Material Properties of Ultra High Performance Conference (UHPC)

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| **Abstract**  Ultra High Performance Concrete (UHPC) is a class of concrete that achieves a high compressive strength and improved durability outcomes when compared to conventional concrete currently used in Australia. UHPC is accompanied by fibre reinforcement and has a high binder content, and minimal and small aggregate in the form of fine sands and ground quartz.  In order to allow UHPC to be used within Australia, the development of both a technical specification and design standard is underway. A sub-committee (BD-090-10) has been established by Standards Australia to develop a new section of AS5100 (Part 10) and the Department of Transport and Planning, Victoria is developing technical specification. Together, these two documents will define the various technical requirements necessary for engineers to enable design, supply and construct UHPC structures. The technical requirements will include material properties, material quality assurance (including a testing regime), and design requirements.  This paper will outline the various material properties that have been adopted in the technical specification and design standard to be used for UHPC. This includes design properties and material models necessary to provide sufficient design guidance for engineers. This paper will describe why the various material properties for UHPC have been adopted including the tensile and compression behaviour, modulus of elasticity, density, poisson’s ratio, coefficient of thermal expansion and shrinkage strain.  The establishment of a technical specification and design standard for UHPC is a significant and important step to enable the material to be more widely used within Australia, with the aim of enabling more innovative bridge design solutions.  **Keywords:** UHPC, Concrete, Standards, Material Properties |

# Introduction

Ultra High Performance Concrete (UHPC) is an emerging material in Australia, although it has been used in prestressed concrete girder simple-span bridges, precast concrete deck panels, and field-cast connections between prefabricated bridge components in Europe, Asia and North America. Unlike conventional concrete (CC), UHPC features a dense matrix of cementitious materials, fine aggregates, and a high concentration of specially engineered fibres uniformly distributed throughout the mixture, offering superior strength, durability, and sustainability compared to CC.

The use of UHPC in Australia is relatively limited, with the only bridge beams constructed in Australia occurring in early 2000 at the Shepherd’s Road Bridge in NSW. The project was a collaboration between VSL, RTA and UNSW (Gowripalan et al.1) and using 'Ductal' (a proprietary UHPC product) to construct the precast bridge beams.

UHPC is characterised by a class of concrete whose compressive strength is higher than 100 MPa. UHPC has the potential to achieve compressive strengths of up to 250 MPa. UHPC is composed of a dense matrix of cementitious materials, fine aggregates, and a high concentration of specially engineered fibres dispersed throughout the mixture. The addition of the fibres significantly enhances the material's tensile strength, ductility, and crack resistance, allowing longer beam lengths, thinner concrete sections and lighter elements. The combination of high-strength cementitious matrix and closely spaced fibres also results in improved durability and performance, making UHPC highly suitable for challenging environments, and enabling a significantly extended design life (Larsen et al.2) beyond the 100 years offered by CC. UHPC also offers the potential to reduce carbon emissions when compared to CC resulting in a more sustainable outcome. The reduced member sizes and increased design life result in lower carbon emissions than CC over the entire design life.

Current Australian Standards (eg AS5100 and AS3600) and technical specifications used in Australia limited concrete strength to a maximum of 100 MPa. Therefore, to enable more broader adoption of UHPC the development of design standards and specification is needed. This activity is currently underway, with the Australian Standards sub-committee BD-090-10 developing a world first, “deem to comply” design standard which will form Part 10 of AS5100. To supplement the design standard, The Department of Transport and Planning in Victoria are developing a technical specification for the material testing and supply and construction requirements.

This paper will summarise the current status of UHPC design standards, specification and guidelines used around the world, and the current status of Australian UHPC technical documents and requirements. As part of the development of an Australian design standard, this paper will outline the various material parameters and properties critical for UHPC. This includes design properties and material models necessary to provide sufficient design guidance for engineers including the tensile and compression behaviour, modulus of elasticity, density, poisson’s ratio, coefficient of thermal expansion and shrinkage strain. Finally, the paper will conclude with a discussion on how Designers and Constructors can utilise these unique characteristics of UHPC material properties to achieve innovative engineering solutions that aren’t offered by CC.

