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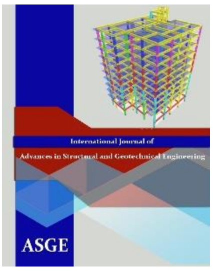

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How Practical Is Ultra High Performance Concrete for Construction Projects

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ABSTRACT

Over the last twenty years, there has been an extensive attention in using Ultra-High Performance Concrete (UHPC) in the buildings and infrastructures construction. Due to that, defining comprehensive mechanical properties and excellent durability of UHPC required to design structural members is worthwhile. It has shown great potential for the next generation infrastructure construction from the sustainability point of view. Ultra-high performance concrete (UHPC) is an advanced construction material that affords new opportunities for the future of the very special structures. This paper presents the state of the art in UHPC with regard to uses in major projects as Highway Bridge, tall building, bomb and nuclear building resistance and pavements. Compiled from hundreds of references representing research, development, and deployment efforts around the world, this report provides a framework for gaining a deeper understanding of UHPC. This article review will assist stakeholders, including many departments as State transportation departments, Army engineer researcher and multinternational companies for construction and design consultants, to grasp the capabilities of UHPC and thus use the material to address pressing needs in different major constructions. Therefore, the uses of UHPC are growing all over the world, in both fields of new construction and retrofitting. So, some application prospects of UHPC are briefly introduced in the paper, and the efforts, which have to be made to turn UHPC into a widespread 'regular' technology, are discussed. This paper aims to help designers, engineers, architects and infrastructure owners to know the capacities of UHPC and thus to increase the applications of this material. The main objective of this to enhance the capability of the business sector to innovate by focusing on long-term research base papered on forging close alliances between research-intensive enterprises and prominent research groups. The corporate partners are leading multinational companies in the cement and building industry and this paper aims to increase their value creation and strengthen their research activities. In addition, the paper addresses what needed to allow future with wider implementation of UHPC.

Keywords: UHPC, Physical, Mechanical, Chemical, Durability aspects, Mixes, Applications, Evaluation.

INTRODUCTION

Concrete, along with steel, is the most widely used material in the construction of infrastructures. (NSC), has many preferable characteristics in comparison to other construction materials, such as the abundant availability and low cost of its raw materials, its simple manufacturing technology, and its convenience in forming.

Despite of NSC advantages there is also disadvantages on long periods specially when revealed to severe environments. NSC has some serious shortcomings, such as low tensile strength, high brittleness, low specific strength, and low energy absorption at failure. Over the last few decades, the durability issues of conventional reinforced concrete (RC) have been highlighted by the observed deterioration of RC structures under severe environment [1].

One of the significant breakthroughs in concrete technology in the 20th century was the development of ultra high performance fiber reinforced concrete (UHP-FRC) or reactive powder concrete (RPC) more commonly known as ultra high performance „ductile" concrete (UHPdC) with compressive strength over 150 MPa and flexural strength over 30 MPa; and fibers added to matrix enhanced durability compared to conventional concrete [2].

Ultra-high performance concrete (UHPC) is a special type of concrete with extraordinary potentials in terms of strength and durability performance [1]. It is shown that UHPC provides a viable and long-term solution for improved sustainable construction owing to its ultrahigh strength properties, improved fatigue behavior and very low porosity, leading to excellent resistance against aggressive environment.

The special properties of UHPC cause the extensive interest in nuclear waste containment structures, high rise structures, long span bridges, walkways repair works and special structures [3 & 4]. As well as this high performance material offers a variety of interesting applications. It allows the construction of sustainable and economic buildings with an extraordinary slim design. Its high strength and ductility makes it the ultimate building material e.g. for bridge decks, storage halls, thin-wall shell structures and highly loaded columns [5]. So UHSC lead to use in a wide range of applications [1]. It is strongly believed that UHPC is well suited for the next generation infrastructure construction.

Currently, the applications of UHPC in construction are very limited due to its higher initial cost, lack of contractor experience and the absence of widely accepted design provisions. However, sustained research progress in producing UHPC using locally available materials under normal curing conditions should reduce its material cost. Furthermore, the development and wide acceptance of an UHPC design code provisions should encourage stakeholders in the construction industry to implement large scale applications. This becomes even more relevant with the more recent push by organizations [4].

Going to UHPC with strength higher than 200 MPa certainly is another big step forward. Various tests have confirmed UHPC's performance in the laboratories [5]. In fact, it is possible to produce concrete with a strength as high as 700 MPa in the laboratory many years ago. However, to reproduce it in a jobsite will be difficult in the absent of quality control in any project

Theoretically, we are able to use UHPC for daily applications, wherever high strength and durability are beneficial. The main components of UHPC which make UHPC properties special UHPC by using high-performance cement with fine quartz sand and eliminating small strong coarse aggregate, high dosage of silica fume and superplasticizer at a very low water to binder ratio can even be lower than 0.2. The reduction of the water-cement ratio results in a decrease in porosity and refinement of capillary pores in the matrix. As well as using steel fibers or polypropylene fibers to prevent brittle failure specifically for post-cracking. Fibers are also added to improve the mechanical properties. In general, with steam curing, we are able to reach strength in the range of 200 MPa or higher [6-8].

The mainly reason for studding UHPC deeply is having very high strength and performance with reducing life cycle cost on long term (maintenance and repair). The cost to repair infrastructure that has been damaged by corrosion is estimated to be approximately $22.6 billion in the United States alone [9,10] . In addition, the necessity for higher strength for the prestressed members and slender columns of high-rise buildings has motivated the recent development of higher-strength concrete mixtures [11].

In order to encourage the use of UHPC practically, it is of great significance to make UHPC to be known and accepted by more engineering and companies. In this paper a general introduction on UHPC is provided. The latest information on the definition, history, development, mix design, general properties, durability and some applications of UHPC is summarized, cost and finally ending by an evaluation [1].

In order to encourage the use of UHPC practically, it is of great significance to make UHPC to be known and accepted by more engineering and companies. In this paper a general introduction on UHPC is provided. The latest information on the definition, history, development, mix design, general properties, durability and some applications of UHPC is summarized, cost and finally ending by an evaluation.

Definition, History and Development of UHPC:

UHPC is a new generation of cementitious material with very high strength, ductility and durability. According to AFGC (French Association for Civil Engineering) recommendations [12], it is defined as a concrete with a characteristic compressive strength between 150 and 250 MPa. (Steel) fibers are added in order to achieve the ductile behavior under tension, and if possible, to dispense with the use of conventional active or passive reinforcement.

The ACI 239 developed the following definition, pending approval: “Ultra-High Performance Concrete (UHPC) is a cementitious, concrete materials that has a minimum specified compressive strength of 150 MPa with specified durability, tensile ductility and toughness requirements; fibers are generally included to achieve specified requirements” (ACI 239 2012)[13]. With appropriate combination of cementitious materials, adequate sand gradation, and incorporation of fiber reinforcement, high-range water reducer (HRWR), and curing regimes, UHPC can be produced to deliver high flowability (selfconsolidating), mechanical properties, and durability [14,15]. Typical behavior of UHPC in a uniaxial state of stress in comparison with other concrete is shown in Fig.1. UHPC is distinguished between other fiber-reinforced concrete (FRC) as a material exhibiting strain hardening in tension [16].

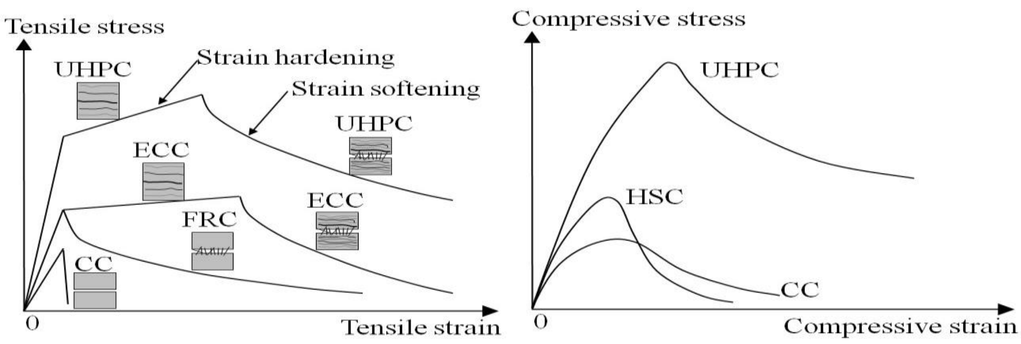

Fig.1Typical response of UHPC in uniaxial stress state compare with conventional concrete (CC), high-performance concrete (HPC), fiber-reinforced concrete (FRC), and engineered cementitious composites (ECC): (a) uniaxial tension, (b) uniaxial compression [16].

Although there is no commonly accepted definition for high-performance concrete (HPC) and ultra high-performance concrete (UHPC), it is generally recognized that these materials exhibit a combination of positive attributes, including higher strength, reduced porosity, high flowability, and improved thermal resistance. These attributes lead to improved performance in severe environments [i.e., high temperature, high relative humidity (RH), chloride and sulfate attack, and carbonation] or challenging design or construction conditions (i.e., congested reinforcements, as in bents or connections) [17,18].

Before 1980s, because of the lack of the advanced technologies, UHPC could only be prepared in the lab with some special methods, such as vacuum mixing and heat curing. At that time, researchers tried different kinds of methods to make the concrete denser and more compact, so that the strength of concrete could be improved. It was reported that the concrete with compressive strength up to 510 MPa could be prepared with vacuum mixing and high temperature curing [20]. Although very high compressive strength could be achieved, the preparation of UHPC was very difficult and energy-consuming at that time.

In the early 1980s, the micro-defect-free cement (MDF) was invented [21]. It is a type of cement paste prepared with cement and special polymers, using a very low water to cement ratio (w/c). The design principle of MDF is to re-move all the defects in the cement paste. The compressive strength of MDP could exceed 200 MPa. But, because of the expensive raw material and complicated preparation process, this material only has very few applications. In spite that MDF had drawbacks, its design principle was passed along. After the invention of MDF, DSP material (densified system containing homogeneously arranged ultrafine particles) was prepared in Denmark by Bache [22]. The defects in DSP were reduced by improving the particle parking density. Superplasticizers and micro-silica were used in this material, along with the heat and pressure cuing. The maximum compressive strength of DSP could be up to 345 MPa. With the increasing compressive strength, the concrete becomes more brittle, which is the major problem for concrete with high strength. Hence, steel fibers began to be used for preparing UHPC in the 1980s. Two good examples are slurry infiltrated fiber concrete (SIFCON) and compact reinforced concrete (CRC), which occurred after DSP, and reinforced with high volume of steel fibers. Both SIFCON and CRC exhibit excellent mechanical properties and durability. However, due to the lack of effective super-plasticizers, they both have workability problems. So they are very difficult to be used for in-situ concrete constructions. Only few cases of practical applications of SIFCON and CRC were reported, and they were only used for part of structures, such as balconies and staircases. Full-scale structural use of these materials was not realized.To sum up, in this period, the particle parking theory was firstly used for UHPC design, and silica fume (SF) and steel fibers began to be added in UHPC. But UHPCs in this stage all have their own problems, e.g. workability issues, so their applications are limited.

In the mid 1980s, HPC with compressive strength up to 110 MPa was considered for precast and prestressed structural members. Compressive strength of UHPC up to 145 MPa was demonstrated by Sobolev [23]. They made attempts to develop UHSC mixtures with locally available materials. Maroliya [24] illustrated that the greatest compressive strengths obtained were 165.6 MPa for UHSC with steel fibers and 161.9 MPa for UHSC without fibers.
Later, in the early 1980s the idea of using concrete with fine aggregate, and dense, and homogenous cements matrix to avoid micro cracks in structures, was developed. Ultra High Performance Concrete is also known as Reactive Powder Concrete (PRC). This is because of the restriction in grain size which limits the size to be less than 1 mm, and also, due to high packing density caused by the addition of various reactive or inert minerals [21]**.**

In the 1990s, reactive powder concrete (RPC) was developed [25], which is a major milestone for the development of UHPC. RPC is composed of very fine powders (cement, sand, quartz powder and silica fume), steel fibers and superplasticizer. The coarse aggregates are eliminated for enhancing the homogeneity of the matrix. By optimizing the granular packing of the dry fine powders, the compact density of RPC could be improved, which gives RPC ultra-high strength and durability. The compressive strength of RPC ranges from 200 MPa to 800 MPa. It has to be noted that, thanks to the development of superplasticizers, RPC shows very excellent workability, which is an essential requirment for the large-scale applications of cement-based materials. This is RPC's most important advantage compared with previous UHPCs.

In the late 1990s, the first marketed UHPC is ductile fiber reinforced fine grained "Reactive Powder Concrete" which was named Ductal®, was developed based on the RPC technology" produced by Lafarge in France or Densit produced in Denmark. Besides, coarse grained UHPC with natural or artificial high strength aggregates were developed, which might be used for highly loaded columns such as in extremely high-rise buildings.After that, another marketed UHPC, BSI/Ceracem® concrete, was developed by group Eiffage [19].

In 1997, the world's first RPC structure, the Sherbrooke Bridge(precast footbridge) in Canada, was built. It was the first time that RPC had been used for building a whole structure Fig.2. However, at that time, because of the high material cost, the applications of RPC were still scarce. In addition, the heat curing and the milling of quartz sand were very energy-consuming, which also limited the applications of RPC [16,19].

Fig.2 Sherbrooke prefabricated pedestrian bridge, 1997, Canada. (ACI 239 C 2015)

Other application in France, two 20.50 and 22.50 m long road bridges at Boutgles-Valence, built in 2001 [26] and the toll-gate of Millau Viaduct Fig. 3 [27].

