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Study on the Properties of Ultra-High-Performance Concrete-A Review

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Abstract -*Over the last two decades, significant progress has been made in the study and implementation of ultra-high-performance concrete (UHPC), which is a material with exceptional mechanical qualities and long-term durability. From a sustainability standpoint, it has showed considerable promise for next-generation infrastructure construction. In general, UHPC outperforms both normal concrete and high-performance concrete in terms of mechanical qualities and durability. As a result, UHPC is being more widely used around the world, in both new construction and retrofitting. This paper will provide an overview of UHPC, with an emphasis on its fundamentals, evolution, and suggested concepts for replacing pricey composites with cementitious materials, design, and applications. Although UHPC offers significant advantages over traditional concrete, its application is limited due to its high cost and restrictive design requirements. As a result, UHPC is a 'future' material that has the potential to improve the sustainability of buildings and other infrastructure components.*

Key Words: Ultra-High-Performance Concrete, Raw Materials, Mix Proportion, Mechanical Properties, Durability, Applications.

1.INTRODUCTION

Concrete technology has advanced tremendously during the previous decades. One of the achievements has been the invention of ultra-high-performance concrete (UHPC), which is a new type of concrete that has emerged in recent decades as a result of its outstanding strength and endurance and it has a compressive strength of more than 150 MPa and a significant increase in durability over high performance concrete (HPC) [5]. Fibers are inserted in the UHPC to create ductile behaviour under tension and, if possible, eliminate the need for traditional active or passive reinforcing. UHPC's strong performance makes it a prospective material for long-term and cost-effective use in a variety of buildings. It is widely considered that UHPC is well suited for the creation of next-generation infrastructure.

Portland cement, reactive powders, supplementary cementitious ingredients, limestone, high-range water reducers, fine sand and water are commonly used to make the material. The use of fine materials for the matrix also results in a thick, smooth surface that is recognized for its aesthetics and ability to transfer form features to the hardened surface with great precision. Even after initial cracking, the ductile characteristic allows the material to deform and support flexural and tensile loads. Based on prior experiences and experiments, by using the modified Andreasen and Andersen particle packing model, it is possible to build a thick and homogenous skeleton of UHPC or UHPFRC with a relatively low binder amount (approximately 650 kg/m3). As a result, it can be quickly deduced that such an optimized concrete design with the proper amount of mineral admixtures can be a promising technique to efficiently generate Ultra-High Performance Concrete [3]. UHPC has a w/c ratio as low as 0.2, resulting in a denser structure with smaller capillary pores. Poor matrix porosity contributes to low permeability, limiting the penetration of harmful agents such as chloride ions and toxic gases.

2.HISTORY AND DEVELOPMENT OF UHPC

Concrete has been utilized in construction since the time of the Romans. To withstand salt water, aggregates like pebbles, bricks, and ceramic tiles were mixed with gypsum and quicklime as a binding agent, as well as volcanic dust known as pozzolana. The usage of Roman materials was decreased, with builders relying on stones and mortar. Modern concrete, on the other hand, was invented in the nineteenth century. During the twentieth century, it was substantially developed as a critical part of most construction and building procedures. By the turn of the century, ultra-high-performance concrete technology, had achieved a remarkable advancement in concrete. This new technology enabled to achieve amazing quality levels [6].

In general, the evolution of UHPC can be split into four periods in terms of time: before the 1980s, 1980s, 1990s, and 2000. Because of the lack of advanced technologies prior to the 1980s, UHPC could only be made in the lab using specialized techniques like as vacuum mixing and heat curing. The micro-defect-free cement (MDF) was invented in the early 1980s. It has a compressive strength of up to 200 MPa. However, because of high cost of raw ingredients and the time-consuming preparation process, this material is only used in a few applications. During this time, the particle packing theory was first applied to UHPC design, and silica fume (SF) and steel fibers were introduced to UHPC for the first time. Reactive powder concrete (RPC) was developed in the 1990s, marking a significant step forward in the development of UHPC. Steel fibers, superplasticizer, and very fine particles (cement, sand, quartz powder, and silica fume) constitute RPC. The coarse particles are removed to improve the matrix's homogeneity. The Sherbrooke Bridge in Canada, the world's first RPC bridge, was completed in 1997. Much progress has been achieved in the development of UHPC since the 2000s [5]. UHPC can now be built at a low cost of materials and with minimal energy use. Several countries have been experimenting with UHPC since the early 2000s. The number of UHPC projects executed each year has gradually increased over the last 15 years. In the United States, UHPC has been used in more than 250 bridges, mostly as precast concrete deck panels and composite connections between supporting girders and precast deck panels [13].

