Classification of Ultra-high Performance Concrete (UHPC)

A. S. J. Smith, and G. Xu

Abstract — Ultra-high performance concrete (UHPC) been an advanced concrete introduced as reactive powder concrete (RPC) over twenty years ago, is now being employed for use in the construction industry of some developed countries like China, Germany and United States of America. Its excellent properties in structural performance and durability make it the civil engineering material that will reshape the future of the construction industry in terms of structural performance; and this paper aims at helping construction experts and developing countries to understand and accept UHPC for use in everyday construction works. The paper gives an in-depth review on the classification of UHPCs based on mix proportion and mechanical properties. Firstly, the mixture design and the mechanical properties of UHPC were discussed. Then UHPC was classified into different types based on mechanical properties and the manufacturer's modification of the ingredients used for reactive powder concrete or multi-scale cement composite production. This review shows that Funk and Dinger model (also known as Modified Andreasen and Andersen model (MAA)) is the most accepted and widely used mix design method for UHPC. It also revealed that UHPC's compressive strength, tensile strength and flexural strength are in excess of 150, 7 and 40 MPa respectively. It further classified UHPC into BCV®, BSI®, Cemtec®, Ceracem, Ductal, DURA and UHPC with coarse aggregate; and this classification (especially UHPC with coarse aggregate) is a good sign that local materials can be incorporated into UHPC by developing countries for cost minimisation.

Key words — Classification, mechanical properties, mixture design, ultra-high performance concrete.

I. INTRODUCTION

Ultra-high performance concrete (UHPC) is a concrete class with exceptional strength compared to conventional concrete or high strength concrete (HSC). It possesses a better rheological, mechanical and durability properties [1]; and has proved to be the civil engineering material to reshape the future of the construction industry in terms of structural performance [2]. Generally, UHPC has a compressive strength of at least 150 MPa [3], achieved using high amount of powder (cement and silica fume/other pozzolanas), nano/micro meter size fine aggregate (usually quartz sand), fibres, superplasticizer, extremely small amount of water-cement/water-binder ratio (w/c or w/b) as its ingredients [4], [5]. Infact, UHPC was initially used to describe a mixture containing silica fume-cement, fibre reinforcement, superplasticizer with a very low w/c or w/b and a very fine

quartz sand without coarse aggregates, making some researchers to suggest that UHPC is not a concrete, because of the absence of coarse aggregate in the mixture [4]. However, the term 'concrete' is selected rather than 'mortar' to describe UHPC added with fine steel fibres to enhance the ductility [6]. UHPC without fibres behaves as a very brittle material; and so, steel or carbon fibres incorporated into its mixture, enhances its ductility property [6], [7]. The market value of UHPC in America was estimated to be about USD\$365.1 million with roads and bridges taking the largest application segment of 42% in 2006 [8]; and the global market size is expected to grow into billions of U.S. dollar in the nearest future due to its gradual acceptance and usage in various countries like Australia, China, France, Germany, Japan, Malaysia, South

Korea, and the United States [9]. Some major projects involving UHPC include: the Bourg-les-Valence bridge built with BSI® in France [10], the Shawnessy tramway station in Calgary, Canada [11], the South Korean Seonyu bridge [12], the Horikoshi C-ramp and the Akakura Onsen Yukemuri bridges [13], the repair of Japan's Hosokawa river tunnel with UHPC [14]. Some examples of UHPC include: Beton composite vicat, beton special industrial, cemtec, compact reinforced composites (CRC) [15], Dura [16], [17], Ductal [18], multi-scale cement composite (MSCC) [19] and reactive powder concrete (RPC) [20].

