International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 6 ǁ June 2023 ǁ PP. 131-140

Effect of Supplementary Cementitious Materials in Ultra - High Performance Concrete; Structural Applications and Challenges: A Review

Aswin kumar M A[1], Anju Paul[2],Dr. Elson John[3]
[1]*Student, Dept. of Civil Engineering, Mar Athanasius College of Engineering*
[2]*Research Scholar, Dept. of Civil Engineering, Mar Athanasius College of Engineering*
[3]*Professor,Department of Civil Engineering, Mar Athanasius College of Engineering, Kothamangalam*

ABSTRACT
Normal concrete made with Portland cement and conventional natural aggregate suffers from several deficiencies. The attempts made to overcome these deficiencies leads to development of new concrete technologies. Ultrahigh performance concrete (UHPC), have a compressive strength more than 150Mpa and also the better performance than conventional concrete. Even though it has great performance, UHPC has a disadvantage in the environmental aspect. It contains large amount of cement content which is responsible for high amount of CO_2 *emissions. So by reducing cement content avoid such issues and also reduces the cost of concrete. Supplementary cementitious materials which is an industrial by-product or say naturally occurring materials can be used to reduce cement content and therefore reduces the environmental impacts from the side of concrete technology. Due to the low w/b in UHPC, the majority of cement particles remain unhydrated. The unhydrated cement can be replaced by inert fillers without mitigating the properties of UHPC. The main functions of the filler are to maximize the particle packing density and provide extra sites for the nucleation and growth of hydration products, thus promoting cement hydration degree. UHPC is increasingly used in local and international construction markets in the construction of high rise structures, long-span precast/prestressed bridge girders, marine, aviation, and defense construction applications due to its superior mechanical properties, and favorable long-term performance. And recent research findings regarding the UHPC mix designs, fresh and hardened concrete properties, and current UHPC applications in the construction industry including specific bridge applications. Despite of UHPC advantages, multiple impediments are present that delays the widespread of UHPC application in the construction industry including lack of design codes and specifications for estimating UHPC performance, the need for special batching, mixing, and curing.*

KEYWORDS: Ultra-high performance concrete, Supplementary cementitious materials, Applications, Challenge

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Date of Submission: 25-05-2023 Date of acceptance: 06-06-2023

I. INTRODUTION

Ultra-high-performance concrete (UHPC) is a type of cement-based composite for new construction or restoration of existing structures to extend service life. UHPC features superior workability, mechanical properties, and durability compared with conventional concrete. Although ultra high- performance concrete (UHPC) has great performance in strength and durability, it has a disadvantage in the environmental aspect; it contains a large amount of cement that is responsible for a high amount of CO2 emissions from UHPC. Supplementary cementitious materials (SCMs), industrial by- products or naturally occurring materials can help to relieve the environmental burden by reducing the amount of cement in UHPC [2]. This paper reviews the effect of SCMs on the properties of UHPC in the aspects of material properties and environmental impacts. It was found that various kinds of SCMs have been used in UHPC in the literature and they can be classified as slag, fly ash, limestone powder, metakaolin, and others. The effects of each SCM are discussed mainly on the early age compressive strength, the late age compressive strength, the workability, and the shrinkage of UHPC. It can be concluded that various forms of SCMs were successfully applied to UHPC possessing the material requirement of UHPC such as compressive strength.[1]

