A Study on Ultra High Performance Concrete Using Minerals Admixtures and Steel Fibers

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is a relatively new construction material, which is a combination of high performance concrete, minerals admixture and steel fibers. The compressive strength reaches beyond 150 MPa, which allows the construction of sustainable and economic buildings with an extraordinarily slim design. In general the aim is to achieve such high strength keeping the cement content under permissible limits. The aim herein is to develop a concrete mix incorporating silica fume, nano silica and ground granulated blast furnace slag (GGBS) with the addition of different percentages of steel fibers, which provides for high performance, durability and better serviceability in addition to overall economy in the long run. In this study, the compressive strength of UHPC is studied closely for different percentages of steel fibers with three w/b ratios (0.24, 0.22, and 0.20). The purpose is to have such proportions of materials, including cement replacement materials like silica fume, nano-silica, GGBS etc., which on mixing would be able to provide compressive strengths in the range of 125 to 150 MPa at 28 days. The studies were carried at an early age of 7 days as well as. The workability of the different mixtures was constantly maintained by optimum usage of super plasticizers. The results showed that with the increase in the amount of steel fibers the compressive strength of the matrix increased. The maximum strength of UHPC, which was achieved under laboratory conditions, was 155 MPa, after 28 days of curing. This strength was achieved for the mix where in the overall binder content included 7% silica fume, 3% nano silica, 10% GGBS (with remaining 80% as cement content) along with the addition of 1.25% steel fiber.

1. INTRODUCTION

Concrete is a widely used construction material in the construction industry. Since ancient time, mankind has been searching for construction materials with higher performance to build taller, longer and sounder structures. The use of cementations material can be traced back thousands of years to Italy, Greece, ancient Egypt and the Middle East. The development of modern Portland cement began in 1756 when in an experiment John Smeaton combined limestone sand additives including trass and pozzolans in different combination for a planned construction of a lighthouse. The production of Portland cement in the modern sense began in 1840s which was initiated by Isaac C. Johnson. Afterwards, the cost and demand of construction materials has risen significantly, which triggered a demand to make much stronger and durable materials. This resulted in development of concrete with strength ranging from 40 to 80 MPa, during the mid-60’s and was named High Performance Concrete (UHPC). It was first used in significant quantities in many major structures in the city of Chicago, USA.

As the development has continued, the definition of high-strength concrete has also changed over the years. In the 1950s, concrete with a compressive strength of 34 MPa was considered high strength, whereas, in the 1960s, concretes with compressive strengths ranging from 41 MPa to 52 MPa were used commercially as high strength concretes. During the early 1970s, concrete with strength of 60 MPa was being produced and was introduced many applications such as high-rise buildings and long-span prestressed concrete bridges. More recently, concrete having compressive strengths over 120 MPa have been developed and are being used for many applications. It is more popularly known as Ultra High Performance Concrete (UHPC). These concrete has a more improved advantage over HPC as it presents a greater interest for concrete construction industry, thus, opening up new vistas for use of new innovative materials With the introduction of UHPC, it is now possible to produce lighter products with thinner sections and open up new possibilities for bridge and high-rise building and offer economic advantages through savings in reinforcing steel and cross sectional dimensions. This would lead to lower dead weight, thus allowing larger spans.
Ultra-High Performance (UHPC) using minerals admixtures with steel fiber is relatively new construction material. Hence, it is a combination of high performance concrete and minerals admixture and steel fiber. UHPC is generally made using fine, coarse aggregates, amounts of water and high quartz, minerals admixtures, steel fiber amounts of cement. Silica fume is generally considered in the preparation of UHPC as it provides more strength. These materials are characterized by a dense microstructure. The sufficient workability is obtained by using superplastisizers in combination with the low water demand of the fresh concrete. The Compressive strength ranges between 120MPa to 150MPa, which allows the construction of sustainable and economic buildings with an extraordinarily slim design. The mechanical performance, durability and ductility behavior of UHPC differs scientifically from normal and high strength concretes due to the high packing density of these materials. The increase in compressive strength decreases the ductility. This matter limits its use in structures.

