DEVELOPMENT OF ULTRA HIGH PERFORMANCE CONCRETE FOR RESISTANCE UNDER HIGH STRAIN RATE IMPACT

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

CIVIL ENGINEERING

With specialization in

STRUCTURAL ENGINEERING

Under the supervision of

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by

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to

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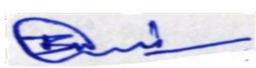
May - 2020

STUDENT'S DECLARATION

I hereby declare that the work presented in the Project report entitled "**Development Of Ultra High Performance Concrete For Resistance Under High Strain Rate Impact**" submitted for partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering at Jaypee University of Information Technology, Waknaghat is an authentic record of my work carried out under the supervision of **Mr. Abhilash Shukla, Assistant Professor**. This work has not been submitted elsewhere for the reward of any other degree/diploma. I am fully responsible for the contents of my project report.



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28 May, 2020

CERTIFICATE

This is to certify that the work which is being presented in the project report titled **"Development Of Ultra High Performance Concrete For Resistance Under High Strain Rate Impact"** in partial fulfillment of the requirements for the award of the degree of Master of Technology in Civil Engineering with specialization in "Structural Engineering" and submitted to the Department of Civil Engineering, **Jaypee University of Information Technology, Waknaghat** is an authentic record of work carried out by **Bhawani Singh (182653)** during a period from July, 2019 to May, 2020 under the supervision of **Mr.Abhilash Shukla (Assistant Professor)** Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of my knowledge.

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I, **Bhawani Singh** would like to acknowledge my work on **"Development Of Ultra High Performance Concrete For Resistance Under High Strain Rate Impact".**

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ABSTRACT

Ultra-high strength concrete (UHPC) is a modern composite material with extremely good mechanical characteristics. Component materials and curing regimes significantly affect the properties of UHPC. For this reason, the influence of supplementary cementitious material (metakaolin) and curing regimes (accelarated curing) on the properties of UHPC has been analyzed. With advances in concrete technology, ultra high performance concrete (UHPC) has become a new focus for researchers and the concrete industry. UHPC is characterized by high compressive strength and excellent durability properties resulting in lighter structures and longer life. Unlike conventional concrete, On the other side optimization of UHPC mix is also necessary to get the desired result. The optimized particle-packing allowed an increase in the concrete compressive strength leading to what was called Ultra-High-Strength Concrete (UHSC), and also an increase in the durability performance of concrete. Particle packing has been recognized to influence mechanical and durability properties of cementitious materials, which are generally favored by optimum packing density. An Ultra-High-Performance Concrete with an optimized particle packing by using a special selection of fine and ultrafine particles, low porosity and high durability. The use of a minimum content of fibers to guarantee a minimum degree of matrix ductility. Particle packing density is always playing an important role in the development of Ultra high strength concrete. In this study Puntke test was adopted to get the highest particle packing density of the cement and mineral admixture. Packing density test (water demand test) was performed on three binary mixture they were C+MK, C+SF, C+UFS. Among the three binary mixtures C+MK showed the highest packing density. C+MK further used to develop mixes. Optimization of mix designs was done by increasing or decreasing the percentage value of used material and further compressive strength test was performed on these trial mixes. Trial mix 13 showed the maximum compressive strength, because of more optimized mix design use in it. Influence of inert admixture and inert fillers were also investigated. For the simulation JHC model was adopted to analyzed the projectile impact.

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CHAPTER 2

LITERATURE REVIEW

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LIST OF ACRONYMS & ABBREVIATIONS

Symbol	**Abbreviation**
b	Binder
BIS	Bureau of Indian Standards
FEM	Finite Element Method
FA	Fly Ash
HRWR	High Range Water Reducers
JHC	Holmquist–Johnson–Cook
LRT	Light Rail Transit
MK	Metakaolin
NS	Natural Sand
NSC	Normal Strength Concrete
PCE	Polycarboxylate Ether
PP	Polypropylene
QP	Quartz powder
SF	Steel Fiber
SP	Superplasticizer
UHPC	Ultra High Performance Concrete
UHPFRC	Ultra High Performance Fiber Reinforced Concrete
w	Water

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the world`s most consumed construction material because of some high-five benefits which include easy availability of raw materials, easy casting and so on. But along with those advantages, there are some drawbacks and shortcomings rendering a reason for most of the structures like skyscrapers; bunker is not made with pure concrete. Still the material engineers, civil engineers and scientists are trying to uplift and enhance the properties lied within the matrix of the concrete mass. Among those efforts one of the listed attempt is development of Ultra High Performance concrete (UHPC) and Ultra High Performance Fiber reinforced concrete (UHPFRC) in structures. Requirement of a good concrete is now becoming a first preference of important structures. Good concrete is a sustainable building material, it is totally friendly towards the environment during its whole life span from its making to its destruction. It's also safe against the impulsive loading which become a very important aspect of safety. Requirement of safe and good concrete takes high to build high rising building, towers etc, these buildings are designed to resist the various natural as well as man-made load events, e.g. earthquake crash of plane now we have to also include the terrorist attacks. So structure should have the ability to resist the impact generated by any penetrating projectile, so it became necessary to examine the damage and after analyses design structure to show protection against the multiple projectile impact. To give the additional safety to important structure`s new high tech concrete like and UHFRC should take under practices. Concrete is an essential material used in concrete structures. It has also contributed to the development of the construction industry. It became the main axis of the construction industry over a hundred years ago, before the First World War broke out. This led to an increased interest in preserving human life and the safety of concrete structures. There has been also a great deal of interest in the impact resistance of concrete against conventional weapons. Petry began research on the impact resistance of concrete and developed the formula for evaluating it in 1910. Research on the impact resistance of concrete has been carried out since the First World War began, and the research continues in the present day. The importance of concrete structures has increased for over a hundred years, and safety-threatening factors have become more diverse. Concrete materials and structural design techniques have advanced a great deal in the academic field.

1.2 UHPC without fiber

Ultra High performance concrete is a new type of concrete which has the outstanding compressive strength and flexural strength, it was first developed in 1980s from since UHPC has been used in the area where extraordinary strength and durability are required, like structure made to resist impact loading, nuclear power plants and bridge panels. UHPC has more advantages as compared to traditional concrete. As UHPC is required less material to meet the same structural property. Fibers are generally added to achieve the desired strength. When used in construction, it has been found that the UHPC has a low overall structural weight, reduced sub-structure, and it has been also found that the it has a very low shipping and installation cost as compare to its other counterparts.

1.3 UHPC with Fiber Reinforced

On the other side Ultra High Performance concrete is the advancement in the UHPC by adding specific and different size of fibers as specified in the literature review, it is an advance construction material in which small size (not greater than 4-6 mm) of coarse aggregate is used. Steel fiber is uniformly distributed in it. The idea of incorporation of steel fibers in fiber reinforced concrete (FRC) is not recently developed, after finding the health-risks associated with asbestos FRC, the steel fiber finds its way around 1960s. The properties of concrete like freeze-thaw, ductility, toughness, shrinkage, impact, abrasion, permeability, bleeding, pumpability, spalling and so on, each of such properties can be improved and enhanced in an appreciable manner with the introduction to fibers and specially steel fibers in the concrete. A significant commercial application of Steel Fiber reinforced concrete can be witnessed in Al McGuire Center a 3700 seat arena in Milwaukee, Wisconsin at Marquette University, America where an Opus North, a design / build construction firm have used 46 pounds of Steel fibers in the concrete to make it no-joint, no-crack floor.

1.4 Material Characteristics

UHPC gets its strength because of its closely packed molecules which has the very strong and tight bond and by matrix which is formed by adding properly measured ingredient and mixing in proper way. Because of its high packing density it is able to resist the maximum compressive strength and also high strain load. Due to its dense structure the chance for the development of capillary pores is very less as compared to the traditional concrete. Material by which the UHPC formed as:-

Cement + Inert admixtures+ Inert fillers + HRWR + water + Steel Fiber

UHPC is also known by the other name which is reactive power concrete, it is formed by using Portland cement, reactive powders, additional binding material, limestone, HRWR, binding materials, fine sand and water when this mixture of ingredient is mixed with the metal, synthetic or organic fiber the UHPC get the ability to resist the flexural strength up to 48 MPa, in most of the cases natural steel fibers, synthetic steel fibers or a combination of both are used to form the UHPC. UHPC pre mixed products are also formed by the researchers to increase the accessibility of UHPC

1.5 Background

US Army Corps of engineers firstly used UHPC in 1980s and after that it frequently used in US 2000 , In 1997 first use of UHPC was in North America for bridge construction and it was a pedestrian bridge in Canada, along with the Germany other countries like Australia , Austria, Italy, Japan, Malaysia etc are using UHPC in bridge construction UHPC also used First time in the Shawnessy Light Rail Transit (LRT) Station, constructed in 2004 and it was the first LRT system which was constructed with the use of UHPC, the first (UHPC) highway bridge was constructed in the United States, completed in May 2006 (Iowa's Wapello County boasts).

1.6 Why we use UHPC?

Why all the countries using UHPC?. UHPC has a greater life span with remarkable strength, ductility and environment resistance ability. Due to the higher material quality and properties, this material gives a possible ways for deign attractive, more durable and impact resistance structures and all others. On the other hand this material also has a better edge in construction speed, artistic structures, maintenance and better life period. It also shows resistance against the corrosion and abrasion. It has been concluded that the compressive strength of UHPC is 10 times greater than the traditional concrete like compressive strength of traditional concrete is 30 to 35 MPa but UHPC posses 125 to 240 MPa strength. if take tensile strength under consideration so the traditional concrete has the tensile strength of 3 to5 MPa but UHPC has up to more than 12 MPa tensile strength now if we talk about the durability so durability is calculated by that how the material show response under unfavorable and extreme condition like resistance against freeze and thaw, chloride resistance etc and UHPC has the ability to resist it properties of UHPC is similar to the hard rock, durability of UHPC which available on commercial level was evaluate by independently by six standardized test and results are shown [1], with the reference of these result we can say that UHPC has great durability as compare to the traditional concrete [2] and also in CO_2 emission cement production posses the 3rd highest source after automobiles and coal plants. UHPFRC has also eliminated the requirement of steel reinforcement in some cases, In specific circumstances, steel fiber can completely eliminate the need of steel reinforcement bar (rebar) in reinforced concrete. There are many projects having industrial flooring made of only steel fiber reinforced concrete without any steel deformed rebar similarly precast lining segments are used in many tunneling projects and they are reinforced only with the steel fibers, it also has the self compacting ability due to its high flow characteristics.

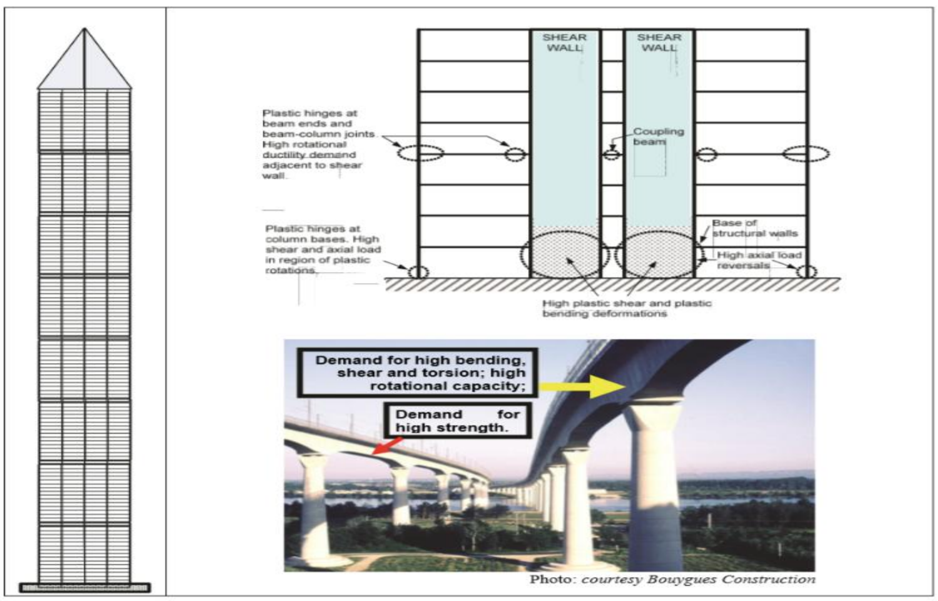


Fig. 1.1. Structures where high performance fiber reinforced concrete and cement is required, and specifically critical locations in these structures. [3]

It can resist the flexural and tensile loads even if the initial crack is occurred , as it is known to us that the UHPC has very dense matrix because of tit it has very small and minimal pore and because of this it has very low permeability because of very low permeability it prevent to enter the harmful substance like chloride etc. Fig.1 shows the types of application where these materials can offer an effective technical solution. Advantages and disadvantages of UHPC are discussed in the next section [4,5].

1.6.1 Advantages

1. Reduction in member size.

2. Increase in the floor area, which can be used further.
3. Reduction in the amount of concrete and time of construction.
4. Less foundation cost due to reductions in self-weight of the structure.
5. Ability to resist high loads with reasonable smaller sizes as compare to traditional concrete.
6. Reduction in floor thickness and beam height.
7. Improved durability and longer life span.
8. Lesser creep and shrinkage.
9. High aversion to chemical attack, crack propagation, etc.
10. Lower costs for maintenance.

1.6.2 Disadvantages

1. Requirement of cost.
2. Combination of proper binding materials that will be designed for mix.
3. No special Indian Standard code provisions are specified for design of concrete design.

However fiber improves the property of traditional concrete but there are some disadvantages are also there while using fibers which are given

1. Uniform fiber mixing and achieving consistent concrete characteristics are complicated.
2. As compared to Normal concrete the UHPC required more accurate configuration.
3. Addition of steel fibers should be in adequate quantity otherwise desirable improvement should not be achieved.
4. However, Workability of concrete is affected when the quantity of fibers is increased. Therefore, to cop of this problem special mixing techniques are preferred for steel fibers. If adequate techniques and optimized proportions are not used, finishing problems occurred with the fibers coming out of the concrete surface.

Portland Cement Association specifies some strength and durability characteristics of UHPC as shown in Table 1.1 and Table 1.2 [6].

Table 1.1. Mechanical property of UHPC [6]

Strength Characteristics		
Compressive (MPa)	Flexural (MPa)	Modulus of Elasticity(GPa)
120 - 150	15 - 25	45 – 50

Table 1.2. Durability of UHPC [6]

Durability Characteristics			
Freeze and thawing (after 300 cycles)	Salt-scaling (loss of residue)	Abrasion (relative volume loss index)	Oxygen permeability
100%	Less than 60 g/m^2	1.7	Less than10-20 m^2

Fig. 1.2. Different type of steel and synthetic fiber [5]

UHPC has improved matrix density, good surface quality and also has the lower water content to get the ultimate and last but not least it has good color integrity as compared to the traditional concrete, the difference between UHPC and normal concrete shown in the following figure

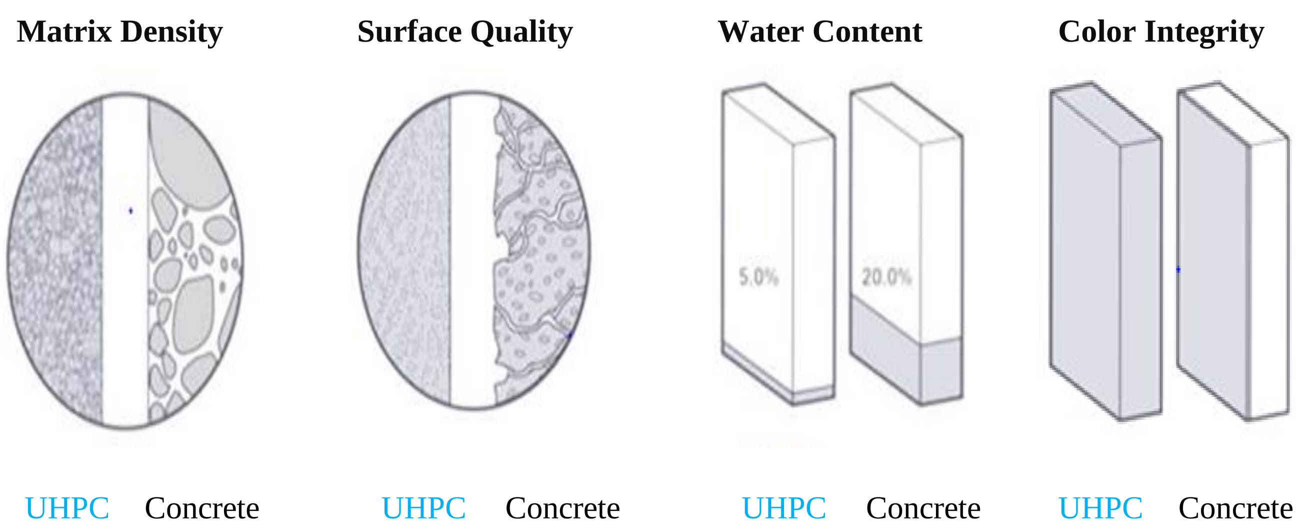


Fig. 1.3. Difference between UHPC and normal concrete [7]

1.7 Objective of Study

1. To determine the ideal combination for the binary blend for high strength concrete by packing density method.
2. The design of UHPC aims to achieve a densely compacted cementitious matrix.
3. To get high compressive strength.
4. To provide an experimental and theoretical basis for the application of UHPC in defensive engineering and for public buildings (schools, hospitals, hotels etc.)

1.8 Methodology.

Adopted methodology for research is given below:

1 Brief analysis of previous literature related to the development of UHPC.
2 Determine the ideal replacement of cement through water demand method.

3 Selection of required materials based on the investigated literature for the production of UHPC.
4 Development of mix design with various percentages of material used Optimization of mix design and investigating the percentages of material constituents on the mix properties.
5 Optimization of mix design by compressive strength testing. To get the suitable mix combination for the development UHPC.
6 Analysis of the results and conclusions on the basis of above procedure.

1.8.1 Outlook of Work.

The work program is compiled as:

1 Water demand tests by Puntke method.
2 Assessment of hardened concrete properties and optimization of mix design through compressive strength testing of cubes.

1.9 Thesis Format.

Chapter 1 (Introduction).

A detailed description about UHPC and UHPFRC, background, advantage and disadvantage, methodology and outlook of the research are given in this chapter.

Chapter 2 (Literature Review).

This chapter deals with the previous researches executed in the development of UHPC. Development of materials, microstructures properties, mix design, mix composition, the effect of various inert admixtures and fillers, application of UHPC and further future challenges are overviewed in this chapter.

Chapter 3 (Materials and experimental program).

Materials used, mix designs, optimization procedure of UHPC, development of trial mixes, production and mixing procedure, curing and tests conducted are discussed in this chapter.

Chapter 4 (Results and discussion).

This chapter deals with the compressive strength results carried out for the optimization of the design mix for the development of UHPC and further potential research findings are discussed

Chapter 5 (Conclusion).

Research conclusion and recommendation for future work are given in this section.

References.

CHAPTER 2

LITERATURE REVIEW

2.1 History

For the construction of taller, better and durable structures mankind has been trying to find out the construction materials with higher and higher performance. They initially started with wood, mud and strow because they were easily available. In many parts of the world, people are still built Mud brick and adobe structures. They can actually last a long time, given that the weather is favorably dry in these areas.

Fig. 2.1. Greek Parthenon [8]

Fig. 2.2. Roman Pantheon [8]

In 2000 BC the Minoan started to use lime mortar. The Greek used it too. But this material was not weather resistance because it can dissolve itself in water. The Romans made a significant improvement on it by adding a volcanic ash from the town of Pozzuoli (hence the name pozzolana). When tools became available, stone was widely used by the Greeks, Egyptians and Romans, as shown in Fig 2.1 and Fig. 2.2.

The Romans were great builders who had left their mark in a vast portion of the world, spanning most of today's Europe and Middle East. They invented the arch, the vault and then the dome and they built many spectacular aqueducts to carry water from the mountain to the cities. The concrete at that time, a mixture of lime, sand, stone and water, is pretty much the same as that used in many areas of the ancient world, or even today in many under-developed countries. The high compressive strength of the ancient cement, in combination with brick and stone, allowed them to build large arches and great domes. A stone girder can hardly span 5 meters. An arch, on the contrary, can span over 50 meters. The Pantheon in Rome, built around 128 AD, has a dome that spans 43.3 meters, with stones and Roman concrete, which was the largest dome in the world for almost 1900 years. Portland Cement was officially introduced by Josepf Aspdin in 1824 and reinforced concrete was first patented by W.B. Wilkinson in 1854. Accordingly, the history of reinforced concrete is only about 150 years.

