OVERVIEW OF UHPC TECHNOLOGY, MATERIALS, PROPERTIES, MARKETS AND MANUFACTURING

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ABSTRACT:

Ductal® is a new material technology that offers a unique combination of superior technical characteristics including ductility, strength and durability, while providing highly moldable products with a quality surface. The technology provides compressive strengths of up to 30,000 psi (200 MPa), with flexural strengths of up to 7,200 psi (50 MPa) and ductility.

The material's unique combination of properties enables the designer to create thinner sections, longer spans and taller structures that are lighter, more graceful and innovative in geometry and form while, at the same time, providing superior durability and impermeability against corrosion, abrasion and impact. The technology provides the precast industry with opportunities to improve many existing products and manufacture new lines of products that will compete with other materials such as stainless steel, cast iron, ceramics and others.

This paper presents the fundamentals of the technology, properties of the materials, new markets under development, project solutions and manufacturing examples for specific applications. The markets and project examples include roof panels, wall panels, 5-sided boxes, anchor plates and others.

Many economies gained from this new technology are a result of engineering new solutions for old problems. By utilizing the unique combination of properties, designs can eliminate passive reinforcing steel and experience reduced global construction costs, form works, labor and maintenance. Additionally, this relates to benefits such as improved construction safety, speed of construction, extended usage life and others.

Keywords: Fiber-reinforced, Impact, Impermeability, Abrasion, Aesthetics, Ultra-High Performance, Durability, Ductile, Usage-life, Composite

INTRODUCTION

In North America today, Ultra-High Performance Concrete (UHPC) is a relatively new material, having limited commercial examples with significant material data. One such technology, "Ductal®", has been commercially available in North America since 2001 (by Lafarge North America Inc.). This paper provides information on UHPCs, based on the research/development and exemplification of this new technology. As well, the technology described herein covers a range of portland cement composites with characteristics including compressive strength of more than 20,000 psi (140 MPa). This technology is based on a range of patents, *Ductal FM, Ductal FO, Ductal AF, RPC 200, RPC 800* and others, developed and owned by Lafarge S.A., Bouygues Construction and Rhodia Chemie S.A..

This technology has a unique combination of superior technical characteristics including ductility, strength and durability, while providing highly mouldable products with a high quality surface aspect. Compressive strengths are up to 30,000 psi (200 MPa) and flexural strengths up to 7,200 psi (50 MPa). UHPC products can reduce global construction costs and labour requirements, improve construction safety, lower maintenance and increase a structure's life span.

The unique combination of properties enables the designer to create thinner sections, longer spans and taller structures that are lighter, more graceful and innovative in geometry and form while, at the same time, providing superior durability and impermeability against corrosion, abrasion and impact. This material provides the precast industry with opportunities to improve many existing products and manufacture new lines of products that will compete with other materials such as stainless steel, cast iron, ceramics and others.

Many economies gained from this new technology are a result of engineering new solutions for old problems. By utilizing its unique combination of properties, designs can eliminate passive reinforcing steel and experience reduced global construction costs, form works, labour and maintenance. Additionally, this relates to benefits such as improved construction safety, speed of construction, extended usage life and others.

This paper presents the material properties, design assumptions for project solutions and the manufacture, installation and assembly procedures for specific projects. Projects described include roof panels, 5-sided boxes and anchor plates.

MATERIAL CHARACTERISTICS

This new material, with a unique combination of technical characteristics including ductility, strength and durability, while providing highly mouldable products with highly mouldable products with a high quality surface aspect, is unlike any other material currently available. It is a high-strength ductile material formulated of constituent materials including portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water and steel or organic fibers. The technology is covered by one of many patents in a range of UHPCs.

Compressive strengths reach up to 30,000 psi (200 MPa)[1], while flexural strengths reach up to 7,200 psi (50 MPa)[1].

The ductile behaviour of this material is a first for concrete, with the capacity to deform and support flexural and tensile loads, even after initial cracking (Figure 1). These performances are the result of improved micro-structural properties of the mineral matrix, especially toughness and control of the bond between the matrix and the fiber.