II.GENERAL BACKGROUND

Ultra high- performance concrete (UHPC) is one of the leading construction materials with greatly advanced properties compared to conventional concrete. A cementitious mixture of which the compressive strength is over 120 MPa belongs to the UHPC category according to ASTM C1856, while the ACI committee reported that the compressive strength of UHPC should be greater than 150 MPa. In addition to the remarkable compressive strength, UHPC, designed based on a particle packing theory, also possesses superior durability compared to conventional concrete with the help of dense microstructure. The disadvantage of UHPC comes from the standard ingredient, specifically, a large portion of Portland cement. The cement industry is well known to generate 8–9% of global CO2 emissions. Even though the structural member size can be smaller with UHPC than conventional concrete because of its high strength, UHPC generally contains cement about three times higher than normal concrete by volume. Furthermore, not all cement particles in UHPC are hydrated in an extremely low w/c ratio environment. The hydration degree is reported as only 52–61% with a w/c ratio of 0.23–0.33and the unhydrated cement makes UHPC not eco- friendly. Therefore, the possible approach to reduce cement content in UHPC is replacing part of the cement with supplementary cementitious materials (SCMs) such as slag, fly ash (FA), limestone powder (LP), metakaolin (MK), and other SCMs. Most SCMs are industrial byproducts or naturally occurring materials: slags are by- products in the production of iron, steel, lithium carbonate, phosphor, or copper; FA is a by- product of a coal power plant; and SF is a by- product from the production of elemental silicon or alloys with silicon. In addition, limestone is a natural occurring material, and MK is obtained from the calcination of kaolinite [8].

III. DEVELOPMENT OF UHPC

Concrete is a cement-based composite material and a hydraulic binder which is formed by combining cement with various aggregates. The structures developed in a higher, larger, deeper direction since the 20th century; therefore, stricter requirements on materials have been placed. In this case, the High Strength Concrete (HSC) with strength exceeding 60 MPa appeared in the late 1970s then and was widely used at that time. Reactive Powder Concrete (RPC) is one of the most typical UHPC, which was first developed in 1993 at the Bouygues Laboratory in France. Its compressive strength is more than 150 MPa. And RPC is divided into two grades, RPC200 (strength below 200 MPa) and RPC800 (strength from 200 MPa to 800 MPa) [10].On the basis of the principle of preparation of RPC, experts from various countries have carried out new UHPC research, but the challenge to improve tensile properties of UHPC still remains. In this case, a fiber-reinforced approach was introduced to achieve a higher tensile strength. In 2009, at the ‘‘Ultra-High Performance Fiber Reinforced Concrete International Conference” held in Marseille, France, it was noted that UHPC would have a new application in environmental protection and super durable performance[5].

IV.EFFECT OF SUPPLEMENTARY CEMENTITIOUS MATERIALS IN ULTRA HIGH PERFORMANCE CONCRETE

Representative SCMs include silica fume, fly ash, slag, glass powder, rice husk ash etc which have been used in UHPC to reduce its cost and carbon footprint and improve properties. Chemically, SCMs feature a high amount of SiO2 or and reactive CaO, which can promote cement hydration through pozzolanic and or hydraulic reactions, especially when the w/b is extremely low [8].

4.1 SLAG

Depending on the main metal oxides, the slag used in UHPC can include iron slag, copper slag,[11] and barium slag[12] . As a typical alternative SCMs, slag is usually used to replace cement with a replacement ratio of 30%–60%, depending on the volume of binder. The slag particles have angular shapes (higher shape factor), increasing inter-particle friction and thus reducing the workability of UHPC compared with using the same amount of fly ash. The d50 of slag ranges from 30 μm to 50 μm, greater than that of cement, which benefits maintaining a low shrinkage. Similar to the fly ash, the lower hydration reactivity of slag retards the hydration process and tends to refine the microstructure of UHPC. In contrast to fly ash, the slag has a low Al2O3 content. The addition of slag in UHPC has less retarding effect on the development of mechanical strengths compared with fly ash.

Fig :1 GROUND GRANULATED BLAST FURNANCE SLAG

Slag tends to decrease the compressive strength of UHPC at an early age because of its low reactivity. Slag has hydraulic properties and reacts with water and the hydration product of slag is calcium silicate hydrate (CSH). Slag is chemically activated by calcium hydroxide (Ca(OH)2) and gypsum in cement, but its reaction speed is slow, whereas SF reacts with Ca(OH)2 first in UHPC because of its fineness. Researchers have also reported that slag decreases the heat of hydration. As a result, slag tends to decrease the compressive strength of UHPC at 3 days or earlier

Slag could enhance the late age compressive strength of UHPC; the secondary pozzolanic reaction between slag and Ca(OH)2 in the pore solution produces additional CSH, which increases the packing density of the UHPC. Liu et al. found that compressive strength increases up to 9% when GGBS content increased to 40% of the binder because the secondary pozzolanic reaction of GGBS is accompanied by consumption of Ca(OH)2 and the densification of the hardened paste.

