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Mechanical and Micro-structural Properties of Ultra-High Strength Concrete: A Review

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HIGHLIGHTS

- Optimum dosage of silica fume can provide better flowability with less porosity.
- Heat curing and steam curing can increase the strength of Ultra-High Strength Concrete (UHSC).
- Proper dosage of fibers can reduce the crack propagation and drying shrinkage.

Abstract: As the demand for higher-strength of concrete is increasing, the research on Ultra-High Strength Concrete (UHSC) has the spectacular development in recent years. The purpose of this paper is to compare and summarize the properties of UHSC with different raw materials based on the published research and share it with researchers involved in the study of UHSC. Thus, papers relevant to UHSC were identified through a systematic literature search. The use of supplementary cementitious materials such as silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBS), nanomaterials and fibers that were widely used in UHSC was investigated. This results in UHSC with promising compressive strength and better workability. Curing under high temperatures found denser microstructure and higher strength than standard curing.

Keywords: Ultra-high strength concrete; Silica fume; Supplementary cementitious materials; Compressive strength.

INTRODUCTION

Ultra-high strength concrete is one of the current developments in the area of concrete that developed to withstand compressive strength greater than 120 MPa and to achieve size efficiency in structural members. The usage of sustainable supplementary cementitious materials and revolutionary developments in superplasticizer admixtures have facilitated in mechanical and durability properties of concrete [1]. UHSC is a type of concrete that has a low binder ratio and consists of various supplementary materials. Generally, it is composed of very fine particles and thus exhibits dense microstructure and ductility and has very low porosity [2]. Besides, its various advantages few risks do occur such as an increase in autogenous shrinkage, high brittleness, and spalling risk under fire.

Several studies on UHSC have been conducted with various additives including mineral admixtures, fibrous materials, and nano mineral materials. The reason for replacing cement with some supplementary cementitious materials was mainly due to the environmental impact during the production of cement and its cost. It is a fact that there were no materials have been discovered yet as the better replacement for cement. So far now research only under partial replacement of cement has been conducted. According to [3], compressive strength of around 170 MPa can be produced with high-volume mineral admixture. Heat- cured specimen with fly ash up to 40% shows increased compressive strength and a further increase in fly ash reduced strength. While steam curing fly ash and slag content up to 60% increased the compressive strength of concrete whereas, 80% replacement leads to a decrease in strength. Optimizing UHSC with compressive strength over 180 MPa using silica fume, blast furnace slag, gypsum, and superplasticizer results in porosity and microhardness near Interfacial Transition Zone (ITZ) was noticeably influenced by the w/b ratio [4]. If the w/b ratio decreases then the porosity also decreased resulting in increases in the hardness in microstructure near ITZ and the compressive strength increases up to 12.5%[28]. The use of small quantities of aluminum oxide nanofibers in an oil well cement based mortar could provide nearly 200 MPa of compressive strength with a considerably lower dosage of silica fume [5]. The mix design of UHSC with manufactured sand (M-sand) and its microstructure was observed for different aggregates such as river sand, granite M-sand, limestone M-sand, and sandstone M-sand. Among these, sandstone M-sand was found to produce higher strength. The microstructure of M-sand was found highly dense and the size of hydration products such as ettringite, calcium hydrate (CH) and calcium silicate hydrate (CSH) gel become much finer compared with conventional concrete. Both silica fume and M-sand makes hydration products of cement much finer than ordinary concrete as M-sand has a definite amount of fines [6].

MATERIALS

The raw materials generally used in UHSC are cementitious components, fine aggregates, water, and high range water reducing admixture (Superplasticizer). Some additives such as quartz powder, fibers, and nano-materials were used by a few researchers. Each material requires optimum particle size, specific area, and mix proportion for better performance of UHSC. The following section discusses the raw materials widely used in UHSC and their properties in detail.

Portland Cement (C)

Since the cement is an earth material it can be composed of numerous chemical compositions. The selection of cement with accepted standards is an important factor. Cement with reduced tricalcium aluminate (C_3A), tricalcium silicate (C_3S) and increase dicalcium silicate (C_2S) to get long-term hydration and dense microstructure [4].