3.RAW MATERIALS AND ITS EFFECT ON UHPC

UHPC is a cutting-edge concrete technology that is gaining widespread notice. Premix, fibers, and liquids were three components of the UHPC used in this investigation. When compared to traditional concrete, UHPC has significantly improved mechanical qualities such as compressive strength, tensile strength, and workability [1]. UHPC compositions normally include Portland cement with a medium fineness and a C3A concentration of less than 8%. The water-to-cement ratio is approximately 0.22. Steel fibers make up 2.5% of the total volume [16].

The properties and working mechanism of common ingredients in new UHPC development, such as binder materials, aggregates, reinforcing fibers, and chemical admixtures, are discussed below.

3.1 Cement

Types of cement used in traditional concrete include Type I to V and white cement, which can all be used to build the UHPC depending on the environmental circumstances and applications. Mostly used cement in this study is Ordinary Portland Cement [3]. Because of the high C3S content and Blaine fineness, Type III and white cement are the most often utilized varieties because they allow quick setting and strength development [2]. The compressive strengths of UHPCs produced by substituting numerous different cements range from 19 ksi (130 MPa) to 32 ksi (221 MPa) [15]

3.2 Supplementary Cementitious Materials

Silica fume, fly ash, slag, glass powder, and rice husk ash are examples of SCMs that have been utilized in UHPC to lower the costs and increase characteristics. Silica fume is produced as a byproduct of the manufacturing of ferro-silicium alloys with an average diameter of 0.2 μm [4]. Silica fume is a common yet important component in UHPC mixtures, with normal usage ranging from 5% to 25% depending on the volume of the binder. Because of the small particle size, adding silica fume (at a concentration of 10%) to UHPC increases particle packing density and consequently workability. However, due of the large surface area, when the content exceeds 10%, the workability may be severely diminished [2]. Fly ash, which is made up of spherical particles, is a byproduct of coal power plants. As a binary, ternary, or quaternary system, it's commonly coupled with GGBFS, SF, and/or steel slag powder, among other things. After standard room curing, the compressive strength of UHPC containing high levels of GGBFS and fly ash reached above 200 MPa [4]. Due to their similar proportion of amorphous silica, rice husk ash is commonly used to partially and/or completely replace silica fume. Due to its porous nature, rice husk ash has a greater surface area (64,700 m2/kg) than silica fume (i.e., 18,500 m2/kg), making it more prone to absorbing free water and water reducer. As a result, adding rice husk ash to the mix can considerably diminish the workability [2]. The slag utilized in UHPC can be iron slag, copper slag, or barium slag, depending on the major metal oxides. Slag is commonly used to substitute cement in alternative SCMs, with a replacement ratio ranging from 30% to 60%, depending on the volume of binder. After autoclaving, the reactive powder concrete with high volume GGBFS had a compressive strength of above 250 MPa. Compressive strength might exceed 400 MPa when external pressure was applied during the setting stages [4].

3.3 Aggregates

UHPC is typically made using finely crushed quartz sand with diameters ranging from 150 μm to 600 μm. The primary fine aggregate utilized to replace quartz sand is river sand. Finer and more evenly sized masonry sand (size range: 0–2 mm) was used to increase particle packing. Masonry sand, on the other hand, is made by crushing and grinding coarse aggregates, resulting in more angular particles than river sand, which reduces the workability of UHPC. Limestone sand is inexpensive, has a uniform composition, huge reserves, and is widely available. Basic principles of developing UHPC have been established in which the coarse aggregates (i.e., size greater than 4.75 mm) are generally eliminated [2].

