A review on ultra high performance ‘ductile’ concrete (UHPdC) technology

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ABSTRACT

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 enhanced durability compared to conventional concrete. In brief, UHPdC is a cementitious based composite material that consists of the distinctive characteristics of the ultra-high performance concrete and high tensile strength steel fibers. UHPdC is a sustainable construction material with considerable amount of durability, ductility and tensile capacity which is mostly appropriate for use in the fabrication of precast members in civil engineering, structural and architectural applications. This paper presents a review on the UHPdC technology including an overview of material characteristics of a Malaysian UHPdC blend (i.e. Dura®), the principles of UHPdC development, its mix design, its advantages, and its applications.

Keywords: Ultra High Performance Fiber Reinforced Concrete (UHP-FRC), Ultra High Performance ‘ductile’ Concrete (UHPdC), Reactive Powder Concrete (RPC), Sustainable Construction Material, Ductility, durability.

1. Introduction

Cement, water and aggregates are the basic constituents for the production of traditional concrete. Since the last three decades, significant progression and development has been made in the field of concrete technology especially during the time of the introduction of additives (supplementary cementitious material) such as pulverized-fuel ash (PFA), silica fume, ground granulated blast furnace slag (GGBS) as well as chemical admixtures such as superplasticizer (water reducing agent), air-entertainer, retarder, etc. and different kinds of fibers such as steel, synthetic and carbon. Production of modern or advanced concrete is impossible without the usage of these innovative ingredients. Normal strength concrete (NSC) was firstly introduced in the early 1900’s. Later on, high performance concrete (HPC) was developed in the 1950’s (Voo and Foster, 2009). In the mid 1990’s, one of the astonishing developments in the field of concrete technology was made by introduction of ultra high performance fiber reinforced concrete (UHP-FRC) by Richard and Cheyrezy
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(1994) which is more commonly known as ultra-high performance ‘ductile’ concrete (UHPdC) or reactive powder concrete (RPC).

1.1 Evolution of Concrete Technology

It can be said that modern use of concrete started by the work of John Smeaton who was born is 1724. He rebuilt a damaged lighthouse namely the Eddystone Lighthouse with one kind of pozzolanic mortar bound with interlocking masonry courses in Cornwell, England, in 1756. In the later years of his life, he built the Rams gate Harbor in Perth, Coldstream Bridges and the Forth and Clyde Ship Canals by adding aggregate to the mix (Skempton, 1982).

For the first time, Jean-Louis Lambot used the reinforcing steel in his boats in early 1850’s (Shaef fer, 1992). The Alvord Lake Bridge in the USA was the first reinforced concrete bridge which was built in 1889 using the concept of reinforced concrete. Considerable development in concrete construction can be seen with the development of prestressed concrete by Eugene Freyssinet as well as the construction of the first major concrete dams, Hoover Dam and Grand Coulee Dam, in the 1930’s (Voo and Foster, 2009; Armstrong, 2001; Shaef fer, 1992).

For the last few decades, great interest in advanced cementitious materials is generally due to their enhanced strength as well as their high-performance properties. HPC for the first time was used in the 1950’s. The 260 m high Water Tower Place was built in 1973 with a Grade 60 concrete (Shaef fer, 1992). Two Union Square (USA), Petronas Twin Towers (Malaysia), Tsing Ma Bridge (Hong Kong) and Trump World Tower (USA) are few examples of broad applications of HPC in bridges and high rise buildings in the following two to three decades (Voo and Foster, 2009).

Since last two decades, astonishing advancements has been made in the field of concrete technology. One of the greatest breakthroughs was the development of fiber reinforced reactive powder concrete (FR-RPC), and more commonly known as the ultra-high performance ductile concrete (UHPdC) in the mid 1990’s. Although vast progress in UHPdC technology has been achieved in recent decades (Voo and Foster, 2009; Fehling et al., 2008; Graybeal, 2006; Schmidt et al., 2004); however, its application in many developing countries is still in its infant stages. Figure 1 presents a schematic drawing which shows the evolution of concrete technology from NSC to UHPdC (Voo and Foster, 2009).

