in contact with the panels) enabled geometric tolerances in the structure as well as deformations due to expected heat absorption. The voids in the panels approach 30% and the patterns in the openings respect aesthetic requirements, allowing for easy casting procedures.

This project demonstrates the ability to produce large, perforated UHPC panels that are cast flat. Many patterns and formats can be achieved, from geometric to organic. However, due to the number of voids, the surface pattern is rather complex and must be cast in a flat, open mold position. Therefore, the filling face remains rough and is placed toward the inside of the building. In order to answer the ever-increasing desire for a smooth form finish on both sides of a perforated panel, a vacuum injection molding system has been developed. This solution enables very complex, perforated panels to be cast while obtaining the same smooth finish on all faces of the element (see Figure 17).

By transforming lattice work even further, it changes from perforated panels into much more than simple cladding. The high mechanical strengths of UHPC enable it to play a structural role in building construction. When the voids begin to exceed 50%, they can no longer be classified as perforated



Figures 15, 16 – Community Center, Sedan, France — perforated UHPC panels create a double-skin facade that provides privacy, sunshade and daylight.

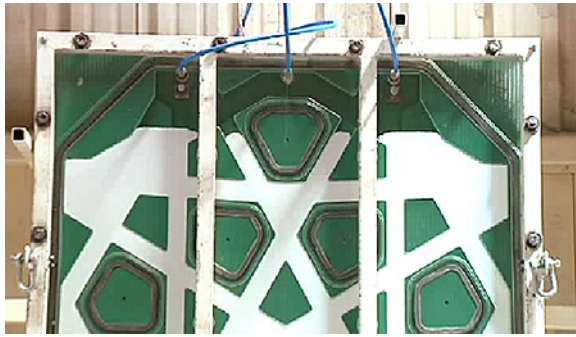


Figure 17 (top, left) – Lattice panels being formed with a vacuum injection molding system. Figures 18, 19: Perforated UHPC panels at Plescop City Hall, France.
(Photos courtesy of Lafarge)



panels, but rather a type of lattice that in turn requires structural design.

The Plescop City Hall in Morbihan, France, has a sunshade system consisting of six UHPC panels that are 50% perforated, up to 5.5 m x 3.9 m x 10 cm thick and covering more than 170 m². Above the perforated panels, curved panels attach to the parapet, which allows the building envelope to be closed (see Figures 18 and 19).

Artisan

UHPC is well-suited for modern and contemporary interior decors including benches, tables, decorative panels, kitchens, bathrooms, floor tiles, fireplaces and planters. A good “fit” for current, modern trends in décor, it provides a bare, natural material for homes and businesses. Because UHPC can replicate mold materials, it easily reproduces the exact texture and grain of the mold, and the concrete can be color-matched to the aesthetic needs of the project.

Interior Decor

With UHPC, designers can create complex, organic interior design elements that are sleek and lightweight. An excellent example is the “banquettes” or benches at Bar Agricole in San Francisco. This project demonstrates new engineering capabilities in concrete technology that are possible with UHPC (see Figure 20). The double-sided seats (approximately 5 ft x 5 ft x 5 ft) resemble a ribbon (1 in thick), extruding from the wall. The designer envisioned the banquettes to be made

with steel, but UHPC proved to be an exceptional alternative material that easily allows for the creation of organic, curvy elements with ambitious angles and no rebar.

UHPC has also been used for creative decorative wall panels with thicknesses ranging from 12 to 20 mm. The panels can feature different formats, colors, textures, lattice shapes, reliefs and forms with varying depths of effects. As well, UHPC can imitate various surface finishes from the mineral aspects of stone to the shiny aspects of glass and oxidized metals. UHPC panels are generally lightweight, slim and easy to attach to walls. Attachments are similar to systems used for sandstone tiles. Many designs for lattice panels are fabricated in 2 dimensions. However, UHPC casting techniques will also permit 3D lattice shapes,

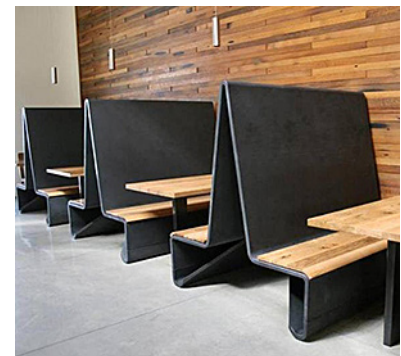


Figure 20: UHPC benches/banquettes at Bar Agricole, San Francisco. (Photo courtesy of Concreteworks Studio)



Figure 21: Lattice-style panels.
(Photo courtesy of Lafarge)



Figure 22 (top left) – Innovative UHPC tables.