The effect of slag on the UHPC shrinkage possibly depends on the type of slag. It has been proved that the addition of GGBS increases the shrinkage of conventional concrete because slag increases the self-desiccation by consuming pore solution (calcium hydroxide) in a small capillary pore structure.However, different effects of different types of slags on the UPHC, shrinkage have been observed in some studies in the literature.

Slag increases the UHPC flowability because of its lower water absorption compared to cement having a slippery surface. The addition of GGBFS and GGBS increases the UHPC flowability by 11.6% and 4.1%, respectively, compared to the reference specimen with SF only. The flowability of UHPC can increase by 17.2% when the cement replacement ratio with PS increased up to 34.2% because it reduces the water absorption [8].

4.2 FLY ASH (FA)

Type C and Type F fly ash have been used in development of UHPC. Type C fly ash undergoes both hydraulic and pozzolanic reactions, but Type F fly ash mainly experiences a pozzolanic reaction due to its lack of CaO. Fly ash commonly replaces cement with volume ratios of 40%–60% for Type C and 10%–30% for Type F. the particle shape of fly ash is more spherical than cement, which reduces inter-particle friction, and thus increases the workability. Additionally, d50 of fly ash ranges from 30 μm to 50 μm, which is coarser than cement and silica fume. Fly ash can mitigate the self-desiccation-induced shrinkage because more free water is available to retain the relative humidity in the pore solution. Due to the lower hydration reactivity, the replacement of cement with fly ash retards the hydration process.The pozzolanic reaction is slow but can refine the microstructure in long term. The refinement of pores benefits the durability of UHPC[5].

The compressive strength data reported show around 95 MPa at 3 days, 110–185 MPa at 28 days, and 152–202 MPa at 91 days with a 10–20% replacement of binder materials. It has been shown that the UHPC with FA exhibits a lower compressive strength than those of reference specimens. Ahmad et al. replaced a part of SF with FA, and found that using FA to substitute the SF up to 11.8% of the binder slightly decreases the compressive strength by 1.9% compared to the reference specimen at 28 days [13]

Fig 2: FLY ASH

Although FA degrades the compressive strength of UHPC, the value is higher than the minimum requirement of 150 MPa and the usage of FA can reduce the cost of UHPC. It has been proved that FA can improve many characteristics of high strength mortar. It found that replacing 12.8% cement with FA decreased the compressive strength by 48.9% and 6.1% at 1 day and 3 days, respectively, because of the high crystallinity of FA. Some of the FA can improve the compressive strength of UHPC. Ferdosian and Camões introduced the method of how to optimize the UHPC mix design that satisfies the requirements of the compressive strength and the flowability using FFA of which the mean particle size is 4.48 μm. They suggested the eco- efficient mix design that releases the lowest CO2 and the cost- efficient mix design that maximizes the amount of FA and sand as well as minimizes the amount of SF. The eco- efficient mix design results in the compressive strength being 6.8% higher than the reference samples using the FA of 34.1% in the binder.

Some researchers reported that FA can improve the workability of UHPC. Li found that the ternary use of FA, MK, and cement can significantly increase the flowability of UHPC by 47% compared to the binary use of cement and SF. Randl et al. found that the addition of FA can increase the flowability of UHPC. The 38.5% replacement ratio of cement with FA can increase the flow diameter of fresh UHPC by 3.6% compared to the reference specimen with SF only. It has been shown that the FA can reduce the shrinkage of UHPC. Li et al. found that the ternary use of FA, MK, and cement can reduce the drying shrinkage of UHPC compared to the reference specimen with SF only because the ternary use can reduce water demand. Yazıcı et al. replaced cement with FA and GGBS to reduce the cement amount in UHPC. It was found that when the content of GGBS in the binder is constant, the 10% replacement ratio of cement with FA results in lower shrinkage than the reference specimen with SF only because of the lower amount of cement in UHPC [8].