UHPC has passed through several stages of development from the 80s to this present time, with the aim of finding the right ingredients, special production method that will lead to high strength UHPC and finding cost effective materials that can partially replace the conventional UHPC materials in order to produce cheap UHPC. This development stages have also witnessed several proposal of many UHPC mixture design methods based on particle packing in order to achieve the aforementioned aims. However, most of the developed mixture design methods have some shortcomings, prompting researchers to improve the already existing methods until the currently used method was developed. For instance, the curve of packing density verses fines content for binary mixtures in linear packing density model (LPDM) developed by Stovall et al. [21] exhibits kinks at maximum packing density value (which was its shortcoming); leading to improvement and subsequent development of the solid suspension model (SSM) by De Larrard and Sedran [22]. Also, most of the researches on UHPC so far are conducted on its mechanical properties using small size specimens like

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cubes, cylinders, dogbones and prisms. For instance, Mujamil *et al.* [23] investigated the mechanical properties of UHPC using conventional water curing under room temperature and accelerated boiled water curing; and proposed a direct relationship between the two curing regime used. Naemi and Moustafa [24] studied the uniaxial compression behaviour of UHPC confined by steel spirals. Prem *et al.* [25] used experimental research to evaluate the mechanical properties of UHPC; and findings showed that the strength properties of UHPC are greatly influenced by fibre volume fraction and fibre aspect ratio.

Although many researches have been conducted on the mix design and mechanical properties of UHPC, condensed and simplified classification, mix design approach and ways of estimating the mechanical properties of UHPC from experiment is seldomly reported. So, this paper is therefore targeted at reviewing the classification of UHPC based on its mechanical properties and the gradual development of UHPC mix design to the presently acceptable method in order to simplify the mix design and the evaluation of its mechanical properties for experts in the construction industry.

II. UHPC MIXTURE DESIGN

The primary aim of developing UHPC mixture design is to rigorously select components using size and particle distribution as parameters to produce concrete that has superior rheological and mechanical properties when compared with a control/reference concrete like normal strength concrete (NSC) or HSC. The Principle of particle packing simply described as the volume of each ingredient in a unit volume, is the design approach generally used for UHPC mixture design to obtain optimum particle packing density, and to also produce ingredients for concrete with minimal voids and high strength [26]. Particle packing improves not only the strength property of UHPC but also its durability due to reduced porosity because packing density can further improve concrete strength even when reduced w/b proves ineffective [27]. Furnas [28] provided the foundation for the mathematical formulation of HPC's mix design involving discrete and continuous distribution. It is believed that the optimum density of a well packed discrete particles is approximately 60%; meaning that, for two class (larger and smaller) sizes, the larger sizes are first packed to 60% density, after which the smaller sizes then fill up 60% of the remaining 40% voids leading to only unfilled void of 16% for two class sizes [29]. For continuous distribution involving many class sizes, the filling continues in order of decreasing fineness. Particle packing method used for UHPC mixture design is divided into discrete element model, analytical model and optimization model.

Discrete element packing model involves the use of computer programs to perform static or dynamic simulation of a random generator system. The static simulation arranges particles haphazardly in a specified space in order of decreasing size without changing their position after placement. So, overlap particles are rejected and the generation process continues to the next solution and the final solution which contains particles of different sizes in a three

dimensional space that do not touch each other; and hence produces a uniform particle distribution. However, the result of static simulation is not fit to be considered as a packed structure because it underestimates the overlapping process. It also neglects the principle of particle interaction, which is the major principle of concrete production. For instance, the static nature of the static simulation model developed in the past [30]-[32] makes it impossible for poisson field positions of the particles to be exploited, which by implication often results in having uniform dispersion of particles instead of being close together. All these shortcomings led to further improvement and the proposal of dynamic simulation. The dynamic simulation uses linear and rotational velocity as well as Newtonian motion algorithm to effect the change of particle position during simulation process until a target packing level is reached [33]. In the dynamic simulation model called SPACE (Software Package for the Assessment of Compositional Evolution) system developed by Stroeven and Stroeven [34], clustering effect (resulting from ingredient mixing) was accounted for, by element motion and inter-element interaction modelling. SPACE provides a better simulation results than static models for structure-sensitive properties like van der Waals force between particles of well packed hydrated cement and the interface, but the drawback of this model is in its design for spherical elements.