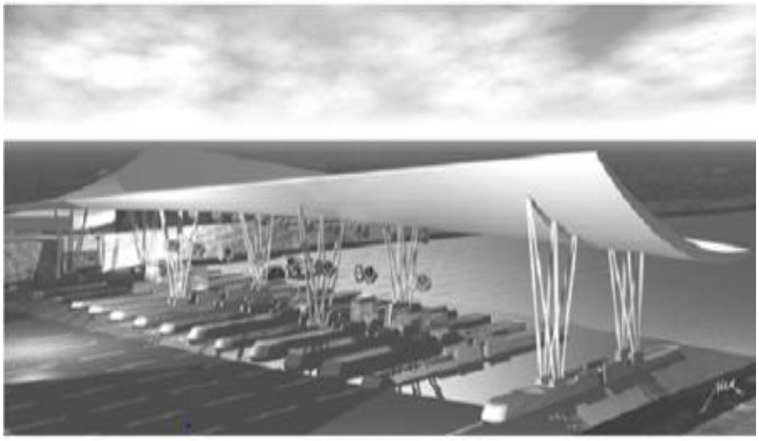

Fig.3 [27]

At the 2000s, much progress has been made on the development of UHPC. Thanks to the progress in mineral binder technology and increased availability of highly effective superplasticizers, to prepare and produce UHPC is no longer a problem. All characteristics and durability of UHPC was also widely studied. With the help of advanced material analysis technologies, the hydration process and microstructure development of UHPC also have been revealed to some extent. Many researchers have proposed numerous formulations for preparing UHPCs. The researchers' efforts were focused on decreeing the material cost and improving the sustainability of UHPC. Now, UHPC can be prepared with a relatively low material cost and energy consumption. Supplementary cementitious materials, such as fly ash (FA), slag and silica fume (SF), can be used for replacing part of cement, which could limit the usage of cement. Furthermore, UHPC can be prepared with normal temperature curing now. Because of the emergence of environmental friendly UHPC with relatively low cost, the applications of UHPC are increasing [19].

In the modern age of concrete design, concrete researchers and developers are taking advantage of secondary cementitious materials to give concrete greater strengths. One of the newest technologies to break into the concrete design arena is the use of pozzolanic nano-particles in the concrete matrix. By using pozzolanic nano-particles, the development of the strength bearing crystals of cement paste can be increased/controlled. K. Sobolev, et al. recognized that by using nano-pozzolanic materials, the strength of concrete can be increased [28].

In March 2012 the 3rd International Symposium on Ultra-High Performance Concrete and Nanotechnology for High Performance Construction Materials was held in Kassel, Germany. In their conference article [29]**,** Naaman and Wille sums of both the Advances in matrix and fibers since the 1960's Table 1 and the developments in high-strength high-performance cement composites from the 1970's in the USA and Europe Table 2.

Greater application of UHPC began around 1985, including heavily reinforced UHPC precast elements for the rehabilitation of deteriorated concrete bridges and industrial floors [5], ductile fiber reinforced fine grained "Reactive Powder Concrete" (RPC), such as "Ductal" produced by Lafarge in France or Densit produced in Denmark. Besides, coarse grained UHPC with natural or artificial high strength aggregates were developed, which might be used for highly loaded columns such as in extremely high-rise buildings [29]. Nowadays a large range of formulations exist which should be adjusted to meet the specific requirements of an individual design, architectural or construction approach.

Table. 1. Chronological Advances in the matrix and fibers since the 1960's [29].

Decade	Cementitious Matrix and Concrete	Fiber
1970's	• Better understanding of hydration reactions; gel structure; • Better understanding shrinkage, creep, porosity, ... • High strength concrete to 50 MPa in practice • Development of water reducers • Advances in concrete treatments and curing conditions	• Smooth steel fibers; normal strength • Glass fibers • Some synthetic fibers
1980's	• Increased development of chemical additives: HWRA, etc.... • Increased utilization of fly ash and silica fume, and other mineral additives, etc.... • Increased flowability (flowable concrete) • Reduction in W/C ratio; • High-Strength-Concrete terminology: up to 60 MPa; special high strength: up to 80 MPa; exotic high strength (special aggregate and curing): up to 120 MPa • High-Performance-Concrete terminology: high-strength-concrete with improved durability properties.	• Deformed steel fibers: normal and high strength • Low-modulus synthetic fibers (PP, nylon, etc..) • Increased use of glass fibers • Micro fibers • High performance polymer fibers (carbon, Spectra, Kevlar, etc..)
1990's	• Increased development in chemical additives: superplasticizers; viscosity agents; etc.... • Increased use of supplementary cementitious materials as cement replacement • UHPC: application of concept of high packing density; addition of fine particles; low porosity; lower water to cementitious ratio; • Self consolidating concrete; self compacting concrete;	• New steel fibers with a twist (untwist during pull-out) • PVA fibers with chemical bond to concrete • Improved availability of synthetic fibers
2000's	• Increased developments of proprietary and non-proprietary UHPC/UHP-FRC • UHPC: improved understanding of high packing density; application of nanotechnology concepts	• Ultra high strength steel fibers: smooth or deformed with diameters as low as 0.12 mm and strengths up to 3400 MPa • Carbon nano-tubes; carbon nano-fibers
2010's	• Increased understanding of the cementitious matrix at the nano-scale • ...???...	• Carbon nano-fibers, graphene, ... • ...???...

Nowadays a large range of formulations exist which should be adjusted to meet the specific requirements of an individual design, architectural or construction approach.

Types UHPC

Various terms are used to refer to cementitious-based composite materials with high compressive strength and enhanced durability. There are several types of UHPC can't be restricted some of them can be listed below:

1. Reactive powder concrete (RPC).
2. Ultra-high performance fiber-reinforced concrete (UHPFRC).
3. Ultra-high-performance concrete enhanced with graphite nanoplatelets and carbon nanofibers (UHPC with GNPs + CNFs)

Table. 2. Developments in high-strength high-performance cement composites from the 1970's to date (in the US and Europe) [29].

Year	f'_c [MPa]	Source/Ref.	Name	Special Conditions
1972	230	Yudenfreund, Skalny, et al.		Paste; vacuum mixing; low porosity; small specimens.
1972	510	Roy et al. (US)		Paste; high pressure and high heat; small specimens.
1981	200	Birchall et al. (UK)	MDF (Micro-Defect-Free)	Paste; addition of polymer; bending strength up to 150 MPa
1981-1983	120 to 250	Bache; Hjorth (Denmark)	DENSIT; COMPRESSIT	Mortar and concrete; normal curing; use of microsilica
1980' all	120 to 250	Bache; Young; Jennings; Aitcin (Denmark; US; Canada)	DSP (Densified Small Particles)	Improved particle packing; use of microsilica; use of superplasticizers;
1980's	Up to 120	Many researchers worldwide (Shah; Zia; Russell; Swamy; Malier; Konig; Aitcin; Malhotra)	High Strength Concrete; High Performance Concrete (HSC; HPC)	Concrete with special additives and aggregates for structural applications; use of superplasticizers; normal curing; better durability
1980's all	Up to 210	Lankard; Naaman (US)	SIFCON (Slurry Infiltrated Fiber Concrete)	Fine sand mortar with high volume fractions of steel fibers (8% to 15% by volume)
1987	Up to 140	Bache (Denmark)	CRC (Compact Reinforced Concrete)	Concrete with high volume of steel fibers used with reinforcing bars
1987	Open range	Naaman (US)	HPFRCC (High Performance Fiber Reinforced Cement Composites)	Mortar and concrete with fibers leading to strain-hardening response in tension
1991	Open range	Reinhardt and Naaman (Germany, US)	HPFRCC (First International Workshop)	Toward reducing the fiber content.
1992	Open range	Li and Wu (US)	ECC (Engineered Cementitious Composites)	Mostly mortar with synthetic fibers; strain-hardening behavior in tension
1994	In excess of 150	De Larrard (France)	Ultra-High Performance Concrete (UHPC)	Optimized material with dense particle packing and ultra fine particles
1995	Up to 800	Richard & Cheyrezy	RPC (Reactive Powder Concrete)	Paste and concrete; heat and pressure curing; particle packing
1998 and later	Up to 200	Lafarge; (Chanvilliard; Rigaud; Behloul) France	DUCTAL	90°C heat curing for 3 days; steel fibers up to 6% (commercially available)
2000 and later	Up to 200	Rossi et al. LCPC (France)	CEMTEC; CEMTEC-multi-scale	Up to 9% fibers; hybrid combinations
Early 2000	Up to 200	Many researchers worldwide (Ulm, Graybeal, Rossi)	UHPC and UHP-FRC	Many formulations based on DUCTAL
2005	Up to 140	Karihaloo (UK)	CARDIFRC	Optimized particle packing and mixing procedure
2005	Up to 200	Jungwirth (Switzerland)	CERACEM	Formulation similar to DUCTAL, larger fibers, larger aggregates
2004	Open range >150	Fehling & Schmidt (Germany)	First International Symposium on UHPC	Many formulations similar to DUCTAL with and without heat curing; with and without fibers.
2005	Open	Schmidt et al. (Germany)	Sustainable Building with UHPC	German DFG funded broader initiative (2005-2012)
2008	Open range >150	Fehling & Schmidt (Germany)	Second International Symposium on UHPC	Many formulations similar to DUCTAL with and without heat curing; with and without fibers.
2011	>150	Accorsi & Meyer (US)	UHPC Workshop	First US Workshop
2011	Up to 290	Wille & Naaman (US-Germany)	UHP-FRC	No heat curing; optimized packing; record direct tensile strength
2011			ACI UHPC Committee 239	First meeting: Oct. 2011 Also: PCI working group
2012	Open range >150	Fehling & Schmidt (Germany)	Third International Symposium on UHPC	

4. Super Heavy Nano Reinforcing Concrete
5. Heavy Reinforced Ultra High Performance Concrete
6. Self-Compacting UHP Fiber Reinforced Concrete
7. HPC with Energetically Modified cement
8. Eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures
9. Engineered Cementitious Composites
10. Steel fibrous cement-based composite (SFCBC).
11. Ultra-high performance concrete (UHPC).
12. Ultra-high performance fiber-reinforced cementitious composite (UHPFRCC).
13. Ultra-high strength concrete (UHSC).
14. Ultra-high strength cement-based composite.
15. Ultra-high strength cementitious material.
16. Ultra-high strength fiber-reinforced cementitious composite.

There are other types of UHPC with high performance properties for different purposes not only increasing strength was the target. We can clarify few types of UHPC with some details.

1-**Reactive powder concrete (RPC)**

A new approach by using ultra-fines materials supported by strong development of new admixtures open the way over the last twenty years to amazing progresses in concrete technology. The range of performances and properties that are today covered by concrete have been expanded in many directions from ordinary concrete up to ultra-high performance concrete or self-compacting concrete, etc. High-strength concrete, however, still a brittle material requiring the use of passive reinforcement [30].
Richard and Cheyrezy, from Scientific Division Bouygues in France, developed a cementitious matrix material known as RPC [25]. This UHPC exhibits compressive strength of 200–800 MPa and flexural strength of 15–20 MPa. The development of RPC is based on the principles of improving homogeneity by elimination of coarse aggregates, granular mixture optimization, application of pressure before and during setting, and enhancement of ductility by incorporating small-sized steel fibers. An ultra dense microstructure enhances the durability of RPC and reduces its permeability. Depending upon the type of aggregates used, the applied curing conditions, and the ultimate strength, these matrices were divided into two categories: RPC-200 and RPC-800. The RPC-200 matrix was fabricated by using OPC, SF, quartz aggregates (sand with particle size of 150–600 μm), crushed quartz (with 50% of the mass below 10 μm) as filler material, and SPs [31]. Steel fibers 13 mm long and 0.15 mm in diameter were also used in order to improve ductility. The RPC-800 matrix used steel aggregates as an additional constituent. The RPC-200 was moist cured at 90°C, whereas the RPC-800 was steam cured at an elevated temperature around 250°C and a presetting pressure was involved. Thus, RPC-800 is only suitable for use in precast elements [1].

Cwirzen et al. [32] RPC by applying two curing regimes: moist curing after demolding at 20°C or heat curing at 90°C for 24 h after demolding and then storing in 95% RH. The compressive strengths were between 130 and 150 MPa, and 170 and 202 MPa, respectively, for the first and second curing regimes. Elsewhere, RPC has been moist cured at 90°C by wrapping polyethylene sheets around RPC precast segments and injecting hot water vapors [33]. Compressive strength of 200–350 MPa was achieved for these RPCs. Due to its superior mechanical properties, RPC-800 can be used in some applications as a replacement for steel in mechanical parts and as an impact-resistant material [1].
A technological breakthrough took place at the turn the 90's with the development of the said Reactive Powder Concrete (RPC) [34], offering compressive strength exceeding 200 MPa and flexural strength over 40 MPa, showing some ductility. Based on the RPC initial research, the Ductal® technology was then developed [30].

The Sherbrooke Bridge in Canada, built in 1997, was the first RPC structure shown in Fig.4. The 60-m-span bridge was built with 42 m3 RPC (Ductal). Top and bottom chord members used RPC of 200 MPa strength, whereas verticals and diagonal members were built with steel tubes filled

with RPC of 350 MPa compressive strength [33]. With the higher strength of RPC, it was possible to make lightweight pre-stressed, posttensioned bridge members. Higher ductility permitted omission of the main reinforcement from the bridge members [1].
Fig. 2 shows the compressive and bending behavior of Ductal®. It can be observed that it has an ultimate bending strength, which is over twice its first crack stress and more than ten times the ultimate stress of conventional mortar. Such very high strength and consequent ductility allows to design structures without any secondary passive reinforcement and no shear reinforcement [35].

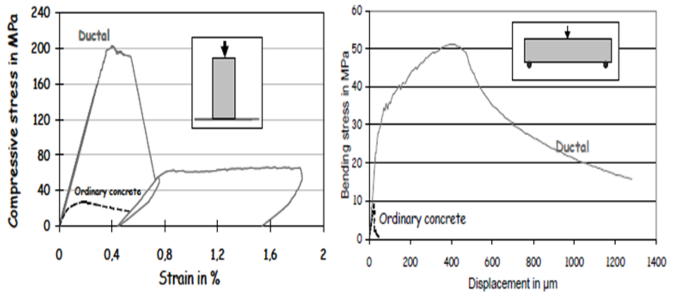

Fig. 4. Figure 11 Ductal® behaviour in compression (left) and in bending (right) [37]

2-Ultra-high performance fiber-reinforced concrete (UHPFRC)

UHPFRC is composed of aggregates, cement, water, additives, admixtures and fibres. The difference between UHPFRC and conventional concretes mix design lies in particular in the amount of binder, the size of the aggregate and the presence of fibres. Use of quite a large amount of super-plasticizers in order to obtain an acceptable workability is also a characteristic of the UHPFRC. Compared to a conventional concrete, the matrix of the UHPFRC is much denser. In order to produce this concrete, it is important to achieve the maximum possible packing density of all granular constituents[38]. This gives both improved mechanical and durability properties. The dense matrix is achieved by optimizing the packing density of all granular raw material, i.e. cement, ultra-thin addition (typically silica fume) and aggregate [39]. Fig. 5 clarifies the mix proportions by volume comparing UHPFRC with normal concrete [29].
No precise definition of UHPFRC has been found in the reviewed literature, but there seems to be a common understanding that this is a concrete with a compressive strength exceeding 150 MPa.
The following characteristics are also prevalent in the literature:[40]

- Direct tensile strength higher than 7-8 MPa
- W/B ratio lower than 0.25, and typically between 0.16 and 0.20
- High content of binder, which leads to the absence of capillary porosity
- Fibers to ensure a ductile behavior

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a breakthrough in modern concrete mix design with compressive strengths benchmarking 150 MPa and above and tensile strengths of over 10 MPa.

