UHPC Perspective from a Specialist Construction Company

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Summary

Ultra-high performance concretes (UHPC) exhibit exceptional mechanical and durability properties. UHPC is a cementitious material consisting of cement, sand, silica fume, silica flour, admixture and water. It is almost self-placing, has a compressive strength of 150-200 MPa and a flexural strength of 30-40 MPa. This paper discusses the development of UHPC in Australia and presents examples of UHPC structures that have been designed and constructed in Australasia from the perspective of a local construction specialist. Applications in Australia and New Zealand include the first road bridge built using UHPC and completed in October 2004, a series of footbridges in New Zealand providing ramp access to train stations, panels at a power station that are subjected to continuous salt water spray and infrastructure protection panels on a freeway sound wall.

Keywords: reactive powder concrete, bridges, pedestrian, durability, project examples

1. Introduction

The Ultra-high performance concrete (UHPC) described in this paper is of the reactive powder concrete (RPC) type known under the brand name of Ductal® and originally developed by Rhodia, Lafarge and Bouygues [1]. The constituents of RPC are cement, fine sand, silica fume, silica flour, superplasticiser, water with a low water-cement ratio, and may include either high-strength steel fibres or non-metallic fibres.

The extremely good durability properties of UHPCs are well documented [2, 3, 4]. The compression strength of UHPC fabricated in Australia is in the order of 200 MPa, flexural strength of up to 40 MPa and a Young's modulus of 47 GPa. The behavior in compression can be described as having a ductile softening plateau. UHPCs are often heat treated to limit the residual shrinkage, normally shrinkage is up to 500microns, and improve mechanical performance. The design and general properties of Ductal® are described in detail in [5]

UHPC has been used around the world predominantly in the construction of pedestrian and road bridges [6], protective panels [7], and architectural applications [8]. This paper provides a summary of the applications in Australia and New Zealand in recent years from a specialist construction company perspective. VSL Australia has been fabricating UHPC solutions for more than six years and the team in Sydney is the Knowledge Centre for UHPC applications in the VSL Group.

2. UHPC Design and Production in Australia

2.1. Early Research

Although research on UHPC in Australia commenced in 1997, large scale production of UHPC only became viable in Australia for the first time in the latter part of 2002 with the first practical application of the material in a road bridge in 2003. The initial investigation focused on producing Ductal®, under license from Lafarge and Bouygues, using locally sourced materials. The main objective of the study conducted at the University of NSW in Sydney, was to optimise the mix design for large scale production, and to produce structural quality UHPC with a compressive strength of 180 MPa. This led to a mix design where all materials, excluding steel fibres, are readily sourced from local supply, reducing the raw material costs of UHPC. Research focus then shifted to the investigation of the performance of UHPC structural elements. Shear testing of seven prestressed I-beams with thin unreinforced webs was conducted [9]; the results from one test are shown in Figure 1.