2.2 Definition and development of UHPC

2.2.1 Definition of UHPC

UHPC is a relatively new generation of cementitious material with very high strength, ductility and durability [9]. Fig. 2.3 shows that, UHPC strengthened with fiber can be treated as a combination of three concrete technologies of self-compacting concrete (SCC), fiber reinforced concrete (FRC) and high-performance concrete (HPC) [10]. French interim recommendations (AFGC 2002) [11] defined UHPC as a concrete with a characteristic compressive strength of at least 150 MPa with the use of steel fiber reinforcement to ensure ductile behavior under tension. Normally, the term UHPC is used to describe a fiber reinforced, superplasticized, silica fume-cement mixture with a very low water cement ratio (W/C), characterized by the presence of a very fine quartz sand that ranges from 0.15–0.60 mm in diameter, instead of the ordinary aggregate.

In fact, some researchers have suggested that UHPC is not a concrete, due to the absence of coarse aggregate in the mixture [12]. However, the term ‘concrete’ is selected rather than ‘mortar’ to describe UHPC added with fine steel fibers to enhance the ductility [14].

2.2.2 Development of UHPC

Being the most popular man-made material in the world, concrete is the basic building material that will continue to be in demand far into the future. It is estimated that the world concrete production is about 6 billion cubic meters per year with China currently consuming about 40% of the world’s concrete production [16]. Superior qualities of concrete such as strength and its durability, ability for it to be placed in many forms made concrete to be considered as the most famous and important material in the construction industry. Concrete is primarily used for its strong compressive strength [17]. Over the last decades, large progress has been taking place on the field of concrete development. Intensive research efforts began in 1930s to improve concrete compressive strength. Fig. 2.4 shows the significant concrete technology achievements for the last 40 years [18].

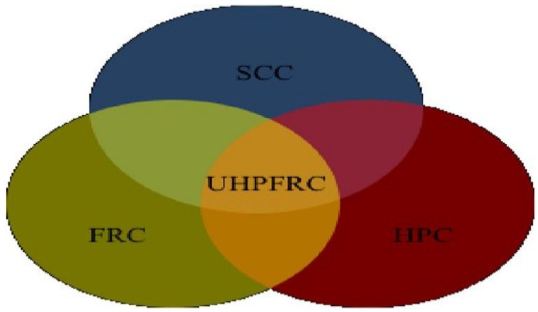


Fig. 2.3. Different types of special concrete [10].

From the graph, it can be seen that the concrete technology progressed slowly during the 1960s with the maximum compressive strength of 15 MPa to 20 MPa. The concrete compressive strength tripled to 45 MPa to 60 MPa over a period of about 10 years. Concrete strength reaches its plateau at about 60 MPa in early 1970s believed due to the technological barrier of the existing water reducer. The available water reducer at that particular time failed to reduce the water to binder ratio (W/B) any further [15]. During 1980s, it is realized that the high-range water reducers, called superplasticizers (SP), can be used to progressively reduce W/B down to 0.30. Reducing the W/B below this was considered a taboo until Bache [19] reported that, with high dosage of SP and silica fume (SF), it was possible to reduce W/B to 0.16. Concrete compressive strength of up to 280 MPa was achieved through compacted granular materials by optimizing the grain size distribution of the granular skeleton. These resulted in the creation of a material with a minimum number of defects, such as micro cracks and interconnected pore spaces, to achieve ultimate strength and durability enhancement.

In general, the developments of UHPC are best described in four stages which are before 1980s, 1980s, 1990s, and after 2000.

Before 1980s; Due to the lack of advanced technology, producing UHPC is only limited in the lab and it required special methods such as vacuum mixing and heat curing. At this time, researchers tried different kind of methods to achieve denser and more compact concrete to improve its strength.

Although high compressive strength of concrete can be achieved, the preparation was very difficult and energy-consuming.

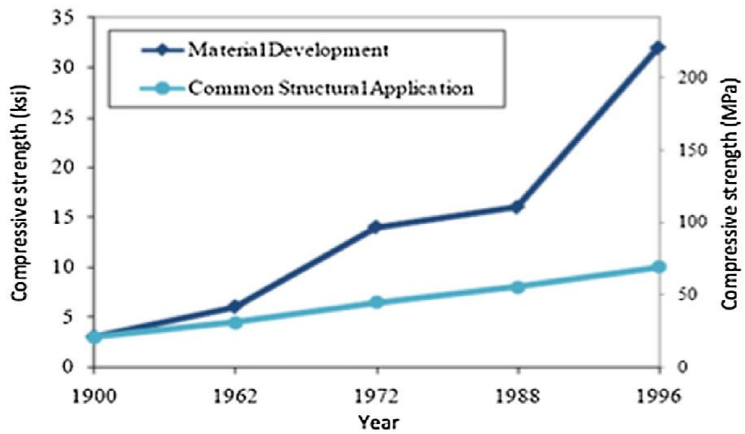


Fig. 2.4. The development of concrete compressive strength for over 100 years [18].

In the early 1980s; The micro defect free cement (MDF) was invented [20]. After the invention of MDF, dense silica particle cement (DSP) was prepared in Denmark by Bache [19]. The maximum compressive strength of DSP can reach up to 345 MPa. However, despite the ultra-high strength increase, these materials become more ‘brittle’. Steel fibers have been introduced in the 1980s to improve the brittleness issue of DSP concretes. This type of steel fiber supplemented concrete can be considered as a relatively new material. It can be characterized by an extremely dense micro structure, very high strength, superior durability, and high ductility.

In 1990s; Richard et al. [9] used components with increased fineness and reactivity to develop RPC via thermal treatment. RPC is a major milestone in the development of UHPC. Its concept was based on the placement of different particles in a very dense arrangement. RPC is the most commonly available type of the UHPC used in laboratory and field experiments and it is characterized by high binder content, very high cement content, very low W/C, use of silica fume (SF), fine quartz powder, quartz sand, SP and steel fibers [9,21]. These steel fibers are generally 12.5 mm in length and 180 mm in diameter [9]. The coarse aggregates are eliminated for homogeneity enhancement of the matrix. The compressive strength of RPC ranges from 200 MPa to 800 MPa.

In 1997, the world’s first RPC structure as shown in Fig. 2.5 was built for pedestrian bridge in Sherbrooke, Canada [14,22]. It was the first time that RPC had been used for building up the whole structure. Despite the success of RPC structures, the applications are still limited due to its expensive material and production cost.

From year 2000 onwards, much progress has been made on the development of UHPC. With further developments of the concrete technology, engineers realized that the advanced concrete, besides the high strength, should also have other excellent properties, which led to the term UHPC and UHPFRC [22]. A wide range of new concrete formulations has been developed to cover an increased number of applications. Supplementary cementitious materials, such as fly ash (FA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), silica fume, metakaolin, ultra fine slag, are used for replacing part of cement in the effort of producing sustainable UHPC and reducing its current cement usage.. From the 2000s, several countries have engaged in various applications of UHPC. In France, a lot of structures such as bridges, facades and slabs have been built with UHPC [23]. UHPC also has growing applications in the maintenance and development of US highway infrastructures [24]. In Australia, significant activities on UHPC development have been carried for bridge structures [25]. In Switzerland, UHPC has been mostly applied to in-situ reinforcement of structures [26]. In Malaysia, UHPC has been used for bridge structures as an effort for sustainable bridge construction initiative [27]. Fig. 2.6 shows one of the completed UHPC bridges in Malaysia, located in Perak.

Fig. 2.5. Sherbrooke pedestrian bridge in Canada [22].

Fig. 2.6. Completed UHPC bridge in Malaysia [27].

2.3 Material Development

2.3.1 Cement

The basic binder used for UHPFRC is Portland cement. The selection of the type of cement requires special consideration as the binder content is much more than the conventional concrete requirement**.** These cements are advantageous because despite their high strength potential and despite the high cement content of fine-grained UHPC (700–850 kg/m^3), the water requirement and the chemical shrinkage are limited and the possibility of an alkali-silica reaction is practically excluded. Nevertheless, when selecting the cement, the individual water requirement should still be considered because the flow behaviour and the amount of superplasticizer required in the UHPC also depend on this. Even after intensive heat treatment at 80–90°C, about 30% of the cement remains unhydrated as a result of the low water content. This is one reason for replacing some of the cement by rheologically similar quartz powder. On the other hand, the high potential for cracks to close themselves is based on this. Cements with low amount of calcium aluminates indicates better results for manufacturing high strength concrete [28]. For UHPC the cement selected should allow high compressive strength in combination with low water demand to also exhibit self-compacting properties. The water demand is related to the Blaine fineness value and chemical composition of the cement [29]. According to research carried out by Hoang, Hadl, and Tue [29] compressive strength of over 160 MPa are achievable only with Portland cement having a low water demand. The research was carried out with 8 different cement types and it was concluded that C_3A free cements are more effective in achieving high strength with low water demand.

2.3.2 Reactive admixtures

2.3.2.1 Silica Fume:

Silica Fume is an amorphous polymorph of silicon dioxide, silica. It is an industrial byproduct of silicon and ferrosilicon alloys, zirconium production and has a typical diameter of 0.2 um. Silica fume is recognized as a pozzolanic material which enhances the mechanical properties of concrete. Silica. During UHPC heat treatment at approx. 80–90°C it contributes partially to the formation of additional strength-forming hydrate phases. As shown in Fig. 2.7 the microstructure is free of pores and practically impermeable. However, without heat treatment, the physical filler effect dominates. Fig. 2.8 shows the silica fume particles in a UHPC matrix shows essentially unhydrated silica fume particles in a dense UHPC matrix.

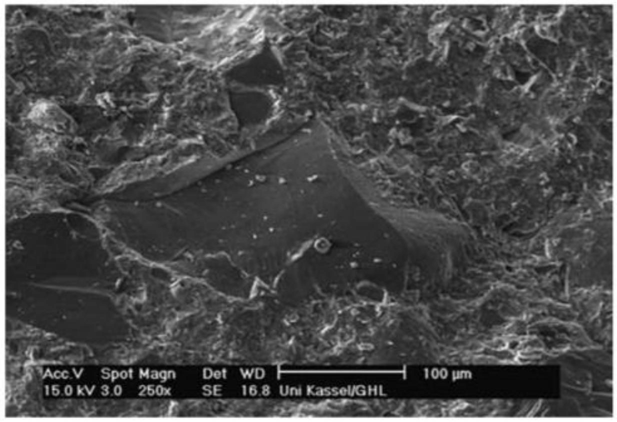


Fig. 2.7. Dense UHPC microstructure with angular aggregate particles [30].

This might be one reason why UHPC stored in water generally exhibits a significantly lower compressive strength (10–20% lower). Owing to its large specific surface of 100 000 cm^2/g and the high interparticle forces, silica fume is the main factor in the determination of water and superplasticizer requirements as well as the rheological properties of the fresh concrete [30]. It should consist of at least 96% by mass of amorphous SiO_2 and contain only little carbon since carbon increases the amount of water and superplasticizer needed.

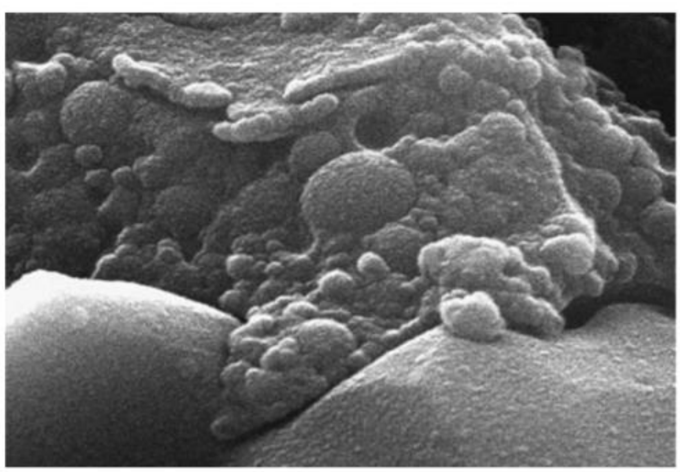


Fig. 2.8. Silica fume particles in a UHPC matrix [30].

Silica Fume serves three major functions when used in concrete:

1. Filling the voids between larger cement particles and filler grains enhancing the packing density.
2. The perfect spherical shape of silica fume particles introduces a lubrication effect that enhances the rheological properties of concrete.
3. The lime resulting from primary hydration of cement reacts with silica fume particles causing secondary hydration [28].

According to an extensive research carried out on the effect of varying material constituents on mechanical properties of concrete by Ibrahim et al. [31], the compressive strength of the mix increased with increase in silica fume content from 10 % to 25 %. As the silica fume content was further increased from 25 % to 30 % no significant change was observed in the compressive strength. Author explained this effect that inclusion of silica fume could cause refinement of pores up to a certain limit, but as the limit is reached no further refinement can take place and an increase in drying shrinkage occurs. Richard et al. [28] suggested that the optimum amount of silica fume for Reactive Powder Concrete (RPC) should be 25 % of the cement amount. This proportion is close to the dosage required for complete consumption of lime resulting from complete hydration of cement. Chan and Chu [32] carried out an experimental investigation to see the effects of silica fume content on the bond strength and pull out energy. They found out that the optimum content of silica fume for maximum bond strength and pull out energy is 20-30 %. The use of silica fume in UHPC accelerates the hydration product as compared with the use of other Supplementry cementitious material (SCMs) [33]. The most effective mineral admixture in reducing water absorption of concrete was silica fume shown in research carried out by Sabet, Libre, and Shekarchi [34]. A 20 % cement replacement by silica fume decreased the water absorption by over 40 %. As the mixtures in their case were cured at 21 º C, temperature and 100 % RH using large amount of silica fume will mean most of that remains unhydrated causing a decrease in compressive strength. This was in agreement with research carried out by showing the influence of temperature on hydration activity and pozzolanic reaction of silica fume.

2.3.2.2 Metakaolin

Metakaolin (MK) is one type of calcined clay and it comes from the calcination of kaolin clay, and there have been some interests in the use of MK in recent year [35]. MK differs from the other cement replacement materials (CRM) (supplementary cementitious materials; SCMs) in that it is not a waste product resulting from industrial activities nor is it completely natural. It is originated from kaolinite clay mineral and is processed for different uses and applications including cementitious systems. MK is mainly produced by calcination (i.e., thermal treatment) of kaolin clays within a temperature ranging from about 600^0C to 800^0C [36]. The main characteristic of MK is the pozzolanic activity, which is the ability of MK to react, in the presence of water, with calcium hydroxide to form hydrated silicate gel hydrate products possessing cementitious properties [37].

Tironi et al. [38] studied the influence of different thermal treatments (i.e., different temperatures) and different durations on the activity index of high purity virgin kaolin with 98% kaolinite. Poon et al. [39] showed that the initial reactivity of MK in blended cement pastes is higher than that of silica fume or fly ash. Due to the high initial reactivity of cement paste with MK, the rate of compressive strength development is higher than cement paste containing silica fume. Curcio et al. [40] indicated that mortars containing MK had higher rate of strength development than that of silica fume. An increase in strength of 30% is obtained when cement is replaced with 10%15% MK. Partial substitution of cement with MK is found to enhance the compressive strength of concrete [41], [42]. However, both MK and silica fume contributes in strength development. MK is relatively cheaper than silica fume and may have greater application in high performance concrete. Siddique and Klaus [43] in his research showed similar results showing an increase in compressive strength and mechanical properties with the use of metakaolin in the mix. The research also found out that mixes made with partial replacement of cement by metakaolin reduces the effect of water penetration through capillary action, is more effective in resisting sulphate attack, reduces permeability of the mix and is more resistant to chemical actions. The incorporation of high reactivity metakaolin replacing 10-15 % cement can control alkali silica reaction.

2.3.3 Inert admixtures

Quartz fillers are crystalline crushed quartz powders with particle size ranging from 1 to 100 µm. Quartz serves two main functions when incorporated into cementitious materials:

1. Improves packing density of the mix.
2. Consumes portlandite by pozzolanic activity [44]

As a rule, various fine quartz powders are used to achieve the optimum packing of the combination of particles. The important factor is that they should undergo highly selective fractionation. As an example, a powder ground to a fineness of approx. 12000 cm^2/g and a powder with approx. 3600 cm^2/g (i.e.

coarser than the cement used) were used the investigations carried out within the scope of the German research programme and in other studies [30]. This enabled the ‘filler effect’ of the cement to be partially replaced and the ‘granular gap’ to the fine sand to be bridged over.

For heat treated high strength concrete crushed quartz is an essential component [28]. Zanni et al. [45] showed that the pozzolanic activity of quartz fillers is highly dependent on heat treatment duration. The research stated that there was no hydration activity observed for quartz fillers at 90ºC for 8 hours. There was an increase of 10 to 25 % observed from 8 to 40 hours and 40 % increase was noted after 40 hours of treatment. This explains the strength contribution of quartz fillers in UHPC when the option of heat curing is available and quite high strengths can be achieved utilizing quartz fillers. AL Salman et al. [46] stated that due to the the smaller average diameter size of quartz sand, it fills all the possible voids between cement, sand and other hydration products resulting in a stiffer mix. This enhances the mechanical properties of the mix and decreases permeability.

2.3.4 Steel Fibers:

Concrete is a brittle material and has very limited post-crack behavior with a sudden failure of the specimen. The steel fibers are incorporated into UHPC to bridge the gap between the cracks and enhance the ductility of the material [44]. Richard et al. [28] proposed that an economic optimum content of 13mm long and 0.15 mm diameter steel fibers is 2 %. In case of heat treatment the research suggested the use of much shorter fibers with length of 3mm. Wille and Naaman [47] carried out a detailed research on the fibers embedded in HSC and UHPC matrix they also investigated that by enhancing the bond between cementitious matrix and fibers through introduction of fine sand particles and metakaolin a bond strength of 20 MPa was achieved showing the high tensile behavior and ductility of UHPC with fiber reinforcement. According to Wu et al. [48] carried out a research to examine the effect of steel fiber content and shape on mechanical properties of concrete. The results showed that hooked end and crimped fibers had a much greater impact on the compressive and tensile strengths rather than the straight fibers. The incorporation of 3 % hooked and crimped fibers increased the compressive strength by 48 % and 59 % at 28 days as compared with straight fibers. The research also described the impact of fiber content on peak loads and showed that though the fibers doesn’t have a significant effect on the first crack strength. It greatly enhanced the peak load and peak deflection values. This explains the conversion of brittle behavior into ductile when incorporation of fibers occurs in UHPC. The toughness is largely increased giving a large area under the deflection curve. According to Sahmaran and Yaman [49] smooth and small diameter steel fibers reduced the water amount required for workability of self-compacting high strength concrete. The increase in compressive strength was influenced by small dimensions and large fiber volume of fibers delaying the micro crack formation and preventing its propagation once they are formed. Wu et al. [48] described that the incorporation of combination of macro and micro steel fibers can lead to tensile strain hardening behavior of the mix. The incorporation of fiber content from 2-5 % increased the compressive strength of specimen by 3.7 to 25 %, flexural strength increased upto 100 % and shear strength up to 260 % as compared with no fiber content [50]. Garas, Kahn, and Kurtis [51] showed that the use of fibers can reduce the drying shrinkage by over 100 %. Wille, Joo, and Antoine [52] showed that by using 1 % of high strength fibers, strain-hardening behavior of the mix can be established. The formation of multiple cracks during strain hardening behavior will lead to a high ductility

2.3.5 Superplasticizers:

A high range water reducing admixture is necessary to achieve required workability of the UHPC mix. Effective superplasticizers for UHPC are based on polycarboxylate ethers (PCE) [30]. Many different PCE superplasticizers are now available. However, most have to be optimized for their interaction with the different cements. Super plasticizers enhance the workability of mix at low water to cement ratio, hence for UHPC where the water to binder ratio is quite low they are a necessary ingredient. Plank et al. [53] studied the effect of two types of polycarboxylates (PCEs) on a cement and silica mix with low water to cement ratio. The research proposed the use of a blended polycarboxylate copolymer to provide better dispersion in both cement and silica. Ma et al. [54] worked on the effect of addition process of superplasticizers in UHPC. The study suggested the stepwise addition of superplasticizers reduces the viscosity of the mix and increases the workability of the mix.