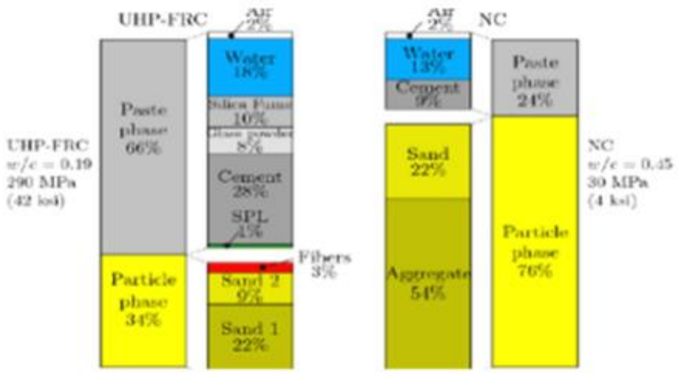

Fig. 5. Example of mix proportions by volume comparing UHPFRC with normal concrete [29]

Previous studies clearly show the advantages of using high-performance fiber-reinforced cementitious composites, such as UHPFRC, engineered cementitious composites, and slurry-infiltrated concrete, in structural members under static loading conditions [41-43].
In related study, [44] found that UHPFRC has outstanding material characteristics, such as self-consolidating workability, very high mechanical properties, and low permeability, all of which result in excellent environmental resistance. Millon et al. [45] that UHPFRC could significantly improve the impact resistance of cladding panels and walls while maintaining its standard thickness and appearance. UHPFRC is a cementitious composite reinforced by fibers with characteristic values exceeding 150 N/mm2 in compressive strength, 5 N/mm^2 in tensile strength, and 4 N/mm^2 in first cracking strength [46]. This concrete also shows compressive strengths over seven times and tensile strengths greater than three times those of conventional concrete [44]. The fibers in UHPC provide tensile capacity across cracks, resulting in high shear capacity in bending members. These fibers improve tensile strength. Parsekian et al.[45] reported that small brass-coated steel fibers with a diameter of 0.185 mm and a length of 14 mm are commonly used as reinforcements in UHPC.

Synthetic fiber and poly-vinyl alcohol have also been used [47]. The high compressive strength of UHPFRC is achieved by the densely packed state of the cement matrix, and its tensile strength is attributed to steel or polypropene fibers embedded in the matrix. The superior characteristics of UHPRFC allow its use in different applications that demand high strength and durability, including bridges, tunnels, and high-rise buildings.
Massive structures may be at risk and endanger lives if UHPFRC is not resistant to fire exposure. Conventional fiber-reinforced concrete exhibits good capacity to absorb impact energy [48].
Despite the positive characteristics of these structures, they are still susceptible to fire. Fire exposure induces temperatures of up to 1000 °C, which could be detrimental to the structural integrity of UHPFRC. Water stored in the fine pores of the dense matrix evaporates under temperature extremities, and pressure builds up internally. When stresses cannot be withstood, explosion of concrete follows, a phenomenon known as spalling. Unfortunately, spalling is unpredictable; it can occur during the heating or cooling of UHPFRC. The behavior of UHPFRC during and after fire exposure requires further study to fully understand the mechanism of failure and risks in using this concrete [49].

3- Ultra-high-performance concrete enhanced with graphite nanoplatelets and carbon nanofibers

Weina Meng and Kamal H.Khayat [50] studied the effect of graphite nanoplatelets (GNPs) and carbon nanofibers (CNFs) on mechanical properties of ultra-high-performance concrete (UHPC) were investigated. A non-proprietary UHPC mixture composed of 0.5% steel micro fibers, 5% silica fume, and 40% fly ash was used. The content of the nanomaterials ranged from 0 to 0.3% by weight of cementitious materials. The nanomaterials were dispersed using optimized surfactant content and ultra-sonification to ensure uniform dispersion in the UHPC mixture. As the content of nanomaterials is increased from 0 to 0.3%, the tensile strength and energy absorption capacity can be increased by 56% and 187%, respectively; the flexural strength and toughness can be increased by 59% and 276%, respectively. At 0.2% of GNPs, the UHPCs exhibited “strain-hardening” in tension and in flexure.

4- Super Heavy Nano Reinforcing Concrete

The purpose of A.A. Smolikov, et. al [51] work is receipt of a multicomponent high-radiation-protective extra-heavy Nano reinforcing concrete modified by additives of different functionality with advanced technological and operational properties .Using of widespread natural fiber filler - chrysotile as- a reinforcement material is largely limited to the relative complexity of fuzz commercial chrysotile -The high bond strength of reinforcing elements with the cement matrix is necessary for obtaining of high-strength concrete.
Summing up, the addition of fiber in the concrete mixture reduces its mobility and causes some difficulties in the preparation of a mixture of cement, water, aggregates and of fibrils. As Increasing the length of fibrils leads to the fact that the concrete mix is becoming more

connecting. An important problem arising in concrete reinforcing by fiber materials, is also a reduction in the workability of concrete mix to increase their content .
An optimal multicomponent mixture of concrete and the technology of preparation of high-quality heat-resistant super-heavy radiation shielding concrete nanoreinforced by chrysotile have been developed. The technical and economic performance indicators of such concretes significantly exceed similar concretes used in domestic practice [51].

5- Heavy Reinforced Ultra High Performance Concrete

The UHPC is consisting of a mixture designed for a certain application (workability, strength, density, shrinkage compensation, etc.) however due to the large experience of 20 years various standard mixes in different ranges and with different properties are available. For a HPC and an UHPC strength is not the only or necessary parameter to measure, other properties can be much more important than the compressive strength of a cube or cylinder.
Especially when durability is important than this can not be related anymore to the compressive strength of the HPC/UHPC like in more traditional concrete. The durability (chloride penetration, frost /thaw resistance) in a HPC with a compressive strength of for instance 100 MPa can be equal to that of an UHPC with a compressive strength of for instance 300 MPa. The explanation for this is that the compressive strength in HPC/UHPC is depending mainly on the quality, size and composition of the aggregates and fibers used in the concrete and not on the binder. Various researches are made to investigate the durability of UHPC under different conditions during the last 25 years and of HRUHPC under different conditions during the last 14 years [52-56]. Further properties can be influenced by the type of binder, special fibers, and special additives to control shrinkage, internal curing compounds, etc. Especially for a self levelling HPC system for thin toppings (C110 -140, thickness 10 – 30 mm) on industrial floors shrinkage control and internal curing compounds are used and this technology will possible also be applied to the UHPC.
The HRUHPC is a composite material which means that all the components (UHPC, fibers, reinforcement and other additional materials) are a part of the hardened matrix and its properties. Since thus the properties of the hardened matrix can be designed in a very wide range and are depending on the components used it is necessary to select these components very well for each application. Properties of the HRUHPC compared to HPC, UHPC and structural steel are shown in Table 3 [57].

Table. 3. Properties of UHPC, HRUHPC and Ductile High Quality Steel [57]

Properties	HPC	UHPC		HRUHPC	High quality steel
		0 - 2% fibers	4 – 12% fibers		
Compressive strength MPa	80	120 – 270	160 - 400	160 - 400	
Tensile strength MPa	5	6 - 15	10 - 30	100 - 300	500
Flexural strength MPa				100 - 400	600
Shear strength MPa				15 - 150	
Density kg/m^3	2.500	2.500 2.800	2.600 3.200	3.000 4.000	7.800
E-modules GPa	50	60 - 100	60 - 100	60 - 100	210
Fracture energy N/m	150	150 – 1.500	5.000 – 4.000	$2 \cdot 10^5$ – $4 \cdot 10^6$	$2 \cdot 10^5$
Strength/ weight ratio m^2/sek^2				$3 \cdot 10^4$-10^5	$7.7 \cdot 10^4$
Stiffness/ weight ratio m^2/sek^2				$2 \cdot 10^7$- $3 \cdot 10^7$	$2.7 \cdot 10^7$
Frost resistance	Moderate/ good	Excellent	Excellent	Excellent	
Corrosion resistance	Moderate/ good	Excellent even with 5-10mm cover	Excellent even with 5-10mm cover	Excellent even with 5-10mm cover	Poor

6- Self-Compacting UHP Fiber Reinforced Concrete

A new generation of concrete, the ultra-high strength fiber-reinforced concretes have been introduced several years ago. The company EIFFAGE began to develop this type of concrete in 1996 under the name BSI. A French and an European patent was registered by EIFFAGE respectively in 1998 and in 1999**.** Since the year 2000, SIKA has developed in the frame of a partnership with EIFFAGE a range of products based on this new technology based on similar raw materials and with very similar mechanical and durability characteristics, called CERACEM. CERACEM is both ultra-high-performance fiber-reinforced concrete and self-compacting concrete. It does not need any further heat treatment to get its design strength. It is prepared out of a premix to which during the mixing the water, a specific Superplasticizer and fibers are added in well-defined proportions. The premix is composed of a selected cement, silica fume, aggregates (0 to 7 mm) and admixtures. It is produced and controlled by SIKA [58]**.**

7- HPC with Energetically Modified cement

A new type of the cement gives possibilities to obtain required workability of the concrete mixtures with low water to binder ratios (w/B < 0.24) and achieve the strength levels up to 200 MPa with binder content not exceeding 550 kg/m3.

The modification process used in this study means a special mechanochemical treatment in vibrating milling equipment of the blend containing Ordinary Portland Cement (OPC) and silica fume (SF), which increases the surface energy and the chemical reactivity of the newly obtained binder. This results in an accelerating effect, which maintains at least for nine months.

Energetically Modified Cement (EMC) is produced by highly intensive grinding/activation of ordinary Portland cement (OPC) together with different types of fillers. Mechanical activation of mixtures containing different types of fillers involves the dispersion of solids and their plastic deformation.

EMC concrete showed rather high durability level during all testing period. Practically no scaling of the concrete has been observed. At the same time reference OPC concrete was totally destructed after about 16 cycles as shown in Fig. 6 This is in line with Bache's observations for high strength concrete with water-to-binder ration 0.25 subjected to similar testing procedure [59].

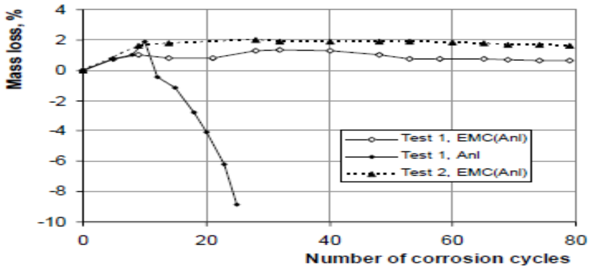

Fig. 6. Mass loss of the concrete versus number of corrosion cycles [59]

EMC cement has an important influence on the strength and structure of the hardened product:

• Ultra high rate of strength development in wide range of curing temperatures.

• Higher absolute values of strength of the cement paste and concrete, which exceed 200 MPa.

• EMC pastes have much lower porosity and more finer pore size distributions.

• The liberated heat are rapid, but it is lower per strength unit compared with the use of non-modified cement.

• The amount of total liberated heat per cement weight for EMC concrete is approximately the same as for the concrete with non-modified cement.

• EMC concrete demonstrated extremely high durability in very severe testing conditions.

8- Eco-friendly Ultra-High Performance Concrete (UHPC)

R.Yu et al. investigated the development of an eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures addressing. The modified Andreasen & Andersen particle packing model is utilized to achieve a densely compacted cementitious matrix. Fly ash (FA), ground granulated blast-furnace slag (GGBS) and limestone powder (LP) are used to replace cement, and their effects on the properties of the designed UHPC are analyzed. The results showed that the influence of FA, GGBS or LP on the early hydration kinetics of the UHPC is very similar during the initial five days, while the hydration rate of the blends with GGBS is mostly accelerated afterwards. Moreover, the mechanical properties of the mixture with GGBS are superior, compared to that with FA or LP at both 28 and 91 days. Due to the very low water amount and relatively large superplasticizer dosage in UHPC, the pozzolanic reaction of FA is significantly retarded. Finally, the calculations of the embedded CO^2 emission demonstrate that the cement and mineral admixtures were efficiently used in the developed UHPC, which reduced its environmental impact compared to other UHPCs found in the previous researches [60].

9- Engineered Cementitious Composites

Engineered cementitious composites (ECC) are a type of high-performance fiber-reinforced cementitious composite (HPFRCC) developed in the early 1990s [61]. Small synthetic fibers are used in ECC to improve its mechanical properties. A moderate tensile strength of 4–6 MPa and a high ultimate tensile strain of 3–5%, which is 300–500 times greater than that of normal concrete, are exhibited by ECC [62]. Further, ECC shows strain-hardening after first cracking, unlike ordinary concrete and conventional fiber-reinforced concrete (FRC) [62,63]. Even at a large imposed deformation, the crack widths of ECC remain small, smaller than 80 μm [64].

Mix Design

The basic concept UHPC mix

Concrete termed UHPC has relatively higher amounts of binders, a water-to-binder (w/b) ratio around 0.2 or less, and compressive strength in excess of 150 MPa. To design and develop very high strength and durability of UHPC, according to recent research, first of all, the composite porosity should be minimized. The maximum packing density should be provided by determination of suitable particle size distribution of granular components. The water-to-binder ratio (w/b) should be reduced by incorporating with high-range water reducer (HRWR).

Secondly, heat treatment and pozzolans (i.e. silica fume, fly ash, and slag) are normally employed to modify the microstructure of concrete matrix. Heat treatment can provide more energy for cementitious materials to hydrate and result in denser microstructure, and thus, increase the properties of UHPC.

Thirdly, the physical homogeneity of materials should be guaranteed. These can be secure by using high mixing energy mixer and incorporating some fine aggregate, for instance, quartz sand [16].

