Studies on Mechanical and Durability Properties of Concrete with Secondary and Ternary Cement Blends

A THESIS SUBMITTED IN PARTIAL FULFILMENT FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

CIVIL ENGINEERING

GOA UNIVERSITY

By

Vinay Mohan Agrawal

Under the Guidance of

Dr. Purnanand P. Savoikar

Goa College of Engineering, Farmagudi – Goa

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SEPTEMBER *2022*

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DECLARATION

I, Vinay Mohan Agrawal hereby declare that this thesis represents work which has been carried out by me and that it has not been submitted, either in part or full, to any other University or Institution for the award of any research degree.

Place: Taleigao Plateau. Vinay Mohan Agrawal

Date:

CERTIFICATE

I hereby certify that the above Declaration of the candidate, Vinay Mohan Agrawal is true and the work was carried out under my supervision.

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Date:

Place: Goa University, Taleigao **Vinay Mohan Agrawal**

Dedicated to my family

THESIS APPROVAL SHEET

Thesis entitled: **Studies on Mechanical and Durability Properties of Concrete with Secondary and Ternary Cement Blends** by **Mr. Vinay Mohan Agrawal** is approved for the degree of **DOCTOR OF PHILOSOPHY.**

Examiners

Supervisor

Chairman

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Place: Goa University, Taleigao

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ABSTRACT

Cement and concrete industry is expanding rapidly with increase in construction of residential, commercial and infrastructural projects around the globe. Ordinary Portland Cement (OPC) is the primary binding material used in production of concrete. Production of OPC emits almost equal quantity of harmful carbon-di-oxide in the environment. Therefore, partial replacement of OPC with some other material is thought of by many researchers in the past. The use of industrial waste such as, fly ash (FA) and ground granulated blast furnace slag (GGBS) as a partial replacement of OPC has been found to be beneficial in concrete. However, the use of FA or GGBS are not very effective in imparting early age strengths and also does not provide significant improvement in durability parameters when used as supplementary cementitious material (SCM) in concrete. Thus, the need of usage of ultra-fine materials such as ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) was thought of, which could improve the mechanical and durability properties of concrete at all ages. The present work focus on use of FA as binary replacement to OPC and UFFA/UFS as ternary replacement of OPC in mortar and concrete.

Chapter 1 discuss a brief introduction to the subject. The chapter details the objectives of the present work with scope and limitations of the same. Novelty of the present work is also listed in this chapter. In Chapter 2, literature survey on industrial by-products, such as, fly ash, ultra-fine fly ash and ultra-fine slag and its effect on mechanical and durability properties of mortar and concrete are discussed. The chapter presents the data on generation, availability and utilization of fly ash in India. The chapter further discusses the physical and chemical characteristics of fly ash with its effect on mortar on concrete. The chapter critically reviews the published literature on usage of ultra-fine fly ash and ultra-fine slag in mortar and concrete. The chapter presents the gaps identified in the previous research findings which have been addressed in this thesis.

Chapter 3 focus on characterization of binders (OPC, FA, UFFA and UFS) and other ingredients used for production of concrete. Chemical and physical characteristics of binders are observed as per standard procedures. These results are validated with code recommendations to ensure their usage as supplementary cementitious material. The chapter presents the Scanning Electron Microscope (SEM) and Energy dispersive X-ray

spectroscopy (EDS) micrographs of OPC, FA, UFFA and UFS. This microstructure analysis provides information on particle size, shape and chemical characteristics of binders.

Chapter 4 provides the mix proportion details of one reference, 21 binary and 30 ternary mixes of binders used in mortar. Reference mix is made of 100% OPC. Binary mixes are composed of OPC –FA, OPC – UFFA and OPC – UFS with 10 – 70% of FA, UFUFA or UFS. Ternary mixes are composed of OPC – FA – UFFA and OPC – FA – UFS combinations. FA is used in 10%, 20% and 30% replacement value. UFFA and UFS have been replaced in the range of 10 – 50% in ternary mixes. The particle packing density of binder mixes, workability and compressive strength at 1, 3, 7, 28, 56 and 90 days of reference, binary and ternary mortars are presented in this chapter. The results of compressive strength of mortars are used to identify the feasible replacement proportion of each binders. It was found that, up to 40% of FA, and up to 20% of UFFA/UFS could be used as feasible replacement percentage in concrete mixes.

