"DEVELOPMENT OF ULTRA HIGH PERFORMANCE CONCRETE USING MINERAL ADMIXTURES AND STEEL FIBERS"

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for the award of degree of

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IN

STRUCTURAL ENGINEERING

Submitted by:

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DECLARATION

The author hereby declares that the thesis entitled **"DEVELOPMENT OF ULTRA HIGH PERFORMANCE CONCRETE USING MINERAL ADMIXTURES AND STEEL FIBERS"**, in whole or part has not been used to obtain any degree in this or any other institute, except where references have been given in text. It is entirely the author's own work. The author confirms that the library may lend of copy this upon request for academic purposes.

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CERTIFICATE

This is to certify that the work presented in thesis entitled **"DEVELOPMENT OF UHPC WITH STEEL FIBERS"** submitted by **PIYUSH KUMAR, Roll No. 801322015** in partial fulfillment of the requirement for the award of degree in **MASTERS OF ENGINEERING IN STRUCTURAL ENGINEERING** at Thapar University,Patiala, is an authentic record of work carried out by the student under my supervision and guidance.

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ABSTRACT

Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) is a relatively new construction material, which is a combination of high performance concrete and fibre reinforcement. 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 UHPFRC is studied closely for different percentages of steel fibers with three w/b ratios (0.22, 0.20, and 0.18). The purpose is to have such proportions of materials, including cement replacement materials like silica fume, nana-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. The workability of the different mixtures was constantly maintained by optimum usage of superplasticizers. The results showed that with the increase in the amount of steel fibers the compressive strength of the matrix increased. The maximum strength of UHPFRC, which was achieved under laboratory conditions, was 158 MPa, after 28 days of curing. This strength was achieved for the mix wherein the overall binder content included 8% silica fume, 2% nano silica, 10% GGBS (with remaining 80% as cement content) along with the addition of 1.5% steel fiber.

Due to its dense intermolecular locking UHPFRC offers new possibilities in the field where concrete has not been considered viable before. Its high strength can be made use of in the construction of bridge decks, large storage halls, thin walled structures, and columns which can sustain high loading.

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CHAPTER 1:
INTRODUCTION

1.1 GENERAL

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 cementitious 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 (HPC). 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 in many applications such as high-rise buildings and long-span presstresed 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.

1.2 DEFINITION OF ULTRA HIGH PERFORMANCE CONCRETE

Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) is relatively new construction material. Hence, it is a combination of high performance concrete and fiber reinforcement. UHPFRC is generally made using fine, coarse aggregates, very low amounts of water and high amounts of cement. Silica fume is generally considered in the preparation of UHPFRC 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 UHPFRC differs scientifically from normal and high strength concretes due to the high-packing density of these materials. Apparently high brittleness of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a major problem. The increase in compressive strength decreases the ductility. This matter limits its use in structures.

1.3 SELECTION OF MATERIALS

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

1.3.1 Cement

Cement is the basic ingredient for making concrete and for the 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:

Maximum Blaine fineness	: 4000 cm^2/gm
Minimum 7 days mortar cube strength	: 28.959 MPa
Mortar air content	: 7 to 10 %

1.3.2 Supplementary cementitious materials

UHPC cannot be developed only by the use of basic concrete materials. Silica fume, GGBS etc. are some of the supplementary cementatious material which are 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.

1.3.3 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 0.15 - 0.30 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 superplasticizer in it. For production of UHPC in the laboratory, in the present study three different water-cement ratios of 0.18, 0.20 and 0.22 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.

1.3.4 Coarse aggregates

Coarse aggregate make up the bulk of concrete mixture. Natural gravel and crushed stones are mainly used for this purpose. Careful consideration must be taken at the time of selecting coarse aggregates. High strength aggregate are not suitable for concrete because of their high modulus of elasticity as compared with the modulus of a cement paste, due to which contrary stress concentrations occur, which damages the concrete structure in mechanical behavior. The presence of aggregates greatly increases the robustness of concrete above that of cement, which otherwise is a brittle material and thus concrete is a true composite material.

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”. [Karmount, M.; (2009)]

1.3.5 Fine aggregates

The characteristic property and quality of fine aggregates affect the properties of concrete in fresh as well as in hardened state. Redistribution of aggregates after compaction often creates homogeneity in the concrete mix system due to the influence of vibrations. This can lead to strength gradients. The presence of aggregates greatly increase the robustness of concrete, above that of cement, which otherwise is a brittle material and thus making concrete a true composite material. The grading of fine aggregate regulates the workability of concrete at a particular water content of the concrete mix as the specific surface of these fine aggregates is relatively much higher than that of coarse aggregates. Sand which has fineness modulus below 2.5 produces concrete which is to sticky and due to this sticky behavior it is very difficult to compact. However, the sand which has fineness modulus of about 3.0 gave the optimum compressive strength and workability. Fine aggregate with the

fineness modulus in the range of 2.5 to 3.2 are the most suitable for production of Ultra High Performance Concrete (UHPC).

1.3.6 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.

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

- They are suitable for high performance concrete
- To produce pump able concrete
- By increasing workability without adding extra water
- Improved cohesion by minimizing segregation and give better finish.
- Chloride free, safe for use in pre-stressed and reinforced concrete
- They can be used with concrete containing micro-silica and other cement replacements.
- They minimize permeability and increase the waterproofing properties of concrete

The major advantages of chemical admixtures include:

- Improved workability - Easier, quicker placing and compaction. It can be used to produce flowing concrete that requires no compaction. Some minor adjustments may be required to produce high workable mix without segregation.
- Increased strength - Provides high early strength if water reduction is taken advantage of. Early strength is increased up to 40 to 50% if water reduction is taken advantage of. Generally, there is an improvement in strength up to 20% depending upon W/C ratio and other mix parameters
- Improved quality - Denser, close textured concrete with reduced porosity and hence enhanced durability. Reduction in W/C ratio
- Enables increase in density and impermeability, thus enhancing durability of concrete.
- Higher cohesion - Risk of segregation and bleeding minimized; thus aids pumping of concrete. Cohesion is improved due to dispersion of cement particles thus minimizing segregation and improving surface finish.

The application instructions of chemical admixtures are as below:

- Dosage: The optimum dosage is best determined by site trials with the concrete mix which enables the effects of workability, strength gain or cement reduction to be

measured. As a guide, the rate of addition is generally in the range of 0.6 - 2% by weight of cement.

- Over dosing**:** An over dose above the recommended level of admixture may result in high workability, air entrainment and retardation of setting time depending on the ambient temperature of cure. As such, more than the recommended dosage may be used if necessary by ascertaining the performance in the lab trials only before using in actual site conditions.

(b) 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:

a. Fly ash
b. Silica fume; and
c. 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:

i) Silica Fume

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 microsilica.

Silica Fume is also collected as a byproduct in the production of other silicon alloys such as ferrochromium, ferromanganese, ferromagnesium, 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 215,280ft^2/lb (20,000 m^2/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 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. 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.

Production of silica fume

The manufacture of ferrosilicon or silicon metal takes place in an arc furnace. The byproduct that is released for the manufacture of these metals is silica fume. The fumes, which have a high content of very fine spherical particles of silicon dioxide, are collected by filtering the gases escaping from the furnaces. Carbon, coke, coal, wood chips and quartz are the raw materials used in the production of silicon metal. These materials are heated to a temperature of 2000^0C in the smelting furnace. The baghouse filter on top of the furnace filters the fumes collected from the process and silica fume is obtained.

DESIRED REACTION: $\mathbf{SiO_2 + 2C = Si + 2CO}$

Fig. 1.1, 1.2 and 1.3 shows the raw materials going into the smelter viz. metallurgical grade quartz, coal and wood chips. These materials are blended into a charge for the furnace shown in Fig. 1.4

Fig: 1.1: Coal

Fig 1.2: Wood Chip

Fig 1.3: Quartz

Fig1.4: Charging deck of the furnace

The tractor is being used to stoke the furnace charge. This is actually the cooler part of the furnace. At the bottom near the electrodes the temperature is 2000^0C. The hood over the

furnace is part of the collection system that collects the silica fume. The product that results from the smelting operation is simply metal that is sized and sold for further processing.

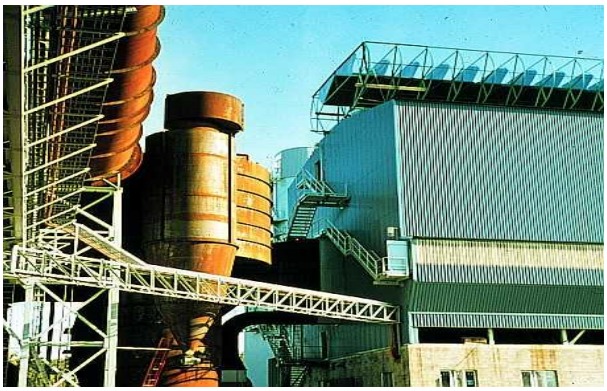

Fig 1.5: Bag house

After being collected over the furnace the silica fume must be transferred, cooled and physically trapped. The large pipe on the left is bringing the silica fume from the furnaces. The vertical cyclones are used to remove oversize and unwanted materials. The large building is a bag house shown in Fig. 1.5 where the fume is captured.

ii) 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

Production of Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) is a by-product of manufacturing of iron in a blast furnace where iron ore, lime stone and coke are heated up to 1500˚C. When these materials melt in the blast furnace, two products are produced – molten iron and molten slag. The molten slag is lighter and floats on the top of the molten iron. The molten slag comprises of mostly silicates and alumina from the original iron ore, combined with some oxides from the limestone. The process of granulating the slag involves cooling the molten slag through high pressure water jets. This rapidly quenches the slag and form granular particles generally not larger than 5mm in diameter. The rapid cooling prevents the formation of larger crystals and the resulting granular material comprises some 95% non-crystalline calcium-aluminosilicates. The granulated slag is further processed by drying and then ground to a very fine powder, which is GGBS (Ground Granulated Blast Furnace Slag) cement. Grinding of granulated slag is carried out in a rotating ball mill. Different forms of slag products are produced depending upon the method used to cool the molten slag. These

products include air-cooled blast furnace slag (ACBFS), expanded or formed slag, palletized slag and granulated blast furnace slag.

iii) 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.
- As a retention and dewatering aid in paper processing
- For surface sizing and anti-slip treatment of natural fibers, textiles
- Surface anti-static treatment of polyester films
- Packaging (Paper Bags) & Cardboard (Box) Paper Coating for Anti-Skid & Anti-Soiling properties, etc.
- Polyester Films / Fibers for Anti-Block & Anti-Slip & Abrasion Resistance etc.
- Coating material for CRGO Electrical Steel Sheets.
- Textile Auxiliary Formulations for spinning & sizing (dimensional stability and anti-skid properties), finishing etc.
- Additive for Floor Wash, for Anti-skid & Anti-soiling properties
- Silicon Wafers for Polishing purpose.
- Waterborne Inorganic Paints / Coatings. Cement Paints / Sealants.
- Construction additives for water proofing/ improving longevity of concrete structures, nano pore coverage in dams, tunnels, buildings etc.

1.3.7 Steel Fibers

They are filaments of wire which are deformed and cut to lengths. It is a cold drawn wire fiber with corrugated and flatted 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 I700 MPa.

1.4 ADVANTAGES OF UHPC

The main advantage that UHPC has over standard concrete is its high compressive strength. Other advantages include low porosity, improved microstructure and homogeneity, high flexibility with the addition of fibers. As a result of its superior performance, UHPC has found application in the storage of nuclear waste, bridges, roofs, piers, seismic-resistant structures and structures designed to resist impact loading. Durability issues in normal concrete have been a major problem for many years and large amount of funds are required to rehabilitation of aging infrastructure. UHPC possesses good durability properties and lower porosity and capillaries thus can be used for repairing works. UHPC construction requires lower maintenance costs in its service life than conventional concrete. UHPC may incorporate larger quantities of steel or synthetic fibers and has enhanced ductility, high temperature performance and improved impact resistance. This enables structural members to be built entirely from fiber reinforced UHPC without the use of conventional transverse reinforcement, relying on the UHPC without traditional reinforcement because of its advantageous flexural strength.

1.5 APPLICATIONS OF UHPC

1.5.1 Bridge Girders

Through collaboration among Iowa Department of Transportation (DOT), ISU, Federal Highway Administration, and Iowa Highway Research Board (IHRB), the State of Iowa has led implementation of bridge girders. The design of the UHPC girder, which led to the first UHPC Bridge in the U.S. in Wapello County, Iowa, this bridge girder has an increased girder

span as it is prestressed with a depth of 1.07m and is designed with 49 strands to span of 33.8 m. This increased girder span allowed the replacement of original two-span bridge with a single span bridge. Due to its higher prestressing, than in a comparable normal concrete girder and higher tensile strength of UHPC helped to eliminate the transverse reinforcement in the girder. *[http://sri.cce.iastate.edu/]*

Fig: 1.6: UHPC Bridge at Wapello County

1.5.2 Bridge Decks

The main advantage of using UHPC in bridge decks is that it prevents early deterioration of deck resulting from cracking that allows penetration of chloride especially during wintry months. It also reduces the dead load of the structure which adversely affects the cost of the project.

1.5.3 Bridge Piles

Studies have shown that tapered, H-shaped, precast, prestressed UHPC piles have increased durability and increases the longevity of bridge foundations. The full-scale vertical and lateral load tests on UHPC piles in the laboratory and field have revealed several other benefits of using UHPC pile such as significantly reduced risk of damage during driving, drivability with a greater range of hammers and strokes, and the possibility of using existing equipment for pile handling and driving. Field experience has shown that UHPC piles can be driven in stiff soil without using any cushion on top of the pile*. [http://sri.cce.iastate.edu/]*

1.5.4 Wind Turbine Towers

Generally the wind turbines use steel tubular towers for supporting utility scale wind turbines. The commonly used wind turbines tower height is about 80 m and this height facilitates the steel tower to be transported in three segments. The new tower concept—termed Hexcrete—comprises of six exterior post-tensioned UHPC columns along with panels

that span the distance between two adjacent columns. These towers can erect to a height of more than 80 m.

Some of the major applications of UHPC have come in structures which require not only very high strength but also have to have a long life. Some interesting structures**,** where UHPC has been successfully developed and used are discussed as below**:**

1.5.5 Sherbrooke footbridge:

The world's first engineering structure designed with UHPC was the Sherbrooke footbridge in Sherbrooke, Quebec, built in 1997. Spanning 60 m, this precast, prestressed pedestrian bridge is a post-tensioned open-web space RPC truss, shown in Figure 1.7(a) below, with 4 access spans made of Ultra High Performance Concrete (UHPC). The main span is an assembly of six 10 m prefabricated match-cast segments. The cross section is made of a ribbed slab 30 mm thick, with a transverse prestressing made of greased-sheathed monostrands. The truss webs are made of RPC confined in stainless steel tubes, shown in Figure 1.7 (b).

The structure is longitudinally prestressed by an internal prestressing placed in each longitudinal flange and an external prestressing anchored at the upper part of the end diaphragms and deviated in blocks placed at the level of the lower flange. The connection between the flanges and truss diagonals is ensured by greased-sheathed monostrands and miniaturized anchorage.

Fig.1.7 (a): Sherbrooke footbridge

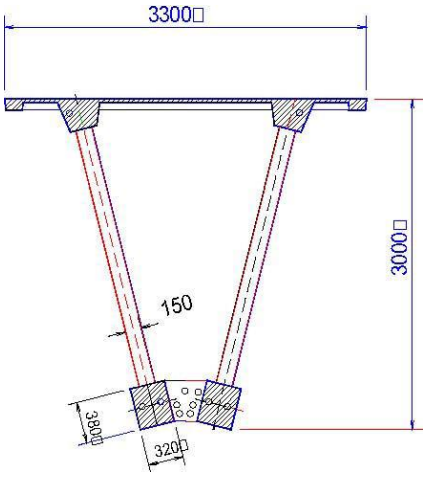

Fig. 1.7 (b): Cross section

[Karmout, M.; (2009)]

1.5.6 The Seoul and Sakata Miral footbridges:

In 2001 and 2002, a footbridge was built over the Han River running across Seoul in South Korea. It is made of an arch spanning 120 m, with two steel access spans, shown in Fig. 1.8 (a)

Fig 1.8 (a): General view of Seoul footbridge [*Karmout, M.; (2009)]*

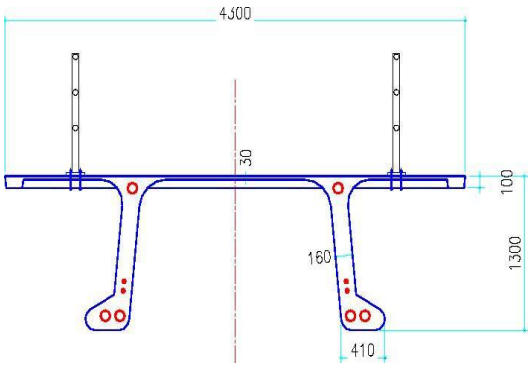

Fig. 1.8 (b): Cross-section [*Karmout, M.; (2009)]*

The arch has a π-shaped cross-section, shown in Fig. 1.8 (b), 1.3 m deep. The upper flange is a ribbed slab 30 mm thick, with a transverse prestressing made of greased sheathed monostrands. The webs are 160 mm thick and are inclined outward. The arch is an assembly of six 20 m prefabricated segments, connected on site by means of temporary supports. The elements are stitched together by an internal longitudinal prestressing placed in haunches in the lower and the upper parts of the webs. This very slim structure has frequencies of vibration sensitive to the pedestrian traffic. Vibration calculation has been carried out and tuned mass dampers have been installed to reduce the effect of the first three modes of

vibration of the footbridge. It is worth mentioning that it is the first Ductal footbridge built in Japan with a span of 50 m. The deck is a simple beam of 2.4 m wide with circular web holes. The structure is longitudinally prestressed by an external prestressing and has no passive reinforcement.

