ULTRA HIGH PERFORMANCE CONCRETE - A NEED FOR A SUSTAINABLE AND DURABLE APPROACH IN CONSTRUCTION INDUSTRY

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ABSTRACT. Being the most popular man made material in the world, concrete is the basic building material that will continue to be in demand far into the future. It is estimated that the world's concrete production is about 6 billion cubic metres per year with China currently consuming about 40% of total concrete production. With increasing demand of concrete along with high cost involved in its production, it has become a need that some advancements should be made in concrete industry and building structures with improved quality concrete. Over the last decades, large progress has been taking place in field of concrete development. This paper will give an overview of UHPC (ultra-high performance concrete) and HPC (high performance concrete) focusing on its fundamental introduction, design, mix proportions, effects of admixtures and SP (superplasticizers), mechanical properties along with the comparison with (NSC) normal strength concrete from selected literatures showing advantages of UHPC over NSC due to improved mechanical and durability performance along with high compressive strengths. UHPC has many advantages over conventional concrete but is still in limited practice due to limited design codes and high cost. This paper also aims to spread awareness about advantages of using UHPC for better acceptance and long life spans of newly constructing concrete structures.

Keywords. Ultra high performance concrete, High performance concrete, Conventional concrete, Admixtures, superplasticizers.

INTRODUCTION

In the world of construction engineering, conventional concrete, also known as normal strength concrete is the foremost important material which has certain unmatched advantages over other materials like ease in availability, low cost of its raw materials, its simple manufacturing technology, and its convenience in forming. In most cases, it prevents corrosion of reinforcing steel bars for long periods of time due to its alkaline environment. Nevertheless, 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 environments. The cost of repairing structures which has been damaged by corrosion in the U.S. is staggering - $276 billion which is approximately 3.1% of nation's GDP (gross domestic product) [8].

UHPC is a new class of concrete that has been developed in recent decades. The main thing that makes it different from conventional concrete is the use of Steel fibre Reinforcement, and some super plasticizers along with replacement of a part of cement with Fly Ash. UHPC is gaining increased interest in many countries with the usage ranging from building components, architectural features, repair and rehabilitation, vertical components such as windmill towers and utility towers to oil and gas industry applications [1].

DEFINITION AND DEVELOPMENT OF UHPC

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 flow ability, and improved thermal resistance. These attributes lead to improved performance in severe environments [i.e., high temperature, high relative humidity (RH), chloride and sulphate attack, and carbonation] or challenging design or construction conditions (i.e., congested reinforcements, as in bents or connections). The relative term HPC was first used only for concrete having higher compressive strength. However, recently the term HPC was introduced to differentiate concretes that exhibit properties beyond just high strength. Because the expected performance for every concrete changes with its application .Until the 1970s, prior to the development of superplasticizers (SPs), concretes with strengths greater than 40 MPa were considered high strength concretes (HSC).[1] After the advent of SPs, 60–120 MPa concretes became easily achievable. The American Concrete Institute (ACI) Committee 363 has revised the definition of HSC to include mixtures with a specified design strength of 55 MPa. The concrete technology progressed slowly during the 1960's with the maximum compressive strength of about 15MPa to 20MPa. Then the concrete compressive strength almost tripled to 45MPa to 60MPa in a period of 20 years. The water reducer used at that time failed to reduce water to binder ratio (w/b) ratio further. Then during 1980's , high rate water reducers known as superplasticizers(SP) further reduced w/b ratio to 0.3 which further increased strength of concrete. With high dose of SP (superplasticizers) and silica fumes (SF), w/b ratio was further reduced to 0.16. In 1980's methods such as vacuum mixing and heat curing were used to achieve denser and high strength concrete with maximum strength which could go up to 510MPa.

