Experience and Applications of Ultra-high Performance Concrete


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ABSTRACT

Ultra-high performance concretes (UHPC) exhibits exceptional mechanical and durability properties. RPC 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 presents examples of UHPC structures that have been designed and constructed in Asia from the perspective of an Australian 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 panels for blast protection. Project examples from Korea and Japan are also described.

KEYWORDS

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

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1. INTRODUCTION

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.

UHPCs also an almost impermeable material with extremely good durability properties[2,3,4,5]. The compression strength of Ductal® fabricated in Australia is in the order of 200 MPa, flexural strength of up to 45 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 ultra-high strength of UHPCs put them outside the direct provisions of the Australian design standards and therefore a specific design guide was required. Research was undertaken at the University of NSW in view of developing a design guide [6] complying with the intent of AS 3600 [7]. This research included beam tests to evaluate shear strength parameters and mechanical strength tests to determine characteristic design strengths [8]. The development of this guide took into account the extensive material research undertaken in France [9].

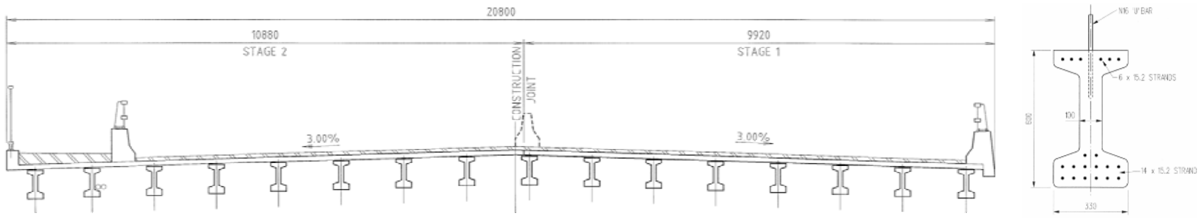
UHPC has been used around the world predominantly in the construction of pedestrian and road bridges, protective panels and architectural applications. This paper provides a summary of the applications in Asia in recent years from an Australian perspective. VSL Australia has been fabricating UHPC solutions for more than five years and the team in Sydney is the Knowledge Centre for UHPC applications in the VSL Group.

2. AUSTRALIA and NEW ZEALAND

2.1 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 replaced an ageing timber bridge. It comprises four traffic lanes and a footway, Fig 1(a). The bridge is a single span of 15m with a 16° skew. The superstructure, shown during construction in Fig 1(b), comprises 16 precast pre-tensioned RPC beams and an in-situ 170mm thick RC deck slab. The concrete slab is cast on 25mm thin permanent precast RPC formwork panels that span between the beams. The I-section beams have a depth of 600mm and are spaced at 1.3m centres.

As part of the RTA (Road Traffic Authority) certification programme for RPC in Australia, the Shepherds creek bridge was load tested on completion of the first two lanes, and again one year later. The tests confirmed that the behaviour of the bridge conformed to the design. Fig 1(c) shows the bridge open to highway traffic. In September 2005, the RTA issued a policy statement giving approval for RPC to be used on RTA bridges and structures. Additional project information can be found in [10].



a. Cross section and beam details

b. Installed beams and formwork slabs

c. Bridge open to traffic

Figure 1: Shepherds Creek Road Bridge: Australia

2.2 A Series of Pedestrian Bridges: Auckland, New Zealand

An important part of the 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 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 has recently been completed using the same Ductal® 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. The third major upgrade was completed at Papakura station in August of 2007 [5,11].

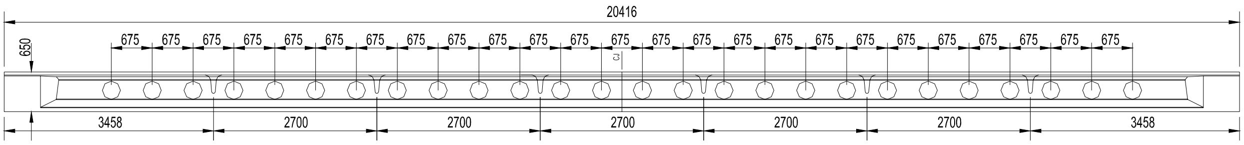
The station at Papatoetoe was the first station to have the new footbridges. The conforming design for the Papatoetoe pedestrian bridge was a conventional prestressed concrete structure until a New Zealand contractor saw an opportunity to reduce the weight and cost by using a UHPC solution proposed by 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 Ductal® 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; Fig 2a and 2b 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 ∅12.7mm post-tensioned strands in the bottom of each leg and six strands at the top to balance stresses. Both tendon profiles are straight and anchored directly against the RPC without the need for further anchorage reinforcement.