1.6 DIFFICULTIES IN PRODUCING UHPC

Some of the difficulties which engineers may encounter in production of UHPC are highlighted as below:

- Superplasticizers are used to attain the necessary slump keeping w/c ratio low. But due to diffusive action of superplasticiser, more surface area of the cement comes in contact with water. Hence, hydration of cement can take place more rapidly, resulting in higher slump loss. Due to this reason, some amount of superplasticiser is added at mixing plant and remaining potion just before concreting is done at the site
- Higher cement content and lower water content have produced the concrete of higher strength. By proportioning water demand in the mixture increased due to large amount of cement in the concrete mix. A high percentage of cement could give rise to massive heat generation with resultant risk of cracking. For this reason, cement is replaced 10-20 % by pozollona (silica fume, flyash etc.) to control heat of hydration.

1.7 LIMITATIONS OF UHPC

Implementation of UHPC in not only developing, but in developed countries like US, is progressing slowly for following reasons:-

1. Lack of design codes for UHPC
2. Risk perception and lack of familiarity with UHPC
3. High Initial cost.
4. The apparent high brittleness of Ultra-High Performance Concrete (UHPC) is a major problem.

The increase in compressive strength decreases the ductility. This matter limits its use in structures. The greatest challenge limiting the use of UHPC by precast producers is that current design codes are not readily adaptable to this class of concrete possessing strengths many times that of conventional concrete. Continued research is needed on the advanced properties of UHPC to provide a valid database for structural design. Even at the federal level where UHPC research has been conducted, officials perceive the risks associated with

a greatly expanded use of a product with a limited history of performance. State highway engineers, in particular, are hesitant to use new technology without a significant history of proven performance in large part because of their responsibility for public transportation safety. This understandable aversion to the risk of specifying and manufacturing products with the relatively new UHPCs also drives up its cost. Whenever a new technology is perceived as risky, whether due to lack of knowledge, producer comfort level or history of use, market forces in any industry will increase the price of using that technology.

1.8 PREVIOUS WORK

The earlier work done to produce UHPC did deliver significant results. In the previous work to develop UHPC, varying proportions of mineral admixtures like silica fume, nano silica and alccofine (GGBS) were used. Nine trial mixes were made with three different w/b ratios of 0.26, 0.24 and 0.22. In all the mix proportions created, the mix containing 2% nano silica, 8% silica fume and 10% GGBS was the most promising mix provided the best result with a compressive strength of 120.8 MPa after 28 days. This mix along with the second best mix was selected for the further work wherein, it was decided to use steel fibers in addition to the mineral admixtures. The purpose of the work was to achieve a 28 days strength range between 130 to 150 MPa.

1.9 OBJECTIVE OF THE PROPOSED WORK

The work is a continuation of the earlier work done as mentioned in the previous subsection to develop even higher strength taking the best results obtained from it. The main objective of the proposed work is to study how UHPC can be developed with varying proportions of mineral admixtures like silica fume, nanosilica and alccofine (GGBS) with the addition of different percentages of steel fibers. The target is to produce concretes with strengths in excess of 120 MPa after 28 days of curing. The ultimate aim is to find the optimum percentages of the ingredients in order to produce concrete having a compressive strength of more than 150 MPa.

CHAPTER 2:
LITERATURE REVIEW

2.1 GENERAL

This chapter presents a review of literature highlighting the work done by various researchers with regards to the strength and durability properties of UHPC. The significant development regarding performance and applications of silica fume and GGBS in high performance concrete that have taken place in the recent past are studied. Although the use of silica fume and GGBS in the concrete has increased significantly in past few years, it's beneficial properties were not well realized until comprehensive research was undertaken, in the late 70's and early 80's, to study the influence of silica fume in Sweden where silica fume concrete was used in tower construction of the new Tijorn cable-bridge. Part of cement was replaced by silica fume to decrease the thermal stresses in massive section without reducing the strength. [Karmount, M.; (2009)]

Silica fume was introduced to the concrete market in the mid to late 1970s. The use of the material increased during the 1980s and 1990s. During this period, silica-fume concrete became recognized for high strength and low diffusivity. Silica fume is currently widely used to produce high-performance concrete. [Long et al. (2002)]

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/m^3 of cement with 70 kg/m^3 of silica fume and the specified compressive strength was 70MPa at 7 days and 86 MPa at 28 days. [Graybeal et al. (2003)]

In 1998, silica fume was used to construct the inner containment (I C Dome) in Kaiga Atomic power project, unit-2 (Kaiga-2) in India. In this project different doses of silica fume (5 to 15 % by weight of cement for two quantities of cement 450 Kg/m^3) were tried. It was observed that, for silica fume quantities of about 7.5 percent by weight of cement, the mix attained its maximum strength and beyond 10 percent the strength reduced. The concrete contained 475 Kg/m^3 of cement with 35.6 Kg/m^3 of silica fume and 75.9 MPa compressive strength was obtained. [Tayeh et al. (2012)]

The other applications of silica fume in cement based materials worldwide are bank Vault constructions, parking garages, repairs overlays for bridge decks, spillways, stilling basins and under water repairs, light weight concrete construction, high strength concrete in high rise

structure, cement grouts for filling post tensioning ducts, high pressure concrete pipes and more recently offshore platform construction. Because of the improved chemical resistance of silica fume concrete, It has also been used in the construction of aluminum and magnesium plants, water and waste water treatment facilities as well as paper mill plants. [Bruhwiler et al. (2008)]

2.2 STRENGTH CHARACTERISTICS OF UHPC

Long et al. (2002) studied the compactness and fluidity of binary and ternary compound paste systems containing ultrafine powders such as pulverized fly ash (PFA), pulverized granulated blast furnace slag (PS) and silica fume (SF). They thoroughly optimize the proportions of compositions and apply the heat treatment to specimens to get a very-high-performance concrete (VHPC) that can offer the compressive strength up to 200 MPa. The chemical compositions and physical properties of PFA, PS and SF are given in Table 2.1(a).

Table 2.1(a): Chemical compositions and physical properties of PFA, PS and SF: *[Long et al. (2002)]*

Composition (%)							Ignition Loss (%)	Mean Diameter (μm)	Density (g/cm^3)
Type	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**			
PFA	21.7	25.8	9.7	3.7	1.2	0.2	1.16	5.8	2.47
PS	28.3	13.6	0.62	38.4	7.2	7.4	0	6.5	2.78
SF	88.2	3.45	0.80	0.00	2.08	0.3	2.52	0.2	2.14

The raw materials that were used to make VHPC were ordinary Portland cement (Chinese Standard 525#) with a 28-day compressive strength of 56.4 MPa), ultrafine powders (PFA, PS and SF) along with the Quartz sand (maximum diameter less than 0.63 mm) was also used. Two kinds of steel fibers with shape of cylinder and different length to diameter ratio (L/D) were incorporated into VHPSFC - based materials. They add 2% of superplasticizer by weight of cement in mortars and cast 40×40×160 mm stainless steel molds and immediately stored in a flog room at 20° C. After 24 h the specimens were demolded, bathed in 20° C water for 72 h and then placed in 95 °C steam room for 72 h. They experimentally showed that the ultrafine mineral powders and W/B are important to the relative density of fresh pastes, which directly determine the properties of hardened cement-based materials. Table 2.1 (b) shows the experimental results of the strength and flowability of UHPC.

Table 2.1 (b): Experimental results of flowability and strength of mortars: *[Long et al. (2002)]*

No.	W/B	Proportions of raw materials (C/PFA/PS/SF)	Flowability (mm)	Flexural strength (MPa)	Compressive strength (MPa)
1	0.180	1:0:0:0.10	190	20.4	151.4
2	0.167	1:0:0:0.20	185	22.2	175.4
3	0.160	1:0:0:0.25	175	22.5	187.8
4	0.154	1:0:0:0.30	160	21.1	186.6
5	0.160	1:0:0.2:0.25	170	28.4	178.6
6	0.160	1:0:0.3:0.25	185	29.5	198.2
7	0.160	1:0:0.4:0.25	200	30.5	193.6
8	0.160	1:0:0.6:0.25	165	27.6	190.0
9	0.160	1:0:0.3:0.30	180	28.4	207.0
10	0.160	1:0:0.4:0.30	190	29.6	200.8
11	0.160	1:0.2:0:0.25	180	24.7	188.2
12	0.160	1:0.3:0:0.25	190	28.5	208.4
13	0.160	1:0.4:0:0.25	200	30.4	197.8
14	0.160	1:0.6:0:0.25	175	30.3	184.0
15	0.160	1:0.3:0:0.30	185	31.0	204.8
16	0.160	1:0.4:0:0.30	195	29.9	213.2

The compressive and flexural strengths of UHPC appear to be controlled essentially by the content of PFA, PS or SF. They found that all concrete specimens have good workability though their W/B is only 0.16. The strength of concrete specimen only containing SF increases with an increment in the contents of SF, and the optimum content of SF is about 0.2–0.3 of the weight of cement. They also noticed that the UHPC samples incorporating SF and PFA or SF and PS have higher compressive strength compared with those only containing SF. The compressive strength of VHPC samples including SF and PFA is slightly higher than that of the samples containing SF and PS.

Graybeal et al. (2003) studied the effect of various curing regimes on compressive strength of UHPC. They employ the concrete containing a large amount of cementitious materials and superplasticizer, and a very small amount of water. The water and accelerator to cementitious material (i.e., cement and silica fume) ratio was kept as 0.15. Table 2.2 (a) provides the composition of the UHPC studied in their research.

Table 2.2 (a): UHPC Composition: *[Graybeal et al. (2003)]*

Material	Amount (lb/yd^3)	Weight (%)
Portland Cement	1200	28.5
Fine Sand	1720	40.8
Silica Fume	390	9.3
Ground Quartz	355	8.4
Superplasticizer	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2
Water	184	4.4

Table 2.2 (b): Compressive Strength of 3 x 6 inch Cylinders: *[Graybeal et al. (2003)]*

Method	Samples	Compressive Strength (ksi)
Steam	96	28.0
Ambient Air	44	18.0
Tempered Steam	18	25.2
Delayed Steam	18	24.9

They casted the specimens of 3 in. diameter by 6 in. long cylinders and various curing regimes namely Steam cured, Ambient Air Cured, Tempered Steam Cured and Delayed Steam Cured were applied to the specimens. They noticed that the curing method applied to the UHPC has a significant effect on the compressive strength of UHPC specimens. The Table 2.2(b) provides the 28 day strength results for the 3 in x6 in control cylinders that were cast from each batch of concrete.

The strength of the steam cured UHPC is approximately 28 ksi. The tempered steam and delayed steam cured specimens exhibited strengths approximately 10% lower. The ambient air cured specimens only achieved 65% of the steam cured specimen strength. They noticed when steam cured procedure is adopted we can achieve a compressive strength of 28 ksi as compared to the lower compressive strength in normal concretes. Thus, curing of UHPC can have a large impact on its properties.

Brühwiler et al. (2008), proposed an idea to use UHPFRC to "harden" those zones where the structure is exposed to severe environmental conditions and high mechanical loading that can significantly improves the structural performance in terms of durability, strength and life-cycle

costs of the rehabilitated concrete structure. They studied the rehabilitation and widening of a short span road bridge with busy traffic using UHPFRC as shown in Fig. 2.1 (a)

(a) The UHPFRC mix contained 1430 kg/m^3 Cement, Microsilica, fine quartz sand with a maximum grain size of 0.5 mm; the Microsilica/Cement and Water/Binder ratio were 0.26 and 0.125 respectively.

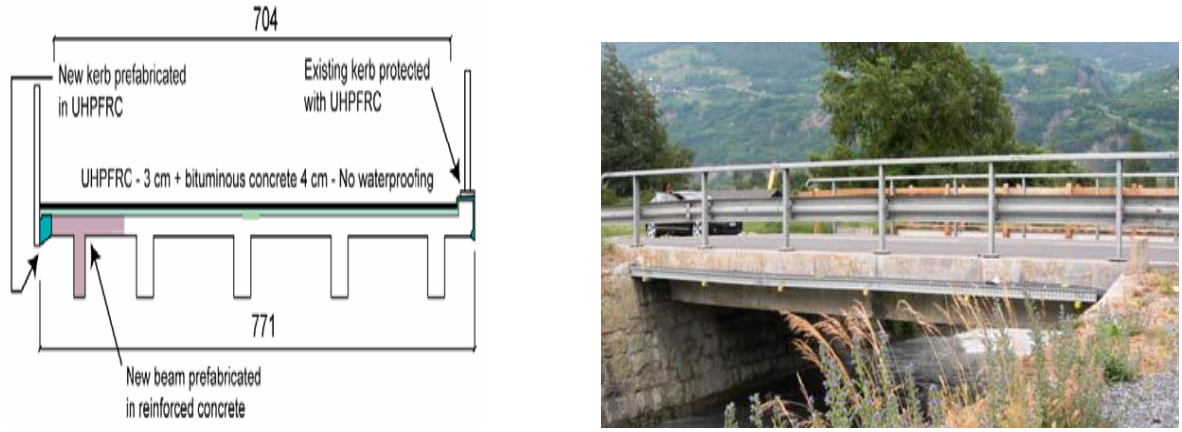

Fig. 2.1 (a): Bridge cross section after rehabilitation *[Bruhwiler et al. (2008)]*

The reinforcement of this ultra-compact matrix was provided by a mix of microfibers (steel wool of 2 to 3 mm length) and macrofibers of 10 mm length with a total dosage of 706 kg/m^3. The analysis of the construction costs showed that the rehabilitation realised with UHPFRC was about 10% more expensive that the conventional solution (providing lower quality in terms of durability and life-cycle costs). Along with this, they also studied the rehabilitation of a bridge pier (suffering from severe environmental exposure) using prefabricated UHPFRC shell elements. In this application, 4cm thick UHPFRC shell elements have been prefabricated to form an outer protection shield for the existing 40 year old reinforced concrete bridge pier which is located very closely to busy highway traffic (as shown in Fig. 2.1 (b)).

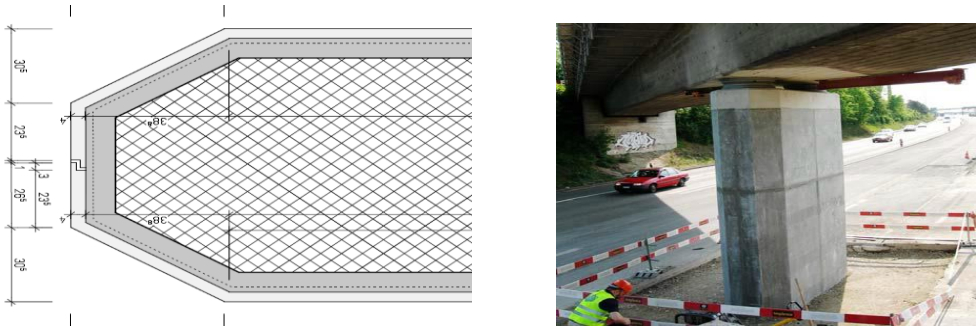

Fig. 2.1 (b): Cross section and general view of the rehabilitated bridge pier *[Brühwiler et al. (2008)]*

In order to significantly improve durability and mechanical strength of such elements, UHPFRC is used following again the concept of locally "harden" the zones of severe exposure. The UHPFRC elements were cast (maximum element height of 4m) in a prefabrication plant, transported to the construction site and mounted, after removal by hydro jetting of up to 10cm of chloride contaminated concrete. The joints between the different UHPFRC shell elements were glued using an epoxy resin. The remaining space between the UHPFRC elements and the existing reinforced concrete was filled with self-compacting mortar. The used UHPFRC recipe contained about 1300 kg/m^3 of cement, a rather small amount of silica fume related to the cement content, quartz-sand, steel fibres by volume, superplasticizer and a W/C-ratio of 0.155. They concluded that the rehabilitated structures have significantly improved structural resistance and durability and strength.

Yang et al. (2009) studied the several possibilities for reducing the price of producing UHPFRC and for bringing UHPFRC at the construction site as an in situ material. They also studied the possibility of using recycled glass cullet and two types of local natural sand as the replacement materials for the more expensive silica sand that is normally used to produce UHPFRC. Also, they investigate the differences in both mechanical and ductility properties due to curing of UHPFRC cubes and prisms at 20°C and 90°C respectively. The chemical, physical and the mechanical properties of cement, GGBS and SF used in this study are shown in Table 2.3 (a).

Table 2.3 (a): Physical, chemical and mechanical properties of cement, silica fume (SF), ground granulated blast-furnace slag (GGBS) ***[Yang et al. (2009)]***

Chemical Composition (%)	**Materials**		
	Cement	**SF**	**GGBS**
SiO_2	18.7	93.1	35
Al_2O_3	6.3	0.9	12
Fe_2O_3	3.2	2.0	0.2
CaO	64.7	0.4	40
MgO	0.7	1.2	10
Na_2O	0.13	0.3	–
SO_3	3.1	0.3	–
Cl^-	0.025	0.09	–
Physical Property			
Bulk Density (kg/m^3)	1200	321.3	1050
Specific Surface (m^2/kg)	460	20,000	470

They investigated the 4 groups of UHPFRC specimens each using a different type of sand. In each group the specimens were cast into 50 mm cubes for compressive strength evaluation. They noticed that the use of a different natural sand, i.e. SS, FOS-I and FOS-II, as the aggregate of UHPFRC had little influence on the compressive strength development.

The particle distribution of 4 types of fine sand as aggregate in the study and the results of measurement of the relative density and water absorption are shown in Table 2.3 (b).

Table 2.3 (b): Density and water absorption of aggregate sand *[Yang et al. (2009)]*

Aggregate	**SS**	**FOS-I**	**FOS-II**	**RGC**
Oven dry density (kg/m³)	2.652	2.645	2.643	2.678
Bulk density (kg/m³)	1.634	1.555	1.537	1.443
Void content	38.4%	41.2%	41.9%	46.1%
Water absorption (%)	0.80	1.17	0.84	0.21

The mix design proportions of UHPFRC are shown in Table 2.3 (c).

