"DEVELOPMENT OF ULTRA HIGH PERFORMANCE CONCRETE USING SILICA FUME, NANO SILICA AND SLAG"

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DECLARATION

The author hereby declares that this thesis entitled "**Development of Ultra High Performance Concrete using Silica Fume, Nanosilica and Slag**", 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 authors own work. The author conforms that the library may lend or 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 Ultra High Performance Concrete using Silica Fume, Nanosilica and Slag**" submitted by **Mr. Sahil Saini** in partial fulfillment of the requirements for the award of degree of **Master of Engineering** in Structural Engineering at **Thapar University, Patiala**, is a bonafide work carried out by the student under our supervision and guidance. The matter embodied in this report has not been submitted anywhere for award of any other degree.

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ABSTRACT

There is a growing interest in the development of new concrete type, due to its high performance, durability, better serviceability and overall economy in the long run.

Ultra High Performance Concrete (UHPC) refers to the materials with a cement matrix and a characteristic compressive strength in excess of 150 MPa. Along with this, UHPC is durable material that provides long service life to the structures constructed or rehabilitated with UHPC.

The present study aims at, developing the concrete mixture incorporating silica fume, nano silica and slag as partial replacement of cement. The aim is to develop the ultra high performance concrete that can provide enhanced mechanical properties of concrete. In this study, the compressive strength and split tensile strength of UHPC concrete mixtures for different percentage of replacement of cement with silica fume, nano silica and slag are reported. It is found out that the maximum increase in compressive strength and split tensile strength is for concrete mix in which 8% silica fume, 2% nano silica and 10% slag is replaced with cement. Also, the effect of water to binder ratio on strength characteristics of UHPC is investigated.

Because of these outstanding properties, UHPC offers new possibilities of lighter and larger structures, hybrid structures, new design and new products with a potential for a better economy and resource consumption than with traditional concrete, steel and other building materials.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Concrete is a widely used construction material in the construction industry worldwide. The use of cementitious material can be traced back thousands of years ago to Italy, Greece, ancient Egypt and the Middle East. Portland cement, an important ingredient in modern concrete was first used in 1824 by Joseph Aspdin in England; however, the production of Portland cement in the modern sense began about 20 years later initiated by Isaac C. Johnson. Since ancient time, mankind has been searching for construction materials with higher and higher performance to build taller, longer and sounder structures. As construction materials cost escalates, demand has risen significantly for stronger and durable materials. This resulted in development, in the mid 60's, of concrete with strength ranging from 40 to 80 MPa, 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. 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. In the early 1970s, 62 MPa concrete was being produced and 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 used for many applications and are more popularly known as Ultra High Performance Concrete (UHPC). These concretes improve upon the advantages of HPC and present 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 Concrete (UHPC) is a new class of concrete technology. When compared with High Performance Concrete (HPC), UHPC tends to exhibit superior properties such as advanced strength, durability, and long-term stability. UHPC is generally made using fine, coarse aggregates, very low amounts of water and high amounts of cement. 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 mechanical performance, durability and ductility behavior of UHPC differs scientifically from normal and high strength concretes due to the high-packing density of these materials. The 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. *[Graybeal et al. (2003)]*

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

Development of UHPC requires utilization of OPC of optimum quality from both workability as well as strength point of view. Variation in cement will cause the compressive strength to fluctuate more than any other single material. Following physical properties are 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

The supplementary cementitious materials other than OPC mainly consists of silica fume, slag etc. which are generally considered in the development of UHPC due to higher requirements of cementitious material content and low w/b ratio for producing high strength concrete. 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-Binder ratio

The acceptability of water for UHPC is not a major problem if potable type water is used. The evolution of UHPC requires a very low w/b ratio i.e. in the range of 0.15-0.30. Basically, the workability of concrete is controlled by use of superplasticiser in it. For production of UHPC in the laboratory, in the present study three water-cement ratios of 0.22, 0.24 and 0.26 have been considered. There is a diverse established effect of w/b ratio on the strength properties of concrete. The strength of concrete increases if we decrease the w/b ratio.

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 given at the time of selection of 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/b ratio. For a given w/b 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/b 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"**.** *[Karmout, 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 generally be classified into two categories of chemical and mineral admixtures. The same are discussed as below, with regards to their use in production of UHPC.

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

- suitable for high performance concrete
- produce pump able concrete
- increase workability without adding extra water
- improved cohesion, minimizing segregation and give better finish.
- chloride free, safe for use in pre-stressed and reinforced concrete
- can be used with concrete containing micro-silica and other cement replacements.
- 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/B ratio and other mix parameters
- Improved quality - Denser, close textured concrete with reduced porosity and hence enhanced durability. Reduction in W/B 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 reduce the cost, reduce permeability, increase strength and change other concrete properties. The three main mineral admixtures that are frequently used are listed below:

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

In the present study as silica fume and GGBS along with nanosilica have been used for development of UHPC, there significance is provided as below:

Silica Fume: A *"Very 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". (ACI 116R-90 cement and concrete technology).* Silica fume, also known as microsilica, is a byproduct of the reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys.

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 fume was 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 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

Electric arc furnaces used in the manufacture of ferrosilicon or silicon metal release silica fume as a byproduct. The fume, which has a high content of very fine spherical particles of silicon dioxide, is collected by filtering the gases escaping from the furnaces, as shown in the fig 1.1.

DESIRED REACTION: $SiO_2 + 2C = Si + 2CO$

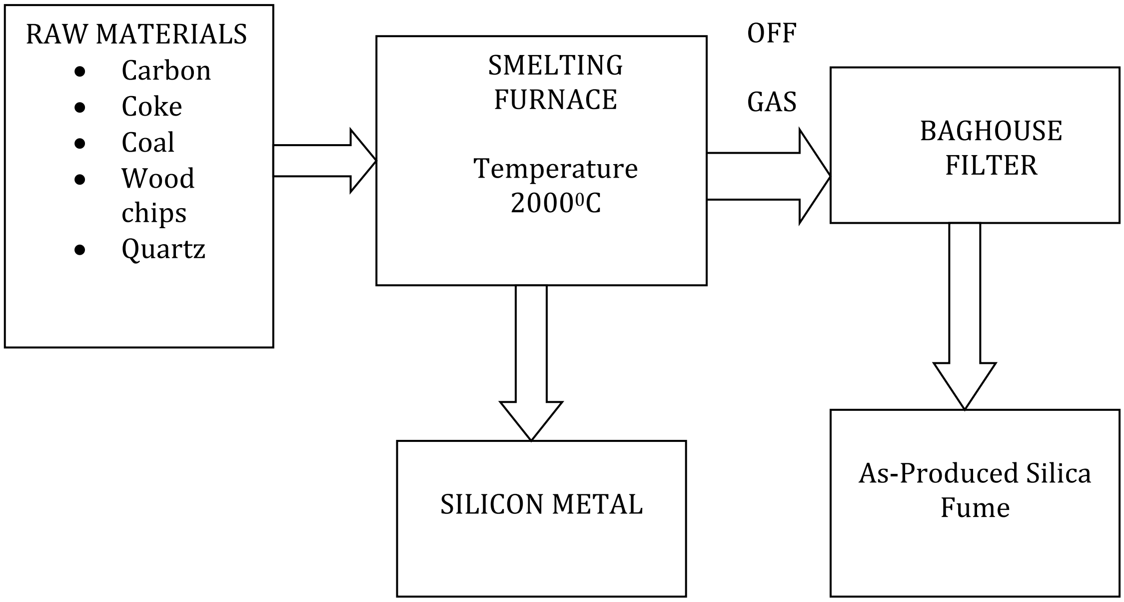


Fig 1.1 Silica fume production

Figure 1.2, 1.3 and 1.4 show 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.

Fig 1.2 Coal and Quartz

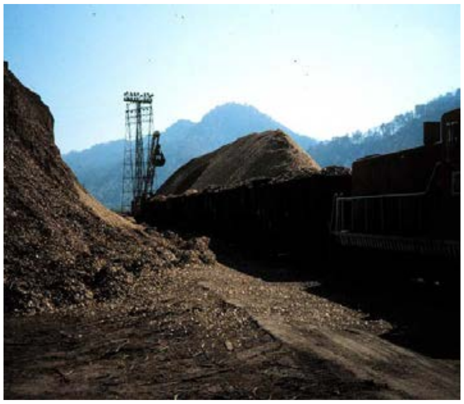


Fig 1.3 Wood chips

Fig. 1.4 Quartz aggregates used as a source of silicon.

Fig 1.5 Charging deck of the furnace

The charging deck of the furnace is shown in figure 1.5. 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^{0}C. 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 1.6 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 figure 1.6 where the fume is captured.

Ground Granulated Blast Furnace Slag (GGBS): *"The 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". (The American Society for Testing and Materials, ASTM, C989-99)*

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.

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.

1.4 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

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**:**

1.5.1 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 Fig. 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 Fig. 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.

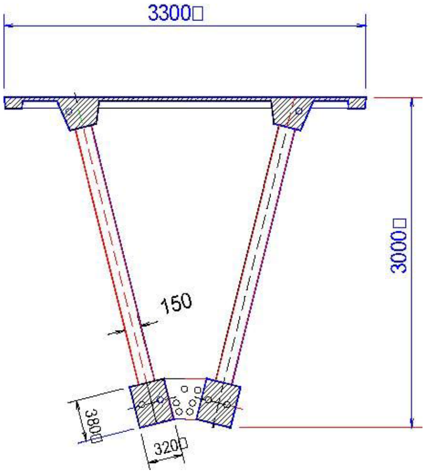


Fig.1.7 (a) Sherbrooke footbridge **Fig. 1.7 (b) Cross section**

[*Karmout, M.; (2009)****]***

1.5.2 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

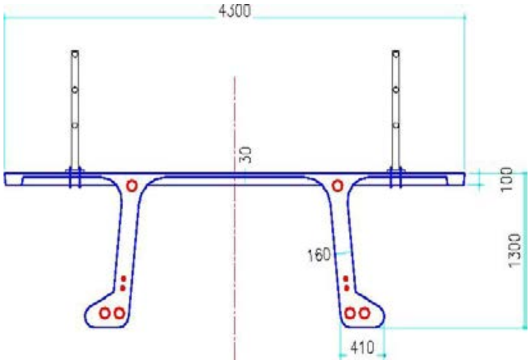


Fig 1.8 (a) General view of Seoul footbridge **Fig. 1.8 (b) Cross-section**

[*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, as shown in Figure below:

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/b 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 U.S. 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 OBJECTIVE OF THE PROPOSED WORK

The main objective of the proposed work is to study as to how by using mineral admixtures like silica fume, nanosilica and alccofine (GGBS) in varying proportions, UHPC can be developed. The target is produce concretes with strengths in excess of 100 to 105 MPa after 28 days of curing. The ultimate aim would be to find out the optimum percentages of the ingredients in order to produce the Ultra High Performance Concrete having a compressive strength in the range of 100 – 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. *[Karmout, 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 VHPC. The compressive and flexural strengths of VHPC 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 VHPC 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.

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	0.16	1:0:0.2:0.25	170	28.4	178.6
6		1:0:0.3:0.25	185	29.5	198.2
7		1:0:0.4:0.25	200	30.5	193.6
8		1:0:0.6:0.25	165	27.6	190.0
9		1:0:0.3:0.30	180	28.4	207.0
10		1:0:0.4:0.30	190	29.6	200.8
11	0.16	1:0.2:0:0.25	180	24.7	188.2
12		1:0.3:0:0.25	190	28.5	208.4
13		1:0.4:0:0.25	200	30.4	197.8
14		1:0.6:0:0.25	175	30.3	184.0
15		1:0.3:0:0.30	185	31.0	204.8
16		1:0.4:0:0.30	195	29.9	213.2

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. They cast 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.

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

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.

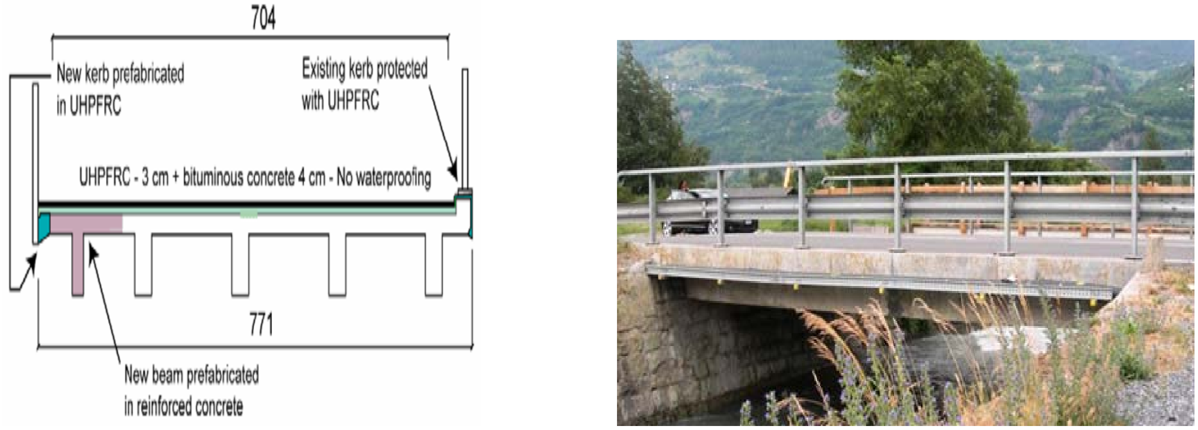


Fig. 2.1 (a): Bridge cross section after rehabilitation *[Bruhwiler et al. (2008)]*

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)).

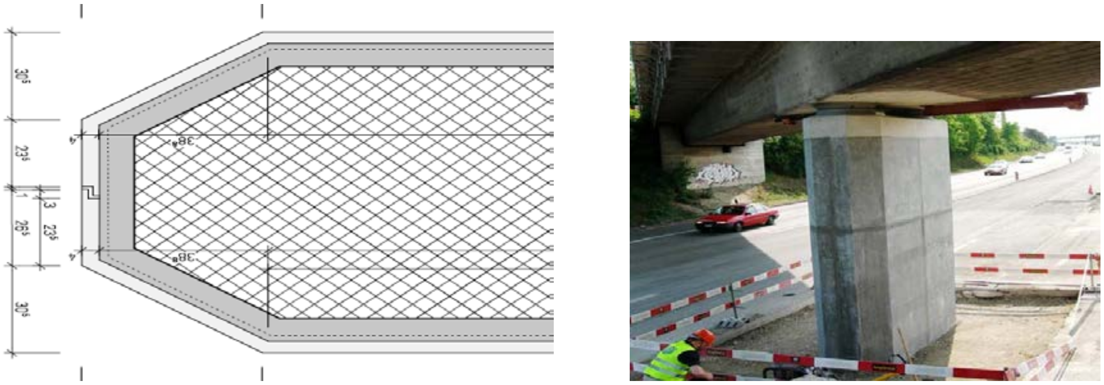


Fig. 2.1 (b) Cross section and general view of the rehabilitated bridge pier *[Brühwiler et al. (2008)]*

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).

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

		Material		
		Cement (52.5N)	*SF*	*GGBS*
Chemical composition (%)	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
Mechanical property of Cement	Age (days)	2	7	28
	Comp. strength (MPa)	37	52	63

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/m^3)	2.652	2.645	2.643	2.678
Bulk density (kg/m^3)	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/m^3)			**Aggregate sand (kg/m^3)**	**Water binder ratio**	**Superplasticizer (% solid by weight of binder)**
Cement	*GGBS*	*SF*			
657	429.8 (35%)	119.4 (10%)	1050	0.15	1.05

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. 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.