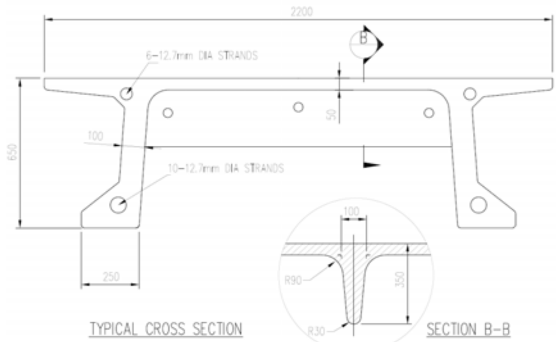
Production of the Papatoetoe bridge beams (Fig 2c) commenced in December 2004 and was completed over a ten week period. To achieve the required architectural shape and surface finish, a special steel formwork was utilised, comprised of a fixed internal form and two side forms that shape the exterior surface and web penetrations. The larger elements were match cast in two segments to allow later transportation on standard 40-foot containers (Fig 2d).

The RPC 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 Ductal® superstructure. This surface was graded in accordance with accessibility guidelines and has a varying thickness.

Steel hand rails were secured directly to the RPC superstructure (Fig 2e).



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



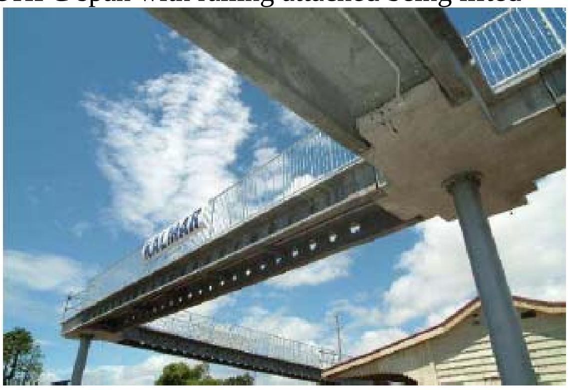
b. Cross section of UHPC beam element

c. Demoulding of match-cast segments

d. Segments in transport

e. UHPC span with railing attached being lifted

f. Completed Papatoetoe Footbridge



g. Penrose Footbridge during construction

Figure 2 Papatoetoe and Penrose Footbridge: Auckland, New Zealand

2.3 Infrastructure Protection Applications

UHPC such as reactive powder concrete (RPC) 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 RPCs enhanced with fine steel fibres is greater than 200 times that of conventional fibre reinforced concrete. Furthermore, under very high strain rates (>250/sec), ultimate compressive and tensile capacities can increase up to 1.5 times [12].

In Australia, VSL has undertaken tests where panels are subjected to large-scale blast effects at various distances, close-charge effects, projectile impacts from armour piercing bullets and fragment simulated projectiles as well as special weapons effects mitigation [13,14]. Panels for the first structure incorporating blast resistant optimised RPC panels were manufactured in March 2005 at the

VSL plant in Melbourne. The client was the Department of Foreign Affairs and Trade of the Australian Government. Panels are up to 4.5m long x 2.0m wide x 100mm thick. They are being used to provide blast resistance to an existing building in a high risk international location. The panels were installed on site in July 2005. Photos of the panels prior to shipment from the VSL factory and as installed on site are shown in Fig 3.

a. UHPC blast resisting panels b. Installed UHPC panels

Figure 3: Optimised UHPC panels for protection of government facility

2.4 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, which 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 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 Fig 4(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 low chloride ion diffusion rate, VSL Australia engineered a structural solution with an estimated design life in excess of 5 times that required.

a. Weir prior to upgrade showing failed planks b. Typical UHPC panel

c. Installation of new UHPC panels d. Weir in operation, August 2004

Figure 4: Photos of Eraring power station weir covers

The UHPC panels have typical dimensions of 11.0m × 2.3m, a nominal thickness of only 25mm, and are supported by two integral 250mm deep beams, as illustrated in Fig 4(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. Fig 4(c) and 4(d) show the installation and completed weir respectively.

2.4.1 Seating Plats for a Stadia

Following repeated interest from construction clients, VSL Australia has investigated the feasibility of an optimised UHPC precast element for stadia seating plats. These plats support stadia seating and are usually fabricated from ordinary concrete, the design of which is governed by vibration comfort requirements and self-weight. In modern stadia, multi-level seating is often levered out to provide maximum capacity, and therefore the weight of the seating plats is a significant factor in the supporting structure design.