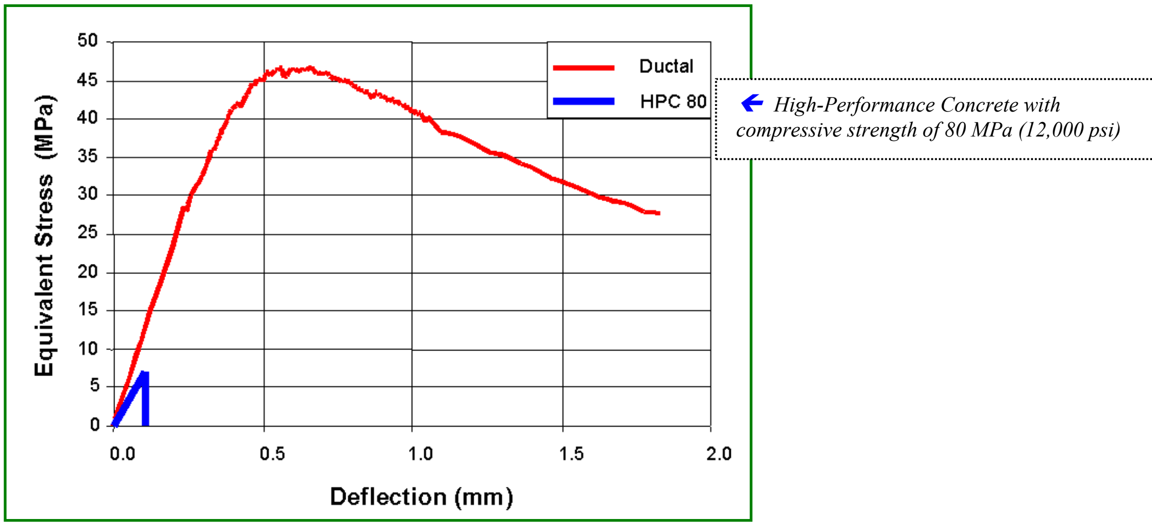

Fig. 1 UPHC Stress-strain curve

There is almost no carbonation or penetration of chlorides and sulfates and a high resistance to acid attack. The superior durability characteristics are due to a combination of fine powders, selected for their relative grain size (maximum 600 microns) and chemical reactivity. The net effect is a maximum compactness and a small, disconnected pore structure.

The material has almost no shrinkage or creep, which makes it very suitable for prestressed applications. The use of this material for construction is simplified through the elimination of reinforcing steel and the ability of the material to be virtually self-placing or dry-cast.

The following is an example of the range of material characteristics for UHPC with metallic fibers[1]:

STRENGTH

Compressive	23 – 33 ksi	(160 - 220 MPa)
Flexural	5,000 – 7,200 psi	(35 - 50 MPa)
Youngs Modulus (E)	8 – 8.5 x 10^6 psi	(55 - 60 GPa)
Total Fracture Energy	1,300 – 2,000 lb (F)- ft/ft^2	(20,000 - 30,000 J/m^2)
Elastic Fracture Energy	1.3 – 2.0 lb (F)- ft/ft^2	(20 - 30 J/m^2)

DURABILITY

Chloride ion diffusion (CI)	0.02 x 10^{-11} ft^2/s	(0.02 x $10^{-12} m^2/s$)
Carbonation penetration depth	<0.02 in.	(<0.5 mm)
Freeze/thaw (after 300 cycles)	100%	
Salt-scaling (loss of residue)	<0.0025 lb/ft^2	(<10 g/m^2)
Abrasion (relative volume loss index)	1.2	

The materials are supplied to the precaster in a three-component pre-mix. The powders are pre-blended in bulk-bags at a blending facility and shipped to the precast plant. Super-plasticizer and steel fibers are supplied separately and introduced into the precaster's mixer at the time of batching.

MARKETS

This new material, with a unique combination of technical characteristics, is unlike any other material currently available. Utilizing this combination of properties to design new solutions for old problems is key to providing ecomonical solutions to customers. A few markets that have been explored and appear interesting are:

Long-span Roofs – spans greater than 50 ft (20 m), particularly in combination with abrasion, corrosion or heavy loads.