Analytical packing model involves the use of formulations to estimate UHPC ingredients to achieve minimal voids. A typical mix design approach from the concept of analytical packing model is the linear packing density model (LPDM) that was developed by Stovall *et al.* [21] based on Mooney [35] suspension viscosity model. In LPDM, a comprehensive and inclusive theory of how multi-sized grains are packed was developed and the packing density for a crowding particles and multi-sized grains is expressed in (1) as a function of the fractional solid volume of each grain size present. The main finding in LPDM is its ability to describe how the size classes of the materials interact.

$$c(t) = \frac{\alpha(t)}{1 - \int_d^t y(x)f(x/t)dx - (1-\alpha(t)) \int_t^D y(x)g(t/x)dx} \quad (1)$$

where, c is the packing density (i.e. minimum $c(t)$ when $y(t) > 0$), t is grain size, $y(t)$ is voluminal size distribution of the grain mixture with $\int_d^D y(x)dx = 1$, d is minimum grain size, D is maximum grain size, $\alpha(t)$ is specific packing density of the t -class, $f(x/t)$ is function accounting for particles loosening effect, $g(t/x)$ is function accounting for particles wall effect.

The calculation of “ c ” using LPDM when compared to experimental results of Standish and Borger [36] and McGeary [37] showed good agreement, however, its linear nature was a major drawback as packing density-fines content curves for binary mixture exhibit kinks (as shown in Figure 1) at maximum “ c ” value; prompting De Larrard and Sedran [22] to use optimum paste thickness concept to develop the solid suspension model (SSM) expressed in (2) for optimization of ingredients. Through SSM, it became possible to use extremely low w/b to make UHPCs with extremely high strength in compression. The discovery in

SSM is the introduction of the virtual packing density (that is, the maximum packing density obtained from placing the particles one by one). The shortcoming of the formation of angular point at the maximum packing density in LPDM that was addressed by SSM is shown in Figure 1.

$$c(t) = \frac{\beta(t)}{1 - \int_a^t y(x)f(x/t)dx - (1 - \beta(t)) \int_t^D y(x)g(t/x)dx} \quad (2)$$

where, $\beta(t)$ is the virtual specific packing density of t -size grains

The overall $\beta(t)$ is estimated using (3) for a t -size class of N different types of grains, each one characterized for $i = 1$ to N , by its own partial volume $y_i(t)$ (noting that $\sum_{i=1}^N y_i(t) = 1$) and $\beta_i(t)$.

$$\frac{1}{\beta(t)} = \sum_{i=1}^N \frac{y_i(t)}{\beta_i(t)} \quad (3)$$

Fig. 1. Packing density-fines content curve for LPDM and SSM [33].

De Larrard and Sedran [38] further used creep and shrinkage as parameters besides rheological and mechanical properties to improve the solid suspension model (SSM) into compressive packing model (CPM) which uses both virtual and actual packing density concept that assumes an additive interaction between the wall effect of coarser grains and the loosening effect of finer grains. CPM is a computer aided mix design software for high performance concrete (HPC), which modified the aggregate coefficient (K_a) in (4) [39] into a compaction index, K as expressed in (5).

$$f_{c28} = \frac{K_a R_{c28}}{\left[1 + \frac{3.1(w/c)}{1.4 - 0.4 \exp(-11s/c)}\right]^2} \quad (4)$$

where, f_{c28} is the compressive strength after 28 days, K_a is aggregate coefficient (it varies by $\pm 10\%$ about a value of 4.91), R_{c28} is cement strength as measured on ISO mortar, w/c = total water (for all mixtures) to cement ratio, s/c = silica fume to cement ratio.