4.3 LIMESTONE POWDER

Limestone powder has been proposed as an alternative type of micro filler for UHPC[14]. The cement replacement ratio was reported to be up to 50% by volume. The d50 of limestone powder ranges from 10 μm to 20 μm, similar to quartz powder. Due to its inert property, spherical shape, and small particle size, the proper addition of limestone powder enhances the workability of UHPC. The use of limestone powder also reduces the autogenous shrinkage and accelerates the hydration reaction due to

(1) the filler effect, the limestone powder does not hydrate but provides extra nucleation sites for hydration of cement and/or other reactive particles;

(2) the dilution effect, the replacement of cement with limestone powder increases the effective water-to-cement ratio which allows more free water for cement hydration and assists in maintaining the internal relative humidity (IRH).

However, if an excessive amount of limestone powder is used, the hydration peak can be significantly reduced, and the porosity is increased. This is because the overuse of fillers may cause a shortage of reactive materials, limiting the amount of hydration products generated [5].

Fig 3: LIMESTONE POWDER

Three different mechanisms of how LP affects the compressive strength of UHPC were observed. First, LP enables the reduction in the amount of superplasticizer to maintain the same flowability. The effect of LP on the hydration of UHPC with different cement replacement ratios. The retardation effect caused by the superplasticizer decreases as LP enables the reduction in the amount of superplasticizer by 62.8%, and, as a result, the early compressive strength is not degraded. It was also found that the 32% replacement ratio of cement with LP results in 10.7% and 16.1% higher compressive strength at 28 days and 56 days, respectively.

LP can significantly improve the workability of UHPC. From literature, that LP can be regarded as a mineral plasticizer that improves the flowability of the UHPC[15]. The 37.3% replacement ratio of cement with LP results in 45.1% higher flowability than that of the reference specimen that contains SF only. The plasticization effect of LP increases the workability of UHPC because of the repulsion between OH group localized on the Ca2+ surface and its lower water absorption. Yang et al. found that the use of LP as a partial substitution of cement can enhance the flowability of UHPC.

LP can lower the shrinkage of UHPC by reducing the amount of cement in UHPC. Li et al. found that a 57.2% replacement ratio of cement with LP can improve the total shrinkage of UHPC compared to that of the reference specimen with SF only. The study insisted that the lower amount of cement in UHPC replaced with LP slows down the hydration and reduces the hydration products, and, thus, results in the lower autogenous shrinkage. It should be pointed out, however, that the high content of LP up to 78.1% of the binder provides more free water, and, thus, drying shrinkage increases. In consequence, the total shrinkage decreases because the reduction in autogenous shrinkage is greater than the increase in drying shrinkage[8]

Although three different mechanisms of how LP increases the compressive strength of UHPC have been proposed, the actual performance of LP in UHPC is debatable. From the literature, it was confirmed that LP increases the workability of UPHC. Therefore, the mechanism of LP to improve the compressive strength of UHPC by reducing water content seems appropriate. The finer LP enhances the compressive strength of UHPC by accelerating the cement hydration. Some studies insisted that the addition of LP decreases the amount of cement in UHPC, which degrades the compressive strength of UHPC. However, their dosages are lower than the other studies showing higher compressive strength with LP, and, therefore, other unknown factors of LP were assumed to degrade the compressive strength.[8]

4.4 METAKAOLIN (MK)

MK obtained by calcining kaolin has the main chemical composition of alumina and silica, and, therefore, MK is also a pozzolanic material. Studies have reported that MK increases the durability of concrete: low permeability, high resistance against frost, and chemical attack[16] .The use of MK only seems to increase the early age compressive strength of UHPC but decreases the late age compressive strength of UHPC. Replacing cement with MK can improve early age compressive strength but the late age compressive strength is decreased compared to UHPC with SF only.It was found that the 16.7% replacement ratio of cement with MK results in 47% higher 1- day compressive strength than the reference specimen with SF only because the use of MK improves the cement hydration at an early age. However, it decreases the 28- day compressive strength by 11.8% compared to the reference sample, of which impact is less significant compared to that of 1- day compressive strength [2].Li and Rangaraju studied the effect of MK on the shrinkage of UHPC.The addition of MK of 16.7% increases the autogenous shrinkage by 0.16%, but it decreases the drying shrinkage by 0.1%. However, no clear explanation of the different effects of MK on the different types of shrinkage is proposed.