Further in 1990's components were used with increased fineness and reactivity to develop rpc (reactive powder concrete) via thermal treatment. Development of RPC was considered as a revolution in the journey of advancement of UHPC. The basic concept of RPC was to prepare a dense arrangement by proper placement of particles. The characteristics of RPC are high binder content, use of silica fumes, lower w/c ratio, fine quartz powder, quartz sand, superplasticizers and steel fibres of generally 12.5mm length and 180μm in diameter. The coarse aggregate are eliminated for homogeneity enhancement in the structure. The composition of RPC along comparison with normal concrete and high performance concrete is given in Table 1 through various mechanical properties.

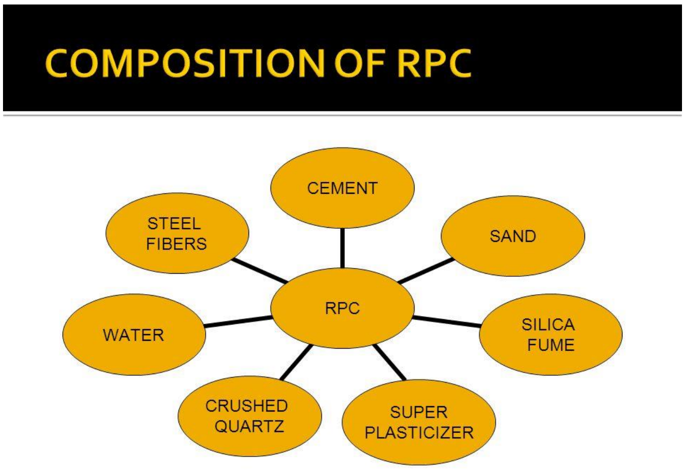

Figure 1 Composition of Reactive Powder Concrete

Table 1 Comparison between UHPC and conventional concrete in use on variousphysical properties

	COMPRESSIVE STRENGTH (MPa)	FLEXURAL STRENGTH (MPa)	YOUNG'S MODULUS (GPa)	WATER ABSORPTION (kg/m^2)	ABRASION COEFFICIENT
RPC 200	170-230	30-60	50-62	0.2	1.3
HPC	60-100	6-10	30-40	0.4	2.8
NC	20-50	2-5	30-40	2.7	4

PRINCIPLES INVOLVED IN DESIGNING UHPC.

- Minimizing composite porosity by optimising the granular size mixture through a wide distribution of powder size particle and reducing the W/B.
- Enhancement of the microstructure by the post set heat treatment to speed up pozzolanic reaction of SF and to increase mechanical properties.

- Improvement of homogeneity by eliminating coarse aggregate resulting in a decrease in mechanical effects of heterogeneity.
- Increase the ductile behaviour by adding adequate volume fraction of small steel fibres.

Application of the first four principles leads to a concrete with a very high compressive strength and the addition of steel fibres helps in improve both tensile strength and ductility of the concrete [1].

HPC AND UHPC MATERIALS AND THEIR CHARACTERISTICS

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) cements are most widely used and recommended by researchers. A cement type with a low tricalcium aluminate (C3A) content, such as ASTM Type IV (ASTM C150/C150M-17) (ASTM 2017), is preferred due to its low heat of hydration and delayed setting time.

Aggregates

The constituents of HPC and 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. Normally, coarse aggregate (e.g., diabase, basalt) smaller than10mm is used. In the case of UHPC, coarse aggregates are normally omitted; only sand between 150 µm and 4.75 mm is used. In HPC, sand finer than 250µm is not recommended because it increases the amount of fines and, hence, increases the water demand of the mixture.

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 theyincrease the ductility, energy absorption, resistance against delamination and spalling, and fatigue resistance of the concrete matrix. These fibers are of different shapes and sizes, and theyare mostly characterized by their lengthto-diameter (l=d or aspect) ratio. Material wise, the fibers are made of steel (typical sizes are l¼ 6–60 mm and d¼ 0.15–0.75 mm,with l=d¼ 30–150) or carbon, polypropylene, polyethylene, polyvinyl alcohol, nylon, polyester, glass, and other similar synthetic materials. These fibers can be used in a hybrid form in which small synthetic fibers arrest micro cracks and large steel fibers stop the propagation of macro cracks. Hybrid-fiber reinforcement results in strain hardening that is several times higher than what is obtainable with a single fiber size. Many researchers have used smaller straight steel fibers 6–13 mm long and 0.6 mm in diameter in HPC and UHPC whereas carbon fibers in UHPC were also studied by some researchers.