2.4 Special Treatments

2.4.1 Application of heat:

The application of heat enhances the microstructure of the UHPC mix and increases its mechanical properties [44]. Ingo et al. [55] proposed early age heat treatment at 90ºC can greatly accelerate the reaction of mineral admixtures and a 7-day compressive strength of up to 225 MPa can be achieved through this technique. Muller et al. [56] stated that heat treatment results in a denser microstructure of the UHPC mix which explains the increase in compressive strength. The research also proposed that quartz filler and reactive admixtures reacts better when heat or pressure treatment is applied. Wu, Shi, and He [57] carried out a research to find out the effect of curing conditions on the mechanical properties of UHPC incorporated with SCMs. The study showed an increase in compressive and flexural strength when the mix was hot water cured than the mix, which was cured under standard conditions. Ibrahim et al. [31] found out that the 28 days compressive strength values were almost similar for mixes that were cured at 90ºC. The compressive strength values were more pronounced at high temperatures this probably was because of the high temperatures activating the quartz powder and other fillers which would act inert without heat treatment. The application of heat curing makes these fillers active by taking part in the hydration reactions resulting in longer C-S-H chains giving a denser microstructure and resulting in higher compressive strength. Bulvar [58] showed that the standard and hot water curing after 56 days has a less pronounced effect and the compressive strength gain rate decreases substantially. Zanni et al. [45] investigated the effect of heat treatment on UHPC. The results showed that the pozzolanic activity of quartz and silica fume depends on the temperature and duration of the curing procedure. From the pozzolanic activity of quartz as nothing was observed when treated for up to 8 hours, but there was a significant rise as the treatment was continued for more than 8 hours.

2.5 Mix designs and Standards

2.5.1 Mixture design for UHPC

Mixture design is a selection of raw materials in optimum proportions to provide concrete with required properties for particular applications. The design of UHPC aims to achieve a densely compacted cementitious matrix with good workability and strength. In recent years, several studies have been conducted aiming at optimizing the mixture proportion of UHPC [69,60,61].

Various models have been reported for the mixture design of UHPC. For instance, Larrad and Sedran [62] proposed a linear packing density model (LPDM) for the mixture design of UHPC. This model was later improved considering the virtual density theory known as solid suspension model (SSM) [56]. This new model allows the production of a fluid mortar with a 0.14 W/B and a compressive strength of 236 MPa with a 4-day curing at 90^{o}C [62]. De Larrad and his team once again did further improvement on the latter model based on the compaction index concept and virtual packing density. This third generation of the packing models known as a compressible packing model (CPM) was proposed for UHPC design [63]. Richard & Cheyrezy [28] have successfully developed two UHPC products, namely

RPC 200 and RPC 800 by optimizing the granular mixture using CPM. Fennis et al. [64] developed an ecological UHPC mixture based on particle packing technology.

Park et al. [65] developed an UHPC with a compressive strength of 180 MPa, by considering the effect of W/B, type, and replacement proportion of filler. Under the guidance of CPM density model, Gong [66] studied the dense packing effect of the gradation of mineral powders and found that the filling effect became more prominent with the decrease of W/C. Yu et al. [63] developed an eco- friendly UHPC by using the modified Andreasen & Andersen particle packing model (shown in Eq. (1)) to achieve a densely compacted cementitious matrix produced with a relatively low binder dosage of about 650 kg/m^3. In this study, they have successfully developed an UHPC with 28 days compressive and flexural strengths of 150 MPa and 30 MPa, respectively.

$$P(D) = \frac{D^q - D^q min}{D^q max - D^q min} \qquad (1)$$

In the past 25 years, the outcome in concrete technology has allowed the production of UHPC with excellent rheological behavior, which includes workability, self-placing and self-densifying properties, improved in mechanical and durability performance with very high compressive strength and non-brittleness behavior [67]. The development of UHPC usually starts with the design of the granular structure of the aggregates; of which the selection and characterization of suitable fines for optimum packing density are of key importance. Packing density always plays an important role in the development of UHPFRC. It has been concluded that the incorporation of ultra-fine powders with a variety of sizes helps to improve the packing property and also help to maximize the benefit of cementitious material [68,69]. A comprehensive overview of various particle packing theories and methods can be found in [64,70,71]. Fennis [64] demonstrate the various methods which calculate the void content in term of water demand like Water demand (France), Puntke test (Germany), Mixing energy method, Proctor test, Centrifugal consolidation, Water demand method (Japan), Rheology – Krieger, and Dougherty. Li et al. [72] performed experiments on the dry and wet packing densities of concrete mixes for different combinations under different levels of compactions using bulk density method and evaluated the solid concentration of particles. The high material cost, complex fabrication technique together with the limited available resources severely limits its commercial development and application in the modern construction industry, especially in the developing countries [73]. These restrictions further motivate the development of cost-effective UHPC using alternative materials with similar functions to substitute the expensive composites of UHPC to increase its acceptance level.

2.5.2 UHPC Standards

The first French recommendations for Ultra-High Performance Fiber-Reinforced Concretes (UHPC) were published in 2002. These recommendations integrates feedback from experience with the first industrial applications and experimental structures described below, as well as more than 10 years of laboratory research. These recommendations are divided in three parts: A first part devoted to a characterization of UHPC, giving specifications on the mechanical performance to be obtained and recommendations for characterizing UHPC. A second part deals with the design and analysis of UHPC structures, the particularity of which is to integrate the participation of fibers and the existence of non-pre-stressed or non-reinforced elements. A third part deals with the durability of UHPC

In mid 2016, two French national standards for UHPC known as NF P18-470 and NF P18-710 were published for UHPC to replace the technical guidelines and professional recommendations generally used in designing UHPC. Below are some of the available guidelines that have been commonly referred by researchers in producing UHPC [67,75].

1. French Recommendations [76]
2. German Recommendations [77]
3. Japanese Recommendations [78]

Availability of the new standards allows clear and codified specifications, which helped further acceptance of UHPC at the international level. The standardization process of UHPC in France was launched in December 2012. These standards were technically elaborated based on the earlier French AFGC recommendations [76] and technical feedback of more than 15 years of UHPC projects and realizations [79]. These standards served as provisions for an appropriate material purchasing, developing and adjusting mixture design, and controlling the production processes.

As suggested in NF P18-470 [74], the mix design of UHPC should obey the following procedure:

1. Establish the nominal mix design.

2 Confirm the mix design by suitability tests.

3 Follow-up manufacture by routine checks.

2.5.3 UHPC production principle

Over the past 15 years of concrete remarkable advances, many researchers have developed UHPC up to a level where they are ready for applications. The compressive strength for designed UHPC could reach up to 200 MPa. The basic idea of producing a concrete with a very high strength and dense microstructure had already been put forward in the 1980s [19]. However, the practical breakthrough came after the development of efficient SP that enabled the production of easy flowing concrete with a high proportion of optimally packed ultrafine particles to minimize the composite porosity using extremely low W/B.

Several researchers [9,18,80,81] have identified the basic principle in designing UHPC, which can be summarized as follows:

1. Minimizing composite porosity by optimizing the granular mixture through a wide distribution of powder size classes and reducing the W/B.
2. Enhancement of the microstructure by the post set heat treatment to speed up the pozzolanic reaction of SF and to increase mechanical properties.
3. Improvement of homogeneity by eliminating coarse aggregate resulting in a decrease in the mechanical effects of heterogeneity.
4. Increase in ductile behaviour by adding adequate volume fraction of small steel fibers.

2.6 Basic material concepts

2.6.1 Microstructure properties

UHPC has excellent performance as compared with normal-strength concretes it is due to its much denser hardened cement matrix with virtually no capillaries. Furthermore, ‘classic’ easy-flowing UHPC is a fine-grained mix, with a maximum particle size of 1mm. Therefore, its internal microstructure is much more homogeneous than customary, coarse-grained concretes and it is essentially more uniformly stressed by external actions. Together, these two aspects result in the compressive strengths of about

150–200N/mm2 so typical of UHPC. The very dense microstructure and high strength so typical of UHPC are due to its very low water/binder ratio of only about 0.20. The matrix therefore has practically no capillaries and is thus diffusion-resistant. Another factor contributing to the high strength is the fact that the ultrafine particles (grain size <125μm) consist of various components like cement, quartz powder and inert or reactive fine fillers that are combined in such a specific way that the ultrafine particles are packed very tightly together. Fig. 2.9 compares the composition (by volume) of normal-strength concrete, highstrength concrete, self-compacting concrete (SCC) and fine- and coarse-grained UHPC for various applications. The use of grading-optimized admixtures made up of several different components leads to a wider concrete technology approach that goes beyond conventional thinking in mass-based water/binder ratios as the key variable determining the strength.

2.6.2 Grading optimization

One way of achieving optimum packing of the fine particles is through experimentation. Another way is to use numerical modelling to optimize the packing density on the basis of the characteristics of the raw materials measured beforehand. In experiments it is possible to approach the optimum packing of the grains iteratively, e.g. using the Puntke method [82].

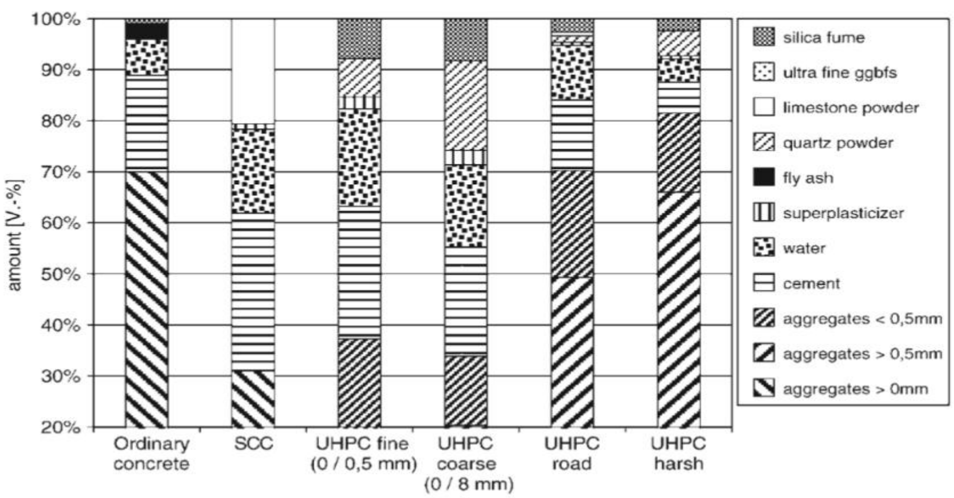


Fig. 2.9. Comparison of mix compositions for normal-strength, high-strength and various UHPCs [30].

It is this that allows the 'filler particles' to reach the spaces allocated to them within the 'scaffold' of larger particles. By varying the volume proportions of the individual grains, the packing density rose from an initially low figure of 65% to more than 83%, i.e. the volume of pores could be reduced from 35 to just 17% by vol. This not only increased the strength accordingly but also significantly reduced the amounts of water and superplasticizer required. As in the past, the results of the calculations must be validated by experiments. Generally, the values do not agree fully with the pore volumes and packing densitiesdetermined experimentally using the Puntke method [30,82]. Workability causes limits on optimizing the packing density. On the one hand, with ever better packing density, the pores between the particles, which otherwise must be initially filled with rheologically inactive water, become smaller before water can function as a lubricant between the grains. On the other, the surface area of the filler materials to be wetted increases progressively with the fineness, and that in turn means more water is needed for wetting. In addition, the interparticle forces between the finest particles increase. They agglomerate to form larger ‘particles’ and therefore can no longer act as optimum filler materials as intended. Furthermore, the viscosity of the fresh concrete increases. Fig. 3 shows the relationship between the principles of filling pores and viscosity using the simple example of two quartz powders with different degrees of fineness. The conflict between maximum packing density on the one hand and the decrease in workability on the other can be resolved by adding a high-performance superplasticizer based on PCE (polycarboxylate ether). In order to guarantee a sufficient effect, the plasticiser must be selected within the scope of suitability testing; it must deagglomerate and liquefy adequately – not only the particular cement, but also all the other fine particles and especially the silica fume. Practical advice can be found in [36].

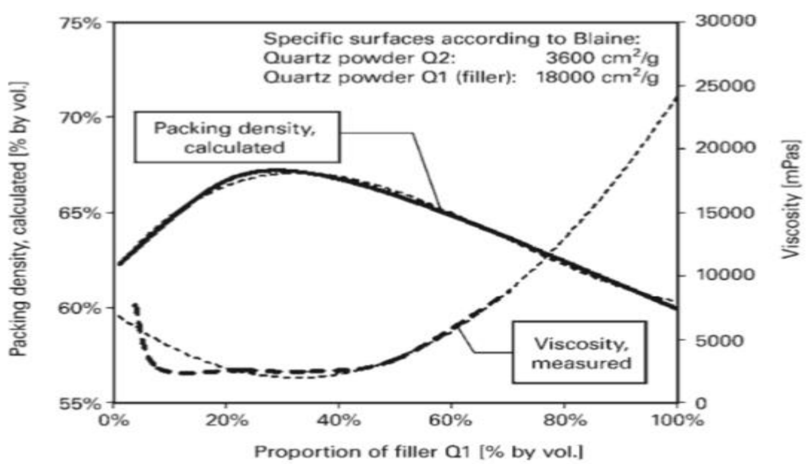


Fig. 3. Relationship between the packing density and workability of an inert paste made from two different fine quartz powders (Q1, Q2) when using superplasticizers (w/c=0.26) [30].

2.7 Mix composition

Designing a UHPC mix begins with selecting and defining the ultrafine materials required to achieve an optimum packing density. The grading of the fine raw materialsis evaluated with a laser granulometer unless the supplier has provided sufficiently accurate information. This is followed by the numerical optimization of the packing density and its experimental validation based on the combination of fine particles, e.g. using the Puntke method.The aim of this is to achieve a maximum water/fines ratio and at the same time low water and super plasticizer requirements [30]. In contrast to normal-strength concrete, the equivalent water/cement ratio (cement + silica fume) in the mix design cannot be varied because even a small increase beyond the value of about 0.20 (max. w/c ratio approx.0.24) normal for UHPC leads to the formation of capillary pores, which reduce the characteristic imperviousness of the microstructure and introduce drying shrinkage in addition to autogenous shrinkage [44]. On the other hand, even a minor increase in the water content (but still within the aforementioned limits) can improve the effect of the superplasticizer. Some commercially available UHPC mixtures are shown in Table 2.1. From the table, it can be observed that high volume of cement content, SF, and sand are normally used in UHPC. The initial cost of UHPC far exceeds the conventional concrete (CC), great efforts have been made on minimizing material cost without sacrificing the beneficial properties of UHPC.

Table 2.1. Composition of commercial UHPC (83,84).

Materials (kg/m^3)	BCV[1]	BSI[1]	Cemtec[1]	Ductal	DURA
Portland cement	2115	1114	1050	712	911
Fine sand	(Premix)	1072	514	1020	911
SF		169	268	231	225
Ground quartz		–	–	211	–
Accelerator	–	–	–	30	–
Steel fibers	156	234	858	156	173
SP	21.5	40	44	30.7	38
Water	159	211	180	109	200

2.7.1 Mixing In practice,

UHPC has been produced with twin-shaft batch mixers, pan mixers and planetary mixers with extra paddles and also intensive mixers. The prerequisite is a sufficiently high mixing energy in order to solubilize the high proportion of ultrafine particles and wet the particle sadequately with water and superplasticizer. When using a pan mixer, it is important to ensure that no ultrafine materials accumulate on the walls and bottom of the mixer because this alters the formulation of the mix.. Intensive mixers have proved to be particularly good at achieving homogeneous mixing of the combination of fine particles, especially for fine-grained UHPC and in both laboratory and practical applications. In mixing procedure, first of all the dry materials are put into the mixer – preferably any coarse aggregate first, then the fine powdery constituents – and premixed dry for between about 5 to 10min. Next, the water plus the superplasticizer is added. The mixing time necessary to achieve a stable,workable consistency must be established in each individual case. Experience shows that it can lie between 15 to 20 min. and depends on the type of mixer and mixing action, the size of the batch, the degree of filling of the mixer, the temperature and, above all, the time the superplasticizer needs to produce the necessary fluidity. Further, the mixing time depends on how long it takes to introduce the well-separated fibres into the fluid concrete and mix them in generaly 2 to 3 min is sufficient. It must also be ensured that the consistency desired for workability really is stable once mixing has ended and that no further fluidization takes place. The fluidization of the concrete can be speeded up by using a high mixing speed up to fluidization and then continuing to mix at a lower speed as the fibres are added. Fig 3.1 shows the typical mixing procedure Detailed information on the mixing of UHPC and how the ultrafine components and the concentration of solids affect the mixing time can be found in [48].

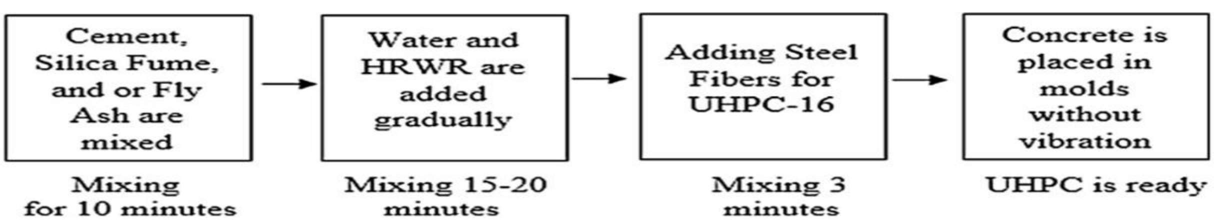


Fig. 3.1. Flow chart for mixing procedure.

2.7.2 Curing and heat treatment

The curing of UHPC already begins during its production. As a consequence of its very low water content, the immediate surface dries very quickly and a dense, tough'elephant skin' just a few tenths of a millimetre thick frequently already starts to form during the longer compaction time needed for UHPC. This prevents deaeration of the concrete and also prevents the surface from being levelled further. The skin can be avoided if open concrete surfaces are covered with plastic sheeting immediately after concreting, an effective curing agent is sprayed over the whole surface or water is applied as a finemist to form a film on the surface. Components made from UHPC are currently mainly produced in precasting plants. As a rule they are heat treated at about 80–90°C, after which no more hydration takes place. The compressive and flexural tensile strengths are therefore higher and the microstructure denser than in the case of curing with water. In addition, no further shrinkage takes place after the heat treatment and the precast elements are dimensionally accurate and free from shrinkage stresses. Generally, the components, or test specimens, are left in the mould for 24h and covered with sheeting before being heated for 2 to 3 days. Heating for longer has no effect. During the heat treatment, the concrete should be covered airtight and thus protected against drying out completely. It is important to ensure that the components are allowed to cool slowly after the heat treatment, e.g. further storage covered in sheeting (also thermal insulation in the event of low temperatures), in order to prevent micro cracks.

2.7.3 Compressive strength

UHPC's principal characteristic is its high strength (>150N/mm2). However, so far there has been no unique definition of a compressive strength class for UHPC. In a similar way to DIN 1045-2, the 28-day compressive strength according to DIN EN 12390-3 could be used, tested on 150mm dia.×300mm high cylinders or 150mm cubes stored in water. But the fact is that almost all UHPC structural elements are currently heat treated at 80–90°C. The compressive strength of heat-treated UHPC is generally about 20–30 N/mm^2 higher than otherwise identical components stored in water..

2.8 Applications of UHPC

The excellent performance of UHPC offers new opportunities for infrastructure works, building constructions with increasing number of applications seen in the recent years. According to the market research reported by Grand View Research (GVR), the UHPC global market size was valued at USD$ 892 million in 2016 and this number is expected to grow by 8.6% to USD$ 1867.3 million in 2025 [85]. UHPC has become a worldwide attention with its commercialization available in many countries, such as Australia and New Zealand [86]. Within the last two decades, extensive research projects had been conducted by the academics and engineers around the world in order to industrialize UHPC technology as the future sustainable construction material [87].

2.8.1 Infrastructures

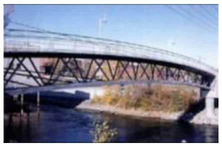
First research and development aiming at the application of UHPC in constructions started around 1985 [88]. Since then, different technical solutions and UHPC formulations were made available to meet the specific requirements of an individual designs, constructions, and architectural approaches. Breakthroughs in UHPC application include the very first prestressed hybrid pedestrian bridge over the Magog River in Sherbrooke, Canada (Table 2.2) built in 1997 [14], the replacement of corroded steel beams in the aggressive environment of Cattenom and Civaux nuclear cooling towers in France [89] and Bourg-les-Valence bridge made for cars and trucks in France constructed in 2001 [90]. Many investigations had been conducted on the optimal designs with UHPC elements, resulting in the development and construction of the UHPC bridges all over the world. In 2002, the Seonyu footbridge in South Korea was constructed using UHPC with a main span of 120 m and was completed in 2004 (Table 2.2) [91]. Being the world's longest span bridge constructed using UHPC, the construction of Seonyu footbridge structure required only about half the material amount that would have been used in traditional concrete construction and yet provides equivalent strength properties [27]. In Japan, the 50 m-span Sakata-Mirai footbridge was completed in 2003. The bridge demonstrated how a perforated web in a UHPC superstructure can both reduce the structure's weight and at the same time can be aesthetically pleasing [92]. The first road bridges to be constructed using UHPC technology make its presence in 2005, with four bridges were constructed around the same time. The Shepherd's Gully bridge located in Australia [93], Bourd-les-Valence bridge in France [94]. Mars Hill Bridge in Wapello Country Iowa was the first UHPC road bridge constructed in the US in 2006 (Table 2) [95]. In 2008, the world's first segmental UHPC composite deck road bridge was constructed at Tokyo International Airport making it the largest UHPC road bridge in the world [92].