2. MATERIALS

2.1 SELECTION OF MATERIALS

Effective production of UHPC could be attained by carefully inspecting, controlling, selecting and proportioning all the necessary ingredients, which go into making of concrete. Ingredient materials with specific requirements for use in UHPC are discussed as below:

2.2 Cement

Cement is the basic ingredient for making concrete and development of UHPC an Optimum quality of OPC should be utilized from both workability as well as strength point of view. Any variation in cement content causes the compressive strength of concrete to fluctuate more than any other single material. Following are the physical properties required for cement to be used in UHPC.

Minimum 7 days mortar cube strength: -- 28.959 MPa
Mortar air content: -- 7 to 10 %

2.3 Supplementary cementsations materials

UHPC cannot be developed only by the use of basic concrete materials. Silica fume, minerals admixtures steel fiber etc are some of the supplementary cementsations material which is generally considered in the development of UHPC. These materials can not only help control the temperature rise in concrete at early ages but can also reduce the water demand for given workability.

2.4 Water-Cement ratio

Water is the binding force of concrete and for the evolution of UHPC a very low w/c ratio i.e. in the range of 0.20 - 0.32 is required. The acceptability of water for UHPC is not a major problem if potable type water is used. Basically, the workability of concrete is controlled by use of super plasticizer in it. For production of UHPC in the laboratory, in the present study three different water-cement ratios of 0.20, 0.22 and 0.24 have been considered. There is a diverse established effect of w/c ratio on the strength properties of concrete, the strength of concrete increases if the w/c ratio decreases.

2.5 Fine aggregates- Aggregate most of which passes 4.75-mm IS Sieve and contains only so much coarser material as permitted in 4.3.

2.5.1 Natural Sand - Fine aggregate resulting from the natural disintegration of rock and this has been deposited by streams or glacial agencies.

2.5.2 Crushed Stone Sand - Fine aggregate produced by crushing hard stone.

2.5.3 Crushed Gravel - line aggregate produced by crushing natural gravel.
2.6 Coarse Aggregate -- Aggregate most of which is retained on 4*75-mm IS Sieve and containing only so much finer material as is permitted for the various types described in this standard.

NOTE - Coarse aggregate may be described as:
   a) Uncrushed gravel or stone which results from natural disintegration of rock.
   b) Crushed gravel or stone when it results from crushing of gravel or hard stone.
   c) Partially crushed gravel or stone when it is a product of the blending of (a) and (b).

It was observed that the size of the aggregate regulates the strength of concrete apart from w/c ratio. For a given w/c ratio, the strength of concrete is decreased as the maximum size of coarse aggregate increased. It was also observed that for optimum compressive strength with high cement content and low w/c ratio the maximum size of coarse aggregate should be kept minimum at the rate of 12.5 mm or 9.5 mm. “It was suggested that ideal aggregate should be angular, clean, cubical, 100 percent crushed and continuously graded with a minimum of flat and elongated particles”.

2.7 Admixture:

The admixtures which are generally used in concrete manufacturing can be classified into two categories namely chemical admixture and mineral admixtures. The same are discussed as below, with regards to their use in production of UHPC.

2.7.1 (Chemical Admixtures): They are basically high performance, High Range Water Reducing (HRWR) & Retarding Admixtures. Their main uses are specified as below:

1. They are suitable for high performance concrete.
2. By increasing workability without adding extra water to produce pump able concrete.

They can be used with concrete containing micro-silica and other cement replacements, improved cohesion by minimizing segregation and give better finish. They minimize permeability and increase the waterproofing properties of concrete.

2.7.2 Mineral Admixture:-Use of mineral admixtures reduces the cost, permeability, and increases strength along with changing other concrete properties. The three main mineral admixtures that are frequently used are listed below:

1. Silica fume
2. Fly ash; and
3. Ground Granulated Blast Furnace Slag

In the present study silica fume and GGBS along with nano silica have been used for developing UHPC. Their significance is provided as below:

2.8 Silica Fume: - Silica fume is used in concrete to improve its strength as well as durability properties, if used in proper proportions. It has been found that silica fume improves compressive strength, bond strength, and abrasion resistance; reduces permeability; and therefore helps in protecting reinforcing steel from corrosion.