2. Ultra-High Performance ‘ductile’ Concrete (UHPdC)

2.1 Definition

According to Federal Highway Administration (FHWA) tech-note on UHPdC (Graybeal, 2011), UHPdC is a cement based composite material which consists of fine granular materials with optimized grading curves, very high strength discrete micro steel fibers and a very low water cement ratio (W/C) less than 0.25. UHPdC is significantly durable compared to NSC and HPC due to the highly reduced and discontinuous pores (i.e. high homogeneity) which reduce the entrance of deleterious material such as chloride and sulfate ions. UHPdC is a high strength, ductile, and sustainable construction material formulated by combining Portland cement, silica fume, fine washed/sieved sand, superplasticizer, water, and steel fibers. UHPdC is an extremely homogenous cementitious blend without using coarse aggregates that can attain compressive strength over 150 MPa (Voo and Poon, 2009; Richard and Cheyrezy, 1995).
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Figure 1: Evolution of concrete technology from NSC to UHPdC (Source: Voo and Foster, 2009)
2.2 Principles of UHPdC Development

UHPdC is established on the principle that a material with a minimum of weaknesses such as micro-cracks and pore spaces shall be capable to reach a superior quantity of the potential ultimate load carrying capacity as defined by its component materials (Richard and Cheyrezy, 1995). According to Richard and Cheyrezy, (1994 and 1995), Bonneau et al. (1996) and AFGC interim recommendations for ultra-high performance fiber-reinforced concrete (2002), the UHPdC is founded on the four principles that can be summarized as follows:

1) Optimized granular packing which improves homogeneity and cause ultra-dense matrix.

2) Extremely low water cement ratio which reduces amount of pores and capillaries, pore sizes, concrete cancer issues e.g. carbonation, improves impermeability, and results in remarkable durability and strength.

3) Inclusion of very high strength micro-fibers which enhances tensile strength and ductility, improves impact and abrasive resistance, and bridge micro-crack more effectively.

4) Steam cured for long period of time which accelerates all early and drying shrinkage, improves overall material properties which cause volumetrically stability, minimal creep, and negligible shrinkage.

2.3 Standard UHPdC Mix Design

Ordinary Portland cement, silica fume, fine aggregates, water, steel fibers and high-range water reducing agent are the main ingredient to produce UHPdC. Table 1 demonstrates a standard UHPdC mix design with 2% by volume of micro steel fibers. The high-range water reducing agent used is Polycarboxylate ether (PCE)-based superplasticizer and no recycled wash water shall be used in the mixture (Voo and Foster, 2010). Even though UHPC demonstrates considerably improved compressive strength and lower porosity; however, UHPC matrix tend to be fragile (i.e. brittle). Thus, micro steel fibers with various dimensions and mechanical properties are commonly used in UHPdC at different concrete volume percentage to develop tensile and flexural strength, resistance to impact or toughness, cracking control, and changing the failure mode by increasing post cracking ductility (Garas et al., 2009; Shah and Weiss, 1998).

Table 1: Standard Mix Design of UHPdC

| Ingredient         | Mass (kg/m3) |
|--------------------|--------------|
| UHPC Premix        | 2100         |
| Superplasticizer   | 40           |
| Steel Fiber        | 157          |
| Free Water         | 144          |
| 3% Moisture        | 30           |
| Targeted W/B Ratio | 0.15         |
| Total Air Void     | < 4%         |

(Source: Voo and Foster, 2010)
According to Japanese society of civil engineers’ recommendations for design and construction of ultra high strength fiber reinforced concrete structures (Draft) (JSCE No.9, 2006), the aggregate size used in the UHPC matrix should be less than 2.5 mm and the water cement ratio should be less than 0.24. In addition, the UHPdC contains more than 2% by volume of steel fibers with the dimensions ranging 10 to 20 mm in length and 0.1 to 0.25 mm in diameter and with a tensile strength over 2000 MPa. The UHPdC members should be steam cured at 90°C for a period of 48 hours. However, other materials outside the above conditions may be used provided it is verified that the physical characteristics of the materials are either equal or beyond the stated values in JSCE No.9 (2006) for strength, durability, and efficiency in construction of UHPdC structures.