According to the United States Federal Highway Administration (FHWA) report published in 2013, a total of 55 bridges using UHPC have been built or are under construction in the US and Canada. There are about 22 UHPC bridges in Europe and 27 UHPC bridges throughout Asia and Australia [24]. Most UHPC structures require only half the section depth of the conventional reinforced or pre-stressed concrete members, which reduces its weight by up to 70% [96]. This lighter weight construction and materials efficiency used in UHPC structures leads to a sustainable structure through its lower carbon footprints [97].

2.8.2 Buildings

In the last decade, UHPC has also gained interest on the field of building components, such as sunshades, cladding, and roof components. UHPC was selected due to its ability to produce slender, light, durable, and aesthetic structures. Among the latest buildings adopting UHPC technology is the Foundation Louis Vuitton pour la Creation in Paris as shown in Table 2 [98]. Completed in 2014, this project is characterized by its high geometric complexity. Another great example is the Museum of European and Mediterranean Civilizations (MUCEM) [99] as shown in Table 2, located at the port area of Marseille in France. It is the first building in the world to make such extensive use of UHPC. As mentioned earlier, UHPC can also be used in roofs and canopies as seen in Shawnessy LRT station in Canada (Table 2).

Table 2.2. Complete UHPC work World Wide.

Location	Application	Year	Advantages	Image
Sherbrooke, Canada	Pedestrian bridg	1997	● 1st UHPC structure	
Seonyu, Seoul, South Korea	Footbridge	2004	● Arch bridge with reduced segments	
Shawnessy LRT Station, Canada	Roof	2004	● Little maintenance 1. Light weight 2. Easy construction	
Bourg-les-Valence, France	Road bridge	2005	90 % reduction on steel reinforcement 1. Lighter structure with 66 % weight reduction than CC	
Mars Hill Bridge, United	Road bridge	2006	● 1st UHPC highway bridge in US	

States			1. Simple construction 2. No shear reinforcement	
MUCEM, Marseille, France	Column & Façade	2013	● Unique design • Y-shaped column • ‘Transparent’ façade	
Jean Bouin Stadium, Paris	Roof & Façade	2013	● Precast UHPC elements • Waterproof roof and façade • Slender structure with unique design	
Foundation Louis Vuitton, France	Cladding UHPC panels	2014	● Innovative design	

2.8.3 Non-structural products

Due to its excellent properties, UHPC has been widely used as an overlay to repair existing concrete structures, improving its mechanical and durability properties for lesser maintenance work [100]. The first application on UHPC overlay was reported on a bridge over the La Morge River in Switzerland [101]. The severely damaged bridge deck and curbs were replaced with UHPC. No cracks were observed on the prefabricated UHPC curb after 1 year of its application. The hydraulic structures repair and rehabilitation using UHPC was done in the Hosokawa River Tunnel in Japan [102], Caderousse and Beaucaire Dams in France [103].

UHPC has the potential to be used for special conditions due to its excellent properties of high flexural strength and dense microstructure. It has been reported that, UHPC was used for cover plates along the high-speed railways in China [104], and for the retrofit of the nuclear reactor containment walls in France [105]. UHPC usage has also been seen in marine areas for its great resistance to the aggressive agents. Several windmills in the sea have been successfully designed as reported by previous researchers [106]. In Japan, the Haneda Airport was extended by using a huge UHPC slab constructed over the sea [92]. To date, this construction is the largest UHPC project realized. The excellent performance of UHPC is responsible for its large potential in various applications, however many have yet to be discovered to utilize its increased strength, durability, and flexural capacity. UHPC is the future construction material, it is here to stay and will grow continuously throughout the world.

2.8.4 Further potential applications

Using UHPC in marine structures is one of the solutions to prevent corrosion of the reinforcement because of its excellent durability allowing great resistance to chloride. Applications of UHPC in marine structures have been reported with promising results [92,99,107]. Most cross-sea bridges built with UHPC exhibit much lower weight, better durability, lower maintenance, and simplified implementation with less cross-section members gives the possibilities of UHPC to be applied in more severe environmental conditions. The ductile behavior of UHPC makes it possible to be used for buildings and structures in seismic regions [108]. It has been reported that, the reinforced UHPC columns or beams were able to dissipate higher energy compared to normal reinforced concrete during the earthquakes, preventing it from collapsing. The high impact resistance of UHPC was also studied and the potential of it to be used in piles was investigated; Two H-shaped precast concrete piles were successfully driven into clay soils and tested under both vertical and lateral loads [109].

The excellent workability enables UHPC to be cast into any shapes. Hence, UHPC blocks with different shapes could be precast. These blocks could be assembled into a structure, just like a jigsaw puzzle. Japan has started the fundamental studies on this concept in the effort to revolutionizing the construction industry [110]. Since UHPC shows very good application prospects, more and more innovative UHPC applications can be seen in the near future.

2.9 Outlook for UHPC Future

Since cost and workability are the two major obstacles, the future of UHPC depends on some breakthrough on these two fronts. Apart from workability, the popularity of a material is affected by its cost. The less a material costs, the more it will be used. The Bessemer and Open Hearth Steel processing in the 1850s made the steel available in large quantities and at affordable prices. Its applications started to mushroom. That was also the time people started thinking of putting steel in concrete to improve its properties. UHPC probably needs a similar breakthrough in construction technology to push it into popular applications. At the present time, the high cost of material is a major hindrance to its widespread use.

On the other hand, if we think of UHPC as concrete, it must be able to work like concrete. This is another major constraint in actual applications. First, UHPC requires much more attention and special equipment to ensure its quality. Second, for today's construction, high strength is usually not very important because all concrete structural elements must have a certain minimum dimension to be workable. Consequently, to fully utilize the capacity of UHPC, we must develop new applications. The very high strength of UHPC will not be necessary if we keep using it on existing types of structures. As indicated by the history, new forms of structures will be developed for a new type of material. This will require us to think "outside the box" to find more appropriate applications that are different from the prevailing forms, just like the application of high strength wires for long span suspension bridges and prestressed concrete structures.

2.9.1 Conclusion

UHPC is a fascinating new material featuring outstanding properties with extraordinary strengths and excellent durability achieved through homogeneity and packing density improvements. Since its introduction in the early 1990s, a great accumulation of knowledge on the material, design, and construction of UHPC structures have been gained with various countries having attempted to introduce it to building and bridge applications. Technical recommendations have been published in France, Japan, Germany, and Switzerland These new standards allow clear and codified specifications, which is anticipated to help further acceptance of UHPC at the international level. For the optimization of UHPFRC materials apart from numerical methods and model water demand methods can be a better alternate. In these methods actual properties of the materials are taken under consideration as compare to various numerical methods and models. Depending upon purity, MK can be an effective pozzolan if used in cement-based system, in that it leads to strength enhancement, lower drying shrinkage, and higher durability. Successful achievements on the application of UHPC can be seen throughout the world. However, UHPC is seeing slow with barriers limiting its applications. High initial cost, limited codes, design difficulties, and complex fabrication technique together with the limited available resources severely hampered its commercial development and application in modern construction industry, especially in the developing countries.

CHAPTER 3

MATERIALS AND EXPERIMENTAL PROGRAME

3.1 Introduction

This chapter describes the experimental program and the constituent materials that were used for the production of UHPC. The experimental program consists of two phases. The first phase involves determining the packing density for different binary combinations. In the second phase, compressive strength was determined for mixtures which showed maximum packing density. In the first phase binary mix was finalized. Puntke method [82] was adopted for determining the packing density of binary mixtures. The basic principle of Puntke test is that the water added to the dry mixture fills the voids between the particles of the mixture and acts as a lubricant which leads to improve the compactness of the mixture. After filling all the voids excess water starts to appear on the surface which indicates the saturation limit. Preliminary mixes were cast with Hobart mixtures. Puntke test was used for the determination of an appropriate combination of fine aggregates and fillers that would correspond to the lowest water demand and the highest packing density. This investigation was useful in getting an appropriate amount of the mixture components which will lead to a mix with excellent compressive strength. The influence of the following components on the packing density and mechanical properties of the mix was evaluated during first and second face respectively.

3.2 Material used

Production of UHPC is required mineral admixtures, binders and fillers silica fume. The cement, silica fume,metakaolin and ultra fine slag constitute the binder component of the mix while quartz fillers and fine sand constitute the aggregate component of the mix. Due to a very low water to binder ratio superplasticizer is also added to the mix. The effect of steel fibers is also studied in this research project. The detailed description of these materials is described in this section. Specific gravity and chemical composition of materials are given in Table 3.1 and Fig. 3.1 shows the material used. Table 3.2 shows the Blain surface area of cementitious material.

1. Cement 2. Metakaolin 3. Ultra fine Slag 4. Silica fume 5. Quartz Powder 6. Quartz Sand 7. Manufactured Sand.

Fig. 3.1. Types of materials.

Table 3.1. Specific gravity and chemical composition of materials.

Material	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O_3**	**K_2O**	**SO_3**	**Specific Gravity**
OPC43	22.60	4.30	2.40	64.40	2.10	0.12	0.40	2.30	3.15
Metakaolin	57.10	34.46	3.94	1.24	1.28	0.3	0.08	-	2.5
Silica fume	97	0.2	0.5	0.2	0.5	0.2	0.5	0.15	2.22
UFS	22	5.4	4.2	63	1.1	-	-	2.3	2.83

Table 3.2. Blain surface area of cementitious material.

Material	**Blain surface area (m^2/kg)**
OPC53	360
Metakaolin	350
Silica fume	>15000
UFS	>1200

3.2.1 Cement

Cement is a fine, grey powder. It is mixed with water and materials such as sand, gravel, and natural stone to make concrete. The cement and water form a paste that binds the other materials together as the concrete hardens. The cement contains two basic ingredients, namely argillaceous and calcareous. IS mark 43 grade cement (Brand- Ambuja cement) was used for all mixes. The cement used was fresh and without any lumps. Testing of cement was done as per IS: 8112-1989. The various test results conducted on the cement are reported in Table 3.3.

Table 3.3. Properties of cement.

S.No.	Characteristics	Values Obtained	Standard values
1.	Normal consistency	31 %	-
2.	Initial setting time (minutes)	90 min.	Not less than 30
3.	Final setting time (minutes)	255 min.	Not greater than 600
4.	Fineness (%)	3.5 %	<10
5.	Specific gravity	3.125	-

3.2.2 Fine aggregates

Coarse aggregates were not used in the mixes to avoid weak zones (ITZ). Although the maximum size of the particles is ~ 600 microns.The natural sand used for the experimental program was locally procured and conformed to Indian Standard Specifications IS: 383-1970 and IS 2116-1980 and has the particle range from 300 to 600 microns. The sand was first sieved through 4.75 mm sieve to remove any particles greater than 4.75 mm and remove the dust. Properties of the fine aggregate used in the experimental work are tabulated in Table 3.4. The aggregates were sieved through a set of sieves to obtain sieve analysis and the same is presented in Table 3.5.

Table 3.4. Properties of fine aggregates.

Material	Specific gravity	Water absorption %
Quartz powder	2.65	Nil
Quartz sand	2.34	Nil
Natural sand	2.6	1

Table 3.5. Sieve analysis of Fine aggregates.

Sieve size	Weight retained (g)	Weight retained (%)	Cumulative Weight (%)
4.75 mm	3	0.3	0.3
2.36 mm	19.5	1.95	2.25
1.18 mm	46.5	4.65	6.9
600 µ	67.5	6.75	13.65
300 µ	132	13.2	26.85
150 µ	520	52	78.85
Pan	211.5	21.15	100
		ΣF = 228.77	

Fineness modulus of Fine aggregates= ΣF/100= 228.77/ 100= 2.28

3.2.3 Quartz Powder

Quartz is a hard, crystalline mineral composed of silicon and oxygen atoms. The atoms are linked in a continuous framework of SiO_4 silicon–oxygen tetrahedral, with each oxygen being shared between two tetrahedral, giving an overall chemical formula of SiO_2. Quartz is the second most abundant mineral in Earth's crust. Quartz powder used has a particle size range from 5 to 25 microns.

3.2.4 Quartz Sand

Quartz is the most important sand-forming mineral because it is resistant to both physical and chemical weathering. Sand that is enriched in quartz is likely old (mature) and has traveled far from the source area, sometimes thousands of kilometers. Long journey is required to allow weathering to break down weaker minerals that were initially present in the rocks. Quartz sand used has a particle size range from 150 to 300 microns.

3.2.5 Metakaolin

Metakaolin confirming to IS 1727 (2018) procured from the Kaomin Industries LLP, Vadodra, Gujarat. Metakaolin is procured from KaoMin Industries, it is produced by heating kaolin to a temperature between 650-900^{0}C. The calcinations make it highly reactive.

3.2.6 Ultra Fine Slag and Silica Fume

Ultra fine slag by the name of ALCCOFINE 1203, is a low calcium silicate based mineral additive and improves the packing density of paste. Its application complies with IRC:SP:70 (2016), IS 456 (2000), IS 12089:1987.

Silica fume, also known as microsilica is an amorphous (non-crystalline) polymorph of silicon dioxide, silica. It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm. The main field of application is as pozzolanic material for high performance concrete.Silica fume is an ultra fine material with spherical particles than 1 micrometer in diameter, this makes it approximately 100 times smaller than the average cement particle and it is confirmed to IS 15388 (2003).

3.2.7 Water

Water free from deleterious materials viz. oil and other impurities were used for casting of concrete specimens. The water was found suitable for concrete mixing and curing as per IS:456-2000 requirements.

3.2.8 Superplasticizer

CHRYSO® fluid premia S5-30 is a water reducing generation superplasticiser, due to its dispersion of cement, produces a reduction of the water/cement ratio or an increase in the workability for a constant water/ cement ratio. It increases the density of fresh concrete. High early and ultimate compressive strengths can be obtained due to its weak retarding action and the effect it has on the hydration of the cement. It is third-generation poly-carboxylic ether superplasticizer was used. The properties of superplasticizer are well confirmed to the requirement mentioned in the IS: 9103-1999 with the help of technical sheets provided by the supplier. It was dark brown in colour with specific gravity of 1.05.

3.2.9 Fibers

Due to the nature of the material, concrete is extremely brittle showing a sudden loss of carrying capacity after the maximum load is exceeded. The addition of fibers, improved the post fracture nature of the material. Crimped shape fibers are used as shown in Fig. 2. The post fracture behavior is governed by the type and amount of fibers introduced into the mix. Fiber specification is shown in the following Table 3.6.

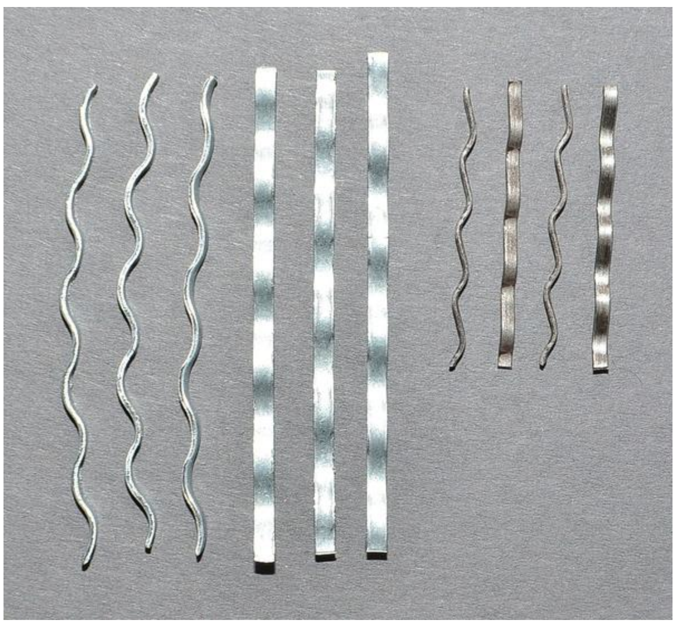


Fig. 3.2. Crimped fibers.

Table 3.6. Fiber specification.

Name of fiber	Cube labels	Specification of fiber	Diameter (d) mm
		Length (mm)	
Steel fiber	M2	8 - 10	0.45
Steel fiber	M3	12 – 15	0.45
Steel fiber (Hybrid)	M4	8 - 15	0.45

3.3 Mix Design:

The optimization procedure of UHPC is a complex task due to the fact that it contains a large amount of binders, fillers and superplasticizers. In order to develop an optimization procedure, a large number of tests were carried out, and relationships were developed between water demand through Puntke tests, and mechanical properties through compressive strength tests. The basic concept was to develop a mix, with excellent compressive strength. In this experiment partial replacement of cement was done with respect to metakaolin (30 %) because after performing the puntke test metakaolin showed the maximum replacement with respect to the cement content as compared to other binary mixtures. Material used are cement, metakaolin, quartz powder, quartz sand, natural sand, superplasticizer and fibers. The main components consist of cementitious paste and sand. The sand used in this study is of two types, quartz sand and natural sand. Quartz powder is used to further increase the density of the mix. The mix design has been prepared for the mixes by keeping the cement content at 630 and 910 kg/m^3. Optimization of mix design was confirmed by the compressive strength test. Coarse aggregates were not used in the mixes because the basic concept for obtaining high performance concrete is to make the matrix as dense as possible and avoid weak zones (ITZ). The densification is possible by the complete elimination of coarse aggregates. Although the maximum size of the particles is ~ 600 microns.

3.3.1 Puntke Test: Puntke [82], developed a procedure to determine the water demand of the dry particle system. The water demand of the dry particle system is used to calculate the packing density of the mix. The water demand determined using this test consists of filling water and adsorbed water. The adsorbed water determines the fluidity of the mix and the filling water determines the packing density. The water demand is found by taking a small amount of the dry powder (50-100g) in a beaker and thoroughly mixing it. Water is added and the container is dropped from a certain height repeatedly until visible moistening on the surface of the material is absorbed. If wetting does not take place, more water is added and the container is dropped again in the same fashion. The water demand calculation is required for calculating the packing density of the mix, which results in obtaining the appropriate amount of material components for the mixes.

3.3.2 Optimization procedure of UHPC

Mixing percentage of mineral admixtures were prepared on the basis of packing density method. Binary mixture was prepared and the percentage replacement was chosen on the basis of samples which gave the higher density. So 70% cement and 30 % metakaolin were choosed and experiment was performed on it. The change in the component percentages of corresponding mixes is listed in Table 3.7,3.9,4.1,4.3,4.5,4.7,4,9,5.1,5.3,5.5,5.7,5.9 and 6.1 and their respective mix proportion are listed in Table 3.8,4,4.2,4.4,4.6,4.8,5,5.2,5.4,5.6,5.8,6,6.2 correspondingly. Four paste mixtures were investigated and labeled as M1, M2, M3, M4 for each and every mix, Quartz powder, quartz sand, natural sand were used as filler in the mix. Where M1 is without fibers and M2, M3, M4 have the different fiber specification as shown in Table 3.6. A polycarboxylate based superplasticizer admixture was used with different percentages. Trial mix1 to Trial mix 6 are taken under CASE 1 and Trial mix 7 to trial mix 10 are taken under Case 2. In Case 3 and Case 4, Trial mix 11, Trial mix 12 and Trial mix 13 are taken respectively.

Case 1

In this case total cementitious material is 900 kg/m^3 and cement content is 630 kg/m^3 (70% cement + 30% metakaolin of the total cementitious material) other percentages used for other materials are listed in Table 3.7, 3.9, 4.1, 4.3, 4.5, 4.7 and corresponding mix proportions are shown in the following tables. In each trial mix only fiber percentages vary from 1.5% to 4% other material percentages are remain same in all the mixes. Initial percentages of this mix are taken from the knowledge of previous researches. The ultimate motto of optimization is to get a high strength mix.

Trial mix 1

Table 3.7. Components.

Material	**Value**
Total cementitios material	900 kg/m^3
Steel fiber	1.5 %
w/c	0.25
Superplasticizer	3%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 3.8. Mix proportion (kg/m^3).