# Benefits of UHPC

The increased compressive and tensile capacities of UHPC, along with the higher density of material has resulted in several benefits UHPC has over CC. The resulting potential applications of UHPC include;

* High compressive and tensile strengths of UHPC allow for reduced section sizes, increased beam lengths, and lighter concrete sections.
* High early concrete strength of UHPC allows in-situ connections between precast elements or deck overlays (particularly during occupations) to occur more quickly.
* Low permeability of UHPC enables it to be used in aggressive environments.
* High density and strength of UHPC means it is advantageous to use in situations that require high security or blast impacts.

As the material becomes more common place, further applications of UHPC are bound to be discovered. However, with the current body of research, the benefits of utilising UHPC as a construction material can broadly be summarised into three key areas; strength, durability and sustainability.

## Strength

The benefits of UHPC in relation to strength lies in both the increased compressive and tensile capacities when compared to CC. The high compressive strength is achieved through a combination of high cement content, small sized aggregate, the addition of silica fume, and low water to-binder ratio which enhances the densification of the matrix. UHPC can achieve up to 250 MPa in compressive strength, although common practice around the world targets a strength of 140 to 150 MPa as the optimum compressive strength. Fibres are also added to the concrete mix to improve crack resistance and fracture toughness giving an increased tensile capacity. The majority of current research of fibres in UHPC centres around use of steel fibres at about 2 to 3% of the content.

## Durability

The absence of an aggregate, the higher cement content and the low water-to-binder ratio in UHPC, when compared to CC, all leads to a denser microstructure. Silica fume further fills the physical pores in the matrix, enhancing bonding and improving the overall density of the material. This results in a material with lower porosity and reduced permeability to air, water and other chemical substance ingress when compared to CC. It has been estimated that the water absorption of UHPC is approximately 60 times lower than that of CC (Ullah et al.3).

A recent study undertaken in Australia by Pasupathy et al.4 identified the dense microstructure of UHPC provides significant advantages over the durability of CC when considering carbonation and chloride resistance. Over a 300-year design life, the carbonation modelling undertaken by Pasupathy et al.4 indicated that the required cover for UHPC is 46% of CC, while chloride modelling showed that the required cover is 24% of CC.

## Sustainability

It is estimated that concrete accounts for approximately 8% of global carbon emissions (Oliver et al.5) making it an important material in the effort to reduce greenhouse gas emissions. The largest contributor to carbon emissions in concrete is cement, which not only requires energy intensive heating of limestone to produce the cement, but carbon dioxide (CO2) is also a by-product of the transformation of the limestone (CaCO3) into lime (CaO). While cement content per cubic metre of concrete material is lower in CC (nominally 10 to 15%), than in UHPC (nominally 35%), there is the potential to take advantage of the higher strengths and longer durability to reduce total concrete volumes, while still providing similar functionality of concrete members.

A recent investigation by Taylor, Pham and Koay6 found that in the Australian context when considering a 100-year design life, it was found that for longer span bridge structures, UHPC produced 71% of the carbon emission when compared to CC. When the design life was increased to 200-years, the investigation found UHPC only produced 35% of the carbon emissions when compared to CC.

# Challenges of Adoption of UHPC in Australia

There has been considerable investigation and research into the material properties and use of UHPC around the world for many years. Many countries are now beginning to utilise the material in permanent construction for transport infrastructure in both new builds as well as for strengthening and rehabilitation. However, in Australia there hasn’t been significant use of UHPC since the early 2000s when the Shepherd’s Road Bridge was built in NSW. Two significant challenges or barriers to the broader adoption of UHPC relate to the development of documented technical requirements in the form of a standard and / or specification, and investment in batching plants and precasting yards suitable for the production of UHPC.

