

## The Future of Ultra-High Performance Concrete

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### Abstract

We live on a planet with a fixed quantity of resources and a large population but growing at a reduced rate. The growing population results in significant pressure on our planet, causing extreme weather and the aging population is creating additional demand with diminishing labor supply. These factors are creating a perfect storm of increased population densities, overload of our infrastructure, exceeding capacity limits of supply chains, an increase in natural disasters and a large, growing momentum for more environmentally, sustainable, resilient infrastructure - the critically important infrastructure that provides our quality of life – clean water, sanitation, the movement and housing of people and goods.

Historically, we have solved the problems of increasing demand by expanding the capacity of our infrastructure. It has become obvious that it is unacceptable to continue providing the same solution to these problems by expanding capacity and consuming our limited resources. In a world demanding a Circular Economy, engineers play a critical role in providing new technological solutions for more sustainable, resilient and greener infrastructure to meet global needs.

New advanced materials, methods and processes are required. While Ultra-High Performance Concrete is not new, in the history of materials it is still in its early development stage and most of its potential is not yet realized or in many cases not recognized by key decision-makers.

This paper reviews the development of UHPC, presenting a future view of how material technology will address many of the world's demand for more sustainable and resilient infrastructure. The paper covers future potential UHPC products/solutions, manufacturing methods and overall market potential.

Key words: UHPC, Durability, Strength, Resiliency, Infrastructure, Market Size, Future, New Applications, Markets

### Introduction

We live on a planet with a fixed quantity of resources and a large population but growing at a reduced rate. The growing population results in significant pressure on our planet, causing extreme weather and the aging population is creating additional demand with diminishing labor supply. These factors are creating a perfect storm of increased population densities, overload of our infrastructure, exceeding capacity limits of supply chains, an increase in natural disasters and a large, growing momentum for more environmentally, sustainable, resilient infrastructure - the critically important infrastructure that provides our quality of life – clean water, sanitation, the movement and housing of people and goods.

Historically, we have solved the problems of increasing demand by expanding the capacity of our infrastructure. It has become obvious that it is unacceptable to continue providing the same solution to these problems by expanding capacity and consuming our limited resources. In a world demanding a Circular Economy, engineers play a critical role in providing new technological solutions for more sustainable, greener, resilient infrastructure to meet global needs.

This paper reviews the development of UHPC, presenting a future view of how material technology will address many of the world's demand for more sustainable and resilient infrastructure. The paper covers future potential UHPC products/solutions, manufacturing methods and overall market potential.

## What is UHPC?

The definition of Ultra-High Performance Concrete (UHPC) may be broadly defined as a cementitious, composite material that has enhanced strength, durability and tensile ductility compared to High Performance Concretes (HPC). UHPC frequently uses fibres for post-cracking ductility, having a specified compressive strength of at least 120 MPa at 28 days, and is formulated with a modified multi-scale particle packing of inorganic materials of less than 0.6 mm diameter (larger sizes can be used) [1]. The material matrix is typically manufactured from combining fine materials such as sand (< 400 microns; larger sizes can be used), ground quartz, Portland cement and silica fume (other nonorganic mineral fillers can be used). The matrix typically contains small fibres 12 mm x 0.2 mm diameter; (larger fibers can be used) in a very high dosage rate of 2% by volume (volume fractions range from 1% to 5 %). Fiber types can be high carbon steel or organic (such as POM, PVA, glass, etc). The high compressive and tensile properties of UHPC also facilitate a high bond stress and hence, a short bond development length for embedded reinforcing or prestressing. The use of fine materials for the matrix also provides a high aesthetic surface with the ability to closely replicate surface textures and finishes. The matrix provides a very dense matrix and low permeability (Chloride ion diffusion less than  $0.02 \times 10^{-12} \text{ m}^2/\text{s}$ ) to prevent the ingress of chlorides or other aggressive agents [2]. Like conventional or HPC, UHPC is a family of products with different formulations that are used for different applications. These formulations vary in raw material ingredient dosages, reinforcing and fiber types and curing conditions.