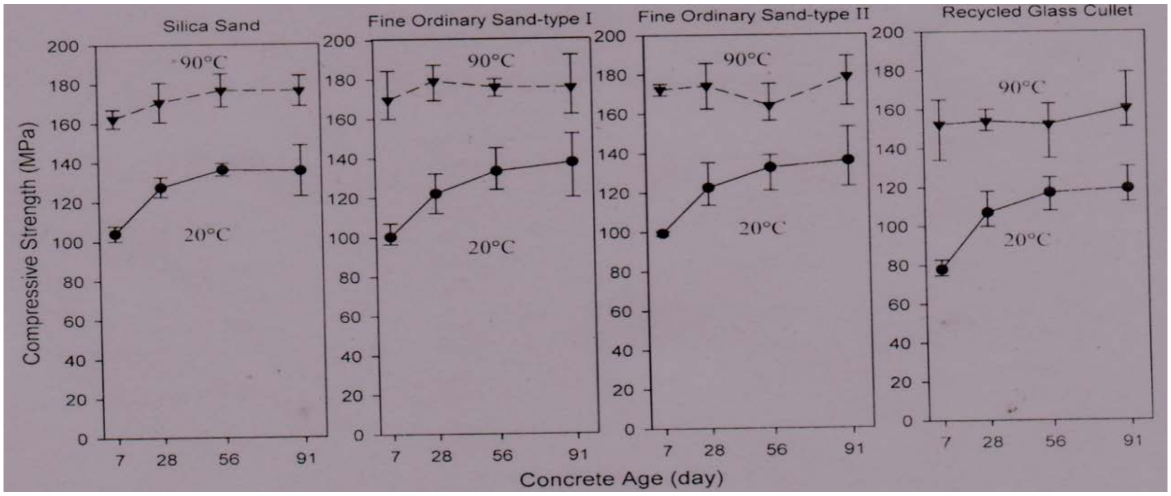


Fig.2.2 Compressive strength versus age of UHPFRC: effect of replacement of sand aggregate with SS, FOS-I, FOS-II and RGC *[Yang et al. (2009)]*

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.

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 2.4 (a).

Table 2.4 (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 2.4 (b), and the experimental results are shown in Fig. 2.3**.** 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.

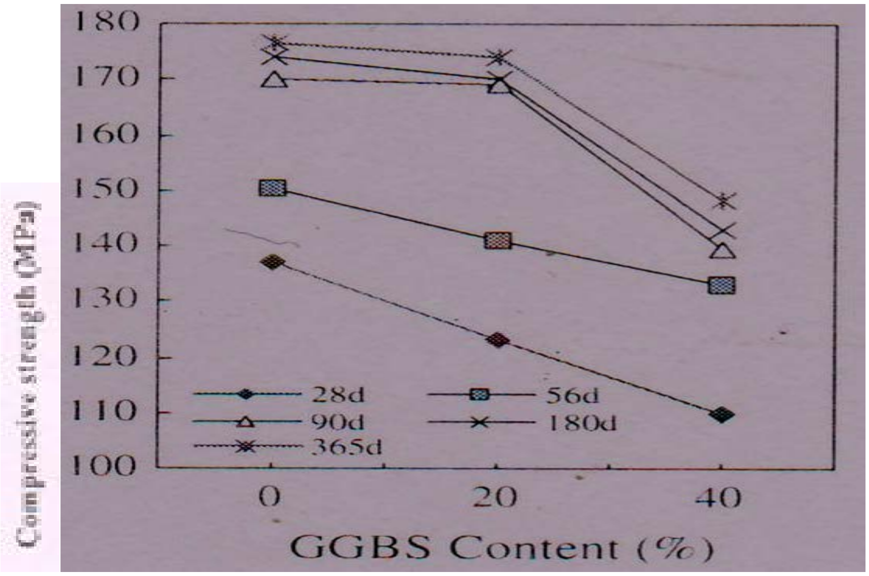


Fig. 2.3 Influence of GGBS content on strength and fluidity of UHPC. ***[Wang et al. (2012)]***

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.

Table 2.4 (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

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 2.5 (a) below. Along with this, two acrylic-based superplasticizers (labeled 'spA' and 'spB') were employed in order to compare their effectiveness for producing UHPFR.

Table 2.5 (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

They prepare Several UHPFRC mixtures by varying the water-cement ratio from 0.20 (RPC-20) to 0.32 (RPC-32) by using an acrylic-based superplasticizer. Also, the materials with a water to cement ratio of 0.24 (RPC-24) and 0.26 (RPC-26) were prepared by alternatively using the two types of acrylic-based superplasticizer i.e. 'spA' and 'spB'. UHPFRC mixture proportions are reported in Table 2.5 (b).

Three prismatic specimens (40×40×160 mm) were manufactured for each mixture and for each curing time in order to evaluate mechanical behavior of the five UHPFRC mixtures Table 2.5 (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. 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. 2.4(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. 2.4 (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 2.5 (b)). Thus, an even higher amount of superplasticizer admixture would be necessary in this case.

Table 2.5 (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

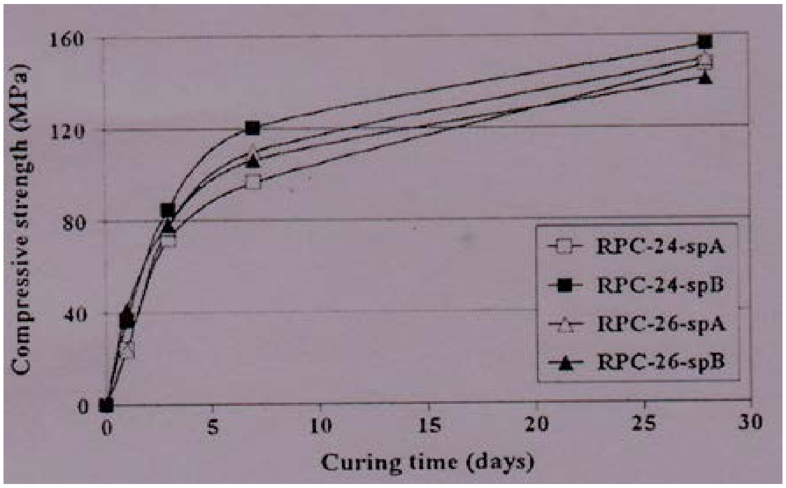


Fig. 2.4 (a) Time evolution of compressive strength for UHPFRCs prepared with w/c of 0.24 and 0.26 by using either 'spA' or 'spB' superplasticizers. ***[Corinaldesi et al. (2012)]***

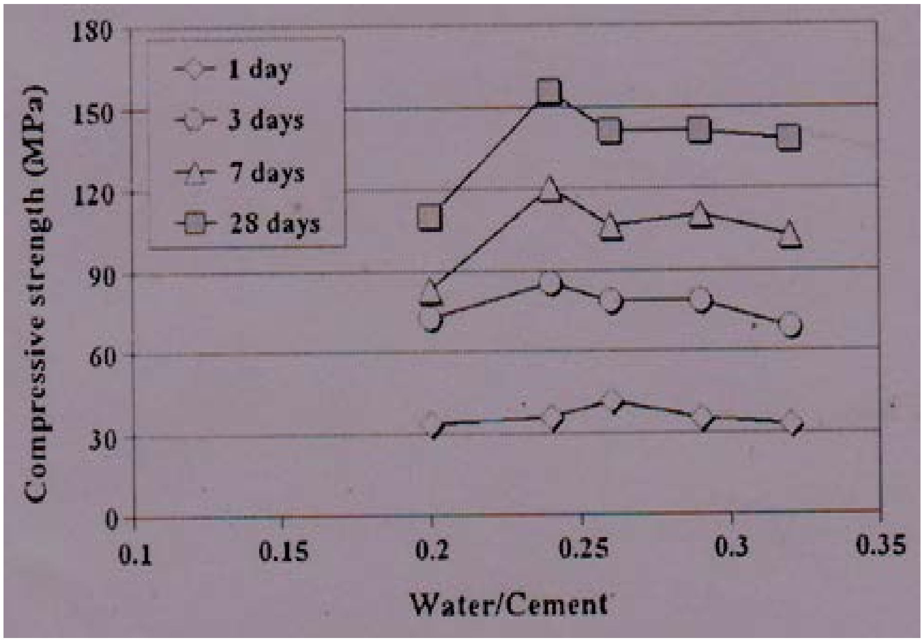


Fig. 2.4 (b) Compressive strength for UHPFRCs prepared by varying the water to cement ratio from 0.20 to 0.32 at different curing times. ***[Corinaldesi et al. (2012)]***

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.

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). 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. 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 2.6.

All materials were prepared in a 20 L Hobart mixer. The volume of each batch was 3.5 Liters. 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).

Table 2.6 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

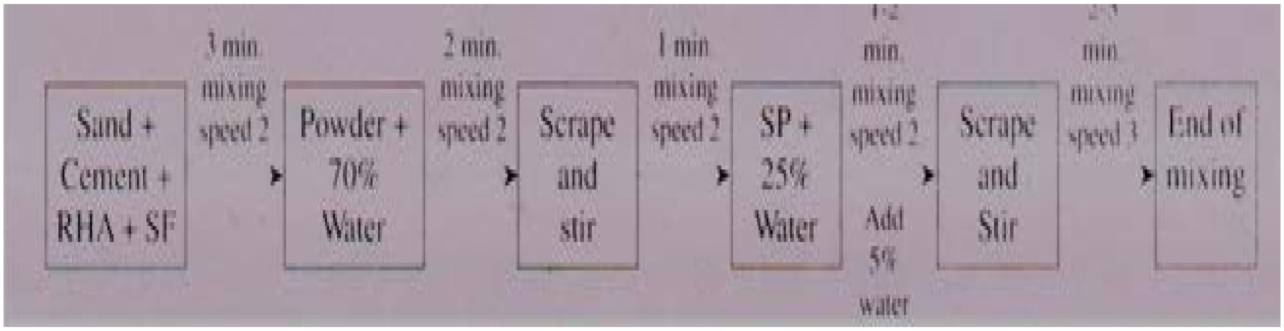


Fig 2.5 (a) Mixing procedure for UHPC. *[Tuan et al. (2011)]*

The Fig. 2.5(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 behavior 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%.

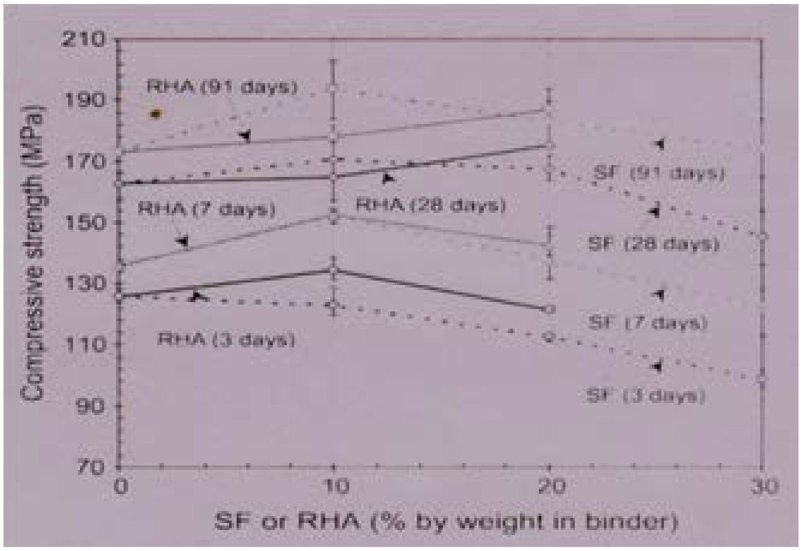


Fig. 2.5 (b) Compressive strength of UHPC samples vs. % SF (dotted line) or % RHA (Solid line), w/b ratio = 0.18, dRHAmean = 5.6 μm. ***[Tuan et al. (2011)]***

2.3 DURABILITY CHARACTERISTICS OF UHPC

Graybeal et al. (2003) studied the durability of UHPC in terms of its resistance to internal and external environmental effects. The researchers conducted chloride ion penetration, abrasion resistance, freeze-thaw, and scaling resistant testing on the specimens to determine the durability of UHPC. Table 2.7(a) shows the typical composition of the ingredients used for making UHPC.

Table 2.7 (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

Rapid chloride ion penetrability test was conducted on UHPC specimens. The electrical current was recorded at 1 minute intervals over the 6 hour timeframe, resulting in the total coulombs passed value as shown in Table 2.7 (b). Two or three specimens were completed for each curing condition and specimens were tested at both 28 and 56 days. The results show that the rapid chloride ion permeability is minimum and decreased significantly between 28 and 56 days for specimens from the Ambient Air curing regime.

Table 2.7 (b) ASTM C1202 Rapid Chloride Ion Penetrability Results: ***[Graybeal et al. (2003)]***

Curing Method	Tests	Age (days)	Avg coulombs passed	Chloride Ion Penetrability
Steam	3	28	18	Negligible
Ambient Air	2	28	360	Very Low
Ambient Air	3	56	76	Negligible
Tempered Steam	3	28	39	Negligible
Tempered Steam	3	56	26	Negligible
Delayed Steam	3	28	18	Negligible

They conducted abrasion resistance test on UHPC in which a rotating abrading wheel bears on and wears away the concrete surface for a period of two minutes. The abrasion testing was performed on three specimens from each of the four curing regimes. Abrasion resistance depends on the surface condition of the concrete thus each specimen was tested on three different surfaces. Following these tests, the cast surface was sandblasted until it displayed a uniform texture. Testing was again repeated for all the specimens to have the test surface ground plane using a cylinder end grinder. They noted that the average weight loss per 2 minute abrading and shows the results in Figure 2.6 (a). The results clearly show that the Ambient Air cured specimens have significantly less abrasion resistance. They also noticed that cast surfaces tend to show more abrasion resistance. This holds true until the surface is broken, after which all equally cured specimens behaved similarly.

They also tested UHPC for freeze-thaw resistance according to ASTM C666. Prisms of 3 in ×4 in × 16 in. were used as specimens in this series of tests. The repeated cycling of specimens between the temperatures of 0° and 40° F. The test was based on the fact that the repeated freezing and thawing will cause microscopic degradation of the concrete resulting in a decreased dynamic modulus of elasticity thus, the cycling was stopped and the dynamic modulus of elasticity of the specimens was measured periodically. Figure 2.6 (b) provides the results from 300 cycles of freeze-thaw testing. The results show that the Steam, Tempered Steam, and Delayed Steam cured specimens all retained dynamic modulus characteristics close to their original characteristics while the Ambient Air cured prisms displayed a continuous increase in dynamic modulus throughout the testing. As every cycle contains a period of time when the prisms are standing in water, it is likely that this water recharge continued the curing process during the months of freeze-thaw testing.