Silica Fume (SF)

Silica fume is the by-product of the manufacture of elemental silica or alloys with silicon that consists of a high content of amorphous silicon dioxide. Incorporating SF is the most effective and economic method because of its fine particle size, filler effect, rheological characteristics and high pozzolanic activity. Generally, a particle size of around 0.02 – 0.3 µm was used so that it can fill the gaps between water and cement and enhance the strength and durability by filling voids made by hydrates. Optimal SF dosage of 15% - 20% showed improved pullout behavior compared with samples without SF. Improved flowability also found with this recommended dosage which was due to its lubricating effect that released some entrapped water between fine particles and show reduced flowability beyond optimal dosage due to its high surface area. Replacing 10 – 20 % SF with cement shows a significant increase in strength. SF can remarkably reduce porosity and permeability thus it is preferred to improve strength, durability, and bond properties [7]. Using SF with more than 92% of silicon oxide (SiO_2) produces C-S-H gel and fills hydrate pores thus increasing fluidity and the compressive strength of the concrete [4]. Improved fluidity can be achieved with well-dispersible silica fume as it exerts ball bearing effect because of its round shape. Total hydration of UHSC can be increased with the addition of 15% of silica fume and decreased when 30% and shows a positive effect in early compression strength [2]. Slag that was incorporated if mixed alone seemed that would decrease the compressive strength but in combination with silica fume increased the compressive strength.

The Calcium hydroxide content found decreased as the slag or silica fume content increased. If the shape of silica fume is irregular it required an increase in superplasticizer dosage [8].

Fly Ash (FA)

Fly ash is a spherical fine residue from the coal power station. Class C fly ash is preferred for the production of UHSC. Using cement not only affects the cost but also the heat of hydration and cause shrinkage thus, the use of fly ash in UHSC show promising effect in reducing the shrinkage of concrete. It is usually combined with GGBS, SF, and/or steel slag powder. An increase in the fly ash replacement ratio and w/b ratio could significantly reduce the drying shrinkage in UHSC [9]. The compressive strength of concrete containing high content of GGBS and fly ash reached over 200 MPa under standard curing, 234 MPa under steam curing, and 250 MPa under autoclave curing [3]. This combination also enhanced flexural strength and significantly improved the toughness of concrete after all curing regimes. But, the modulus of elasticity decreased with more than 30% replacement of cement.

Ground Granulated Blast Slag (GGBS)

Slag at an early age decreases the compressive strength of the concrete due to its low reactivity and later due to its pozzolanic activity increases the strength. In UHSC, the cement was replaced with 20% - 60% GGBS, the compressive strength with high volume of GGBS was over 250 MPa after autoclaving. If an external pressure was applied during setting stages, compressive strength could reach up to 400 MPa [3].

Fine Aggregate

Aggregates with higher strength, durability, proper grain size distribution, shape, and good fire resistance are required for UHSC [4]. Replacement of quartz sand with treated and untreated copper slag in UHSC made it possible to produce concrete with compressive strength of more than 150 MPa under normal curing [10]. Utilizing pretreated fine lightweight aggregate and replaced with river sand with around 10% enhanced the flexural strength but no improvement was found in the compression strength and increased driving force of water, huge water supply for hydration, and minimized the porosity and drying shrinkage [11]. Since UHSC has relatively large early autogenous shrinkage and a high risk of crack, coral sand is an internal curing agent employed and it effectively inhibited the self-desiccation inside the concrete and reduces its autogenous shrinkage, improving fluidity [12].

Fibers

Incorporating proper fibers in the concrete can effectively prevent or control crack initiation or the propagation and improve tensile capacity and ductility. The aim of using fibers in the concrete is to reduce the brittleness of cementitious matrix as it can influence the cracking behavior. Using fibers, even few cracks formed were found with reduced crack width. This led to increased stiffness and higher values of maximum loads [13]. Some fibers such as steel fibers, polypropylene fibers, carbon fibers, and nylon fibers are used in UHSC production. Among these fibers, steel fibers are the most commonly used ones as their tensile property is over 2000 MPa. The concrete with steel fibers were found to decrease in filling and passing ability of UHSC. The risk of spalling increased with an increase in concrete strength thus, UHSC was found vulnerable to fire spalling. Incorporating polypropylene fibers in UHSC in order to improve permeability, higher aspect ratio fibers were efficient to bridge the isolated pores. The polypropylene fiber of dosage 1.3 kg/m^3 can prevent UHSC from explosive spalling and steel fibers may relieve but cannot prevent spalling of concrete. Optimum dosage of polypropylene fiber that was around 115 – 135 MPa strength is recommended and using excessive is wasteful as it increases the cost and reduces the workability of fresh concrete [14]. When water vapor within the polypropylene fiber evaporated below its melting point, mass loss was observed at 216°C approximately and burnt completely at 450°C. Nylon fibers showed mass loss five times greater than polypropylene fibers. The spalling test result indicated that both polypropylene and nylon fibers exhibit equivalent control performance when mixed at the optimum level. Shape, length, aspect ratio and fiber content may affect the mechanical properties of concrete [15].