CPM involves: firstly dividing a mix of particles into n classes of monosize particles, computing the bulk volume of the dominant class i (i.e., the virtual packing density), noting the smallest computed value among the n values. Secondly, it computes the actual packing density; and finally, the compaction index (K) is used to characterize the placing

process by considering the difference between the actual packing density and the virtual packing density.

$$K = \sum_{i=1}^n K_i = \sum_{i=1}^n \frac{\Phi_i}{1 - \frac{\Phi_i}{\Phi_i^*}} \quad (5)$$

where, K is compaction index that shows how virtual packing values are close to the actual packing's, K_i is compaction index of each dominant class, Φ_i = volume of the i grains in the compacted mix, Φ_i^* is maximum value of Φ_i introduced into the mix.

In CPM, it was found that the compaction index allows the incorporation of both the fresh properties (through yield stress, plastic viscosity and slump) and hardened properties (like heat of hydration, strength and deformability in terms of creep and shrinkage) of HPC into the mix parameters, in order to produce the best estimates for the packing density of a coarse and fine aggregates mixture with a sand/total aggregate ratio (S/A) of 0.40-0.60. However, comparison of experimental results and data with CPM [40] revealed that CPM is not suitable for packing density estimation beyond S/A of 0.40; and this therefore makes optimization method the preferable mix design for UHPC.

Optimization method involves modifying the particle size distribution (PSD) of the various UHPC ingredients against an existing grading curve until optimum packing density and minimum porosity is achieved. Fuller and Thompson [41] presented the first grading curve based on (6) which recognizes the maximum possible size in a given distribution and uses a distribution modulus (q) of 0.5 as suggested by Fuller and Thompson.

$$P(D) = 100 \times \frac{D^q}{D_{max}^q} \quad (6)$$

where, $P(D)$ is the volume fraction of the total solids smaller than size D , D is the particle size (μm), D_{max} is the maximum particle size (μm), q is the distribution modulus (found using the proportion of fine and coarse particles).

The format of (6) represents the relation between a perfectly packed arrangement surrounding a specific coarse particle and a fine particle. Andreassen and Andersen [42] also used (6) to propose a grading curve (called Andreassen and Andersen (A & A) curve) for continuous PSD; and Andreassen and Andersen model can be used to achieve a minimal porosity through optimal PSD of the various ingredient particles in the concrete mix. Andreassen and Andersen suggested a q value in the range of 0.33 to 0.5, but found from experiment that q value of 0.37 gives the optimum packing density. Andreassen and Andersen model, as a limitation, only considers the maximum size of the ingredient being designed, failing to give a well packed concrete for mixes containing a very fine ($< 250 \mu m$) ingredients. So, Funk and Dinger [43] proposed that a finite minimum size of a particle must be included in any realistic PSD, and hence modified Andreassen and Andersen equation to develop the model in (7). Funk and Dinger found that the model (based on experiment) gives the best packing density for ultra-fine granular mixtures. This is because the model permits the use of a lower q value, which by implication

allows more fine particles to fill up the voids between particles of larger sizes. q is a very important factor in Funk and Dinger model as it is used to change the ratio between coarse and fine particles. Moreover, it allows the use of one equation for the targeted grading curve in order to compose the ideal graded mixtures for different concretes.

$$P(D) = 100 \times \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \quad (7)$$

where, D_{min} is the minimum particle size (μm); $q < 0.25$ for fine particles.

The application of Funk and Dinger model is basically seen in the comparison of the curve of each concrete ingredient with the grading curve from (7) using different q values. It is recommended that q be varied between 0.2 and 0.365 when a particle is being optimized as the use of 0.365 in (3) results in the densest packing of a particle. Meanwhile, a slight change below and above 0.365 leads to slight and substantial changes in porosity respectively [43]. Funk and Dinger's mix design method has been used in several studies over the years for the design of UHPC ingredients; and it has proved to be the most efficient method. For example, Yu *et al.* [44] used (7) to design a dense and homogeneous UHPC that has as low as 650 kg/m^3 cement. Yu *et al.* [45] developed an optimization algorithm based on Least Squares Method using Funk and Dinger model as a target curve to assess the properties of ultra-high performance fibre reinforced concrete (UHPFRC). And it was found from Yu *et al.* [45] that UHPFRC's workability can be improved, and its cost can also be minimized by replacing the large content of unhydrated cement (left after 28 days curing) by fillers. Fan *et al.* [46] implanted steel fibres into Funk and Dinger model to propose a new mix design that can be used to find the equivalent spherical diameter of steel fibres; and found that this new mix design can be used to minimize the negative effect of steel fibres on UHPC packing. Peng *et al.* [47] optimized the mix proportion of RPC based on Funk and Dinger equation, and also developed a mix proportion design method for RPC containing phosphorus slag that attains a very high strength in less than a week. Fig. 2 shows the PSD curve for Fuller and Thompson, Andreasen and Andersen, and Funk and Dinger.