Chemical admixtures

The invention of water reducers or SPs revolutionized the concrete industry. With high-range water reducers (HRWRs), it is possible to obtain a flow able 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. Higher vibrations or compaction efforts were required for such concrete, which was a health concern for the labourers. This problem initiated the research on flow able concrete and the use of SP in concrete. To respond to this problem, SCC was developed. 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. The first three families (lignosulphonates, SMF, and SNF) disperse the cement matrix based on electrostatic charges, whereas PCE-based SPs use a stirring process to deflocculate the powder particles. It is observed that PCEs are much more efficient than sulphonated formaldehydes and give more flow at the same w/b ratio [8].

UHPC TODAY

Obviously, “high” is a relative term. The term “ultra-high” is more so. The Laurentienne Building in Montreal, built in 1984, used a 106 MPa high performance concrete and the Two Union Square Building in Seattle, USA, built in 1988, utilized a 145 MPa high performance concrete. Going to a UHPC with strength higher than 200 MPa certainly is another big step forward.

Various tests have confirmed UHPC’s performance in the laboratories. They show high strength and durability. Theoretically, we are able to use it for daily applications, wherever high strength and durability are beneficial. The basic principle is to use stronger aggregates, micro silica, and water reducing agents to raise its strength, steel fibers to prevent brittle failure and polypropylene fibers to increase its fire resistance, and so forth. In general, with steam curing, we are able to reach strength in the range of 200 MPa or higher. The resulting concrete basically meets all eight performance criteria of the FHWA for high performance concrete. The material itself is therefore available. The problem is the ease of application and the price.

As a matter of fact, it is possible to produce concrete with a strength as high as 700 MPa in the laboratory many years ago. But to reproduce it in a jobsite will be difficult.

The Sherbrooke Pedestrian Bridge in Canada and the Seonyu Pedestrian Bridge in Korea are certainly showcase structures for UHPC [1].

Figure 2 Seonyu Pedestrian Bridge in Korea Figure 3 Laurentienne Building in Montreal

EFFECTS OF MINERAL ADMIXTURES ON UHPC

The variation of compressive strength of high-pressure steam cured and standard cured specimens are presented in Fig 4. It may be concluded from Fig 4 that increasing FA content up to 40% cement replacement causes an increase in compressive strength values. More than 40% of FA content causes a reduction in compressive strength sharply. Furthermore, at all FA replacement levels, compressive strength of high-pressure steam cured (2 MPa, 210 °C) specimens is more than the water-cured specimens. After 8 h of high-pressure steam curing, compressive strength of control mixture is 170 MPa, while compressive strengths of FA20 and FA40 mixtures are 171.4 and 171 MPa, respectively. In other words, at 40% FA replacement level UHSC with cement content of 510 kg/m^3 can be obtained [2].

It can be seen from the Fig 4, the duration of high-pressure steam curing and preheating period also affects the compressive strength. Beyond 8 h of curing reduction in compressive strength was observed.