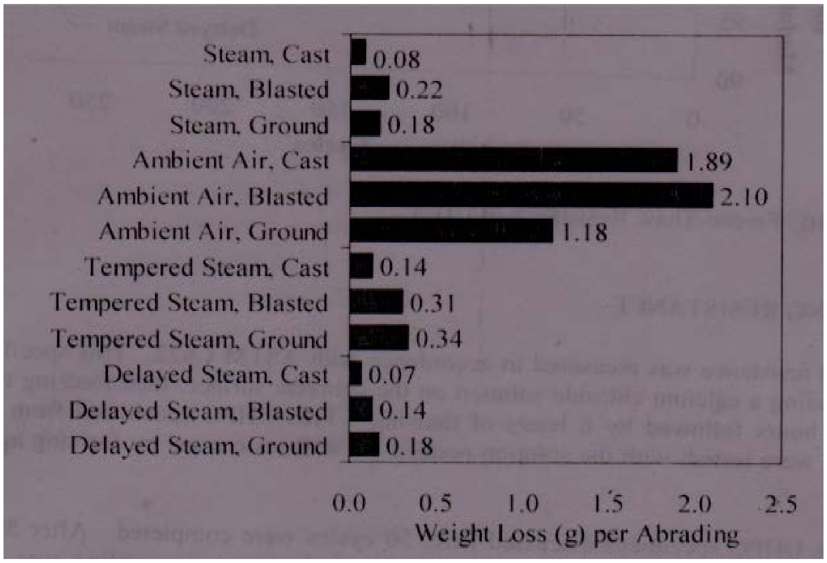


Figure 2.6 (a) ASTM C944 Abrasion Resistance *[Graybeal et al. (2003)]*

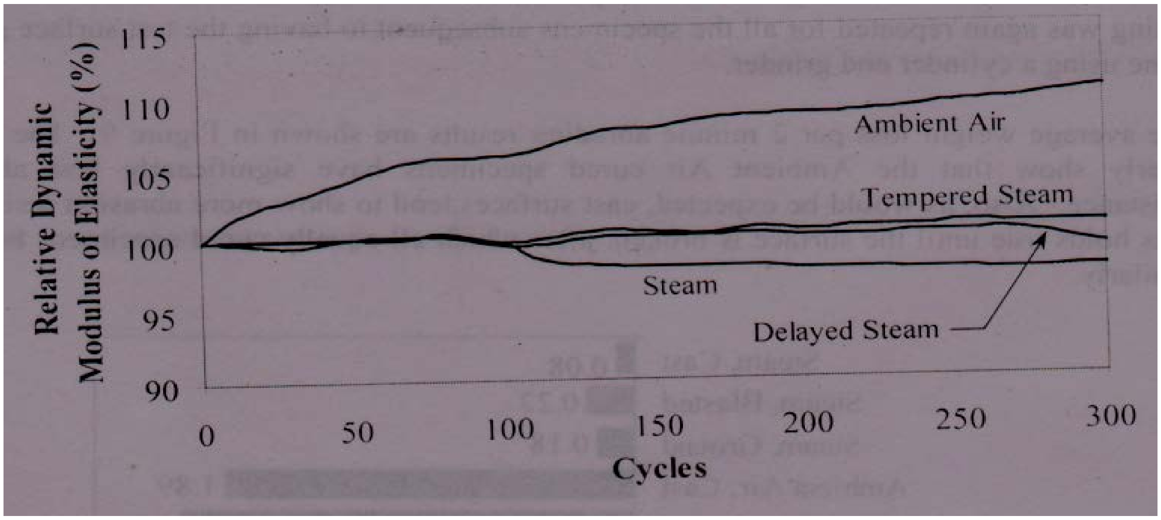


Figure 2.6 (b) Freeze-Thaw Resistance of UHPC: *[Graybeal et al. (2003)]*

They also conducted scaling resistance test in accordance with ASTM C672. In this test, calcium chloride solution was ponded on the concrete surface, and then allowed for freezing the specimen (for 18 hours) followed by thawing (for 6 hours). Two UHPC specimens from each curing regime were tested, with the solution ponded on surfaces created by forming against a steel mold. For the UHPC specimens discussed here, 50 cycles were completed. After 50 cycles, the texture of the test surfaces get altered visually while no scaling was observed on UHPC. At last they concluded that as compared to normal concretes, a steam cured UHPC section should be effectively immune to freeze-thaw, scaling, and chloride ion penetration damage.

Parant et al. (2007) studied and patented a new ultra high performance fibre reinforced cement composite (UHPFRCC) with the introduction of three steel fibre sizes leads to a multiscale fibre reinforced cement composite (MSFRCC). The Multiscale fibre reinforced cement composite mix design (MSFRCC) composition is shown in Table 2.8.

Table 2.8 Composition of MSFRCC *[Parant et al. (2007)]*

Raw materials		Proportioning mixing
OPC	CPA CEM I 52.5 R	1050 kg/m^3
Sand	Quartz 125–400 µm	514 kg/m^3
Silica fume	Zirconium	268 kg/m^3
Superplasticizer	Polyphosphonate - 30%	44 kg/m^3
Total water		211 L
Steel fibre content		858 kg/m^3
Silica fume/cement		0.255
Superplat/binder		1.02%
Sand/cement		0.49
Total water/binder		0.16

They conducted an innovative corrosion test under loading to check the durability of the specimen. Pre-cracked thin slabs were damaged by fatigue under loading corresponding to service load (30 MPa in bending test) then maintained under bending at the same level. A part of these slabs undergoes 30 weekly wetting–drying cycles in a chloride solution (NaCl 5%, 20 °C). A reloading to failure is led. Two series of eleven thin prismatic specimens, with one heat treated were tested. The main results they concluded from the study were that there was no degradation of the MSFRCC mechanical properties due to aggressive environment and if corrosion takes place, it does not affect the fibres, even the smallest ones and the nearest to the cracks. They also noticed that for the specimens that were pre-damaged by fatigue and were stored in chloride solution, the mechanical characteristics do not show any evolution. In both the cases, the autogenous healing does not happen since no sufficient water flow migrates toward micro-cracks was there. At last they concluded that the very fine crack widths created, allowed a fast self-healing of micro-cracks, limiting the influence of the external environment conditions. Thus show that it is a durable material having a long life even when subjected to the severe environmental conditions.

Graybeal et al. (2007) studied the durability of a commercially available UHPC through six standardized durability tests and the results were reported. The typical Composition of UHPC is shown in Table 2.9 below:

Table 2.9 Composition of UHPC: *[Graybeal et al. (2007)]*

Constituent	Amount (kg/m^3)	% by weight
Portland cement	712	28.5
Fine sand	1,020	40.8
Silica fume	231	9.3
Ground quartz	211	8.4
Superplasticizer	30.7	1.2
Accelerator	30	1.2
Steel fibers	156	6.2
Water	109	4.4

They subjected the concrete to four different curing regimes to take off the various potential states of the concrete depending on the consistency and completeness of the curing procedure followed. Those concretes were then subjected to six standardized durability tests. Regardless of the curing treatment applied, UHPC exhibits enhanced durability properties over normal concretes that are being used today. In terms of freeze–thaw degradation resistance, the relative dynamic modulus of this concrete was at least 96% after being subjected to two times the normal number of ASTM C 666 freeze–thaw cycles. The concrete was safe against ASTM C 1260 ASR deterioration, against ASTM C 672 scaling deterioration, and to AASHTO T259 chloride penetration. The ASTM C 1202 Coulomb test result was negligible if any steam based curing treatment was applied, and ranged from very low at 28 days to negligible at 56 days in the absence of any curing treatment. The curing treatment applied to the concrete can affect the durability properties. They noticed that the application of steam cured treatment to the specimen decreases the ability of chloride ions to penetrate into the concrete. Steam-based curing treatments also significantly enhanced the abrasion resistance of the concrete.

Filho et al. (2012) studied the sustainability assessment for an Ultra High Performance Fiber Reinforced Cement Composite (UHPFRCC). The material durability related properties such as capillary water absorption, gas permeability through specimen were measured. The composition of the UHPFRCC is shown in Table 2.10.

Table 2.10 Composition of the UHPFRCC *[Filho et al. (2012)]*

Materials	**Mass unit (kg/m^3)**
Blast furnace slag cement III/40	1011
Sílica fume	58
Sílica flour 325#	79
Aggregates 150–300 lm	60
Aggregates 425–600 lm	823
Micro fibers de wollastonite	76
Steel fibres	158
Plasticizer PA	50
Water	162
Air (%)	3.75

The water/binder ratio of the mixture was kept as 0.17 leading to outstanding performances of the cementitious composite. The capillary water absorption tests was conducted on 4 cylindrical specimens (50×100 mm) which were immersed under water for 36 days and an average water ingress of 0.065 g/mm^2 was observed. Gas permeability test was conducted at specimen with a diameter of 100 mm and a thickness of 10 mm. During the test, no gas flow was observed through the specimen when a maximum pressure of 0.5 MPa allowed to be used in the pressure chamber. Thus, specimens show resistance against gas flow so it is almost impermeable. The last test conducted was the chloride ingress test on cylindrical specimen with a diameter of 100 mm and a thickness of 50 mm imposed to electrical current (60 V) according to the ASTM C 1202. The results showed negligible ingress of chlorides through the specimen. The results showed that the UHPFRCC is an enormously dense material which exhibits almost no permeability and porosity and is durable thus enhancing its service life.

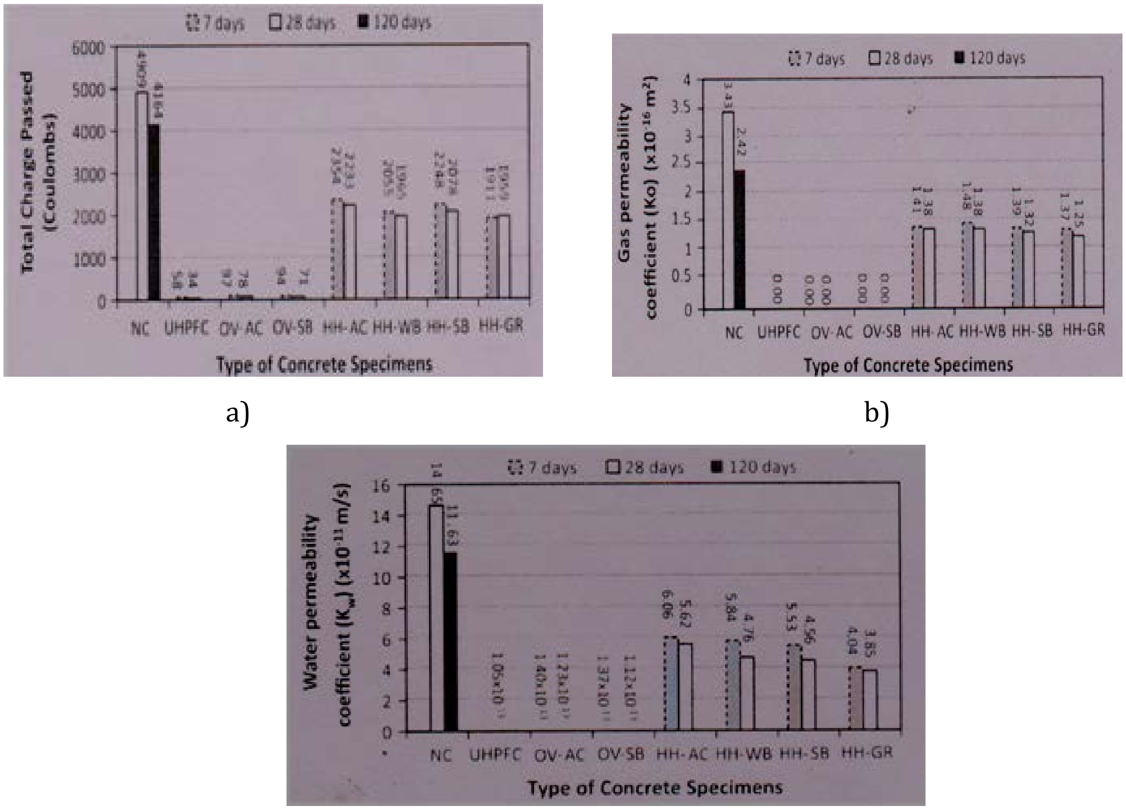
Tayeh et al. (2012) experimentally examined the permeability characteristics of the interface between normal concrete (NC) substrate which represents old concrete structures and an overlay of ultra high performance fiber concrete (UHPFC) as a repair material. The permeability characteristics were evaluated 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 2.11.

Table 2.11 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. 2.7 (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. 2.7 (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. 2.7 (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.



a)

b)

c)

Fig. 2.7 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. 2.7 (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.

CHAPTER 3

MATERIALS AND DESIGN METHODOLOGY

3.1 GENERAL

The present chapter deals with the material properties and the results obtained from the various test conducted on the material used for the development of Ultra High Performance Concrete. In order to achieve the objective of the present study, an experiment was conducted to determine the compressive strength and split tensile strength of concrete specimens made by using silica fume, nano silica and GGBS along with the OPC 53 grade cement and aggregates.

3.2 CHARACTERISTICS OF MATERIALS USED

The properties of various materials used for making UHP concrete mixes were determined in laboratory as per relevant IS codes of practice. The materials used in the present experimental study undertaken for the development of UHPC were cement, coarse aggregates, fine aggregates, super-plasticizer and water, in addition to silica fume, nano silica and alccofine (GGBS) in varying proportions. The importance of study of the various properties of material is used to check the acceptance of materials with the codal provision requirements and to enable an engineer to design a concrete mix for a particular strength. The description of various materials along with their investigated properties which were used in this study are detailed in the following sub-sections:

3.2.1 Portland Cement

Cement is the most active component of concrete and usually has the greatest unit cost, and its selection and proper use are important in obtaining most economically the balance of properties desired for any particular concrete mixture. It fills up voids existing in the fine aggregate and makes the concrete impermeable. It provides strength to concrete by binding the aggregates into a solid mass due to its setting and hardening properties when mixed with water. It constitutes only about 20% of the total volume of concrete mix but has significant effect on the strength and durability of the concrete mix formed. Portland cement referred to as Ordinary Portland Cement is the most important type of cement and is a fine powder produced by grinding Portland cement clinker. OPC is classified into 3 grades namely 33 Grade, 43 Grade, 53 Grade depending upon the strength of 28 days. The specification for the cement of any grade is given by the various IS codes. IS 12269: 2013 provides the specification of the 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 (Ultratech Cement) from a single lot was used throughout the course of the investigation. It was fresh and without any lumps. The physical properties of the cement are determined from various method of physical test for hydraulic cement (IS 4031) and the requirement conforming to IS 12269: 2013 are listed in the Table 3.1. Cement was carefully stored to prevent deterioration in its properties due to contact with the moisture.

Table 3.1 Properties of OPC 53 Grade

Characteristics	**Values Obtained Experimentally**	**Value Specified by IS 12269: 2013**	**Method of Test ,Ref to**
Specific Gravity	3.12	-	IS 4031 part 11
Standard Consistency, percent	28		IS 4031 part 4
Initial Setting Time, minutes	55 minutes	30 (minimum)	IS 4031 part 5
Final Setting Time, minutes	165 minutes	600(minimum)	IS 4031 part 5
Compressive Strength 3 days 7 days 28 days	 29.56 N/mm^2 39.85 N/mm^2 55.60 N/mm^2	 27 N/mm^2 (minimum) 37 N/mm^2 (minimum) 53 N/mm^2 (minimum)	IS 4031 part 6

3.2.2 Aggregates

Aggregates occupy a large volume in the concrete mixture and give dimensional stability to concrete. In cement concrete, aggregates are generally used in two size groups: Coarse aggregates – Particle size more than 4.75mm and Fine aggregates (sand) particle size less than 4.75mm. Coarse aggregates make solid and hard mass of concrete with cement and sand and also increase the crushing strength of concrete. It also reduces the cost of concrete, since it occupies major volume. Sand consists 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 the coarse aggregate and reduces shrinkage and cracking 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 provide about 75% volume to concrete so it is extremely important that the aggregates should meet certain requirement if the concrete is to be workable, strong, durable and economical. The aggregates must be proper shape, clean hard and well graded.