It could be argued that investment in suitable UHPC facilities by industry will only occur when clear guidance on technical requirements for the use of UHPC is provided. Therefore, the first step in enabling more broader use of UHPC in Australia is the development of clear technical requirements that are accepted by relevant government authorities and industry organisations.

The following sections will review the status of technical documents and requirements associated with UHPC around the world as well as the activities underway within Australia to develop a new section of AS5100 dedicated to UHPC.

# UHPC Standards and Specifications Worldwide

There has been growing interest in UHPC worldwide over recent years, with examples of UHPC bridges and structures emerging in Australia, North America, Europe, and Asia. To support the growing interest in the use of UHPC, many countries have developed guidelines and design rules to enable Designers and Suppliers of UHPC to utilise the emerging material. The first comprehensive design guidelines for UHPC were developed by the French in 2002. These guidelines have been revised and expended over the years, and in mid-2016, two national standards for UHPC were released in France: NF P18-4707 and NF P18-7108. These documents enable the design of UHPC elements, development of mix designs, and control and verification of the production of UHPC. The comprehensive nature of these guidelines has meant they are often adopted by other countries and form the basis for other international guidelines. However, they are not formal design standards and specifications, but rather recommendations of good practice.

Other countries that have developed guidelines or formative technical documents related to UHPC include Japan, US, Canadia, Germany, and internationally, the International Federation for Structural Concrete (fib)9 has developed a Model Code with design recommendations for use of fibres in UHPC. However, like the French standards, they are an informative document with no ‘official’ status making use of them difficult without an informed and willing asset owner. The other challenge with current international guidelines related to UHPC are they require the Designer to utilise material properties of a known UHPC mix type. There are no ‘deem to comply’ design standards where material properties are pre-described in the form of minimum characteristic values. As a result, UHPC Suppliers often drive the design outcomes. Figure 1 shows the process for development of material properties when Designer uses a pre-determined concrete mix design. Typically, the supplier of the material will continue to test and optimise the mix design until the desirable mechanical properties of the UHPC are achieved. The Designer then goes on to use the specific suite of material parameters into their design solution.

Figure 1 Process of development of the UHPC material properties using a pre-determined mix design.



## Development of a UHPC Australian Standard

In 2024, Standards Australia endorsed the establishment of a working committee to develop an Australian Standard for UHPC (sub-committee BD-090-10). The standard will from part of the AS5100 Bridge Design suite of documents, with a new section 10 dedicated to UHPC. The intent is for the Australian UHPC standard to be a formalised technical document, with minimum characteristic material properties that can be adopted by Designers with the knowledge that a range of Suppliers can achieve the nominated material parameters.

# Material Properties of UHPC

Material properties are a critical input for Designers, Suppliers and Users of materials to define and communicate the intended performance of the manufactured element. By in large, the traditional approach taken in Australia for elements like steel and concrete, is that common grades or class of material are defined with set parameters for all aspects of the material of that grade or class.

UHPC offers a different challenge, where there exists an opportunity to vary parameters within class or grades to achieve different outcomes. These differences mainly come about from varying fibre content as well as additives for the purposes of constructability or durability. Further, because UHPC is an emerging material in Australia, there are limited suppliers of UHPC and subsequently, the capability of the local market has not been tested to understand what material characteristics can be achieved in an Australian context.

The intended approach of the upcoming Australian Standard AS5100.10 is for Designers to nominate minimum characteristic values for the UHPC material properties to align with the intended purpose of the concrete element. The chosen range of material properties is reported by the Designer on the drawings and /or in the Design Report. However, to ensure Suppliers who develop innovative solutions or processes for the development of UHPC are still able to utilise their specific material parameters for the design, the upcoming Australian Standard AS5100.10 will enable both minimum characteristic values to be chosen by Designers, or specific tested UHPC developed by Suppliers as shown in Figure 2.

Figure 2 Process of development of the UHPC material properties using either minimum characteristic values or a pre-determined mix design.



The resulting material properties defined at the design stage can be used for a range of purposes throughout the life of the UHPC element. The following section describes the anticipated use of the material properties of UHPC in the design, supply, construction, and rehabilitation and strengthening phases of the element.