### 2.4 Material Characteristics of UHPdC

Table 2-(a) shows the material characteristics of NSC, and high performance concrete (HPC). Table 2-(b) presents the mechanical properties of two commercial blends of UHPdC known as Ductal® and Dura®. Comparison between tables 2-(a) and 2-(b) shows that UHPdC generally has superior mechanical and durability properties over NSC and HPC in all disciplines (Voo and Foster, 2010).

**Table 2-(a): Material Characteristics of Normal Strength Concrete (NSC) and High Performance Concrete (HPC)**

| Characteristics                                      | Unit | Codes / Standards                  | NSC       | HPC       |
|-------------------------------------------------------|------|------------------------------------|-----------|-----------|
| Specific Density, $\delta$                           | kg/m³| BS1881:Part 114-1983              | 2300      | 2400      |
| Cylinder Compressive Strength, $f_{cy}$              | MPa  | AS1012.9-1999                      | 20 – 50   | 50 – 100  |
| Cube Compressive Strength, $f_{cu}$                  | MPa  | BS6319: Part 2-1983               | 20 – 50   | 50 – 100  |
| Creep Coefficient at 28 days, $\phi_c$               |      | AS1012.16-1996, ASTM C512         | 2 – 5     | 1 – 2     |
| Poisson’s Ratio, $\nu$                               |      | BS1881:Part 121-1983              | 20 – 35   | 35 – 40   |
| Split Cyl. Cracking Strength, $f_{sc}$                | MPa  | BS:EN 12390-6-2000, ASTM C496     | 2 – 4     | 4 – 6     |
| Split Cyl. Ultimate Strength, $f_{ut}$               | MPa  |                                   | 2 – 4     | 4 – 6     |
| Flexural 1st Cracking Strength, $f_{flex,1P}$        | MPa  | ASTM C1018-1997                   | 2.5 – 4   | 4 – 8     |
| Modulus of Rupture, $f_{ed,1P}$                       | MPa  | (Four-Point Test on Un-notched Specimen) | 2.5 – 4   | 4 – 8     |
| Bending Fracture Energy, $G_{I,0.46mm}$              | N/mm |                                   | < 0.1     | < 0.2     |
| Bending Fracture Energy, $G_{I,3.0mm}$               | N/mm |                                   | < 0.1     | < 0.2     |
| Bending Fracture Energy, $G_{I,10mm}$                | N/mm |                                   | < 0.1     | < 0.2     |
| Toughness Indexes                                     |      |                                    | 1         | 1         |
| $I_3$                                                 |      |                                    | 1         | 1         |
| $I_{10}$                                              |      |                                    | 1         | 1         |
| $I_{20}$                                              |      |                                    | 1         | 1         |
| Rapid Chloride Permeability                           | coulomb | ASTM C1202-2005, ASTM C1556-2004 | 2000 – 4000 | 500 – 1000 |
| Chloride Diffusion Coefficient, $D_a$                 | mm²/s | ASTM C1556-2004                   | 4 – 8 $\times$ 10⁻⁶ | 1 – 4 $\times$ 10⁻⁶ |
| Carbonation Depth                                     | mm   | BS:EN 14630-2003                  | 5 – 15    | 1 – 2     |
| Abrasion Resistance                                   | mm   | ASTM C944-1999                    | 0.8 – 1.0 | 0.5 – 0.8 |
| Water Absorption                                      | %    | BS1881:Part 122-1983              | > 3       | 1.5 – 3.0 |
| Initial Surface Absorption                            | ml/(m²s) | BS1881:Part 208-1996             | 0.7 (10 min) | 0.1 (10 min) |
|                                                       |      |                                    | 0.2 (120 min) | 0.05 (120 min) |