Anchor Blocks/Plates – ability to resist heavily concentrated loads in corrosive environments, with enhanced aesthetics.

Kennels/ Animal Proof Waste Containers – thinned-walled, aesthetically pleasing, corrosion resistant and durable against denting.

Acoustic Panels – thin panels replicating gypsum acoustic panels capable of resisting corrosion and impact or abuse.

Structural Wall panels – thin-walled with rib, lightweight load-bearing panels, with enhanced architectural finishes.

Bridges – long spans, shallower profiles, lighter-weight spans with improved impermeability, abrasion resistance, durability.

EXAMPLE OF PROJECTS

The following is a selection of projects which demonstrate the use of this technology:

THE JOPPA PROJECT

The Joppa project was an upgrade to an existing manufacturing facility in Joppa, Illinois. The total upgrade, at an estimated cost of twenty million dollars, included the installation of three new clinker silos. It is the roofs of the silos that were of interest for UHPC versus steel analysis of a long-span roof.

The technology was used for one of the three clinker silo roofs (Figure 2) and a conventional steel solution used for the other two. This case presents the properties of the material, the design assumptions for the two roof solutions, manufacture of the panels and erection/assembly of the roofs.

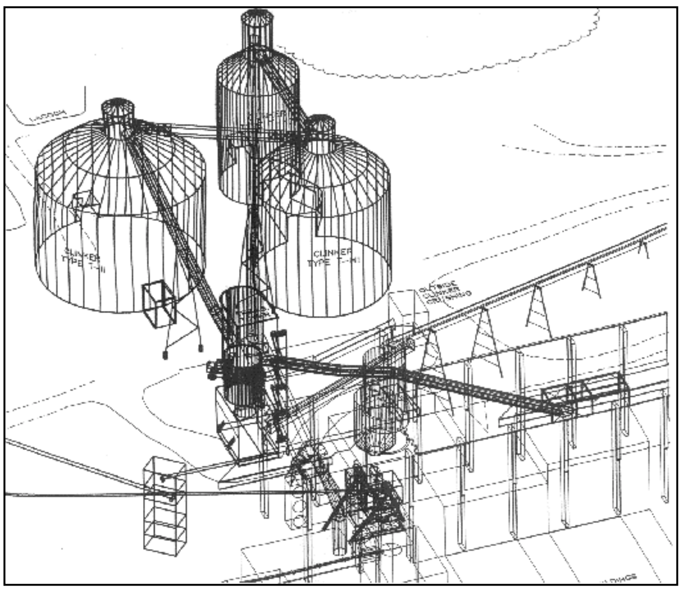

Fig. 2 Schematic : General arrangements – clinker storage & handling

The clinker silo walls are slip formed concrete of 58 ft (18 m), 100 ft (30 m) and 121 ft (37 m) in diameter with truncated, cone shaped roofs of UHPC or steel. The roofs are attached to the top of the slip form silo walls and provide a tension ring at the base. The top of each roof supports a mechanical penthouse floor with an intregal steel compression ring attached.

The demonstration roof consists of twenty-four precast, pie-shaped panels with a $^{5}/_{8}$ in. (15 mm) skin thickness for a 58 ft (18 m) diameter silo roof (Figure 3). The panels were designed to act as a thin shell, supporting a two-storey mechanical penthouse, centered at the top of the cone- shaped roof. The ultra-light, thin precast panels did not use any reinforcing bars.