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

The coarse aggregates used in the present study were a mixture of two locally available crushed stones of 20mm and 10mm sizes. The aggregates were washed to remove dirt, dust and then dried to surface dry condition. The specific gravity and other physical properties of coarse aggregates are given in Table 3.2. The sieve analysis of coarse aggregate was done in the laboratory and the values obtained are shown in the Table 3.3 for the 20mm aggregate and Table 3.4 for the 10mm aggregate.

Table 3.2 Properties of Coarse Aggregates

characteristics	**Value**	
Color	Grey	
Shape	Angular	
Maximum size	20mm	10mm
Specific Gravity	2.71	2.75
Water Absorption	0.3%	0.5%

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	28	0.93	99.07	0.93
4	10	2876	95.87	3.20	96.8
5	4.75	75	3.20	0	99.3
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	21	0.7		
Total		**3000**		**SUM**	**697.03**
FM = 6.97					

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	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 most of which 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 resulting from natural disintegration of rocks; crushed stone sand, i.e. the fine aggregate produced by crushing hard stone; crushed gravel sand, i.e. the fine aggregate produced by crushing natural gravel. Depending upon the particle size distribution IS 383 has divided the fine aggregate into four grading zones (Grade I to IV). The grading zones become progressively finer from grading zone I to IV. In this experimental program fine aggregates were collected from the local supplier and were conforming to grading zone II. It was free from silt and clay particles. Sieve analysis and physical properties of fine aggregates are tested as per IS: 383 and result are shown in Table 3.5.

Specific gravity of fine aggregates was experimentally determined as 2.60.

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	5	0.5	99.5	0.5
2	2.36	59	5.9	93.6	6.4
3	1.18	136	13.6	80	20
4	600 µ	243	24.30	55.7	44.3
5	300 µ	415	41.5	14.2	85.8
6	150 µ	122	12.2	2.0	98.0
7	Pan	20	2.0		
TOTAL		**1000**		**SUM**	**255**
Zone II			**FM= 2.55**		

c) Silica fume: Silica fume was used in cement concrete as a replacement for cement to study its effectiveness for development of ultra-high performance concrete. Silica fume was obtained from Elkem India Pvt. Limited, Delhi, India. Silica fume received was grey in color. Physical and chemical properties of silica fume were provided by Elkem India Pvt. Limited.

Physical properties: Physical properties are important in both the micro-filler and pozzolanic roles of silica fume. The very small size of silica fume particles is also one of its key to 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)	< 4×10^{-6} in (<1μm)
Bulk density (as-produced form)	8 to 27 lb/ft^3 (130-430 kg/m^3)
Bulk density (slurry)	11to12 lb/gal (1320-1440 kg/m^3)
Bulk density (densified)	30 to 45 lb/ft^3 (480-720 kg/m^3)
Specific gravity	2.20
Specific Surface Area (BET) “nitrogen adsorption method”	60,000 to 150,000 ft^2/lb (13,000 to 30,000 m^2/kg)

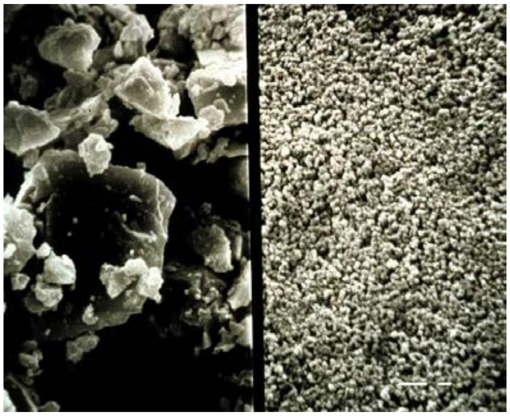


Fig. 3.1 Cement grains and silica fume particles *[Wang et al. (2012)]*

Cement grains and silica fume particles are shown in Fig. 3.1 at same magnification. The ACI 234R-96 report estimates that for 15% silica fume replacement of cement, there are approx 2,000,000 particles of silica fume for each grain of Portland cement.

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

Amorphous: This term simply means that silica is not a crystalline material. A crystalline material will not dissolve in concrete, which must occur before the material can react. The crystalline material present in concrete is sand and though it is essentially silicon dioxide (SiO_2), it does not react because of its crystalline nature.

Silicon dioxide (SiO_2): This is the reactive material in silica fume.

Trace Elements: 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.

The benefits seen from adding silica fume are the result of the changes to the microstructure of the concrete. These changes result from two different but equally important processes. The first of these is the physical aspect of the silica fume and second is its chemical contribution.

d) GGBS (Grand Granulated Blast Furnace Slag)/Alccofine: Alccofine was used in cement concrete as a replacement for cement to study its effectiveness for development of ultra-high performance concrete. Alccofine was obtained from Ambuja Cements Ltd. (ALCCOFINE MICRO MATERIALS RANGE), Mumbai. Alccofine 1101 has an average particle size of 4 to 5 microns; the top size d_{90} is only 10 microns. The computed Blaine value is around 8000 cm^2/gm. Alccofine 1101 should always be used with suitable water reducing admixture. Various physical and chemical properties of alccofine material are given below:-

Setting Time:

Initial setting time > 2 to 3 hours

Final setting time < 6 hours

Technical data:

Fineness: 8000 cm^2/gm (computed Blaine value)

Specific gravity: 3.10

Bulk density: 650-700 kg/m^3

Particle size distribution:

< 2.5 microns: 10 %

< 6 microns: 50 %

< 12 microns: 90 %

It is important to employ efficient mixing equipment while using Alccofine 1101. Colloidal mixers of high speed paddle mixers are recommended. Minimum speed of colloidal mixer should be 1500 rpm and over mixing should be avoided.

e) Nano silica (colloidal silica): 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 it has an amorphous (random) rather than a crystalline Structure. There is stable dispersion of amorphous spherical particles of silicon dioxide in water. It is in liquid form and its particle size is much smaller than silica fume and alccofine particles.

Physical and Chemical Properties: It is a white translucent liquid having no odor and has complete solubility. Specific gravity of nano silica is of the range 1.38-1.39 having particle sizes ranging from 1 - 100 nm

3.2.3 Water

The potable water is generally considered satisfactory for mixing and curing of concrete. Accordingly potable water was used for making concrete available in material testing laboratory. It was free from any detrimental contaminants and was good potable quality.

3.2.4 Superplasticizers

Conplast® SP430 procured from FOSROC Constructive Solutions was used in the present study. Conplast SP430 complies with IS: 9103:1999 and BS: 5075 Part 3. Conplast SP430 is based on Sulphonated Napthalene Polymers and supplied as a brown liquid instantly dispersible in water. Conplast SP430 has been specially formulated to give high water reductions up to 25% without loss of workability or to produce high quality concrete of reduced permeability. Table 3.8 shows the characteristics of Conplast SP430.

The dosage of super plasticizer recommended is 0.6% to 2% by weight of cementitious material. In this study, to attain medium workability of the control mix, super plasticizer amount of 0.6% of cement content was used, and for the other mixes the quantity of super plasticizers were found out depending upon the trials for achieving medium range of workability. The properties of superplasticizer are provided in Table 3.7.

Table 3.7 Properties of superplasticizer used

S. No.	Characteristics	Value
1	Type	Sulphonated Napthalene Polymers
2	Form	Liquid
3	Colour	Light brown
4	Specific gravity	1.220 to 1.225 at 30^0C
5	Air Entrainment	Approx. 1% additional air is entrained

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.

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.

3.3.3 Compressive Strength of Concrete

The cubes of 150 x 150 x 150mm were cast under standard laboratory conditions were tested after a curing period of 7and 28 days. The time was reckoned from the time of addition of water to the dry ingredients. The specimens were tested on 500 tons capacity Automatic Compression Testing Machine (ACTM). The specimens were removed from curing tank and wiped with cloth for any traces of surface water. After keeping at room temperature for half an hour they were placed in position. 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 15 MPa per minute until the failure of the specimen takes place. The photograph (Fig. 3.2) shows testing of cube and cylinder specimens under compression testing machine.

Fig 3.2 Compressive strength test setup

3.3.4 Split Tensile Strength of Concrete

The test was conducted according to IS Code 5816-1970. This test was carried out by placing a cylindrical specimen, 300mm long and 150mm in diameter, horizontally between the loading surfaces of a compression testing machine and the load was applied until failure of the cylinder, along vertical diameter. The loading condition produces a high compressive stress immediately below the two generators to which the load is applied. But the larger portion corresponding to depth was subjected to a uniform tensile stress acting horizontally. It is estimated that the compressive stress is acting for about 1/6 depth and the remaining 5/6 depth is subjected to tension. In order to reduce the magnitude of the high compression stresses near the points of application of the load, narrow packing strips of plywood were placed between the specimen and loading platens of testing machine.

The magnitude of tensile stress (T) acting uniformly to the line of action of applied loading is given by formula:-

$$T = 0.637\ P/DL$$

Where,

T= split tensile strength (in MPa)

P = Applied load

D = Dia. of concrete cylinder sample (in mm)

L = length of concrete cylinder sample (in mm)

3.4 MIX DESIGN PROPORTION

3.4.1 Test Data for materials

1.	Cement Used	OPC grade 53
2.	Specific Gravity of Cement	3.12
3.	Specific Gravity of Coarse Aggregate (20 mm)	2.71
4.	Specific Gravity of Coarse Aggregate (10 mm)	2.75
5.	Specific gravity of Fine Aggregate	2.60
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

Three different water cement ratios of 0.22, 0.24 and 0.26 were considered in the development of UHPC to have the desired results. For each w/b ratio, nine trial mixes were made (i.e. T1, T2, T3, T4, T5, T6, T7, T8 and T9) and then for each of the mixes six cubes and six cylinders were cast to determine compressive strength and split tensile strength after 7 days and 28 days, respectively. The percentage variation of ingredients used in developing the UHPC is shown in Table 3.8 below:

Table 3.8 Percentage of ingredients in various trial mixes

Trial mix	Nano silica (%)	Silica Fume (%)	Alccofine (%)
T1	0	0	0
T2	0	10	0
T3	2	8	0
T4	0	10	10
T5	0	10	20
T6	2	8	10
T7	2	8	20
T8	3	7	10
T9	3	7	20

The various mix proportions of ingredients used for the development of UHPC are shown in Table 3.9(a), (b) and (c) for the three water-cement rations, wherein the OPC 53 grade cement was replaced by nanosilica, silica fume and alccofine 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 between 0.6 to 2.0 %.

Table 3.9 (a) Mix proportion of trial mixes for w/b ratio = 0.26

w/b ratio	0.26							
	W	C	FA	CA(20mm)	CA(10mm)	NS	SF	AF
	(kg/m^3)	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	%	%	%
T1	150	577	617.5	845	286	0	0	0
T2	150	519.2	611	836	283	0	10	0
T3	150	519.2	607	830	281	2	8	0
T4	150	461.5	611	836	283	0	10	10
T5	150	403.8	611	835.5	282.6	0	10	20
T6	150	461.5	606.6	830	281	2	8	10
T7	150	403.8	606.5	830	281	2	8	20
T8	150	461.5	604.5	827	280	3	7	10
T9	150	403.8	604.4	827	279.7	3	7	20

Table 3.9 (b) Mix proportion of trial mixes for w/b ratio = 0.24

w/b ratio	0.24							
	W	C	FA	CA(20mm)	CA(10mm)	NS	SF	AF
	(kg/m³)	*(kg/m³)*	*(kg/m³)*	*(kg/m³)*	*(kg/m³)*	%	%	%
T1	150	625	596	829	281	0	0	0
T2	150	562.5	589	819	277	0	10	0
T3	150	562.5	584	813	275	2	8	0
T4	150	500	589	819	277	0	10	10
T5	150	437.5	589	819	277	0	10	20
T6	150	500	584	813	275	2	8	10
T7	150	437.5	584	812	275	2	8	20
T8	150	500	582	809	274	3	7	10
T9	150	437.5	582	809	274	3	7	20

Table 3.9 (c) Mix proportion of trial mixes for w/b ratio = 0.22

w/b ratio		0.22						
	W	C	FA	CA(20mm)	CA(10mm)	NS	SF	AF
	(kg/m³)	*(kg/m³)*	*(kg/m³)*	*(kg/m³)*	*(kg/m³)*	%	%	%
T1	152	691	567	802	271	0	0	0
T2	152	621.8	559.5	791	267.5	0	10	0
T3	152	621.8	555	784	265	2	8	0
T4	152	552.7	559.5	791	268	0	10	10
T5	152	483.6	559	791	267.5	0	10	20
T6	152	552.7	554.5	784	265	2	8	10
T7	152	483.6	554.5	784	265	2	8	20
T8	152	552.7	552	780.5	264	3	7	10
T9	152	483.6	552	780.5	264	3	7	20

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

The chapter deals with the presentation of results obtained from various strength tests conducted on the ultra-high performance concrete mixes. In order to achieve the objective of study of development of UHPC, an experimental program was devised in which the various percentages of silica fume, nano silica and GGBS were incorporated into the mix along with OPC 53 grade cement and the aggregates 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 3.9(a), (b), and (c) in the previous chapter. The experimental program consisted of casting, curing and testing of controlled and silica fume-GGBS-nano silica concrete specimen at different curing ages. The experimental program included the following:

1. Testing of properties of materials used for making concrete.
2. Design of mixes for ultra high performance concrete by making trials.
3. Casting and curing of specimens.
4. Cubical specimens of size 150mm x 150mm x 150mm were tested for the compressive strength of concrete.
5. Cylindrical specimens of size 300mm x 150mm dia. were tested for the split tensile strength of concrete.

4.2 COMPRESSIVE STRENGTH TEST RESULTS

4.2.1 Compressive strength

The main function of the concrete in 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 silica fume-blast furnace slag based concrete. The modified mixture with varying percentage of blast furnace slag and silica fume as a partial replacement of cement were prepared and cast into cubes. In this study the mix was done by mixer available in the laboratory. The cement, GGBS and silica fume were first mixed properly by hand making a uniform colored blend. The fine and coarse aggregates were added into the mixer and were mixed properly. After this, the blend is incorporated into the mixer and was rotated to mix properly for 4-5 minutes. After this water, which was admixed with the superplasticizer and desired amount of nanosilica, is added into the mixer. The mixer is rotated for 10-12 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 between 0.6 to 2.0 %.

The cubes were tested at the age of 7 and 28. The time was reckoned 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. The specimens were removed from curing tank and wiped with cloth for any traces of surface water. After keeping at room temperature for half an hour they were placed in position. 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 15 MPa per minute until the failure of the specimen takes place.