1-Minimization of porosity.
2-Modification of the matrix microstructure
3-Increasing the homogeneity of the material

Design is the utilization of superplasticizers to obtain workable concretes at low water/cement ratios and the incorporation of microsilica to achieve an optimal packing density of the cementitious materials [15,65]. Additionally, due to the pozzolanic reaction microsilica maximizes strength properties and impermeability of the hardened concrete, and Fig. (7 & 8) clarifies that UHPC is impermeable with nano pore size leading to very high durability properties.

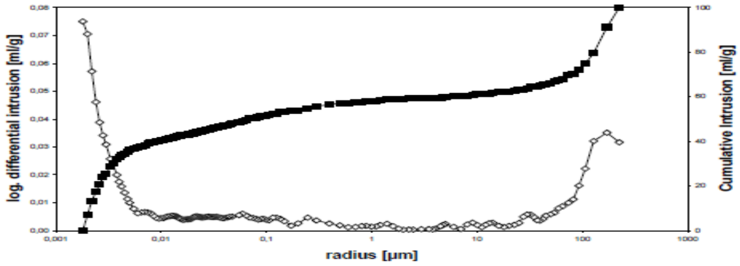

Fig.7. Mass Pore-size distribution of the internal UHPC mixture M1Q. The low total porosity and particularly the very low amount of capillary pores are the reasons for UHPC's enhanced long-term performance [66].

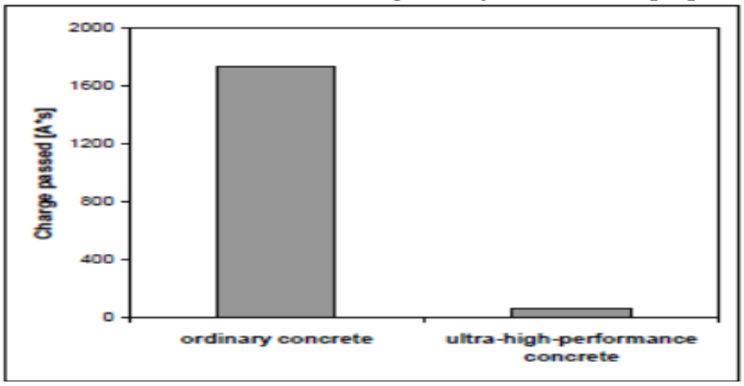

Fig.8. Rapid, the 'diffusion' front of chloride ions was visualized using a special staining method chloride permeability test [66] results for the internal UHPC mixture M1Q and normal concrete acc. EN 206.

Constituent Materials of UHPC.

The constituents of UHPC should be of very high quality because low-quality or weak aggregates will hinder not only the development of compressive strength but also the tightness of the packing density [1].

1- Cementitious materials.

A) Cement

Various types of portland cements have been used in the manufacturing of HPC and UHPC. However, ASTM Types I/II and IV (ASTM C150/C150M-17) (ASTM 2017)[67] cements are most widely used [8,18] A cement type with a low tricalcium aluminate (C_3A) content, such as ASTM Type IV (ASTM C150/C150M-17).

It has been observed in a research that a combined C2S + C3S composition greater than 65% in cement is preferred for developing UHPC (Wille et al. 2011) [73]. According to researchers [74] cement with a $d_{50} \approx 10$ µm is recommended for UHPC.

B) Supplementary Cementitious Materials

Generally, the addition of supplementary cementitious materials (SCMs) in concrete has two distinct advantages. First, they provide a pozzolanic reaction and convert calcium hydroxide (CH) to C-S-H gel, according to which has cementitious as shown in the equation below.

$$Ca(OH)_2 + SiO_2 + nH_2O \rightarrow Ca.SiO.\ nH_2O$$

properties and a less-porous microstructure compared to NSC without SCM [75], Second, due to their fineness, SCMs fill the voids of concrete mixtures, reducing their porosity.

Reduction in porosity, as mentioned earlier, enhances the mechanical (strength and modulus of elasticity) and rheological (flow and filling ability) properties of concrete by releasing the water that would otherwise be trapped in pores. Commonly used SCMs and fillers are SF, FA, quartz powder (QP), GP, ground granulated blast-furnace slag (GGBS), rice husk ash (RHA), and lime powder (LP) Fig. 9 shows the size ranges of different constituents in UHPC [73].

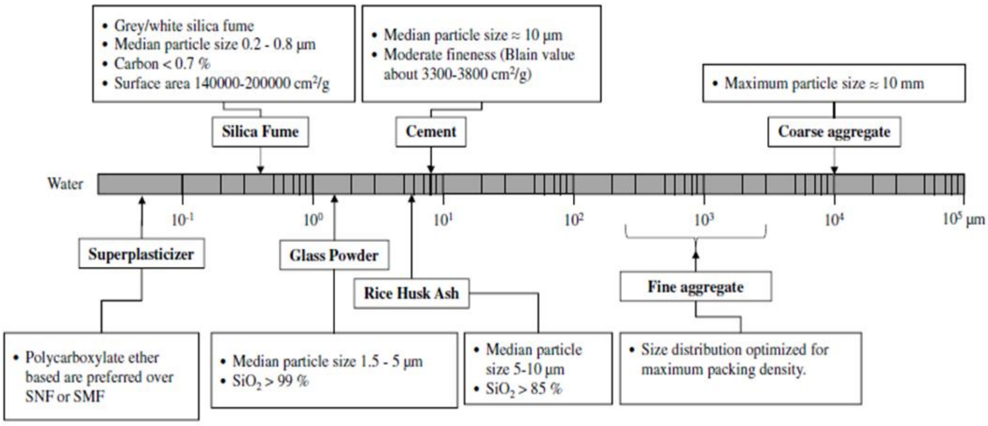

Fig. 9. Size distribution of constituents of UHPC [adapted from Materials and Structures[1,28]]

There are four mechanisms of silica fume to enhance the properties of UHPC. First, its small grain size can fill the empty spaces between the much larger grains of cement and aggregate, so that the packing density of the dry ingredient can be maximized. Secondly, the perfect sphericity of the basic particles can enhance the lubrication of the mixture. Thirdly, due to pozzonlanic reaction, the silica fume can react with $Ca(OH)_2$ to form dense C-S-H. Finally, apart from the quantitative reduction of Portlandite in mixture, the nucleation abilities of silica fume can promote the precipitation of hydration product. It is also observed that the addition of silica fume can modify the interfacial transition zone between aggregate and paste by hindrance of precipitation of large and oriented Portlandite crystals on the surface of aggregate [76]. Furthermore, the use of silica fume can change the average C/S ratio in C-S-H phase from about 1.7 to 1.2, which is beneficial with limiting the progress of corrosion, especially in the presence of alkaline ions [77]. Research has shown that low carbon content silica fume is preferred to achieve good workability [78]. In most publication, the silica fume is a required component of UHPC. However, 25% silica fume, by volume is routinely added in UHPC. The high amount of silica fume may have adverse effect on workability and the cost-effectiveness of UHPC. The optimum amount is still in desired to be investigated.

A byproduct created during the combustion of coal in coal-fired power plants, FA must be disposed of or recycled. Two types of FA are mentioned in ASTM C618-15 (ASTM 2015a): F and C, differ-entiated by their chemical composition. Two main requirements of ASTM C618-15 (ASTM 2015a) [79] for FA to be used in concrete are as follows: There must be <4% loss on ignition (LOI) and 75% of ash should be smaller than 45 μm. Type F is normally moresuitable for concrete on the basis of durability performance. Annually, 131 million tons of FA are produced by 460 coal-fired power plants in the United States alone . About one-fifth of the 690 million metric tons of rice paddy waste produced worldwide annually becomes RHA. Approximately 8.1 million metric tons of waste glass is produced worldwide [1].

GGBS as a supplementary cementitious materials, the ground granulated blast-furnace (GGBS) was also reported used in UHPC to improve its properties and cost-effectiveness [80,81]. GGBS is a glassy material from by-product of blast furnace iron-making [16].

2- Aggregates

A)Fine aggregates

Fine aggregates as sand plays the role of confining the cement matrix to add strength and replacing binder to reduce the cost of concrete. A variety of quartz sand is usually used for UHPC, under steam curing conditions records high strength than room temperature curing. However, under room temperature curing, the use of quartz sand is not economical, since the benefit of it could not be utilized. Moreover, the high cost of quartz sand is the disadvantage that restricts the wider usage of UHPC [16]. In HPC, sand finer than 250 μm is not recommended because it increases the amount of fines and, hence, increases the water demand of the mixture [1], only sand between 150 μm and 4.75 mm is used [16].

B) Coarse aggregates

Normally, coarse aggregate (e.g., diabase, basalt) smaller than 10 mm is used. In the case of UHPC, coarse aggregates are normally omitted [16], Compressive strength of UHPC up to 145 MPa was demonstrated by Sobolev [6]. This value of compressive strength was achieved by using high-performance cement and eliminating the coarse aggregate [82].

3- Fibers

Use of discrete fiber reinforcement in HPC and UHPC is a necessity given the brittle nature of the matrix. These fibers are distributed in such a way that they increase the ductility, energy absorption, resistance against delamination and spalling, and fatigue resistance of the concrete matrix [1].

Steel fibers are normally incorporating in UHPC. Current UHPC are classified into two groups according to the type of steel fiber used in UHPC matrices. In the first group, high strength smooth steel fibers with diameter less than 0.2 mm and fiber length less than13 mm, are applied in UHPC matrices [83,84]. The use of the micro straight steel fiber normally required relatively high amount (i.e. $V_f \geq 26\%$) to secure the strain hardening behavior. The large amount of fiber significantly increases the cost of UHPC. For example, 4% of fiber can be more expensive than the matrix material. Thus, from a cost perspective, the fiber volume contents should be minimized for practical application of UHPC. In the second group, relatively small amount of deformed steel fibers (i.e. hooked-end and twisted fibers) with less than 2% was reinforced in a UHPC matrix to produce the strain hardening behavior accompanied with multiple micro-cracks [73].

Many researchers have used smaller straight steel fibers 6 –13 mm long and 0.6 mm in diameter in HPC and UHPC[[69,78,85,86], carbon fibers in UHPC were also studied by some researchers [87-89] A fiber volume fraction of 1.0–2.0% is recommended by Wille (2013) based on previous UHPC mix proportion studies [73,90,91]. at recent years, researchers produced UHPC using nano carbonfibers. The flowability of concrete mixtures is affected by incorporated fibers. Nevertheless, researchers have successfully developed self-compacting HPC and UHPC mixtures with steel fibers [63]. Fibers are an essential ingredient in DSP, CRC, ECC, and RPC [1].

Sbia et al. (2014) [87] prepared UHPC mixtures by using OPC Type I, SF (mean particle size of 200 nm), ASTM C494/C494M16 (ASTM 2016) Type F PCE-based SP (ADVA Cast 575, W.R. Grace, Columbia, Maryland), silica sand (Sand 1: 0.1–0.18 mm, and Sand 2: 0.18–0.5 mm), granite gravel (3.5 mm mean, 8 mm maximum particle size), oxidized carbon nanofiber (60–150 nm in diameter, 40–100 μm long, Pyrograf III Type PR24.102 [92].

Maroliya [93] illustrated that the greatest compressive strengths obtained were 165.6 MPa for UHSC with steel fibers and 161.9 MPa for UHSC without fibers. Charron et al. [94] studied the permeability of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). UHPFRC presented outstanding hardened properties, and a highly low permeability was noticed.

4- Chemical Admixtures & W/C ratio

The invention of water reducers or SPs revolutionized the concrete industry. With high-range water reducers (HRWRs), it is possible to obtain a flowable concrete at low water content and achieve higher strengths; in other words, SPs save cement while achieving higher strengths by reducing the water content. The history of SPs is considered to have initiated in Japan and Germany in the 1960s. At 1964 in Japan the first SP was introduced; it consisted of beta-naphthalene sulfonates. Higher vibrations or compaction efforts were required for such concrete, which was a health concern for the laborers. This problem initiated the research on flowable concrete and the use of SP in concrete. The SPs that are commonly available in the market and used in concrete are lignosulphonates, sulphonated melamine formaldehyde (SMF), sulphonated naphthalene formaldehyde (SNF), and polycarboxylate ether (PCE). These admixtures are available in liquid form with around 40% solids content and a specific density of 1.06 [1,15]

Finally, In HPC water to cement ratio ranges usually between 0.28 and 0.38. Allena and Newtson [95] reported that the water to cement ratio in ultra-high performance concrete can even be lower than 0.2.

UHPC Mix Design Development (state of art)

It is important for potential developers to know what type of ingredients they should look for. The following paragraphs describe the type of materials most commonly used by selected researchers to cast HPC and UHPC. In this section several state-of-the-art mixture proportions of UHPC (**Figs. 10 and 11**) are presented [1].

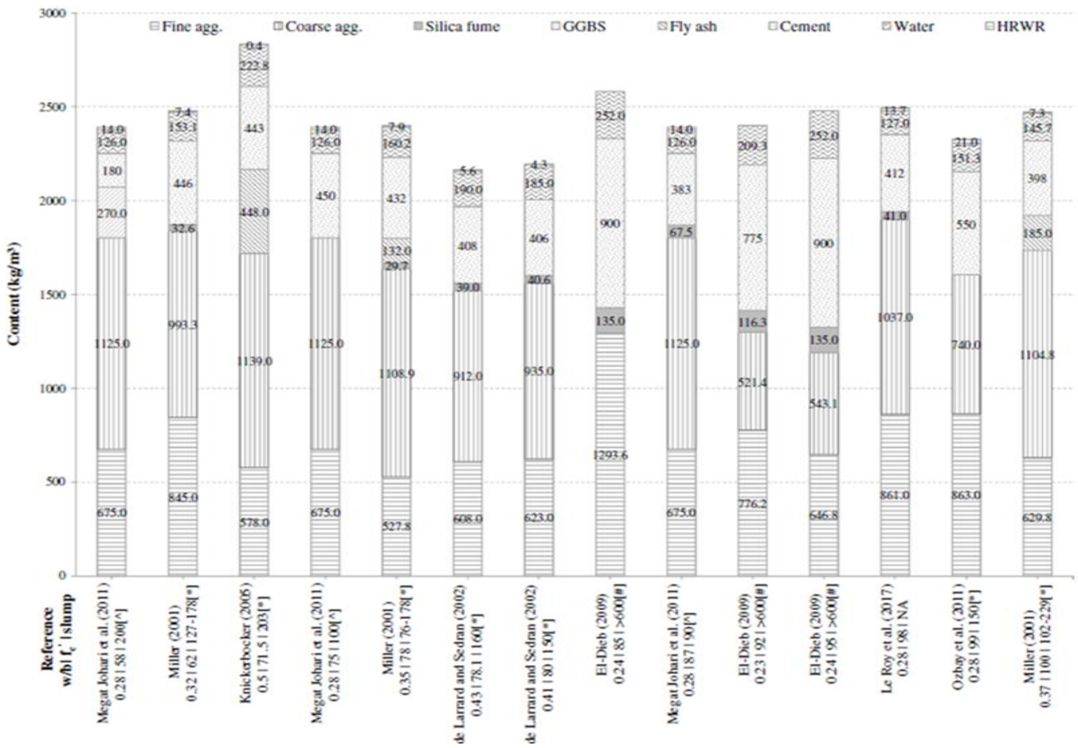

Fig. 10 Materials and mixture proportions of UHPC: reference, w/c, compressive strength (f'c), and slump presented below each mixture; % fiber content shown in box on top [1].