While UHPC has been under research and development globally for over a quarter of a century, it is still a relatively new material technology compared to conventional concrete [3]. The use of this technology is slowly increasing and gaining acceptance in numerous applications, such as bridges, architectural products, security, water / waste-water, building elements and others throughout the world. It is the superior mechanical properties of UHPC, particularly durability and tensile ductility that provide the benefits and reason for potential users of the technology, irrespective of the challenges of deploying this technology. The lack of UHPC specific codes and standards, a lack of understanding and comfort by the general practitioner, and a common agreement on what exactly is UHPC are some of the major factors in slowing the implementation of this technology.

Several jurisdictions have commenced the process of writing codes, standards, specifications or guides for UHPC, such as the American Concrete Institute (USA), the American Society of Testing and Materials (USA), the Federal Highway Administration (USA), the Canadian Standards Association (Canada), the Swiss Institute of Engineers and Architects (Switzerland), the French Society of Civil Engineers (France), the Japanese Society of Civil Engineers (Japan), Korean Concrete Institute (Korea), China Concrete & Cement-based Products Association (China), Scientific Technical Spanish Association of Concrete (Spain) and others [4]. The majority of these code/standards writing bodies as well as National Specifying Agencies all differ, in their respective documents, on what they consider as UHPC.

In the overall history of concrete, UHPC is still a very young material, although it has been researched for approximately 40 years and in development for nearly 30 years.

A global definition of Ultra-High Performance Concrete (UHPC) may be broadly defined as a ***“cementitious, composite material that has enhanced strength, durability and tensile ductility compared to high performance concretes and shall contain fibers or mesh for post-cracking ductility, have specified compressive strength of at least 120 MPa at 28 days”*** [4].

## Global Challenges

The world population just passed the eight billion mark, in November 2022 and according to the United Nations it will hit 10 billion around Y2050 and peak by Y2080 [5]. While the population continues to grow with increased pressure on our planet, it is growing at a slowing rate, which results in an overall

aging of society. This increasing demand (more people) with reducing supply (less working age people), creates a shortage of labor, which will drive the demand for robotics and Artificial Intelligence (AI).

A growing population generates more environmental demand on our planet and our aging infrastructure, the infrastructure that provides societies quality of life – clean water, sanitation, the movement and housing of people and goods. While it is possible to debate the direct and indirect impact an increasing population has on our climate, it is evident in recent years that the planet is having more occasions of extreme / severe weather. Severe weather events can overload the capacity of existing and aging infrastructure, resulting in deterioration and premature failure.

This combination of increasing demand, more severe weather, aging infrastructure, and reduced labor supply provides many innovative opportunities to solve these challenges (See Figure 1). While many of the solutions will be social, this paper will only address technology-based solutions for infrastructure, such as repurposing, improved resiliency and lower embodied energy.