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 Compressive strength test machine

Table 4.1 Compressive Strength test results

w/b ratio	**0.26**									
Mix Des.	*W (kg/m^3)*	*C (kg/m^3)*	*FA (kg/m^3)*	*CA(20mm) (kg/m^3)*	*CA(10mm) (kg/m^3)*	*NS %*	*SF %*	*AF %*	**7 d MPa**	**28 d MPa**
T1	150	577	617.5	845	286	0	0	0	**42.7**	**64.0**
T2	150	519.2	611	836	283	0	10	0	**47.5**	**72.2**
T3	150	519.2	607	830	281	2	8	0	**48.6**	**74.8**
T4	150	461.5	611	836	283	0	10	10	**52.6**	**78.8**
T5	150	403.8	611	835.5	282.6	0	10	20	**55.4**	**84.1**
T6	150	461.5	606.6	830	281	2	8	10	**59.6**	**89.3**
T7	150	403.8	606.5	830	281	2	8	20	**56.6**	**86.1**
T8	150	461.5	604.5	827	280	3	7	10	**53.3**	**81.0**
T9	150	403.8	604.4	827	279.7	3	7	20	**49.7**	**74.8**
w/b ratio	**0.24**									
Mix Des.	*W (kg/m^3)*	*C (kg/m^3)*	*FA (kg/m^3)*	*CA(20mm) (kg/m^3)*	*CA(10mm) (kg/m^3)*	*NS %*	*SF %*	*AF %*	**7 d MPa**	**28 d MPa**
T1	150	625	596	829	281	0	0	0	**51.6**	**75.8**
T2	150	562.5	589	819	277	0	10	0	**54.2**	**80.1**
T3	150	562.5	584	813	275	2	8	0	**56.2**	**83.7**
T4	150	500	589	819	277	0	10	10	**62.5**	**93.8**
T5	150	437.5	589	819	277	0	10	20	**65.5**	**96.9**
T6	150	500	584	813	275	2	8	10	**72.5**	**105.2**
T7	150	437.5	584	812	275	2	8	20	**68.5**	**101.3**
T8	150	500	582	809	274	3	7	10	**64.5**	**95.5**
T9	150	437.5	582	809	274	3	7	20	**60.5**	**90.1**
w/b ratio	**0.22**									
Mix Des.	*W (kg/m^3)*	*C (kg/m^3)*	*FA (kg/m^3)*	*CA(20mm) (kg/m^3)*	*CA(10mm) (kg/m^3)*	*NS %*	*SF %*	*AF %*	**7 d MPa**	**28 d MPa**
T1	152	691	567	802	271	0	0	0	**63.5**	**95.3**
T2	152	621.8	559.5	791	267.5	0	10	0	**66.7**	**98.7**
T3	152	621.8	555	784	265	2	8	0	**68.5**	**102.1**
T4	152	552.7	559.5	791	268	0	10	10	**71.6**	**105.3**
T5	152	483.6	559	791	267.5	0	10	20	**74.8**	**112.2**
T6	152	552.7	554.5	784	265	2	8	10	**80.5**	**120.8**
T7	152	483.6	554.5	784	265	2	8	20	**76.5**	**113.2**
T8	152	552.7	552	780.5	264	3	7	10	**73.2**	**109.8**
T9	152	483.6	552	780.5	264	3	7	20	**70.4**	**104.2**

4.3 SPLIT TENSILE STRENGTH TEST RESULTS

The split tensile strength of concrete was tested by casting cylinders of size 150mm x 300mm. The material ingredients for developing UHPC were properly weighed as per the calculated mix design for different water-cement ratio and thoroughly mixed to get the uniform mixture. The quantity of water and other admixtures were added in the dry mixture as per the respective mix design and mixed using a mixer. The concrete mix was then filled in the cylinder moulds and vibrated to ensure proper compaction. The top surface of the mould was properly finished by making use of trowel. The finished specimens were left to harden in air for a period of 24 hours. The specimens are removed out from the mould after 24 hours of casting and placed in water tank for curing periods of 7 and 28 days.

The split tensile strength test was conducted according to IS Code 5816-1970. This test was carried out by placing a cylindrical specimen of size 300mm x 150mm diameter horizontally between the loading surfaces of a compression testing machine and the load was applied until failure of the cylinder, along vertical diameter as shown in Fig 4.2. The loading condition produces a high compressive stress immediately below the two generators to which the load is applied. But the larger portion corresponding to depth was subjected to a uniform tensile stress acting horizontally. It is estimated that the compressive stress is acting for about 1/6 depth and the remaining 5/6 depth is subjected to tension. In order to reduce the magnitude of the high compression stresses near the points of application of the load. The results are shown in the Table 4.2.

Fig. 4.2 Split Tensile Strength Test

Table 4.2 Split Tensile Strength test results

w/b ratio										**0.26**
Mix Des.	*W*	*C*	*FA*	*CA(20mm)*	*CA(10mm)*	*NS*	*SF*	*AF*	**7 d**	**28 d**
	(kg/m^3)	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*%*	*%*	*%*	**MPa**	**MPa**
T1	150	577	617.5	845	286	0	0	0	2.2	2.8
T2	150	519.2	611	836	283	0	10	0	2.3	2.9
T3	150	519.2	607	830	281	2	8	0	2.4	3.0
T4	150	461.5	611	836	283	0	10	10	2.5	3.3
T5	150	403.8	611	835.5	282.6	0	10	20	2.6	3.5
T6	150	461.5	606.6	830	281	2	8	10	2.7	3.8
T7	150	403.8	606.5	830	281	2	8	20	2.6	3.6
T8	150	461.5	604.5	827	280	3	7	10	2.5	3.3
T9	150	403.8	604.4	827	279.7	3	7	20	2.4	3.1
w/b ratio										**0.24**
Mix Des.	*W*	*C*	*FA*	*CA(20mm)*	*CA(10mm)*	*NS*	*SF*	*AF*	**7 d**	**28 d**
	(kg/m^3)	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*%*	*%*	*%*	**MPa**	**MPa**
T1	150	625	596	829	281	0	0	0	2.4	2.9
T2	150	562.5	589	819	277	0	10	0	2.5	3.1
T3	150	562.5	584	813	275	2	8	0	2.6	3.2
T4	150	500	589	819	277	0	10	10	2.7	3.3
T5	150	437.5	589	819	277	0	10	20	2.9	3.6
T6	150	500	584	813	275	2	8	10	3.0	3.9
T7	150	437.5	584	812	275	2	8	20	2.8	3.6
T8	150	500	582	809	274	3	7	10	2.6	3.5
T9	150	437.5	582	809	274	3	7	20	2.5	3.3
w/b ratio										**0.22**
Mix Des.	*W*	*C*	*FA*	*CA(20mm)*	*CA(10mm)*	*NS*	*SF*	*AF*	**7 d**	**28 d**
	(kg/m^3)	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*(kg/m^3)*	*%*	*%*	*%*	**MPa**	**MPa**
T1	152	691	567	802	271	0	0	0	2.5	3.1
T2	152	621.8	559.5	791	267.5	0	10	0	2.6	3.2
T3	152	621.8	555	784	265	2	8	0	2.7	3.3
T4	152	552.7	559.5	791	268	0	10	10	2.8	3.6
T5	152	483.6	559	791	267.5	0	10	20	2.9	3.7
T6	152	552.7	554.5	784	265	2	8	10	3.2	4.2
T7	152	483.6	554.5	784	265	2	8	20	2.8	3.9
T8	152	552.7	552	780.5	264	3	7	10	2.7	3.6
T9	152	483.6	552	780.5	264	3	7	20	2.6	3.5

4.4 DISCUSSION OF COMPRESSIVE STRENGTH TEST RESULTS

4.4.1 Compressive strength variation for different mixes at fixed w/b ratios

The table 4.1 and Figs. 4.3 to 4.5 show the strength gain for different mixes, cast using varying proportions of the binders in the mix.

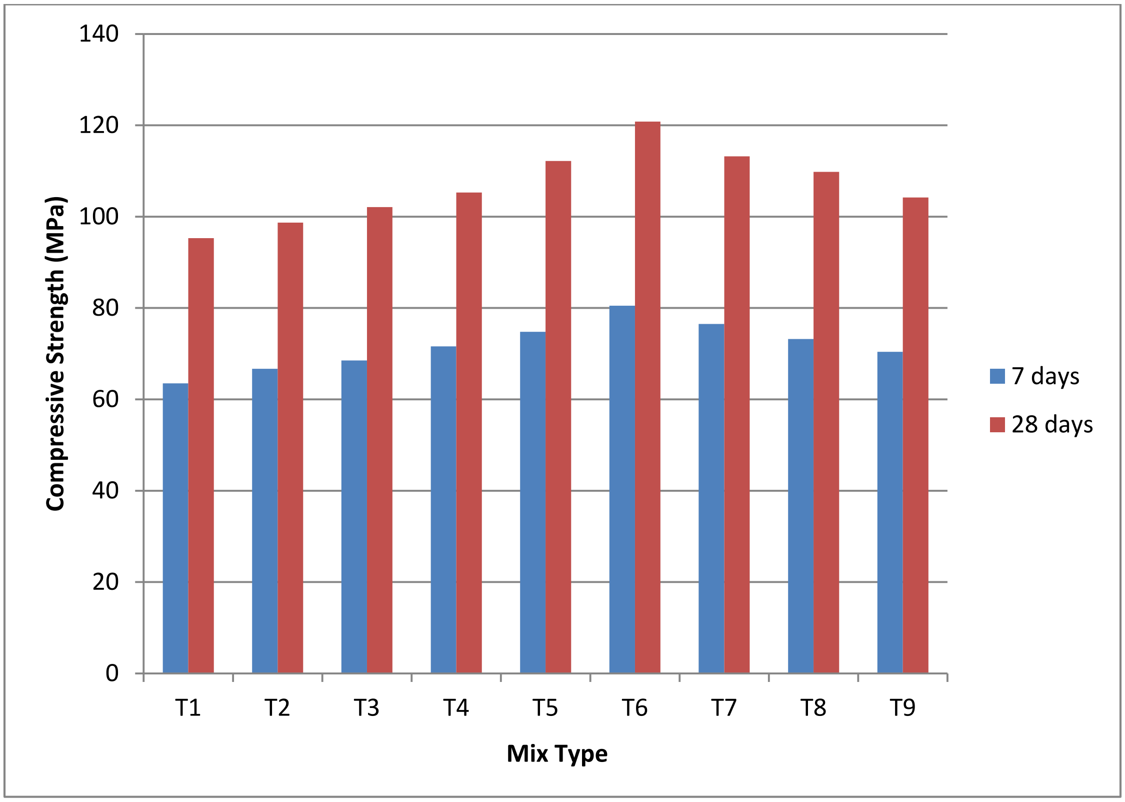


Fig 4.3 Variation in compressive strength for various mixes for w/b = 0.22

The Fig. 4.3 shows the variation in compressive strength values for different mixes cast keeping the water-binder ratio fixed at 0.22. It can be seen from the figure that the gain in compressive strength from 7 to 28 days, is uniform, in the range of 45 to 50%, for all the mixes.

The mix T1 (containing 0% nano silica, 0% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 63.5 MPa and 95.3 MPa respectively. A gain in strength with age is observed. The increase in strength is 50.1% at 28 days. The concrete mix T2 (containing 0% nano silica, 10% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 66.7 MPa and 98.7 MPa respectively. The UHPC Concrete mix T3 (containing 2% nano silica, 8% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 68.5 MPa and 102.1 MPa respectively. The UHPC Concrete mix T4 (containing 0% nano silica, 10% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 71.6 MPa and 105.3 MPa, respectively.

The UHPC Concrete mix T5 (containing 0% nanosilica, 10% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 74.8 MPa and 112.2 MPa respectively. The UHPC Concrete mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 80.5 MPa and 120.8 MPa respectively. The UHPC Concrete mix T7 (containing 2% nano silica, 8% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 76.5 MPa and 113.2 MPa respectively. The UHPC Concrete mix T8 (containing 3% nanosilica, 7% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 73.2 MPa and 109.8 MPa respectively. The UHPC Concrete mix T9 (containing 3% nanosilica, 7% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 70.4 MPa and 104.2 MPa respectively.

From the above observations it can be seen that, only a few mixes viz. T1 and T2, which had either cement only as the binder or had only silica fume in addition to cement, could not achieve the 100MPa strength value after 28 days curing. Similarly, at 7 days curing a maximum strength of 60MPa was achieved by all the mixes. The mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine) could achieve a maximum compressive strength of more than 120 MPa after 28 days curing and a compressive strength of more than 80MPa at 7 days curing period. This was closely followed by mixes T7 and T4 which contained same amount of silica (10% silica fume or 2% nanosilica with 8% silica fume), but had higher, 20%, alccofine content in it.

The compressive strength further decreased when either nanosilica was removed from the mix or when its percentage was increased to 3%.

Thus, it can be said that by using varying combinations of the binder ingredients, it is possible to produce a mix with 28 days compressive strength more than 100 MPa at a w/b ratio of 0.22. Although the requirements for UHPC requires the compressive strength to be in the range of 120 to 150 MPa, only one mix combination T6, containing 2% nanosilica, 8% silica fume and 10% alccofine, could achieve that range of strength after 28 days of curing. This combination indicates that the optimum percentage of nanosilica, silica fume and alccofine are mandatory for the development of UHPC, as the microstructure of concrete gets modified even with slight variations in the same.

Thus, it can be concluded that it would be possible to produce mixes with a compressive strength of nearly 120 MPa, at 28 days curing, with a w/b ratio of 0.22, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.

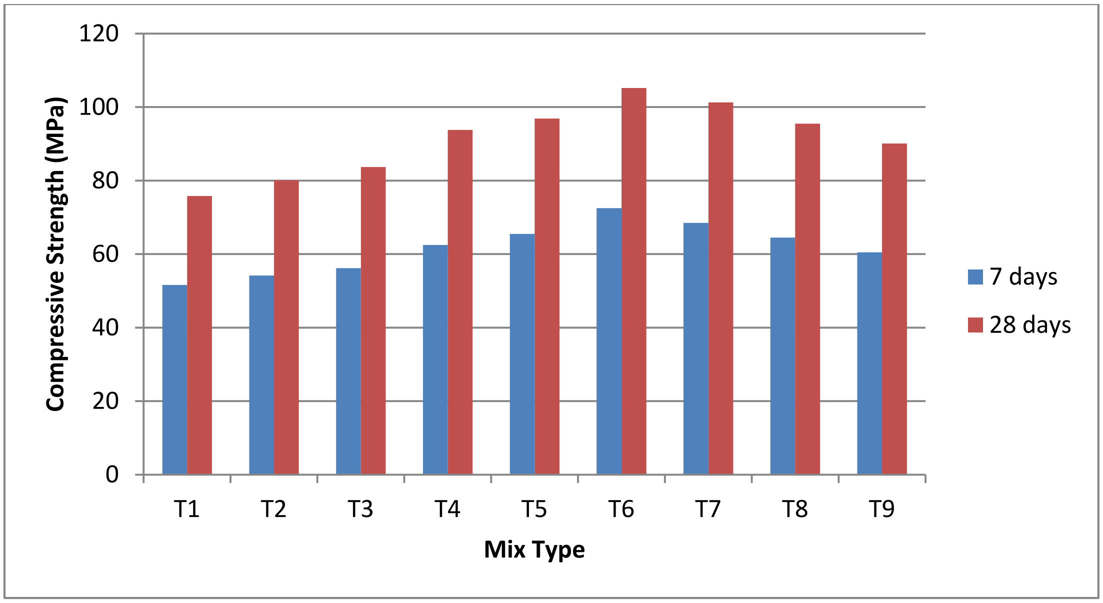


Fig 4.4 Variation in compressive strength for various mixes for w/b = 0.24

The Fig. 4.4 shows the variation in compressive strength values for different mixes cast keeping the water-binder ratio fixed at 0.24. It can be seen from the figure that the gain in compressive strength from 7 to 28 days, is uniform, in the range of 45 to 50%, for all the mixes.