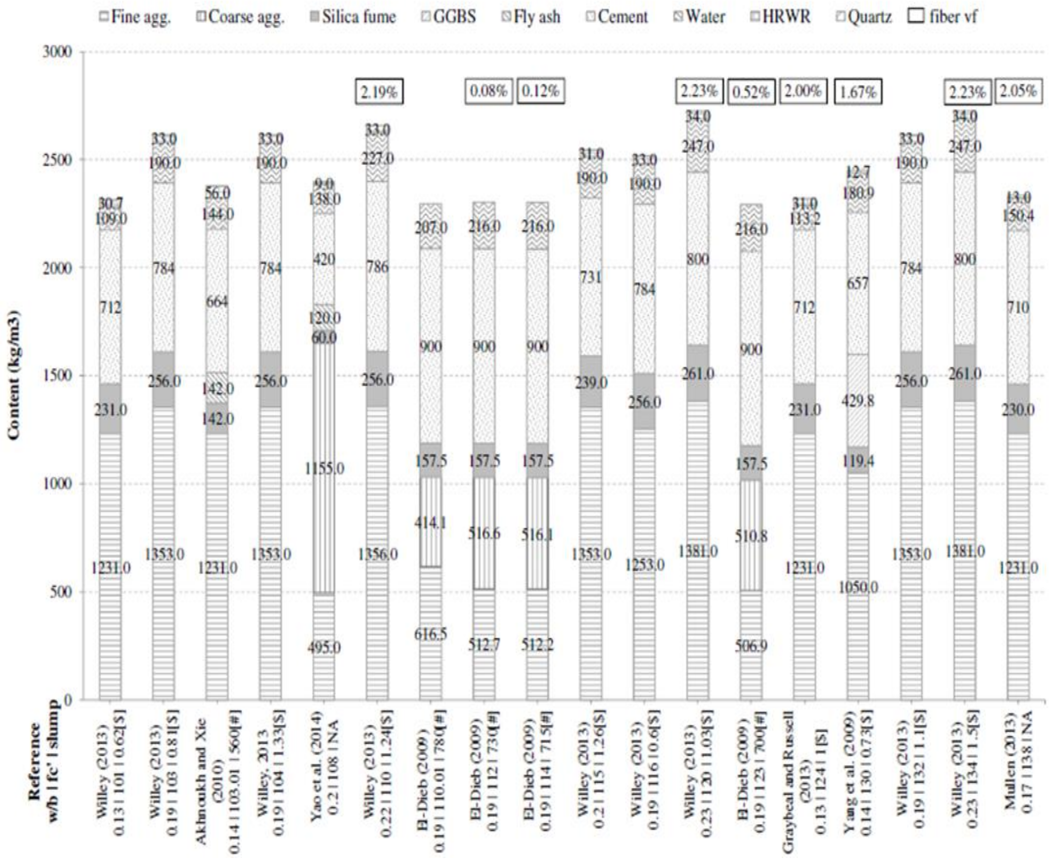

Fig. 11. Materials and mixture proportions of UHPC: reference, w/c, compressive strength (*f*'c), and slump presented below each mixture; % fiber content shown in box on top [1]

According to the American Coal Ash Association (ACAA), in 2005, 71 million tons of FA was produced, out of which 29 million tons (41%) was used in the concrete industry. By 2014, production had decreased to 50 million tons and 23 million tons (46%) of FA was used in the construction indus-try in different roles, such as in concrete, grout, structural fill, and embankments (ACAA 2015). Hence, using these materials as fillers or pozzolans in concrete also has a positive environmental impact [96].

It is understood that the resulting composite has a very high packing density, leading to significantly higher durability compared to conventional concrete, and it may incorporate discontinuous fibers, leading to significantly higher ductility and durability of the cracked matrix due to smaller crack widths [91]. For concrete named UHPC has relatively higher amounts of binders, a water-to-binder (w/b) ratio around 0.2, and compressive strength in excess of 150 MPa [1].

To reduce the entrained air in the pastes, vacuum mixing was adopted. For mixing, a two-compartment chamber was used, one filled with cement and lignosulfonate, the other filled with water mixed with potassium carbonate. The air was exhausted from the chamber. The maximum compressive strength of 25-mm paste cubes at 1 day was 96 MPa, at 28 days it was 204 MPa, and at 180 days it was 250 MPa [97], studied the effects of initial porosity, w/c ratio, type of cement, and curing conditions on the strength of cement pastes. Pressures of 45, 206, and 420 MPa were applied to cement paste cylinders of 3.2 cm in diameter and maximum 28-day com-pressive strengths of 235, 313, and 333 MPa, respectively, were found. The w/c ratio was varied from zero to an optimum value. The optimum w/c was defined as, for a given pressure and applied time, water would not be pressed out of the cement paste. A linear relationship was observed between initial porosity and compressive strength. Results showed that initial porosity was lower in samples pressed at optimal w/c than in those molded in dry form (zero w/c ratio). With increasing molding pressure, initial porosity decreased. **Fig. 12** shows that at a given maturity, there is a linear relationship between compressive strength and porosity. The extrapolation of obtained straight lines gave a theoretical compressive strength of approximately 490 MPa for pastes having zero porosity [98].

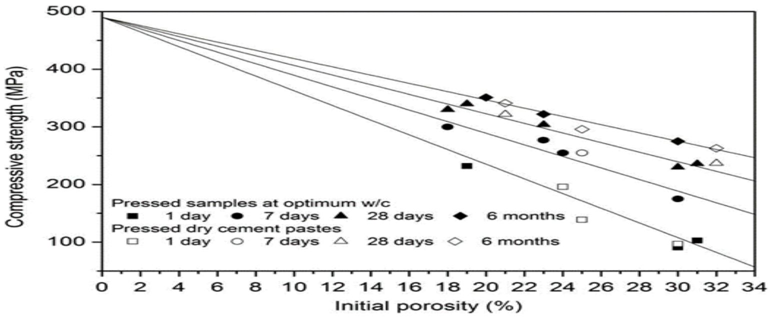

Fig.12. Strength-porosity relationship of pressed and dry cement pastes at different ages (data from Bajza 1972) [98].

It was observed that a linear plot expresses the existing strength-porosity relationships most accurately. Rößler and Odler [99] reported that, at equal porosity, the strength of the samples prepared under pressure was distinctly lower than that of those prepared by simple casting. Pressure applied on fresh concrete removes the voids (entrapped air) and organizes the ingredients in a densely packed structure; hence, it increases the strength of the hardened concrete. Thus, the methods adopted to prepare cement paste specimens also influence their strengths. Kolias (1994) [100] studied the compressive strength of 70 cubes against total porosity, and a linear relationship with total porosity was observed [101], the effect of higher porosity on the strength of lime-pozzolan mortars used to repair old monuments, and reported the same trends.

After several decades of development, one of the most popular approaches to prepare UHPC is: High quality cement + supplementary cementitious materials + low w/c or water to binder ratio (w/b) + fine aggregates + superplasticizer + steel (or organic) fibers. The key principle is to improve the homogeneity and packing density of the mixture. The homogeneity of the mixture could be improved by eliminating the coarse aggregates, which results in a more uniform stress distribution when loaded. The packing density could be maximized by optimizing the particle size distribution of raw materials. Thus, smaller particles could fill the voids between the bigger particles. Due to the low w/b and the pozzolanic reaction of supplementary cementitious materials (especially SF), UHPC could attain a very dense micro-structure and thus excellent performance. The addition of steel fibers helps to improve both the tensile strength and ductility of UHPC [19].

Reda et al. (1999) studied the microstructure of HPC and UHPC. The mixture included OPC, SF, and SP. Limestone or calcined bauxite was used as coarse aggregates and silica sand was used as a fine aggregate. To improve the fracture toughness and other mechanical properties, Panex polyacrylonitrile (PAN)-based microcarbon fibers 3–6 mm long (Zoltek, St. Louis, Missouri) were incorporated. All the concrete samples were cured at 50°C and some concrete samples were also cured under pressure to remove air voids. The achieved compressive strength was 150 MPa without fibers and 210 MPa with carbon fibers. Very dense microstructures were observed as compared to ordinary concrete; the large chunks of CH present in ordinary concrete were absent; and the pozzolanic reaction of SF was observed to convert these CH crystals to C-S-H gel. The carbon fibers were covered with such dense gel that it provided a better bond between the fibers and the cement paste [102].

Graybeal 2006 reported the results of different curing conditions on Ductal (UHPC) by Lafarge (Paris, France) with OPC, SF, find sand, ground quartz, SP (Glenium 3000 NS, BASF, Florham Park, New Jersey), accelerator (Rheocrete CNI, BASF, Florham Park, New Jersey), and 2% by volume steel fibers (0.2 mm in diameter, 13 mm long). Four different curing conditions were studied [24]:

(1)steam curing at 90°C and 95% RH for 48 h after demolding,(2)curing in an ambient laboratory environment from casting until testing, (3) steam curing at 60°C and 95% RH for 48 h after de-molding, and (4) steam curing at 90°C and 95% RH for 48 h start-ing 15 days after casting. The average compressive strengths were193, 126, 174, and 172 MPa, respectively, for each of these curing conditions.

Wong and Kwan (2008) presented a threetier system to obtain higher packing densities for concretes. They proposed to calculate the wet packing density of cementitious materials cement, SF, fly ash (FA), etc.] instead of the dry packing density. This was done to remove the strong electrostatic and surface forces in the fine grains. To overcome these forces, water was added to the cementitious materials to reduce flocculation and the measured packing density was higher. The basic concept is to divide the concrete mix into three tiers with increasing particle size ranges. First, the cement paste (cementitious materials + water + SP) is prepared. Then, the mortar (cement paste + aggregate particles smaller than 1.2 mm) and the final concrete mix (mortar + aggregate particles larger than 1.2 mm) are attained. The packing density is maximized at every stage. The bulk density of powder material less than 100 μm largely depends on compaction. Additionally, direct methods of measuring packing density may give erroneous results because the air entrapped in cementitious materials is neglected [103].

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The three-tier system measures the wet packing density of cement pastes because in concrete the densest pastes are actually more important than the packed dry cementitious material. This model also takes into account the addition of SPs and water in achieving the maximum packing density of cement pastes.

Tuan [104] compared the composition and properties of normal strength concrete (NSC), high strength concrete (HSC) and UHPC. Details are shown in Table 4. Normally, UHPC has higher cement content, lower w/b and no coarse aggregate. Depending on the specific application, coarse aggregates are sometimes used, as well as a variety of chemical and mineral admixtures .

Table. 4 Examples of composition and properties of NSC, HSC and UHPC [104]

	NSC	HSC	UHPC
Component (kg/m^3)			
Portland cement	<400	400	600–1000
Coarse aggregate	≈1000	900	-
Sand	≈700	600	1000–1200
Silica fume	-	40	50–300
Reinforcement/Fibers	designed	designed	40–250
Superplasticizer	-	5	10–70
Water	>200	100–150	110–260
Other parameters			
Maximum aggregate size (mm)	19.0–25.5	9.5–12.5	0.15–0.6
w/c ratio (by weight)	0.40–0.70	0.24–0.38	0.14–0.27
w/b ratio (by weight)	-	<0.28	<0.27

Yoo et al. (2013) prepared a mixture of UHPC mixture with fibers by using OPC (CEM I), SF, fine sand (≤0.5 mm), fillers of size 2 mm having 98% SiO_2, and no coarse aggregates. To improve workability, PCE-based SP was added. After demolding, the specimens were cured at 90 2°C for 3 days. The highest compressive strength was found to be 207.2 MPa for specimens with 3% steel fiber (0.22 mm in diameter, 13 mm long) content by volume. The effects of the volume fraction of fiber on load-carrying capacity, elastic modulus in compression, flexural strength, and deflection capacity were investigated. The capacity and elastic modulus in compression were improved with an increase in fiber content up to 3%. A modulus of elasticity of 52.7 GPa was found for 3% fiber content for these UHPCs; the samples with 4% fiber content exhibited the lowest compressive strength and modulus of elasticity, which was attributed to the less homogeneous mixture obtained with the higher fiber content [105].

Alkaysi and El-Tawil 2015 used cement, SF, two types of fine sand, HRWR, and 1% steel fibers (by volume) to prepare the UHPC mixtures. The 28-day compression strength was greater than 180 MPa [106].

Azad and Hakeem 2013 designed UHPC using OPC Type I, fine sand, SF, SP (Glenium 51, BASF, Florham Park, New Jersey), and 6.3% steel fibers (0.15 mm in diameter, 12.7 mm long) by weight of UHPC. The mixing time was about 14 min, and the mix-tures were first heat cured at 90°C for 2 days, then moist cured in-side molds until 28 days before testing. Researchers achieved a UHPC with a 28-day compressive strength of 160 MPa, a direct tensile strength of about 12 MPa, and flexural strength of 32 MPa [107].

Wille 2013 carried out research on the development of a cost-effective nonproprietary UHPC to be used for highway bridges. Several concrete mix proportions with 12 different types of cements, 5 types of SF, 13 types of SCM, 8 types of HRWR, and 5 types of steel fibers were tested. The recommended UHPC mix proportions used portland cement Type II/V, gray SF, Class C FA, Premia 150 HRWR, fine basalt aggregates, and Nycon straight steel fibers. The recommended UHPC mix cost about \$983=m^3 (half of the cost was due to steel fibers), and achieved compressive strength from 155 to 200 MPa and tensile strength above 5 MPa [18].