Table 2.3 (c): Mix design of UHPFRC *[Yang et al. (2009)]*

Concrete mix proportion Cementitious component (level of cement replacement) (kg/m³)			**Aggregate sand (kg/m³)**	**Water binder ratio**	**Superplasticizer (% solid by weight of binder)**
Cement	*GGBS*	*SF*	1050	0.15	1.05
657	429.8 (35%)	119.4 (10%)			

However replacement of natural sand with RGC resulted in a slightly lower compressive strength but faster strength gain at early age. Fig. 2.2 shows the development of the compressive strength of UHPFRC using SS, FOS-I, FOS-II and RGP under 20°C and 90°C curing. The compressive strength of specimens using SS, FOS-I and FOS-II and cured at 90°C all fell within the range 160–180 MPa at age 91 days and within the range of 140–160 MPa for the RGC specimens. None of the specimens cured at 90°C showed a significant gain in strength after the 7 days of hot curing. UHPFRC specimens cured at 20°C continued to increase in compressive strength over time after the initial 7 day period, but at a diminishing rate as shown in Fig. 2.2 (a). After 91 days the 20°C cured specimens had a very high compressive strength but did not match that of the 90°C cured specimens. From observation of the rate of increase in strength it

seems unlikely that the strength of the 20°C cured specimens would reach that of the 90°C cured specimens at later ages.

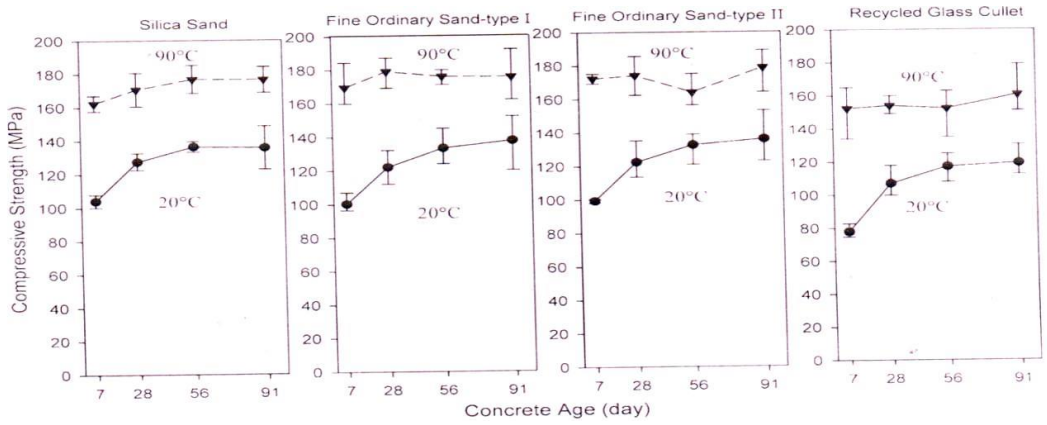

Fig.2.2: Compressive strength versus age of UHPFRC: effect of replacement of sand aggregate with SS, FOS-I, FOS-II and RGC *[Yang et al. (2009)]*

However, the compressive strengths of 20°C cured UHPFRC at 28 day age, i.e. 100–130 MPa, are still considered as very high strength and this can be applied very effectively for building structures.

Tuan et al. (2011) studied the possibility of using RHA (Rice husk ash) to produce UHPC. The limited available resource and the high cost of silica fume (SF) in producing ultra-high performance concrete (UHPC) leads to the search of substitution by other materials with similar functions, especially in developing countries (like India). In order to study the effect of RHA replacement, fineness of RHA and the synergic effect of RHA and SF, a set of 15 mixtures were prepared is shown in Table 2.4 (a).

Table 2.4 (a): UHPC compositions used in this study: *[Tuan et al. (2011)]*

Water to binder ratio (by weight)	Sand to binder ratio (by weight)	RHA (% by weight)	SF (% by weight)	The mean particle size of RHA (dRHAmean), μm
0.18	1	0–10–20		5.6
0.18	1		10–20–30	
0.18	1	10–20–30	10	5.6
0.18	1	20		9.0–6.3–5.6–3.6
0.18	1	5	15	5.6
0.18	1	15	5	5.6
0.15–0.18–0.20–0.23	1	10	10	5.6

They burnt the Rice husk in a drum under uncontrolled combustion conditions and the ash obtained was ground in a vibrating ball mill for 90 min. All materials were prepared in a 20 L Hobart mixer. The volume of each batch was 3.5 Litres. Fig.2.5 (a) shows the mixing procedure. The authors studied the effect of the percentage of cement replacement by RHA on compressive strength of UHPC and the results were as shown in the Fig.2.5 (b).

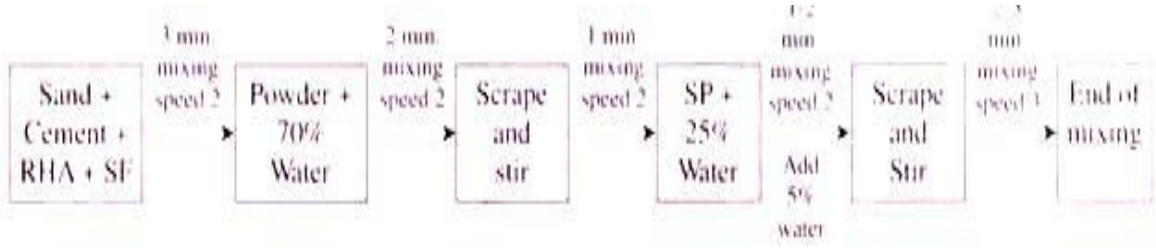

Fig 2.3 (a): Mixing procedure for UHPC. ***[Tuan et al. (2011)]***

The Fig. 2.3(b) shows that for the samples containing SF, the highest compressive strength of UHPC was achieved with 10% SF replacement of cement. The higher replacement level, especially beyond 20%, led to reduction in compressive strength. The use of RHA as a partial replacement of cement revealed the different behaviour of compressive strength development. The compressive strength of UHPC was obtained highest by using 10% RHA at 3 and 7 days, as compared to the compressive strength of UHPC that was obtained by using 20% RHA at 28 and 91 days. Based on these result, it was found that RHA can be used to produce UHPC for a replacement level less than 30%.

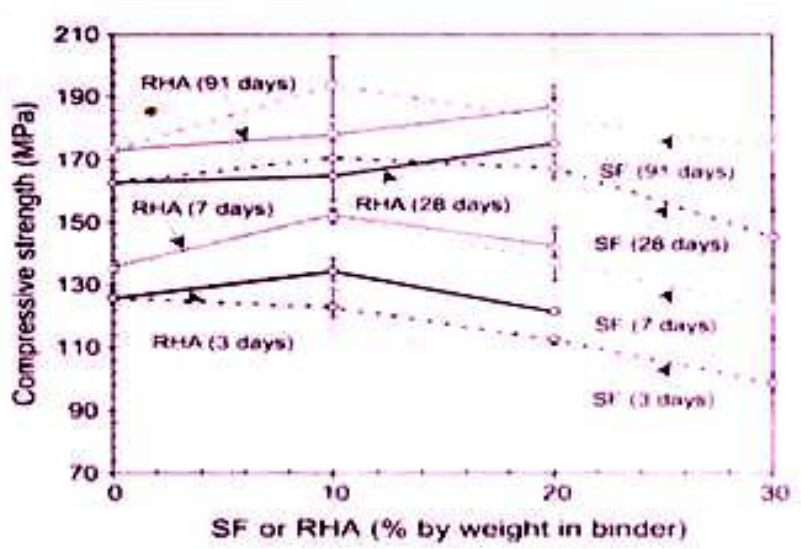

Fig. 2.3 (b): Compressive strength of UHPC samples vs. % SF (dotted line) or % RHA (Solid line), w/b ratio = 0.18, dRHAmean = 5.6 µm. ***[Tuan et al. (2011)]***

Wang et al. (2012) Studied the effect of ground granulated blastfurnace slag (GGBS) content replacement on fluidity and compressive strength of UHPC and focused on the preparation of UHPC with common technology and ordinary raw materials. During their studies they adopt the common and easy to obtain raw materials along with the common technologies for preparation of UHPC, that include mixing of fresh concrete with normal forced mixer, pouring, compaction by vibrating, and curing at room temperature. A large quantity of superfine mineral additives such as silicafume (SF), ground granulated blast furnace slag (GGBS), and limestone powder (LP) was added to optimize the composition and micro-structure of the hydrated binder paste, and to reduce the hydration heat. The chemical compositions and physical properties of each cementitious material are listed in Table 2.5 (a).

Table 2.5 (a): Chemical compositions and physical properties of binders: *[Wang et al. (2012)]*

Binder	**Chemical compositions (%)**								**Specific surface area (m^2/kg)**	**Density (g/cm^3)**
	CaO	*SiO_2*	*Al_2O_3*	*MgO*	*Fe_2O_3*	*TiO_2*	*SO_3*	*LOI*		
C	59.37	20.86	9.28	2.07	3.74	0.47	2.49	1.47	330	3.10
SF	–	95.19	–	0.80	0.13	–	–	2.81	20,000	2.23
GGBS	50.44	30.36	16.90	1.84	0.34	0.57		2.42	870	2.75
LP	52.12	3.45	1.47	0.77	0.24	–	–	40.22	600	2.75

They studied the influence of GGBS replacement of cement on strength and fluidity of UHPC. Three mixes with different GGBS replacement and 10% SF by mass content are listed in Table 2.5 (b), and the experimental results are shown in Fig. 2.4.

Table 2.5 (b): Mixture proportions for test of influence of GGBS replacement on strength and fluidity of UHPC. *[Wang et al. (2012)]*

Mix	**Binder (kg/m^3)**	**Binder components (%)**			**W/B**	**Water (kg/m^3)**	**Superplasticizer (kg/m^3)**	**Fine aggregate (kg/m^3)**	**Coarse aggregate (kg/m^3)**
		C	***SF***	***GGBS***					
2-1	900	90	10	0	0.18	162	18	616	923
2-2	900	70	10	20	0.18	162	18	616	923
2-3	900	50	10	40	0.18	162	18	616	923

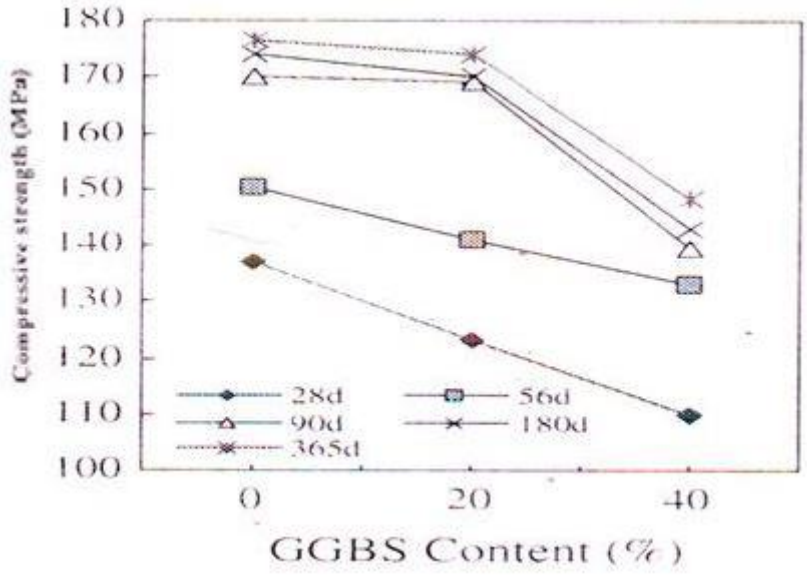

Fig. 2.4: Influence of GGBS content on strength and fluidity of UHPC. ***[Wang et al. (2012)]***

Compared with mixture 2-1 concrete, which had no GGBS, mixture 2-2 containing 20% by weight GGBS replacement had higher fluidity, much lower compressive strength at early ages (28 d and 56 d), but approximately equal strength at later ages (90 d, 180 d and 365 d). Mixture 2-3 containing 40% by weight GGBS had a very low compressive strength and fluidity at all ages compared to the control mixture 2-1.

They concluded that with extremely low W/B, high binder content, multi-addition of SF, GGBS, LP, and high standard superplasticizer (and retarder), UHPC can be prepared with common technology and without removing the coarse aggregate.

Corinaldesi et al. (2012) studied the effect of varying the water - cement ratio from 0.20 to 0.32 on the development of compressive strength, flexural strength and elastic modulus of UHPFRC. The chemical composition of cement and silica fume employed in the experiment is shown in Table 2.6 (a) below. Along with this, two acrylic-based superplasticizers (labeled 'spA' and 'spB') were employed in order to compare their effectiveness for producing UHPFR. Three prismatic specimens (40×40×160 mm) were manufactured for each mixture and for each curing time in order to evaluate mechanical behaviour of the five UHPFRC mixtures Table 2.6 (b), they were soft cast in steel forms (vibrated for 30 seconds after casting), then wet cured at 20°C (standard curing) for flexural and compressive strength measurements.

They evaluated the compressive strength after 1, 3, 7 and 28 days of curing. At first, the compressive strength of UHPFRCs prepared with different types of superplasticizer was compared, in order to determine the most effective admixture.

Table 2.6 (a): Chemical composition of cement and silica fume. ***[Corinaldesi et al. (2012)]***

Oxide (%)	Cement	Silica fume
SiO_2	29.67	98.87
Al_2O_3	3.74	0.01
Fe_2O_3	1.80	0.30
TiO_2	0.09	0.08
CaO	59.25	0.23
MgO	1.15	0.01
SO_3	3.25	0.23
K_2O	0.79	0.08
Na_2O	0.26	0.00
Loss on ignition (LOI, %)	11.6	0.0

Table 2.6 (b): UHPFRC mixture proportions. ***[Corinaldesi et al. (2012)]***

Mixture	RPC-20	RPC-24	RPC-26	RPC-29	RPC-32
Water/cement	0.20	0.24	0.26	0.29	0.32
Water/binder	0.16	0.19	0.21	0.23	0.26
Slump flow of fresh mortar, %	2	14 (with 'spA') 22 (with 'spB')	21 (with 'spA') 26 (with 'spB')	31	39
Mixture proportions, kg per m^3 of concrete					
Water (including that of superplasticizer)	194	227	248	280	306
Cement	960	960	960	960	960
Silica fume	240	240	240	240	240
Steel fibers	192	192	192	192	192
Superplasticizer (dry mass)	24	24	24	24	24
Sand	960	960	960	960	960

The results obtained for UHPFRC with w/c of 0.24 and 0.26 by using either 'spA' or 'spB' superplasticizers are given in Fig. 2.5(a).

For the UHPFRCs containing the 'spB' admixtures that were prepared by varying water/cement from 0.20 to 0.32, the time evolution of their compressive strength is shown in Fig. 2.5 (b). They noticed that after 1 day of curing the compressive strength was always higher than 30 MPa. It is quite evident that the positive effect obtained by lowering the water to cement ratio was not valid for UHPFRCs with water to cement ratio lower than 0.24. In fact, the concrete prepared with w/c of 0.20 showed the lowest compressive strength. It may be due to low compaction capacity of the material due to the poor workability of the fresh concrete (see Table 2.6 (b)). Thus, an even higher amount of superplasticizer admixture would be necessary in this case.

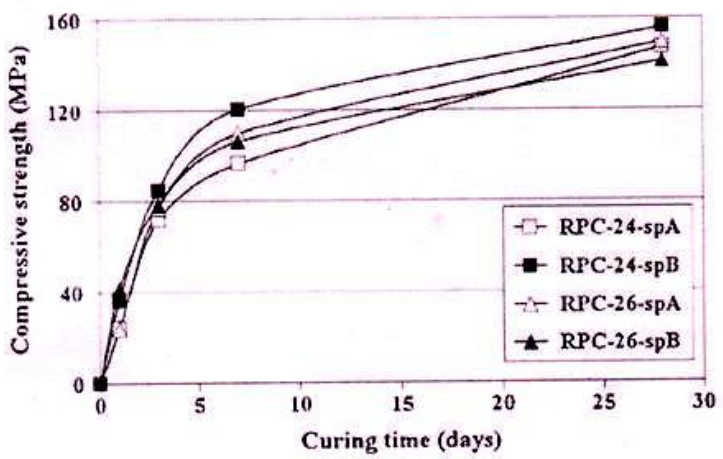

Fig. 2.5 (a): Time evolution of compressive strength for UHPFRCs prepared with w/c of 0.24 and 0.26 by using either 'spA' or 'spB' superplasticizers. ***[Corinaldesi et al. (2012)]***

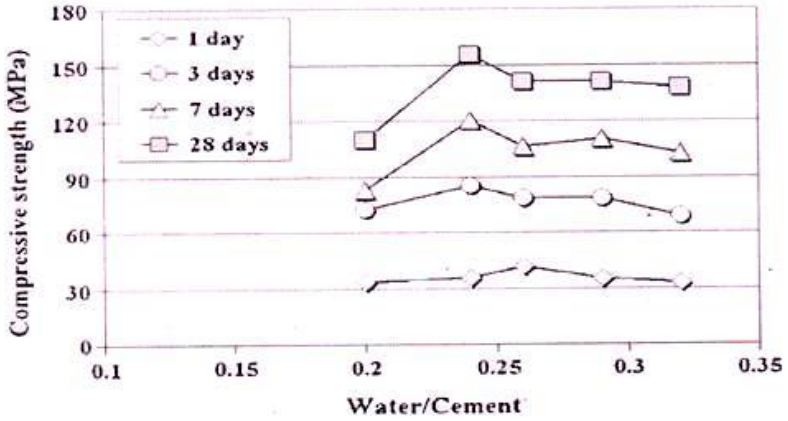

Fig. 2.5 (b): Compressive strength for UHPFRCs prepared by varying the water to cement ratio from 0.20 to 0.32 at different curing times. ***[Corinaldesi et al. (2012)]***

They noticed that the optimum workability and mechanical performance was obtained when the most recent type of acrylicbased superplasticizer (labeled 'spB') and a water to cement ratio of 0.24 were adopted. In particular, 28-day compressive strength of 156 MPa was achieved from this UHPFRC.

Tayeh et al. (2012) experimentally examined the permeability characteristics of the interface between normal concrete (NC) substrate which represents old concrete structures and an overlay of ultra-high performance fiber concrete (UHPFC) as a repair material. The permeability characteristics were evaluated by means of the rapid chloride permeability, gas and water permeability tests. The specimens with two different concrete grades were used in this study, one being a Grade-40 normal concrete and the other one is a Grade-170 UHPFC. Mix proportions for NC substrate and UHPFC are shown in Table 2.7.