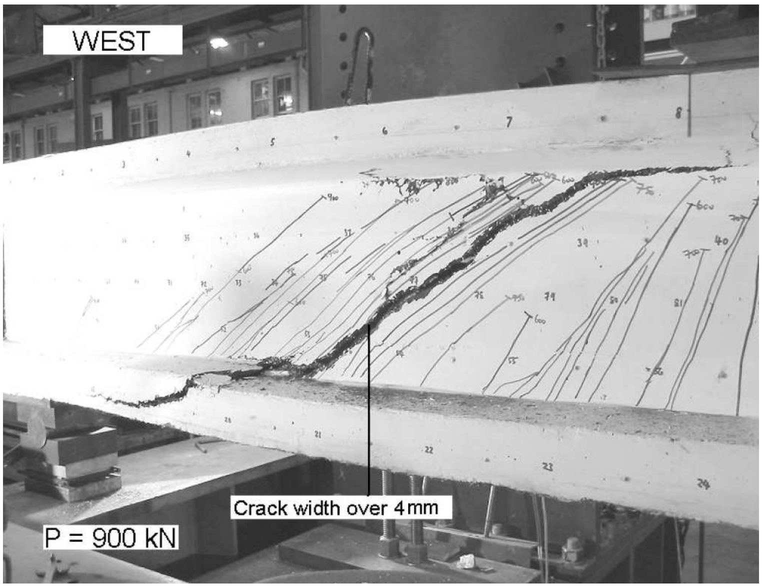


Fig. 1 UHPC beam No. 2 after shear failure

2.2. Developing a Design Guide

As the ultra-high strength of UHPCs put them outside the direct provisions of the Australian design standards, a specific design guide was required. The research undertaken at the University of NSW was in view of developing a design guide complying with the intent of AS 3600 [10]. The beam tests evaluated shear strength parameters and mechanical strength tests determined characteristic design values [11]. The development of this guide took into account the extensive material research undertaken in France in developing the AFGC-SETRA recommendations on UHPFRC [12] and applying these to local conditions. The guide outlines material values to be used in design, guidance on calculating flexural, shear and torsional strength of members, deflections including long term deflections, and provides worked examples for a range of prestressed beam designs [13].

2.3. Development Project - Shepherds Creek Road Bridge: NSW, Australia

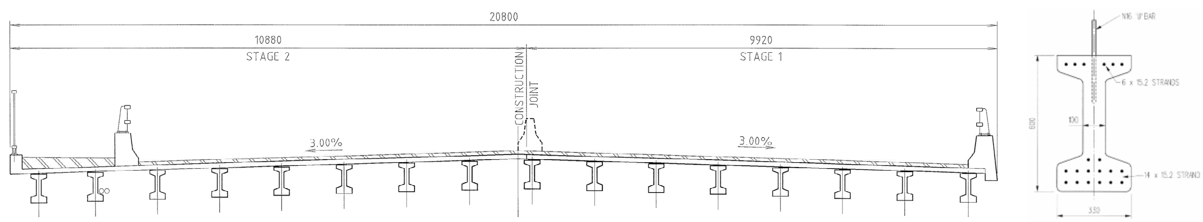
Secondary transport roads in Australia are dominated by short span highway bridges, many of which are approaching design life and carrying capacity limits. The Shepherd's Creek Bridge, approximately 150km north of Sydney, replaced an ageing timber bridge and was the first bridge in the world to be constructed using UHPC for normal highway traffic. It was also the first application of UHPC in Australia. The construction of this bridge was considered by the Roads and Traffic Authority NSW (RTA) as an evaluation trial of the materials, design procedures and constructability of UHPC.

The bridge comprises four traffic lanes and a footway, Figure 2(a). The substructure comprises driven steel piles with a cast-in-place capping beam. The bridge is a single span of 15m with a 16° skew. The superstructure, shown during construction in Figure 2(b), comprises 16 precast pre-tensioned UHPC beams and an in-situ 170mm thick reinforced concrete deck slab. The concrete slab is cast on 25mm thick permanent precast UHPC formwork panels that span between the beams. The I-section beams have a depth of 600mm and are spaced at 1.3m centres.

The construction method is the same as that for conventional bridges with concrete beams and slabs. The beams have the significant advantage that they weigh only 4.2 tonnes for a length of 15.1m. This compares to about 9 tonnes for a conventional prestressed beam. The permanent formwork slabs also have the advantage of being very light.

The design of the bridge was based on the Australian UHPC design guide and local concrete and loading standards. Structural testing at the University of NSW confirmed the performance of various UHPC elements, such as the permanent formwork slabs shown under test conditions in Figure 3(a).

As part of the RTA (Road Traffic Authority) certification programme for UHPC in Australia, the Shepherds Creek bridge was load tested on completion of the first two lanes, and again one year later. The test load induced effects into the bridge was equivalent to 1.5 times the T44 serviceability load (i.e. the equivalent of effects of a 650 kN truck). The tests confirmed that the behaviour of the bridge conformed to the design. Figure 2(c) shows the bridge open to highway traffic. In September 2005, the RTA issued a policy statement giving approval for UHPC to be used on RTA bridges and structures. Additional project information can be found in [14].



a. Cross section and beam details

b. Installed beams and formwork slabs

c. Bridge open to traffic

Fig. 2 Shepherds Creek Road Bridge: Australia

a. 25mm thick formwork slab, span 1.3m load 18 kPa

b. Test slab at a simulated wheel load of 250kN

Fig. 3 Testing conducted prior to bridge construction

2.4. Current Design and Production Capability

Optimised UHPC sections typically involve complex geometries, such as penetrations in beam webs, and therefore high level analysis is required to ensure that the superior properties of UHPC are utilised. The use of finite element analysis (FEA) conducted using a high level finite element code enables the design team to optimise the section design while achieving the performance requirements. Complex loading regimes, such as harmonic loading at varying frequencies, can easily be investigated with this level of analysis.