For this comparison a typical span of 13m was taken, for which the standard concrete plat is L-shaped. The optimised UHPC plat is designed to maximise vibration comfort, minimise self-weight and provide superior durability ensuring lower maintenance costs and a long design life. The reduced self-weight provides a reduction in direct costs in the supporting structure and erection including faster crane movements, multiple unit lifting for faster installation and fewer truck movements on site. Fig 5 shows the optimised UHPC plat section and 3-unit assembly, with Table 1 listing the primary performance advantages. While no UHPC plats have been fabricated to-date, the concept is being explored for application in new and for the upgrade of existing stadia in Australia, New Zealand, Switzerland and the UK.

Table 1 Performance advantages of optimised UHPC stadia seating plats

Performance Criteria	Typical Concrete Plank	UHPC Optimised Plank
Weight	8.6 t	4.2 t
Deflection (Dead & Dynamic Live Load)	6.5mm	4.0mm
Vibration (1st Mode, higher is better)	7.6 Hz	12.5 Hz
Durability	Acceptable by Design	Significantly better

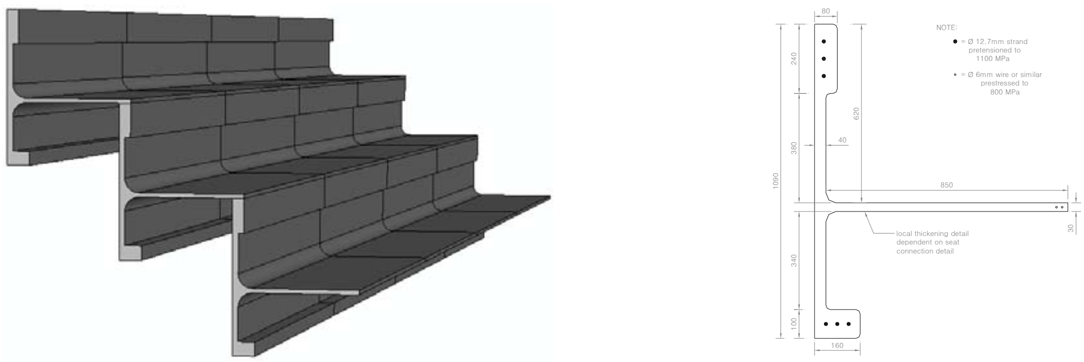


Figure 5: Concept for optimised UHPC stadia seating plats

3. JAPAN

3.1 Sakata-Mirai Footbridge: Sakata, Japan

Sakata-Mirai Bridge was designed to fit into the graceful and monotone local environment. The bridge takes full advantage of the characteristics of Ductal® and does not use any passive reinforcement, instead achieving strength through external prestressing. The bridge is extremely light with a dead weight of only 56 tonnes; approximately a fifth of the dead load of an equivalent ordinary PC structure, resulting in an economic advantage of around 10% [15]. Fig 6 shows the bridge, which consists of a single 50.2m span, and a typical cross section at mid-span showing the two external

prestressing tendons consisting of 31-∅15.2mm strands. The section height varies from 550mm at the supports to a maximum of 1650mm at mid-span (Fig 6) to satisfy deflection limits of span/600. A 3-D non-linear FEM analysis taking into account the holes was utilised to carry out detailed design verification. The bridge consists of six (6) precast segments that were erected onto temporary steel girders on piled abutments. An in-situ joint was used to connect the segments prior to post-tensioning.

Figure 6 Sakata-Mirai Footbridge: Japan

3.1.1 Other Bridge Applications

Bridge and related applications of UHPC in Japan have been predominantly in the form of box girders with very thin webs often similar to the ideas of the Sakata-Mirai Footbridge described above; the Table below lists known projects utilising UHPC supplied kindly by Hiroshi Shiratani of the Taisei Corporation.

Fig 7 on the right, shows the unique application of UHPC for the Torisaki River Bridge. Here a corrugated steel web girder, erected by incremental launching, uses UHPC for the lower chords of the launching nose portion. The bridge has a maximum span of 54.5m, and a launching nose length of 45m. After completion of launching, the nose portion is transformed to the permanent girder.