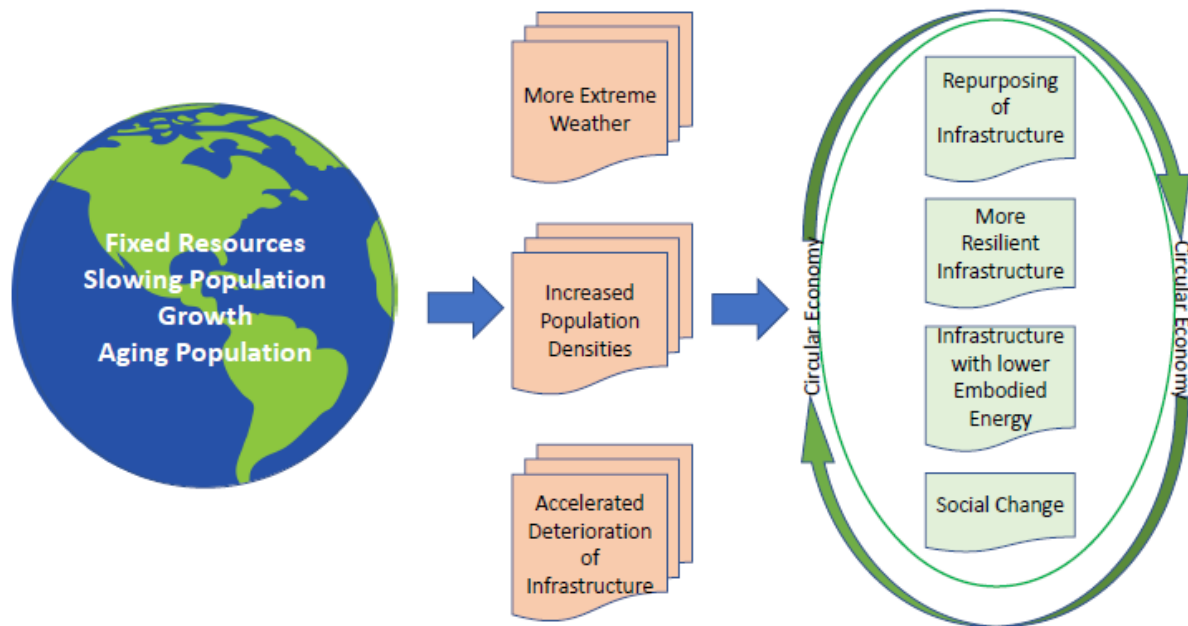


Figure 1: Global Trends; Challenges & Required Changes to Adapt

### Opportunities - Future Markets/ Applications

While UHPC has been under research, development and commercialization globally for over a quarter of a century, it is still a relatively new material technology compared to conventional concrete. New UHPC suppliers are entering the market in an ever-expanding number of countries worldwide and UHPC is gaining broader acceptance within early adopting countries, while an increasing number of new applications continue to grow. The superior mechanical properties of UHPC, particularly durability and tensile ductility provide benefits and a sound reason for potential users, irrespective of the challenges of deployment. New and complementary technologies remove barriers to entry. New complementary technologies such as 3D printing, robotics, AI and others improve the manufacturing efficiencies for UHPC applications. The adaptation of casting techniques such as spin casting, injection casting, displacement casting, extrusion and semi-rotational formworks provide Technology Synergies. With Technology Synergy, the result of a combination of complementary technologies provides a result greater than the sum of the parts ( $1 + 1 > 2$ ).

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The following is a select list of applications highlighting where UHPC's properties provide a strong advantage for traction and growth:

- Very long-span bridges > 500 ft. - The FHWA has developed a 300 ft girder design [6] and Dura in Malaysia has produced 300 ft bridges. With further optimization and post-tensioning, clear spans using UHPC will increase.
- Tall slender buildings – UHPC has been used for columns and link-beams in shear walls of high-buildings. The high strength permits more slender columns thereby facilitating higher buildings with improved floor utilization. The use of UHPC link-beams in shear walls and the improved column ductility facilitates an optimized lateral system to resist wind and seismic loadings.
- Iconic shapes – from the very early days of UHPC development, architects utilized this material to create thin, curved, perforated facades, canopies and trellis, with high aesthetic surface aspect. With the elimination of reinforcing bars, UHPC provides architects with a new freedom of design.
- Hollow poles, piles and pipes – spun-cast, vibro-compaction and gravity methods have been used to produce hollow-circular elements. High-mast tapered poles have been spun-cast in self stressing prestressed moulds.
- Off-shore floating structures – UHPC is highly suitable to resist the harsh sea environment from the salt, freeze/thaw, abrasion and risk of impact. This jacketed UHPC systems can provide the required protection for the voided floatation.
- High Security – UHPC has high resistance against terrorism or accidental impact due to its toughened matrix. The material has been used in safes / vaults, armouring of embassies and other installations requiring improved protection or security.
- Energy Grid – UHPC has been developed for power poles, cross-arms for high-voltage transmission and grillage foundations for soft soils and northern perma-frost.
- Wind turbines – for both on-shore and off-shore wind turbines, UHPC will facilitate the development by providing strong and durable solutions. Iowa State University has developed a UHPC high tower wind turbine design that can be used to achieve taller towers for turbines, thereby improving energy efficiency.
- Living Buildings – living buildings can have green rooves or walls such as shown in Figure 2 below. UHPC provides a strong, durable but light weight method to provide the structure to support the living systems.



*Figure 2: Living Building, Orlando, FL*

- High Speed Mass Transit - guide rails for Mag-Lev have been developed in Japan in the early 2000's. UHPC can also be used to produce the high abrasion resistant thin-walled tubes for Hiper-Loop. The tubes can have unbalanced pre-stressing to produce smooth gradual curvature in the tube.