Other researchers have also used different approaches including statistical models to develop several mixture design methods for UHPC. Laskar [48] used the correlation between concrete rheology and compressive strength to propose HPC design concept that also allows the estimation of key rheological parameters for a reference strength. Fennis *et al.* [49] developed the compaction-interaction packing method of mix design using surface forces as a modelling parameter. Ghafari *et al.* [50] reported a statistical approach used to make economical UHPC with a low cement ingredient that gives high compressive strength without thermal curing. So the generally accepted method of preparing UHPC by researchers is to technically add the following ingredients together: high amount of powder (cement and silica fume/other pozzolanas), nano/micro meter size fine aggregate (usually quartz sand), fibres, high range water reducer or superplasticizer, extremely low w/c or w/b.

Although several efforts have been made to develop UHPC mixture design, it should be noted that workability and strength are the indices mostly used for UHPC mixture design despite the importance of UHPC durability. Also, the inter-particle forces due to the extremely fine nature and shape of UHPC ingredients are also not considered. Therefore, new mix design model that also considers key durability properties as well as the shape and fine nature of UHPC ingredients need to be developed. This may be done through the use of statistical analysis tools like regression to develop series of equations from the effect of different contents of UHPC ingredients on any durability properties; and incorporating them into any of the applicable existing UHPC design methods.

Fig. 2. PSD curve used for UHPC optimization model [33].

III. MECHANICAL PROPERTIES OF UHPC

A. UHPC's Compressive, Tensile and Flexural Strengths

UHPC exhibits an extremely high strength in compression, usually not less than 150 MPa [51]. This property is one of the key design indices that influence the bearing capacity of a concrete member; and so it is utilized as an advantage to design all UHPC members with small dimensions [52]. Studies have shown that the compressive strength of UHPC specimens is enhanced by thermal curing [53], [54]. UHPC made using small size cube specimens gives higher experimental compressive strength than bigger sizes and cylindrical ones [55]. UHPC behaves in a linear elastic manner up to about 80% of its compressive strength [56]; and the compressive strength of a UHPC's cylinder and cube specimens subjected to a uniaxial compression test is estimated using (8) and (9) respectively. Figure 3A shows a typical behaviour of UHPC subjected to uniaxial compression force.

$$f_c = \frac{P}{\pi r^2} \quad (8)$$

$$f_c = \frac{P}{l^2} \quad (9)$$

where, f_c is the compressive strength of UHPC, P is applied load, r is radius of the cylinder, l is the length of the cube.

Concrete is generally believed to perform poorly in tension but UHPC's strength in tension is overwhelmingly high,

usually not less than 7 MPa [57], when compared with normal concrete. The tensile strength of UHPC is greatly enhanced by fibre presence and described using its ductile behaviour. UHPC specimen when subjected to uniaxial tension test has four phases of response [58] as shown in Figure 3B, and for a cylinder specimen, it is determined using ASTM C496/C496M-11 [59]:

$$f_{st} = \frac{2P}{\pi lD} \quad (10)$$

where, f_{st} is tensile strength, P is the applied load that caused failure in tension, l is the length of the cylinder specimen, D is the diameter of the cylinder specimen.