Table 2 List of UHPC Bridge Applications in Japan

Name [Location]	**Type**	**Span [m]**	**Width [m]**	**Completion Date**	**Notes**
Horikoshi Ramp [Fukuoka]	Highway	16	8.5	11-2005	Composite I-girder
Torisaki River [Hokkaido]	Highway	45	11.3	12-2006	Launching nose
DNP Tokai Factory	Motorway	2.9	6.5		
Akakura [Yamagata]	Footbridge	35	3.5	01-2004	Box girder
Tahara Bridge [Aichi]	Footbridge	12	2.6	04-2004	Box girder
Toyota Gym [Aichi]	Footbridge	28	4.5	02-2007	Box girder
Sanken-ike [Fukuoka]	Footbridge	2-40	3.5	06-2007	Box girder
Keio Uni [Tokyo]	Footbridge	11	2.0	03-2005	
Hikita [Tottori]	Footbridge	63.3	3.0	Construction	Box girder (web & flange only)

Figure 7: Other UHPC Bridges in Japan; Left: Akakura Footbridge, Right: Torisaki River Bridge

3.1.2 Haneda Airport Slabs

The expansion of Haneda Airport Runway D will utilise the world's largest single project application of UHPC in the world to date; work on the project started in July of 2007, with initial experimental works conducted two years prior. In addition to supplying the preblend Ductal® material, Taiheiyo Cement (under licence from Lafarge) is also responsible for the mixing operation for the UHPC slabs. The project is an excellent example of how weight savings and durability make for an overall economical UHPC solution. Fig 8 shows the runway extension over water that is supported by a complex steel jacketed structure.

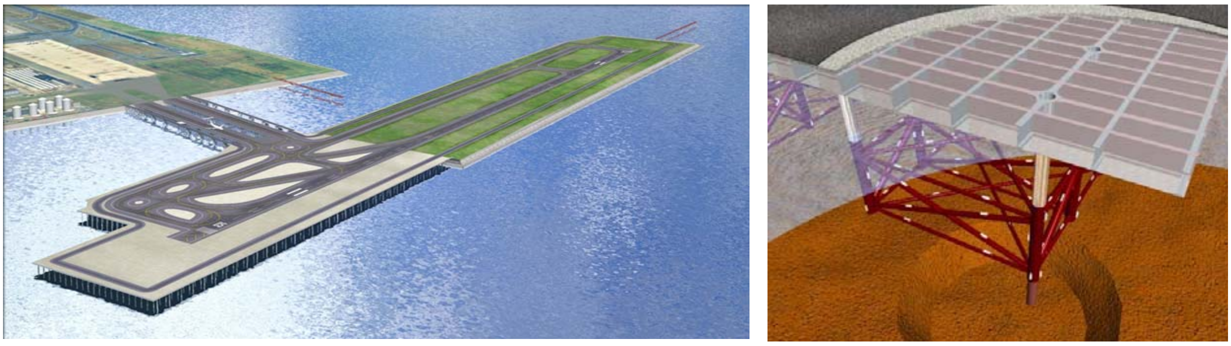


Figure 8 Haneda Airport Runway D; Left: Panoramic View, Right: Pier Section

The cost reduction in the required steel jacket fabrication for the supporting structure yields an overall construction cost saving for the project, a direct function of the weight savings achieved through the use of the UHPC slabs. The high level of mechanical performance, good fatigue, freeze and thaw performance, and excellent durability further enhances the whole-life costing of the project.

Table 3 Testing of UHPC slab

	Prestressed Concrete Slab	**UHPC Slab**
Weight per Slab	221 kN (100%)	97 kN (44%)
Average Dead Load including Fillers	7.84 kN/mm^2	3.83 kN/mm^2
Average Slab Depth	320mm	135mm

The plan dimensions of the UHPC precast slabs for the piers of the Haneda Airport Runway D are 7.8m x 3.6m. There are approximately 7,000 slab units that provide an area of 200,000m^2; equivalent to 24,000m^3. The UHPC slabs are ribbed, pre-tensioned with high-strength strand and have an effective depth of only 135mm. The slabs were designed for ultimate wheel loads of 320kN. Prototype testing of the slabs, shown in Fig 9, yielded an ultimate carrying capacity of 600kN/wheel. Table 3 gives a comparison between the UHPC slab weights and prestressed concrete slab. A low carbonation rate, water permeability and good salt damage resistance helped in achieving the 100 year design life in the aggressive environment.

Figure 9 Testing of UHPC slab

4. KOREA

Since the introduction of UHPC, Ductal® licensed by Lafarge and utilised on the Sunyudo Bridge, VSL Korea has been actively seeking projects to utilise these UHPC materials again.