Fig 4 METAKAOLIN(MK)

MK tends to decrease the compressive strength of UHPC. It decreases the workability of UHPC and its beneficial effect on the shrinkage is not clear. Based on the fact that MK is not naturally stored but needs to be calcined, it is also difficult to find the merits of MK in material cost and CO2 emission compared to slag, FA, or LP. Therefore, the usage of MK in UHPC seems not suitable. However, another possible application was found; the geopolymer or alkali- activated concrete resulted in a compressive strength of over 150MPa. As geopolymer is well known for its lower CO2 emission compared to OPC, developing geopolymer UHPC with MK can be an interesting research subject [8].

4.5 RISE HUSK ASH

Rice husk ash is usually used to partially or entirely replace silica fume due to their comparable amount of amorphous silica. The d50 of rice husk ash ranges from 5 μm to 20 μm, which is 50–100 times larger than that of silica fume. However, rice husk ash possesses a higher surface area (i.e., 64,700 m2/kg) than silica fume (i.e., 18,500 m2/kg) due to its porous structure, making it prone to absorbing more free water and HRWR [17]. As a result, the workability can be significantly reduced with the addition of rice husk ash. Additionally, the high water absorption can cause rice husk ash to absorb the mixing water during the mixing process thus to gradually release to the UHPC matrix during the hydration process, which delays the decrease of internal humidity of pores in UHPC and hence mitigates the autogenous shrinkage. the addition of rice husk ash also refines the microstructure, which improves the durability as well as the mechanical performance of UHPC at longer lifespans [5].

Fig 5 RISE HUSK ASH

RHA obtained by burning rice husk has a very high specific surface area, higher than 250 m2/g. The small particle size and the amorphous structure of RHA make it a "highly active pozzolan". Van Tuan et al. indicated that cement hydration can be accelerated by the addition of RHA of which mean particle size is 5.6 μm, and it can reduce porosity and improve the compressive strength of concretes . The 10% replacement ratio of cement with RHA can increase compressive strength by 10.6% and 8.8% at 3 days and 28 days, respectively. It was also found when the grinding time increases to produce the fine RHA, the pore structure of RHA is gradually collapsed resulting in the lower porosity of RHA. This collapse of RHA can improve the compressive strength of UHPC[8]. It was also found that SF and RHA has a synergic effect on the compressive strength of UHPC; the SF contributes to the early age compressive strength, while RHA to the late age compressive strength.

V.STRUCTURAL APPLICATIONS OF UHPC

5.1 UHPC in Bridge Engineering—THE EXPERIENCE IN SOUTH KOREA

In South Korea, UHPC is a cementitious composite containing discrete fibers for post cracking ductility, having minimum characteristic compressive and tensile strengths of 120 MPa and 7 MPa respectively. In 2002, South

Korea started the development of UHPC. Since then, it has succeeded in improving its fluidity, tensile strength, and shrinkage performance of the material, as well as its economic efficiency, to see its application in no less than 16 bridges by 2020[7]. The world's first UHPC pedestrian cable-stayed bridge was erected in 2009. In 2012, the design of a UHPC cable-stayed road bridge was reflected in the turnkey tender of a long-span bridge to link an island with the continent on the Southern coast of South Korea. In 2012, a UHPC road bridge was constructed for the very first time in South Korea. In 2015, the Hawkeye UHPC Bridge was built in Iowa, USA, concurrently with the Ka Thae Myaung Bridge in Myanmar using the UHPC technology developed in South Korea. Finally, the access bridge to the Legoland Theme Park connected to the Chuncheon Legoland Theme Park, which is expected to open in May 2021, was completed in 2017 as the first UHPC cable-stayed road bridge in the world.