For sectional analysis, the design team utilise ISPARC, a specially developed software package. The section analysis uses a layered approach and estimates the section behaviour from stressing up to yielding of the steels and into high-overload whilst taking into account material non-linearity and section geometry. Through collaboration with the software developers, UHPC material models have been included thus allowing the user to choose between a number of influencing parameters including fibre type and curing regime.

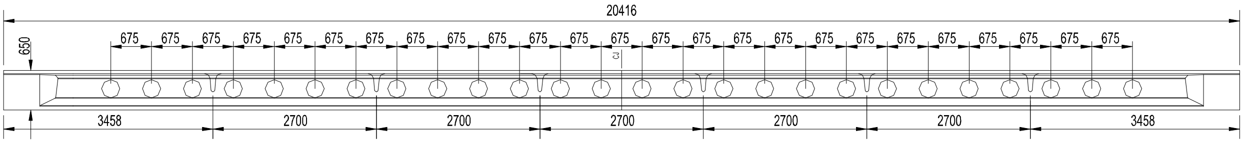
VSL facilities in Melbourne are comprised of a UHPC batching plant, a dry casting area with twin 5t capacity overhead cranes and a large storage and handling area. A special 1.5m^3 planetary high-shear mixer is required for the batching of UHPC and forms an integral part of the batching plant.

VSL source, blend and package the raw powder materials ready for later use. The full procurement cycle is subject to stringent quality control processes. Experience has demonstrated that UHPC requires a much higher level of control to ensure the end material properties are achieved.

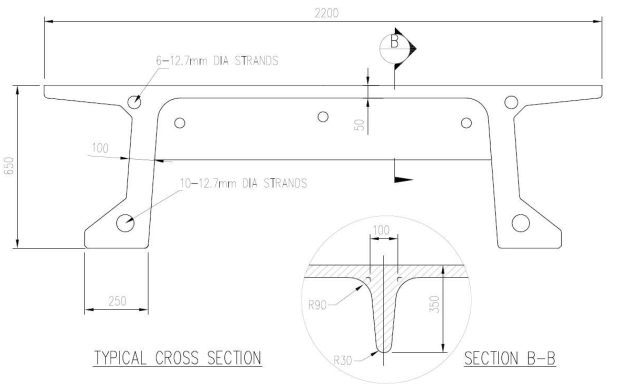
3. Australia and New Zealand Project Examples

3.1. A Series of Pedestrian Bridges: Auckland, New Zealand

An important part of the railway station redevelopment being undertaken by the Auckland Regional Transport Network Ltd is a series of new footbridges, providing ramp access for pedestrians to cross the railway tracks. To-date, five (5) stations have had the footbridges replaced, the first being Papatoetoe Station which is described in the following paragraphs. A second footbridge at Penrose Station also in Auckland was completed using the same UHPC bridge element utilised on the Papatoetoe Station footbridge. The bridge has a total length of 265m consisting of 15 spans of mostly 20m, and was opened to the public in March 2006. A third major upgrade was completed at Papakura station in August of 2007.



a. Typical elevation of a 20.4 m π-shaped UHPC (Ductal®) beam



b. Cross section of UHPC beam element

c. Demoulding of match-cast segments

d. Segments in transport

e. Lifting a UHPC span (with hand railing attached)

f. Completed Papatoetoe Footbridge

g. Penrose Footbridge during construction

Fig. 4 Papatoetoe and Penrose Footbridges: Auckland, New Zealand

The station at Papatoetoe was the first station to have the new footbridges. The conforming design for the Papatoetoe pedestrian bridge was a conventional prestressed concrete structure until a New Zealand contractor saw an opportunity to reduce the weight and cost by using UHPC (Ductal®) solution proposed by VSL Australia. The main advantage of the alternative solution is the significant weight reduction, resulting in reduced design earthquake actions imposed by the New Zealand design code and cost savings in the substructure and erection.