Nano-materials

Nano-materials are spherical particles with particle sizes less than 100 nm and possess a high surface area to volume ratio thus, possess dense microstructure leading to reduced porosity. Good dispersion and optimal bond strength are the key requirements for incorporating nano-materials in the cement matrix. Generally, the dosages of nanomaterials are expected to be effective in small quantities [16]. The introduction of proper quantities of nanomaterials in concrete found both compression and flexure strength found increased as the % of multiwalled carbon nanotubes (MWCNTs) increased and significantly affected the chloride penetration until the dosage of 0.05%. Reduced porosity with the addition of MWCNTs was found which may be due to the surfactant that formed foaming within the cement matrix and improved pore structure [17]. The powder nano-SiO_2 had a particle size of around 20 nm and SiO_2 content of around 99.8%. In this regard, it acts as a filler material, accelerates heat of hydration and densifies the microstructure of concrete, increased bond strength considerably at an early age up to 7 days, and increased slightly until 91 days. Greater strength was achieved due to a change in the C-S-H structure with high curing temperature. Optimal usage of nano-SiO_2 was found to be 1% for better performance and improved the chemical bond of C-S-H to fiber at age. The optimum dosage for nano-SiO_2 and nano-calcium carbonate (nano-$CaCO_3$) was found to be 0.5 – 1.5% and 1.5 – 4.8% respectively [18].

Iron tailing powder (ITP)

Replacing cement with iron tailing powder in the range of 10 – 15 % in UHSC was because of its outstanding pozzolanic activity and filling effect it accelerates cement hydration and helps in producing denser concrete. ITP has a fine particle size that helps to form dense particle packing, outstanding pozzolanic reactivity, filling effect, and low cost. The addition of ITP at an optimal level (15%) obtained better compressive strength, flexural strength, and increased residual compressive strength up to 200°C. Microstructure observation of UHSC with ITP showed denser, complete structure and high-temperature resistance (up to 800°C). It is noted that ITP took part in the chemical reaction and generated the additional hydration products [19].

Superplasticizer (SP)

As UHSC is majorly composed of fines, it is necessary to use a superplasticizer to provide better flowability in concrete without an additional amount of water. Polycarboxylate ether-based superplasticizer is found to be effective for UHSC. Loss of flowability of concrete especially during pumping concrete for skyscrapers may cause a lack of workability. Thus SP was utilized in the UHSC to the improve flowability of the mix [4]. Generally, an increase in superplasticizer dosage prolongs the setting time. Effective dispersion of silica fume is necessary to achieve increased flowability of the UHSC mix. Comparing methacrylate ether-based polycarboxylic ether and allyl ether-based polycarboxylic ether with different lengths and properties, Methacrylate based polycarboxylic ether primarily dispersed cement whereas allyl ether-based polycarboxylic ether is effective in dispersing silica fume. In this regard, a blend with allyl ether-based polycarboxylic ether was found best performing in UHSC [8].

CURING REGIME

The influence of the type of curing makes an impact on the overall performance of the UHSC, thus it is necessary to study its effects on concrete. Standard curing, steam curing, and autoclave curing are commonly used methods of curing. The details of these methods were discussed in the following section.

Standard Curing

Standard curing is where cast specimens were immersed in water until the day of testing. The curing age ensures denser microstructure and a higher degree of hydration and better bond properties CH reacted with SF to form CSH and effectively strengthen ITZ [7].

Steam Curing

In steam curing, the concrete specimen was immersed in water for 24 hrs and cured in a steam curing chamber at 70°C - 90°C for 24 hrs followed by immersion in water until testing. For the same mix proportion, the improvement in compressive strength from 25 - 60 % by steam curing to standard curing is possible. The effectiveness of steam curing is independent of FA and increases with GGBS content. FA is less adaptable for steam curing thus SF or GGBS must be combined with FA for better results under steam curing [3].