Willey 2013 conducted a series of trials to obtain a proper mixture design for UHPC and a curing method. Portland cement of ASTM Type I, Type I/II, Type III, and Type V (ASTM C150/C150M-17) (ASTM 2017), Lafarge cement, SF, fine sand, ground quartz, a SP, an accelerator, and steel fibers were used in the mixes [18].

Three curing methods were used: (1) placing a wet ragon top of freshly cast specimens at room temperature for 24 h, demolding, and further curing in a moist room until testing; (2) sub-merging the freshly cast specimens into a room temperature lime water bath for 24 h, demolding, and curing specimens in a moist curing room until testing; and (3) submerging the freshly cast specimens in a room temperature lime water bath for 24 h, demolding, curing in a 90°C hot water bath for 72 h, and then keeping in a moist cure room (~23°C, >95% RH) until testing [. Researchers tested flow and compressive strength at 4, 7, 14, and 28 days. Results showed an increase from 60 to 133% in ASTM C1437-15 (ASTM 2015b) flow (the flow is defined as "the resulting increase in average base diameter of the mortar mass, expressed as a percentage of the original base diameter") and 60–154 MPa in 28-day compressive strength. It was shown that the third curing method yielded the highest concrete strength [18].

Mixing Procedures

In preparing UHPC, the mixing time, mixing speed, temperature, and mixing sequence should be carefully considered to obtain the desired properties [108]. Because HPC and UHPC have much smaller-sized ingredients than conventional concrete, a different procedure for mixing is adopted that ensures the breakage of agglomerated small particles and a homogenous dispersion. Compared to that for conventional concrete, a higher energy is required during the mixing of HPC and UHPC; hence, the mixing time needs to be increased. Due to increased input energy, large amounts of cementitious materials, reduced or omitted coarse aggregate, and low water content, HPC and UHPC may overheat. Therefore, modified mixing procedures are required that avoid overheating [26]. Different researchers adopted specific mixing protocols to achieve a homogenous mixture. Wille et al. (2011c) mixed all dry ingredients first before adding water and HRWR [100]. Other researchers studied the influence of SP addition time on the properties of fresh UHPC [7,109]. The SP was added to the UHPC in two different ways: direct addition and stepwise addition. An enhancement in dispersion and flowability was observed with the stepwise addition of SP.

Mixing procedures used by different researchers are summarized in Tables 5a & 5b. The mixing procedure is clearly more involved for UHPC mixtures than for conventional concrete.

Table. 5a Summary of mixing procedures [1]

Reference	Procedure	Mixer	Flow (mm)	f_c' (MPa)
Wille et al. (2011c)	1. Dry mix sand/aggregate and SF for 5 min. 2. Add cement and supplemental material, mix for additional 5 min. 3. Add 1/3 of HRWR to water. 4. Add water-HRWR mixture within 1 min after pouring is started. 5. Add remaining HRWR within 1 min after pouring is started. 6. Increase mixing speed. 7. Add fibers if applicable. 8. Continue mixing until fluidity is optimized (between 5 and 10 min).	60-L horizontal pan mixer (60 rpm)	910[a]	210
Ma et al. (2002)	1. Dry mix all materials using intensive mixer for 2 min. 2. Add water and SP and mix about 6 min. 3. Continue mixing until flowing and homogenous concrete is formed.	Intensive mixer	710[a]	166
Long et al. (2002)	1. Mix dry ingredients at low speed for 1 min. 2. Add 1/2 quantity of mixing water containing SP and mix for 2–3 min at low speed. 3. Add remaining SP and water and mix for more than 2-3 min at high speed.	Coupled speed mixer (Chinese Standards GB/T 1346-89)	200[b]	208

UHPC Properties

1- Physical properties

The recent target of researchers is to produce UHPC with very dense pore less microstructure, and packing density can be improved indirectly by using a flow cone test. In order to improve packing density (and thus compressive strength), the amount of water is kept constant and the flowability of the paste is increased by optimizing the ingredients of concrete [90]. The optimized proportion of cement, silica fume (SF), filler material like fine glass powder (GP) (with particle size between that of cement and SF), and fine sand (with a grain size distribution selected for maximum bulk density) could be achieved by a flow cone test.

A) Strength-Porosity Relationship for Concrete

Papayianni and Stefanidou (2006) studied the effect of higher porosity on the strength of lime-pozzolan mortars used to repair old monuments, and reported that the pore structure of UHPC is characterized with the absence of capillary pores and lower total porosity. The fine pore structure is the reason why UHPC has a particularly high resistance to chloride penetration, carbonation and freezing-thawing attack [101]. Another aspect of the microstructure of UHPC is the pore structure, i.e. pore size distribution and the total porosity. Fig.13 shows the pore size distribution of UHPC, HPC and NC, tested by mercury intrusion porosimetry (MIP). It can be seen that, compared with HPC and NC, the main features of UHPC pore structure are the absence of capillary pores and lower total porosity. The fine pore structure is the reason why UHPC has a particularly high resistance to chloride penetration, carbonation and freezing-thawing attack [110]. As a result, the sxtremely high resistance e.g to chloride diffusion is shown in Fig.14.

Table. 5b Continue Summary of mixing procedures

Reference	Procedure	Mixer	Flow (mm)	f'_c (MPa)
Sbia et al. (2014)	1. Mix cement, SF, sand, and gravel at low speed for 5 min. 2. Mix at low speed for 1 min and add water and dispersed nanomaterials. 3. Mix at medium speed for 2 min. 4. Mix at high speed for 2 min, after adding steel fibers.	Hobart Model A200F	200^b	150
Willey (2013)	1. Mix dry materials for about 10 min, until homogenous mix is achieved. 2. Add 3/4 of water and SP, mix for about 20 min. 3. Add remaining water and SP, mix for about 40 min.	Hobart mixer (19 L)	250^b	156
de Larrard and Sedran (1994)	1. Prepare mortars by adding water and 33% SPs to SF and mixing using three-speed mixer until homogenous slurry is achieved. 2. Add cement with additional 50% of SP. 3. Add sand and mix for 1 min at high speed. 4. Complete mixing with addition of remaining 17% SP and mixing for additional 1 min at high speed.	Conventional three-speed mixer (blender)	—	235.8
Deeb et al. (2012)	1. Dry mix coarsest constituent (coarse aggregates) and finest constituent (SF). 2. Add next-coarsest (sand) and next-finest constituents (cement) into first mixture. 3. Mix constituents for 2 min before each addition and continue until all dry materials are added. 4. Mix 2/3 of total amount of SP with water. Add 1/2 this liquid solution to dry constituents and mix for 2 min. 5. Add remaining 1/2 water-SP solution and mix for additional 2 min. 6. Continue this process until all water-SP mixture is added: about 10 min. 7. Add remaining 1/3 SP and mix for 2 min.	Planetary mixer	910^a	162
Sobuz et al. (2016)	1. Mix all dry components (cement, silica fume, and aggregates) for 1 min until well combined. 2. Add water and SP, mix until concrete is visibly flowable: between 7 and 35 min depending on total water content. 3. After concrete starts to flow, add fibers and mix for additional 5 min.	Pan mixer (80 L)	773^a	158
Tafraoui et al. (2009)	1. Mix dry powders at low speed for 2 min 2. Add water and 1/2 SP and mix at low speed for 3 min. 3. Add remaining SP and mix at low speed until start of fluxing. 4. Add fibers and mix at high speed for 1 min.	Mortar mixer (10 L)	—	192

Porosity can be measured by ASTM C1754/C1754M-12 (ASTM 2012) or RILEM CPC 11.3 (RILEM 1994).

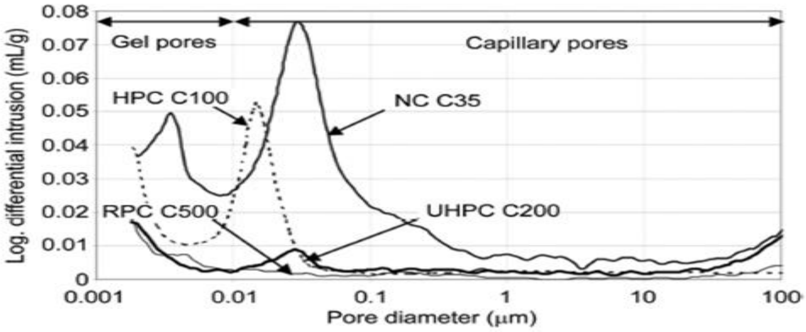

Fig.13. Pore size distribution of UHPC, HPC and NC [110].

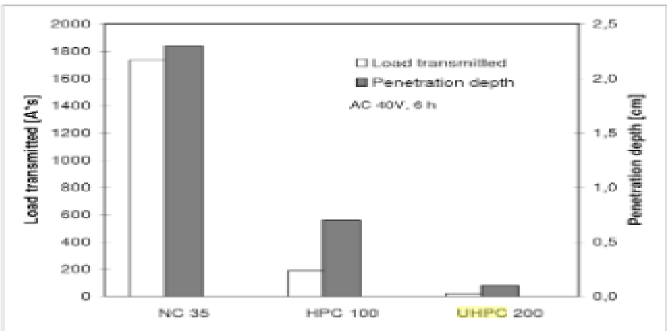

Fig.14. Chloride diffusion values of UHPC, HPC and Normal strength concrete [110]

Finally, Capillary pores and air voids adversely affect the strength and durability of concrete, particularly when they are interconnected [72].

B) Thermal properties

The thermal expansion coefficients of UHPC measured by various researchers are in the range of 10 to 15 μm/m/K. In the French Interim Recommendations [12], 10.4–11.8 μm/m/K have been recorded as the general value. This value is in the same range as for normal concrete of about 11.0 μm/m/K .

2- Mechanical properties

Table 6. summarizes the mechanical properties of UHPC for designing purpose, based on the reviewed studies and comparison of different paper results [111].

Table. 6 Summary of UHPC mechanical properties [111]

Characteristic	Property
Compressive Strength	It depends on the percentage of fiber reinforcements in UHPC. For the designing purpose, using 18 and 24 ksi as 28-days age UHPC were recommended for the steam-cured and air-cured condition, respectively.
Tensile Strength	Its range is between 0.9 and 1.3 ksi. Using the following equation was conservative. $f_{ct} = 6.7\sqrt{f'_c}$
Modulus of Elasticity	$E(psi) = 46{,}200\sqrt{f'_c}\,(psi)$ or 7,300 to 7,500 ksi for 28-days age UHPC
Strain at peak compressive strength	Its range is between 0.0035 and 0.004. Using 0.0032 was recommended.
Density	Its range was between 155 lb/ft^3 and 160 lb/ft^3.
Poisson's ratio	0.2

As shown in **Table 6**, the UHPC has unique properties and high density in comparison with conventional concrete.

A) Compressive strength

Compressive strength is an important property in the design of any concrete structure. The typical compressive strength of UHPC is in the range of 150 to 250 MPa. UHPC shows a linear elastic behavior until about 70% to 80% of the compressive strength.
The failure of UHPC without fibers is of explosive nature. There is no descending branch in the stress-strain-diagram as shown in Fig. 15. The addition of fibers could improve the compressive strength of UHPC. A typical stress-stain curve for UHPC is shown in Fig. 16. Due to the crack-bridging effect of the fibers the curve has a descending branch. The range of the possible descending de-pends on the fiber content and fiber orientation [112].

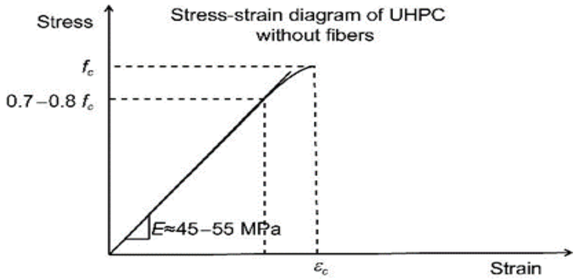

Fig. 15 Compressive stress-strain-diagram of UHPC without fibers [112]

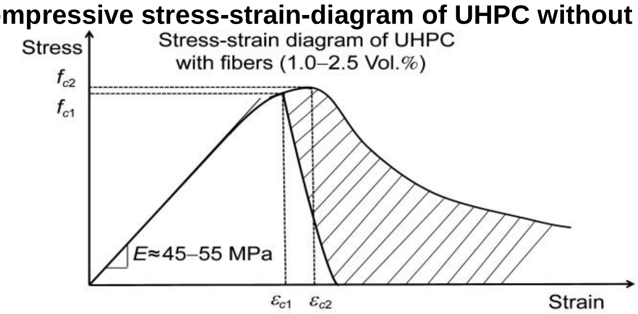

Fig.16 Compressive stress-strain-diagram of UHPC with fibers [112]

The compressive strength of UHPC is one of the important features that are necessary for designing a member. As UHPC has different ingredients from typical concrete, it may show different behavior, especially due to the steel fibers content. Based on the research by Aaleti, Petersen [113], the 28-days compressive strength of UHPC (f'_c) depends on the curing type process. It was defined that for steam-cured and air-cured conditions, the compressive strength of concrete should be considered 24 ksi and 18 ksi, conservatively. It is even much stronger than epoxy grouts that are used in bridges cast-in field joints, and pourbacks of post-tensioned bridges [114].

Graybeal and Baby [115] recently developed an equation for UHPC which represents compressive strength gain at any age after casting cured under standard laboratory condition.

To investigate the bond properties of UHPC, Graybeal [116, 117] performed an experimental test and identified that the average compressive strength of UHPC with 1 and 7 days age were 96 MPa and 130 MPa, respectively.

Richard reported that compressive strengths as high as 550 MPa can be achieved at atmospheric pressure and heat treating at 250 °C [118]. With pressure, compressive strengths as high as 810 MPa are possible. With conventional production capabilities and curing at 90 °C, strengths of 280 MPa can be achieved.

Additional compressive strength data are available in many of the publications about research and applications of UHPC. These data indicate that the initiation of strength gain and subsequent rate of strength gain depend on the particular UHPC constituent materials, mix proportions, and the curing conditions [26].

B) Tensile strength

Depending on the content and type of the fibers, the tensile strength of UHPC is normally in the range of 7 to 15 MPa. Due to the crack-bridging effect of fibers, the tensile behavior of UHPC becomes ductile.