The mix T1 (containing 0% nanosilica, 0% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 51.6 MPa and 75.8 MPa, respectively. A gain in strength with age is observed. The increase in strength is 46.9% at 28 days. The concrete mix T2 (containing 0% nanosilica, 10% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 54.2 MPa and 80.1 MPa, respectively. The UHPC Concrete mix T3 (containing 2% nanosilica, 8% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 56.2 MPa and 83.7 MPa, respectively The UHPC Concrete mix T4 (containing 0% nanosilica, 10% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 62.5MPa and 93.8 MPa, respectively. The UHPC Concrete mix T5 (containing 0% nanosilica, 10% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 65.5 MPa and 96.9 MPa respectively. The UHPC Concrete mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 72.5 MPa and 105.2 MPa, respectively. The UHPC Concrete mix T7 (containing 2% nanosilica, 8% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 68.5 MPa and 101.3 MPa, respectively. The UHPC Concrete mix T8 (containing 3% nanosilica, 7%

silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 64.5MPa and 95.5 MPa, respectively. The UHPC Concrete mix T9 (containing 3% nanosilica, 7% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 60.5 MPa and 90.1 MPa, respectively.

From the above observations it can be seen that for a water-binder ratio of 0.24, only T1 mix which had cement only as the binder could not achieve 80MPa strength value after 28 days curing. Just as was observed for mixes with a w/b ratio of 0.22, the mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine) could achieve a maximum compressive strength of more than 105 MPa after 28 days curing. This was closely followed by mixes T7 and T4 which contained same amount of silica (10% silica fume or 2% nanosilica with 8% silica fume), but had higher, 20%, alccofine content in it.

The compressive strength further decreased, on the same lines as for w/b ratio of 0.22, when either nanosilica was removed from the mix or its percentage was increased to 3%.

Thus, it can be concluded that it would be possible to produce mixes with a compressive strength of nearly 100 MPa, at 28 days curing, with a w/b ratio of 0.24, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.

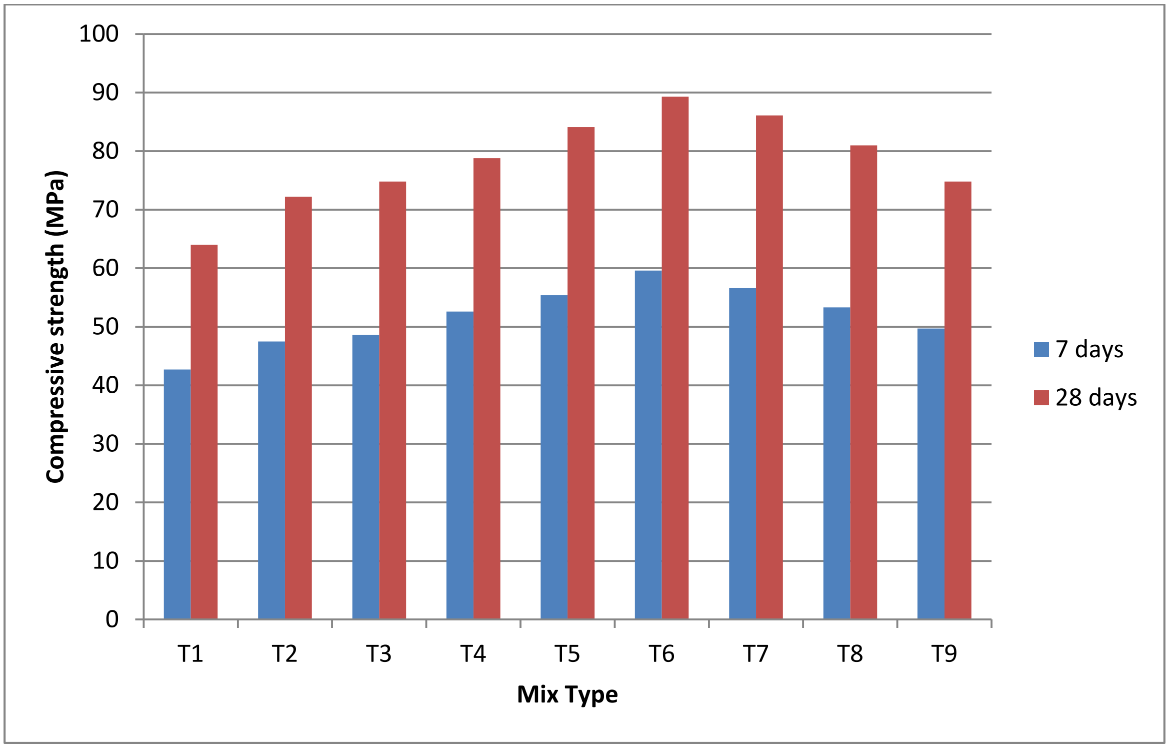


Fig 4.5 Variation in compressive strength for various mixes for w/b = 0.26

The Fig. 4.5 shows the variation in compressive strength values for different mixes cast keeping the water-binder ratio fixed at 0.26. It can be seen from the figure that the gain in compressive strength from 7 to 28 days, is uniform, in the range of 48 to 55%, for all the mixes, which is higher than that obtained for the other two w/b ratios of 0.22 and 0.24.

The mix T1 (containing 0% nanosilica, 0% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 42.7 MPa and 64.0 MPa, respectively. A gain in strength with age is observed. The increase in strength is nearly 50% at 28 days. The concrete mix T2 (containing 0% nanosilica, 10% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 47.5 MPa and 72.2 MPa, respectively. The UHPC Concrete mix T3 (containing 2% nanosilica, 8% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the compressive strength of 48.6 MPa and 74.8 MPa, respectively The UHPC Concrete mix T4 (containing 0% nanosilica, 10% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 52.6 MPa and 78.8 MPa, respectively. The UHPC Concrete mix T5 (containing 0% nanosilica, 10% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 55.4 MPa and 84.1 MPa respectively. The UHPC Concrete mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 59.6 MPa and 89.3 MPa, respectively. The UHPC Concrete mix T7 (containing 2% nano silica, 8% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 56.6 MPa and 86.1 MPa, respectively. The UHPC Concrete mix T8 (containing 3% nanosilica, 7% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the compressive strength of 53.3 MPa and 81.0 MPa, respectively. The UHPC Concrete mix T9 (containing 3% nanosilica, 7% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the compressive strength of 49.7 MPa and 74.8 MPa, respectively.

From the above observations it can be seen that for a water-binder ratio of 0.26, only T1 mix which had cement only as the binder could not achieve 70MPa strength value after 28 days curing. Just as was observed for mixes with a w/b ratio of 0.22 and 0.24, the mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine) could achieve a maximum compressive strength of nearly 90MPa after 28 days curing. This was closely followed by mixes T7 and T4 which contained same amount of silica (10% silica fume or 2% nanosilica with 8% silica fume), but had higher, 20%, alccofine content in it.

The compressive strength further decreased, on the same lines as for w/b ratio of 0.22 and 0.24, when either nanosilica was removed from the mix or its percentage was increased to 3%.

Thus, it can be concluded that it would be possible to produce mixes with a compressive strength of nearly 90 MPa, at 28 days curing, with a w/b ratio of 0.26, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.

From the discussions for all w/b ratios, as above, it can thus be concluded that the optimum concentration of nanosilica in the mix for achieving the highest strength of UHPC mixes at 7 as well as 28 days curing is 2% with a total concentration of silica in the mix being limited to 10%. Also the alccofine content can be limited to 10 to 20% depending upon whether it is being used with nanosilica or without.

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

Figs. 4.6 and 4.7 show the variation of compressive strength with the water-binder ratio for all the mixes with and without supplementary cementitious materials, at curing ages of 7 and 28 days, respectively.

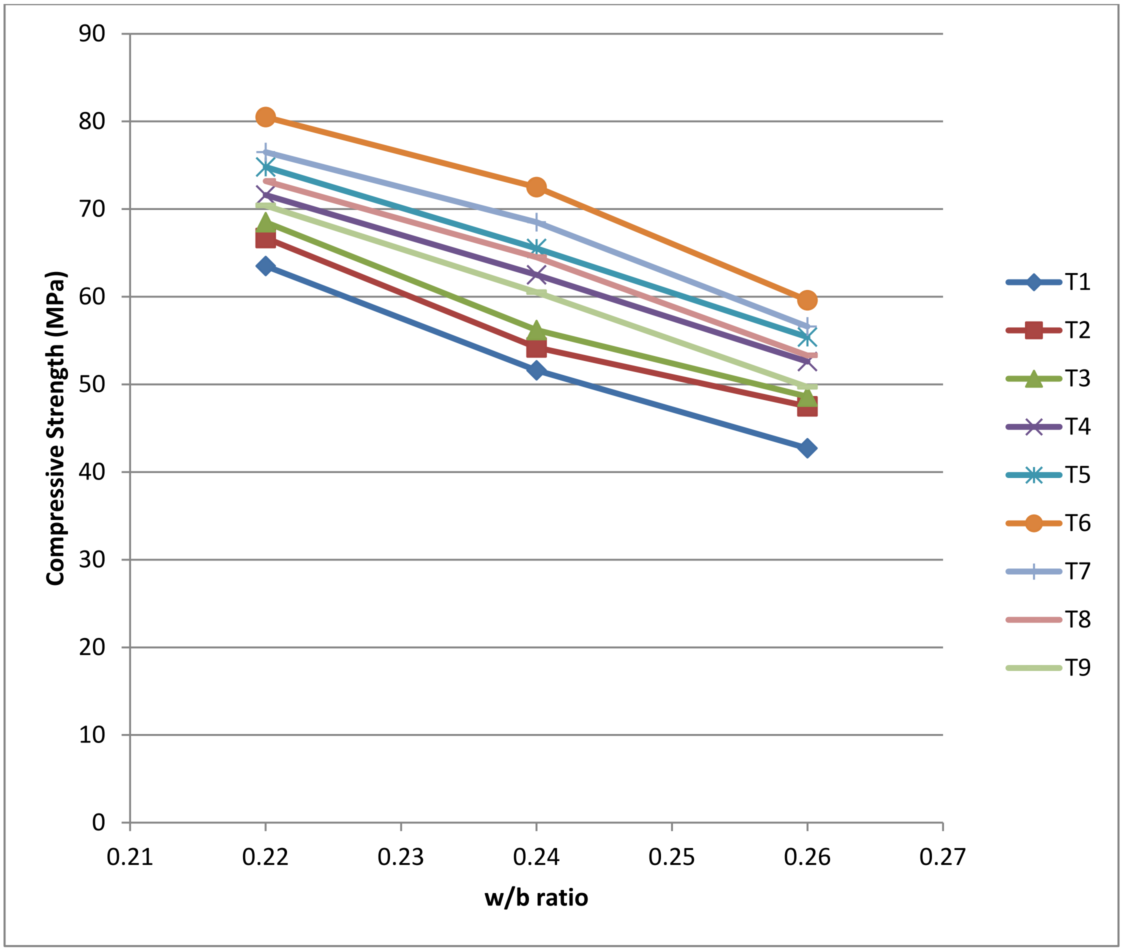


Fig 4.6 Variation of compressive strength for different w/b ratio at 7 days

It can be observed from the Fig. 4.6 that the maximum compressive strength at 7 days for all w/b ratios could be achieved for T6 mixes, which contained 2% nanosilica, 8% silica fume and 10% alccofine, in addition to the cement content. The maximum compressive strength at 7 days came out to be nearly 80 MPa for w/b ratio of 0.22, 72 MPa for w/b ratio of 0.24 and about 60 MPa for w/b ratio of 0.26. The lowest 7 days strengths were obtained for the mixes which had cement only as the binder material in the mix. This was found to be true for all the w/b ratios.

On further observation, it was found out that there is nearly 30 to 35% increase in the strength, for all the w/b ratios, moving from mixes having only cement as the binder to the mix having the most optimum combination for maximum strength.

This clearly shows that supplementary cementitious materials play a significant role in strength development of high strength concrete mixes.

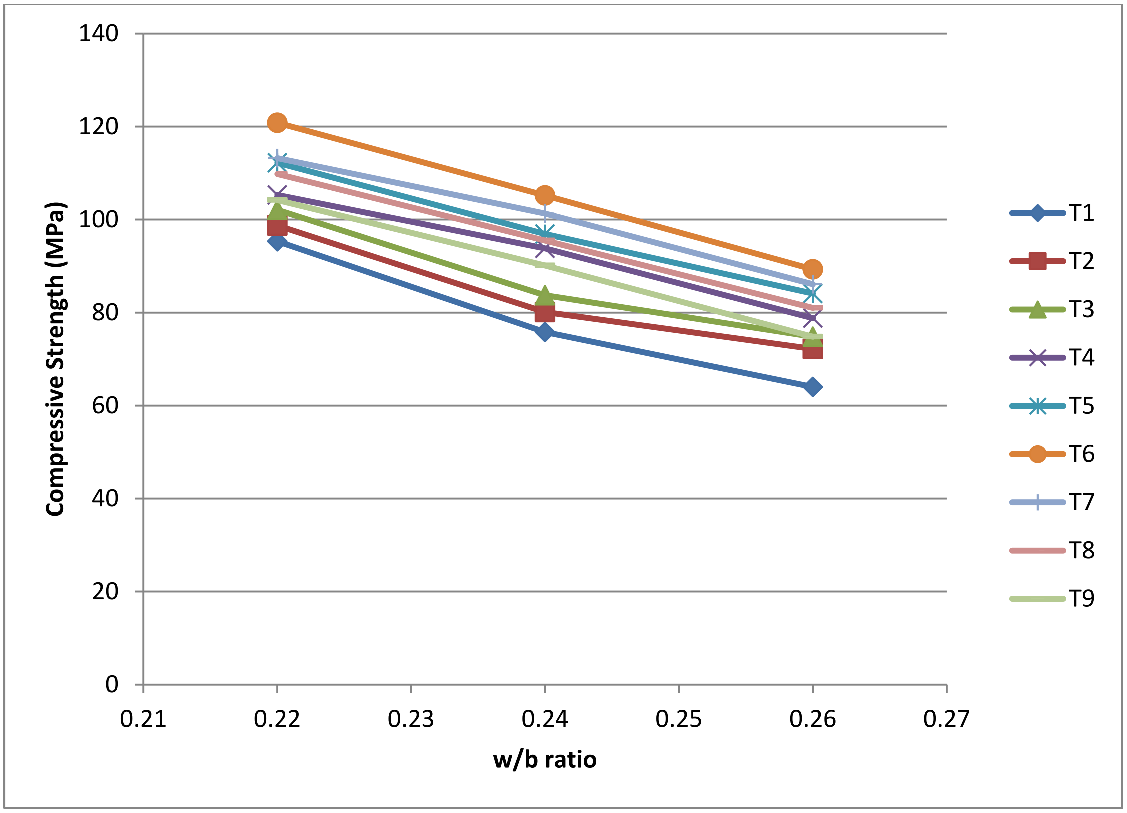


Fig 4.7 Variation of compressive strength for different w/b ratio at 28 days

It can be observed from the Fig. 4.7 that the maximum compressive strength at 28 days for all w/b ratios, following a similar trend as at 7 days, could be achieved for T6 mixes, which contained 2% nanosilica, 8% silica fume and 10% alccofine, in addition to the cement content. The maximum compressive strength at 7 days came out to be nearly 121 MPa for w/b ratio of 0.22, 105 MPa for w/b ratio of 0.24 and about 90 MPa for w/b ratio of 0.26. The lowest 28 days strengths were obtained for the mixes which had cement only as the binder material in the mix. This was found to be true for all the w/b ratios.