The strength of UHPC in flexure, provided mainly through steel fibres [60], is usually higher than 40 MPa; and it is mainly influenced by fibre aspect ratio, fibre orientation and type of aggregate [61], [25], [62]. Research findings have shown that UHPC specimens cured thermally and those made with quartz sand instead of conventional sand exhibit higher strength in flexure [63], [64], [65], with its response shown in Figure 3C. UHPC's flexural strength is estimated based on ASTM C1018 [66] recommendation using ASTM C78 [67]:

$$R = \frac{P \times L}{b \times d^2} \quad (11)$$

where, R is the modulus of rupture or cracking stress, P is the first crack load or ultimate load, L is the specimen span length, b is the average width of specimen, d is the average depth of specimen.

Fig. 3A. Typical UHPC's Compressive strength of UHPC [68].

Fig. 3B. Typical UHPC's tensile strength of UHPC [58].

Fig. 3C. Typical UHPC's flexural strength [69].

B. UHPC's Stress-Strain Relationship, Elastic Modulus and Poisson's Ratio

UHPC's stress-strain relationship (shown in Fig. 4A and 4B) whether loaded in compression or tension, depends on fibre presence and its orientation in the mix composition. UHPC without fibres fails abruptly without prior signs with nearly linear stress-strain diagram; but those with fibres have both elastic and strain hardening phases with either a short or long descending curve after attaining its ultimate strength [51], [25]. When UHPC contains high fibre quantity, its stress-strain curve usually has an inflection point where the stress drops and rises again to its peak in a continuously repeated pattern until the UHPC matrix-fibre bond is lost [70]. The stress-strain behaviour of UHPC in compression can be evaluated using [71]:

$$\frac{f_c}{f'_c} = \frac{n(\epsilon_{cf}/\epsilon'_c)}{n-1+(\epsilon_{cf}/\epsilon'_c)^{nk}} \quad (12)$$

where, f_c is the compressive stress, f'_c is the peak compressive stress, ϵ_{cf} is the longitudinal compressive strain, ϵ_c is the peak strain resulting from the compressive strength, n is the curve fitting factor, k is the factor accounting for post-peak decay in stress.

Fig. 4A. Stress-strain relationship of UHPC without fibres [72].

Fig. 4B. Stress-strain relationship of UHPC with fibres [72].

The modulus of elasticity of UHPC is usually in excess of 40 GPa, and it is influenced by mixture design, type of aggregates and curing method [73]. The poisson's ratio of UHPC is in the range of 0.19-0.24 [74], and it is not affected by the curing method. Equations (13) and (14) developed by Graybeal [75] and Haber et al. [76] can be respectively used to estimate the elastic modulus and poisson's ratio of UHPC.

$$E_c = 3840\sqrt{f'_c} \text{ in MPa or } E_c = 1460\sqrt{f'_c} \text{ in ksi} \quad (13)$$

$$\nu = \frac{\varepsilon_{circ,30} - \varepsilon_{circ,10}}{\varepsilon_{axial,30} - \varepsilon_{axial,10}} \quad (14)$$

where, E_c is the compressive elastic modulus, f'_c is the compressive strength of UHPC, ν is the poisson's ratio, $\varepsilon_{circ,30}$ is the circumferential strain at 30% of peak load, $\varepsilon_{circ,10}$ is the circumferential strain at 10% of peak load, $\varepsilon_{axial,30}$ is the axial strain at 30% of peak load, $\varepsilon_{axial,10}$ is the axial strain at 10% of peak load.

IV. CLASSIFICATION OF UHPC

UHPC was first introduced as RPC by Richard and Cheyrezy [77]. It came in two classes as: class 200 MPa and class 800 MPa with their mix proportion shown in Table I; but in recent times, it is classified into different types based on the manufacturer's modification of the various ingredients used for RPC or MSCC production. UHPC is classified into the following types with their typical mix ratios shown in Tables I and II:

A. Beton Composite Vicat (BCV®)

BCV® is a UHPC produced by cement manufacturer, Vicat [78] and contractor Vinci; and it is available in two versions: structural type and decoration/colour type. Its strength in compression, tension and flexure depending on the formulations is usually not less than 180, 10 and 35 MPa respectively [79]. This UHPC has been used for several projects in the past, some of which include: using it in Switzerland to floor the Lauterbrunnen footbridge. It was also used to construct stays for a rainwater treatment reservoir in Les Houches, France [11].