Fig:6 World's first cable-stayed UHPC pedestrian bridge, constructed in 2009

Korea Institute of Civil Engineering & Building Technology (KICT) started research and development focusing specifically on the application of UHPC to cable-stayed bridges in 2007, aiming to overcome the challenge posed by the traditional cost of UHPC. In a cable-stayed bridge, the cables account for a substantial part of the construction cost. The size of the cables and foundations can be dramatically reduced if the weight of the superstructure is lightened by using UHPC. However, such saving are likely to be counterbalanced by the additional cost brought by the application of UHPC. A comparatively small pedestrian bridge was considered in 2009 in the early stage of the research, and this bridge became the very first cable-stayed UHPC bridge to be designed and erected The bridge links two buildings of KICT. The bridge was designed as a cantilevered structure to minimize the demands placed on the connected buildings. Tuned mass dampers were installed at the free ends of the cantilevers to improve its serviceability in terms of deflection and acceleration. Four UHPC segments were manufactured in the form of an edge girder with a width of 2.5 m (8.2 ft), a length of 7 m (23 ft), a girder height of 0.3 m (1 ft), and a deck thickness of 70 mm (2.75 in.) using a UHPC specific batch plant. Each of the two cantilevered parts was connected to the buildings by assembling two UHPC segments, and the equilibrium of the structure was realized by counter blocks made of normal concrete cast-in-place on the deck. The bridge constitutes the first cable-stayed UHPC bridge in the world, even though it is a pedestrian bridge having a span length of 18 m (59 ft) [4].

5.2 CANADA SHERBROOKE OVERPASS

In 1997, the first UHPC pedestrian bridge in the world was built in Sherbrooke Quebec, Canada , marking the formal application of UHPC in bridge engineering[6]. At that time, the local government hoped to use an unprecedented new type of bridge to demonstrate the up-to-date achievement in bridge construction, and contrasted the new bridge with its adjacent old steel truss girder bridges, highlighting the elegant aesthetic effects of the prefabricated space truss of the bridge. The bridge superstructure is a posttensioned open-web space truss composed of six prefabricated match-cast segments that were assembled on site using internal and external post-tensioning. The deck and top and bottom chords are made of UHPC with a compressive strength of 200 MPa. For the diagonal web members, the UHPC is confined in stainless steel tubes and can withstand 350 MPa in compression. The 3 m deep truss spans 60 m across the Magog River (in dowtown Sherbrooke) in a circular arch.

Fig 7: Canada Sherbrooke Overpass

Due to using the new materials and design method, this overpass structure has demonstrated many advantages, such as excellent durability and low cost for maintenance, etc. The construction of the Sherbrooke Overpass with success was a remarkable event that symbolized a new door opened for application of UHPC materials in bridge engineering [4].

5.3 DAMS AND LOCKS

Dams and locks are exposed to water and ships throughout their entire life. Continued abrasion significantly reduces concrete rebar cover leading to corrosion and loss of structural strength. Construction and retrofitting with field cast or shotcrete UHPC provides high durability against abrasion and high strength against ship impacts.

5.4 MARINE STRUCTURES

Traditional concrete materials fail to possess both physical strength and chemical durability when applied to marine structures as chlorides can penetrate the concrete and cause damage to the steel reinforcement. UHPC's unique impermeable properties against chlorides make it an ideal solution to prevent future rebar corrosion and future maintenance of existing marine structures. This helps to achieve structural integrity in the long-term.

5.5 AIRPORTS

Whether you're building new or rehabilitating existing runways or apexes, UHPC extends the service life and decreases the need for recurring maintenance. The use of UHPC helps improve wear resistance, bearing capacity, and increased the life-cycle while reducing the project completion time.

5.6 PARKING STRUCTURES.

Whether it's the preservation of parking garage decks or the retrofitting of inverted tee beams, the properties of UHPC make it an innovative, durable, and effective solution to extend the life of parking structures.

5.7 TREATMENT PLANTS

Treatment plants require innovative concrete technology to fight against abrasion, acids, sulfates, and carbonation. Due to its impermeability, UHPC increases the durability and lifespan of treatment structures.

5.8 RAILWAY STRUCTURES

Many of our bridges are in need of significant repair, including railway structures. UHPC is ideal to strengthen and provide corrosion protection for aging railway bridges including beams, piers, and abutments. Deteriorated railway ties can be replaced with field cast UHPC to increase the longevity of the railway.