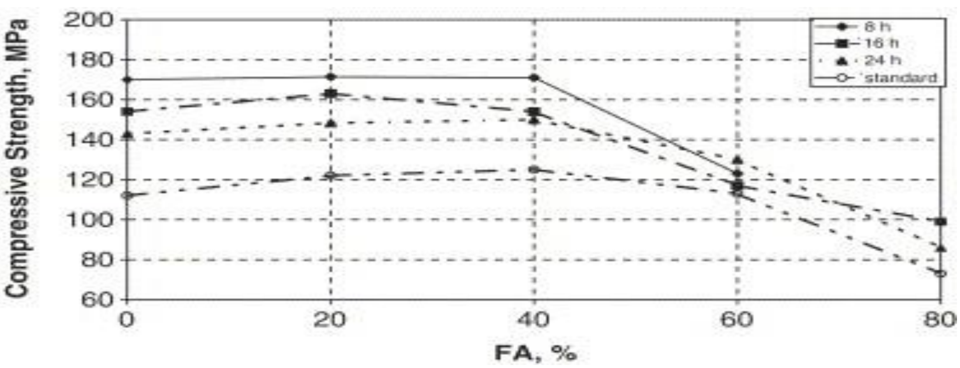

Figure 4 The effect of fly ash content and autoclave period on compressive strength.

The compressive strength vs PS content and autoclaving period relation and control specimens are shown in Fig 5. It can be seen from the Fig 5 that, increasing PS content up to

60% cement replacement caused increase in compressive strength values. This trend is independent from the curing condition. However, 80% PS replacement causes reduction in compressive strength sharply. After 8 h of high-pressure steam curing, compressive strength of control mix is 170 MPa, while compressive strengths of PS20, PS40 and PS60 mixtures are 178.7, 185 and 168.9 MPa, respectively. In this case UHSC could also be achieved with high volume PS60 binder phase. Cement content of this mixture is only 340 kg/m^3. Furthermore, even 80% replacement level with 16 h autoclave curing UHSC can also be obtained. Compressive strength of this mixture is over 140 MPa. Furthermore, at all PS replacement levels, compressive strength of high-pressure steam cured specimens is more than water cured specimens. Subjecting the high-pressure steam curing beyond the 8 h generally caused a reduction in compressive strength. Moreover, from the point of compressive strength, difference between autoclave and water curing increases with increasing PS replacement [4].

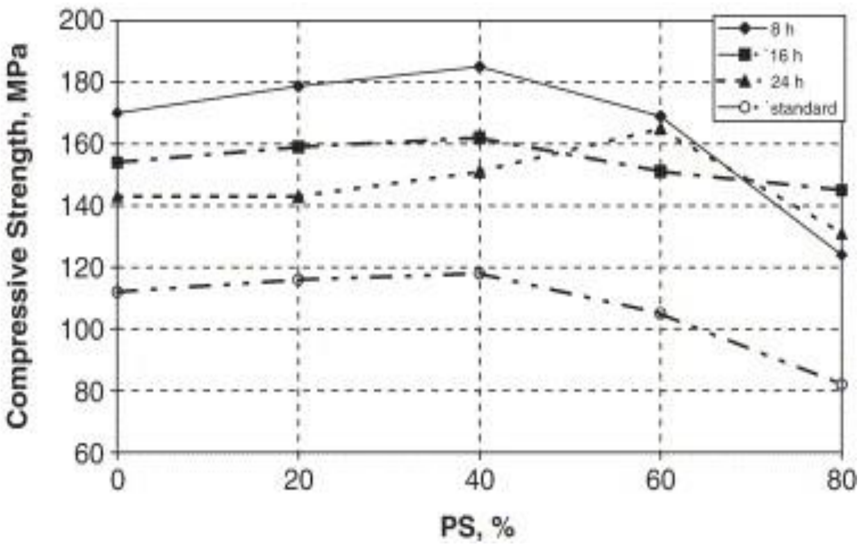

Figure 5 The influence of blast furnace slag content and autoclave period on compressive strength

EFFECT OF SHRINKAGE ON UHPC AND CONVENTIONAL CONCRETE

Early age shrinkage

Fig. 6 presents the early age shrinkage strain results versus time. Early age shrinkage tests were performed for a period of 24 h. All test results were adjusted so that time was measured from 90 min after water was added to the mixture. This time limit was used because in the first 90 min the skeletal structure of the cement paste is not rigid enough to produce repeatable results. Average early age shrinkage of fiber reinforced UHSC was 1,758 μ after aperiodof24h.It was reportedthattheaverage early age shrinkage of conventional concrete was 400 μ under the same curing conditions and with specimens that had the same exposed surface area to volume ratio used in the present work. Consequently, it appears that the UHPC shrank about 340% more than conventional concrete. These large volume changes must be accommodated in structural design. The comparison of early age shrinkage of conventional concrete and UHSC is illustrated in Fig. 7 [3].