* **Design** – As the Designer undertakes the design process, they will need to consider the objectives of the materials being used by the various elements. These objectives will then dictate the preferred material properties which for UHPC will require the Designer to choose parameters for strength, durability and performance. As the Designer is the first user of UHPC they will have a significant influence over later users of the material. Therefore, they need to clearly consider future stages and the optimal suite of parameters they nominate for the material properties. As highlighted in Figure 2, the Designer may nominate minimum characteristic material property values for a nominated category of UHPC, or the material properties of a specific UHPC concrete mix.
* **Supply** – The supplier of the UHPC concrete mix must verify the actual material properties of the UHPC are equal to or above the values nominated by the Designer. The new AS5100.10 will outline the testing regime necessary for suppliers to verify the material properties. Supplier must also provide additional information of the mix design to inform the Contractor and Asset Owner of the UHPC element of properties and characteristics associated with the material. For example, additional information provided by the Supplier includes the mix components including raw materials, supplementary cementitious materials and chemical admixtures, special storage instructions, mixing instructions, and curing type / process.
* **Construction** – The Contractor must understand the specific characteristics of both the material properties and the mix design so they can appropriately use the UHPC material in the desired application, whether as a prefabricated section or cast in-situ.
* **Rehabilitation and Strengthening** – Over the life of the asset, it is anticipated rehabilitation and strengthening may occur due to changes in the operation of the structure. When undertaking any modifications due to rehabilitation or strengthening, the material properties are necessary to allow engineers to understand the material properties associated with the UHPC.

## Material Properties – Strength

The strength related material properties are associated with compressive and tensile strength and strain. Like with CC, the compressive strength forms the key component for defining the class of concrete (eg like CC is nominally referred to as 25 MPa, 32 MPa, 40 MPa, etc. concrete, UHPC will be class along the compressive strength eg 120 MPa, 150 MPa, etc). However, the tensile strength and strain of UHPC is highly dependent on the amount, type, size and orientation of fibre used in the concrete mix. That is, the tensile strength is not directly related to the compressive strength, but rather is highly influenced by the fibres that are added to the mix. Subsequently, the amount of steel fibre added to UHPC has found to result in strain hardening as stress is continually applied (El-Helou, Haber and Graybeal10). Specifically El-Helou, Haber and Graybeal10 found that UHPC with less than 2% steel fibre reinforcement resulted in strain hardening with a stress plateau, while UHPC with more than 3% steel fibre reinforcement resulted in strain hardening with an increase in post-cracking stress. The AASHTO11 Guide Specification depicted the two types of responses as visualised in Figure 3.

Figure 3 Idealised tensile stress-strain model for UHPC with a stress plateau (left) and an increase in post-cracking stress (right) (AASHTO11).

A diagram of a stress curve

Description automatically generatedA diagram of a straight line

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In the new AS5100.10 the full list of strength related UHPC material properties includes;

* Compressive strength and corresponding compressive strain 28 days.
* Cracking tensile strength and strain, which occurs at the onset of the formation of the first crack under uniaxial loading.
* Crack localisation tensile strength and strain, which occurs when the tensile stress continuously decreases with increasing strain.
* Modulus of Elasticity.
* Density.
* Poisson's Ratio.

## Material Properties – Durability

The durability properties of UHPC relate to the resistance of the element to long term effects which may compromise the mechanic properties and its ability to continue to sustain loading. As previously mentioned, UHPC exhibits exceptional durability properties when compared to CC. This is associated with the dense, low permeable micro-structure of the material. A key consideration for AS5100.10 will be to nominate the design life of the material. All other parts of AS5100 adopt a 100-year design life, however, many researchers have shown UHPC can easily continue to exhibit the nominated mechanical properties for over 200 to 300 years. While the premise of AS5100.10 will align with the other parts of AS5100, it should be noted that UHPC is a material that can last much longer than the 100 years.