Silica fume has been used as an addition to concrete up to 15 percent by weight of cement although the optimum proportion is ranged between 7 to 10 percent. A fine non-crystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or alloys containing silicon is known as condensed silica fume or micro silica. Silica Fume is also collected as a byproduct in the production of other silicon alloys such as ferrochromium, ferromanganese, ferromagnesian, and calcium silicon (ACI Comm. 226 1987b). Before the mid-1970s, nearly all silica fumes were discharged into the atmosphere. After environmental concerns necessitated the collection and land filling of silica fume, it became economically justified to use silica fume in various applications.

Silica fume consists of very fine vitreous particles with a surface area on the order of 215,280ft2/lb (20,000 m2/kg), when measured by nitrogen absorption techniques, with particles approximately 100 times smaller than the average
cement particle. Because of its extreme fineness and high silica content, silica fume is a highly effective pozzolanic material (ACI Comm. 226 1987b; Luther 1990). Silica fume is used in concrete to improve its strengths as well as durability properties, if used in proper proportions. It has been found that silica fume improves compressive strength, bond strength, and abrasion resistance; reduces permeability; and therefore helps in protecting reinforcing steel from corrosion.

Silica fume has been used as an addition to concrete up to 15 percent by weight of cement, although the optimum proportion is ranged between 7 to 10 percent. With an addition of 15 percent, the potential exists for very strong, brittle concrete. It increases the water demand in a concrete mix; however, dosage rates of less than 5 percent will not typically require a water reducer. High replacement rates will require the use of a high range water reducer.

2.9 Ground Granulated Blast Furnace Slag (GGBS)

It is a non-metallic product consisting essentially of calcium silicates and other bases that is developed in a molten condition simultaneously with iron in a blast furnace.

2.10 Nano Silica

Colloidal silica is a nano metric particle size solution of silica particles in water or other mediums. It finds uses in diverse applications which can be briefed as follows:
Ceramic slurry binder for making investment casting shells. Grain binder in refractory, refractory monolithic, gunning and ramming masses, LCC, ULCC , high temperature refractory and ceramic products like vacuum formed fiber shapes, high temperature ceramics , insulation wools , fabrication of artificial dentures etc.

2.11 Steel Fibers

They are filaments of wire which are deformed and cut to lengths. It is a cold drawn wire fiber with corrugated and flattened shape. They are used for the reinforcement of concrete, mortar and other composite materials.

There are a number of different types of steel fibers with different commercial names. The steel fibers are categorized into four groups depending on the manufacturing process viz: cut wire (cold drawn), slit sheet, melt extract and mill cut. They can also be classified according the shapes viz: straight steel fiber, intended steel fiber and hooked steel fiber. Various notations are used for to segregate the type of the steel fibers. (h x w x l) to nominate the straight rectangular section steel fibers.

The letters h, w and l stand for section depth, width and the fiber length respectively. (d x l) was used to name circular or semi-circular section straight or deformed steel fibers; d and l stand for diameter and length respectively. Hook-ended steel fiber (i.e. 80/60 H means aspect ratio/Length of steel fiber). Major efforts have been made in recent years to optimize the shape and size of the steel fibers to achieve improved fiber-matrix bond characteristics and to enhance fiber dispersion. The high tensile stresses localized at cracks necessitate that steel fibers have high tensile strength. Typical steel fiber tensile strengths are ranged between 1100 and 1700 MPa.

2.12 ADVANTAGES OF UHPC

1. Its high compressive strength.
2. Low porosity of UHPC.
3. Improved microstructure and homogeneity, high flexibility with the addition of fibers.
4. UHPC has found application in the storage of nuclear waste, bridges, roofs, piers, seismic - resistant structures and structures designed to resist impact loading.
5. UHPC construction requires lower maintenance costs in its service life than conventional concrete.
6. UHPC may incorporate larger quantities of steel or synthetic fibers and has enhanced ductility, high temperature performance and improved impact resistance.

3. LITERATURE

General review of papers has been conducted on the mix proportions, compression strength properties of ultra high performance concrete. The following literature review discusses the mix proportions, properties, design and
application of UHPDC. The development of these materials has been undertaken by numerous research and engineers worldwide in hopes to promote UHPDC as an ultimate sustainable construction material for the future. In addition, a brief summary of modeling of UHPDC in compression as well as tension were presented. Also some reports from American concrete institutes for ultra high performance concrete were presented.