Longer term shrinkage

Fig. 8 presents the longer term shrinkage results versus time. Results from the longer term shrinkage tests had exceptionalrepeatability, so the four lines indicated in the legend cannot be individually distinguished. Longer term shrinkage was measured using a length comparator at frequent intervals up to an age of 30 days. Specimens were kept in a water bath at 50°C to an age of 26 days. Then, the specimens were dry cured in an oven at 200°C until 28 days. After 28 days, specimens were allowed to air cure at 20°C to an age of 30 days. An average expansion of 168μ was observed at three days. This expansion was caused by thermal expansion as the specimens were moved from curing at ambient temperature (20°C) to wet curing at 50°C. Chemical shrinkage between 3 and 10 days reduced the expansion at 10 days to a value of 64 μ. This decrease in expansion was expected to continue until 26 days because the curing temperature was constant during this period. However, expansion was observed between 10 and 14 days raising the average expansion to 164 μ at 14 days. The cause of this expansion has not been isolated. However, the expansion between 10 and 14 days was 100 μ (0.01%), which was not great enough to warrant substantial concern. A gradual decrease in expansion occurred between 14 and 25 days, and the average expansion at 26 days was measured to be 145 μ. After 26 days, the specimens were moved to an oven at 200°C for dry curing until 28 days. This temperature increase caused the expansion to 1,039 μ at 27 days. The decrease in expansion from day 27 to day 28 is attributed to accelerated drying shrinkage. After 28 days, specimens were air dried at ambient temperature (23°C) until 30 days. Shrinkage strains of 1326 μ and1248μ were observed at 29 and 30days, respectively. Because thespecimenswereremovedfromtheovenat200°Candallowedtoair cure at ambient temperature, a substantial increase in shrinkage was observed at 29 days (Fig. 7). Expansion from 29 days to 30 days appears to have been caused by the specimens drawing moisture from the air [3].