(Photo courtesy of Lafarge)

Figure 23 (above) – Large-format floor tiles.

(Photo courtesy of Bill Gockeler)

Figure 24 (left) – Bio-ethanol fireplace.

(Photo courtesy of Lafarge)

further challenging the designers' creativity. Adding texture further enhances the customized panel design. In many cases, harmony within a room or atrium can be achieved by continuing the bare and natural look from the floor slabs into a decorative wall pattern (see Figure 21).

Tables are typically built out of a flat tabletop and some sort of base. With UHPC, designers can create a vast range of tables for any occasion using modern, unique, innovative forms with blended materials, material surface effects and integral colors. The material's high moldability and superior strength allow for the creation of large, thin tabletops with perforated or solid surfaces. Specialized liners in the precast molds are used to create effects such as crocodile or lizard skin, wood grain or a perfect, polished look. In many cases, the edges of the table have an extremely slim look, generating "wow effects" for boardrooms or dining tables (see Figure 22). This look is often achieved by hiding ribs or thickening the table in the center to ensure its structural integrity. The design can be enhanced by including LED lights or optical fibers in the tabletops that glow in the dark.

The fiber reinforcement of UHPC formulations makes it possible to produce large format, ultra-thin floor tiles with a

thickness similar to ceramic tiles or parquet strips. Installation is easy and simple, similar to regular tiling, without the need for setting of materials such as a self-leveling concrete or lacquered concrete. The tiles can be placed on supports and are extremely useful for renovation projects (see Figure 23). The material's extremely low water permeability enables interior and exterior applications, even for bathrooms.

Since UHPC is very compact with minimal porosity, unique kitchen and bathroom elements may be produced in a vast range of colors and shapes, such as: countertops, sinks, shower bases, bathtubs and small tiles. Generally, these elements are light and easy to install.

UHPC can be molded to imitate stone or contemporary looks with a wide variety of attractive surface finishes or textures for surround fireplaces and planters. A current trend is the production of bio-ethanol fireplaces, which store ecological fuel and may be ignited indoors (see Figure 24).

Due to the material's low porosity and water permeability, UHPC is an excellent material for the production of planters or decorative containers. By integrating color and textures, exceptional horizontal and vertical elements can be created (see Figure 25).

Urban Furnishings

UHPC can be used for the production of practical, unique street furnishings in urban settings. Its combination of properties provides functionality, durability, aesthetics and a

wide range of colored or textured options. Its impact- and weather-resistant qualities (freeze/thaw), durability and low maintenance make it an excellent alternative to traditional materials such as steel, cast iron, aluminum, plastic or wood. Depending on the design, it can complement, blend and be used in combination with these materials. Benches, decorative panels, bollards and street furniture are just some examples of the many possibilities (see Figures 26-31).



Figure 25 – Planters.
(Photo courtesy of Szolyd Development)

If a precaster/artisan can develop a “signature” urban furniture element, the fabrication facility can develop a standard precast element that may be cast repetitively. Below are some examples of urban furnishings made with architectural UHPC.

Mega Architectural Projects

“Mega” Architectural UHPC projects have been utilized in

Paris, France. In 2011 and 2012, two large projects – the Stade Jean Bouin, and the Museum of Civilizations in Europe and the Mediterranean (“MuCEM”) – were constructed using architectural UHPC precast elements. These projects take advantage of the superior properties of UHPC with architectural and structural properties such as ease of curvature and texture, as well as high compressive and flexural strengths.