Mix	**Cement**	**water**	**NS**	**QP**	**QS**	**MK**	**Steel fiber (8 -10 mm)**	**Steel fiber (12 -15 mm)**	**SP (3%)**
M1	630	225	541	240	515	270	0	0	27
M2	630	225	541	240	515	270	36.72	0	27
M3	630	225	541	240	515	270	0	36.72	27
M4	630	225	541	240	515	270	18.36	18.36	27

Trial mix 2

Table 3.9. Components.

Material	**Value**
Total cementitios material	900 kg/m^3
Steel fiber	**2%**
w/c	0.25
Superplasticizer	3%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 4. Mix proportion (kg/m^3).

Mix	Cement	Water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP (3%)
M1	630	225	541	240	515	270	0	0	27
M2	630	225	541	240	515	270	48.96	0	27
M3	630	225	541	240	515	270	0	48.6	27
M4	630	225	541	240	515	270	24.48	24.48	27

Trial mix 3

Table 4.1. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**2.5%**
w/c	0.25
Superplasticizer	3%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 4.2. Mix proportion (kg/m^3).

Mix	Cement	Water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	225	541	240	515	270	0	0	27
M2	630	225	541	240	515	270	61.2	0	27
M3	630	225	541	240	515	270	0	61.2	27
M4	630	225	541	240	515	270	30.6	30.6	27

Trial mix 4

Table 4.3. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**3%**
w/c	0.25
Superplasticizer	3%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 4.4. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	225	541	240	515	270	0	0	27
M2	630	225	541	240	515	270	73.44	0	27
M3	630	225	541	240	515	270	0	73.44	27
M4	630	225	541	240	515	270	36.72	36.72	27

Trial mix 5

Table 4.5. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**3.5%**
w/c	0.25
Superplasticizer	3%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 4.6. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	225	541	240	515	270	0	0	27
M2	630	225	541	240	515	270	85.68	0	27
M3	630	225	541	240	515	270	0	85.68	27
M4	630	225	541	240	515	270	42.84	42.84	27

Trial mix 6

Table 4.7. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**4%**
w/c	0.25
Superplasticizer	3%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 4.8. Mix proportion (kg/m^3).

Mix	Cement Kg/m^3	Water Kg/m^3	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	225	541	240	515	270	0	0	27
M2	630	225	541	240	515	270	97.5	0	27
M3	630	225	541	240	515	270	0	97.2	27
M4	630	225	541	240	515	270	48.6	48.6	27

Case 2

In this case total cementitious material is 900 kg/m^3 and cement content is 630 kg/m^3 (70% cement + 30% metakaolin of the total cementitious material) other percentages used for other materials are listed in Table 4.9, 5.1, 5.3, 5.5 and corresponding mix proportions are shown in the following tables. In trial mixes fiber percentages used are 2.5%, 3%, 3.5% and 4%. In this case percentage of superplasticizer is taking 5% in all the mixes.

Trial mix 7

Table 4.9. Components.

Material	**Value**
Total cementitios material	900 kg/m^3
Steel fiber	**2.5%**
w/c	0.25
Superplasticizer	5%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 5. Mix proportion (kg/m^3).

Mix	**Cement**	**water**	**NS**	**QP**	**QS**	**MK**	**Steel fiber (8 -10 mm)**	**Steel fiber (12 -15 mm)**	**SP**
M1	630	210	541	240	515	270	0	0	45
M2	630	210	541	240	515	270	61.2	0	45
M3	630	210	541	240	515	270	0	61.2	45
M4	630	210	541	240	515	270	30.6	30.6	45

Trial mix 8

Table 5.1. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**3%**
w/c	0.25
Superplasticizer	5%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 5.2. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	210	541	240	515	270	0	0	45
M2	630	210	541	240	515	270	73.58	0	45
M3	630	210	541	240	515	270	0	73.58	45
M4	630	210	541	240	515	270	36.79	36.79	45

Trial mix 9

Table 5.3. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**3.5%**
w/c	0.25
Superplasticizer	5%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 5.4. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	210	541	240	515	270	0	0	45
M2	630	210	541	240	515	270	85.7	0	45
M3	630	210	541	240	515	270	0	85.7	45
M4	630	210	541	240	515	270	42.89	42.89	45

Trial mix 10

Table 5.5. Components.

Material	Value
Total cementitios material	900 kg/m^3
Steel fiber	**4%**
w/c	0.25
Superplasticizer	5%
Quartz powder	5%
Quartz sand	50%
Natural sand	50%

Table 5.6. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	630	210	541	240	515	270	0	0	45
M2	630	210	541	240	515	270	98.04	0	45
M3	630	210	541	240	515	270	0	98.04	45
M4	630	210	541	240	515	270	49.02	49.02	45

Case 3

In this case total cementitious material is 1300 kg/m^3 and cement content is 910 kg/m^3 (70% cement + 30% metakaolin of total cementitious material) other percentages used for other materials are listed in Table 5.7, 5.9 and corresponding mix proportions are shown in following tables. In trial mixes fiber percentages used are 1.5% and 2%. In this case percentage of superplasticizer is taken 4% in all the mixes.

Trial mix 11

Table 5.7. Components.

Material	Value
Total cementitios material	**1300 kg/m^3**
Steel fiber	**1.5%**
w/c	**0.22**
Superplasticizer	**4%**
Quartz powder	**25%**
Quartz sand	50%
Natural sand	50%

Table 5.8. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	910	278	286	181	276	390	0	0	52
M2	910	278	286	181	276	390	35.59	0	52
M3	910	278	286	181	276	390	0	35.59	52
M4	910	278	286	181	276	390	17.7	17.7	52

Trial mix 12

Table 5.9. Components.

Material	Value
Total cementitios material	**1300 kg/m^3**
Steel fiber	**2%**
w/c	**0.22**
Superplasticizer	**4%**
Quartz powder	**25%**
Quartz sand	50%
Natural sand	50%

Table 6. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	910	278	286	181	276	390	0	0	52
M2	910	278	286	181	276	390	47.46	0	52
M3	910	278	286	181	276	390	0	47.46	52
M4	910	278	286	181	276	390	23.73	23.73	52

Case 4

In this case total cementitious material is 1300 kg/m^3 and cement content is 910 kg/m^3 (70% cement + 30% metakaolin of the total cementitious material) other percentages used for other materials are listed in Table 6.1 and corresponding mix proportions are shown in the following tables. In trial mixes fiber percentage used was 4% because the trial mix 10 showed the higher compressive strength as compare to other trial mix as shown in Table 4.2 in chapter 4. In this mix more optimize percentages was used as used in Trial mix 10. This trial mix is an upgraded mix version of Trial mix 10.

Trial mix 13

Table 6.1. Components.

Material	Value
Total cementitios material	**1300 kg/m^3**
Steel fiber	**4%**
w/c	**0.22**
Superplasticizer	**4%**
Quartz powder	**30%**
Quartz sand	50%
Natural sand	50%

Table 6.2. Mix proportion (kg/m^3).

Mix	Cement	water	NS	QP	QS	MK	Steel fiber (8 -10 mm)	Steel fiber (12 -15 mm)	SP
M1	910	278	269	217	259	390	0	0	52
M2	910	278	286	181	276	390	95	0	52
M3	910	278	286	181	276	390	0	95	52
M4	910	278	286	181	276	390	47.48	47.48	52

3.4 Production and Mixing procedure

3.4.1 Mixing

The mixing efficiency and mixing performance depends highly on the mixing procedure and mixer type. For the most efficient and consistent mixing of UHPC electrically driven high energy mechanical mixer has been used successfully as shown in Fig. 3.3. This mixer disperses the water and admixtures onto the cement without heating the mix via kinetic energy created by the mixing process. The procedure followed for mixing of the materials is based on the traditional techniques and recommendation, steps are as follows 1) Materials were weighed according to the mix design prepared, 2) All the constituents were mixed in the dry state with the help by using electrically driven high energy mechanical mixer IS 10890 (2018) of the epicyclic type (imparting both planetary and a revolving motion to the mixer paddle) for approximately 2 minutes, 3) 50% water (calculated water according to water to cementitious ratio) and 50% superplasticizer were added to the mixer and mixed for another 2 minutes, 4) Remaining portion of superplasticizer and water were added and mixed for another 2 min at high speed 5) Materials were mixed at for 2.5 minutes, 6) Further, mixing was carried out for about 1.5 minutes at the higher speed. Till this point of time, thick paste was formed for casting.

Fig. 3.3. Hobart mixer.

3.4.2 Casting

After mixing a standard cube, mould of 70.5 × 70.5 × 70.5 mm, was used, conformed to Indian Standard Specifications 10080-1982. Moulds were placed on the vibrating table. Addition of concrete in mould was done in three phases by filling one third of the mould and vibrating. This process continued till the filling of moulds with concrete. Vibration for the expulsion of air continued for minimum two minutes. A total of 13 trial mixes was performed with four cubes each mix cast. During casting, the mix was filled into the respective mould in three layers providing some vibration to ensure the uniform distribution of steel fiber as shown in Fig. 3.4. The demoulding was done after 24 hours as shown in Fig. 3.7.

Fig. 3.4. Casted cube samples.

3.4.3 Curing

After casting of specimens, the specimens were covered with plastic sheet to avoid the loss of moisture. Cubes were taken out from the moulds after 24 hours. Accelerated curing was used in the experiment to obtain the early high strength. Curing process was done up to 3 days at a temperature of 90^{o} C. Under special requirements (time constraints) to determine the strength of concrete it may not be feasible to wait as long as 28 days, BIS has recommended accelerated curing test (on accelerated-cured concrete test specimens) to determine grade of concrete in about 28 hrs and governed by IS: 9013- 1999.

3.5 Tests Conducted

3.5.1 Particle Packing Density

Principle:- Particle packing density is measured by using Puntke's Test. The basic principle of the test is that the water which is added to the dry materials fills the voids in between the particles and act as a lubricant to make the materials into compact efficiently. The water which is excess after completely filling the voids will be on the surface indicating the saturation limit.

Procedure:- Distilled water is added gradually working the mixture with a stirrer until it acquires a closed structure after the repeated tapping of the beaker. In the next step, water is added drop by drop with a pipette, mixing carefully, until the saturation point is reached as shown in Fig. 3.5. At this point, the surface smoothes itself after repeated tapping of the beaker and appears glossy. The total time taken for each experiment was approximately10 minutes

Fig. 3.5. Glossy Mix.

Fig. 3.6. Dry Mix.

Packing density = (1-Vw)/(Vp+Vw) **(1)**

Vw= Volume of water (cm^3), Vp= Volume of Particle (cm^3)

The various required performance attributes of HPC, including strength, workability, dimensional stability and durability, often impose contradictory requirements on the mix parameters to be adopted, thereby rendering the concrete mix design a very difficult task. The conventional mix design methods are no longer capable of meeting the stringent multiple requirements of HPC. Packing density is a new kind of mix design method used to design different types of concrete. To optimize the particle packing density of the concrete, the particles should be selected to fill up the voids between large particles with smaller particles and so on, in order to obtain a dense and stiff particle structure. Higher degree of particle packing leads to minimum voids, maximum density and requirement of cement and water will be less. In this work the co-relation curves are developed for packing density method between compression strength and water cement ratio, paste content to reduce the time involved in the trial to decide the water cement ratio and paste content for a particular grade of concrete. For the test 3 types of binary combination was adopted which are cement with Ultra fine slag, cement with silica fume and cement with metakaolin. Results are shown in chapter 4, and separate plots are formed for each binary mix, which shows the maximum particle density with respect to percentage replacement of mineral admixture. Replacement which shows the maximum packing density has chosen for mix design.

3.5.2 Compressive strength of Concrete

The compressive strength test was carried out as per IS: 516-1979. In this test three cubes from each mix were tested. The test was carried at the end of 3 days of curing (Accelerated curing). The compressive strength of each mix was taken as the average strength of three cubes. Concrete compressive strength was measured using 70.7 × 70.7 × 70.7 mm^3 cube specimens (Fig. 4), conforming to Indian Standard Specifications IS 4031-part 6 (2019).

Principle: Specimens are loaded to failure in a compression testing machine conforming to IS: 14858 (2000). The compressive strength is calculated from the maximum load sustained by the specimen.

Apparatus: Compression testing machine (Fig. 3.9).

Procedure: The bearing plate was cleaned and the excessive moisture was removed from the sample. The weight of the sample and volume was measured. The specimen was centered with respect to lower platen to an accuracy of 1 % of cube size. Loading rate was selected as per standards. The cubes were loaded till failure and the compressive strength value was noted from the testing machine.

Fig. 3.7. Cubes.

Three samples were tested for each mix and the mean value was termed as the compressive strength of the mix**.** Tested cube specimens are shown in Fig. 3.8.

Fig. 3.8. Tested specimens.

Fig. 3.9. CTM Machine.

Fig. 4. Mould for Mortar cube.

Fig. 4.1 Testing of mortar cube.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the result and observations of the experiments presented in Chapter 3. In the first phase packing density of binary combinations were evaluated. In the second phase, compressive strength was determined for binary combination which showed the maximum packing density The effect of investigated parameters are discussed in details in the following sections.

4.2 Binary mixtures

In this phase partial replacement of cement was done on the mass basis with metakaolin, silica fume, ultrafine slag respectively. Minimum and maximum packing density obtained was 0.56 and 6.0 respectively. The replacement was varied from 2.5% to 30 %. The packing density ranges with the maximum replacement of mineral admixture are shown in Table 4.1.

4.2.1 Cement + Metakaolin

Thirty-seven mixes combinations were assessed. The replacement of cementitious materials was varied from 5 % to 30%. It has been observed that the packing density increased up to 30% replacement levels and then started to decrease as Fig. 4.1 shows the variation in packing density with different replacement levels of cement. It is noted that the increase in fine content in the mix increased the specific surface area and as a result water demand increased. In other words, the interstitial water arrives at its minimum, the overall adsorbed water rises due to the large specific surface area of mineral admixtures. In this case, the packing density was observed in the range of 0.50 to 0.60.

4.2.2 Cement + Silica fume

Results indicated that the minimum water requirement gradually declines as the fine content increased to 17.5%. Since the void content decreased, resulting in increasing levels of compactness. With the further increase in fine particles resulted in increase of water demand and the packing density decreased as as Fig. 4.2 shows the variation in packing density with different replacement levels of cement. Owing to the packing effect of mineral admixture, the packing density of system increased and the interstitial water declines with increasing silica fume. Hence, decreasing the minimum water requirement. The range of packing density observed was in between 0.53 to 0.56.

4.2.3 Cement + Ultra Fine Slag

After 12.5% replacement of cementitious material with cement, the packing density started to decrease as Fig. 4.3 shows the variation in packing density with different replacement levels of cement. More water requirement causes a suspension in the system. In this case, the range of packing density was in the range of 0.52 to 0.59.

Table 4.1. Maximum packing density of trial combinations.

Mix	OPC%	MK%	SF%	UFS%	Packing Density (ϕ)
C+MK	70	30	0	0	0.60
C+SF	82.5	0	17.5	0	0.56
C+UFS	87.5	0	0	12.5	0.59

Note:- C- Cement, MK- Metakaolin, SF- Silica fume, UFS- Ultra Fine Slag.

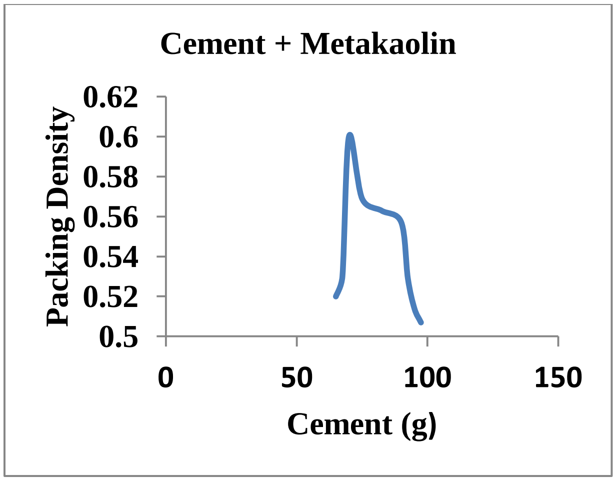


Fig. 4.1. Cement and Metakaolin

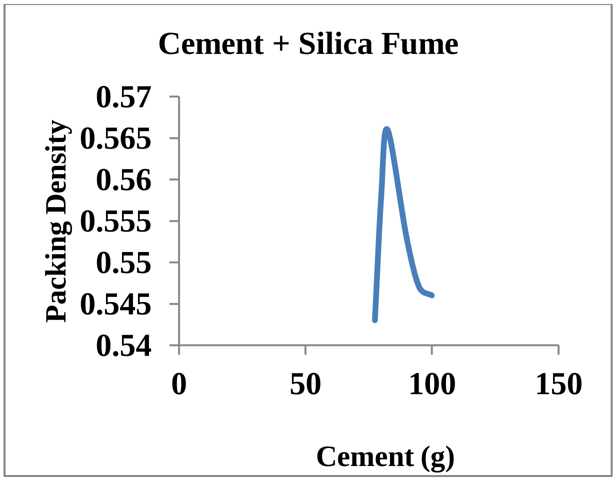


Fig. 4.2. Cement and Silica fume.

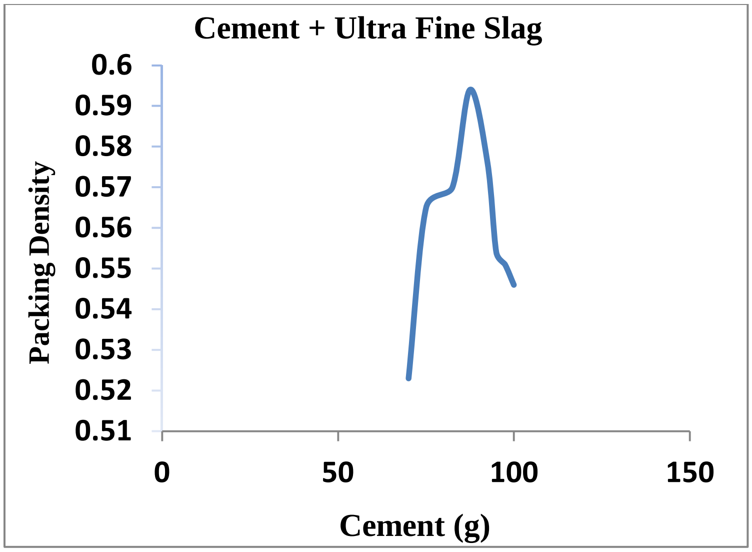


Fig. 4.3. Cement and Ultra Fine Slag

The packing density of the cementitious materials has great impact on the strength of the concrete produced. First of all, the reduction in water demand due to a higher packing density would allow the use of a lower water/cementitious ratio for achieving higher strength. Secondly, better packing would reduce the permeability of the bulk of cementitious materials and thus bleeding of the fresh cement paste. Thirdly, better packing would reduce the porosity of the transition zone by filling up the voids formed as a result of the wall effect of the aggregate with very fine particles. The water requirement increased slightly with the increase in the quantity of the fines in the combination corresponding to the maximum density for a combination. The maximum value of the packing density obtained was 0.60 of the mix which contains 70% cement, 30% metakaolin content. With the increase in the fine content, the requirement of water has also increased by a small amount. Result emphasized that cement and metakaolin (C+MK) showed higher packing density than the cement and silica fume (C+SF) and cement and ultra fine slag (C+UFS) mixtures as shown in Fig. 6. Possible explanation is the fineness and high reactive nature of metakaolin which leads to filling all the voids between the particle and constituted a dense paste. Cement and silica fume (C+SF) mixture showed the lowest packing density among all mixtures. Silica fume did not pack well to give maximum packing density due to its small particle size. Effective packing can be attained by selecting proper proportions and particle size gradation to fill the voids between the larger particles.

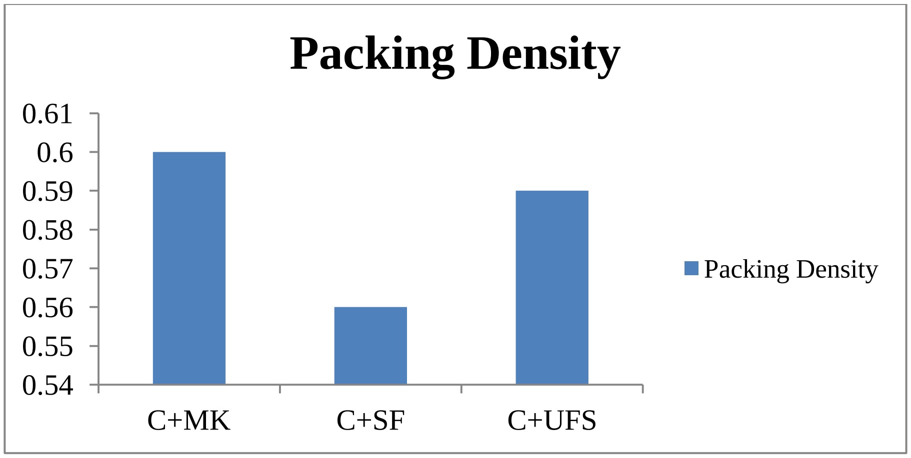


Fig. 4.4. Packing density of different binary mixes.