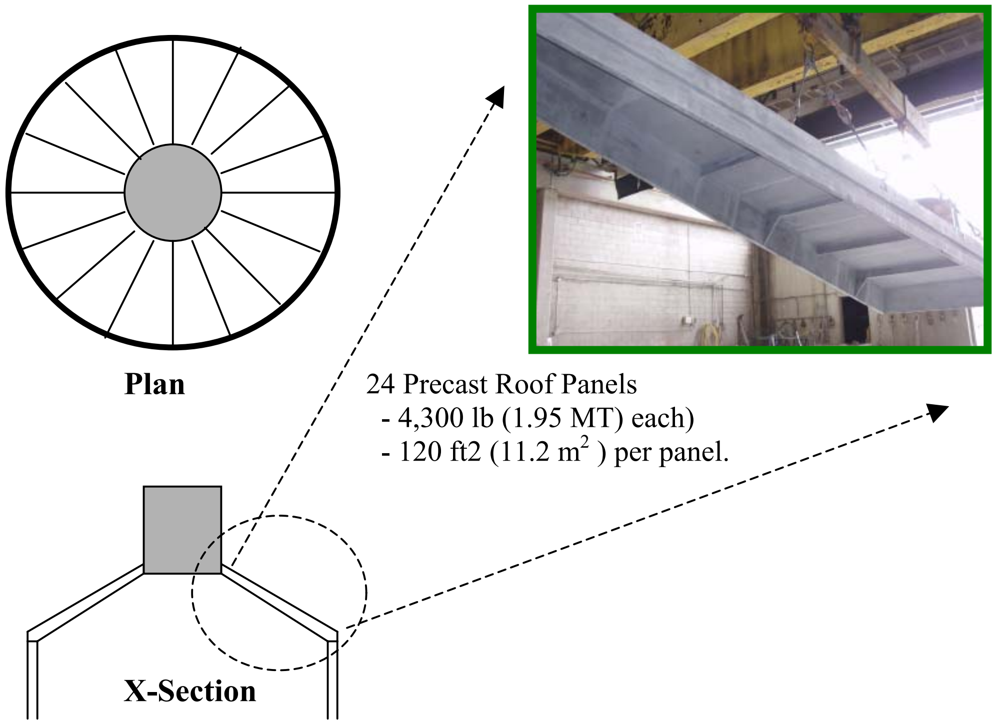

Fig. 3 Plan and section of the clinker storage silo

Due to fast track requirements and the owner's concern that a new technology may interfere with the schedule, a decision was made to carry two designs in parallel through to the award. The steel and precast options were each designed by the engineers and tendered competitively.

Table 1 summarizes the test data results from the production of the 24 roof panels cast at a precast plant in Winnipeg, MB, Canada. For the roof panels, "Ductal CS1000" was specified in the contract document. This is one of several in the product range, formulated specifically for structural use in civil engineering projects. The mean compressive strength of 24,000 psi (166 MPa) was supplied to comply with the specification minimum requirement of 23,000 psi (160 MPa).

Table 1: Test Results – Joppa Precast Panels

Property	**Mean Value at 20 hours – Release**	**Mean Value after 48 h Thermal Treatment**	**Standard Deviation**
Compressive Strength	7,250 psi (50.0 MPa)	24,000 psi (166.0 MPa)	1,500 psi (10.8 MPa)
Flexural Strength	-	5,500 psi (37.9 MPa)	600 psi (4.1 MPa)

The Design

The technology's combination of technical characteristics means that using it in a conventional manner will not maximize the efficiency of the material. Therefore a new solution was required for the Joppa roof.

Considering that (today) it is a precast product plus the owner's requirements for an airtight solution, several shell options were considered. Taking into consideration these constraints plus the loading and geometric requirements and properties, a thin shell plate was selected. It was also decided that a truncated cone would be the most efficient roof profile.

From this point, finite element analysis was used to predict the shell stresses and potential buckling. The principal compressive stresses due to the conical forces resulted in a required shell thickness of ½ in. (12 mm). Buckling, demoulding, handling, transportation and erection conditions dictated radial side stiffener beams, pre-stressed with four strands, at each side of the precast panels. Secondary bending stresses due to uniform roof live loading and buckling requirements dictated transverse ribs. See Figure 4 for a plan and cross-section of a typical panel.