5.9 INDUSTRIAL FLOORS

Industrial floors are oftentimes exposed to harsh environments and impacts. UHPC is a supreme material due to its chemical resistance and low permeability. Both its chemical and physical resistance are ideal for a variety of industrial flooring projects.

VI. CHALLENGES

Proprietary UHPC mixes display superior characteristics compared to other types of conventional concrete mixes. Despite of its advantages and increased market share, there are many impediments that delays the wide spread of proprietary UHPC mixes and developed non-proprietary mixes in the local and international construction market.The main impediments include:

1) Lack of specifications and code provisions: which provide accurate estimation for UHPC sections structural capacity under different types of static and dynamic loading. Currently, guidelines and specifications are developed in France, Japan, and Australia to standardize UHPC mixes behavior and performance. In the United States, UHPC has been commercially available for the past 2 decades. However, no authoritative document is published to describe UHPC constituents, mixing, batching, and quality control procedures. Similarly, there are no design code that can be used in accurately calculating a UHPC member performance. Current projects conducted at Federal and State levels depend on foreign guidelines and conducted lab tests. In addition, reliability studies and calibration of available international guidelines and specifications is not are required to ensure the consistency of design upon implementation of the limited resources available for design and construction.

2) Lack of industry experience: among different contractors and subcontractors regarding the batching, mixing, and quality control procedures. Proprietary UHPC mixes incorporating steel fibers requires a multi-step batching and specific curing regimen.

3) High material cost of proprietary UHPC mixes: due to the incorporation of relatively large amount of random steel fibers, high cost SCMs, and high dosage of chemical admixture. The average cost of proprietary UHPC mixes ranges from $2500 to $3000 per cubic meter as compared to $170 per cubic meter for conventional concrete mixes [3].

VII. CONCLUSIONS

The various types of SCMs such as slag, FA, LP, MK, and others were successfully applied to UHPC, satisfying material requirements such as compressive strength. Based on the discussions, their effects are summarized as follows:

(1) The main purposes of the usage of SCMs are to decrease the material cost and the environmental impact caused during material production by a partial replacement of cement or silica fume. Since most SCMs are industrial by- products from plants or naturally occurring resources, the usage of SCMs corresponds well to this purpose; it was confirmed that the e- CO2 of UHPC is lower when the dosage of an SCM is higher.

(2) Slag tends to decrease the compressive strength of UHPC at an early age because of the slow hydration of slag, but it increases the late age compressive strength through the pozzolanic reaction between slag and Ca(OH)2 that increases the packing density of the UHPC. The finer particle size of slag exhibits higher compressive strength. Slag also increases the workability of UHPC because of its lower water absorption compared to cement.

(3) FA degrades the compressive strength of UHPC; however, some of the FFA can enhance compressive strength. The ternary use of SCMs including FA can be another feasible option to reduce the amount of cement in UHPC. The effect of FA on the workability of UPHC is different among studies. It is also proved that FA is effective to reduce the shrinkage of UHPC.

(4) LP enhances the compressive strength of UHPC with the three mechanisms:

i) LP decreases the water demand of UHPC, that is, it increases the workability of UHPC,

ii) LP has a pozzolanic reaction with SF, which increases the late age compressive strength, and iii) LP can accelerate the cement hydration. However, some cases that LP degrades the compressive strength of UHPC were observed. LP can decrease the shrinkage of UHPC by reducing the amount of cement in UHPC.

(5) MK seems to increase the early age compressive strength of UHPC, but decreases the late age compressive strength. It was confirmed that the MK of the finer particle size can overcome the degradation of the early age compressive strength. It was reported that MK decreases the autogenous shrinkage while it increases the drying shrinkage. Another application of MK was found; the alkali- activated material synthesized using slag, MK, and sodium silicate solution results in the proper compressive strength over 150 MPa.

(6) RHA has a synergic effect on the compressive strength of UHPC resulting in the higher compressive strength at both early and late age compared to the reference specimen only with SF.

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