Graybeal [115] proposed an idealized tensile stress-strain response of UHPC which is shown in Figure 6. This response is based on direct tension tests of two UHPCs with multiple fiber contents. The behavior can be divided into four phases. Phase I is the elastic phase, when the matrix stands the loads. Phase II is the multi-cracking phase, wherein multiple tightly-spaced cracks form in the UHPC matrix. The cracks occur when the stress in the matrix exceeds the tensile strength of matrix. Phase III is the strain hardening phase. Individual cracks become wider in this phase, and no new cracks form. Lastly, Phase IV is the strain softening phase. The cracks begin to localize in this phase, and fibers begin to be pulled out from the matrix. After that, the material fails.

It should be noted that the tensile stress-strain curve may not act exactly as illustrated in Fig. 17, because the post-cracking behavior (phases II, III and IV) of UHPC largely depends on the content, type and orientation of the fibers. If very few fibers or even no fibers are used, there will not be phases II, III and IV.

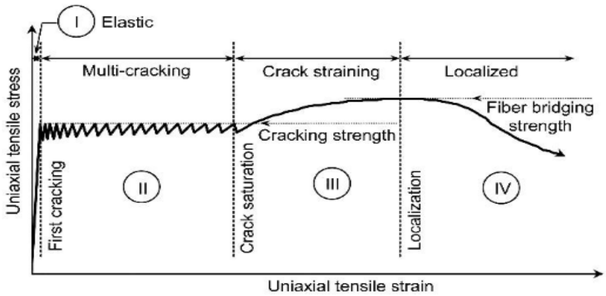

Fig. 17 Idealized uniaxial tensile response of UHPC [115].

C) Modulus of elasticity

Due to the dense microstructure, the elastic modulus of UHPC is higher than that of NC and HPC when the same type and amount of aggregates are used. Normally, the value ranges from 40 to 70 GPa, depending on the composition of the mixture, amount and type of the aggregates and the curing regime [19].

D) Shrinkage

Three types of shrinkage may be present in UHPC: chemical shrinkage, autogenous shrinkage and dry shrinkage. All these three kinds of shrinkages are mainly affected by w/b and cement content. For UHPC, due to the very low w/b and high cement content, the autogenous shrinkage is predominant. In the early age, the high autogenous shrinkage leads to a high risk of micro-cracking if the UHPC element is restrained.

Several methods have been developed to offset the autogenous shrinkage of UHPC. One is to use an expansive additive or shrinkage reducing additive [119,120]. They both have been proved to be very effective to reduce the autogenous shrinkage of UHPC. But the dosages of these additives have to been carefully determined. Another solution is internal curing, which is defined by the American Concrete Institute (ACI) as "supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation". Lightweight aggregate is the most common material used as a water reservoir. However, the size of the lightweight aggregate makes it unsuitable to be used in UHPC. Researchers throughout the world are also investigating the possibility of using superabsorbent polymers (SAP) [121] and

RHA [104,27] as internal curing agent. RHA is considered as a very promising material to act as internal curing agent in UHPC because of its porous structure and pozzolanic reactivity [104].

The development of drying shrinkage of UHPC is similar as HPC. Due to the low w/b, high density of the matrix and the presence of fibers, the amount of drying shrinkage of UHPC is lower compared with that of HPC. For heat treated UHPC, dry shrinkage can be neglected after the end of heat treatment.

E) Creep

The creep of UHPC is generally less than that of NC and HPC. The creep of concrete can be expressed as a creep coefficient (=creep strain/initial strain) or specific creep (=creep strain/applied stress). The creep coefficient of UHPC ranges from 0.3 to 0.85, and the specific creep rang-es from 5 to 47 µm/m/MPa [7]. For comparison, the specific creep for NC is in the range of 35 to 140 µm/m/MPa.

3- Chemical properties (Microstructure)

From material science point of view, the chemical properties of a material are determined by its microstructure, which is the same case for UHPC. The outstanding mechanical properties and durability of UHPC result from its very dense and compact microstructure.

The microstructure of UHPC could be observed by Scanning Electron Microscope (SEM). Fig. 18 is a Backscattering Scanning Electron (BSE) image of a UHPC paste containing FA and SF. Because of the low w/b, large amount of unreacted cement and FA particles can be seen in the image. No visible capillary pores and cracks can be found, as well as the portlandite ($Ca(OH)_2$) crystals [19].

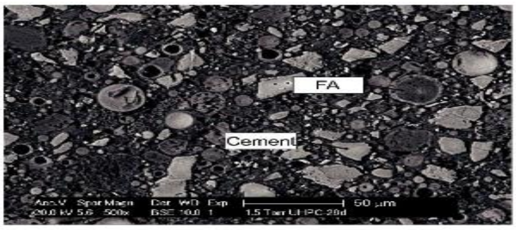

Fig. 18 Microstructure of UHPC paste containing FA and SF, *w/b*=0.18, 28d [19]

Another difference of NC and UHPC in microstructure lies in the interfacial transition zone (ITZ) between the paste and aggregate particles. The thickness of ITZ in NC is normally in the range of 20 to 100 µm. While, the thickness of this zone in UHPC is found to be very small (2 µm) [104], or even none [19]. Fig. 19 shows ITZ between the paste and sand particles in UHPC. It seems that ITZ almost dis-appears. Nanoindentation tests also showed that ITZ didn't exist in UHPC [135]. Fig. 20 shows the bond between the steel fiber and the UHPC matrix. It can be seen that the steel fiber is closely wrapped up by the matrix, showing a strong bond between them. Hence, the fibers could effectively bridge the cracks and thus improve the ductility of UHPC [19].

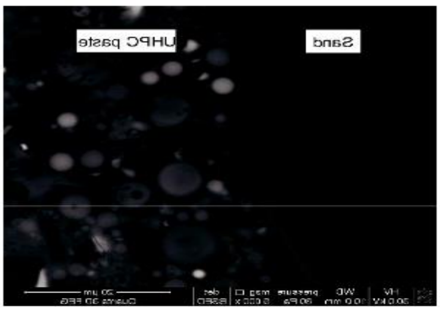

Fig 19 ITZ between sand and paste in UHPC[19].

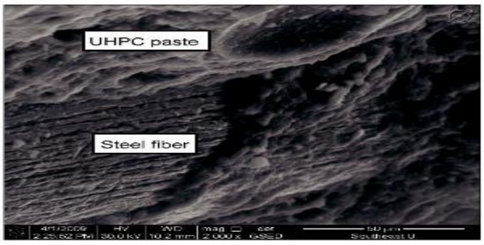

Fig 20 ITZ between steel fiber and paste in UHPC, *w/b*=0.18, 28d [19].

DESIGN GUIDELINES

The literature search identified the following national recommendations for UHPC:

- Design Guidelines for Ductal Prestressed Concrete Beams (Australia) [122]
- Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures by the Japan Society of Civil Engineers [123]
- .Ultra High Performance Fibre-Reinforced Concretes, Interim Recommendations prepared by AFGC (French Association of Civil Engineers) and SETRA (French Road and Traffic Government Agency (SETRA-AFGC 2002)[124]
- French Association for Civil Engineering, Ultra high performance fiber-reinforced concrete, Recommendations, revised edition, 2013 [19].

Design Aspects

As a rule, the design of concrete structures has to be a basis on reliable but simplified materials referene values, e.g. for the strength and the deformation behavior. For ordinary concrete those approaches are given in the relevant standards. For UHPC two similar approaches have been developed, one established by AFGC/SETRA in France in 2002 (SETRA-AFCG 2002) and one as part of the state-of-the-art report of the DAStB in Germany in 2003 (DAStB UHPC 2003).they both consider the fact , that as a rule the material properties of fiber reinforced UHPC show a significant higher deviation due to an inhomogeneous distribution and orientation of the fibers in the matrix.

The French recommendations consist of three parts:

the first part gives specifications on the mechanical performance to be obtained and recommendations For characterizing UHPC including checks to finished products and of the concrete being produced, the second part deals with the design and analysis of structures made with fibre reinforced, non-prestressed and/or non-reinforced UHPC elements and third part dealing with the durability of you UHPC [110] .

Durability

Apart from being far stronger than NC, UHPC also has out-standing qualities in terms of durability. The durability of concrete is determined to a great extent by its microstructure, especially pore structure. For NC, transportation of water and harmful agent, as chloride and sulfate, mainly occurs in capillary pores. While, UHPC is considered to be a capillary pores free material. Meanwhile, its total porosity is much lower than that of NC. For these reasons, UHPC has been considered as a material with outstanding resistance to harmful agents. In the past, most of the durability researches on UHPC were conducted under a single environmental effect, such as chloride ingress, carbonation and freeze-thaw cycles. In recent years, durability of UHPC under coupled mechanical and environmental effects and in field also has been studied due to the increasing applications of UHPC under complicated service conditions [19].

If deemed necessary, some durability characteristics of the optimized UHPC mixture can be investigated. For example, electrical resistivity can be measured in accordance with ASTM C 1760, and frost durability can be determined in accordance with the ASTM C 666, Procedure A [16].

The improved resistance of UHPC to all kinds of harmful gases and liquids, to chloride and freezing and thawing attacks is related to the improved density most of the great grain structure of the matrix and much denser contact zone between the matrix and the (coarse) aggregates as well as by denser structure of hydration products **Fig. 21** gives impression of the dinner structure [110].

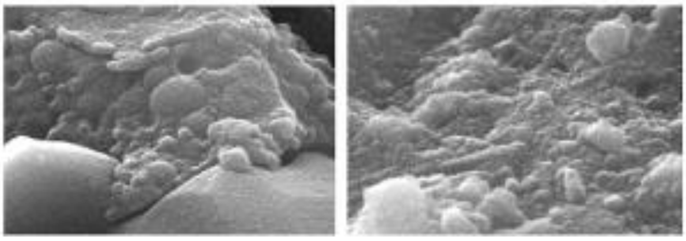

Fig. 21 structure of UHPC matrix [110]

The following Table 7 Characteristic durability values obtained for UHPC compared to the values corresponding to traditional concrete, and to HPC.The results presented above confirm the position of UHPC with respect to other types of concrete: for all the “conventional” durability indicators, the values obtained for UHPC indicate a clear improvement in durability [110].

Table. 7 Characteristic durability values for UHPC, HPC and Normal strength concrete

Indicator	Ordinary Concrete C 35 EN 206	High Performance Concrete C 100/115 EN 206	Ultra High Perf. Concrete
Total porosity [%]	app. 15	app. 8	4-6
Capillary pores [%]	app. 8	app. 5	1.5-2.0
Nitrogen permeability [m^2]	10^{-16}	10^{-17}	$<10^{-18}$
Chloride-ion diffusion (6h quick-migration test) [2)] Depths of intrusion [mm]	23	8	1
Carbonation depth (after 3 years) in mm (20 °C, 65% r. humidity)	7	4	1.5
Freeze-salt-resistance (scaling in [g/m^2]) [1)]	< 1500 (air entrained)	150 (air entrained)	20…50 water … heat cured
Water absorption factor [3)]	60	11	1

[1)] CDF- test, 28 cycles, limit 1500 g/m^2 [2)] (Tang and Nielsson 1992)
[3)] DIN 52617

A) Durability of UHPC under single environmental load

Table 8 shows the comparison of the mechanical properties and durability of RPC, HPC and NC [125]. For instance, the chloride diffusion coefficient of RPC200 is 1/30 of HPC and 1/55 of NC. The other properties of RPC200 are also much better than those of NC and HPC. Recent study performed by Kono [126] showed that, after 2.5 years immersion in artificial sea water, the chloride penetration depth in UHPC was only around 2 mm and the apparent diffusion coefficient was determined to be 3.377×10^{-14} m^2/s. Pierard [127] studied the durability of different types of UHPC. The accelerated carbonation tests, accelerated chloride diffusion tests, freeze-thaw performance tests, alkali-silica reaction tests, sulphate attack tests and sulphuric acid tests were performed on UHPC. All the results showed that UHPC exhibited extremely good durability under the experimental conditions.

Table 8 summarize mechanical and durability properties for RPC, HPC and NC [125]

	Compressive Strength (MPa)	Flexural strength (MPa)	Young's modulus (GPa)	Fracture energy (kJ m^{-2})	Cl^- Diffusion coefficient ($m^2 s^{-1}$)	Oxygen permeability (m^2)	Water Absorption (kg m^{-2})	Abrasion coefficient
RPC200	170–230	30–60	50–62	15–40	0.02×10^{-12}	10^{-16}	0.2	1.3
HPC	60–100	6–10	30–40	0.14	0.60×10^{-12}	10^{-17}	0.4	2.8
NC	20–50	2–5	30–40	0.12	1.10×10^{-12}	$<10^{-19}$	2.7	4.0

B) Durability of UHPC under coupled effect of mechanical and environmental loads

Realizing that the UHPC structures are always designed to stand severe coupled effects of mechanical and environ-mental loads, experimental studies on the durability of UHPC under these conditions were also conducted.

The permeability of UHPC after tension to different ex-tents was studied by Charron [128,129]. Results indicated that the permeability of UHPC rose up to three orders of magnitude (1.8×10^{-12} to 2.9×10^{-9} m/s) when the residual deformation after tension increased from 0.05% to 0.88%. It meant that the cracks had significant impacts on the permeability of UHPC. It is foreseeable that cracks would show great negative influence on the resistance to chloride penetration, carbonation and sulfate ingress. Compared to the permeability of NC (4.8×10^{-11} m/s) [130], the permeability of sound UHPC is 1–2 orders of magnitude lower. The permeability of UHPC with a residual deformation of 0.33% is close to that of NC. In general, the permeability of UHPC is much lower than that of NC, but the cracks, which originate from the mechanical load, influence the permeability of UHPC remarkably.

Parant [131] tracked the change of mechanical properties of UHPC under coupled effects of flexural load, chloride penetration and wetting-drying cycles. The stress ratio of the flexural load was 50%, the concentration of the NaCl solution was 5 g/l, the wetting-drying cycles were carried out with one day wet and six days dry, and the test period lasted one year. After the experiment, no matter the flexural strength or stiffness, the mechanical properties of UHPC Realizing that the UHPC structures are always designed to stand severe coupled effects of mechanical and environ-mental loads, experimental studies on the durability of UHPC under these conditions were also conducted.

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C) Field tests on the durability of UHPC

Since UHPC was invented, it has been used for some structures. Feedbacks on the durability of UHPC in some of these structures have been received.