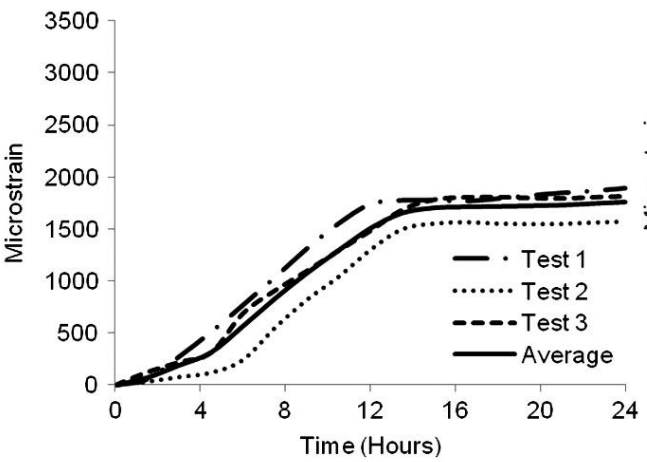

Figure 6

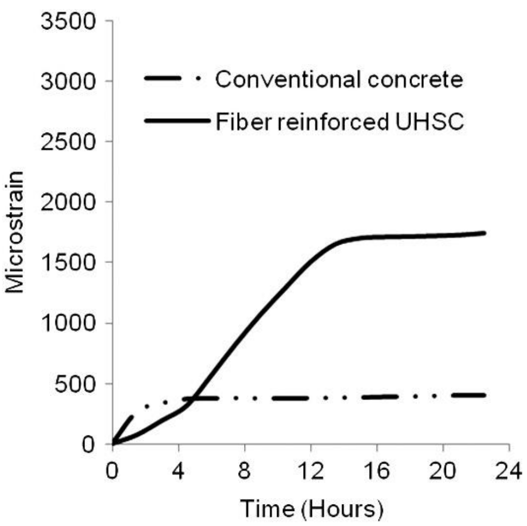

Figure 7

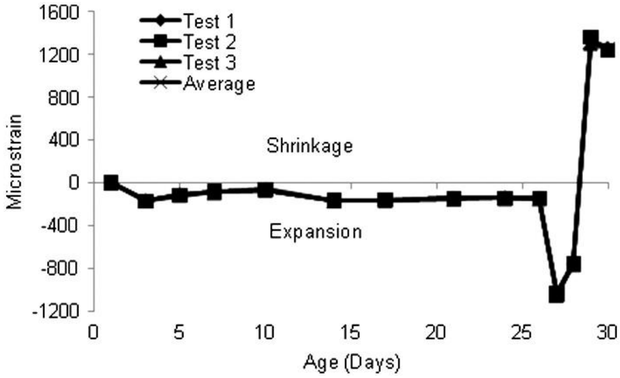

Figure 8

POTENTIAL APPLICATIONS OF UHPC

The excellent performance of UHPC offers new opportunities for infrastructure works, building constructions and many niche markets with increasing number of applications seen in the recent years. According to the market research reported by Grand View Research (GVR), the UHPC global market size was valued at USD$ 892 million in 2016 and this number is expected to grow by 8.6% to USD$ 1867.3 million in 2025 . UHPC has become a worldwide attention with its commercialization available in many countries, such as Australia and New Zealand , Austria , Canada , US , Germany , France , Italy , Japan , Malaysia , Netherlands , Slovenia , and South Korea . Within the last two decades, extensive research projects had been conducted by the academics and engineers around the world in order to industrialize UHPC technology as the future sustainable constructionmaterial. A complete search of the literature has identified more than 200 completed bridges constructed using UHPC in one or more of their components. Other applications of UHPC can also be seen in buildings, structural strengthening, retrofitting, precast elements and some special applications. Both private and governmental bodies are currently turning their attention and initiative towards utilizing UHPC as the future sustainable construction material [1].

According to the United States Federal Highway Administration (FHWA) report published in 2013, a total of 55 bridges using UHPC have been built or are under construction in the US and Canada. There are about 22 UHPC bridges in Europe and 27 UHPC bridges throughout Asia and Australia. In these applications, UHPC can be used as beams, girders, deck panels, protective layers, field-cast joints between different components and etc. Compared to traditional reinforced concrete bridges, most bridges built with the UHPC components or joints exhibit slender appearance with significant reduction in the volume and self-weight, simplified implementation, and better durability. Most UHPC structures require only half the section depth of the conventional reinforced or pre-stressed concrete members, which reduces its weight by up to 70%. This lighter weight construction and materials efficiency used in UHPC structures leads to a sustainable structure through its lower carbon footprints.

The ductile behaviour of UHPC makes it possible to be used for buildings and structures in seismic regions. It has been reported that, the reinforced UHPC columns or beams were able to dissipate higher energy compared to normal reinforced concrete during the earthquakes, preventing it from collapsing. The excellent workability enables UHPC to be cast into any shapes. Hence, UHPC blocks with different shapes could be precast. These blocks could be assembled into a structure, just like a jigsaw puzzle. Much time and labour can be saved to build this kind of UHPC structure. Japan has started the fundamental studies on this concept in the effort to revolutionizing the construction industry. Since UHPC shows very good application prospects, more and more innovative UHPC applications will be seen in the near future.