(Source: Voo and Foster, 2010)
UHPdC has a compressive strength and post cracking tensile strength of greater than 150 MPa and 5 MPa, respectively. In general, the tensile behavior of UHPdC can be identified as "strain hardening", where the composite material continues to resist higher residual tensile strength after the concrete matrix has cracked. In other words, the post cracking strength of UHPdC is greater than the matrix cracking strength due to the usage of very high strength micro steel fibers. The type, amount, orientation and distribution of steel fibers significantly influence the post cracking tensile strength and strain capacity of the UHPdC (Graybeal, 2011). Based on the JSCE No.9 (2006) guidelines, UHPdC should have the characteristic compressive strength, tensile strength and first cracking strength beyond 150 MPa, 5MPa and 4 MPa, respectively.

### Table 2-(b): Mechanical properties of two commercial blends of UHPdC known as Ductal® and Dura®

| Characteristics                          | Unit | Codes / Standards                  | DURA® | DUCTAL® |
|------------------------------------------|------|------------------------------------|--------|---------|
| Specific Density, δ                      | kg/m³ | BS1881:Part 114-1983              | 2350–2450 | 2440–2550 |
| Cylinder Compressive Strength, fcm       | MPa   | AS1012.9-1999                      | 120–160 | 123–210 |
| Cube Compressive Strength, fcm           | MPa   | BS6319: Part 2-1983                | 130–170 | 158–220 |
| Creep Coefficient at 28 days, φc         |       | AS1012.16-1996                     | 0.2–0.5 | 0.29–0.66 |
| Post Cured Shrinkage                     | µε    | AS1012.16-1996                     | <100   | 0       |
| Modulus of Elasticity, Eo                | GPa   | BS1881:Part 121-1983              | 40–50  | 50–53   |
| Poisson’s Ratio, ν                       |       |                                    | 0.18–0.2 | 0.2     |
| Split Cyl. Cracking Strength, f1          | MPa   | BS:EN 12390-6-2000                | 5–10   | 8.6–12.4 |
| Split Cyl. Ultimate Strength, fup         | MPa   | ASTM C496                          | 10–18  | 18.3–26.5 |
| Flexural 1st Cracking Strength, f1,4P     | MPa   | ASTM C1018-1997                   | 8–9.3  | 9–9.7   |
| Modulus of Rupture, f5,4P                 | MPa   | (Four-Point Test on Un-notched Specimen) | 18–35 | 40–50 |
| Bending Fracture Energy, Gf,ω=0.46mm      | N/mm |                                    | 1–2.5  | N/A     |
| Bending Fracture Energy, Gf,ω=3.0mm       | N/mm |                                    | 10–20  | N/A     |
| Bending Fracture Energy, Gf,ω=10mm        | N/mm |                                    | 15–30  | N/A     |
| Toughness Indexes                         |       |                                    |        |         |
| I5                                        | 4–6   |                                    | 5.3–6.2 | 4–6     |
| I10                                       | 10–15 |                                    | 11.8–14.4 | 10–15   |
| I20                                       | 20–35 |                                    | 25.9–32.8 | 20–35   |
| Modulus of Rupture, f5,3P                 | MPa   | JCI-S-002-2003                     | 18–35  | 40–50   |
| Bending Fracture Energy, Gf,ω=0.46mm      | N/mm | (Three-Point Test on Notched Specimen) | 1–2.5 | N/A     |
| Bending Fracture Energy, Gf,ω=3.0mm       | N/mm |                                    | 10–20  | N/A     |
| Bending Fracture Energy, Gf,ω=10mm        | N/mm |                                    | 15–30  | N/A     |
| Rapid Chloride Permeability              | coulomb | ASTM C1202-2005                  | <200   | <50     |
| Chloride Diffusion Coefficient, Dc        | mm²/s | ASTM C1556-2004                   | 0.05–0.1 x 10⁻⁶ | 0.02 x 10⁻⁶ |
| Carbonation Depth                        | mm    | BS:EN 14630-2003                 | <0.1   | <0.5    |
| Abrasion Resistance                      | mm    | ASTM C944-1999                   | <0.03  | <0.03   |
| Water Absorption                         | %     | BS1881:Part 122-1983             | <0.2   | N/A     |
| Initial Surface Absorption               | ml/(m²s) | BS1881:Part 208-1996         | <0.02 (10 min) | <0.01 (120min) | N/A |