Sakata-Mirai Footbridge [126] is the first bridge constructed with UHPC in Japan in 2002. This bridge is built to span the Noota River that flows through the urban area of Sakata City The location is about 3.4 km from the Japan Sea coastal line, so this footbridge is exposed to severe corrosive environment. After more than 10 years exposure, chloride profiles in UHPC of the bridge were tested. The results showed that the chloride penetration depth was less than 1 mm in the UHPC samples, and the chloride diffusion coefficient was around 1×10^{-15} m^2/s. The mechanical properties of field UHPC samples were also tested. The compressive strength of the samples increased due to the ongoing hydration of cement in 10 years. The flexural strength was almost the same as 10 years ago. So, in conclusion, this 10 year old UHPC footbridge still maintains good condition even against severer environments.

UHPC bridges at Bourg-les-Valence in Southeastern France are the oldest UHPC road bridges in the world [132]. They were completed in 2001 and the decks were made of BSI/Ceracem® concrete with compressive strength of 180 MPa. After 12 years of service, cores were drilled from one of the bridge spans for long-term performance investigation. Mechanical and durability characteristics were measured with the drilled specimens. Free chloride content was determined with an extraction and titration method. At the surface of all the specimens, the detected contents were close to the precision of the test method, which is 0.02 g of chloride in 100 g UHPC without fibers. Although the use of de-icing salts is not intense in this region, such limited con-tents confirm that chlorides have not penetrated inside UHPC and can not contribute to the rebar corrosion. As the same to that in Sakata-Mirai Footbridge, the compressive strength of the drilled samples is close to 20% higher than that at 28 days.

Three series of UHPC have been placed at the mid-tide level of a marine exposure site at Treat Island, Maine since 1995 [133]. The exposure conditions at Treat Island are very aggressive for concrete with tides and an average of 100 cycles of freeze and thaw per year. Mechanical properties and chloride profiles were tested. After 13 years exposure, the UHPC beams appeared to be in excellent condition. The chloride penetration depth was about 7 mm. While for HPC in the same condition, the penetration depth had reached 20 mm.The calculated chloride diffusion coefficient of UHPC was 1/10 of HPC.

Repair and Retrofitting

All researchers and engineering in repairing and strengthening field used UHPC as a repairing material, very limited studied made on repairing and retrofitting UHPC as Aamer N. Abbas [134] et al. (2016) studied behavior of normal and reactive powder concrete beams repaired with epoxy resin. Such type of epoxy technique made for cracks width less than (0.05) mm, also the load-deflection behavior, ultimate capacity, mode of failure, stiffness and toughness were studied.

More over great experimental work have been conducted in China university by Li**. et al. (2016)** on repairing damaged UHPC slabs under the effect of (0.5 & 1 Kg TNT) (bomb) which caused concrete spalling **[135]** .

It is challenge in the future for researchers and engineering in repairing and strengthening field to have many alternatives of repairing materials with strength more than UHPC strength by testing different repaired UHPC structural element, then getting the optimum repairing material for UHPC elements.

All infrastructures companies for construction ang engineers around the world as State transportation departments, Army engineer researcher, multinternational companies for construction and design consultants are interested in all the new studied in UHPC to grasp the capabilities of UHPC and thus use the material to address pressing needs in different constructions as Roads and bridge construction, Building construction, Military construction and Anti-detonating Construction.

Moreover, UHPC is best choices in retrofitting field using it as a repairing material cause of UHPC durability advantages due to using MS + NS mixture, it's recommended to assess the proposed MS + -NS mixing ratios during any further study. In addition to the required pozzolanic material's compliance with ASTM C1240 [136], the following guidelines are suggested for any further study using mixture of nano-micro silica particles and provided denser microstructure than just using either the MS or NS particles separately. to enhance the concrete durability specially in repairing and retrofitting structural elements [26]:

1. Minimum very fine impurities should be provided, in the concrete constituents, considering that NS and MS are an additional source for very fine materials required for better gardening and pore filling.
2. Parametric study, based on the compressive strength of mortar specimens, is useful approach to determine the optimum nano-micro silica mixture ratio and the corresponding dispersion process. The proposed 2%NS + 8%MS mixture can be used as initial replacement ratio.
3. Rapid chloride ion penetrability and water permeability can provide reliable prediction for the durability performance (e.g. corrosion protection and sulphate resistance) of the concrete specimens made of the explored mixtures.

Frequent Applications

The applications of UHPC are increasing in the recent years in Europe, North America, Japan, Korea, China and Australia. While, in some other countries, such as Egypt, only limited applications were realized.

The applications of UHPC are increasing constantly. From the 2000s, several countries have engaged in the application of UHPC. Delightful achievements have been made on the application of UHPC, but there are still barriers that impede the wider applications of UHPC. Table?? summarize UHPC applications around world [4].

The main applications of UHPC are bridges, buildings, structural strengthening and retrofitting, and some special applications [19]. Some specific examples will be given in the following sections.

A) Bridges

The advanced mechanical properties and durability of UHPC make it possible to reconsider the conventional de-sign methods for many common bridge components. Many investigations have been conducted on the optimal designs with UHPC elements, resulting in the development and construction of the UHPC bridges all over the world. According to the state-of-the-art report [7] on UHPC published by U.S. Federal Highway Administration in 2013, 55 bridges using UHPC have been built or are under construction in U.S. and Canada.

Most bridges built with the UHPC components or joints exhibit slender appearance, much lower weight, simplified implementation and better durability than built with traditional reinforced concrete bridges.

B) Buildings

In addition to the applications on bridges, the field of building components, such as sunshades, cladding and roof components, was the leading domain of UHPC applications in the last decade. UHPC could be used to produce very slender, durable and aesthetic structures.

One of the newest buildings where UHPC is used is the Fondation Louis Vuitton pour la Creation in Paris Fig. 22 [19]. This project is characterized by the high geometric complexity. The cladding is created from 19000 unique, prefabricated panels of UHPC. Each one is different from others, moulded individually and installed using a butt joint. The visualization of this building is shown in Figure 21. The construction will be finished in 2014.

Another great example is the Museum of European and Mediterranean Civilizations (MUCEM) [19] as shown in **Fig.** 23, which is located in the port area of Marseille in France. It is the first building in the word to make such extensive use of UHPC, and Table. 9 listed some UHPC applications around world [4]

Fig.22 Fondation Louis Vuitton pour la Creationin, Paris, France[19].

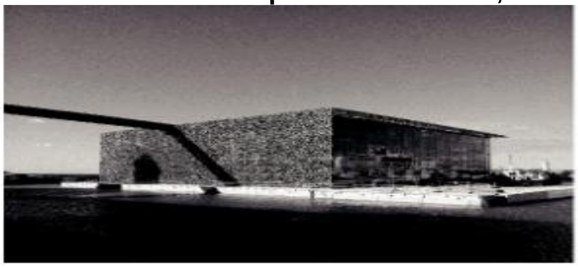

Fig. 23 MUCEM, Marseille, France [19].

Table. 9 Example of UHPC applications around world [4]

Structures/applications	Location	Completion/production year	Compressive strength (MPa)	Flexural strength (MPa)
Sherbrooke footbridge	Sherbrooke, Canada	1997	200	40
Joppa clinker silo	Illinois, USA	2001	220	50
Seonyu footbridge	Seoul, Korea	2002	180	32
Sakata Mirai footbridge	Sakata, Japan	2002	238	40
Millau Viaduct toll gate	A75 Motorway, France	2004	165	30
Shepherds creek bridge	Sydney, Australia	2005	180	–
Blast resisting panels	Melbourne, Australia	2005	160	30
Papatoetoe footbridge	Auckland, New Zealand	2006	160	30
Glenmore/Legsby bridge	Calgary, Canada	2007	–	–
Gaertnerplatz bridge	Kassel, Germany	2007	150	35
UHPC girder bridge	Iowa, USA	2008	150	–
Wind turbine foundations	Denmark	2008	210	24
Haneda Airport slabs	Tokyo, Japan	2010	210	45
Whiteman Creek bridge	Brantford, Canada	2011	140	30
Sewer pipes	Germany	2012	151	–
Spun concrete columns	Germany	2012	179	–
UHPC truss footbridge	Spain	2012	150	–

Data collected from Schmidt et al. (2004, 2012), Fehling et al. (2008) and Talebinejad et al. (2004).

C) Structural strengthening and retrofitting

UHPC also has been widely used as an overlay to repair the reinforced or prestressed concrete bridge decks. It could increase the mechanical properties and durability of the bridges and result in less maintenance. This kind of applications is mainly in France and Swiss. The first application was on a bridge over the river La Morge, in Chateauneuf/Conthey nearby Sion, Wallis, Swiss. Originally, the bridge deck had no waterproofing membrane and the curbs were severely damaged by chloride induced corrosion. Then the downstream curb, upstream curb and the upper surface of the bridge deck were replaced with UHPC. After rehabilitation, the bridge served well and no cracks can be found on the surfaces of the prefabricated UHPC curb after one year.

UHPC could also be used to repair and protect the hydraulic structures. The first example is the repair of the Hosokawa River Tunnel in Japan .Then, UHPC was used to repair the Caderousse and Beaucaire dams on the Rhone River in France in 2010 to 2012 . The slabs and the hydraulic vertical screen were repaired and strengthened [19].

Cost

The initial unit quantity cost of UHPC far exceeds that of conventional concrete. Consequently, applications have focused on optimizing its use by reducing concrete member thickness, changing concrete structural shapes, or developing solutions that address shortcomings with existing non-concrete structural materials. UHPC is a very durable product, and structures that use it are expected to have a longer service life and require less maintenance than structures built with conventional concrete.

As a case study Piotrowski and Schmidt conducted a life cycle cost analysis of two replacement methods for the Eder bridge in Felsberg, Germany[137]. One method used precast UHPC box girders filled with lightweight concrete. The second method used conventional prestressed concrete bridge members. Although the UHPC had higher initial costs, the authors predicted the life cycle cost over 100 years would be less for the UHPC bridge [26].

The initial cost of UHPC far exceeds that of conventional concrete. Consequently, great efforts have been made on minimizing material costs without sacrificing the beneficial properties of UHPC. Through careful selection of the raw materials, it was possible to produce UHPC with outstand-ing performance and moderate material costs. The possibil-ity of replacing SF in UHPC with metakaolin, pulverized FA, limestone microfiller, siliceous microfiller, micronized phonolith, or rice husk ash (RHA) has been investigated [138-140]. Several researches have shown that fine ground quartz sand could be replaced by well-graded natural sand with a maximum size of 2–8 mm [141,142] With the growing concern on the concept of sustainability, supplementary cementitious materials, such as FA and slag, have been widely used to partially replace cement when preparing UHPC. The volume fraction of steel fiber also could be re-duced if UHPC is reinforced with conventional steel rebar. It can be said that, a relatively low cost is possible now to prepare UHPC. The preparation of UHPC is becoming more economical and sustainable.

Evaluation

This paper will help engineers and new researchers in the field to learn the fundamentals of HPC and UHPC mixture proportioning, material selection, and mixing procedures, and to build on and improve UHPC characteristics and will help designers, engineers, architects and infrastructure owners to know the capacities of UHPC and thus to increase the applications of this material.

The main objective of this study is to enhance the capability of the business sector to innovate by focusing on long-term research base papered on forging close alliances between research-intensive enterprises and prominent research groups. The corporate partners are leading multinational companies in the cement and building industry and this paper aims to increase their value creation and strengthen their research activities.

From this extensive review it can be noticed that low porosity and a higher packing density are essential to achieve high strength, acceptable flowability, and minimal segregation.

Earlier techniques like pressure mixing, pressure with heat curing, and vacuum mixing used to cast low-porosity concrete are practical at the laboratory scale. However, for large-scale casting, these techniques cannot develop further.

In evaluating the characteristics of a hydrated cement paste, pore size distribution is considered a better criterion than total capillary porosity. Capillary pores with a size of 50 nm are referred to as macropores and are influential in determining strength and permeability characteristics. Pores smaller than 50 nm are referred to as micropores; these pores are like gel pores, affecting drying shrinkage and creep. Hence, porosity and pore structure are important in the mechanical and durability properties of concrete. The factors affecting pore volume and size distribution are initial w/c ratio, degree of hydration, fineness of cement, and curing type and duration [72].

A basic question comes to mind when selecting materials for special applications as offshore or marine applications — Under which type of load should one classify the maximum strength? Some materials are equally strong in compression, tension, and shear. However, many materials show marked differences; for example, cured concrete has a maximum strength of 14 MPa in compression but only 3 MPa in tension. Carbon steel has a maximum strength of 386 MPa in tension and compression but maximum shear strength of only 290 MPa; therefore, when dealing with maximum strength, it is always necessary to state the type of loading.

During the selection of materials for special structures, the following factors are normally accounted for: (1) physical and chemical properties of materials, (2) cost, (3) fabrication facilities, and (4) maintenance cost (5) type of loading. Chosen materials should avoid catastrophic failure. Besides meeting the design requirements, they should withstand hazards (including those arise during operations). During selection, a few material (physical) characteristics are important. Yield strength becomes the first consideration, whereas Young’s modulus and ductility follow it. Poisson’s ratio is also important as structures are under multiaxis loading. Due to the dynamic nature of environmental loads, fatigue performance and fracture resistance also become equally important. Note that the physical characteristics are presented in the literature based on the data taken from standard specimens. Structure loading in the actual environment differs markedly from those of any tests conducted in controlled laboratory conditions. This warrants change in allowable stress levels for various stuctures conditions. This is taken care in design in terms of material allowance, either by increasing the thickness of the members or by using an appropriate factor of safety. Apart from the cost of materials and their availability in the desired cross section and size, it is vital to understand their fundamental characteristics and performance under different environmental conditions to make such an important decision [143].

The quality of cast-in-place UHPC can be considerably affected by the mixing, placing, and curing methods used. Some projects have been conducted to extend the use of UHPC to the field, focusing on cast-in-place technologies [144-146].

One of the difficulties of casting the UHPC on site is the need for a specially-designed mixer for UHPC that is usually used in a laboratory or a plant. As one of the strategies to cope with this problem, a portable mixer optimized for the UHPC mixture has been developed because the quality of the UHPC using a conventional mixer may be subject to large variation [146]. Another important factor that affects the quality of cast-in-place UHPC is the curing method. Possible curing methods on site may differ from those of precast UHPC segments fabricated in the ideal conditions of a plant. Generally, in precast UHPC, a standard steam curing method is adopted to obtain rapid strength development. However, in cast-in-place UHPC, which is the main focus of this study, curing methods are often limited in terms of curing temperature, curing period, and moisture condition [147].

Summing up material for construction should be carefully chosen so that the service life of special structures is guaranteed.

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