In the new AS5100.10, durability properties are likely to consider the following elements;

* **Abrasion** – for elements which are exposed to moving objects that have the potential to be worn down (including water flow). Research shows UHPC is favourable for high abrasion resistance due to the high compressive strength, high tensile strength, small sized aggregates, the use of supplementary cementitious materials, curing conditions, and surface finishing (Pyo, Abate, and Kim12).
* **Absorption** – the low permeability of the dense concrete matrix gives UHPC a lower water absorption rate than CC. It has been estimated that the water absorption of UHPC is approximately 60 times lower than that of CC (Ullah et al.13).
* **Chloride Ion Penetration** – Pasupathy et al.4 investigated the chloride diffusion of UHPC compared to CC, and found over a 300-year design life, the concrete cover required for a UHPC element was 35 mm, while for a CC element a 150 mm thick cover was necessary.
* **Sulphate Resistance** – sulphate attacks can result in microcracks forming from expansion stress, reduce the bonding ability of steel fibres, and corrosion of the steel fibres (Yang et al14). Factors impact the resistance of UHPC to sulphate include the amount and type of SCMs, the amount of sulphate in the water and sand, and the density of the concrete microstructure. Typically, UHPC has a higher performance to sulphate resistance than CC.

## Material Properties – Time Dependent

The time dependent properties of UHPC display more advantageous outcomes than CC. Typically, time dependent parameters occur at much slower rates for UHPC and CC. Parameters that are related to time dependent aspects of UHPC material properties include;

* **Creep Coefficient** – UHPC, like CC, exhibits creep behaviour, meaning it undergoes continuous deformation under sustained load over time, however this effect is generally low compared CC.
* **Shrinkage** – while UHPC generally has lower drying shrinkage compared to CC, it can still experience significant autogenous shrinkage (shrinkage due to internal chemical reactions) due to its high cement content.
* **Thermal Expansion** – The coefficient of thermal expansion for UHPC is relatively high compared to CC, as it expands and contracts more significantly with temperature fluctuations due to its high cement content and lack of coarse aggregate.

# Characteristics of UHPC

The material properties of UHPC lead to unique characteristic which users of the materials can take advantage of. The following section outlines some of these unique characteristics and how the materials properties of UHPC enable their outcome.

## Shear Strength

The shear strength of UHPC is influenced by several factors, including fibre content and orientation, the concrete compressive and tensile strengths, addition of any longitudinal reinforcement or prestressing, shear reinforcement, and the span to depth ratio (Voytko, Calvi, and Stanton15). Depending how these various parameters contribute to the concrete behaviour, the shear strength of UHPC can range from 28 MPa to 48 MPa. However, the most significant characteristic of UHPC that contributes to shear strength is the addition of fibres, which enables stress distribution beyond the first appearance of shear cracking, and allows a more ductile failure behaviour compared to UHPC. Essentially the fibre act like micro-reinforcement that delay initiation of cracking and prevent propagation (Huang and Yao16). Therefore, it is not necessary to include any traditional shear reinforcement, as the inclusion of the fibre provides a similar response.

In the new AS5100.10, it is proposed to utilise the modified compression field theory to calculate the shear capacity of the UHPC beams. The exclusion of traditional shear reinforcement means that current shear calculations that utilise truss models with a fixed crack angle will likely not correctly predict the actual capacity of the UHPC section. The modified compression field theory allows a more advanced approach where the crack angle varies based on the loading conditions and beam span to depth ratio, and it also considers the interaction between concrete compression and tensile stresses along the crack path.

## Early Achievement of Strength

A well-known feature of CC is the hardening process which results in strength growth of concrete. Overtime, CC continues to gain strength, potentially for years after the concrete element has been cast. The industry accepted benchmark for measurement of concrete strength is the 28 day strength when around 90% of the CC strength has been achieved. The 28 day benchmark is also the mechanism used to categorise the material strength for design purposes and Designers utilise this value in engineering calculations.

In contrast, the hardening process for UHPC occurs much faster than CC. The higher percentage of silica fume and quartz flour means mechanical properties are developed faster and a high early age strength and stiffness is achieved earlier than CC (Buttignol, Sousa, and Bittencourt17).