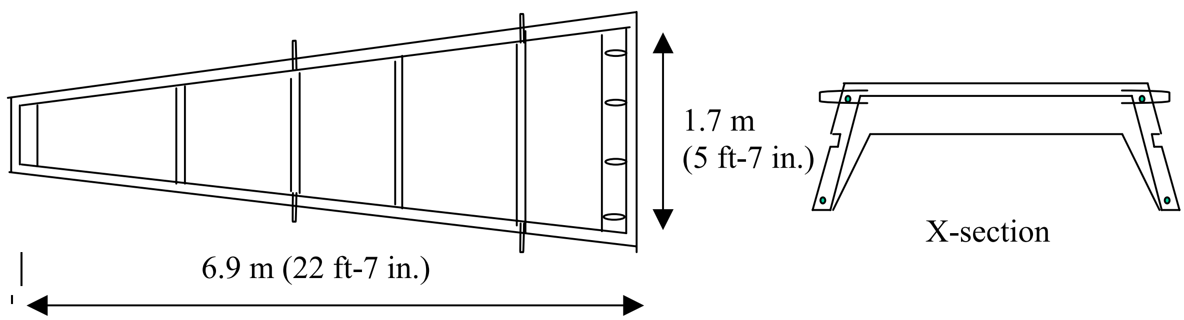

Fig. 4 Sketch of the panel for the silo roof

The final, finite element modeling of the roof with all loads and geometry revealed very low service stress levels. Minimum geometries and buckling generally governed the final design.

The steel roof (Figure 5) was a conventional steel frame with radial beams and purlins, covered with a corrugated steel deck membrane.

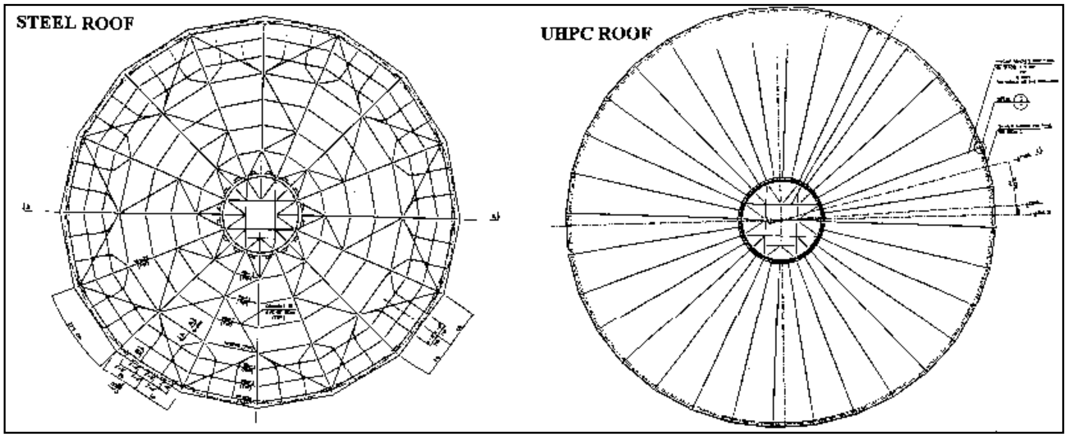

Fig. 5 Steel framing (left) vs. precast framing (right) for the silo roof

Manufacturing and Transportation of the Panels

The precast panels were manufactured (Figure 6) in Winnipeg, Manitoba, Canada and trucked to the site in Joppa, Illinois, USA. A three-component pre-mix was supplied to the precast plant and batched in a two cubic meter Nikko horizontal twin turbine mixer.


Fig. 6 Casting of a panel at the precast plant

Batch sizes of 1.2 yd^3 (0.9 m^3) were mixed and placed into the steel forms in one continuous casting. QA/QC testing on each batch included flow tests, fiber content, cylinders for compressive strengths and prisms for flexural strengths.

Following casting, the panels were covered with a tarpaulin and steam cured at 100° F (40° C) for 16 hours. The following day, when the panels attained 6,000 psi (40 MPa) minimum compressive strength, the strands were cut and the panels removed from the forms. At the end of each week, the panels were stacked in piles of four and thermally treated at 190° F (90° C) for 48 hours (Figure 7).

Fig. 7 Stack casting for 48 h thermal treatment

Transportation of the panels from Winnipeg to Joppa was via flat-deck trucks, (Figure 8) in loads of eight per truck (three loads for a total of twenty-four panels).