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- Repair and Rehabilitation – with our aging infrastructure, the repair and rehabilitation market is a very large opportunity where UHPC can extend the service life well beyond the original intended life. This is currently one of the largest markets for UHPC, uses such as, pier jacketing, deck overlays, connections between precast bridge elements and beam-end repairs.
- Volumetric Modular Housing – with our growing population there is an immense need for the housing of people. The use of precast insulated UHPC sandwich panels with waffle deck roof and floors is a light weight and highly energy efficient method to build cost-effective housing. As opposed to the “Ikea” style precast, Volumetric is completely assembled and ready to move in when delivered.
- Most infrastructure components – the preceding list highlights some of the future uses for UHPC, however, Figure 2 provides a visual overview of the many uses of UHPC for infrastructure.

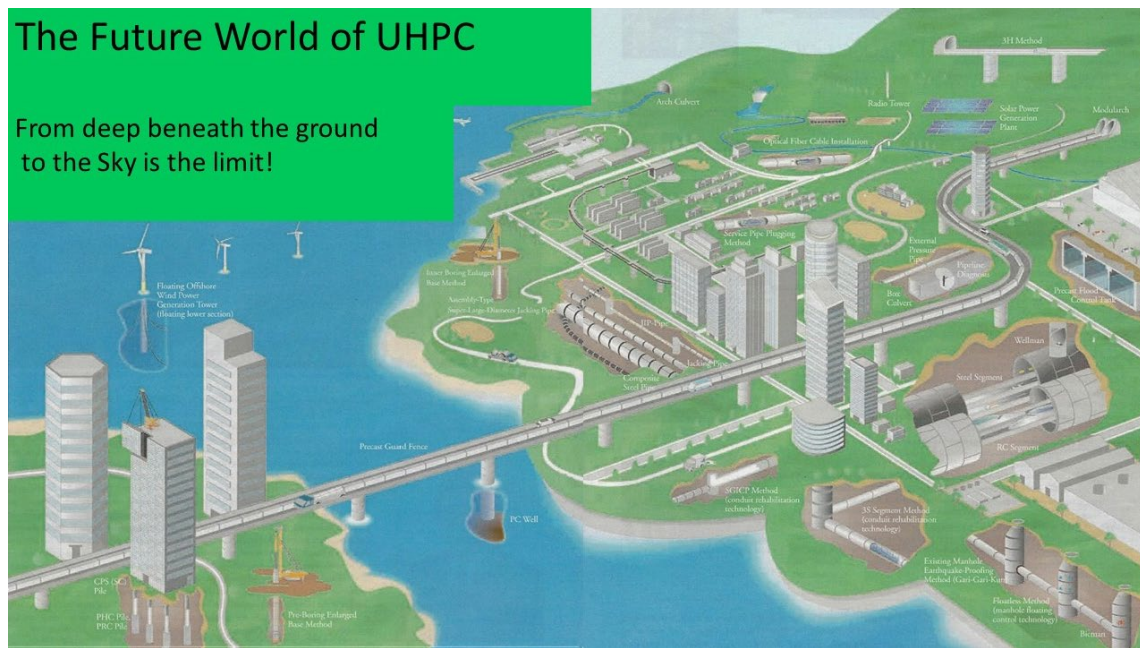


Figure 2: UHPC Applications in a Future World [7]

Many of these applications are in varying stages of development and commercialization by entrepreneurial companies. Over the next several years these innovative solutions will continue to enter the market.

**"You can't just ask customers what they want and then try to give that to them. By the time you get it built, they'll want something new."** By Steve Jobs

Most people don't even know what they want until they see it. So sometimes you have to give people what they need, not what they're asking for. This is [exactly what Jobs did](#) when he disrupted the cellphone market with the iPhone.

When trying to forecast the size of the UHPC market, taking a page from Steve Job's book will provide a fundamental understanding of how markets for breakthrough technologies develop [8]. Just like forecasting the smartphone market, who would have forecast that nearly everyone on the planet would have a smartphone, sometimes several or that smartphone technology would leapfrog land line phones to accelerate the adoption in developing countries. Even with the high cost to purchase a smart phone or large monthly subscriptions, purchasers see the value and make the purchase.