Stade Jean Bouin

The Stade Jean Bouin in Paris, France, has played an important role in the history of rugby since 1925. It has been redesigned and rebuilt to host up to 20,000 spectators in a way to reduce its impact on the urban landscape as much as possible. This objective represented a real technical challenge and a first worldwide for architect Rudy Ricciotti, who has created a remarkable, precast UHPC lattice-style facade system that is light and airy (see Figures 32 & 34). The 23,000 m² envelope, including a 12,000 m² roof, is made of 3,600 self-supporting UHPC triangular panels, each averaging 8 m to 9 m long by 2.5 m wide and 4.5 cm thick. The envelope totally covers the stadium in an amorphic fashion, designed to protect spectators from the



Figures 26 – UHPC modular island.
(Photo courtesy of Szolyd Development)



Figure 27 _ Ultra-thin UHPC chair.
At Yves Saint Laurent store.
(Photo courtesy of Lafarge)



Figures 28 (above) and 29, 30, 31 (below) – UHPC Urban Furnishings.
(Photos courtesy of Lafarge)





Figure 32 – Mega project: Stade Jean Bouin, a 23,000 square meter UHPC lattice envelope and roof. (Photo: Nanick Guihodo)

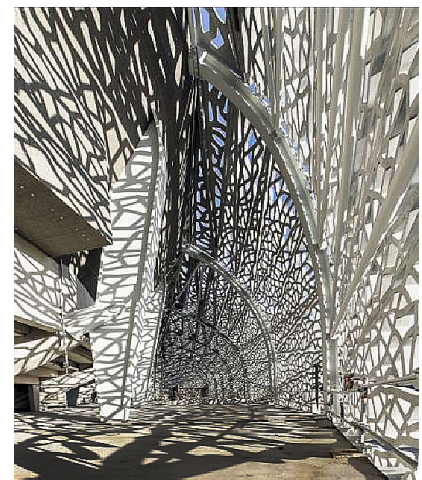


Figure 33 (left) – Stade Jean Bouin’s UHPC lattice roof system with glass inserts. (Photo courtesy of Olivier Amsellem). **At right, the open lattice facade allows sunlight to filter through.** (Photo © courtesy of Lisa Ricciotti).

elements and provide an acoustic screen in consideration of the surrounding neighborhoods. This remarkable project is a first of its kind and the result of years of studies and tests, particularly with respect to the incorporation of light-diffusing glass.

MuCEM

The Museum of Civilizations in Europe and the Mediterranean (MuCEM) was slated to come to fruition just a few months before Marseille became the European Capital of Culture in 2013. This innovative project, designed by Rudy Ricciotti and Roland Carta, demonstrates architectural and structural qualities of UHPC in dimensions that have never been seen before. Precast UHPC was used to construct: a 78-m-long

footbridge (see Figure 34); structures for an “abstract cube” with a 15,000 m² surface area; flooring; and a complex lattice-style envelope (see Figure 35) with a series of “Y” and “N”-shaped, slender columns (see Figure 36) in 20 basic designs that create 80 different combinations. The columns are designed to carry the entire load. The assembly technique required production tolerances to be less than 2 mm on elements that are 9 m tall. According to the architect, “The building was subject to the most stringent requirements: a pioneering building method and maximum requirements in terms of both seismic strength and fire resistance, as specified and tested by the CSTB.”

SECTION 7: COMMERCIALIZATION AND



Figures 34, 35 – Mega project: MuCEM with UHPC lattice facade, roof and footbridge. (Photos © courtesy of Lisa Ricciotti)