While it is likely the new Australian Standard will benchmark against the 28 day concrete strength to align with other practices in Australia, users of UHPC have the potential to take advantage of the early high concrete strength to strip formwork or apply loading to the UHPC element. In fact, in FHWA publication “Design and Construction of Field-Cast UHPC Connections”, (Graybeal18), they recommend formwork may be stripped after the UHPC compressive strength reaches 97 MPa and if accelerators are added and/or heat applied during the curing process the strength can be achieved within 12 hours. Further, the publication suggests that permanent and/or traffic loading may be safety applied once the material reaches 97 MPa without experiencing any adverse effects.

Subsequently, the material properties that result in early achievement of strength and stiffness make UHPC a highly suitable material for cast in-situ for connection or strengthening works where occupations of a asset are limited. In the US, the use of UHPC as a deck overlay to strength the existing bridge deck is widespread.

## Fibres

UHPC can trace its origins back to the second half of the 20th century when researches looked to increase the compressive strength of concrete and developed a mix with a denser matrix (using finer materials and removing course aggregate) and lowering the water to cement ratio. This resulted in a stronger, yet brittle material with sudden failure occur at first crack formation. However it wasn’t the mid-1990s researchers experimented with fibres to increase the tensile capacity and ductility (Yoo, Banthia, and Yoon19).

The added fibres to the concrete mix act to bridge across cracks in the concrete and prevent them propagating further. With the right amount of fibres (nominally higher than 2%), strain hardening behaviour is obtained. This enables load and tensile stress to increase after cracks have occurred, when further improves the ductility of the material. The size of the fibres is reasonably small, varying in length from 6 to 20 mm and thickness of 0.01 to 0.5 mm. However, type, size and orientation of the fibres all play an important part of achieving the optimal outcome and highest tensile capacity. Currently most research into fibres in UHPC centres around steel, although polyvinyl alcohol (PVA), and polypropylene fibres are in use. Steel fibres have been more common in construction applications due to their high strength and suitability for use in fresh and hardened concrete.

Suppliers have used straight, hooked, crimped, corrugated etc fibre types. It appears the trade off in choosing the shape of the steel fibre relates to a decision between workability and strength. While deformed fibres with hooks or crimps offer a higher pullout capacity when the UHPC material is in tension, when the concrete is being mixed, the deformed fibres may

The final consideration Designers and Suppliers will need to consider when utilising UHPC is the impact the orientation and distribution of fibre will have on tensile and shear strength of the element. It is imperative the fibres are adequately distributed throughout the concrete mix to ensure consistency and confidence in the cured UHPC mix. However, Suppliers will also need to consider the orientation of fibres, particularly when considered thin sections. The French Code (NF P18-4707) introduces a parameter called the ‘orientation factor’ which enables Designers and Suppliers to achieve a higher capacity if through experimental data they can show there is alignment of the fibres in the direction perpendicular to the potential cracking plane. For global effects, like bending and shear, the French Code suggests an orientation factor of up 1.25, while for local effects, like diffusion of prestressing forces, they suggest an orientation factor of up to 1.75.

# Conclusion

The establishment of the Australian Standards AS5100 sub-committee, BD-090-10, is important milestone into the broader adoption of UHPC within Australia. When completed, AS5100.10 will offer Designers a ‘deem to comply’ technical standard that engineers can use with confidence to design, supply, construct and maintain structural assets.

The material properties that will be adopted in A5100.10 will enable engineers to take advantage of the benefits of UHPC, whether it is due to the increased strength, durability, or sustainability of the material. The new standard will include design properties and material models necessary to provide sufficient design guidance for engineers including the tensile and compression behaviour, modulus of elasticity, density, poisson’s ratio, coefficient of thermal expansion and shrinkage strain.

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| **Acknowledgments**  The authors wish to acknowledge the Australian Standards AS5100.10 BD-090-10 sub-committee. |