On further observation, it was found out that there is nearly 30 to 35% increase in the strength, for all the w/b ratios, moving from mixes having only cement as the binder to the mix having the most optimum combination for maximum strength.

This clearly shows that supplementary cementitious materials play a significant role in strength development of high strength concrete mixes.

4.5 DISCUSSION OF SPLIT TENSILE STRENGTH TEST RESULTS

4.5.1 Split tensile strength variation for different mixes at fixed w/b ratios

The Table 4.2 and Figs. 4.8 to 4.10 show the tensile strength gain for different mixes, cast using varying proportions of the binders in the mix.

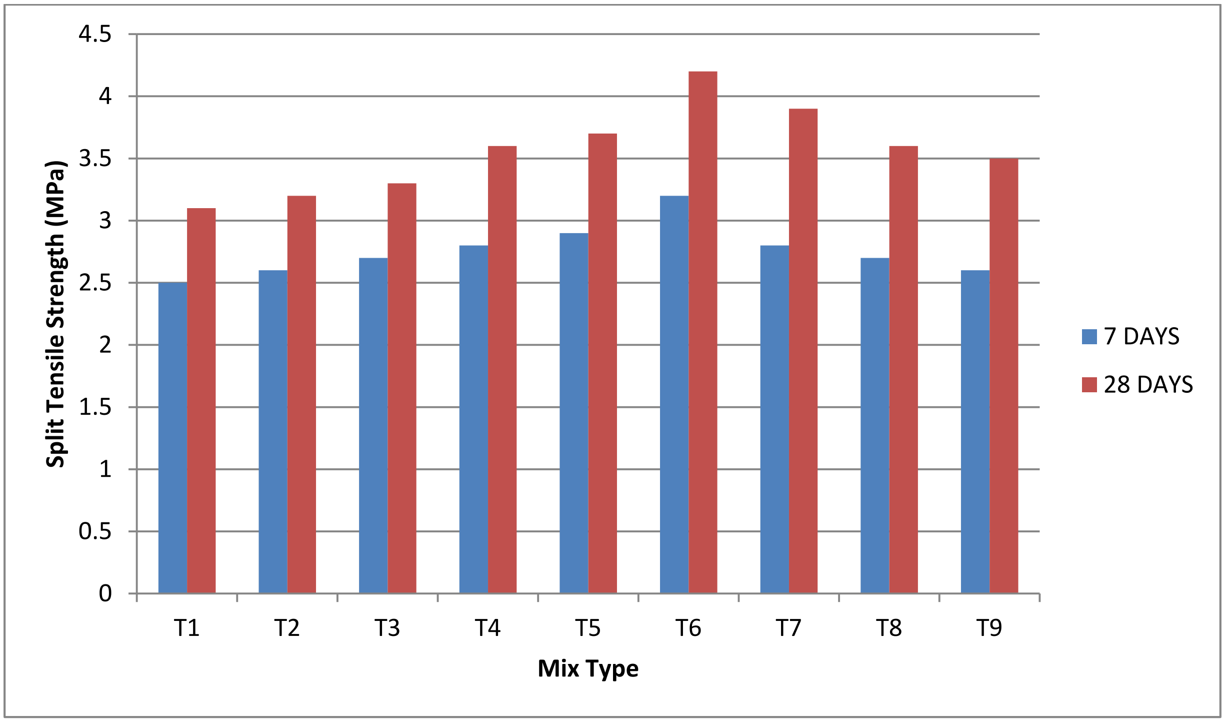


Fig 4.8 Variation in split tensile strength for various mixes for w/b = 0.22

The Fig. 4.8 shows the variation in split tensile strength values for different mixes cast keeping the water-binder ratio fixed at 0.22. It can be seen from the figure that the gain in split tensile strength from 7 to 28 days, is uniform, in the range of 22 to 40%, for all the mixes.

The mix T1 (containing 0% nano silica, 0% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.5 MPa and 3.1 MPa respectively. A gain in tensile strength with age is observed. The increase in tensile strength is 24% at 28 days. The UHPC concrete mix T2 (containing 0% nano silica, 10% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.6 MPa and 3.2 MPa respectively. The UHPC Concrete mix T3 (containing 2% nano silica, 8% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.7 MPa and 3.3 MPa respectively The UHPC Concrete mix T4 (containing 0% nano silica, 10% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.8 MPa and 3.6 MPa, respectively. The UHPC Concrete mix T5 (containing 0% nanosilica, 10% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.9 MPa and 3.7 MPa respectively. The UHPC Concrete mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 3.0 MPa and 4.2 MPa respectively. The UHPC Concrete mix T7 (containing 2% nano silica, 8% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.8 MPa and 3.9 MPa respectively. The UHPC Concrete mix T8 (containing 3% nanosilica, 7% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.7 MPa and 3.6 MPa respectively. The UHPC Concrete mix T9 (containing 3% nanosilica, 7% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.6 MPa and 3.5 MPa respectively.

From the above observations it can be seen that, only a few mixes viz. T1, T2 and T3, which had either cement only as the binder or had only silica fume or nano silica in addition to cement, could not achieve 3.5 MPa tensile strength value after 28 days curing. Similarly, at 7 days curing a maximum tensile strength of at least 2.5 MPa was achieved by all the mixes. The mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine) could achieve a maximum split tensile strength of more than 4 MPa after 28 days curing and a split tensile strength of more than 3.2 MPa at 7 days curing period. This was closely followed by mixes T7 and T4 which contained same amount of silica (10% silica fume or 2% nanosilica with 8% silica fume), but had higher, 20%, alccofine content in it.

The split tensile strength further decreased when either nanosilica was removed from the mix or when its percentage was increased to 3%.

Thus, it can be said that by using varying combinations of the binder ingredients, it is possible to produce a mix with 28 days split tensile strength more than 3.5 MPa at a w/b ratio of 0.22. Although the requirements for UHPC requires the split tensile strength to be in the range of 4.0 to 4.5 MPa, only one mix combination T6, containing 2% nanosilica, 8% silica fume and 10% alccofine, could achieve that range of tensile strength after 28 days of curing. This combination indicates that the optimum percentage of nanosilica, silica fume and alccofine are mandatory for the development of UHPC, as the microstructure of concrete gets modified even with slight variations in the same.

Thus, it can be concluded that it would be possible to produce mixes with a split tensile strength of nearly 4 MPa, at 28 days curing, with a w/b ratio of 0.22, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.

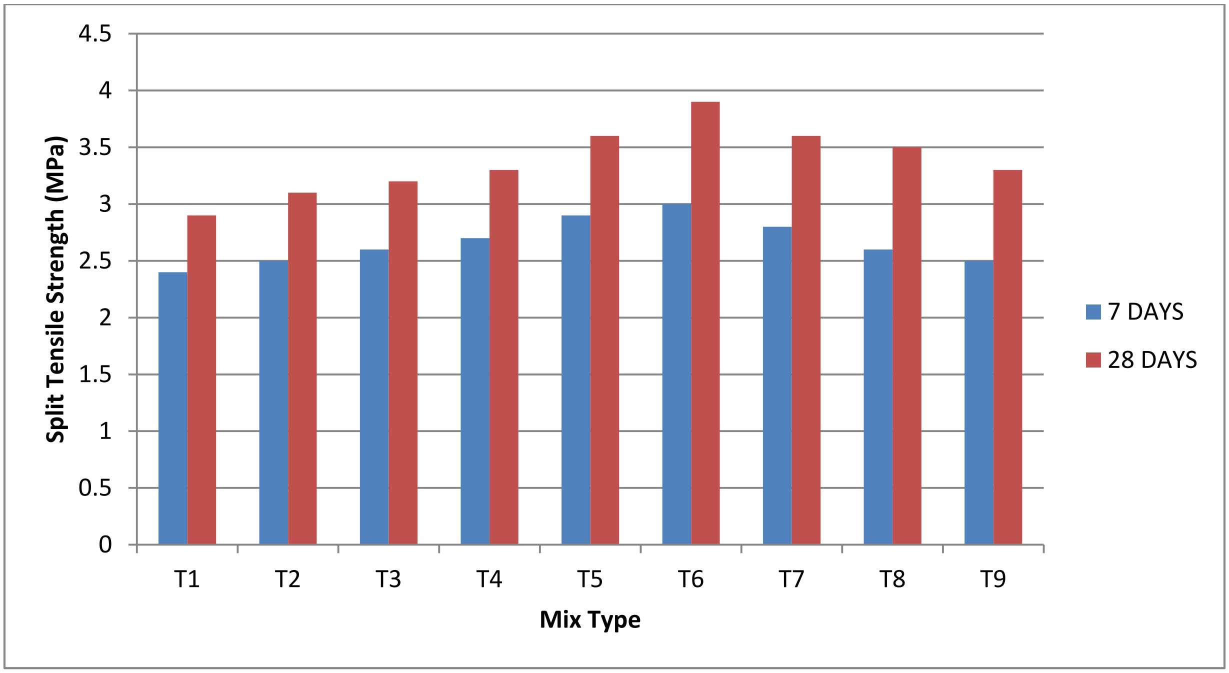


Fig 4.9 Variation in split tensile strength for various mixes for w/b = 0.24

The Fig. 4.9 shows the variation in split tensile strength values for different mixes cast keeping the water-binder ratio fixed at 0.24. It can be seen from the figure that the gain in split tensile strength from 7 to 28 days, is uniform, in the range of 20 to 37%, for all the mixes.

The mix T1 (containing 0% nano silica, 0% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.4 MPa and 2.9 MPa respectively. A gain in tensile strength with age is observed. The increase in tensile strength is 20.83% at 28 days. The UHPC concrete mix T2 (containing 0% nano silica, 10% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.5 MPa and 3.1 MPa respectively. The UHPC Concrete mix T3 (containing 2% nano silica, 8% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.6 MPa and 3.2 MPa respectively. The UHPC Concrete mix T4 (containing 0% nano silica, 10% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.7 MPa and 3.3 MPa, respectively. The UHPC Concrete mix T5 (containing 0% nanosilica, 10% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.9 MPa and 3.6 MPa respectively. The UHPC Concrete mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 3.0 MPa and 3.9 MPa, respectively. The UHPC Concrete mix T7 (containing 2% nano silica, 8% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.8 MPa and 3.6 MPa respectively. The UHPC Concrete mix T8 (containing 3% nanosilica, 7% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.6 MPa and 3.5 MPa respectively. The UHPC Concrete mix T9 (containing 3% nanosilica, 7% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.5 MPa and 3.3 MPa respectively.

From the above observations it can be seen that, the mixes viz. T1 and T2, which had either cement only as the binder or had only silica fume in addition to cement, could not achieve to maintain 3.0 MPa tensile strength value after 28 days curing. Similarly, at 7 days curing a maximum tensile strength of at least 2.4 MPa was achieved by all the mixes. The mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine) could achieve a maximum split tensile strength of 3.9 MPa after 28 days curing and a split tensile strength of more than 3.0 MPa at 7 days curing period. This was closely followed by mixes T7 and T4 which contained same amount of silica (10% silica fume or 2% nanosilica with 8% silica fume), but had higher, 20%, alccofine content in it.

The split tensile strength further decreased when either nanosilica was removed from the mix or when its percentage was increased to 3%.

Thus, it can be said that by using varying combinations of the binder ingredients, it is possible to produce a mix with 28 days split tensile strength nearly 4.0 MPa at a w/b ratio of 0.24. Although the requirements for UHPC requires the split tensile strength to be in the range of 4.0 to 4.5 MPa, even the mix combination of T6, containing 2% nanosilica, 8% silica fume and 10% alccofine, could hardly achieve the lower range value of tensile strength after 28 days of curing. This combination indicates that the optimum percentage of nanosilica, silica fume and alccofine are mandatory for the development of UHPC, as the microstructure of concrete gets modified even with slight variations in the same, on the same lines as for compressive strength development.

Thus, it can be concluded that it would be possible to produce mixes with a split tensile strength of nearly 3.8 MPa, at 28 days curing, with a w/b ratio of 0.24, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.

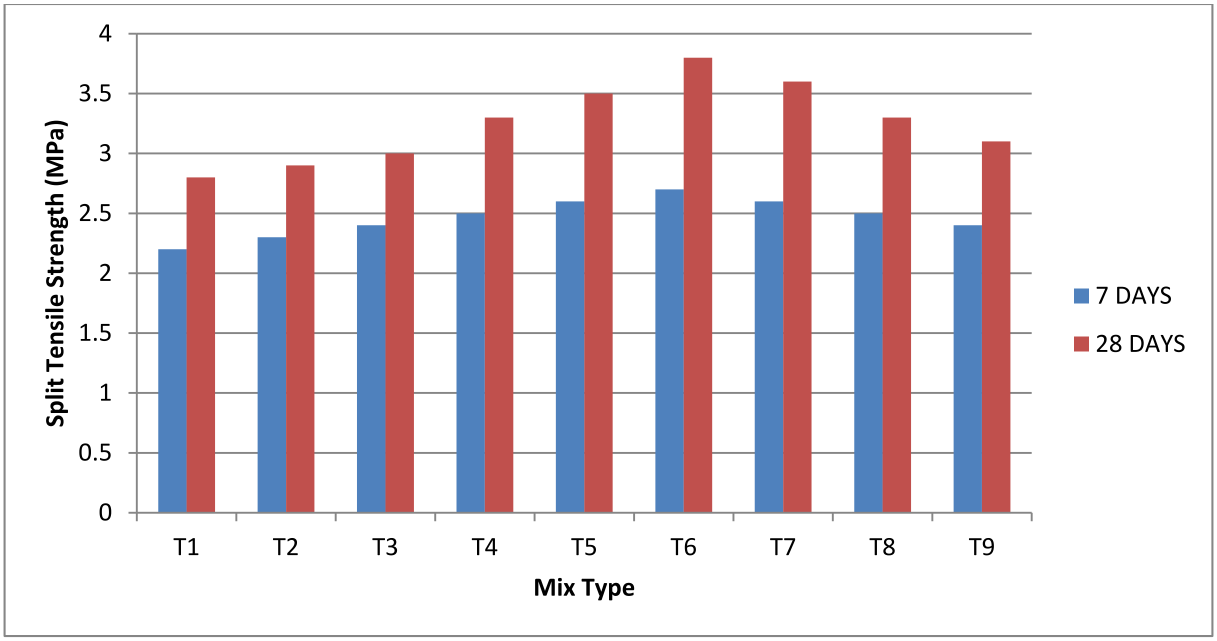


Fig 4.10 Variation in split tensile strength for various mixes for w/b = 0.26

The Fig. 4.10 shows the variation in split tensile strength values for different mixes cast keeping the water-binder ratio fixed at 0.26. It can be seen from the figure that the gain in split tensile strength from 7 to 28 days, is uniform, in the range of 25 to 40%, for all the mixes, which is higher than that obtained for the other two w/b ratios of 0.22 and 0.24.