4.1 Sunyudo Footbridge: Seoul, Korea

To date, the Sunyudo (Peace) Footbridge in Seoul (Fig 10a) is the largest RPC bridge in the world with a single span of 120m [16]. It is comprised of six precast and post-tensioned segments of PI-

shaped section. The section developed for the Sunyundo Footbridge, consists of a transversally ribbed upper slab and two girders. The width of the arch is 4.3m, has a section depth of 1.3m and a thin (30mm) slab supported by transversal ribs at 1.225m, and two longitudinal ribs at the extremities of the transversal section. This ribbed slab is supported by two 160m thick webs. The transversal ribs are prestressed by ∅12.7mm sheathed and greased monostrands. Small specially adapted anchors similar to those used in the construction of the Sherbrooke footbridge were used to transfer the prestressing forces. In the longitudinal direction, the structure is prestressed by three tendons in each leg. The arch is supported at each end by two reinforced concrete foundations 9m deep resisting the horizontal thrust of the arch.

Figure10 Sunyudo Footbridge: Seoul, Korea

4.2 Realization of a Hanging Walkway

VSL has had numerous enquiries in Asia for light-weight, highly durable walkway attachments to existing or new road bridges. In the past these types of structures have often been constructed from steel, with ordinary concrete solutions being too heavy, but recent whole-of-life and other durability considerations have steered engineers to look into UHPC solutions; one of these is a hanging walkway for the proposed Gyeomjae Bridge in Korea. A typical cross-section of the hanging walkway solution is shown in Figure 11. The concept significantly reduces the size of the concrete box girder and separates pedestrian and road traffic. At the time of writing, the project is undergoing final design consideration.

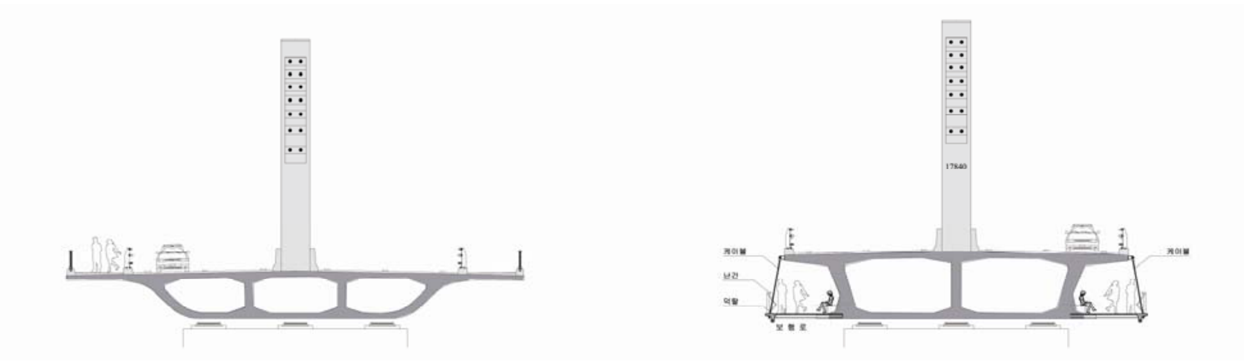
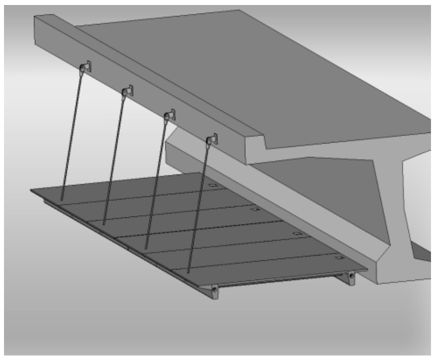


Figure 11 Gyeomjae Bridge; Left: Conforming Design, Right: Design with UHPC hanging walkway

The proposed UHPC walkway consists of thin plank type segments (as shown on the right), post-tensioned through a longitudinal rib to form modules that can be lifted into place as a single unit. The planks are further ribbed transversely to provide torsional rigidity and bending strength. The UHPC modules are suspended off the concrete box girder using hanger bars and a steel pin joint on the inside. Each UHPC module with a width of 4m and 6m length weighs only 4.5t.



5. CONCLUDING REMARKS

The paper has provided an overview of the application of an UHPC, mainly named Ductal® throughout Asia from an Australian perspective. 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 form a solution. In 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 blast effects damage mitigation.

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