Heat Curing

In heat curing, specimens were immersed in water for 24 hrs and allowed to dry at room temperature. Air-dried specimens were then subjected to a temperature of 160°C for 24 hrs in a heat curing chamber [10]. Heat-cured UHSC shows high strength when compared with other methods and thus it can be a promising material for special prefabricated/prestressed concrete members. The UHSC shows low porosity, especially under heat curing. Fine silica is also essential for heat curing without it the rapid formation of hydration products may lead to lower compression strength. For the same mix proportion, it is possible to improve compressive strength from 10 - 60 % by heat curing than standard curing [3]. The disadvantage is the cost of setting up the plant. The reason for the strength increase in the heat curing method was due to the formation of a longer CSH chain attributed to the rapid hydration of cement with the pozzolanic activity of SF and quartz powder [10].

MECHANICAL PROPERTIES

Compressive strength

Table 1 presents the overview of the compressive strength of UHSC with different mixes based on literature. The mechanical properties of the concrete showed improved strength when subjected to high temperatures (60°C) than those cured at low temperatures [20]. A summary of tests for compression strength with a w/b ratio between 11% – 15% of proportioned mix 14.5% found higher compressive strength at the early stage and testing after 28 and 91 days, 12.5% found higher compressive strength due to lower w/b leads to decreased porosity [4]. In highlight, it is found w/b ratio of 11.5% found lower compressive strength which may be due to insufficient water and incomplete hydration of cement. Incorporating SF in UHSC showed a positive effect on compressive strength [21]. The increase in compressive strength with silica fume of 30% was 94 – 106% and when steel fiber was added with the same mix compressive strength increased by about 1 – 8%. The 40% of cement replacement with fly ash improved compressive strength by about 5 – 10% [3]. When incorporating MWCNTs of dosage 0.05% bwoc (by the weight of cement) provides an improvement in compressive strength up to 120 MPa [17]. The UHSC mix with 15% silica fume and 10 – 15% slag is suggested to be optimum to produce UHSC with compressive strength of more than 120 MPa [2]. Incorporating the optimum dosage of nano-SiO_2 can improve the compressive strength of concrete by around 4.76%. The increase in compressive strength in early ages was more with nano-SiO_2 and at 7 – 28 days strength increase was more with nano-$CaCO_3$ [18]. CH intensity was decreased in UHSC by incorporating 2 - 4% nano-SiO_2 due to the consumption of CH by nano-SiO_2 and further addition decreased the ability to enhance the compressive strength of UHSC due to the high surface energy of nano-SiO_2 [22]. The compressive strength increased by over 30% with an optimum dosage of nano-SiO_2. Replacing quartz sand with copper slag can produce compressive strength of over 150 MPa with untreated copper slag and over 200 MPa with treated copper slag under normal curing. Compared with normal curing, specimens of steam-cured and heat cured have an average increase of about 14% and maximum strength was achieved by heat curing [10]. Replacing 15% of cement with treated sugarcane bagasse ash (TBA) can improve the compressive strength up to 13% under normal curing and which further increased up to 23% and 50% under steam curing and heat curing respectively [23].

Table 1. Compressive strength of different UHSC mix.

SCM	Other components	w/b	Optimum % (bwoc)	Compressive strength (MPa)			References
				with 0%	with optimum %	% increase in strength	
SF	C	0.16	15	108.8	123.3	13.32%	[2]
SF	C	0.18	20	89	115	29.21%	[7]
SF	C	0.18	30	76	152	100%	[21]
SF	C + Steel fiber	0.18	30	78.5	154.5	96.81%	[21]
Slag	C	0.16	25	108.8	113.7	4.50%	[2]
SF + Slag	C	0.16	11.1+16.7	108.8	126.9	16.63%	[2]
FA	C + SF	0.13	40	114	124	8.77%	[3]
GGBS	C + SF	0.13	40	114	118	3.50%	[3]
ITP	C + SF	0.37	15	130	148.8	14.46%	[19]
Nano-SiO_2	C	0.2	4	100	128	30.32%	[22]

Cont. Table 1

Nano-SiO_2	C + SF	0.18	1	105	110	4.76%	[18]
Nano-$CaCO_3$	C + SF	0.18	4.8	105	118	13%	[18]
MWCNT	C + SF + GGBS	0.2	0.05	116.7	122.1	4.63%	[17]
GONS	C + SF + GGBS	0.2	0.01	117.3	126.5	7.82%	[24]
TBA	C + SF + Steel fiber +Quartz powder	0.18	15	180	191	6%	[23]

Flexural strength

Table 2 presents the overview of the flexural strength of UHSC with different mixes based on literature. The addition of Graphene oxide nanosheet (GONS) in the range of 0.01 – 0.03% bwoc causes a nearly 7% increase in the flexural strength of concrete. Similar results were found in incorporating MWCNTs in the range of 0.05% bwoc [24]. Incorporating silica fume of dosage up to 30% increased flexural strength by about 64% and a significant increase in strength was found with the addition of steel fibers [21]. It is possible to produce UHSC with a flexural strength of 45 MPa by replacing quartz sand with copper slag under normal curing [10]. Observing the use of steel fiber showed a stitching effect and prevented ductile failure.