Fig. 8 Trucking eight panels per truck

Erection and Installation of the Panels

Upon arrival at the site, all twenty-four panels were unloaded and staged in position for installation to the roof. A mobile crane was used to install and temporarily hold the circular steel beam penthouse floor in place until the panels were installed. The panels were lifted one at a time (Figure 9), alternating opposite sides and bolted to the steel penthouse floor and top of the concrete silo wall (Figure 10).

Fig. 9 Site staging and erection of the panels

Fig. 10 Flying panels into place using a mobile crane

When all panels were bolted into place, the crane was disconnected from the penthouse floor, free to start other work on the site. Grouting between the precast panels completed the air- and watertight roof system. The penthouse and connecting conveyors were then installed (Figure 11).

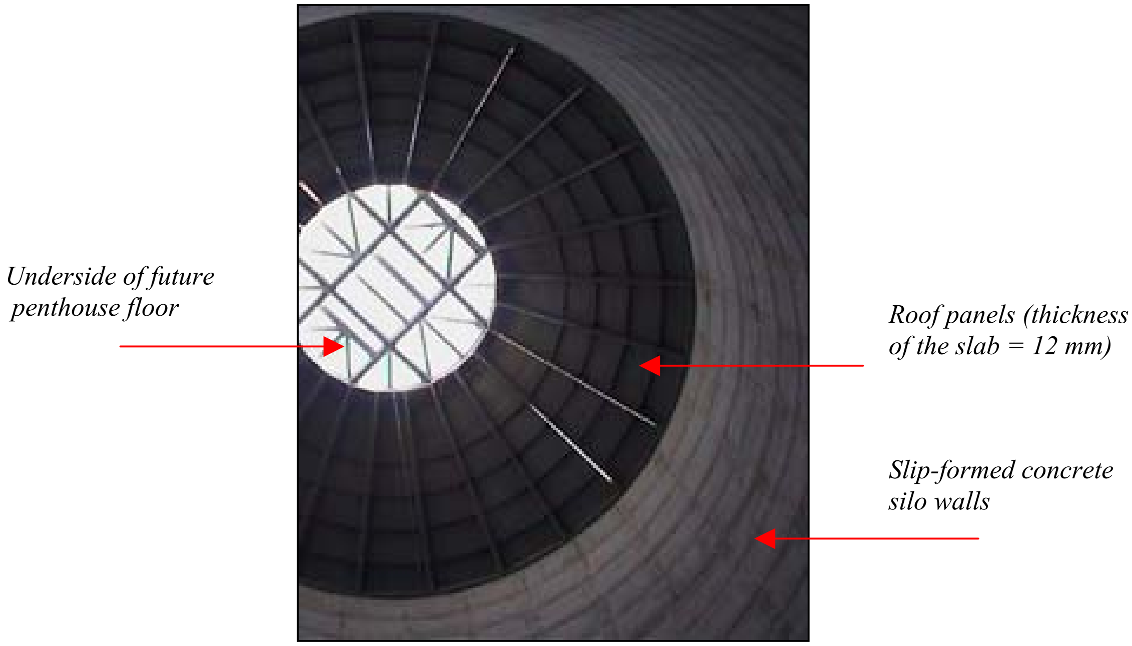

Fig. 11 View from underside, looking up at panels

The new roof system resulted in significant on-site construction time savings (Table 2), with just 11 days to install compared to 35 days for the steel system. Additionally, it was discovered that the precast roof panels were more accommodating to the construction tolerances for out-of-roundness and flatness of the top of the slip-formed silo walls.

Table 2 : Comparison of the Roof Installation Schedule

Item	**Steel Roof (days)**	**Precast Roof (days)**
Pre-Erection Survey	2	1
Pre-erection set-up (cranes & scaffolding)	5	1
Installation of Penthouse Floor (Temporary Compression ring)	1	1
Installation of panels	-	3
Grouting of Panels	-	5
Installation of Steel Roof Framing	12	-
Installation of Steel Roof Deck (Membrane)	10	-
Grouting Steel Base Plates for beams at top of Silo walls	1.5	
Installation of Closure Ring & Flashing for Steel Roof Deck (Membrane)	3.5	-
Total (Construction days)	**35**	**11**

This project (Figure 12) was the first of its type in the world for the use of a UHPC material in a long-span roof structure. While this solution demonstrates many of the benefits of the material technology, it is apparent that the true benefits are not yet fully recognized. Furthermore, the optimized profiles and use is still in its infancy and, in the next few years, much progress is anticipated in the area of optimized solutions.