(Source: Voo and Foster, 2010)

## 2.5 UHPdC versus Conventional Steel Fiber Reinforced Concrete (SFRC)

UHPdC, with respect to general mechanical characteristics, is superior to conventional steel fiber reinforced concrete (SFRC). The tensile strength of the steel fibers used in conventional SFRC is usually up to 1000 MPa and the fiber fracture may take place during cracking; while, the very high strength micro steel fibers used in UHPdC have tensile strengths above 2000
MPa, thereby fiber fracture will never occur, which ensures the high ductility of UHPdC during cracking. As a result of greater mechanical properties, UHPdC demonstrates “strain hardening” and “displacement hardening” behaviors during tensile stresses, while such behaviors might not be captured in conventional SFRC (Voo, 2006c).

2.6 Rusting of steel fibers in UHPdC

Generally, due to oxidation of steel fibers located at the surface of the concrete, some rust stain may come into view on the outer surface of the structural elements. However, this corrosion of steel fibers at the surface of the concrete is not structurally considerable. Experimental investigations have shown that even in an aggressive environment with high potential corrosion, rusting of the steel fibers will not permeate beyond a depth of 2 mm from the outer surface of the concrete, because the UHPdC matrix is at least 20 times more impermeable compared to conventional concrete, thereby, oxygen, moisture and chloride ions are not able to penetrate deeper into the concrete. Therefore rusting of steel fibers will stop at the surface rust zone and will not spread further. Although, the steel fibers at the surface of the concrete will rust and expand 30% of its original volume; however, due to the small size of the steel fibers, this increased volume due to the expansion will not produce adequate internal stress to spall the adjacent ultra high strength concrete. Hence, at serviceability conditions, the possibility of rusting of the internal steel fibers is insignificant (Voo, 2006c).

2.7 Features of the UHPdC Members

Based on the exceptional material characteristics of UHPdC, members made from UHPdC are supposed to have the following features:

2.7.1 Aesthetic

In terms of aesthetic, based on the elimination of coarse aggregates, superior homogeneity and granular packing distribution of the UHPdC matrix, products made from UHPdC are capable of achieving extraordinary finished surface compared to conventional concrete. Painting or coating is also not needed as the natural fair-face concrete finish will maintain its properties over time (Voo and Foster, 2010).

2.7.2 Workability

Although extremely low water cement ratio (W/ C less than 0.20) in UHPdC leads to a remarkable reduction in the porosity of the UHPdC matrix, and improves impermeability; thereby, results in significant durability and strength; however, in order to have adequate flowability, an ultra high-range PCE based superplasticizers should be used. Thus, UHPdC behaves similar to self compacting concrete (SCC). This characteristic enables the opportunity of casting very slender elements (Voo and Foster, 2010; Abdelrazig, 2008).

2.7.3 Durability

According to Graybeal and Tanesi (2007), apart from the curing treatment used, UHPdC has a very dense matrix with very small and discontinuous pores which leads to extensively improved durability properties compared to NSC and HPC. However, steam-based curing increases the degree of the concrete hydration, enhances the microstructure of the concrete, and reduces its permeability; thereby, it can considerably increase the durability properties of
UHPdC. For instance, it notably increases the abrasion resistance and remarkably decreases the ability of chloride ion to penetrate into the concrete.

### 2.7.4 Ductility

In order to improve the tensile fracture properties of UHPC matrix, ultra-high strength micro steel fibers should be added to provide ultra high performance-fiber reinforced concrete (UHP-FRC) which is commonly known as UHPdC. According to Rossi et al. (2005), the addition of the steel fiber significantly improve the ductile behavior of UHP-FRC until flexural failure and the ultimate tensile strain capacity of UHP-FRC up to $5 \times 10^{-3}$ can be achieved. According to Voo and Foster (2010), due to the bridging effects of the steel fibers which limits crack propagation, displacement-hardening behavior can be seen in UHPdC specimens. Besides, multiple fine cracks present the significant ductility of UHPdC specimens compared to conventional RC.