[Richard and Cheyrezy 1994] is the latest ultra-high-strength Portland cement-based material that has been developed. It can achieve a compressive strength of up to 800 MPa, though this is not the ultimate strength that is likely to be achieved. All these materials have one thing in common: their w/c ratio is much lower than that of high-performance concrete.

[Collepardi et al. (1996) 2] studied the influence of the super-plasticizer type on the compressive strength of reactive powder concrete RPC. Two types of Portland cement were used having different $C_3A$ content.

[Graybeal et al. (2003)] In 1982, the sale of silica fume in Quebec, Canada started picking up because of the availability of this product. One of first major use of the silica fume concrete in the U.S. was the rehabilitation of the stilling basin of Kinzua Dam in 1983. The concrete contained 386 Kg/m3 of cement with 70 kg/m3 of silica fume and the specified compressive strength was 70MPa at 7 days and 86 MPa at 28 days.

[Richard and Cheyrezy 1995; Ma and Schneider 1996] The results of careful thinking how to exploit these technological breakthroughs and/or some fundamental knowledge about low-porosity materials has led to the development over the past 30 years of a number of Portland cement-based materials that present remarkable mechanical properties.

4. EXPERIMENT WORK

4.1 Slump test

Slump is a measurement of concrete's workability, or fluidity. It's an indirect measurement of concrete consistency or stiffness. A slump test is a method used to determine the consistency of concrete. The consistency, or stiffness, indicates how much water has been used in the mix. The stiffness of the concrete mix should be matched to the requirements for the finished product quality.

Procedure of concrete slump test

1. The mold for the slump test is a frustum of a cone, 300 mm (12 in) of height. The base is 200 mm (8 in) in diameter and it has a smaller opening at the top of 100 mm (4 in).
2. The base is placed on a smooth surface and the container is filled with concrete in three layers, whose workability is to be tested.
3. Each layer is tamped 25 times with a standard 16 mm (5/8 in) diameter steel rod, rounded at the end.
4. When the mold is completely filled with concrete, the top surface is struck off (levelled with mould top opening) by means of screening and rolling motion of the temping rod.
5. The mould must be firmly held against its base during the entire operation so that it could not move due to the pouring of concrete and this can be done by means of handles or foot - rests brazed to the mould.
6. Immediately after filling is completed and the concrete is leveled, the cone is slowly and carefully lifted vertically, an unsupported concrete will now slump.
7. The decrease in the height of the center of the slumped concrete is called slump.
8. The slump is measured by placing the cone just besides the slump concrete and the temping rod is placed over the cone so that it should also come over the area of slumped concrete.
9. The decrease in height of concrete to that of mould is noted with scale. (usually measured to the nearest 5 mm (1/4 in).

4.2 Compressive strength test

The cubes of dimensions 150 x 150 x 150mm were casted under standard laboratory conditions and were tested after a curing period of 7 and 28 days. The time was calculated from the time when water was added to the dry
The specimens prepared were tested on 500 tons capacity Automatic Compression Testing Machine (ACTM). The specimens after being taken out from curing tank were wiped with cloth for any traces of surface water; they were then kept at room temperature for half an hour to remove the surface moisture. According to Indian standard procedure laid down in IS: 516-1959 the cubes were placed in such a way that the load was supplied at the right angle to the faces of cube rotating them at 900. Load was applied continuously at the rate of 5 MPa per second until the failure of the specimen takes place.

4.3 Mix proportions used in the present study

For the development of UHPC two trial mixes were taken in this study with three different water binding ratios of 0.20, 0.22 and 0.24 constituting a total of six mixes (M1, M2, M3, M4, M5 and M6). In addition to the mixes six different percentages (0.00, 0.25, 0.50, 0.75, 1.00, and 1.25) of steel fibers were added to each mix and each water binding ratio to study the effect on concrete compressive strength. The percentages of steel fibers are w.r.t cement content. Six cubes were casted for each mix and each percentage of steel fibers to determine the compressive strength after 7 and 28 days, respectively.

4.4 Compressive strength

The main function of concrete in a structure is mainly to resist the compressive forces. When a plain concrete member is subjected to compression, the failure of the member takes place in its vertical plane along the diagonal. The vertical cracks occur due to lateral tensile strain. A flow in the concrete, which is in the form of micro crack along the vertical axis of the member, will take place on the application of axial compression load and propagate further due to the lateral tensile strain.