Table 2.7: Mix proportions for NC substrate and UHPFC *[Tayeh et al. (2012)]*

Concrete type (kg/m^3)	**NC substrate**	**UHPFC**
OPC (Type 1, 42.5R)	400	768
Coarse aggregate (max. 12.5 mm)	930	–
River sand (F.M. = 2.4)	873	–
Mining sand (<1180 µm)	–	1140
Silica fume (23.7 m^2/g)	–	192
Steel fiber (Lf = 10 mm, df = 0.2 mm)	–	157
Superplasticizer (PCE-based)	4	40
Water	200	144
Total	2407	2441
W/B	0.5	0.15
Cube strength, fcc,28d	45 MPa	170 MPa
Split cylinder tension strength, fsp,28d	2.75 MPa	15.3 MPa

They conduct the Rapid chloride permeability test on specimens and demonstrate the RCPT results in Fig. 2.6 (a) in term of total charge passed (TCP) in coulombs for the NC substrate, UHPFC, and composite of NC/UHPFC with different NC substrate surface preparation. Lower the TCP value, greater the resistance to chloride ion penetration. From Fig. 2.6 (a), we see that the monolithic UHPFC specimen exhibits the lowest TCP values (i.e. 58 and 34 coulombs at 7 days and 28 days, respectively), followed by all the OV composite specimens which exhibit TCP values of less than 100 coulombs. Based on the TCP of both the UHPFC monolithic samples and the OV composite samples, they noticed that recorded TCP values fall under the category of

"Negligible Chloride Permeability" according to ASTM C1202, which proves that UHPFC is an excellent choice and can be used for repair/rehabilitation work on old or aging concrete structures where durability is important. The NC monolithic specimen exhibits the highest TCP value (i.e. more than 4000 coulombs). This level of TCP for the NC substrate falls under the category of "High Chloride Permeability", which shows that conventional concrete is not suitable for aggressive environmental exposures such as in marine zone. They also conducted the Gas permeability test on the specimens and present the result in the form of gas permeability coefficient (GPC), in Fig. 2.6 (b). The figure shows that the monolithic UHPFC exhibits zero value of GPC together with all the OV composite specimens. The monolithic NC specimen records the highest GPC value (i.e. 3.43×10^{-16} m^2 at 28 days) that clearly shows that the gas mostly passed through the half semi-circle portion of the NC substrate during the test with little or no influence of the interfacial bond.

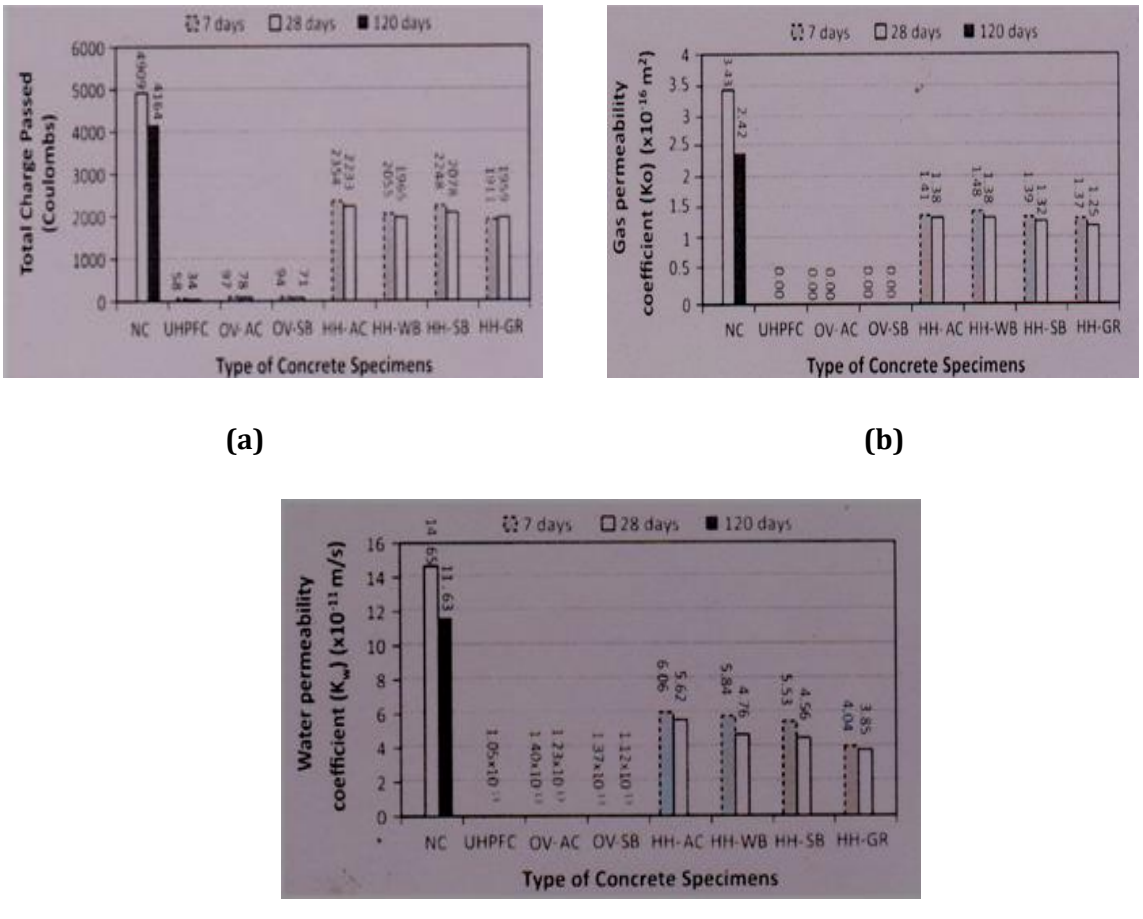

Fig. 2.6: Experimental test results on (a) Rapid chloride permeability, (b) Gas permeability and (c) Water permeability *[Tayeh et al. (2012)]*

They also perform the water permeability test on the specimens in the form of water permeability coefficient (WPC) as presented in Fig. 2.6 (c) clearly showing that the monolithic UHPFC exhibits extremely low value of WPC, followed by all the OV composite specimens which also display negligible value of WPC

The monolithic NC specimen exhibits the highest WPC of 14.65 $\times 10^{-11}$ m/s at 28 days, which is 1331 times higher than that of the UHPFC samples. On the other hand, the recorded WPC for all the composite HH specimens' ranges from 3–6$\times 10^{-11}$ m/s, which suggest that all of the water mostly passed through the semi-circle NC substrate halve of the composite samples. At last, it was concluded that RCPT, gas and water permeability confirm that UHPFC has very low permeability characteristics causing high resistance against chloride penetration as well as gas and water permeation. Thus, the UHPF could form a good interfacial bond with the NC substrate and improved the resistance of the NC substrate against the penetration of chloride and other aggressive fluids. Such attributes is expected to increase the service life of the repaired structures. The results shows that the newly overlay UHPFC achieves high bond strength and bonds efficiently with the NC substrates.

R. Yu. et. al. (2014) devised a method for the development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC).they studied towards an efficient utilization of binders and fibres in UHPFRC, with the modified Andreasen & Andersen particle packing model and the hybridization design of fibres are utilized. They particularly designed and tested the UHPFRC with ternary fibres. The flowability, mechanical properties and flexural toughness of the designed UHPFRC were measured and analysed.

Table 2.8: Densities of the material used *[R. Yu. et. al. (2014)]*

Materials	Type	Specific Density (kg/m^3)
Cement	CEM I 52.5 R	3150
Filler	Limestone powder	2710
Fine Sand	Microsand	2720
Coarse Sand	Sand 0-2	2640
Superplasticizer	Polycarboxylate ether	1050
Pozzolanic Material	Nano-silica (NS)	2200
Waste Materials	Waste Bottom Ash (WBA)	2690
Fiber – 1	Steel Fiber (SF)	7800
Fiber - 2	Polypropylene (PPF)	920

Table 2.9: Recipes of the developed UHPFRC *[R. Yu. et. al. (2014)]*

No.	C	LP	M-S	N-S	nS	W	SP	LSF	SSF	HF
	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)
1	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0	0
2	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	2.0	0	0
3	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	1.5	0.5	0
4	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	1.0	1.0	0
5	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.5	1.5	0
6	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	2.0	0
7	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0	2
8	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.125	0.375	1.5
9	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.5	0	1.5
10	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0.5	1.5

C: cement, LP: limestone powder, M-S: microsand, N-S Normal Sand, nS: nano-silica, W: water, SP: superplaticizer, LSF: long straight fibre, SSF: short straight fibre, HF: hooked fibre.

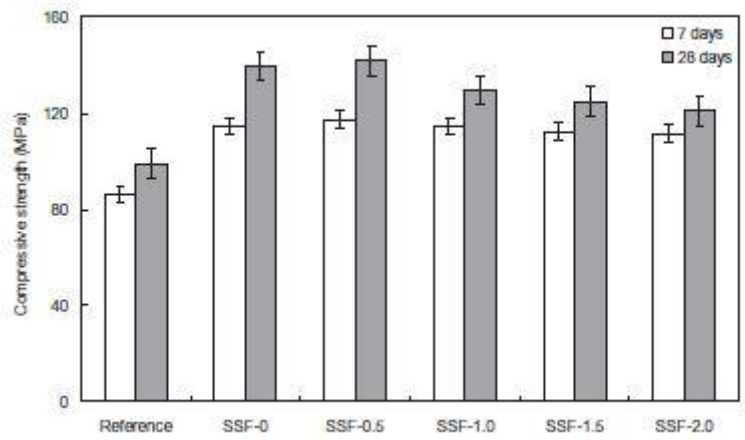

Fig 2.7 (a): Compressive strength of the developed UHPFRC with only straight steel fibers *[R. Yu. et. al. (2014)]*

Fig. 2.7 (a) shows the compressive strength of UHPFRC with only straight steel fibres. It can be observed that additional steel fibres significantly increased the compressive strength of UHPFRC. Also is was seen that the mixture with LSF (1.5% Vol.) and SSF (0.5% Vol.) showed the highest compressive strengths, which are 117.1 MPa and 141.5 MPa after curing for 7 and 28 days, respectively. It can be attributed to the combined effect of hybrid fibres in restricting the cracks development. Moreover, the compressive strength results demonstrated that, based on the modified Andreasen & Andersen particle packing model and appropriate fibre hybridization design it was possible to produce UHPFRC with a relatively low binder and fibre content.

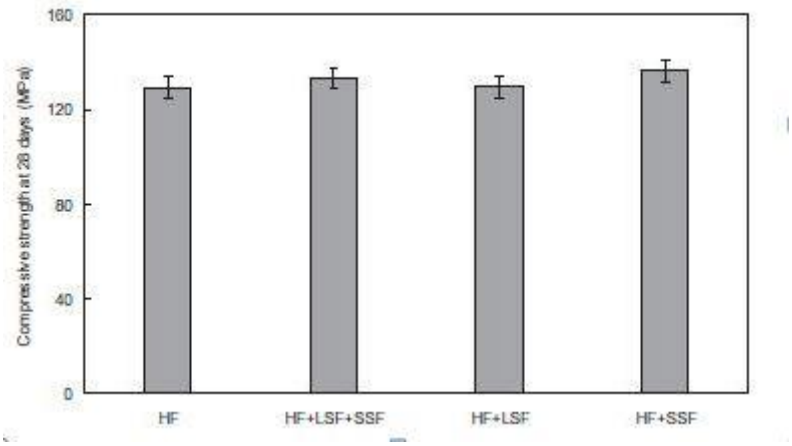

Fig 2.7 (b): Compressive strength test results of developed UHFRC with hooked fibers (HF, HF + LSF +SSF, HF + LSF and HF + SSF representing mixture from7 & to 10 respectively) *[R. Yu. et. al. (2014)]*

Fig 2.7 (b) illustrates the compressive strength of UHPFRC with hooked steel fibres (HF). It was found that the 28 days compressive strength of all the design mix fluctuated around 135 MPa, and the difference between the mixtures with HF was relatively small. The mixture with HF and SSF showed the highest compressive strength at 28 days (136.5 MPa), while the reference mixture (with only HF) was the lowest – 129.2 MPa. Moreover, in the mixtures HF + LSF + SSF, HF + LSF and HF + SSF, the HF amount was the same (1.5% Vol.), and their compressive strengths followed the order: HF + SSF > HF + LSF + SSF > HF + LSF. Hence, the conclusion was drawn that when the total fibre amount was the same, the mixture with hybrid fibres showed a higher compressive strength than the one with HF only and in the hybrid fibres system, the total fibre and the HF amounts were kept the same, the SSF was more efficient in improving the compressive strength than the LSF.

The results showed that, based on the optimized particle packing and hybrid macro and micro fibres, it was possible to produce UHPFRC with a relatively low binder amount (about 620 kg/m3) and low fibre content (Vol. 2%). Moreover, due to the mutual effects between the utilized fibres, the hybrid fibre reinforced UHPFRC showed an improved flowability and better mechanical properties. It was also found that the flexural toughness of UHPFRC was dominated by the hooked steel fibres.

Ehsan Ghafari et. al. (2014) conducted an experimental study aiming to evaluate the influence of nanosilica (nS) addition on properties of ultra-high performance concrete (UHPC). Thermo gravimetric analysis results indicated that nS consumed much more $Ca(OH)_2$ as compared to silica fume, specifically at the early ages. They also studied the mercury intrusion porosimetry measurements which proved that the addition of nS particles leads to reduction of capillary pores. Scanning electron microscope observation revealed that the inclusion of nS can also

efficiently improve the interfacial transition zone between the aggregates and the binding paste. With the addition of nS also resulted in an enhancement in compressive strength as well as in transport properties of UHPC. The optimum amount of cement replacement by nS in cement paste to achieve the best performance was 3 wt.%. However, the improper dispersion of nS was found as a deterrent factor to introduce higher percentage of nS into the cement paste.

Table 2.10: Composition of UHPC mixture (by weight (kg.m3)) *[Ehsan Ghafari et. al. (2014)]*

Sample	Cement	SF	nS	Sand	Water	SP
M0 (Control)	950	255	-	873	189	31
M1	941.5	255	9.5	873	189	31
M2	932	255	19	873	189	31
M3	921.5	255	28.5	873	189	31
M4	912	255	38	873	189	31

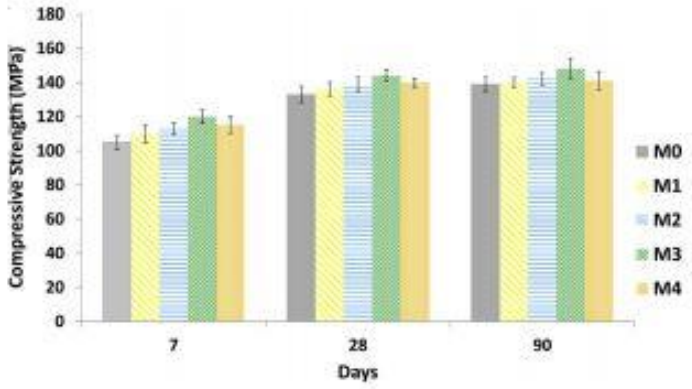

Fig 2.8: Compressive strength (MPa) of nS particle blended concrete specimens *[Ehsan Ghafari et. al. (2014)]*

They concluded that the addition of 3 (wt.%) nS resulted in a 24% increase at 7 days, which was 40% higher than that observed with the reference mixture. The higher compressive strength was due to faster pozzolanic reactivity of nanoparticles, in the presence of Ca(OH)2, making the microstructure denser. Additionally, the incorporation of nS particles accelerated the hydration process of C_3S clinker phase due to the large and highly reactive surface of the nanoparticles. However, the results showed that the addition of nS had a modest effect at the age of 28 and 90 days, so that the highest compressive strength was 144 MPa and 148 MPa for M3 specimen, which was only 8% and 6.5% higher than the reference mixture. This behaviour confirms the fact that the most part of the pozzolanic reactivity of nS in cement paste is completed at early

ages compressive strength decreased slightly when the replacement level reached 4% wt.%. Thus, a higher replacement of cement by nS did not lead to an improvement in compressive strength, which can be due to improper dispersion of nS particles in the mixture.

CHAPTER 3:
MATERIAL AND DESIGN METHODOLOGY

3.1 GENERAL

The selections of materials have to be ascertained for purpose of achieving the desired strength of concrete. The present chapter presents the properties of various materials used for development of UHPC and the results obtained from the various test conducted on them. In order to achieve the desired strength required for a mix to be designated as a UHPC, varying percentages of mineral admixtures like Silica Fume, Nano silica, Ground Granulated Blastfurnace Slag (GGBS)were used along with steel fibres and with OPC 53 grade cement and aggregates.

3.2 CHARACTERISTICS OF MATERIALS USED

The chemical and physical properties of various materials used for making Ultra High Performance concrete mixes were determined in laboratory as per the relevant IS codes of practice. The materials used in the present experimental study for the development of UHPC are cement, coarse aggregates, fine aggregates, and water along with superplasticizer, in addition to silica fume, Nano silica, GGBS (Alccofine) and steel fibers in varying proportions. The various properties of material are evaluated to check their acceptance for use in concrete making as per the relevant codal provision requirements. The significance of which allows an engineer to design a concrete mix for a particular strength. The description of various materials along with their examined properties which were used in this study is detailed in the succeeding subsections.

3.2.1 Portland cement

Cement is the most active component of concrete and usually has the greatest unit cost. Its selection and proper use is important in obtaining the most economical balance of properties which are desired for any particular concrete mixture. The main property of cement is to fill up voids existing between the fine aggregates and make the concrete impermeable. It provides strength to concrete by formulating a bond between the aggregates forming a solid mass due to its setting and hardening properties when mixed with water. The constitution of cement is only about 20% of the total volume of concrete mix but it significantly affects the strength and durability of the concrete mix formed. Portland cement referred to as Ordinary Portland Cement (OPC) is the most important type of cement and is produced by grinding Portland cement clinker into fine powder. Basically OPC is classified into 3 grades namely 33 Grade, 43 Grade, 53 Grade depending upon the strength achieved in 28 days. The specification for the cement of any

grade is given by the various IS codes. IS 12269:2013 provides the specification of OPC 53 Grade. According to IS 12269 Ordinary Portland cement, 53 grade shall be manufactured by intimately mixing together calcareous and argillaceous and/or other silica, alumina or iron oxide bearing materials, burning them at a clinkering temperature and grinding the resultant clinker so as to produce a cement capable of complying with this standard. No material shall be added after burning, other than gypsum (natural mineral or chemical), water, performance improver(s), and not more than a total of 1.0 percent of air-entraining agents or other agents including coloring agents, which have proved not to be harmful. Ordinary Portland Cement (OPC) of 53 Grade (Elephant Cement) from a single lot was used throughout the course of the study. It was noted that the cement was fresh and free from any lumps. It was carefully stored to prevent deterioration in its properties due to contact with the moisture. The physical properties of the cement were determined as per the standard physical test procedure laid down in relevant code and were checked for conformation as per IS 12269: 2013. The test results are listed in the Table 3.1.