### 2.7.5 Sustainability

On the subject of sustainability, UHPdC technology is a green technology which supports the concept of sustainable development. In other words, using UHPdC enables slender sections thereby, using less cement in the concrete and using less concrete in the members. According to shocking reports of many scientists worldwide, global warming is the most destructive problem which people encounter nowadays. With using UHPdC some preliminary savings in terms of cost, lower embodied energy and CO$_2$ emissions can be achieved compared to conventional approaches. In addition, its sustainability is even more considerable than others types of concrete with respect to life-cycle (Voo and Foster, 2010).

### 2.8 UHPdC Benefits

UHPdC as a new generation of sustainable construction material has the potential to be used in many structural and non-structural applications due to its extraordinary characteristics such as significant strength and durability (Matte and Moranville, 1999; Roux et al., 1996; Torrenti et al., 1996; Richard and cheyrezy, 1995).

Recently, UHPdC has been recognized as a new construction material for precast prestressed concrete highway bridges due to its reduced maintenance cost compared to steel and conventional concrete bridge girders. In addition, secondary shear reinforcement is not required in the UHPdC bridge girders due to its improved tensile behavior (Voo et al., 2010; Voo et al., 2006). The elimination of the conventional steel reinforcement bars and stirrups can lead to a considerable savings in human labors, supervision and quality control. Therefore, in terms of construction management, the construction time and labor costs may also be drastically reduced, which will result in saving immediate project costs. In addition, it will lead to save considerable maintenance costs and also long-term service costs. Besides, by using UHPdC, due to elimination of conventional reinforcement and the self-heating potential of UHPdC after cracking, designers and architects will have flexibility and freedom of innovative design which enables design of more irregular and thin concrete structures which are more aesthetically interesting (Voo and Foster, 2009).

Also, handling, transportation and installation of UHPdC members are more convenient due to the ultra-light weight property of UHPdC, usually by a factor of two, compared to conventional reinforced concrete (RC) or prestressed concrete (PC) elements. Thereby, it will...
lead to additional cost savings and increase safety margins in the construction procedures (Voo, 2006a). In terms of structural design, concerning long-term behavior, UHPdC demonstrates remarkable characteristics such as low creep and shrinkage, thereby most of the design considerations associated with time dependent strains can be eliminated (Voo and Foster, 2009; Cheyrezy, 1999; Rechard and Cheyrezy, 1995).

UHPdC offers excellent durability with high impermeability against physical and chemical aggressive environment, high resistance to corrosion, abrasion and impact loads. Due to the low and discontinuous porosity of UHPdC, mass transfer is minimal; thereby, penetration of liquid, gas or radioactive materials almost impossible. These characteristics make UHPdC unique for the storage of nuclear waste and hazardous material (Voo and Foster, 2009; Matte and Moranville, 1999; Torrenti et al., 1996; Rechard and Cheyrezy, 1995).

Gilbert et al. (2000) compared the structural steel sections with the corresponding prestressed UHPdC beam and column sections with equivalent bending strength and flexural toughness as shown in figure 2. The comparisons showed that the UHPdC members can be manufactured with similar strength, toughness and weight to structural steel members; however, the UHPdC members have remarkable durability which eliminates the necessity of corrosion protection in an aggressive environment.