4.5 Test procedure and Results

Test specimens of size 150×150×150 mm were prepared for the testing the compressive strength of both controlled as well as steel fiber-silica fume-blast furnace slag based concrete. The modified mixture with varying percentage of steel fibers was prepared and casted into cubes with partial replacement of cement with blast furnace slag and silica fume. In this study the mix was prepared using a pan mixer available in the laboratory. The cement, GGBS and silica fume were first mixed properly by hand to make a uniform colored blend. The fine and coarse aggregates along with steel fibers were added into the mixer and were mixed properly.

After that, the blend was incorporated into the mixer and was rotated to mix properly for 4-5 minutes. Half of the water was added to the mix to make a saturated mix. The super plasticizer and nano silica were then poured into the remaining water and were added to the mix. The mixer is rotated for 5-7 minutes to achieve the proper mix of desired concrete. A constant workability, of 80 to 90mm slump, was maintained for all the mixes by varying the super plasticizer dosage.

The cubes were tested at the age of 7 and 28 days. The time was calculated from the time of addition of water to the dry ingredients.

<table>
<thead>
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<th>Table 1 Compressive strength results for trial mix 1</th>
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<tr>
<td><strong>MIX 1</strong></td>
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<td><strong>w/b = 0.24</strong></td>
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<td><strong>Fiber (%)</strong></td>
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<td><strong>W</strong> kg/m3</td>
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<tr>
<td>0.25</td>
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<tr>
<td>0.50</td>
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<td>0.75</td>
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Table 2 Compressive strength results for trial mix 2

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<th>CA20</th>
<th>CA10</th>
<th>NS</th>
<th>SF</th>
<th>GGBS</th>
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<th>28D</th>
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<tr>
<td>Fibers</td>
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<td>%</td>
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CONCLUSION

The compressive strength test was performed after 7 and 28 days of curing of concrete specimens. Super plasticizer was used in all then mixes at the rate of 1.25% to 2.00% of the binder content, depending upon the desired workability.

The workability of mix was maintained by adding super plasticizer only. Based upon the results discussed in the previous chapter, following are the major conclusions which can be drawn from the study:

1. The supplementary cementitious materials like silica fume, nanosilica and GGBS play a significant role in strength development of the concrete mixes.
2. With the addition of steel fibers to the mix a significant increase of 5 to 25% in strength development can be achieved.
3. The reduction in w/b ratio considerably increases the strength of the mix by 10 to 30%.
4. It is possible to produce mixes with a compressive strength of over 100 MPa, after 28 days curing, with maximum w/b ratio of 0.24, with the addition of steel fibers and optimized mix containing nano silica, silica fume and GGBS as supplementary cementitious materials.
5. With higher percentage of replacement of cement the strength was nearly equal to the mix containing higher amount of cement.
6. The addition of 1.25% steel fibers tends to give better strength results as they provide more pinching force to the micro cracks developed within the concrete.
7. It is possible to produce UHPC with compressive strength higher than 120 MPa, for mixes with w/b ratio of 0.20 with or without steel fibers and having 3% nano silica, 7% silica fume, and either 10% or 20% GGBS.
8. Similar concrete with strength higher than 120 MPa can also be achieved at w/b ratio of 0.20 with fiber addition of 0.75% of more for both types of mixes.
9. For a w/b ratio of 0.24 only mix M1 could achieve more than 120 MPa strength having 1.25% steel fibers in the mix.
10. It possible to produce mixes with a compressive strength of 150 MPa at 28 days with a w/b ratio of 0.20, by using 3% nano silica, 7% silica fume, and 10% GGBS as supplementary cementitious materials with addition of 1.25% steel fibers.

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[3]. Collepardi et al. (1996) studied the influence of the super-plasticizer type on the compressive strength of reactive powder concrete RPC durability by ASCE publications 1996.
[4]. Ehsan Ghafari et. al. (2014) experimental study aiming to evaluate the influence of nano silica (nS) addition on properties of ultra-high performance concrete (UHPC).
[9]. Richard and Cheyrezy 1994, is the latest ultra-high-strength Portland cement-based material that has been developed. It can achieve a compressive strength of up to 800 MPa, though this is not the ultimate strength that is likely to be achieved.