4.3 Compressive strength

In the second phase, compressive strength was calculated for binary mix which showed the maximum packing density. Combination C+MK was adopted to determine the compressive strength as it possesses the maximum packing density. Table 4.2 summarizes the results of compressive strengths for 13 trial mixtures. Trial mixes are categorized into four cases according to the material percentage used, as discussed in chapter 3.

Table 4.2. Compressive strength of trial mixes.

Trial Mix Number	**Compressive strength (N/mm^2)**	**Average compressive strength (N/mm^2)**
CASE 1		
Trial Mix 1		34.25
M1	24	
M2	35	
M3	37	
M4	41	
Trial Mix 2		38.75
M1	30	
M2	40	
M3	42	
M4	43	
Trial Mix 3		40.5
M1	35	
M2	41	

M3	42	
M4	44	
Trial Mix 4		42.32
M1	36	
M2	50	
M3	48	
M4	35.3	
Trial Mix 5		42.6
M1	40	
M2	46.1	
M3	41.8	
M4	42.52	
Trial Mix 6		48.66
M1	42	
M2	52.36	
M3	44	
M4	56.3	
CASE 2		
Trial Mix 7		41.94
M1	32	
M2	42.9	
M3	40.92	
M4	51.96	
Trial Mix 8		48.5
M1	35	
M2	40.52	
M3	62.19	
M4	56.3	
Trial Mix 9		48.7
M1	38	
M2	55	
M3	52	
M4	50	
Trial Mix 10		58.27
M1	42.93	
M2	71.02	
M3	65.6	
M4	53.56	
CASE 3		
Trial Mix 11		51
M1	41	
M2	51	
M3	58	
M4	54	

Trial Mix 12		54.17
M1	44.53	
M2	54.16	
M3	60	
M4	58	
CASE 4		
Trial Mix 13		93
M1	70	
M2	106.56	
M3	105.61	
M4	90	

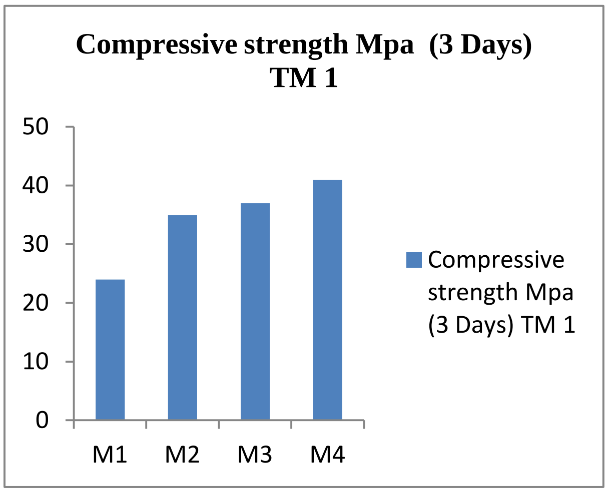


Fig. 4.5. Compressive strength Trial mix 1.

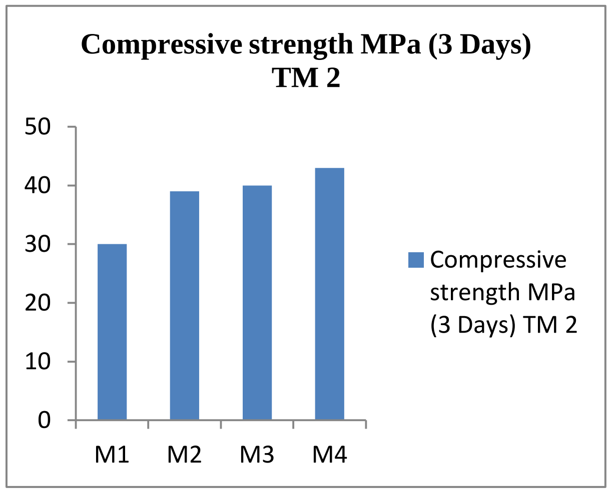


Fig. 4.6. Compressive strength Trial mix 2.

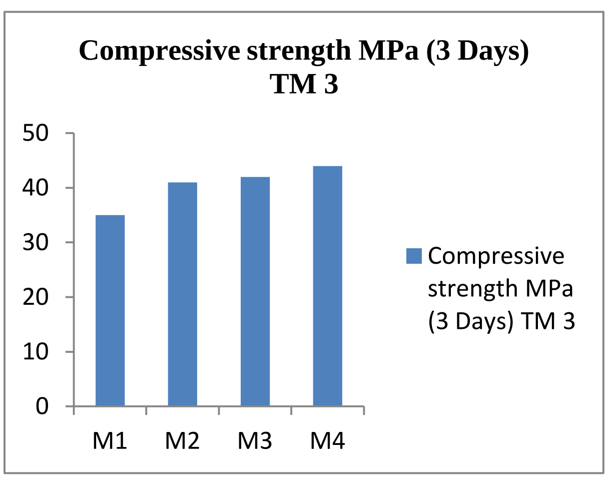


Fig. 4.7. Compressive strength Trial mix 3.

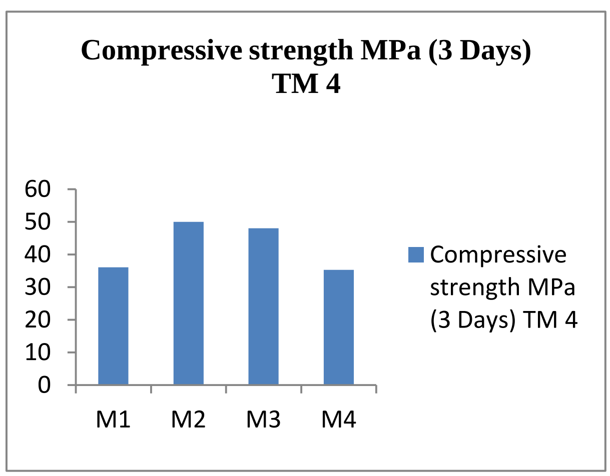


Fig. 4.8. Compressive strength Trial mix 4.

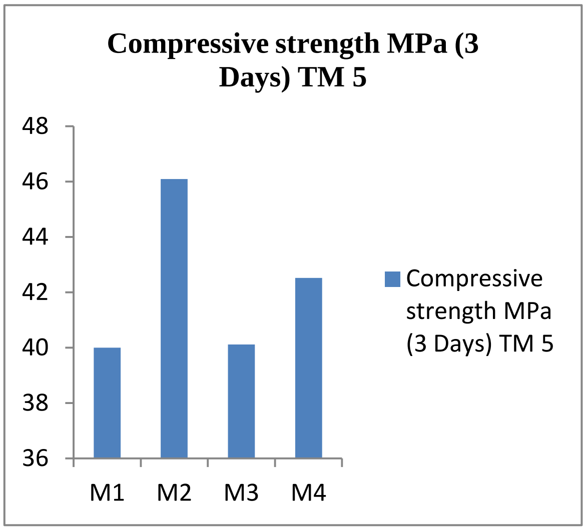


Fig. 4.9. Compressive strength Trial mix 5.

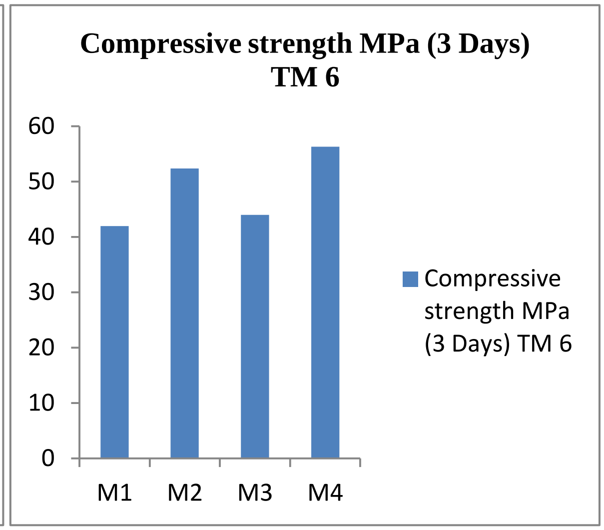


Fig. 5. Compressive strength Trial mix 6.

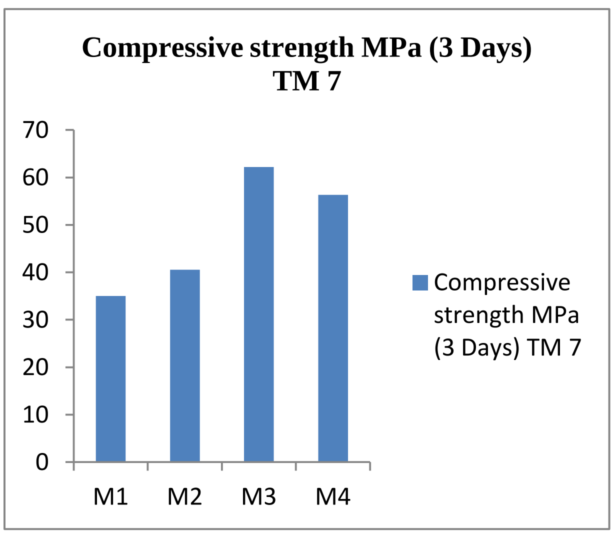


Fig. 5.1. Compressive strength Trial mix 7.

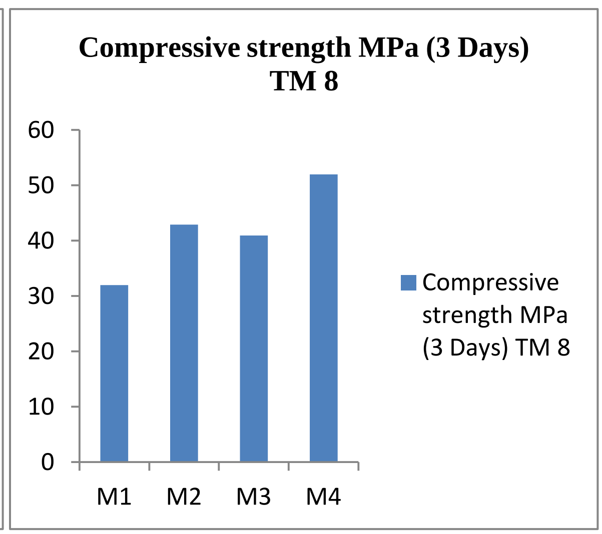
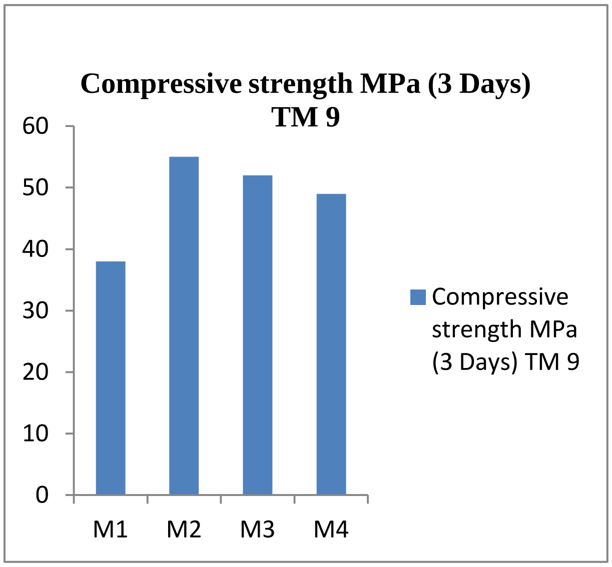


Fig. 5.2. Compressive strength Trial mix 8.



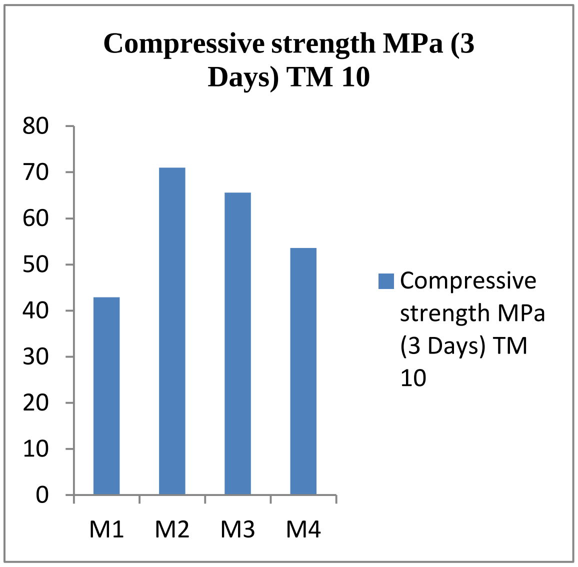
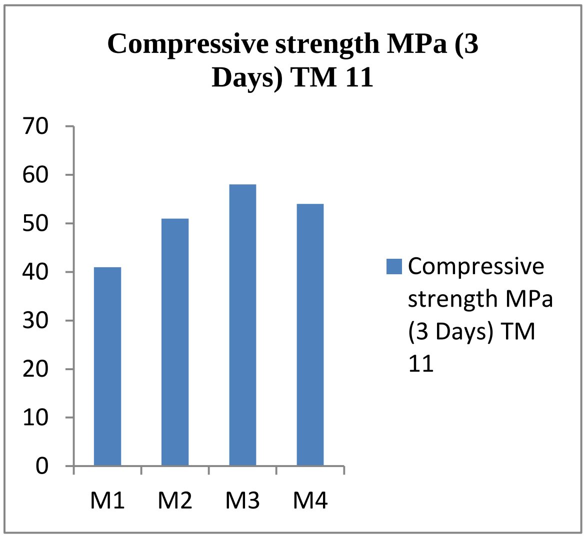


Fig. 5.3. Compressive strength Trial mix 9. **Fig. 5.4.** Compressive strength Trial mix 10.



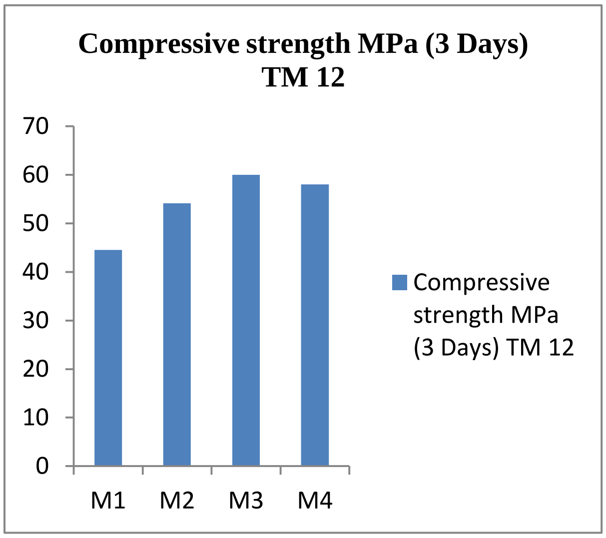


Fig. 5.5. Compressive strength Trial mix 11. **Fig. 5.6.** Compressive strength Trial mix 12.

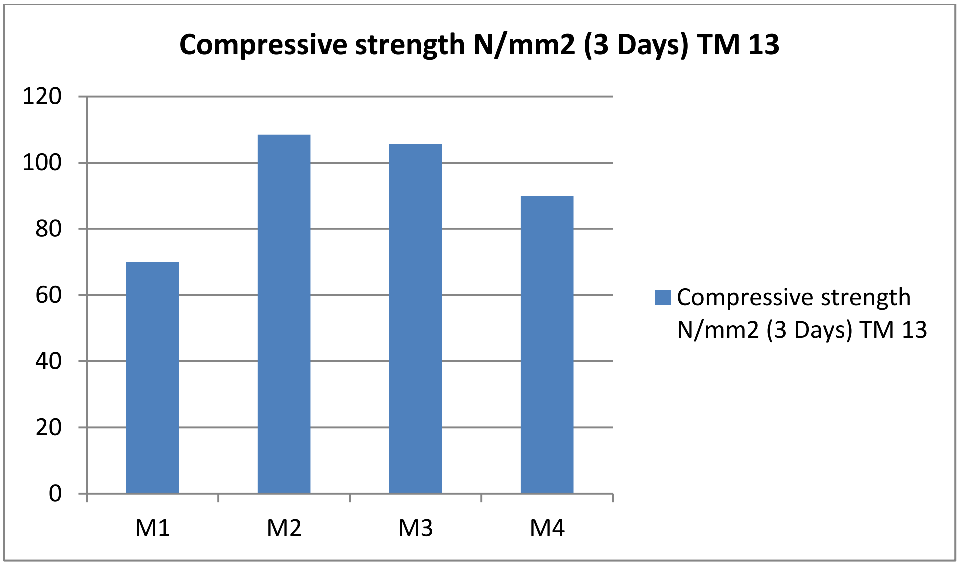


Fig. 5.7. Compressive strength Trial mix 13.

In case 1 and case 2 the total amount of cementitious material is 900 kg/m^3 and in case 3 and case 4 total amount of cementitious material are 1300kg/m^3. Case 1 and case2 have a w/c ratio of 0.25. Case 3 and case 4 have w/c ratio 0.22 respectively. The cementitious materials consisted of 70% cement content and 30 % metakaolin content. The mixture proportions of these mixes are presented in chapter 3 and the results of compressive strength is shown in Table 4.2 and in Fig. 4.5 to Fig. 5.7.

In case 1, it has been observed that when the percentage of fiber increased from 1.5% to 4% in trial mix 1 to trial mix 6 respectively, the compressive strength of samples was also increased as shown in Fig. 4.5 to Fig. 5. In this case the maximum average compressive strength is 48.66 MPa. It is because the fiber addition provides more ductile nature of the sample. But this case did not show the compressive strength which is required for the development UHPC. It is because in this case the value of w/c ratio is high which courses dispersion between the particle and leads to decreases the compressive strength. High water content is responsible for void formation. Another reason is that it is a first phase of the trial, so optimum percentages of material is not sure.

In case 2 the amount of super plasticizer was increased up to 5% for a better cement dispersion, The most optimize amount of superplasticizer interacts with all the fine particles for an overall enhanced dispersion. In this case fiber percentage used was 2.5%, 3%, 3.5% and 4%, which showed the maximum average compressive strength of 58.27 MPa as shown in Table 4.2. Individual trial mix results are shown in Fig. 5.1 to Fig. 5.4. It has been observed that the there was increase in the average compressive strength of 9.61 MPa as compared to case 1.

In case 3 the amount of cementitios material, quartz powder, were increased up to 1300kg/m^3 and 25 % respectively and water cement ratio and amount of super plasticizer were decreased to 0.22 and 4% respectively. Fiber percentages were 1.5% and 2%, which showed the maximum average compressive strength of 54.17. In this case only two percentage of fiber is used which is 1.5% and 2%, other percentages like 2.5%, 3%, 3.5%, 4% are taken as a future scope. Trial mix results are shown in Fig. 5.5 to Fig. 5.6.

Case 4 showed the maximum average compressive strength, because in this case the most optimized amount of binder, fillers, super plasticizer and fine aggregates were used. Optimized amount of materials leads to give a dense structure due to low porosity. In this case total cementitious material is 1300 kg/m^3 and cement content is 910 kg/m^3 (70% cement + 30% metakaolin of the total cementitious material) other percentages used for other materials are listed in Table 6.2 in chapter 3. In this case fiber percentage used was 4% and the same component was used as used in trial mix 10 except with some component percentage because the trial mix 10 showed the high compressive strength as compare to other trial mix so we have to optimize this mix more. This trial mix is a upgraded mix version of Trial mix 10. This case showed the maximum average compressive strength of 93 MPa as compare to the other case. Fig. 5.8 shows the average compressive strength of all trial mixes. It has been concluded that in the case 4 (trial mix 13), sample M2 (8 to 10 mm steel fiber) with optimum percentage value of 4% showed the highest compressive strength of 106.56 MPa as shown in Fig. 5.7.

Although there is no any uniform decrease or increase was seen in the samples of trial mixes. It has been clearly noticed that each case gave the more optimized value for materials for the next case. Case1 gave the average compressive strength value of 34.25 but case 4 gave the average compressive strength value of 93 MPa means case 4 has more optimized materials.