Table 3.1: Properties of OPC 53 Grade

Characteristics	**Experimental Values Obtained**	**IS 12269:2013 Specified Values**	**Test Method Referred to**
Specific Gravity	3.14	-	IS 4031 Part 11
Standard Consistency (in %)	28	-	IS 4031 Part 4
Setting Time (min)			IS 4031 Part 5
Initial	54	30 (Minimum)	
Final	174	600 (Maximum)	
Compressive Strength			IS 4031 Part 6
3 Days	28.46 N/mm^2	27 N/mm^2	
7 Days	38.72 N/mm^2	37 N/mm^2	
28 Days	55.27 N/mm^2	53 /mm^2	

3.2.2 Aggregates

Aggregates occupy the majority of the volume in the concrete mixture and give a dimensional stability to concrete. Generally in concrete the aggregates used are of two size groups:

- Coarse aggregates – which have particle size greater than 4.75mm and,
- Fine aggregates (sand) - which has particle size less than 4.75mm.

Coarse aggregate make a solid hard mass of concrete with cement and sand increasing the crushing strength of concrete. The cost of concrete is reduced significantly, since it occupies the

majority of the volume. Sand is made up of small angular or rounded grains of silica and is commonly used as a fine aggregate in cement concrete. It fills the voids existing in between the coarse aggregate and reduces the shrinkage and cracking properties of concrete. It helps in hardening of cement by allowing the water through its voids. The fine aggregate assist the cement paste to hold the coarse particle in suspension, this action promotes plasticity in the mixture and prevent the possible segregation of paste and coarse aggregate. The aggregates constitute about 80%of the total volume of concrete. So, it is extremely important that the aggregates should meet basic requirement for the concrete to be workable, strong, durable and economical. The aggregates must be of proper shape and size, clean hard and well graded.

a) Coarse aggregates: The aggregate retaining over IS sieve 4.75mm are termed as coarse aggregate. The coarse aggregates may be of following types: - Crushed gravels or stone, obtained by crushing gravel or hard stone or uncrushed gravel resulting from the natural disintegration of rocks. Partially crushed gravel or stone is obtained as a product of blending of above two types. The nominal sizes of gravel or stone is 10mm-20mm, however the sizes may be of 40mm or more as they have been used in Self Compacting Concrete (SCC) and in dry lean concrete. The characteristics of different type of aggregates (crushed aggregates) tend to improve the strength because of interlocking of angular particle, while the rounded aggregates improves the workability due to their lower internal friction.

The coarse aggregates used in the present study, obtained locally, were a mixture of crushed stones of 20mm and 10mm sizes. The aggregates were thoroughly washed to remove dirt, dust and then dried to surface dry condition. They were then put into the oven for a period of 24 hours so as to remove the excess moisture present. The aggregates taken out were then cooled down to the room temperature to be used in the concrete mix. The specific gravity and other physical properties of coarse aggregates are shown in Table 3.2. The values obtained by the sieve analysis of coarse aggregate done in the laboratory for 20mm aggregate are shown in the Table 3.3 and that for the 10mm aggregate in Table 3.4

Table 3.2: Properties of Coarse Aggregates

Characteristics	**Value**	
Color	Grey	
Shape	Angular	
Maximum size	20mm	10mm
Specific Gravity	2.77	2.75
Water Absorption	0.37%	0.42%

Table 3.3: Sieve Analysis of Coarse Aggregates (20mm)

S.No.	IS-Sieve (mm)	Wt. Retained (gm)	%age Retained	%age passing	Cumulative % retained
1	80	0.00	0.00	100.00	0.00
2	40	0.00	0.00	100.00	0.00
3	20	51	1.70	98.30	1.70
4	10	2846	94.87	3.43	96.57
5	4.75	103	3.43	0	100
6	2.36	0	0	0	100
7	1.18	0	0	0	100
8	600	0	0	0	100
9	300	0	0	0	100
10	150	0	0	0	100
11	Pan	0	0	**SUM**	**698.27**
Total		**3000**		**FM = 6.98**	

Table 3.4: Sieve Analysis of Coarse Aggregate (10mm)

S.No.	IS-Sieve (mm)	Wt. Retained (gm)	%age Retained	%age passing	Cumulative % retained
1	80	0.00	0.00	100.00	0.00
2	40	0.00	0.00	100.00	0.00
3	20	447	22.35	77.65	22.35
4	10	415	20.75	56.90	43.10
5	4.75	1055	52.75	4.15	95.85
6	2.36	80	4.00	0.15	99.85
7	1.18	0	0	0	100
8	600	0	0	0	100
9	300	0	0	0	100
10	150	0	0	0	100
11	Pan	3	0.15	**SUM**	**661**
Total		**2000**		**FM = 6.61**	

b) Fine aggregates: The aggregates that pass through 4.75mm IS sieve are termed as fine aggregates. The fine aggregates may be of following types:

Natural sand, i.e. the fine aggregate which results from natural disintegration of rocks;

Crushed stone sand, i.e. the fine aggregates produced by crushing hard stone; and

Crushed gravel sand, i.e. the fine aggregates produced by crushing natural gravel.

IS 383 has divided the fine aggregate into four grading zones (Grade I to IV) depending on the particle size distribution. The grading zones become gradually finer from grading zone I to grading zone IV. In this experimental program fine aggregates lying in grading zone II were collected from the local supplier. The fine aggregates were washed to remove silt and clay and were then oven dried for a period of 24 hours. They were then brought down to room temperature and were then used in the concrete mix. Sieve analysis, carried out as per IS: 383, confirmed that the sand was in grading zone II and the results are shown in Table 3.5.

Specific gravity of fine aggregates was experimentally determined as **2.55.**

Table 3.5: Sieve Analysis of Fine Aggregate

S.No.	IS-Sieve (mm)	Wt. Retained (gm)	%age Retained	%age passing	Cumulative % retained
1	4.75	24	2.4	97.6	2.4
2	2.36	86	8.6	89.0	11.0
3	1.18	191	19.1	69.9	30.1
4	600 µ	151	15.1	54.8	45.2
5	300 µ	259	25.9	28.9	71.1
6	150 µ	247	24.7	4.2	95.8
7	Pan	42	4.2	-	-
TOTAL		**1000**		**SUM**	**255.6**
Zone II				**FM= 2.56**	

3.2.3 Silica fume

Silica fume was used in the design mix as a replacement for cement to study its effectiveness for development of ultra-high performance concrete. Silica fume was obtained from KGR Agro Fusions (P) Ltd., Ludhiana Punjab. The color of silica fume received was bluish grey. Physical and chemical properties of silica fume were provided by KGR Agro Fusions (P) Ltd.

***a) Physical properties*:** The physical properties of silica fume are important in both the micro-filler and pozzolanic roles. The very small size of its particles is also one of the key to its performance. The various physical properties of silica fume are shown in Table 3.6.

Table 3.6: Physical properties of silica fume

Particle size (typical)	<1μm
Color	Bluish Grey
Bulk density	550-700 kg/m^3
Specific gravity	2.40

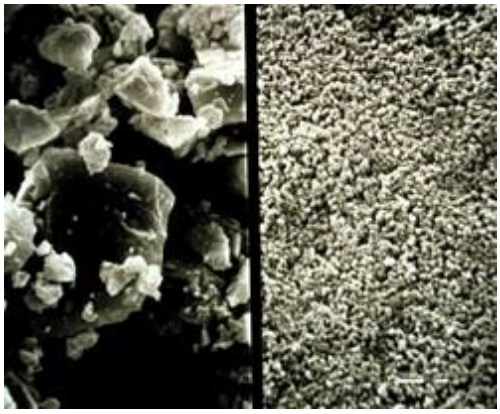

Fig. 3.1: Cement grains and silica fume particles

The above figure shows cement grains and silica fume particles at same magnification. According to the ACI 234R-96 report estimates that when silica fume is replaced by 15% of cement, there are approximately 2,000,000 particles of silica fume for each grain of Portland cement.

***b) Chemical properties of silica fume*:** The primary chemical properties of silica fume are briefed as below:-

Silica fume is amorphous in nature i.e. it does not dissolve in concrete before the material can react. This term simply means that silica is not a crystalline material. The crystalline material present in concrete is sand and though silica fume is essentially silicon dioxide (SiO_2), but it does not react because of its non-crystalline nature.

Silicon dioxide (SiO_2) is the reactive material in silica fume. There may be additional materials in the silica fume based upon the metal being produced in the smelter from which the fume was recovered. Usually, these materials have no impact on the performance of silica fume in concrete. In the present study the silica fume that was collected for the supplier had the following chemical composition shown in Table 3.7.

Table 3.7: Chemical composition of silica fume

SiO_2	Al_2O_3	Carbon	CaO	MgO	FeO	TiO_2
92.55%	0.06%	<1%	0.10%	0.10%	0.02%	0.03%

Addition of Silica fume results in changing the microstructure of the concrete. This change results from two different but equally important processes, first the physical aspect of the silica fume and second is its chemical contribution.

3.2.4 GGBS (Grand Granulated Blastfurnace Slag)/Alccofine

Alccofine was used in the design mix as another replacement material for cement to study its effectiveness for development of ultra-high performance concrete. Alccofine 1101, obtained from Ambuja Cements Ltd. (ALCCOFINE MICRO MATERIALS RANGE), Mumbai has an average particle size of 4 to 5 microns; the top size d_{90} is only 10 microns. The computed Blaine value is about 8000 cm^2/gm. Alccofine 1101 is to be used with suitable water reducing admixture. Various physical and chemical properties of Alccofine material are given in Table 3.8.

Table 3.8: Properties of Alccofine

Initial Setting Time	> 1 Hour
Final Setting Time	< 6 Hours
Fineness	8000 cm^2/gm
Specific Gravity	3.10
Bulk Density	650 – 700 kg/m^3
Particle Size Distribution	
< 2.5 microns	10%
< 6 microns	50%
< 12 microns	90%

3.2.5 Nano silica

The size of nano silica is very small; much smaller than the size of silica fume and GGBS (Alccofine), hence it is available in liquid form. Colloidal silica is a nano metric particle size solution of silica particles in water or other mediums. It is composed of the same substance (silicon dioxide) as quartz sand but has an amorphous (random) rather than a crystalline structure. There is stable dispersion of amorphous spherical particles of silicon dioxide in water.

Physical and Chemical Properties: It is a white translucent liquid having no odour and has complete solubility. Specific gravity of nano silica is of the range 1.37 - 1.40 having particle sizes ranging between 1 - 100 nm.

3.2.6 Steel Fibers

The role of fibers is to arrest the advancing of crack by applying pinching forces at the crack tips, to delay the propagation of cracks across the matrix and create a slow cracking propagation stage. This increases the ultimate cracking strain of the matrix by many times as compared to that of unreinforced matrix. The introduction of small, closely spaced and randomly oriented fibers transforms a brittle material, having low tensile strength and impact resistance, to a much stronger composite with superior cracking resistance, improved ductility and distinctive post cracking behaviour prior to failure. Steel fibers are of different types namely straight steel fiber, indentation steel fiber and hooked ends steel fiber. In the present study indentation steel fiber (SHAKTIMAN ® Steel Fiber) are used which were obtained from Stewols India (P) Ltd., Nagpur. The specifications of the fibers used are given in **Table 3.9.**

Table 3.9: Specification of steel fibers

Ultimate Strength as per ASTM A820M	>1100 MPa
Diameter	0.60 mm
Length	30 mm
Aspect Ratio	50

The fibers are distributed randomly in the concrete. The function of this irregular distribution is to fill the cracks in the composite. Fibers when utilized in concrete, generally manage the plastic shrink cracking and drying shrink cracking. They also lessen the permeability of concrete and therefore reduce the flow of water. Some types of fibers create greater impact, abrasion and shatter resistance in the concrete. The actual function of the fibers is to increase the concrete toughness.

3.1.6 Water

Water is used as a binding agent for the concrete mix. Potable water is normally considered satisfactory for mixing and curing of concrete. In the current study accordingly potable water available in the material testing laboratory was used for making concrete. It was free from any detrimental contaminants and was of good potable quality.

3.1.7 Superplasticizers

Different types of superplasticizers were examined for their effects on mix workability in order to develop UHPC mixes. The superplasticizers from MR.7, Prema Construction Aids and BASF were used but were neither able to provide the required workability nor the strength even after increasing the dosage. The superplasticizer from the earlier study was used too but it was not

able to provide the required workability and strength, which can attributed to the change in material properties and also to the addition of steel fibers.

AURAMIX 400 procured from FOSROC Constructive Solutions was then tested and used in the present study. It is a unique combination of the latest generation superplasticizers and based on a polycarboxylic ether polymer with long lateral chains which greatly improves cement dispersion. It is a high performance retarding superplasticiser intended for applications where retardation and long workability retention are required. Table 3.8 shows the characteristics of AURAMIX 400.

The optimum dosage of AURAMIX 400 to meet the specific requirement was determined by trials using the constituent materials. The normal dosage ranges between 0.5 to 3.0 ltrs/ 100kg of cementitious material. Depending on the workability to be achieved the range of dosage can be altered.

In this study, to attain medium workability of the control mix, generally super plasticisers of the amount of 1.25% to 2.00% of cement content was used, and for the other mixes the quantity of superplasticizers were found out depending upon the trials for achieving medium range of workability. The properties of superplasticizer are provided in Table 3.10.

Table 3.10: Properties of superplasticizer

S. No.	Characteristics	Value
1	Type	Polycarboxylic Ether Polymer
2	Physical State	Liquid
3	Colour	Light Yellow
4	Specific gravity	1.22
5	pH	Minimum 6
6	Chloride Content	Nil

3.3 TEST METHODS

The procedure of methods used for finding the properties of cement, coarse aggregates, fine aggregates and strength of cement concrete is given below:

3.3.1 Specific gravity

Specific gravity is ratio of weight of a given volume of the substance to the weight of an equal volume of some reference substance, or equivalently the ratio of masses of equal volume of two substances. The specific gravity of cement is found out as per the procedure given in IS: 2720 –

(Part 3): 1980 and that for aggregates the procedure is followed according to IS: 2386 (Part 3): 1983.

3.3.2 Sieve analysis for coarse and fine aggregates as per IS 2386 (Part - 1) 1963

Sieve analysis is used for determination of particle size distribution of fine and coarse aggregates by sieving or screening though a predefined set of sieves.

3.3.3 Compressive Strength of Concrete

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 ingredients. 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 90^0. Load was applied continuously at the rate of 5 MPa per second until the failure of the specimen takes place. The photograph (Fig. 3.2) shows testing of cube specimen under automatic compression testing machine.

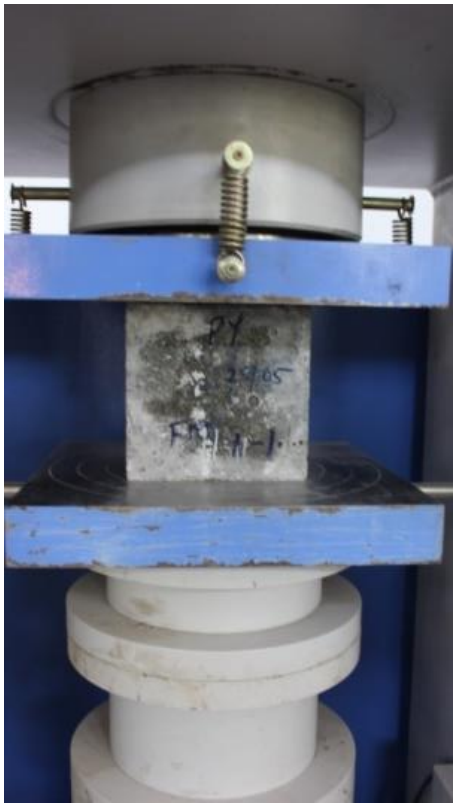

Fig 3.2: Compressive strength test setup

3.4 CONCRETE MIXTURE PROPORTIONING

3.4.1 Test Data for materials

1. Cement Used — OPC grade 53
2. Specific Gravity of Cement — 3.14
3. Specific Gravity of Coarse Aggregate (20 mm) — 2.77
4. Specific Gravity of Coarse Aggregate (10 mm) — 2.69
5. Specific gravity of Fine Aggregate — 2.55
6. Free Surface Moisture of Coarse Aggregate (20mm &10mm) — Nil
7. Sieve Analysis of Coarse Aggregate — Conforming to Table 4(IS: 383-1970)
8. Sieve Analysis of Fine Aggregate — Conforming to Zone II (IS: 383-1970)

3.4.2 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 0.18, 0.20 and 0.22 constituting a total of six mixes (M1, M2, M3, M4, M5 and M6). In addition to the mixes seven different percentages (0.00, 0.25, 0.50, 0.75, 1.00, 1.25 and 1.50) 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. The percentage variation of ingredients used in developing the UHPC is shown in **Table 3.10** below:

Table 3.11: Percentage of ingredients in various trial mixes

Trial Mix	**1**	**2**
Silica Fume (%)	8	8
Nano Silica (%)	2	2
GGBS (%)	10	20
Steel Fibres (%)	0.00	0.00
	0.25	0.25
	0.50	0.50
	0.75	0.75
	1.00	1.00
	1.25	1.25
	1.50	1.50

The various mix proportions of ingredients used for the development of UHPC for the three water-binder ratios used, where in parts of OPC 53 grade cement were replaced by nanosilica, silica fume and GGBS in different percentages in different trial mixes. A constant workability of 75 to 90mm slump was maintained for all the mixes by varying the superplasticizer dosage. The dosage for each mix is also shown in Table 3.12 (a), (b) and (c).