3.4 Chemical Admixture

To change the fresh and/or hardened qualities of UHPC, chemical admixtures are used. UHPC has employed a high-range water reducer (HRWR) to obtain a self-consolidating feature. Poly carboxylate ethers (PCE) are the most effective at dispersing cement particles among the several varieties, SP with a solid content of 20% was used. The SP dosage was modified to provide a mini-slump flow between 240 and 250 mm with no vibration consolidation [8].

3.5 Fibers

In UHPC, fibers are employed to increase tensile characteristics by preventing crack start and propagation. Steel fibers improve material qualities such as tensile strength, ductility, crack spacing reduction, and energy dissipation by incorporating them into the ultra-high performance concrete matrix [2]. The degree of the effects is influenced by fiber material strength, cementitious matrix – fiber bond ability, fiber aspect ratio (length: diameter), fiber volume content, and fiber surface morphology. When compared to UHPC with untreated steel fibers, the tensile strength and strain capacity of UHPC with roughened steel fibers increased by 15% and 16%, respectively [15].

4. MIXING PROPORTION AND MIXING PROCEDURE

UHPC mixes typically contain 650 to 900 kg/m3 cement, as well as micro-silica and fine particles (quartz, basalt, and other fine particles) with a maximum grain size of 1 mm. Between 0.13 and 0.17 is the water/binder ratio. To make an ultra-compact matrix, the components are combined with a superplasticizer. Recently, limestone filler has been employed to replace a large percentage of cement and increase workability, resulting in a more cost-effective and ecologically friendly UHPC [9]. Typically, silica fume usage ranges from 5% to 25% (about 231kg/m3), depending on the volume of the binder content [2]. Superplasticizer, a high-range water-reducing additive of about 30.7 kg/m3 were combined with the UHPC. The straight steel fibers with a diameter of 0.2 mm and a length of 12.5 mm were used. Fibers with a concentration of 2% by volume (or 240kg/m3), were added to the mix. Cement is replaced by FA, GGBS, and LP [3].

The premix was dry mixed for approximately 4 minutes at first. After that, half of the superplasticizer and half of the water were added to the mixture and stirred for another 15minute. After that, the remaining superplasticizer was added, and the components were combined until the dry powder mix became a wet paste concrete (approximately 2 min). Steel fibers were gradually incorporated into the wet concrete slurry in the mixer by hand. The UHPC was then ready to be cast after another 6 minutes of mixing to ensure correct fiber distribution. The casting began as soon as the mixing was finished. All UHPC specimens were cast within 15 minutes of the mixing being completed. Because of the fibers, the UHPC was scooped into the molds rather than rodded. To avoid moisture loss, the exposed surfaces of each specimen were subsequently wrapped in plastic [1].

Performance-based approaches were developed to design UHPC blends in accordance with desired performance for various applications. First, the binder combination is broken down into three steps: (i) choose binder combinations based on flow characteristics; (ii) narrow down binder combinations based on particle packing, flowability, and mechanical properties; and (iii) finalize binder combinations based on rheology properties such as plastic viscosity and yield stress [2].

5. MECHANICAL PROPERTIES OF UHPC

5.1 Fresh Behaviour Of UHPC

The relative slump of fresh UHPC mixtures versus the volumetric water to powder ratio demonstrates that the relative slump of all concrete mixtures grows linearly as the water amount is increased. The water requirement of each mixture in the investigation follows the following order: Flyash (FA)<Limestone powder (LP)< GGBFS <reference sample. In GGBFS, a great number of angular particles may be seen, whereas FA particles are more spherical. As a result, among all the analyzed concrete mixtures, the FA combination has the lowest demand water quantity. To make a UHPC that flows well, the water amount should be controlled precisely [3].

5.2 Bond Strength

The challenge of bond strength between these two materials is highlighted by casting UHPC adjacent to concrete at various ages or even casting UHPC next to steel. To quantify the interfacial bond strength, a bi-surface shear test configuration was chosen to assess the bond strength for smooth and rough interface surfaces between the two materials. Ten cubical specimens with 153 mm sides were made for the study. The cube's concrete substrate takes up two-thirds of the volume, while UHPC takes up the remaining third. It should be emphasized that normal strength concrete (NSC) was cast in the first stage, and UHPC was applied as an overlay after 56 days in the second stage. The interface surface preparation of these specimens was used to split them into two groups. The concrete surface was left as-cast in the first group, which termed as "Smooth." The concrete surface was roughened with sandblasting in the second group, with an average surface roughness of 1.72 mm as "Rough". The bisurface shear test setup used a loading plate with dimensions of 38 mm 51 mm 153 mm, resulting in two shear planes. The universal testing machine (UTM) was employed with a load rate of 935 N/s, which corresponds to a bond strength of 0.02 MPa/sec [12].