B. Beton Special Industrial (BSI®)

BSI® UHPC was developed by Quillery (a French UHPC developing company) in 1996 [80] as a new concrete with extremely small size particles, having about 2.5 vol. % steel fibres [81]. It is coarser than RPC [57] and it has about 220 MPa strength in compression [82]. The first industrial application of BSI® was in 1998, where it was used to produce beams that were in turn used to replace the steel beams of the cooling towers in Civaux power plant. Further application was also seen in the construction of the Bourges-Valence bridges in 2001.

C. Cemtec®

Cemtec is a UHPC developed in 2001 at the Central Laboratory for bridges and roads in Paris, employing Rossi et al. [83] Multi-Scale Fibre Reinforced Concrete concept. Cemtec contains three different metal fibres unlike the two

in MSCC. It also has 11 vol. % fibres unlike the 7 vol. % in MSCC; and both short and long fibers are incorporated into its mix in order to improve its tensile strength, bearing capacity and ductility. Its strength when compressed is about 205 MPa; it has about 55 GPa as its modulus of elasticity and has a poisson ratio of 0.21 [84]. The fibre length of this UHPC ranges from 1 to 20 mm [85].

D. Ceracem

Ceracem was developed in 2000 by Sika in partnership with the Eiffage company in Paris as an application of technology to BSI® [11]. Its high strength in compression (199 MPa), tension and flexure that reaches up to 227, 8.8 and 30 MPa respectively can be achieved without further heat treatment after the initial thermal curing [86]. It is produced in premix form, and it is composed of 47% cement, 7% microsilica and 45% fine aggregate [87] plus the other usual UHPC ingredients. This UHPC usually contain 2 to 3% fibre volume content whose length is between 13 and 20 mm [85]. One major application of this UHPC was in the construction of the toll-gate roof for the Millau's viaduct in 2003.

E. Ductal

French UHPC developing company called Bouygues in conjunction with Lafarge company and Rhodia company developed this UHPC in 1996 [81]. It is characterized with very high compressive and flexural strengths that reach up to 207 MPa and 50 MPa respectively. It also has better durability potentials than the then RPC from which it was developed [88]. It is marketed by Lafarge Inc. and Bouygues [57]. It has been used in several projects like the construction of the Seonyu footbridge in South Korea in 2002; and the incorporation of Ductal UHPC into the state road 211 bridge construction near Athens in Georgia in 2016 [89].

F. Dura

This UHPC was introduced in Malaysia in 2006 as a pre-blended powder designed to give superior strength characteristics in compression (about 160 MPa) and flexure (about 30 MPa) [57]; as well as high structural performance using as low as 0.13 w/b [90]. It was developed and marketed by the Dura Technology Sdn. Bhd in two different weights of 10.5 kg/m³ bags and 400 kg/m³ super sacks [91]. It became available in the market as a construction material in 2009 in Malaysia for use in rehabilitating deteriorated reinforced concrete structures; and for making structural members prone to harsh environment among other applications. This class of UHPC since its introduction has been used for various applications in Malaysia, some of which include: the use of UHPC prestressed beams and columns to completely replace conventional steel beams in the Wilson Hall portal frame warehouse in Malaysia in 2012 [92]; and the use of Dura to construct a retaining wall (which was five times lighter than a similar one constructed with conventional concrete) for the 90 m long monsoon drain in Ipoh, Perak, Malaysia.