![Figure 2: Comparisons between UHPdC and Structural Steel (Source: Gilbert et al., 2000)](image)

2.9 Evolution and Applications of UHPdC

Reactive powder concrete (RPC) was firstly introduced by Richard and Cheyrezy (1994 and 1995) in the mid 1990’s which the compressive strength of the RPC was greater than 200 MPa and modulus of rupture of 25 to 50 MPa have been reported. According to Adeline et al. (1998), the first application of RPC was the RPC in-filled steel tube composite used in the construction of a footbridge in 1997 at Sherbrooke, Canada. Since then, RPC has caught the attention of academics, engineers and many governmental departments worldwide. Deem (2002) reported that the first fully RPC/UHPdC footbridge spanning 120 meters in the world was constructed in Seoul, South Korea in 2002. Subsequently, a motorway bridge was designed by VSL (Australia) at Shepherds Gully Creek, Australia, and was opened to traffic in 2005 (Cavill and Chirgwin, 2003). Accomplished bridge projects using RPC/UHPdC such as Sherbrooke footbridge (in Canada), Seonyu footbridge (in South Korea), Bourg-Les-
Valence Bridge (in France), and Shepherds Gully Creek Bridge (in Australia) emphasize the high capability of UHPdC to be used in infrastructural projects (Voo and Foster, 2009). Figure 3 presents a schematic drawing showing the evolution of UHPdC technology with respect to structural and architectural applications from 1995 to 2010.

According to FHWA tech-note on UHPdC (Graybeal, 2011), the UHPdC can be used in a broad range of highway infrastructure applications due to its high compressive and tensile strengths and its enhanced durability properties; thereby allowing a longer design/service life and thin overlays, claddings, or shells. In USA, three UHPdC prestressed concrete girder simple-span bridges have been constructed. In addition, UHPdC is also being considered to be used in a range of other applications such as precast concrete piles (Vande Voort et al., 2008), seismic retrofit of substandard bridge substructures (Massicotte and Boucher-Proulx, 2010; Brühwiler and Denarié, 2008), thin-bonded overlays on deteriorated bridge decks (Schmidt et al., 2008), and security and blast mitigation applications (Green, 2010; Rebentrost and Wight, 2009). According to Cavill and Chirgwin (2003), UHPdC is the best choice to be used in bridge constructions specifically when the bridge is located in an aggressive environment, when the weight is an important issue during construction as well as in the final structure, when fatigue or impact loads are serious issues, and when there are some priorities for architectural concerns.

Abdelrazig (2008) mentioned some of the projects accomplished in 2003 to 2005 using Ceracem® as shown in table 3, which also represent the various areas of UHPdC applications.

| Project/Client                  | Application                              | Year       |
|---------------------------------|------------------------------------------|------------|
| 1. Bridge 7 at Villepinte       | Decorative façade panels                 | 2003       |
| 2. Underpass at St-Lô           | Precast cornices                         | 2003       |
| 3. Toll barrier at Millau       | Slender prestressed shell structure      | 2003-2004  |
| 4. Aqueduct over the LGV Est    | Prestressed canal aqueduct               | 2004       |
| 5. Shell Petrochemicals plant   | Impermeable bulkheads                    | 2004       |
| 6. Renovation of GECTER building| Slender, fire resistant columns          | 2004       |
| 7. Lecture theatre at Cachans College | Acoustic panels                           | 2004       |
| 8. Valabres viaduct             | Strengthening of a pier                  | 2004       |
| 9. St-Julien canal, Mt Denis    | Anti abrasion lining                      | 2004       |
| 10. Marseille City Hall          | Planting containers                      | 2005       |
| 11. Viaduct over the Cher        | Decorative facing panels                 | 2005       |
| 12. Zonnestraal monument (NL)   | Innovative structure with complex shapes & design | 2005       |

(Source: Abdelrazig, 2008)

UHPdC is commercially available in Malaysia under the trade-mark Dura® since 2006. Recently several projects have been accomplished using Dura-UHPdC in Malaysia as follows:

- The world first portal frame building named Wilson Hall with a roof coverage area of 2861 m² was constructed using the precast Dura-UHPdC system in 2008 (Voo and Poon, 2008).
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Evolution of UHPC Technology

Figure 3: Evolution of UHPdC technology (Source: Voo, 2006a)
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- The total of 56 m long anti-climb protective wall panel with a total height of 7 m and a total width of 2 m was placed at the Wilson Hall in 2008. Each wall panel has a self-weight of 2400 kg per piece (Poon et al., 2009).