5.3 Compressive Strength

The compression test was performed using 50*50*50 mm cubes in accordance with BS 1881-116. This experiment was carried out at the ages of 7, 14, and 28 days. For each mixture, three samples were tested, and the average of these three samples were recorded. The highest compressive strengths were found in the 0.12 w/b group, while the variations were minor. Raising the fiber content until it reaches 1.5 percent, improves the strength; however, once this fiber content is reached, the strength enhancement stays at a certain level, regardless of w/b or age. [11]. The compressive strength of the mixes with 0.12 w/b ratio was higher by 8.3% and 21.7% at 14 and 28 days, and by 10.6% and 25.7% at 14 and 28 days for the mixes with 0.14 w/b ratio, respectively, than at 7 days. The compressive strength of 50 mm cube was 24.8 ksi (171 MPa) for UHPC. Furthermore, the decrease in strength reported in UHPCs as the w/b ratio increases could be due to the creation of additional undesirable calcium hydroxide particles during the hydration process. According to the testing, the presence of fiber in the case of UHPC results in the cylinder being intact after failure [1].

5.4 Tensile Strength

5.4.1 Flexural Strength

One of the tests used to determine the tensile qualities of UHPC was flexural toughness. For this experiment, 500mm x 150mm x 150mm prisms were used. This testing method relies on simple beam bending theory and linear elastic stress-strain behaviour up to failure. The average tensile strength of UHPC and standard concrete in flexural tests was 3.17 ksi (21.9 MPa) and 0.7 ksi (4.9 MPa), respectively. Due to the presence of fibers in UHPC, the beam remains unbroken, whereas NC prisms fail due to brittle behaviour [1].

5.4.2 Splitting Tension

The splitting tension test method involves compressing a cylindrical test specimen on its side until it splits into two lengthwise parts when its tensile strength is attained. As a result, the splitting tensile strength is calculated using the specimen's peak load. Three-inch diameter cylinders were employed in this experiment. For these tests, the load rate was set at 210 lb/s [1]. Due to the presence of fibers, the UHPC cylinders did not break into two pieces. UHPC had a tensile strength of 3 ksi (20.7 MPa) whereas ordinary concrete had a tensile strength of 0.48 ksi (3.5 MPa). The addition of fibers often increases the tensile strength of concrete. This is due to the fibers ability to seal tensile cracks, therefore preventing fracture propagation. [11].

5.5 Modulus of Elasticity

The elastic modulus was determined using 150 mm Cubic specimens. The samples were loaded up to a maximum load of 40% for the compressive strength test's maximum load; matching stress was determined, and the elastic modulus was calculated as the average of the three sets of readings using the stress–strain response. It was discovered that by adding micro glass fibers to the UHPC, the static elastic modulus rose consistently up to a volume fraction content of MGF, regardless of the water to-binder ratios (1.5 percent). When compared to the references, the UHPFRC mixes improved by 5.8 percent and 8.3 percent at 1.5 percent for the first and second groups, respectively. These findings suggest that UHPFRC mixes containing an optimal dosage of micro-glass fibers could result in a UHPFRC with a high rigidity [11]. In tension and compression, the modulus of elasticity of UHPFRC is 45 to 50 GPa, which is a low value given the rigidity of new structures in structural UHPFRC. The apparent modulus of elasticity of UHPFRC decreases with increasing hardening strain in the tensile strain hardening region [9].

6. DURABILITY PROPERTIES OF UHPC

In terms of durability, UHPC has outstanding qualities. One of the main goals of UHPC concrete is for it to be durable, similar to rock, and last for a long time without deteriorating in quality. In general, concrete structures can be placed in locations where they would be exposed to harsh environmental conditions such as water penetration, chemical attacks, steel corrosion, alkali silica reaction, freeze-thaw cycles, and carbonation. Long-term exposure to such harsh circumstances can cause concrete structures to deteriorate, raising maintenance expenses [6]. UHPC is a material that does not have capillary pores. Meanwhile, it has a substantially lower overall porosity than regular concrete. As a result, UHPC is considered a material with outstanding chemical resistance [5].