Fig. 12 All 3 clinker silos and connecting feeder conveyors. (Precast roof at right)

ANIMAL PROOF WASTE CONTAINERS & DOG KENNELS

Animal proof waste containers and dog kennels are both thin-walled, five-sided boxes, with doors/gates; one designed to keep animals in and the other designed to keep animals out. Both products require a high quality surface finish on all surfaces with rounded corners to prevent injury. The kennels and waste containers are required to resist denting, rusting and abuse in a corrosive environment.

The kennels are 6 ft x 5 ft x 4 ft (1.8 m x 1.5 m x 1.2 m) with a wall thickness of ¾ in. (20 mm), for a total material volume of 0.26 yd^3 (0.2 m^3) of material per kennel. The waste containers are 3 ft x 18 in. x 18 in. (1.0 m x 0.5 m x 0.5 m) with a wall thickness of ¾ in. (20 mm), for a total material volume of 0.06 yd^3 (0.05 m^3) of material per container.

The selected production method was to use double-sided moulds for a five-sided box (Figure 13) and an injection casting technique (Figure 14). All elements were cast upside-down and injected at the bottom of the mould, under constant pressure. A pressure vessel filled with the fluid material was connected to the mould with a flexible tube through a knife valve gate. Typical injection casting times were 10 minutes. The quality and tightness of the moulds were very important to ensure a high quality surface finish and to avoid leakage of the fluid material while injecting.

Fig. 13 Inside of mould, showing openings for the top and rear doors

Fig. 14 Set-up for injection casting of animal proof waste containers

The final products (Figures 15 & 16) were an excellent example of new products with improved characteristics and economical benefits.

Fig. 15 Form and prototype waste container

Fig. 16 Six finished dog kennels

ANCHOR PLATES / BLOCKS

In 2002, precast retaining wall panels were manufactured for placement beneath a highway bridge in Calgary, Alberta, Canada. Due to restricted site accessibility, it was decided that off-site construction of the wall panels would speed up the schedule by permitting earlier installation of the super-structure prior to completing the earthworks, sub-structure and retaining structures.

The engineer designed a post-tensioned, soil anchor precast retaining wall system, bearing on a lean concrete strip footing, utilizing soil anchor rods grouted into stable soil. The soil anchor rods were then bolted with anchor plates into pockets, cast into the precast wall. The anchor plates were designed (in parallel) in both galvanized steel and UHPC.

The retaining wall consisted of 42 precast units of 15 ft (4.9 m) long, varying in thickness from 12-18 in. (300 mm to 550 mm) and up to 10 ft-2 in. (3.1 m) in height (Figure 17). Each wall panel is set in place on a lean concrete mud slab, then tied back with steel soil anchors to resist the soil pressure (Figure 18). Following the grouting of the anchor rods into stable soil, 64 precast anchor blocks were installed and a bell nut threaded onto the end of the rod.