Table 3.12 (a): Mix proportions for w/b = 0.22

Materials	Mix 1	Mix 4
Water (kg/m^3)	150	150
Cement (kg/m^3)	545.45	477.27
FA (kg/m^3)	545.04	543.91
CA (20mm) (kg/m^3)	809.71	808.03
CA (10 mm) (kg/m^3)	259.18	258.64
NS (kg/m^3)	13.64	13.63
SF (kg/m^3)	54.55	54.45
AF (kg/m^3)	68.18	136.36
Superplasticizer (kg/m^3)	9.54	8.52
Steel Fibers (kg/m^3)	0	0
	1.36	1.19
	2.73	2.39
	4.09	3.58
	5.45	4.77
	6.82	5.96
	8.18	7.16

Table 3.12 (b): Mix proportions for w/b = 0.20

Materials	Mix 2	Mix 5
Water (kg/m^3)	155	155
Cement (kg/m^3)	620.00	542.50
FA (kg/m^3)	505.29	504.02
CA (20mm) (kg/m^3)	763.20	761.28
CA (10 mm) (kg/m^3)	244.30	243.68
NS (kg/m^3)	15.50	15.50
SF (kg/m^3)	62.00	62.00
AF (kg/m^3)	77.50	155.00
Superplasticiser (kg/m^3)	13.18	12.01
Steel Fibers (kg/m^3)	0	0
	1.55	1.35
	3.10	2.71
	4.65	4.07
	6.20	5.42
	7.75	6.78
	9.30	8.14

Table 3.12 (c): Mix proportions for w/b = 0.18

Materials (kg/m^3)	Mix 3	Mix 6
Water	160	160
Cement	711.11	622.22
FA	459.78	459.30
CA (20mm)	706.12	705.38
CA (10 mm)	226.02	225.80
NS	17.78	17.78
SF	71.11	71.11
AF	88.89	177.78
Superplasticiser	17.78	16.44
Steel Fibers	0	0
	1.78	1.56
	3.56	3.11
	5.33	4.67
	7.11	6.22
	8.89	7.78
	10.67	9.33

CHAPTER 4:
RESULTS AND DISCUSSION

4.1 GENERAL

The chapter herein deals with the presentation of the results obtained from the compressive strength tests conducted on the ultra-high performance concrete mixes. In order to achieve the objective of study for the development of UHPC, an experimental program was devised in which different percentages of silica fume, nano silica, GGBS and steel fibers were incorporated into the mix along with aggregates and cement (OPC 53 Grade)to determine the best proportion of materials that can provide the enhanced mechanical properties. The mixes were cast using the proportions as laid down in Tables 3.12 (a), (b) and (c) in the previous chapter. The experimental program consisted of casting, curing and testing of concrete specimen at different curing ages of 7 days and 28 days. The experimental program included the following:

1. Obtaining and testing of properties of materials used for making concrete.
2. Making trial design mixes for ultra-high performance concrete.
3. Casting and curing of specimens.
4. Cubical specimens of size 150mm x 150mm x 150mm were tested for the compressive strength of concrete.

4.2 COMPRESSIVE STRENGTH TEST RESULTS

4.2.1 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.

4.2.2 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 superplasticizer 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 75 to 90mm slump, was maintained for all the mixes by varying the superplasticizer 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. The specimens were tested on 500 tones ACTM as shown in the Fig. 4.1 as per the procedure laid down in section 3.3.3 in the previous chapter.

The photograph showing the testing of cube specimens under compression testing machine is provided as below (Fig. 4.1). The test results for the 7 and 28 days for control mix as well as modified mixes are shown in the Table 4.1.

Fig 4.1: Cube under compression in Automatic Compression Testing Machine (ACTM)

Table 4.1: Compressive strength results for trial mix 1

MIX 1			**w/b = 0.22**							
Fibers	**W**	**C**	**FA**	**CA (20)**	**CA (10)**	**NS**	**SF**	**GGBS**	**7D**	**28D**
(%)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)	MPa	MPa
0	150	545.45	545.04	809.71	259.18	2	8	10	**70.8**	**99.3**
0.25	150	545.45	545.04	809.71	259.18	2	8	10	**72.4**	**100.5**
0.50	150	545.45	545.04	809.71	259.18	2	8	10	**74.6**	**103.7**
0.75	150	545.45	545.04	809.71	259.18	2	8	10	**75.8**	**108.8**
1.00	150	545.45	545.04	809.71	259.18	2	8	10	**78.3**	**112.6**
1.25	150	545.45	545.04	809.71	259.18	2	8	10	**79.2**	**116.2**
1.50	150	545.45	545.04	809.71	259.18	2	8	10	**81.2**	**120.6**
MIX 2			**w/b = 0.20**							
Fibers	**W**	**C**	**FA**	**CA (20)**	**CA (10)**	**NS**	**SF**	**GGBS**	**7D**	**28D**
(%)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)	MPa	MPa
0	155	620.00	505.29	763.20	244.30	2	8	10	**78.2**	**108.6**
0.25	155	620.00	505.29	763.20	244.30	2	8	10	**80.1**	**111.0**
0.50	155	620.00	505.29	763.20	244.30	2	8	10	**83.4**	**114.6**
0.75	155	620.00	505.29	763.20	244.30	2	8	10	**86.8**	**119.4**
1.00	155	620.00	505.29	763.20	244.30	2	8	10	**89.1**	**124.6**
1.25	155	620.00	505.29	763.20	244.30	2	8	10	**91.3**	**129.3**
1.50	155	620.00	505.29	763.20	244.30	2	8	10	**95.6**	**134.2**
MIX 3			**w/b = 0.18**							
Fibers	**W**	**C**	**FA**	**CA(20)**	**CA (10)**	**NS**	**SF**	**GGBS**	**7D**	**28D**
(%)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)	MPa	MPa
0	160	711.11	459.78	706.12	226.02	2	8	10	**93.2**	**130.2**
0.25	160	711.11	459.78	706.12	226.02	2	8	10	**97.2**	**134.6**
0.50	160	711.11	459.78	706.12	226.02	2	8	10	**100.3**	**137.5**
0.75	160	711.11	459.78	706.12	226.02	2	8	10	**102.2**	**141.8**
1.00	160	711.11	459.78	706.12	226.02	2	8	10	**104.6**	**145.7**
1.25	160	711.11	459.78	706.12	226.02	2	8	10	**107.2**	**150.6**
1.50	160	711.11	459.78	706.12	226.02	2	8	10	**110.3**	**158.2**

Table 4.2: Compressive strength test results for trial mix 2

MIX 4			**w/b = 0.22**							
Fibers	**W**	**C**	**FA**	**CA (20)**	**CA (10)**	**NS**	**SF**	**GGBS**	**7D**	**28D**
(%)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)	MPa	MPa
0	150	477.27	543.91	808.03	258.64	2	8	20	**69.2**	**97.6**
0.25	150	477.27	543.91	808.03	258.64	2	8	20	**70.8**	**99.8**
0.50	150	477.27	543.91	808.03	258.64	2	8	20	**71.2**	**102.6**
0.75	150	477.27	543.91	808.03	258.64	2	8	20	**73.4**	**104.7**
1.00	150	477.27	543.91	808.03	258.64	2	8	20	**75.5**	**107.6**
1.25	150	477.27	543.91	808.03	258.64	2	8	20	**77.2**	**110.2**
1.50	150	477.27	543.91	808.03	258.64	2	8	20	**78.8**	**116.6**
MIX 5			**w/b = 0.20**							
Fibers	**W**	**C**	**FA**	**CA (20)**	**CA(10)**	**NS**	**SF**	**GGBS**	**7D**	**28D**
(%)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)	MPa	MPa
0	155	542.50	504.02	761.28	243.68	2	8	20	**77.3**	**104.3**
0.25	150	542.50	504.02	761.28	243.68	2	8	20	**79.3**	**108.3**
0.50	150	542.50	504.02	761.28	243.68	2	8	20	**82.5**	**114.6**
0.75	150	542.50	504.02	761.28	243.68	2	8	20	**84.2**	**120.3**
1.00	150	542.50	504.02	761.28	243.68	2	8	20	**85.6**	**121.2**
1.25	150	542.50	504.02	761.28	243.68	2	8	20	**88.3**	**126.3**
1.50	150	542.50	504.02	761.28	243.68	2	8	20	**92.3**	**130.2**
MIX 6			**w/b = 0.18**							
Fibers	**W**	**C**	**FA**	**CA (20)**	**CA (10)**	**NS**	**SF**	**GGBS**	**7D**	**28D**
(%)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(%)	(%)	MPa	MPa
0	160	641.67	445.20	683.72	218.85	2	8	20	**90.2**	**128.6**
0.25	160	641.67	445.20	683.72	218.85	2	8	20	**93.7**	**130.5**
0.50	160	641.67	445.20	683.72	218.85	2	8	20	**94.8**	**136.6**
0.75	160	641.67	445.20	683.72	218.85	2	8	20	**95.6**	**137.2**
1.00	160	641.67	445.20	683.72	218.85	2	8	20	**100.8**	**140.9**
1.25	160	641.67	445.20	683.72	218.85	2	8	20	**102.4**	**141.8**
1.50	160	641.67	445.20	683.72	218.85	2	8	20	**105.6**	**146.5**

4.4 DISCUSSION OF COMPRESSIVE STRENGTH TEST RESULTS

4.4.1 Effect variation in percentage of steel fibers on compressive strength of concrete for trial 1

The control mix **M1**, a w/b ratio as 0.22 (containing 8% silica fume, 2% nano silica, and 10% GGBS) is observed to have a compressive strength of 70.8 MPa and 99.3 MPa respectively after 7 and 28 days curing. For the same mix when 0.25% steel fiber are added to the mix, the 7 and 28 days compressive strength was recorded as 72.4 MPa and 100.5 MPa, respectively inducating a small increase in strength. Subsequently, when the percentage of steel fiber was increased to 0.50% the compressive strength was recorded as 74.6 MPa and 103.7 MPa for 7 and 28 days, respectively again a marginal increase in strength. When percentage of steel fiber was increased to 0.75% the compressive strength for 7 days and 28 days was 75.8 MPa and 108.8 MPa, respectively. Further when percentage of steel fiber was increased to 1.00%the compressive strength after 7 days and 28 days was recorded as 78.3 MPa and 112.6 MPa respectively. However, when percentage of steel fiber was increased to 1.25% the compressive strength for 7 days and 28 days was observed as 79.2 MPa and 114.2 MPa. Lastly, when percentage of steel fiber was increased to 1.50% the compressive strength at 7 days and 28 days was found to be 80.9 MPa and 120.6 MPa. Fig 4.2 shows the trend of increase in strength with varying percentages of steel fibers in Mix 1.

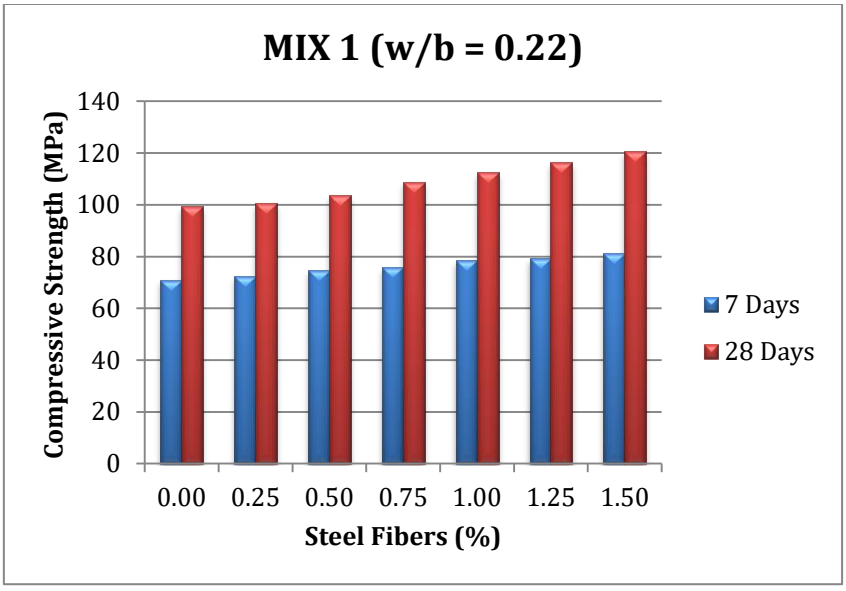

Fig 4.2: Variation of compressive strength for Mix 1 with w/b = 0.22

From the above recorded values it can be seen that for Mix 1 with w/b = 0.22, without the addition of steel fibers the mix was able to achieve strength merely at 100 MPa after 28 days of

curing. It can also be seen from the trend of values that a marginal increase in the percentage of fibers does not increase in the percentage of fibers does not lead to a significant increase in strength at both 7 and 28 days. However, a higher percentage increase in strength is observed at 28 days curing period. With the addition of 0.25% steel fibers the strength of the mix increased to 100.5 MPa after 28 days of curing. With further increasing the percentage of steel fibers gradually to the mix, the strength increased gradually. It can also be seen that at 7 days of curing with the addition of steel fibers the mix was to able achieve a strength of above 70 MPa. Thus, it can be said that with the increase in percentage of steel fibers the compressive strength also increased indicating that the micro cracks developed in the mix were prevented. Since the requirement for UHPC need the compressive strength to be in the range of 120 to 150 MPa, only one mix having a percentage of steel fibers of 1.50% could achieve that range after 28 days of curing. This indicates that for the development of UHPC, a high percentage of steel fibers are necessary along with the optimum percentage of nano silica, silica fume and GGBS at the w/b ratio of 0.22.

Thus, it can be concluded that it is possible to produce mixes with a compressive strength of over 120 MPa, at 28 days of curing, with w/b ratio of 0.22 having 1.50% percentage of steel fibers, with a judicious mix of 2% nano silica, 8% silica fume and 10% GGBS as supplementary cementious materials.

The control mix **M2**, a w/b ratio as 0.20 (containing 8% silica fume, 2% nano silica, and 10% GGBS) is observed to have a compressive strength of 78.2 MPa and 108.6 MPa respectively after 7 and 28 days curing. For the same mix when 0.25% steel fiber are added to the mix, the 7 and 28 days compressive strength was recorded as 80.1 MPa and 111.0 MPa, respectively inducating a small increase in strength. Subsequently, when the percentage of steel fiber was increased to 0.50% the compressive strength was recorded as 83.4 MPa and 114.6 MPa for 7 and 28 days, respectively again a marginal increase in strength. When percentage of steel fiber was increased to 0.75% the compressive strength for 7 days and 28 days was 86.8 MPa and 119.4 MPa, respectively. Further when percentage of steel fiber was increased to 1.00% the compressive strength after 7 days and 28 days was recorded as 89.1 MPa and 124.6 MPa respectively. However, when percentage of steel fiber was increased to 1.25% the compressive strength for 7 days and 28 days was observed as 91.3 MPa and 129.3 MPa. Lastly, when percentage of steel fiber was increased to 1.50% the compressive strength at 7 days and 28 days was found to be 95.6 MPa and 134.2 MPa. Fig 4.3 shows the trend of increase in strength with varying percentages of steel fibers in Mix 2.

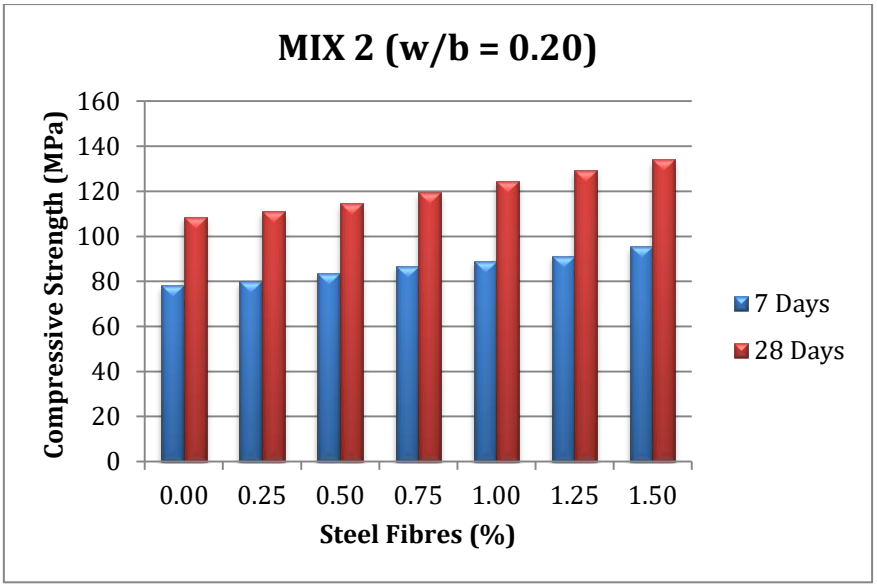

Fig 4.3: Variation of compressive strength for Mix 2 with w/b = 0.20

From the above recorded values it can be seen that for Mix 2 with w/b = 0.22, without the addition of steel fibers the mix was able to achieve strength of 108.6 MPa after 28 days of curing. It can also be seen from the trend of values that a marginal increase in the percentage of fibers does not increase in the percentage of fibers does not lead to a significant increase in strength at both 7 and 28 days. However, a higher percentage increase in strength is observed at 28 days curing period. With the addition of 0.25% steel fibers the strength of the mix increased to 111.0 MPa after 28 days of curing. With further increasing the percentage of steel fibers gradually to the mix, the strength increased gradually. It can also be seen that at 7 days of curing with the addition of steel fibers the mix was to able achieve a strength of above 75 MPa. Thus, it can be said that with the increase in percentage of steel fibers the compressive strength also increased indicating that the micro cracks developed in the mix were prevented. Since the requirement for UHPC need the compressive strength to be in the range of 120 to 150 MPa, only mix having a percentage of steel fibers between 1.00 and 1.50% could achieve that range after 28 days of curing. This indicates that for the development of UHPC, a high percentage of steel fibers are necessary along with the optimum percentage of nano silica, silica fume and GGBS at the w/b ratio of 0.20.