6.1 Freeze Thaw Resistance

Ultra-high performance concrete specimens showed no signs of degradation after 32 freeze-thaw cycles. After 112 cycles, specimens with strengths between 140 and 160 MPa showed no deterioration. The influence of silica fume and high-volume Class C fly ash on the durability of self-compacting concretes was investigated, and it was discovered that a 10% by volume inclusion of silica fume resulted in improved freeze-thaw resistance and increased compressive strengths [15].

6.2 Chloride Ion Penetration Resistance

UHPC was able to achieve permeability values of fewer than 100 coulombs for both air-cured and steam-cured specimens using fast chloride permeability tests. In materials with coulomb values less than 100, chloride ion penetration is considered low. Most known chloride permeability studies are for proprietary materials, and there is currently no data for non-proprietary mixtures [14].

6.3 Fire Resistance

Although there is no free water in UHPFRC, it has a low fire resistance and is comparable to concrete. Adding polypropylene fibres, on the other hand, can prevent UHPFRC from spalling, giving acceptable fire safety for most applications [9].

7. APPLICATIONS

UHPC's applications have been steadily rising in recent years because of its higher performance. Bridges, buildings, structural strengthening and retrofitting, and other unique applications are the principal applications of UHPC. The following sections will provide some concrete instances.

Bridges: When compared to standard reinforced concrete bridges, most bridges designed using UHPC components or joints have a leaner appearance, are lighter, easier to install, and last longer [10]. UHPFRC was used as thin waterproofing layers (instead of the conventional waterproofing membranes) and as reinforcement layers for bridge deck slab strengthening.

Structural strengthening and retrofitting: The hydraulic structures could potentially be repaired and protected with UHPC. The rehabilitation of the Hosokawa River Tunnel in Japan is the first example. Repairs and reinforcements were made to the slabs and the hydraulic vertical screen. Rehabilitation and protection of heavily corroded rebar kerbs, parapets, crash barrier walls, and piers of bridges exposed to chloride [5].

Buildings: Building components, including as sunshades, cladding, and roof components, were the dominating domain of UHPC applications in the recent decade, in addition to bridge applications [7]. UHPC could be utilised to create structures that are thin, long-lasting, and attractive. The Fondation Louis Vuitton pour la Creation in Paris is one of the newest structures to use UHPC [5].

Protection Layer: Chemical and aggressive wastewater protection for concrete buildings such as containers. A formwork was used to apply the UHPFRC coating to the walls. A significant benefit of employing UHPFRC is the comparatively thin layer, which allows for a reduction in container storage volume [9].

8. CONCLUSION

UHPC is currently one of the most advanced cementitious materials technologies. It's an innovative new material with outstanding properties including great strength and durability, which were achieved by increasing homogeneity and packing density. Since its introduction in the early 1990s, a considerable deal of information has been learned about the material, design, and construction of UHPC structures, with several countries attempting to use it to building and bridge applications. In France, Japan, Germany, and Switzerland, technical suggestions have been published. In UHPC, the use of widely available additional cementitious materials such as fly ash and slag to replace cement and silica fume might dramatically cut material costs. At the same time, UHPC with the correct amount of extra cementitious ingredients could achieve compressive strength of 150– 200 MPa following normal curing. Steel fibers are frequently used in UHPC matrices. The correct fiber dosage could help increase mechanical performance. Experiments on the materials included cylinder and cube compressive strength tests, as well as three point flexural strength, briquette tensile, and splitting tension tests, to determine the basic behavior of UHPC and normal concrete. According to results obtained during the experimental section of the study, the compressive strength of commercial UHPC used in this analysis were three to four times greater than standard strength concrete. In addition, UHPC specimens possessed a two-fold higher modulus of elasticity than NC specimens. With a rising number of applications in recent years, UHPC's remarkable performance offers up new opportunities for infrastructure projects and building construction.

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