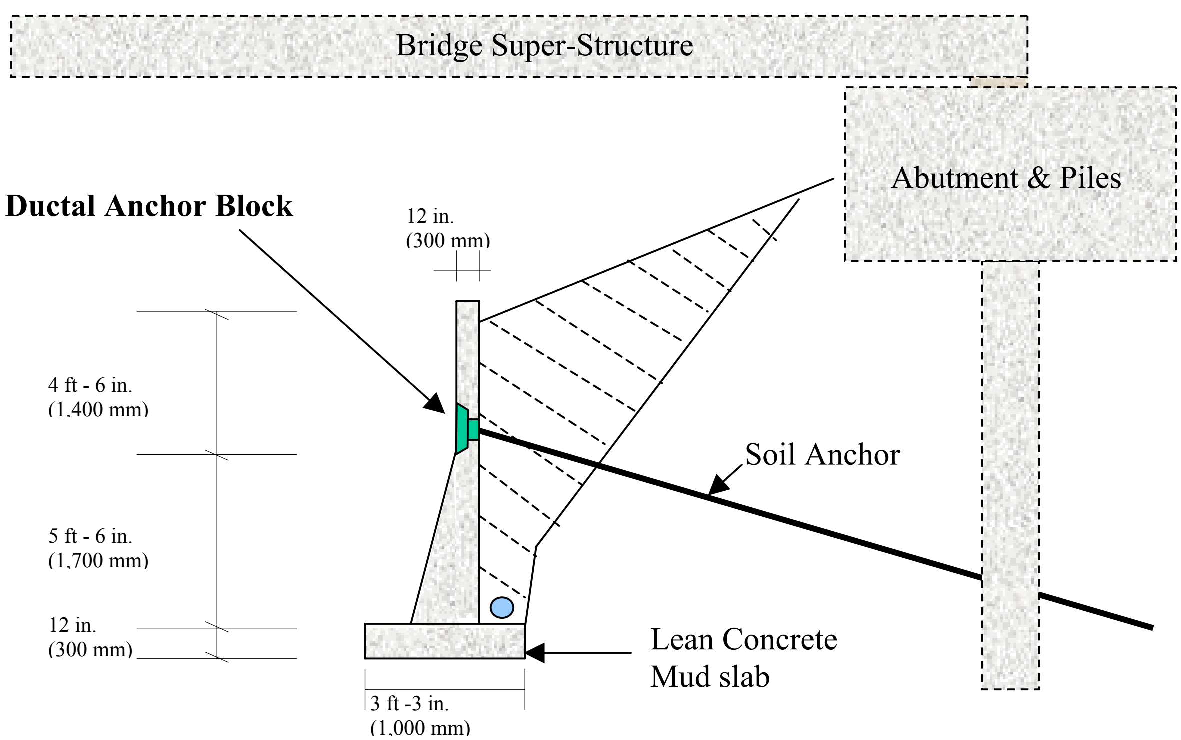

Fig. 17 Schematic of retaining wall with precast anchor blocks

Fig. 18 Precast retaining wall

The anchor blocks, manufactured at a precast plant in Calgary, were 20 in. x 20 in. x 11 in. (506 mm x 506 mm x 280 mm) thick and used approximately 4 m^3 (5 yd^3) of UHPC.

Steel moulds were manufactured for casting the block-outs in the precast retaining walls. The same moulds were then used for the anchor blocks, resulting in a match casting of the blocks and pockets (Figure 19). This also provided moulds with watertight joints to prevent leakage of the fluid material during the casting operations. A plastic insert was cast into the top side of the mould to form a precise pocket to accept the counter sunk bell nut.

Fig. 19 Casting the anchor blocks

The specifications required a compressive strength of 22,000 psi (150 MPa) and the mean compressive strength obtained was 27,000 psi (188 MPa). Batch sizes were 0.3 yd^3 (0.22 m^3) to cast 3 anchor blocks in one casting. Total production took 11 days. The anchor blocks were assembled in the precast yard on pallets (Figure 20) and shipped to the project site as required by the schedule. Each block had a mass of 350 lb (160 kg).

Fig. 20 Anchor blocks ready for shipping

The anchor blocks were installed at the site using a bobcat and two men. Following the placement of the blocks into the wall pockets, the bell nut was threaded onto the soil rod (Figures 21 & 22).

Fig. 21 Anchor plate installed in the precast retaining wall

Fig. 22 Anchor plate installed, elevation view

CONCLUSIONS

The technology's unique combination of superior properties enabled the designer to create thinner sections and longer spans for a tall structure that is lighter, more graceful and innovative in geometry and form. Overall, the solutions offer advantages such as speed of construction, improved aesthetics, superior durability and impermeability against corrosion, abrasion and impact – which translates to reduced maintenance and a longer life span for the structure. While these solutions presented demonstrate many of the benefits of the material technology, it is apparent that the true benefits are not yet fully recognized. Furthermore, the optimized profiles and use is still in its infancy and, in the next few years, much progress is anticipated in the area of optimized solutions.

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