The Papatoetoe Footbridge has a total length of 175m consisting of ten simply supported spans, with the majority of spans being 20m long. There are two shorter spans of 8.2 and 10.2m. The bridge spans are formed using two precast UHPC segments. The deck is 50mm thick, contains no ordinary reinforcement, and has two symmetrical legs with large circular holes that provide architectural interest and reduce weight; Figures 4(a) and 4(b) give details. Ribs protrude 350mm below the top of the deck slab at 2.7m centres along the beam to add torsional rigidity. The tension steel is provided by ten (10) Ø12.7mm post-tensioned strands in the bottom of each leg and six (6) strands at the top to balance the stresses. Both tendon profiles are straight and anchored directly against the UHPC without the need for further anchorage reinforcement.

Production of the Papatoetoe bridge beams (Figure 4(c)) commenced in December 2004 and was completed over a ten week period. To achieve the required architectural shape and surface finish, a special steel formwork was utilised, comprised of a fixed internal form and two side forms that shape the exterior surface and web penetrations. The larger elements were match cast in two segments to allow later transportation on standard 40-foot open containers (Figure 4(d)).

The UHPC beams were post-tensioned on site after delivery to New Zealand. Prior to erection a topping surface made of ordinary concrete was applied to the superstructure. This surface was graded in accordance with accessibility guidelines and has a varying thickness. Steel hand rails were secured directly to the UHPC superstructure (Figure 4(e)). A more detailed account of the design is given in [5] and of the construction account in [15].

3.2. Durability Application: Eraring Power Station Covers

The attemperating weir at Eraring power station is used to take salt water from Lake Macquarie in New South Wales (Australia), which is combined with warm water from the power station and then discharged back into the lake over large boulders. This process generates continuous spray of salt water that needs to be contained to avoid severe corrosion to the power station facilities.

The weir consists of three cells that are 11m wide. A spray cover consisting of conventional precast pre-tensioned concrete planks had contained the spray for only 14 years before a number of planks started to collapse due to corrosion, see Figure 5(a). The owner required a replacement cover that had a design life of at least 100 years. Using reactive powder concrete, with its extraordinary durability properties such as its low chloride ion diffusion rate, VSL Australia engineered a structural solution with an estimated design life in excess of 5 times that required.

The UHPC panels have typical dimensions of 11.0×2.3m, a nominal thickness of only 25mm, and are supported by two integral 250mm deep beams, as illustrated in Figure 5(b). The panels were precast and pre-tensioned and are extremely light compared to other systems weighing only 3.5 tonnes each. A total of 920m^2 of UHPC panels were supplied and installed in August 2004. Figures 5(c) and 5(d) show the installation and completed weir respectively.

3.3. Infrastructure Protection Application: Southern Link Upgrade Panels

As part of the Monash Freeway upgrade south of the Melbourne, Australia CBD, a noise wall was to be installed on top of an existing Yarra River Bridge parapet. The clearance between the noise wall and parapet face was not sufficient to prevent a truck impacting the noise panels, therefore the parapet width needed to be increased. Precast UHPC panels proved an economic alternative to in-situ casting of concrete to increase the parapet width. The panels ranged in length from 1.3 to 4.1m featuring a tapered shape in cross section with thicknesses ranging from 65mm to 35mm. The panels contained no reinforcement other than steel fibres, and a white pigment was added to lighten the panels to better match the new structure. The high fracture toughness of UHPC will ensure that the panels provide excellent protection for the noise wall given an impact by a truck or other vehicle. Figure 6 shows the panels installed on the existing parapet, and the precast elements ready for dispatch from the precast facility.

(a) Weir prior to upgrade showing failed planks *(b) Typical UHPC panel*

(c) Installation of new UHPC panels *(d) Weir in operation, August 2004*

Fig. 5 Photos of Eraring power station weir covers

a. Panels installed on noise wall *b. Panels ready for dispatch*

Fig. 6 Noise wall protection panels

3.4. Explosive and High Impact Loading: Research and Application

UHPCs such as Ductal® exhibit exceptional energy absorption capacity and resistance to fragmentation, making it ideal for panels and components that need to perform under explosive, impact or shock loads. The flexural toughness of UHPCs enhanced with fine steel fibres is greater than 200 times that of conventional fibre reinforced concrete. Furthermore, under very high strain rates (>250 1/sec), ultimate compressive and tensile capacities can increase up to 1.5 times [16, 17].