Increase in the percentage of quartz powder also enhance the compressive strength of the samples. Optimization of quartz powder is also important to make a dense matrix. The compressive strength values were more pronounced at high temperatures this probably was because of the high temperatures activating the quartz powder and other fillers which would act inert without heat treatment. The application of heat curing makes these fillers active by taking part in the hydration reactions resulting in longer C-S-H chains giving a denser microstructure and resulting in higher compressive strength.

Partial substitution of cement with MK is found to enhance the compressive strength of concrete [41,42]. The strength enhancement is likely to be due to the large surface area of MK which fills the pores, the acceleration of cement hydration due to large surface area, and the pozzolanic reaction of MK with calcium hydroxide [41]. The filler effect is immediate, the acceleration of cement hydration takes place during the initial stages.

A small increase in w/c beyond the optimum value leads to the formation of capillary pores, which reduce the characteristic imperviousness of the microstructure. In fact, the most important parameter has always been the w/c ratio, as discover in the nineteenth century by Féret [111] for cement pastes and later on by Abrams [112] for concrete. These ratios control the microstructure of the cement paste in both the fresh and hardened states, and ultimately increases the various concrete properties. Concrete compressive strength continues to increase as the w/c ratio decreases because concrete compressive strength depends on the proximity of the cement or the binder particles in the hardened matrix rather than on the amount of cement hydrates formed.

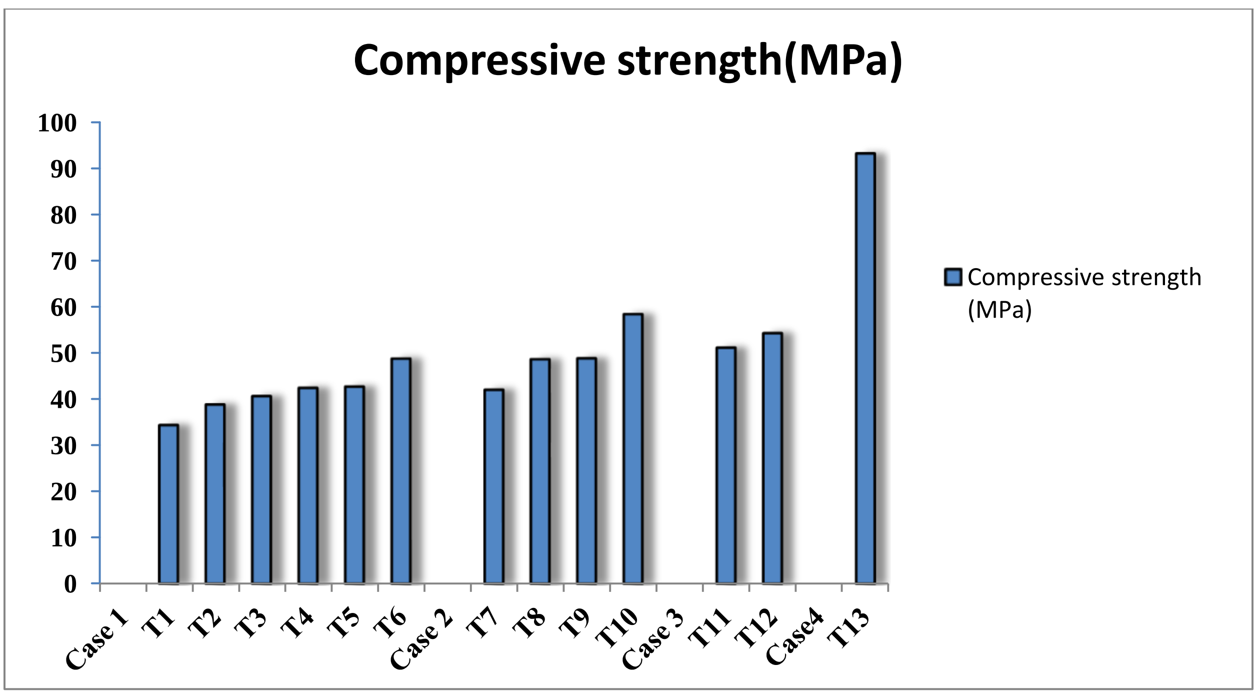


Fig. 5.8 Average compressive strength of all trial mixes.

Optimizing the particle packing density of concrete mixtures has several advantages for concrete properties. Adding fine particles to a particle structure helps filling up the voids in the particle structure leaving only minimum space for water. In this way adding fine particles will reduce the water requirement [113]. Increased packing density of the aggregates, improves strength as long as all voids between the aggregates are filled with cement matrix [114]. A strong aggregate structure with a high packing density will restrain the amount of shrinkage and creep that can actually be realized. Furthermore, a lower water/cement ratio reduces shrinkage, because of the reduced amount of evaporable water in the cement paste [115].

Failure of the cubes in which no steel fiber reinforcement was provided exerts brittle nature during compression testing as shown in Fig 5.9. Fig 5.9 (4) showed the tested cube sample without fibers. Fig 5.9 (3), Fig 5.9 (2), and Fig 5.9 (1) show the 8 to 10 mm steel fibers, 12 to 15 mm steel fibers and hybrid (8 to 15mm) steel fibers respectively. From the figure it has been clear that the mass loss is high in sample without fiber as compare to samples with fibers. Due to the nature of the material, concrete is extremely brittle, showing a sudden loss of carrying capacity after the maximum load is exceeded. The addition of fibers, improved the post fracture nature of the material.

(1) (2) (3) (4)

Fig. 5.9 Tested cube samples with fiber and without fiber.

CHAPTER 5

NUMERICAL SIMULATION

5.1 General

For the numerical simulation it is necessary to adopt a material model for the observation of dynamic response of concrete target under high strain rate impact so it is well known that to analys the projectile impact on concrete targets , Holmquist Johnson cook model is widely used although we also have the other model like RHT, EOS etc but the HJC model is able to describe the mechanical behavior of concrete when it subjected to high strain rate and it is very simple to use so to find out the parameters use in the HJC model we have some methods like quasi static uniaxial compression test ,triaxial compression test , SHPB test and Hugoniot test which gives us the values used in the HJC model in the same way. [116] found out the parameters by using the methods as we discussed above and they also used finite element program and numerically simulated the perforation and penetration on high strength concrete and high strength rock target of strength up to 157 MPa, so for the validation of the proposed parameter they compare the depth of penetration experimentally and residual velocity.

Holmquist–Johnson–Cook (HJC) constitutive model (Holmquist et al. [117]) can well describe the mechanical behavior of concrete-like materials subjected to large strains, high strain rates. Total 19 parameters are utilized in HJC model to describe the basic mechanical properties, strength features, equation of state (EOS), strain rate effect, and damage as shown in Table 5.1.

Holmquist Johnson cook model is widely used although we also have the other model like RHT, EOS etc but the HJC model is able to describe the mechanical behavior of concrete when it subjected to high strain rate and it is very simple to use so to find out the parameters use in the HJC model we have some methods like quasi static uniaxial compression test, triaxial compression test , SHPB test and Hugoniot test which gives us the values used in the HJC model in the same way. JHC parameter used by the various researchers are shown in Table 5.2.

Table 5.1. Parameters of HJC constitutive model.

	Strength parameter				Equation of state parameter				Damage parameter			Strain rate parameter
	A	B	N	S_{max}	P_{lock}	K1	K2	K3	D1	D2	EFMIN	C
116	0.30	1.73	0.79	7	3.47	116	-243	506	0.04	1.0	0.01	0.005
117	0.79	1.60	0.61	7	0.8	85	-171	208	0.04	1.0	0.01	0.007

Table 5.2. JHC parameter.

Ref	Density(kg/m^3)	2440	D2	1.0
120	Specific Heat(J/kg)	654	EFMIN	0.01
	A	0.79	P_{crush}(GPa)	0.016
	B	1.60	u_{crush}	0.001
	N	0.61	K1(GPa)	85
	C	0.007	K2(GPa)	-171
	fc(GPa)	0.048	K3(GPa)	208
	SMAX	7.0	P_{lock}(GPa)	0.80
	Shear Modulus(GPa)	14.86	u_{lock}	0.10
	D1	0.04	T(GPa)	0.004
Ref	Density(kg/m3)	2440	D2	1.0
121	Specific Heat(J/kg)	654	EFMIN	0.01
	A	0.79	P_{crush}(GPa)	0.016
	B	1.60	u_{crush}	0.001
	N	0.61	K1(GPa)	85
	C	0.007	K2(GPa)	-171
	fc(GPa)	0.048	K3(GPa)	208

	SMAX	7.0	P_{lock}(GPa)	0.80
	Shear Modulus(GPa)	14.86	u_{lock}	0.10
	D1	0.04	T(GPa)	0.004
Ref	Density(kg/m3)	2440	D2	1.0
122	Specific Heat(J/kg)	654	EFMIN	0.01
	A	0.30	P_{crush}(GPa)	-
	B	1.73	u_{crush}	-
	N	0.79	K1(GPa)	116
	C	0.005	K2(GPa)	-243
	fc(GPa)	-	K3(GPa)	506
	SMAX	7.0	P_{lock}(GPa)	3.47
	Shear Modulus(GPa)	-	u_{lock}	-
	D1	0.04	T(GPa)	-
Ref	Density(kg/m3)	7830	D5	0.61
123	Specific Heat(J/kg)	-	EFMIN	0.01
	A(MPa)	0.30	P_{crush}(GPa)	-
	B(MPa)	1.73	U_{crush}	-
	N	0.26	K1(GPa)	-
	C	0.014	K2(GPa)	-
	fc(GPa)	-	K3(GPa)	-
	S_{MAX}	7.0	P_{lock}(GPa)	-
	Shear Modulus G(GPa)	77	u_{lock}	-
	D1	0.05	T(GPa)	-
	D2	3.44	Young's modulus (E)	200
	D3	-2.12		
	D4	0.002		

In the field of numerical analysis various finite element codes are used to study the various parameters, to analysis the dynamic strain rate impact on concrete. Various models and corresponding study parameter are shown in Table 5.3. Numerical simulation provides aa fast and effective method to analyze the various properties of concrete. Finite element method gives a advance edge for researchers to check their field data in it and analyze it more precisely. Generally used study parameters are penetration depth, crater diameter, loss of Mass, magnitude and vicinity of the damage, volume of spalling, scabbing, ballistic resistance. It has been clear that JHC model is appropriate to analyze the ductile damage of concrete.

Table 5.3. Model and study parameter.

Ref	**Finite element code**	**Study parameter**	**Model for simulation**
116	-	Penetration Depth, Crater Diameter, Loss of Mass	-
118	-	penetration depth, crater diameter and mass loss.	-
119	AUTODYN	Crater diameter, penetration depth, debris fragment mass and residual penetration potential of the bullet.	RHT (Riedel, Hiermair, Thoma), EOS (Equation of state), SPH(smooth particle hydrodynamics)
120	ABAQUS	magnitude and vicinity of damage, volume of spalling and scabbing, ballistic resistance for three different concretes have been compared with their numerical reproductions	Holmquist-Johnson-Cook
121	ABAQUS	Behavior of concrete a against projectile impact , volume of spalling and scabbing, ballistic	Holmquist -Johnson-Cook

		resistance for two different concretes have been compared with their numerical reproductions	
124	LS-DYNA/ANSYS	Penetration depth, damage, and crater size	For bullet Holmquist -Johnson-Cook The equation of state for bullets used in this study was EOS_GRUNEISEN , The materi model used for concrete was the K&C model (MAT_CONCRETE_DAMAGE REL3 in LS-DYNA)

Various ballistic resistance test have been performed by the various resercher with the different target and projectile dimensions as shown in Table 5.4.

Table 5.4. Target and Projectile specification.

Ref	Type concrete	Target Dimensions mm)	Target Thickness (mm)	Projectile Dimensions(mm)		Weight projectile	Projectile type and properties
				Length(mm)	Diameter(mm)		
116	UHPFRC	300 ✕400	50	23.3	7.92	8.04g	Deformable
				26.7	7.92	8.04g	Non Deformable
118	UHPC, UHPFRC	300✕400	50	23.3	7.92	8.04g	Lead inside, steel jacket, Deformable
119	UHPFRC	300✕400	50 and 45	23.3	7.92	8.04g	Deformable
				23.3	7.92	8.04g	Non Deformable

	UHPC	300×400					
120	Plain, Reinforced and prestressed	450×450	60 and 10	225	19	0.5 Kg	Steel
121	Plain and Reinforced	450×450	50	225	19	0.5kg	Hardened steel
				450	19	1kg	Hardened steel
123	UHPC	Diameter (mm) 300	300	52	14.8	43g	Deformable Steel

5.2 Simulation

A numerical simulation was performed to find out the most appropriate JHC parameter. The geometric modelling of the target and the projectile was carried out on ABAQUS/CAE. The square targets of span 300 mm×300 mm and thickness 20 mm were modelled as three dimensional deformable continuum and partitioned in three different zones in order to discretize and assign fine meshing in the contact zone, Fig. 5.1. The ENCASTRE option has been used to enable fixed boundary condition at all the edges of the concrete target as shown in Fig. 5.2. The concrete plate was modelled with eight node linear hexahedral reduce integration brick elements (C3D8R) of mm size in the primary impact zone (inner circle geometry) of the target. The meshing of the target was carried out for obtaining accurate results within reasonable computational time as shown in Fig. 5.3. The aspect ratio of the elements was maintained unity in the primary impact zone of diameter 8 mm. The aspect ratio, however increased slightly away from the impact zone. Projectiles was modeled as three dimensional analytical rigid shell with appropriate dimensions of their length (20 mm), mass (0.21 g), diameter of cylindrical shaft (8mm) and nose radius (3 CRH). Bullet and target specifications are given in Table 5.5. Contact between projectile and the target was defined as penalty algorithm. The projectile was considered as the master surface and the contact region of the target as node based slave surface. A reference point was assigned at the centroid of the projectile for assigning mass, 0.21g and moment of inertia.

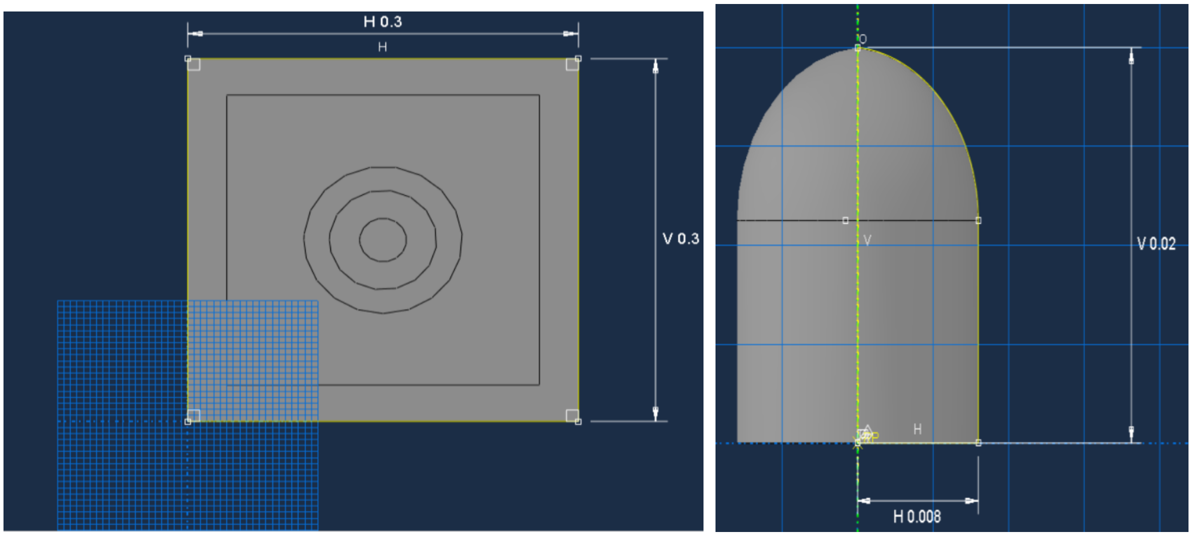


Fig. 5.1. Target size and Bullet specification.

Table 5.5. Target size and Bullet specification.

Type of concrete	**Target Dimensions(m)**	**Target Thickness (m)**	**Projectile Dimensions(mm)**		**Weight of projectile**	**Muzzle Velocity (m/s)**
			Length(m)	**Diameter(m)**		
UHPFRC	0.3 ×0.3	0.02	0.02	0.008	0.21 g	80

For ductile damage JHC model was preferred because according to the previous researcher it is the most suitable damage model for concrete because it is the most appropriate for predicting the behavior of concrete under high strain rate. All the material parameters employed for concrete, enlisted in Table 5.6. Value for JHC model are taken after performing various simulations for the confirmation of parameters, only the most suitable parameters are shown in this section which gives the appropriate results.

Table 5.6. Material parameters for JHC constitutive model.

Density (kg/m^3)	2880
Young`s modulus (N/m^2)	70×10^{10}
Poisson`s ratio	0.33
A (N/m^2)	6×10^{7}

B (N/m^2)	35×10^7
n	0.71
m	1.5
Melting temperature (Kelvin)	775
Transition temperature (Kelvin)	294
d1	0.1
d2	0.6
d3	-1.3
d4	0.005
Strain rate (s^{-1})	1
C	0.07

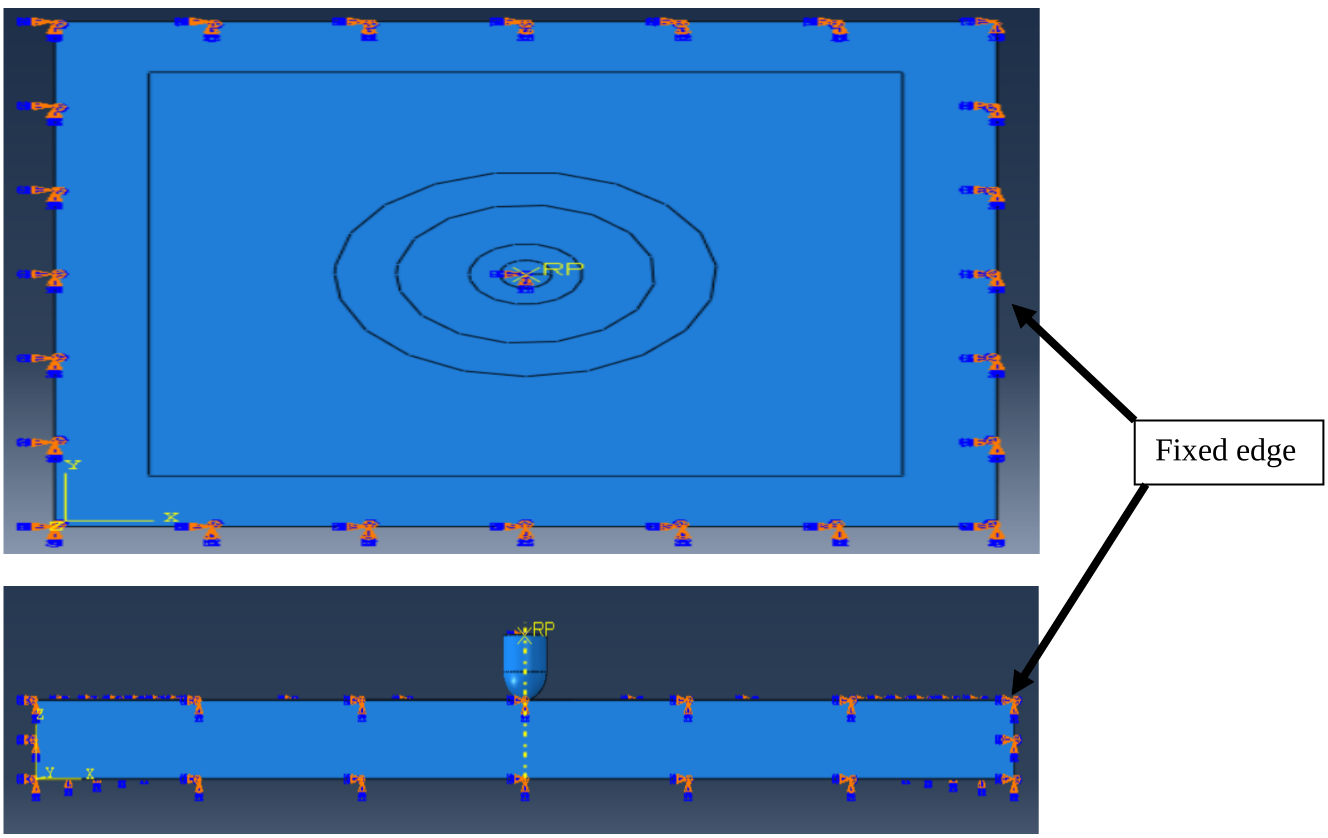


Fig. 5.2. Boundary conditions on bullet and concrete target.