High strength and high performance concretes have been widely used in India during the last three decades for construction of nuclear power projects, long span bridges, high-rise buildings and water resources projects.High strength concrete is used where strength is the basic consideration, e.g. in buildings, industrial structures. It is noteworthy that IS 456 (draft revision) defines 'High Strength Concrete' from Grades M65 to M100, but does not mention high performance concrete. On the other hand, where durability is added consideration, e.g. in river bridges, high performance concrete is used. IRC Concrete Bridge Code IRC 112:2011 defines 'High Performance Concrete' from Grades M30 to M90. Domes of Reactor buildings in nuclear power projects at Kaiga, Tarapur and RAPP (Fig 8) were among the first to use high performance concrete. The performance characteristics required were; moderate compressive and high tensile strength; very high durability; low creep and shrinkage; low permeability and good workability [6].

Figure 9 Nuclear power dome construction at Kaiga, India

CHALLENGES

In the last two decades, UHPC has been used for both structural and non-structural precast components in many countries. However, this outstanding technology has struggled to become a mainstream technology for everyday use due to its high initial costs and the lack of design codes.

The design and construction methods for the UHPC structures are different from the traditional provisions for conventional reinforced concrete. To date, the number of skilled architects, engineers, and experts in the UHPC design and construction is still limited. Since wide application prospect can be seen for UHPC, skilled teams which are familiar with UHPC technology and specific design issues are needed. At present, only around five major players for global UHPC market could be identified, with products mainly distributed in Europe and North America. In Malaysia, only one locally blend UHPC are commercialized under the name Dura® since 2006. Although this product has successfully been used in local bridge construction, more studies are required for material optimization in producing locally blends UHPC to further improve its properties and to reduce its cost and minimize the environmental impact [7].

CONCLUSIONS

The main conclusion of this extensive review is that low porosity and a higher packing density are essential to achieve high strength, acceptable flow ability, and minimal segregation. Even after three decades of research on HPC and UHPC, design standards that can be used to obtain a specified strength and workability are still lacking. Most of the research started from a reference concrete mixture and then many trials were performed to achieve the desired properties. In commercial use, several trials were done before casting the concrete for structural applications. The quantities in the mixture proportion were found to vary substantially in a range depending upon the targeted strength. At the same w/c ratio very different compressive strengths were achieved; a mixture proportion with higher cement content may not produce higher strength and workability, depending on the type of cement, SCM, and aggregates used.

UHPC is a fascinating new material featuring outstanding properties with extraordinary strengths and excellent durability achieved through homogeneity and packing density improvements. Since its introduction in the early 1990s, a great accumulation of knowledge on the material, design, and construction of UHPC structures have been gained with various countries having attempted to introduce it to building and bridge applications. Technical recommendations have been published in France, Japan, Germany, and Switzerland. Two French national standards were published in 2016 for UHPC to replace the technical guidelines and professional recommendations that have been generally referred in designing UHPC. These new standards allow clear and codified specifications, which is anticipated to help further acceptance of UHPC at the international level. Some applications in Europe, North America and Asia have shown proven benefits on UHPC technology focusing on the sustainability and service life. Over 10 years journey of UHPC constructions in Malaysia, more than 90 bridges have been constructed, with another 20 at various stages of tender, design, and construction.

Successful achievements on the application of UHPC can be seen throughout the world. However, UHPC is seeing slow with barriers limiting its applications. High initial cost, limited codes, design difficulties, and complex fabrication technique together with the limited available resources severely hampered its commercial development and application in modern construction industry, especially in the developing countries. In order to make use of the large potential of UHPC, the industry should cooperate in a much better way with academic institutions, governmental bodies, owners and end users. The knowledge and practical experiences on this new material should be laid on the table and shared between all concerned authorities. Due to the material sensitivity of UHPC, local recommendations and designstandards should be established. More studies on the development of sustainable and cost-effective UHPC using alternative materials with similar functions to substitute the expensive composites of UHPC and to minimize the environmental impact are needed for greater UHPC acceptance. Designers, architects and engineers should be more open to this new material and technology. With all these efforts mentioned, UHPC may turn to be the constructionmaterial for both present uses and future exploitation with more complete solution for sustainable constructions.

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