Thus, it can be concluded that it is possible to produce mixes with a compressive strength of over 120 MPa, at 28 days of curing, with w/b ratio of 0.20 having steel fibers in the range of 1.00 to 1.50%, with a judicious mix of 2% nano silica, 8% silica fume and 10% GGBS as supplementary cementious materials.

The control mix **M3**, a w/b ratio as 0.18 (containing 8% silica fume, 2% nano silica, and 10% GGBS) is observed to have a compressive strength of 93.2 MPa and 130.2 MPa respectively after 7 and 28 days curing. For the same mix when 0.25% steel fiber are added to the mix, the 7 and 28 days compressive strength was recorded as 97.2 MPa and 134.6 MPa, respectively inducating a small increase in strength. Subsequently, when the percentage of steel fiber was increased to 0.50% the compressive strength was recorded as 100.3 MPa and 137.5 MPa for 7 and 28 days, respectively again a marginal increase in strength. When percentage of steel fiber was increased to 0.75% the compressive strength for 7 days and 28 days was 102.2 MPa and 141.8 MPa, respectively. Further when percentage of steel fiber was increased to 1.00% the compressive strength after 7 days and 28 days was recorded as 104.6 MPa and 145.7 MPa respectively. However, when percentage of steel fiber was increased to 1.25% the compressive strength for 7 days and 28 days was observed as 107.2 MPa and 150.6 MPa. Lastly, when percentage of steel fiber was increased to 1.50% the compressive strength at 7 days and 28 days was found to be 110.3 MPa and 158.2 MPa. Fig 4.4 shows the trend of increase in strength with varying percentages of steel fibers in Mix 3.

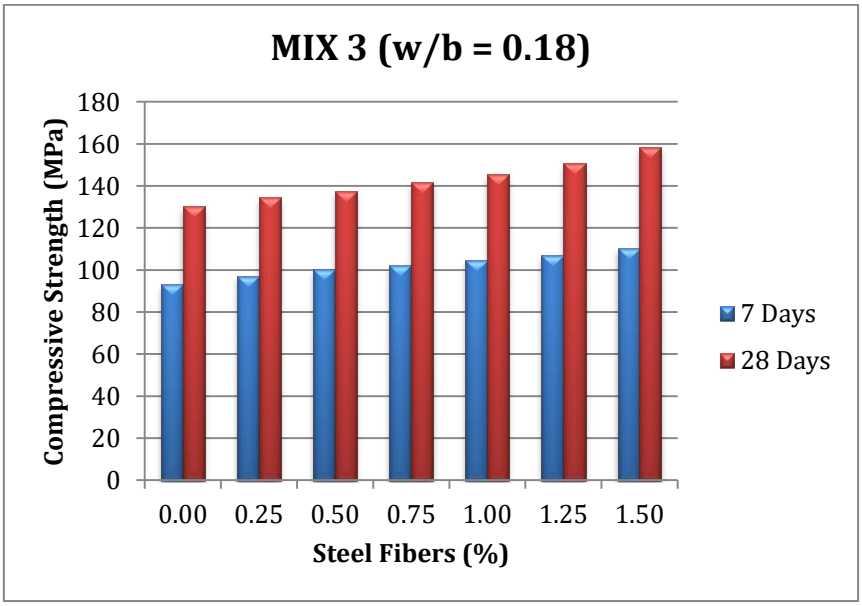

Fig 4.4: Variation of compressive strength for Mix 3 with w/b = 0.18

From the above recorded values it can be seen that for Mix 3 with w/b = 0.18, without the addition of steel fibers the mix was able to achieve strength of 130.2 MPa after 28 days of curing. It can also be seen from the trend of values that a marginal increase in the percentage of fibers does not increase in the percentage of fibers does not lead to a significant increase in strength at both 7 and 28 days. However, a higher percentage increase in strength is observed at 28 days curing period. With the addition of 0.25% steel fibers the strength of the mix increased

to 134.6 MPa after 28 days of curing. With further increasing the percentage of steel fibers gradually to the mix, the strength increased gradually. It can also be seen that at 7 days of curing with the addition of steel fibers the mix was to able achieve a strength of above 90 MPa. Thus, it can be said that with the increase in percentage of steel fibers the compressive strength also increased indicating that the micro cracks developed in the mix were prevented. Since the requirement for UHPC need the compressive strength to be in the range of 120 to 150 MPa, all the mixes with or without of steel fibers were able to achieve that range after 28 days of curing. This indicates that for the development of UHPC, a high percentage of steel fibers are necessary along with the optimum percentage of nano silica, silica fume and GGBS at the w/b ratio of 0.18.

Thus, it can be concluded that it is possible to produce mixes with a compressive strength of over 120 MPa, at 28 days of curing without steel fibers at w/b ratio = 0.18. When the 1.25 and 1.50% of steel fiber were added to the mix the compressive strength achieved was beyond 150 MPa with a judicious mix of 2% nano silica, 8% silica fume and 10% GGBS as supplementary cementious materials.

4.4.3 Effect variation in percentage of steel fibers on compressive strength of concrete for trial 2

The control mix **M4**, a w/b ratio as 0.22 (containing 8% silica fume, 2% nano silica, and 20% GGBS) is observed to have a compressive strength of 69.2 MPa and 97.6 MPa respectively after 7 and 28 days curing. For the same mix when 0.25% steel fiber are added to the mix, the 7 and 28 days compressive strength was recorded as 70.8 MPa and 99.8 MPa, respectively inducating a small increase in strength. Subsequently, when the percentage of steel fiber was increased to 0.50% the compressive strength was recorded as 71.2 MPa and 102.6 MPa for 7 and 28 days, respectively again a marginal increase in strength. When percentage of steel fiber was increased to 0.75% the compressive strength for 7 days and 28 days was 73.4 MPa and 104.7 MPa, respectively. Further when percentage of steel fiber was increased to 1.00% the compressive strength after 7 days and 28 days was recorded as 75.5 MPa and 107.6 MPa respectively. However, when percentage of steel fiber was increased to 1.25% the compressive strength for 7 days and 28 days was observed as 77.2 MPa and 110.2 MPa. Lastly, when percentage of steel fiber was increased to 1.50% the compressive strength at 7 days and 28 days was found to be 78.8 MPa and 116.6 MPa. Fig 4.5 shows the trend of increase in strength with varying percentages of steel fibers in Mix 4.

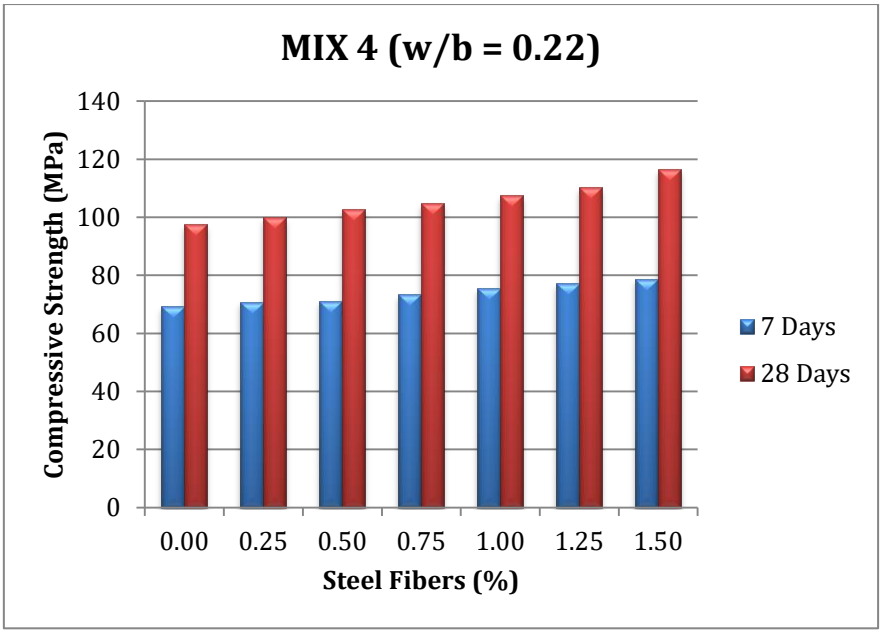

Fig 4.5: Variation of compressive strength for Mix 4 with w/b = 0.22

From the above recorded values it can be seen that for Mix 4 with w/b = 0.22, without the addition of steel fibers the mix was able to achieve strength merely at 100 MPa after 28 days of curing. It can also be seen from the trend of values that a marginal increase in the percentage of fibers does not increase in the percentage of fibers does not lead to a significant increase in strength at both 7 and 28 days. However, a higher percentage increase in strength is observed at 28 days curing period. With the addition of 0.25% steel fibers the strength of the mix increased to 99.8 MPa after 28 days of curing. With further increasing the percentage of steel fibers gradually to the mix, the strength increased gradually. It can also be seen that at 7 days of curing with the addition of steel fibers the mix was to able achieve a strength of above 70 MPa. Thus, it can be said that with the increase in percentage of steel fibers the compressive strength also increased indicating that the micro cracks developed in the mix were prevented. Since the requirement for UHPC need the compressive strength to be in the range of 120 to 150 MPa, no mix could achieve that range after 28 days of curing. This indicates that for higher replacement of cement the development of UHPC is tough, even at high percentage of steel fibers at the w/b ratio of 0.22.

Thus, it can be concluded that with higher percentage replacement of cement, to reduce the effective cost the current mix was only able to achieve compressive strength as high as 115 MPa with a judicious mix of 2% nano silica, 8% silica fume and 20% GGBS as supplementary cementious materials.

The control mix **M5**, a w/b ratio as 0.20 (containing 8% silica fume, 2% nano silica, and 20% GGBS) is observed to have a compressive strength of 77.3 MPa and 104.3 MPa respectively after 7 and 28 days curing. For the same mix when 0.25% steel fiber are added to the mix, the 7 and 28 days compressive strength was recorded as 79.3 MPa and 108.3 MPa, respectively inducating a small increase in strength. Subsequently, when the percentage of steel fiber was increased to 0.50% the compressive strength was recorded as 82.5 MPa and 114.6 MPa for 7 and 28 days, respectively again a marginal increase in strength. When percentage of steel fiber was increased to 0.75% the compressive strength for 7 days and 28 days was 84.2 MPa and 120.3 MPa, respectively. Further when percentage of steel fiber was increased to 1.00% the compressive strength after 7 days and 28 days was recorded as 85.6 MPa and 121.2 MPa respectively. However, when percentage of steel fiber was increased to 1.25% the compressive strength for 7 days and 28 days was observed as 88.3 MPa and 126.3 MPa. Lastly, when percentage of steel fiber was increased to 1.50% the compressive strength at 7 days and 28 days was found to be 92.3 MPa and 130.2 MPa. Fig 4.6 shows the trend of increase in strength with varying percentages of steel fibers in Mix 5.

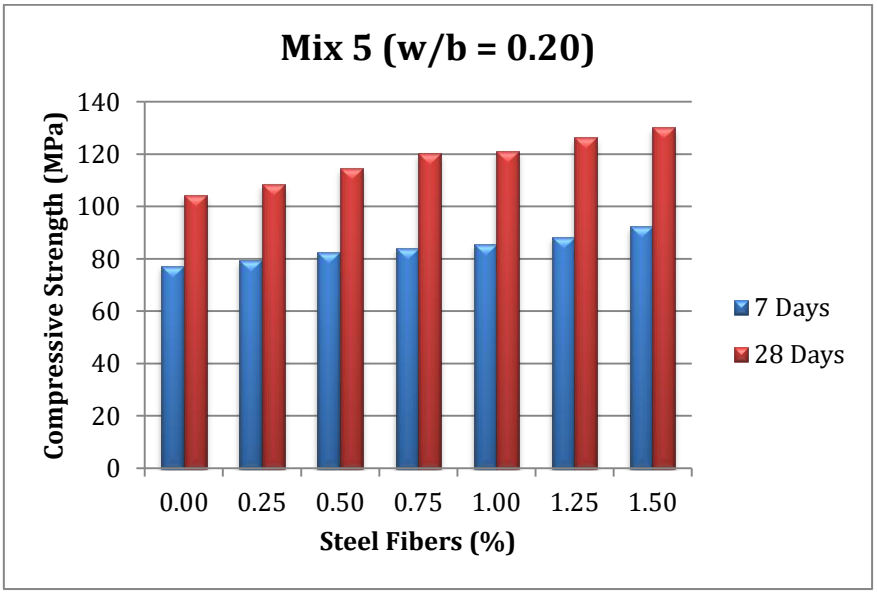

Fig 4.6: Variation of compressive strength for Mix 5 with w/b = 0.20

From the above recorded values it can be seen that for Mix 5 with w/b = 0.20, without the addition of steel fibers the mix was able to achieve strength of 104.3 MPa after 28 days of curing. It can also be seen from the trend of values that a marginal increase in the percentage of fibers does not increase in the percentage of fibers does not lead to a significant increase in strength at both 7 and 28 days. However, a higher percentage increase in strength is observed at 28 days curing period. With the addition of 0.25% steel fibers the strength of the mix increased

to 108.3 MPa after 28 days of curing. With further increasing the percentage of steel fibers gradually to the mix, the strength increased gradually. It can also be seen that at 7 days of curing with the addition of steel fibers the mix was to able achieve a strength of above 75 MPa. Thus, it can be said that with the increase in percentage of steel fibers the compressive strength also increased indicating that the micro cracks developed in the mix were prevented. Since the requirement for UHPC need the compressive strength to be in the range of 120 to 150 MPa, only mix having a percentage of steel fibers between 0.75 and 1.50% could achieve that range after 28 days of curing. This indicates that for the development of UHPC, a high percentage of steel fibers are necessary along with the optimum percentage of nano silica, silica fume and GGBS at the w/b ratio of 0.20.

Thus, it can be concluded that it is possible to produce mixes with a compressive strength of over 120 MPa, at 28 days of curing, with w/b ratio of 0.20 having steel fibers in the range of 0.75 to 1.50%, with a judicious mix of 2% nano silica, 8% silica fume and 20% GGBS as supplementary cementious materials.

The control mix **M6**, a w/b ratio as 0.18 (containing 8% silica fume, 2% nano silica, and 20% GGBS) is observed to have a compressive strength of 90.2 MPa and 128.6 MPa respectively after 7 and 28 days curing. For the same mix when 0.25% steel fiber are added to the mix, the 7 and 28 days compressive strength was recorded as 93.7 MPa and 130.5 MPa, respectively inducating a small increase in strength. Subsequently, when the percentage of steel fiber was increased to 0.50% the compressive strength was recorded as 94.8 MPa and 136.6 MPa for 7 and 28 days, respectively again a marginal increase in strength. When percentage of steel fiber was increased to 0.75% the compressive strength for 7 days and 28 days was 95.6 MPa and 137.2 MPa, respectively. Further when percentage of steel fiber was increased to 1.00% the compressive strength after 7 days and 28 days was recorded as 100.8 MPa and 140.9 MPa respectively. However, when percentage of steel fiber was increased to 1.25% the compressive strength for 7 days and 28 days was observed as 102.4 MPa and 141.8 MPa. Lastly, when percentage of steel fiber was increased to 1.50% the compressive strength at 7 days and 28 days was found to be 105.6 MPa and 146.5 MPa. Fig 4.7 shows the trend of increase in strength with varying percentages of steel fibers in Mix 6.

From the above recorded values it can be seen that for Mix 6 with w/b = 0.18, without the addition of steel fibers the mix was able to achieve strength of 128.6 MPa after 28 days of curing. It can also be seen from the trend of values that a marginal increase in the percentage of fibers does not increase in the percentage of fibers does not lead to a significant increase in strength at both 7 and 28 days. However, a higher percentage increase in strength is observed at

28 days curing period. With the addition of 0.25% steel fibers the strength of the mix increased to 130.5 MPa after 28 days of curing. With further increasing the percentage of steel fibers gradually to the mix, the strength increased gradually. It can also be seen that at 7 days of curing with the addition of steel fibers the mix was to able achieve a strength of above 90 MPa. Thus, it can be said that with the increase in percentage of steel fibers the compressive strength also increased indicating that the micro cracks developed in the mix were prevented. Since the requirement for UHPC need the compressive strength to be in the range of 120 to 150 MPa, all the mixes with or without of steel fibers were able to achieve that range after 28 days of curing. This indicates that for the development of UHPC, a high percentage of steel fibers are necessary along with the optimum percentage of nano silica, silica fume and GGBS at the w/b ratio of 0.18.

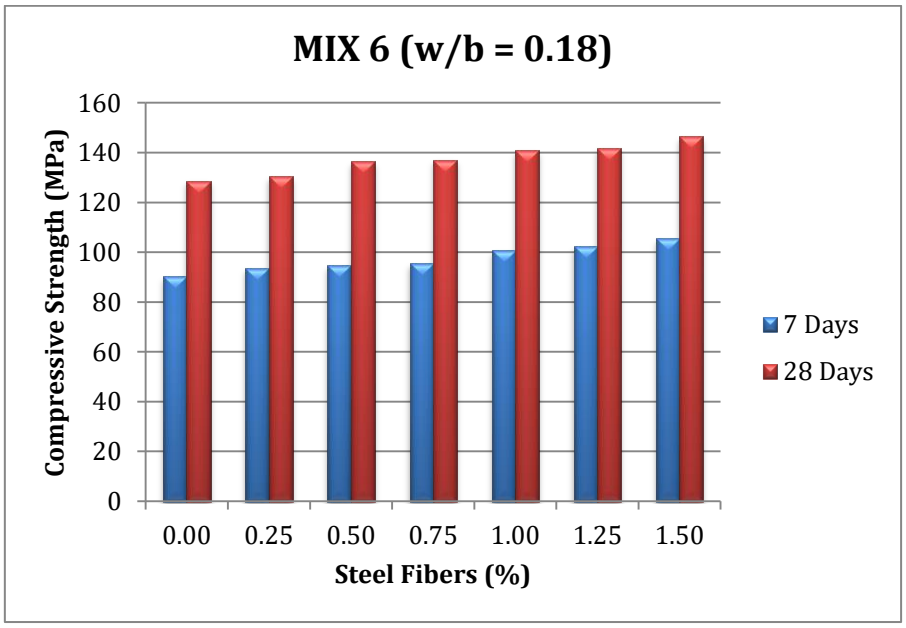

Fig 4.7: Variation of compressive strength for Mix 6 with w/b = 0.18

Thus, it can be concluded that it is possible to produce mixes with a compressive strength of over 120 MPa, at 28 days without of steel fibers. Though increasing the percentage of steel fiber gave more strength with a judicious mix of 2% nano silica, 8% silica fume and 20% GGBS as supplementary cementious materials.