The mix T1 (containing 0% nanosilica, 0% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the tensile strength of 2.2 MPa and 2.8 MPa, respectively. A gain in strength with age is observed. The increase in strength is nearly 28% at 28 days. The UHPC concrete mix T2 (containing 0% nano silica, 10% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.3 MPa and 2.9 MPa, respectively. The UHPC Concrete mix T3 (containing 2% nano silica, 8% silica fume and 0% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.4 MPa and 3.0 MPa respectively. The UHPC

Concrete mix T4 (containing 0% nano silica, 10% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.5 MPa and 3.3 MPa, respectively. The UHPC Concrete mix T5 (containing 0% nanosilica, 10% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.6 MPa and 3.5 MPa respectively. The UHPC Concrete mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.7 MPa and 3.8 MPa, respectively. The UHPC Concrete mix T7 (containing 2% nano silica, 8% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.6 MPa and 3.6 MPa respectively. The UHPC Concrete mix T8 (containing 3% nanosilica, 7% silica fume and 10% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.5 MPa and 3.3 MPa respectively. The UHPC Concrete mix T9 (containing 3% nanosilica, 7% silica fume and 20% alccofine), after 7 days and 28 days was found to be having the split tensile strength of 2.4 MPa and 3.1 MPa respectively.

From the above observations it can be seen that for a water-binder ratio of 0.26, only T1 and T2 mixes which had cement only as the binder or silica fume as binder in addition to cement, could not achieve 3.0 MPa tensile strength value after 28 days curing. Similarly, at 7 days curing a maximum tensile strength of at least 2.2 MPa was achieved by all the mixes. The mix T6 (containing 2% nanosilica, 8% silica fume and 10% alccofine) could achieve a maximum split tensile strength of 3.8 MPa after 28 days curing and a split tensile strength of more than 2.7 MPa at 7 days curing period. This was closely followed by mixes T7 and T4 which contained same amount of silica (10% silica fume or 2% nanosilica with 8% silica fume), but had higher, 20%, alccofine content in it.

The split tensile strength further decreased when either nanosilica was removed from the mix or when its percentage was increased to 3%.

Thus, it can be said that by using varying combinations of the binder ingredients, it is possible to produce a mix with 28 days split tensile strength nearly 3.0 MPa at a w/b ratio of 0.26. Although the requirements for UHPC requires the split tensile strength to be in the range of 4.0 to 4.5 MPa, even the mix combination of T6, containing 2% nanosilica, 8% silica fume and 10% alccofine, could hardly achieve the lower range value of tensile strength after 28 days of curing. This combination indicates that the optimum percentage of nanosilica, silica fume and alccofine are mandatory for the development of UHPC, as the microstructure of concrete gets modified even with slight variations in the same, on the same lines as for compressive strength development.

Thus, it can be concluded that it would be possible to produce mixes with a split tensile strength of nearly 3.5 MPa, at 28 days curing, with a w/b ratio of 0.26, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.

4.5.2 Effect of w/b ratio on split tensile strength of different mixes

Figs. 4.11 and 4.12 show the variation of split tensile strength with the water-binder ratio for all the mixes with and without supplementary cementitious materials, at curing ages of 7 and 28 days, respectively.

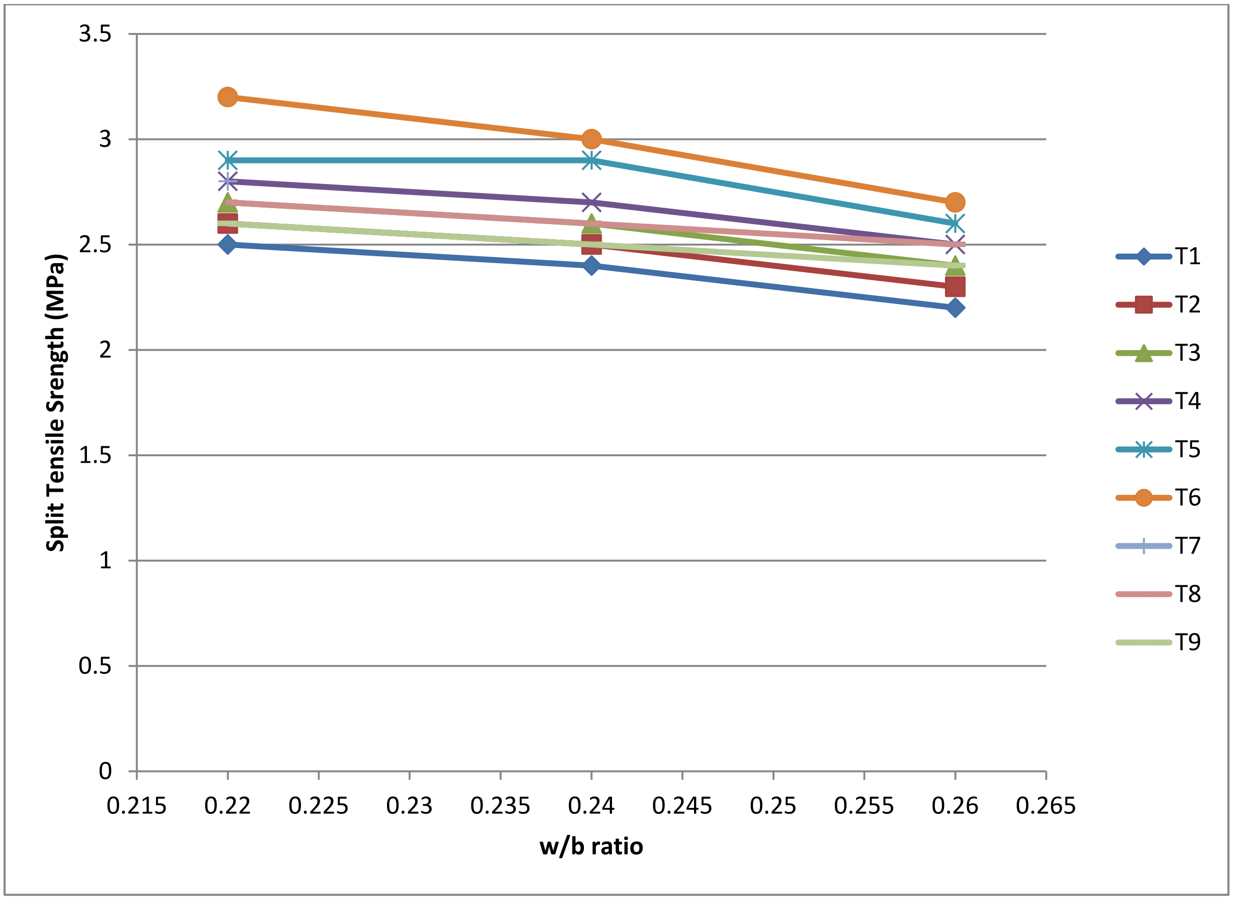


Fig 4.11 Variation of split tensile strength for different w/b ratio at 7 days

It can be observed from the Fig. 4.11 that the maximum split tensile strength at 7 days for all w/b ratios could be achieved for T6 mixes, which contained 2% nanosilica, 8% silica fume and 10% alccofine, in addition to the cement content. The maximum tensile strength at 7 days came out to be nearly 3.2 MPa for w/b ratio of 0.22, 3.0 MPa for w/b ratio of 0.24 and about 2.7 MPa for w/b ratio of 0.26. The lowest 7 days strengths were obtained for the mixes which had cement only as the binder material in the mix. This was found to be true for all the w/b ratios.

On further observation, it was found out that there is nearly 20 to 40% increase in the strength, for all the w/b ratios, moving from mixes having only cement as the binder to the mix having the most optimum combination for maximum strength.

This clearly shows that supplementary cementitious materials play a significant role in strength development of high strength concrete mixes.

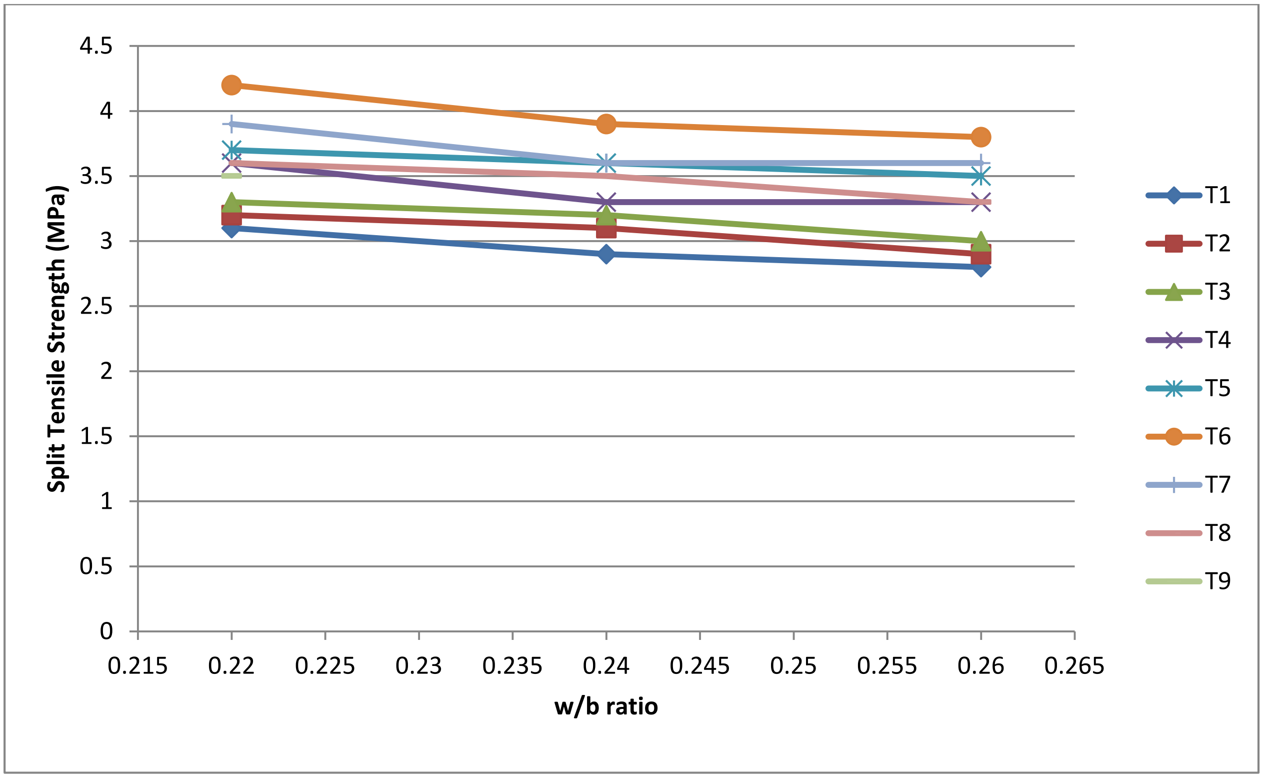


Fig 4.12 Variation of split tensile strength for different w/b ratio at 28 days

It can be observed from the Fig. 4.12 that the maximum split tensile strength at 28 days for all w/b ratios, following a similar trend as at 7 days, could be achieved for T6 mixes, which contained 2% nanosilica, 8% silica fume and 10% alccofine, in addition to the cement content. The maximum split tensile strength at 28 days came out to be nearly 4.2 MPa for w/b ratio of 0.22, 3.9 MPa for w/b ratio of 0.24 and about 3.8 MPa for w/b ratio of 0.26. The lowest 28 days strengths were obtained for the mixes which had cement only as the binder material in the mix. This was found to be true for all the w/b ratios.

On further observation, it was found out that there is nearly 20 to 40% increase in the strength, for all the w/b ratios, moving from mixes having only cement as the binder to the mix having the most optimum combination for maximum strength.

This clearly shows that supplementary cementitious materials play a significant role in strength development of high strength concrete mixes.

CHAPTER 5

CONCLUSION AND RECOMMENDATION FOR FURTHER STUDIES

5.1 GENERAL

The present study was undertaken to develop the Ultra High Performance Concrete and to investigate the compressive strength and split tensile strength of concrete specimens with different level of replacement of cement with silica fume, nanosilica and alccofine in concrete mix. Cement was partially replaced with silica fume, nanosilica and alccofine in various percentages as shown in Table 5.1.

Table 5.1 Percentage of ingredients in various trial mixes

Trial mix	Nano silica (%)	Silica Fume (%)	Alccofine (%)
T1	0	0	0
T2	0	10	0
T3	2	8	0
T4	0	10	10
T5	0	10	20
T6	2	8	10
T7	2	8	20
T8	3	7	10
T9	3	7	20

The compressive strength and split tensile strength tests were performed after 7 and 28 days of curing of concrete specimens. The trial mixes were made for three w/b ratios of 0.22, 0.24 and 0.26. Superplasticizer was used in all the mixes at the rate of 0.8 to 1.5% of the binder content, depending upon the desired workability. The workability of mix was controlled by adding superplasticiser only. Based upon the results discussed in the previous chapter, following are the major conclusions which can be drawn from the study:

5.2 COMPRESSIVE STRENGTH

- Supplementary cementitious materials like silica fume, nanosilica and alccofine play a significant role in strength development of ultra-high performance concrete (UHPC) mixes.
- A 30 to 35% increase in the strength, for all the w/b ratios, moving from mixes having only cement as the binder to the mix having the most optimum combination for maximum strength.

- It is possible to produce mixes with a compressive strength of nearly 90 MPa, after 28 days curing, with a w/b ratio of 0.26, with an optimized mix of nanosilica, silica fume and alccofine as supplementary cementitious materials.
- Mixes with a compressive strength of nearly 100 MPa at 28 days curing with a w/b ratio of 0.24, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.
- It possible to produce mixes with a compressive strength of nearly 120 MPa at 28 days with a w/b ratio of 0.22, by using optimized percentages of supplementary cementitious materials like nanosilica, silica fume and alccofine in addition to cement in the mix.
- The optimum concentration of nanosilica in the mix for achieving the highest strength of UHPC mixes at 7 as well as 28 days curing is 2% with a total concentration of silica in the mix being limited to 10%. Also the alccofine content can be limited to 10 to 20% depending upon whether it is being used with nanosilica or without.

5.3 SPLIT TENSILE STRENGTH

- It is possible to produce mixes with a split tensile strength of nearly 3.5 MPa, after 28 days curing, with a w/b ratio of 0.26, with an optimized mix of nanosilica, silica fume and alccofine as supplementary cementitious materials.
- Mixes with a split tensile strength of nearly 3.8 MPa at 28 days curing with a w/b ratio of 0.24, with a judicious mix of nanosilica, silica fume and alccofine as supplementary cementitious materials in optimized proportions.
- It possible to produce mixes with a split tensile strength of nearly 4.0 MPa at 28 days with a w/b ratio of 0.22, by using optimized percentages of supplementary cementitious materials like nanosilica, silica fume and alccofine in addition to cement in the mix.
- The optimum concentration of nanosilica in the mix for achieving the highest split tensile strength of UHPC mixes at 7 as well as 28 days curing is 2% with a total concentration of silica in the mix being limited to 10%. Also the alccofine content can be limited to 10 to 20% depending upon whether it is being used with nanosilica or without.

5.4 SCOPE FOR FURTHER WORK

- By using various combinations of concrete ingredients including supplementary cementitious materials UHPC of 120 MPa strength at 28 days could be developed. In the work a minimum w/b ratio of only 0.22 has been used. Work can be extended to using still lower w/b ratios to achieve higher ranges of UHPC strength.

- The work can also be extended to include the use of different fibres and see their effect on the strength development of UHPC mixes.
- The work can also be extended to study the durability aspects of UHPC mixes.

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