- Dura-UHPdC L-shaped short-retaining wall with the dimensions of 3 m in length, 1.5 m in height and 30 to 50 mm thick was lately utilized in the construction of a 90 m long monsoon drain for a housing development project in Ipoh, Malaysia. Dura-UHPdC short-retaining wall has a self-weight of 260 kg/m; however, conventional RC L-shaped wall weighs 1200 kg/m (i.e. five times lighter than the conventional RC wall) (Voo and Foster, 2010).

- The medium traffic motorway bridge crossing a river named Sungai Linggi, connecting two villages called Kampung Linsum and Kampung Siliau was constructed in Negeri Sembilan, Malaysia in January 2011. The bridge was constructed using a single 50 m long, 1.75 m deep and 2.5 m wide at the top U-trough girder, with a 4 m wide cast-in-situ 200 mm thick reinforced concrete deck in the top. To date, this bridge is the first UHPdC composite motorway bridge in Malaysia and may be the longest one in the world (Voo et al., 2011).

- A newly medium traffic motorway bridge crossing a river at Kampung Ulu Geroh was constructed in Perak, Malaysia in February 2012. The bridge was constructed using two pieces 25 m long, 1.5 m wide and 1.325 m deep T post-tensioned beam. To date, this bridge is the first full UHPdC motorway bridge in Malaysia using the UHPdC beam deck system.

UHPdC as a new generation of ultra-high performance sustainable construction material can be used in the fabrication of precast elements for civil engineering, structural and architectural applications (Voo and Poon, 2009). In general, the applications of UHPdC can be summarized into the following categories:

1) Infra-structural application: such as ultra-light and slender sections for pedestrian and highway bridges.

2) Impact resistance structures: such as security panels against impact, seismic and blast loads, crash safety barriers.

3) Prestressed elements: such as piles, culverts, retaining walls, pipes, safety vaults and etc.

4) Building applications: such as ultra-slender beam, slab and column systems, long span floors and roofs.

5) Other applications: such as architectural features, acoustic barrier, structural walls, marine/sea walls and decks, anchorage plates, leave in-place forms/moulds, container, storage tanks (Voo, 2006b).

2.10 Commercial UHPdC Blends

Within the last two decades, significant research projects had been conducted by the academics and engineers around the world in order to industrialize UHPdC technology as an
alternative construction material that supports the concept of sustainable development (Voo and Poon, 2009). So far many researchers around the world have developed such concretes that could be categorized as UHPdC such as Ductal®, Ceracem®, Densit®, Ducon® and Dura® as shown in table 4. Although there are differences between these types of UHPdCs; however, there are many overall similarities.

| UHPdC Blends | Established Date | Established Place |
|--------------|------------------|-------------------|
| Densit®      | Developed in 1960’s | Denmark           |
| Ductal®      | mid1990’s-current | France            |
| Ceracem®     | 2000-current     | France, Swiss     |
| Ducon®       | 2004-current     | Germany           |
| Dura®        | 2006-current     | Malaysia          |

Note: *Licensed to Canada, Australia, Japan, Europe, and USA.

4. Conclusion
Noticeable development has been made in concrete technology during the last two decades. One of the significant advances in the 20th century was the development of a new generation of highly cementitious based composite material known as Ultra-High Performance ‘ductile’ Concrete (UHPdc) with compressive strength over 150 MPa and flexural strength over 30 MPa and remarkably improvement in durability similar to natural rocks. Since the first introduction of UHPdc in 1994 by Richard and Cheyrezy, extensive research and development on this material has been undertaken by numerous research groups and engineers worldwide in hopes to promote UHPdc as an ultimate sustainable construction material for the future. Over the years, the material characteristics of UHPdc have been studied in depth and its practical applications have been demonstrated in various countries throughout the world. Some of the most common applications consist of pedestrian and motorway bridges, archi-structural feature such as built facades, retaining walls, bridge joint, airport runway deck, beam/column systems and many others. The UHPdc technology including summary of the material characteristics of a Malaysian UHPdc blend (i.e. Dura®), the principles of UHPdc development, its mix design, its advantages, and its applications is reviewed in this paper.

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