4.4.3 Effect of w/b ratio on compressive strength of different mixes

Figs. 4.8 and 4.9 show the variation of compressive strength with steel fibers for the three water-binder ratio for all the mixes at curing ages of 7 and 28 days, respectively.

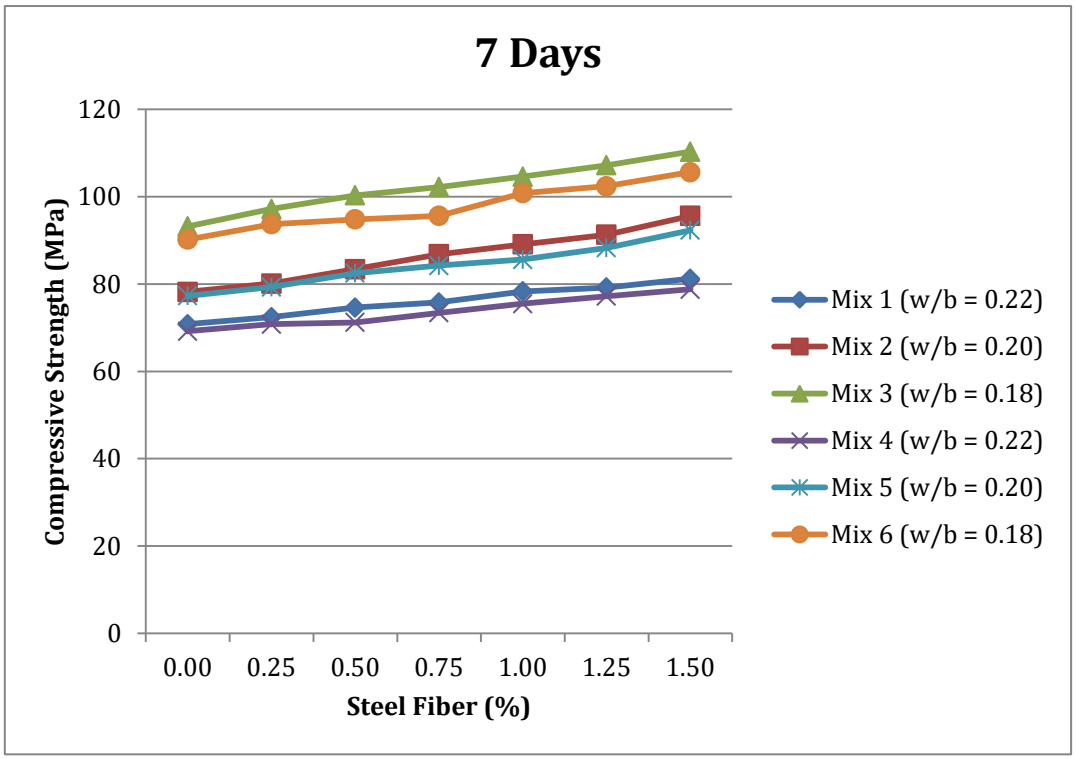

Fig 4.8 (a): Variation of compressive strength for all mixes at 7 days

From the above graph it can be observed that the maximum compressive strength at 7 days is for the mix 3 which contained 2% nano silica, 8% silica fume and 10% GGBS with w/b ratio of 0.18. It is closely followed by mix 6 having the same w/b ratio with higher percentage of replacement of cement. The lowest 7 days strengths were obtained of the mix 4 which had higher percentage of cement replacement.

Although all the mixes with the same w/b ratios followed closely to each other but when the mix having the same proportion of cement replacement are compared it can be seen that for all the percentages of steel fibers there is 10 - 15% increase in strength with the decrease in w/b ratio.

This clearly shows that water reduction and the addition of steel fibers plays a significant role in development of UHPC.

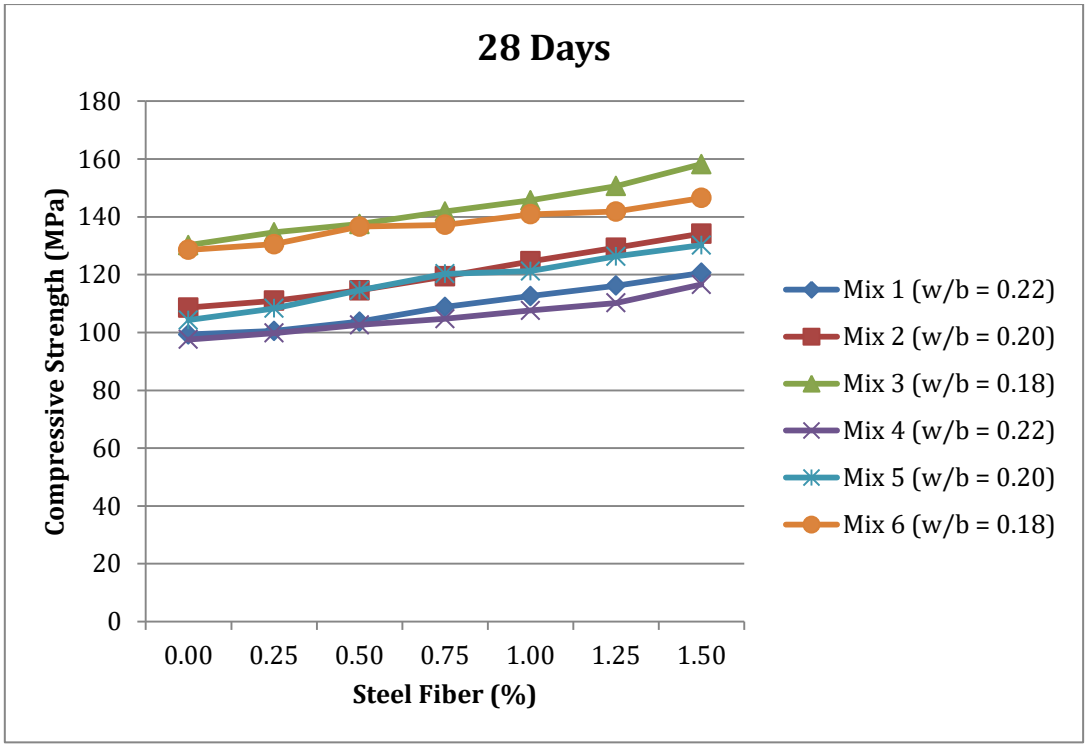

Fig 4.9 (b): Variation of compressive strength for all mixes at 28 days

From the above graph it can be observed that the maximum compressive strength at 28 days is for the mix 3 which contained 2% nano silica, 8% silica fume and 10% GGBS with w/b ratio of 0.18, following the same trend as of 7 days. It is closely followed by mix 6 having the same w/b ratio with higher percentage of replacement of cement. The lowest 28 days strengths were obtained of the mix 4 which again had higher percentage of cement replacement.

Although all the mix with the same w/b ratios followed closely to each other but when the mix having the same proportion of cement replacement are compared it can be seen that for all the percentages of steel fibers there is 10 - 15% increase in strength with the decrease in w/b ratio.

This clearly shows that water reduction and the addition of steel fibers plays a significant role in development of UHPC. It also can be seen that UHPC range can be achieved at a lower cost by replacing higher percentage of cement (Mix 6), but for a concrete mix with optimized proportions of supplementary cementitious materials (Mix 3) the strength can reach beyond 150MPa.

4.4.4 Ultra High Performance Concrete Mixes

All the mixes with more than 120 MPa strength at 28 days curing are shown in Fig. 4.9 (a) and (b) and more than 150 MPa strength are shown in Fig 4.10.

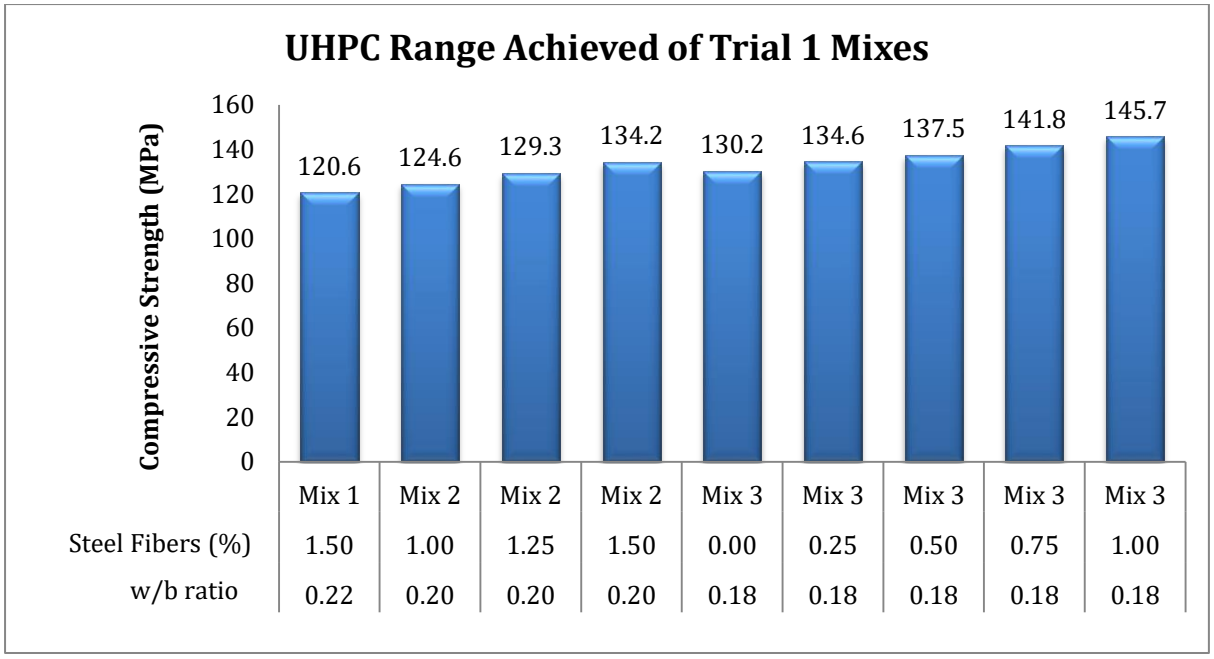

Fig. 4.9 (a): Ultra High Performance Concrete range achieved for Trial 1 Mix

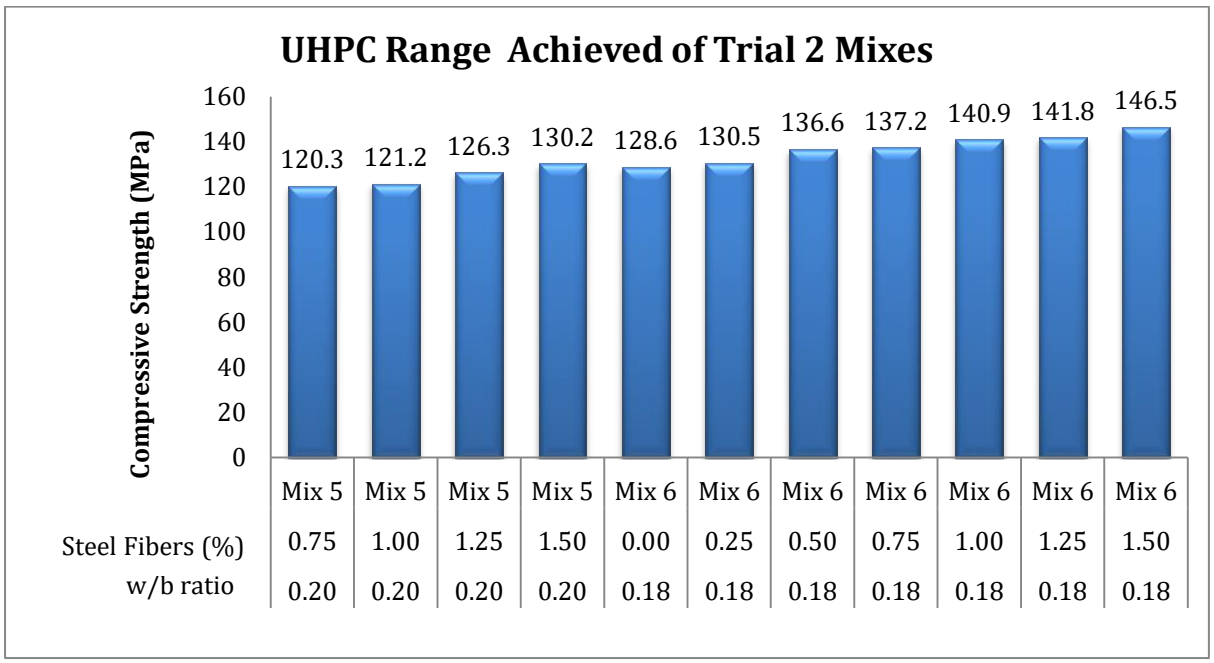

Fig. 4.9 (b): Ultra High Performance Concrete range achieved for Trial 2 Mix

Thus it can be seen from the Figs. 4.9 (a) and (b) that out of a total of 42 mixes tested for strength requirements of Ultra High Performance Concrete only 22 could achieve the desired result. Also Fig 4.10 shows that out of total 42 mixes tested only 2 could achieve compressive strength beyond 150 MPa.

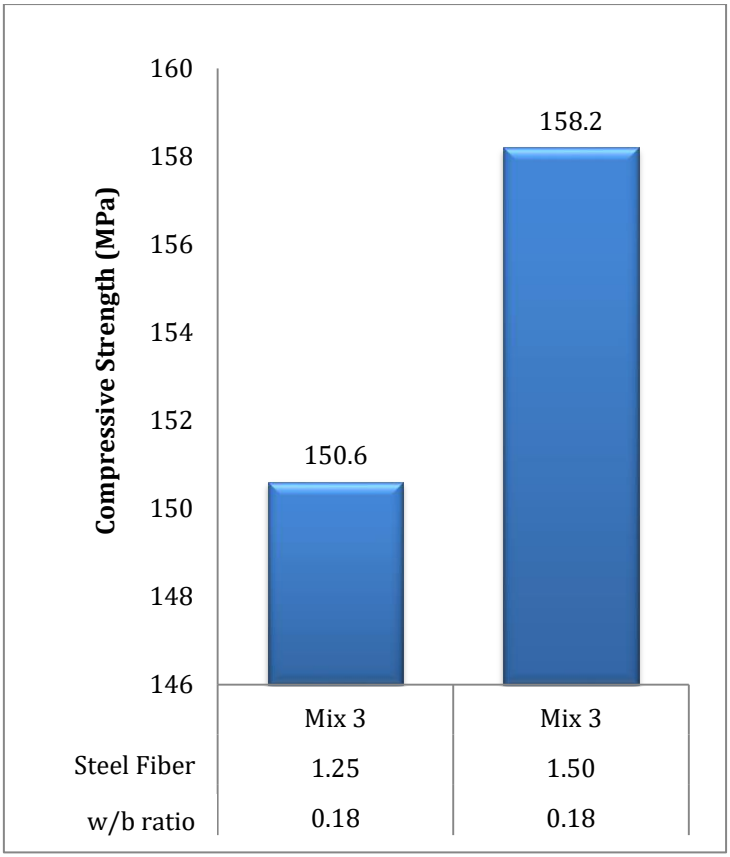

Fig 4.10: UHPC range beyond 150 MPa

CHAPTER 5:
CONCLUSIONS

5.1 GENERAL

The present study was undertaken to develop Ultra High Performance Fiber Reinforced Concrete and to investigate the compressive strength of concrete specimens with the addition of different percentages of steel fibers and by replacing cement partially with silica fume, nano silica and GGBS in concrete mix. **Table 5.1** shows the percentage of cement replaced and steel fibers added to the mix.

Table 5.1 Percentage of ingredients in various trial mixes

Trial Mix	**1**	**2**
Silica Fume (%)	8	8
Nano Silica (%)	2	2
GGBS (%)	10	20
Steel Fibres (%)	0.00	0.00
	0.25	0.25
	0.50	0.50
	0.75	0.75
	1.00	1.00
	1.25	1.25
	1.50	1.50

5.2 COMPRESSIVE STRENGTH

The compressive strength test was performed after 7 and 28 days of curing of concrete specimens. Three different w/b ratios of 0.22, 0.20 and 0.18 were used. Superplasticizer was used in all the 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 superplasticizer only. Based upon the results discussed in the previous chapter, following are the major conclusions which can be drawn from the study:

- The supplementary cementitious materials like silica fume, nanosilica and GGBS play a significant role in strength development of the concrete mixes.
- With the addition of steel fibers to the mix a significant increase of 5 to 25% in strength development can be achieved.
- The reduction in w/b ratio considerably increases the strength of the mix by 10 to 30%
- It is possible to produce mixes with a compressive strength of over 100 MPa, after 28 days curing, with maximum w/b ratio of 0.22, with the addition of steel fibers and optimized mix containing nano silica, silica fume and GGBS as supplementary cementitious materials.
- With higher percentage of replacement of cement the strength was nearly equal to the mix containing higher amount of cement.
- The addition of 1.5% steel fibers tends to give better strength results as they provide more pinching force to the micro cracks developed within the concrete.
- It is possible to produce UHPC with compressive strength higher than 120 MPa, for mixes with w/b ratio of 0.18 with or without steel fibers and having 2% nano silica, 8% silica fume, and either 10% or 20% GGBS.
- 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.
- For a w/b ratio of 0.22 only mix M1 could achieve more than 120 MPa strength having 1.5% steel fibers in the mix.
- It possible to produce mixes with a compressive strength of 150 MPa at 28 days with a w/b ratio of 0.18, by using 2% nano silica, 8% silica fume, and 10% GGBS as supplementary cementitious materials with addition of 1.5 % steel fibers.

5.3 SCOPE FOR FURTHER WORK

- Work can be extended to study different properties like flexural strength, ductility, durability of UHPFRC.
- Work can be extended to study the effect of different types of steel fibers on strength properties.

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