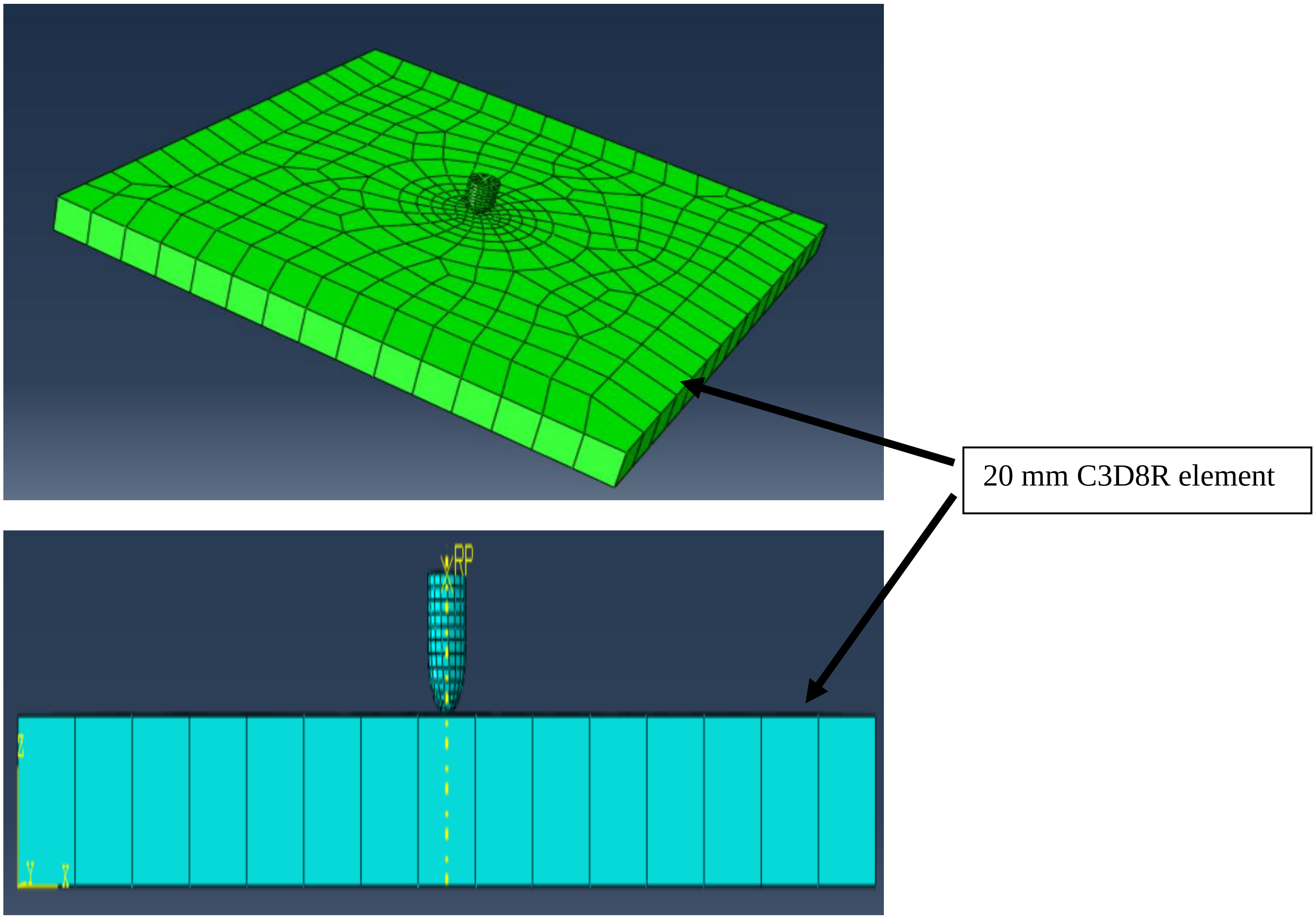


Fig. 5.3. Finite element meshing on specimens.

5.2.1 Result

Contours were generated on the target surface. The area at which bullet was strike showed the maximum value of stress and the value of stress was decreasing towards the outer region other than the surface at which the bullet was hit. An impression was formed on the surface at which the bullet was strike, although there was no any perforation was seen. The contours show the stresses generated on the surface as shown in Fig. 5.5. Based on the cavity expansion theory, under the projectile penetrations, a spherically symmetric cavity is assumed expand radially from the projectile surface, and the cavity radius increases from zero at a constant velocity. Generally, cavity expansion produces plastic-cracked-elastic response regions for concrete material as shown in Fig. 5.4.

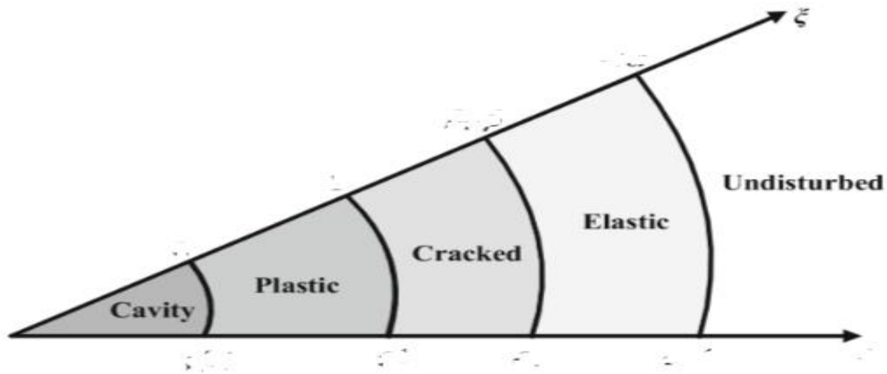


Fig. 5.4. Failure mode of concrete target.

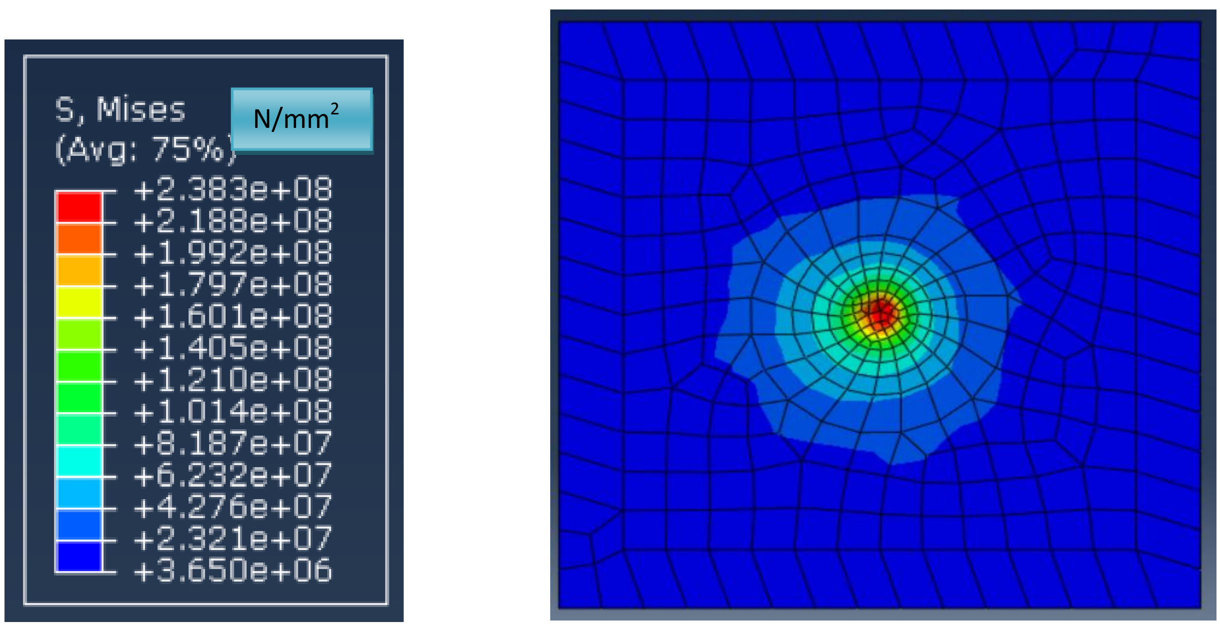


Fig. 5.5. Failure mode of concrete target.

The damage mode in the simulation shows that the deflection on the crater, propagation of stress waves are clearly identified on the surface of the concrete target as shown in the Fig. 5.6. No brittle or severe damage was noticed on the target. JHC parameters plays an important role in investigating the ductile damage of concrete only appropriate JHC parameters give the exact results, in this case the results are quite satisfactory, so we can say that the parameters used in this simulation are appropriate.

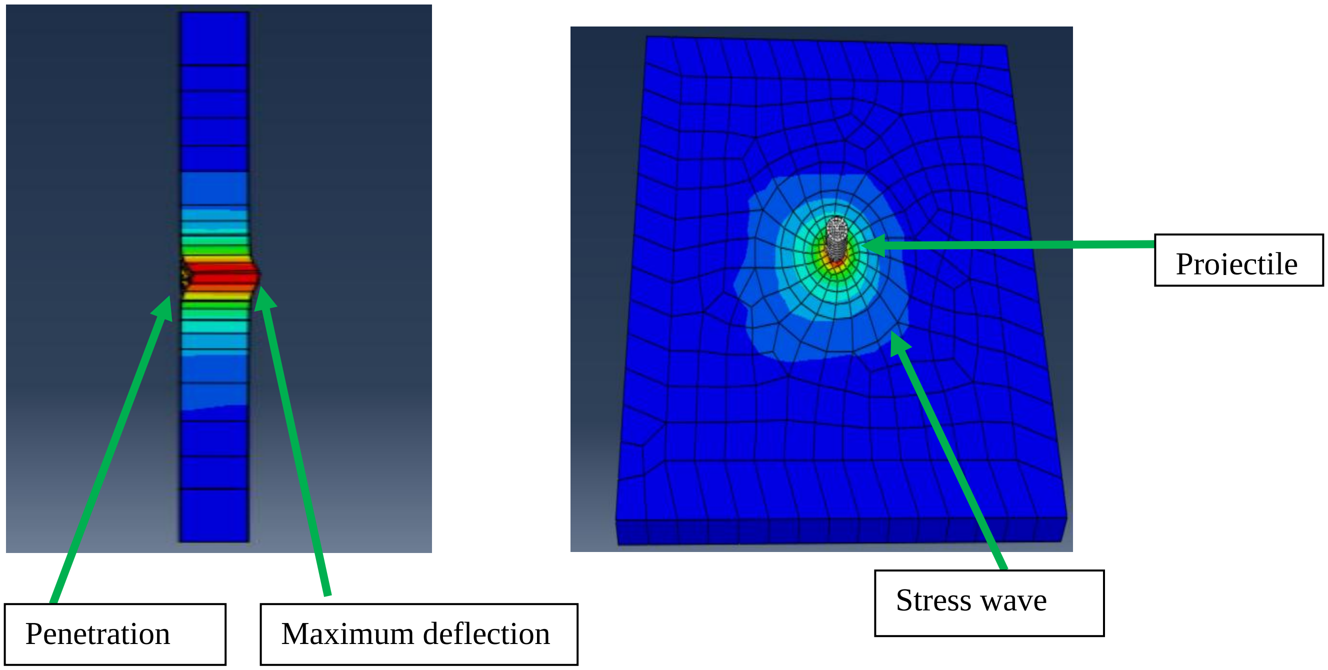


Fig. 5.6. Deflection generated on concrete target.

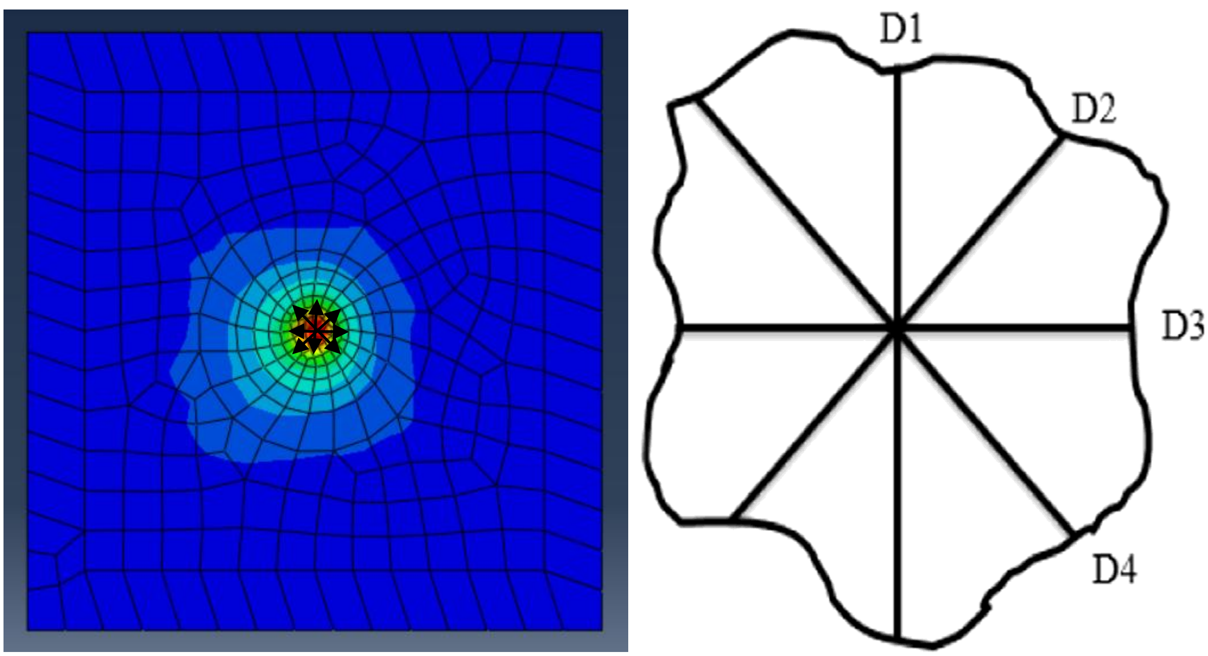


Fig. 5.7. Measurement of average (equivalent) diameter on crater.

The equivalent diameter of the surface crater was obtained as the average of four diameters measured in different orientations as shown in Fig. 5.7. The equivalent average diameter was 40.7 mm

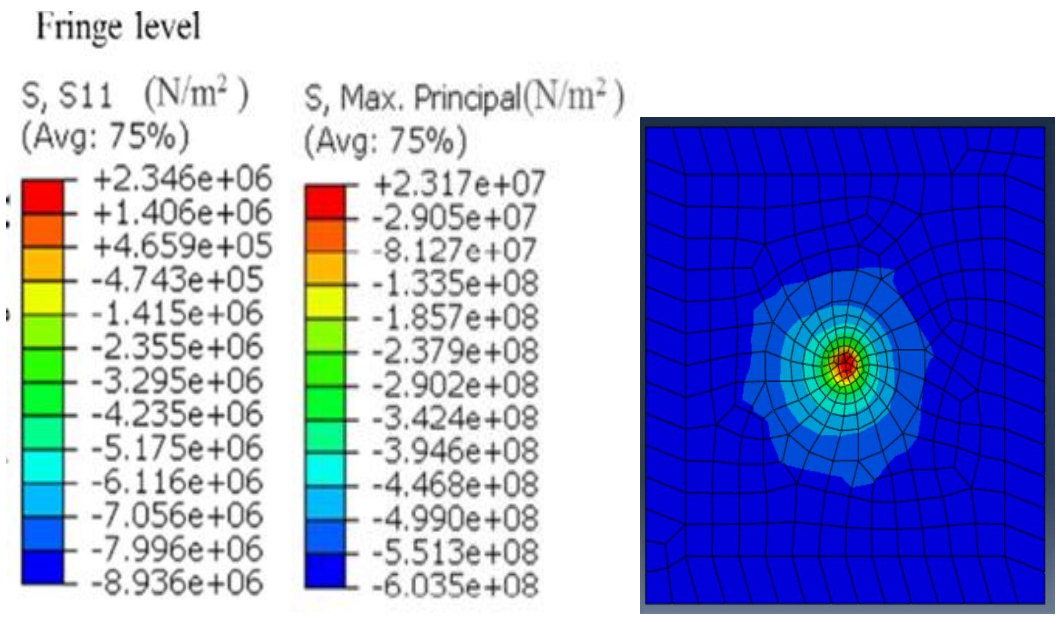


Fig. 5.8. Principal stress contours in concrete target during perforation.

The simulation results of the ballistic tests in the form of stresses developed in the concrete target during perforation are shown in Fig. 5.8. The positive sign denotes tensile stresses and the negative sign compressive stresses. In general the concrete has been found to be in compression except at the edges where nominal tensile stresses were seen to have developed.

From the literature review and performed simulation, it has been clear that for the analysis of the concrete damage JHC model is most suitable as it relates to the actual properties of concrete. On the other side variation in result when it compared to the actual field test is very less.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

From the study conducted, the following conclusions are drawn:

1. Packing density of particles is increasing as the amount of mineral admixtures and fillers are increased, which leads to increase in the specific surface area of the particle and also increase the water demand, but increase in water leads to increase the void use of super plasticizer is necessary to maintain the water demand.
2. In all the binary combinations, C+MK showed the highest packing density of 0.6 as compared to C+SF and C+UFS.
3. Result emphasized that the particle packing density is maximum when replacement was 30% with metakaolin, 17.5% with silica fume and 12% with ultra fine slag.
4. Puntke test gave a good correlation for achieving the maximum packing density of different filler combinations resulting in maximum compressive strength.
5. It was found out that appropriate amount of supplementary cementitious materials (SCMs) can be used to replace cement. The replacement of cement by SCMs provides excellent compressive strength values. A maximum compressive strength of 106.56 MPa was observed when 30 % of the cement was replaced by metakaolin.
6. Case 4 has the most optimized percentage values with total cementitious material of 1300kg/m^3, optimum steel fiber percentage of 4%, w/c of 0.22, super plasticizer 4%, quartz powder of 30% of total volume of aggregate and quartz sand and natural sand are used 50% of remaining volume of aggregate.
7. The optimum amount of w/c ratio was found to be 0.22. Increasing the w/c ratio above 0.22 caused significant difference compressive strength values.
8. The impact of steel fiber on the compressive strength of the mixes was quite notable. In case 1 average compressive strength was increased from 34.25 MPa to 48.66 MPa when fiber dosage increased from 1.5 to 4%. In case 2 average compressive strength was increased from 41.94 MPa to 58.27 MPa when fiber dosage increased from 2.5 to 4%. In case 3 average

compressive strength was increased from 51 MPa to 54 MPa when fiber dosage increased from 1.5 to 2%. Case 4 showed the highest average compressive strength of 93 MPa.

9. The failure pattern of the test specimens was also affected by the inclusion of fibers. Sudden brittle failure was observed in sample with no steel fibers while a ductile failure was observed for samples incorporated with steel fibers.
10. Samples without fiber reinforcement show the higher mass loss as compared to the sample with fiber reinforcement.
11. JOHNSON-COOK model is suitable to well describe the mechanical behavior of concrete like material subjected to high strain rate impact.

6.2 Recommendations for future research

The research study was mainly focused on the development of UHPC. The following recommendations are given for future purposes.

1. Further study can be carried out on evaluation of mechanical properties of UHPC such as the stress-strain behavior in compression and tension, static and dynamic modulus, drying and autogenous shrinkage and creep etc.
2. The effect of orientation of steel fibers on the properties of UHPC and the type of steel fibers can be studied in detail. Further optimization is required in case 3.
3. Different types of fibers can be studied such as propylene fibers, plastic fibers and other metallic fibers. The use of plastic fibers can be effective in not only reducing the cost of the material but can also be effective for aesthetic applications where steel fibers can have a negative impact on the aesthetics.
4. The effect of different types of superplasticizer content on the properties of UHPC can be studied.
5. The behavior of UHPC under severe conditions can be also studied, the effect of freezing and thawing cycles on the properties of UHPC can be analyzed.
6. From the optimized value of case 4, slabs can be prepared to analyze the dynamic effect on concrete.
7. Investigation on the long term strength development of UHPFRC can be performed with supplementary cementitious materials.

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Publication 1

Singh B.,Pathania A., Gupta M., Saini A., Shukla A. “Influence of the packing density of fine particles in ternary, quaternary and quinary blends on High Performance Concrete” [**Paper accepted and currently in press] Journal: RILEM Bookserie.**

Publication 2

Singh B., Shukla A. “A review on Mechanical properties of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC)” [**Paper accepted and currently in press**] **Journal: International Journal Of Current Advanced Research.**

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