Competition and the parallel development of complementary technologies, like 5G networks, has greatly facilitated the adoption rates faster than many predicted.

In the early 90's UHPC was clearly identified as a breakthrough technology that would have a long S-curve growth (start off very slow, gather momentum with the steep growth until maturity, then level-off – see Figure 3) due to many significant barriers to entry, like a lack of codes / standards and a conservative customer base controlled by conservative professional engineers whose job is to design infrastructure while protecting the public. Additionally, it was recognized that this technology is well suited for the precast industry due to the increased control in application. The superior material properties of UHPC opened the door for optimized product shapes but was met with the need for sizeable investments in plant equipment (new formworks and batch plant modifications) which would further slow a broad-based development of the UHPC products offered to the market.

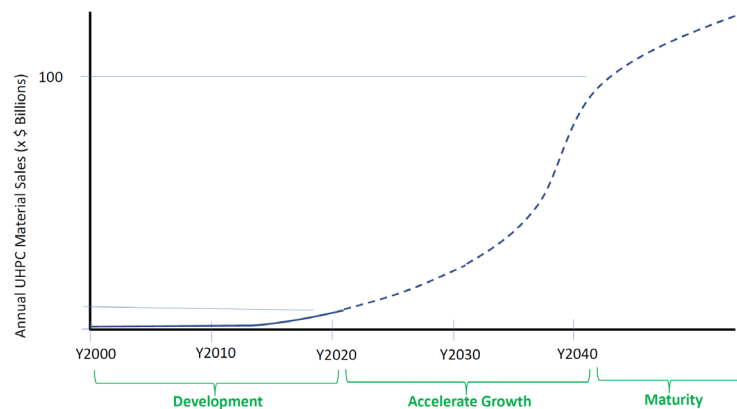


Figure 3: S-Curve for UHPC Development (Annual Sales \$-Volume vs Year).

While these “Barriers to Entry” were being addressed by industry pioneers, there were niche areas of adoption of the technology for markets like facades, iconic architecture, bridge connections between precast bridge elements and bridge overlays. While architects recognized the freedom of design provided by UHPC and used it to create iconic buildings, there was still a reluctance from precasters to fully embrace the technology due to a belief that the material unit cost was too high compared to more conventional concretes. Beyond the cost, precasters were hesitant to adopt disruptive new technology while they were operating at or exceeding full capacity; many deemed that it was not worth the risk/reward. At the same time the US Federal Highway Administration (FHWA) embarked on an R&D program on UHPC and a development program to deploy this material into highway bridges to address the deteriorating bridges in the US. This work by the FHWA provided an accelerated adoption of UHPC for connections between precast bridge elements. Recently a similar program by the FHWA has led to the use of UHPC for bridge overlays, notably the mega-projects, the Delaware Memorial Bridge and the Sumner Tunnel (Boston, MA). Many US bridge agencies are watching these two-mega projects with the anticipation of using this material on their projects. While UHPC overlays are a more recent application of this technology in the US, it has been slowly gaining acceptance in Switzerland where several hundred bridges utilized this solution. UHPC has also been developing for the past 20 years in countries such as France, China, Malaysia, Japan, and others.

Until 2015, there was a limited number of commercial suppliers for UHPC due to time and investment to develop UHPC products, patents, and a conservative industry. Since 2015 the number of new UHPC suppliers globally has increased at an accelerated pace providing competition and further innovations and optimizations on the material supply and costs.

## **The UHPC Market in Y2040**

Today, in the USA there are 85 long-span suspension bridge that are more than 50 years old in need of deck repairs, there are 400,000 state bridges structural deficient or functionally obsolete, CALTRANS has identified 6,000 bridges in need of an overlay and there are over 1,000 major tunnels. All of these structures can have their useful life significantly increased with UHPC overlays and precast solutions with UHPC connections. The quantity of UHPC required to fix these bridges is in excess of \$2 billion for just the UHPC materials alone.