TABLE I: TYPICAL MIX RATIOS OF COMMERCIALY AVAILABLE UHPC [57], [93], [84], [86], [77]

Materials	Ratios to 2 decimal places							
	RPC 200	RPC 600	BCV®	BSI®	Cemtec®	Ceracem	Ductal	DURA
Portland cement	1	1		1	1		1	1
Fine aggregate	1.06	0.20	Premix: 1	0.96	0.49	Premix: 1	1.43	1
Silica fume	0.24	0.23		0.15	0.26		0.32	0.25
Ground quartz	-	0.39	-	-	-	-	0.30	-
Accelerator	-	-	-	-	-	-	0.042	-
Steel fibres	0.17	0.63	0.074	0.21	0.82	0.083	0.22	0.19
Superplasticizer	0.015	0.019	0.010	0.036	0.042	0.019	0.043	0.042
Water	0.16	0.19	0.075	0.19	0.17	0.083	0.15	0.22

TABLE II: TYPICAL UHPC PRODUCED WITH BASALT COARSE AGGREGATE [97], [99], [95]

Materials	UHPC1 (Ratio)	UHPC2 (Ratio)	UHPC3 (Ratio)
Portland cement	1	1	1
Fine sand	1.28	2	0.81 (Quartz sand)
Silica fume	Micro silica=0.067 Limestone powder=0.27	Silica fume=0.20 fly ash=0.40 slag=0.40	not quantified
Coarse aggregate	0.85	2	1.83
Steel fibres	2 vol. %	0.59	-
Superplasticizer	0.016	0.05	not quantified
Water	0.27	0.30	0.30

G. UHPC with Coarse Aggregate

Coarse aggregates and other chemical and mineral admixtures [51] have been incorporated into UHPC mix and cured at room temperature by various researchers to produce sustainable and cost effective UHPC. Although UHPCs are designed without coarse aggregate in order to achieve minimal paste thickness, homogeneity of paste matrix and to improve its strength [94], studies have shown that UHPCs made with coarse aggregate like basalt (< 10 mm) is less costly with better elastic modulus, workability and short mixing time [95]. UHPC with coarse aggregates also acts as a concrete material that bears up crack propagation, and hence increases the impact resistance of UHPC [96]. Yujing *et al.* [97] has reported that UHPC with crushed basalt cured on a long-term basis, exhibits higher compressive strength than that without coarse aggregates. The high cost of producing UHPC is to a large extent caused by the large quantity of powder [44] needed to fill voids, to ensure a uniform and a well packed mix without too much pores [98]. So, the use of coarse aggregate in UHPC results in the use of lower content of powder [95]. Use of coarse aggregates in UHPC has also been reported by some researchers to lead to reduced compressive, tensile [99] and flexural strengths [95]; making it impossible for strong realisation to be made on the use of coarse aggregate in UHPC members because of limited research. Hence, member performance and test on durability properties of UHPC beams, columns and slabs need to be researched. UHPC mix with different content of basalt coarse aggregate is shown in Table II.

V. CONCLUSIONS

This paper classified UHPC into different types based on its mix proportion and mechanical properties with the purpose of informing experts and developing nations on the need to use UHPC in everyday construction work. UHPC is basically designed using particle packing procedure as this helps in minimising the presence of voids and also enhances its resistance to any liquid or chemical penetration. The most accepted and widely used model for UHPC mix design is the modified Andreason and Andersen model developed by

Funk and Dinger; and its acceptance is due to its applicability in solving the problem of minimum and maximum particle size of grains in any UHPC ingredient. UHPC can be classified into BCV®, BSI®, Cemtec®, Ceracem, Ductal, DURA and UHPC with coarse aggregate based on its mechanical properties and the modification of the ingredients used for reactive powder concrete or multi-scale cement composite production. The strength of UHPC in compression, tension and flexure is usually in excess of 150 MPa (regardless of the curing process applied), 7 MPa (for all curing regimes except air) and 40 MPa, respectively. UHPC's modulus of elasticity and poisson's ratio is about 40-70 GPa and 0.19-0.24 respectively. The stress-strain behavior of UHPC in terms of having either ascending or both ascending and descending curve under compressive or tensile loading, depends on the presence and orientation of fibres in its mixture composition.

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