In Australia, VSL has undertaken tests where panels are subjected to large-scale blast effects (at various distances), close-charge blast effects, projectile impacts from armour piercing bullets, fragment simulated projectiles as well as investigating ways to mitigate the effects of special weapons. Panels for the first structure incorporating blast resistant optimised UHPC panels were manufactured in March 2005 at the VSL plant in Melbourne (Figure 7(a)); photos of the installed panels are shown in Figure 7(b).

a. UHPC blast resisting panels

b. Installed UHPC panels

Fig.7 Optimised UHPC panels for protection of high risk facility

4. Prospective Applications and Challenges to Overcome

Lafarge has been successful in delivering a number of UHPC facade projects that exploit the materials unique properties producing elements that are not normally manufactured from cementitious materials. Figure 8 illustrates two such examples. This market holds great potential for UHPC in Australia, given the aesthetic possibilities of the material, and the weight savings that can be achieved when the mechanical properties are fully utilised.

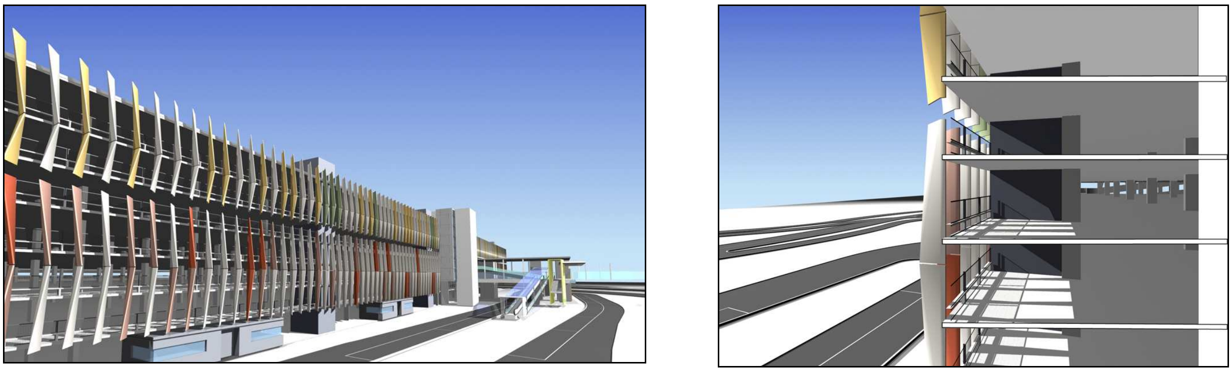
a. RATP Administration Centre in Thiais [18]

b. Sunscreeens on Clichy Swimming Pool Complex [19]

Fig. 8 Facade applications in France by Lafarge

Although a facade project utilising UHPC has not yet been realised in Australia, VSL is actively working in this area researching, promoting and developing our capabilities. VSL is supporting a MSc dissertation from the University of Bath, UK with cooperation from Gifford LLP UK. The thesis entitled "The techno-economic viability of ultra high performance fibre reinforced concrete in curtain wall framing" will investigate such issues as how to design curtain walls with UHPC, developing standard connections details, acoustic resistance and sustainability.

VSL is working with a leading Australian architecture firm detailing UHPC facades on new buildings (Figure 9). Aesthetics are a key requirement for such projects and consequently VSL has invested in research to demonstrate the vibrant colours that can be achieved with the addition of oxide pigments. The detailing of connections is a challenge given the thin sections that can be achieved; standard precast connections may not be practical, requiring designers to think beyond the norms of precast concrete connection design. UHPC architectural solutions require greater quality control during production and an attention to detail during mould preparation to ensure an excellent surface finish is achieved.



a. Architectural model, east facade *b. Architectural model, cross section*

Fig. 9 Concept of slender UHPC facade elements for car park building

5. Concluding Remarks

The paper has provided an overview of the development and application of an UHPC, mainly named Ductal® in Australia. While UHPC is not a replacement for conventional concrete, it can create opportunities and provide economical and innovative solutions in areas where normal concrete struggles to provide a solution. In Australia and throughout Asia, VSL and other Lafarge licensees have successfully developed and shown the benefits of UHPC as an alternative to conventional road bridge construction, for footbridge applications in earthquake prone areas, and in applications requiring durability or unique aesthetics.

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