As of today, the US architectural market for UHPC mass produced flat panels is mostly limited by the production capacity of only two companies (TAKTL and Envel Facades). The limited use of UHPC facades by architects on their iconic building designs is also limited by the capacity of the industry and a perceived high material cost. With the recent entry of many new UHPC suppliers with different supply chains, the lower unit price is facilitating a wider acceptance of UHPC. With only a very small portion of the façade market, UHPC facades have the potential to be \$100 million market in the USA alone.

China is another very large market where new material suppliers are entering the market and the technology is being accepted in both the architectural building and bridge market. China has many great examples of iconic architecture utilizing UHPC. China is developing new design codes for UHPC which will facilitate engineers to use UHPC in structures on a wider basis.

In the Middle East (ME) UHPC has been gaining acceptance for many iconic buildings such as the Lusail Towers which were constructed leading up to the World Cup 2022. With Saudi Arabia Vision 2030 [9] giga-project such as ROSHN, NEOM, and several others, and the interest expressed by the ME players it is anticipated the market for UHPC materials only could be as much as \$10 Billion.

Dura in Malaysia has constructed more than 200 bridges with UHPC over the past 15 years [10] and continues to gain acceptance with longer spans. Current sales of UHPC products only in Malaysia are estimated at US\$15M annually and expected to grow to \$ 50 million by 2040.

The India market has a very large pent-up demand for infrastructure and housing to meet the needs of a growing middle-class. An example is the recent announcement of the government to construct 27.2 million houses before the Indian general election in 2024. Additionally, the president of India has stated that the government will spend Rs15,000 crores (US\$ 1.8 Billion) over the next three years to deliver safe housing, clean drinking water and sanitation, education, and health and nutrition [11]. Recently there have been several new entrants of UHPC material suppliers, in India. It is expected that the UHPC market in India will demonstrate a leap-frog development and that this market could reach \$50 Billion for UHPC materials supply.

Japan has recently announced a program (Shutoko Renewal Project) to rebuild its highway infrastructure to replace the majority of its roads and bridges built over 60 years ago for the Tokyo Olympics in 1964 [12]. In Y2018 the Metropolitan Expressway Company (Greater Tokyo area) completed nearly 50,000 repairs to the aging existing concrete and steel structures. The Shutoko Renewal Program is designed to provide a 100-year service life to the replaced infrastructure, opening the door for more resilient infrastructure.

***By 2040, the global demand for UHPC materials is estimated to be \$100 billion per year, with an overall industry size of \$1 trillion annually, when the full construction industry based on UHPC construction is included.***

## Conclusions

- 1) We live on a planet with a fixed quantity of resources and a large population but growing at a reduced rate. The growing population results in significant pressure on our planet, causing extreme weather and the aging population is creating additional demand with diminishing labor supply. These factors are creating a perfect storm of increased population densities, overload of our infrastructure, exceeding capacity limits of supply chains, an increase in natural disasters and a large, growing momentum for more environmentally, sustainable, resilient infrastructure, such as UHPC. It has become obvious that it is unacceptable to continue providing the same solution to these problems by expanding capacity and consuming our limited resources.
- 2) The superior mechanical properties of UHPC, particularly durability and tensile ductility provide benefits and a sound reason for potential users, irrespective of the challenges of deployment for a new material technology.
- 3) Since 2015 the number of new UHPC suppliers globally has increased at an accelerate pace providing competition and further innovations and optimizations on the material supply and costs.
- 4) Numerous good examples of successful local deployments of UHPC have been shown. The wider based deployment of these applications will occur. It is not a case of "if" but "when". The rapid expansion of UHPC suppliers provides support for this prediction.
- 5) When trying to forecast the size of the UHPC market, taking a page from Steve Job's book will provide a fundamental understanding of how markets for breakthrough technologies develop.
- 6) UHPC is a breakthrough technology which typically has a long S-curve development growth (start off very slow, gather momentum with the steep growth until maturity, then level-off). Following 25 years of slow development growth, UHPC is just at the start of the steep expansive growth.
- 7) By 2040, the global demand for UHPC materials is estimated to be \$100 billion per year, with an overall industry size of \$1 trillion annually, when the full construction industry based on UHPC construction is included.

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