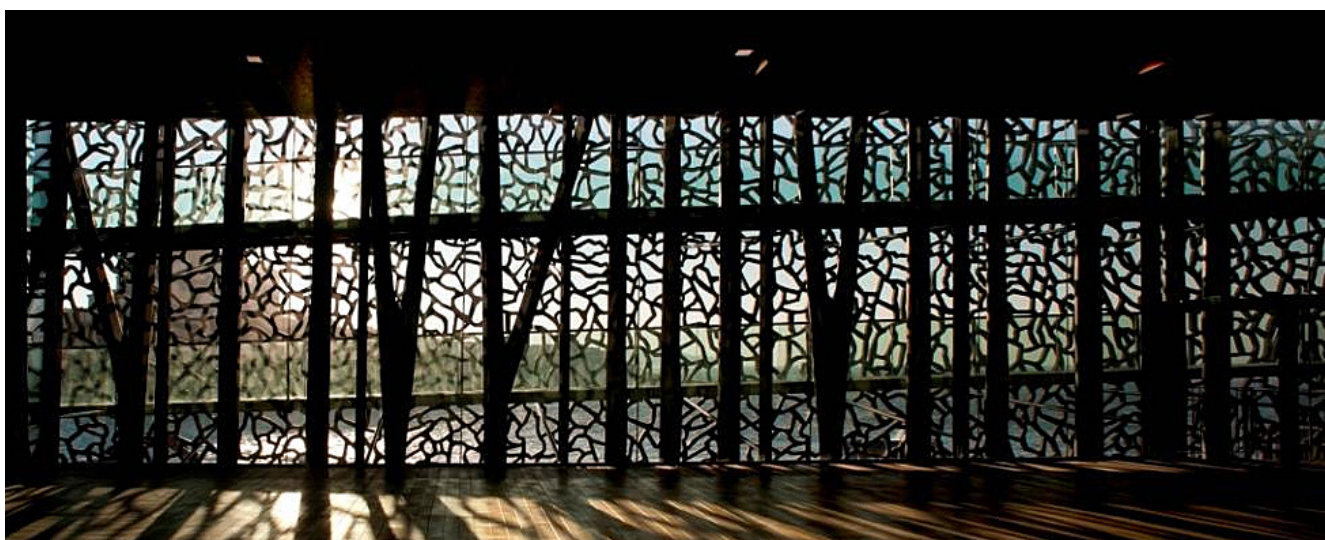


Figure 36 – MuCEM’s UHPC lattice facade features tree-like, UHPC columns. (Photo © courtesy of Lisa Ricciotti)

THE ECONOMICS OF UHPC

For manufacturers to successfully commercialize precast UHPC elements, a business plan for the proposed solution must be developed and validated. Once precasters understand the material’s technical properties, they may seek “problems that require a solution” which, in turn, must be validated by an economic analysis (compared to current alternatives).

When looking at the pricing structure for UHPC, precasters should keep in mind that a new, innovative solution with superior technical characteristics will result in a very different look and size compared with elements produced with alternative, traditional materials such as wood, metals or conventional concrete. The economics of the entire solution must be validated; it is not simply a unit price comparison.

UHPC, as with metals or conventional concrete, offers a wide range of products with a range of unit selling prices, but

it is used in different ways. The range in unit price is between concrete and metals and, when used in an optimized manner, it provides solutions that are extremely durable and cost-competitive.

When comparing the cost of UHPC versus the cost of ready mix concrete (sold in North America between \$77/yd³ to \$139/ yd³ [\$100/m³ to \$180/m³]), pricing can vary from \$1,925/ yd³ to \$3,460/ yd³ (\$2,500/m³ to \$4,500 /m³), depending on the formulation within the UHPC range of products for various applications. This pricing structure also varies in different markets and regions around the world.

This pricing comparison may seem interesting; however, when buying various types of steel, an order of magnitude of \$6,150/ yd³ (\$8,000/m³) for black steel and \$23,000/ yd³ (\$30,000/m³) for stainless steel is evident. This clearly shows that the entire economics of the finished UHPC solution (including material, manufacturing and distribution costs plus market economics) must be considered when reviewing the pricing structure,

which should not be based on unit pricing of materials. When compared with conventional concrete, UHPC is priced higher, but the volume of material required is greatly reduced. It also provides many superior benefits and cost-effective solutions that are not possible with conventional concrete.

Before commencing any major production facility investments, it is recommended that manufacturers develop a business plan for their proposed UHPC solution. This requires the precaster's review of distribution and promotion strategies as an expert with respect to local markets, accessibility and market tolerance. In addition, the precaster will develop a value proposition for any new, innovative UHPC solutions. Once the business plan has been completed, prototypes of the proposed solution must be tested, optimized and certified. These procedures will result in a clear understanding of the required equipment and capital investments. Ultimately, successful UHPC commercialization relies heavily on these

business strategies in order to create continuous sales and efficient production.