Table 2. Flexural strength of different UHSC mix.

SCM	Other components	w/b	Optimum % (bwoc)	Flexural strength (MPa)			References
				with 0%	with optimum %	% increase in strength	
SF	C	0.18	20	19	25	31.57%	[7]
SF	C	0.18	30	8.95	14.73	64%	[21]
SF	C + Steel fiber	0.18	30	19.98	30.26	51.45%	[21]
ITP	C + SF	0.37	15	20.5	25.5	26.10%	[19]
Nano-SiO_2	C + SF	0.18	1	22	24	9.00%	[18]
Nano-$CaCo_3$	C + SF	0.18	3.2	21.5	24	11.63%	[18]
MWCNT	C + SF + GGBS	0.2	0.05	9	9.68	7.50%	[17]
GONS	C + SF + GGBS	0.2	0.01	8.92	9.98	11.88%	[24]

MICROSTRUCTURE

Porosity was higher at early ages while using silica fume and higher at later ages while using slag. With the increase in the amount of silica content porosity decreased. Silica fume improves pore structure through its filler effect and pozzolanic effect [2]. Pore diameter ranges from 3.75 nm to 100 μm and porosity never exceeds 10% in the volume of concrete [25]. Decrease in porosity with an increase in ground copper slag content in UHSC [10]. A UHSC with 3% bwoc of nano-$CaCO_3$ effectively decreases the porosity in concrete and makes the concrete denser and more homogeneous [18]. Similarly, nano-SiO_2 with a dosage of 1% bwoc effectively reduced the porosity. Both nano-materials showed nucleation and filling effects. The UHSC that incorporated nano-SiO_2 particles resulted in a refined microstructure with an increased volume of meso-pores by 70% [26]. A specimen without incorporating ITP found several microcracks, voids, and un hydrated cement particles whereas, the denser microstructure was found when incorporating ITP. Some microcracks found at 800°C improved the high-temperature resistance of concrete [19]. MWCNT when well-dispersed acts as a bridge between microcracks and guarantee the load transfer under tension [17]. More capillary voids and microcracks with an increase in unground copper slag that was found in reduced levels in the case of ground copper slag. An increase in large-size copper slag particles leads to the formation of several voids, cracks and reduced strength. Thus, copper slag with reduced particle size enables its ability to better adhesion with hydrated cement paste [10]. In steam-cured concrete, though the crystallinity of cement paste is higher, a more open paste structure is found which may be the reason for surface absorption and chloride ion penetration. Polycarboxylate superplasticizer also has some effects on making smaller hydration products. Closely packing of small-sized particles with higher surface energy makes the concrete denser resulting in high strength [27].

DISCUSSION

The main purpose of the partial replacement of cement with any supplementary materials was to reduce the cost and environmental impact without sacrificing the strength of concrete. In this regard, all the materials discussed above correspond well with this purpose.

Silica fume of optimum dosage proves to provide better flowability and strength with reduced porosity and calcium hydroxide content due to its outstanding filler effect and pozzolanic activity. But higher silica fume content may generate autogenous shrinkage, and proper dosage of fibers, when added with UHSC mix, reduced drying shrinkage and crack propagation.

Incorporating fly ash in UHSC showed reduced heat of hydration which also reduced shrinkage in the concrete to a promising level. No effective mechanical properties were found to develop due to the replacement of fly ash in UHSC.

Slag may show reduced compressive strength at the early stage, later improved strength was found due to its finer particle size and packing density.

Fibers with a high aspect ratio were found to bridge isolated pores efficiently and were capable of reducing the effect of spalling in concrete.

The optimum dosage of nanomaterials such as MWCNTs, nano-SiO_2, and nano-$CaCO_3$ when well dispersed in UHSC, may produce dense microstructure and show reduced porosity.

Using supplementary cementitious materials that are finer than cement, superplasticizer provides the lubricating effect among the materials and improves the flowability of the concrete.

Steam curing and heat curing are beneficial in improving the compressive strength of UHSC. At high temperatures, the pozzolanic reaction between CH and silica fume improves the microstructure of the concrete. The only drawback of heat curing is its capital cost.

Conflicts of interest: the authors declare no conflict of interest.

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