Fresh, mechanical and durability properties of one reference, 3 binary and 27 ternary concrete mixes are investigated and presented in Chapter 5. Reference concrete mix is made of 100% OPC. Binary mix is composed of OPC – FA combination with 20%, 30% and 40% FA. Ternary mix is made in OPC – FA – UFFA or OPC – FA – UFS combinations. In ternary combination the FA replacement is 10, 20 or 30% with an additional ternary replacement of UFFA or UFS in 5%, 10%, 15% and 20% each. Workability in terms of slump value is observed for all 31 concrete mixes. Compressive strength at 3, 7, 28, 56 and 90 days, split tensile strength and flexural strengths are observed for all concrete mixes. With regards to durability parameters, chloride migration coefficient at 7, 28 and 90 days and water permeability under pressure at 28 and 90 days are observed. Initial & secondary sorptivity and volume of permeable voids are also observed as part of durability study for all concrete mixes. It was observed that with use of UFFA and UFS in ternary concrete mixes, the mechanical and durability properties could be significantly improved. This improvement is attributable to finer particle size, higher surface area and high pozzolanic reactivity of UFFA and UFS which results in compact and dense microstructure in ternary concrete mixes.

Chapter 6 presents the cost analysis of different concrete mixes as per commercial rates of binders. Three optimization methods are used to identify the best

alternate concrete mix with regards to cost, measured mechanical and durability properties. Three optimization methods used in the present thesis are: a) Taguchi-Grey relational analysis (GRA), b) Technique for order of preference by similarity to ideal solution (TOPSIS) and c) Desirability function approach (DFA). The chapter discuss the step by step procedure of these optimization methods. The results of these methods were used to rank the concrete mixes. The best alternate concrete mix reported by all three optimization method was found as 30T15UF i.e. ternary concrete mix with 55% OPC – 30% FA – 15% UFS. The spearman's rank order correlation method is adopted to find the preferred optimization methods among the three methods used. Chapter 7 gives the summary and conclusion of the present study and scope of future work.

Key words: *ordinary Portland cement; fly ash; ultra-fine fly ash; ultra-fine slag; binary blend; ternary blend; compressive strength; chloride migration; permeability; sorptivity; optimization methods.*

Chapter 1

Introduction

1.1 General

Ordinary Portland Cement (OPC) or Portland cement is the primary binding material used in the production of concrete. Owing to high mechanical and durability characteristics, concrete is the most used material in construction and building industry. Its use has been significantly increased in past three decade due to growing building and infrastructure developments around the world. The production of Portland cement and concrete requires extraction of natural minerals, sand and aggregates. Production of Portland cement contributes huge emission of harmful gases particularly CO_2 in the environment (Part et al., 2015; Schneider et al., 2011). According to researchers and International Energy Agency, the production of OPC releases around 6 – 7 % of total manmade CO_2 emission (Prusty and Pradhan, 2020; Yusuf et al., 2014). Reducing the usage of Portland cement in concrete by an alternate and sustainable material with cementitious property is necessary as it will substantially reduce the overall CO_2 footprint in the environment.

Supplementary Cementitious Material (SCM) when blended with OPC exhibits enhanced cementing action and provides better properties of cement/binder paste. Many materials have been successfully used as SCMs in the past as partial replacement of OPC (Gupta and Chaudhary, 2020; Kara De Maeijer et al., 2020). Major SCMs include industrial wastes, bio ashes, natural sources such as volcanic ash, and municipal and solid waste ash (Chakraborty et al., 2017; Mehra et al., 2018; Patel et al., 2019; Singh et al., 1996). Common industrial waste include industrial by-products such as fly ash (FA), granulated slag, silica fume and surkhi. Other industrial wastes are limestone, lime sludge, red mud, jarosite slurry etc. Bio ashes are composed of aquacultural and agricultural wastes such as rice husk ash, bamboo leaves ash, wheat straw ash etc. As part of natural sources, metakaolin as calcined pozzolana and volcanic ash, tuffs, clay, and shales as natural pozzolana are used as SCMs. Municipal solid waste ash comprises of ashes after combustion, i.e. sewage sludge ash and powdered/ground glass ash. Every SCM have different effect on properties of cement or concrete depending on its mineralogical, physical and chemical characteristics.

These SCMs are often classified as waste due to challenges related to their disposal and effective utilization. In the view of the environmental concerns, these wastes are observed to be utilised in construction industry in different forms such as SCMs and as fine or coarse aggregates. Fly ash, a by-product from combustion of pulverised coal for production of electricity and heat, pose serious threat to the environment. Disposal of fly ash in soil or on water degrade the natural soil and water bodies. Fly ash may also spread in air during recycling or disposing which may cause serious health hazards due to smaller (less than 10 μm) particle size (Wu et al., 2016). Blast furnace slag, commonly known as slag is a by-product of steel manufacturing industry. Slag is obtained during reduction stage, when iron ore is converted to pig iron (Martins et al., 2021). Similar to fly ash, slag also poses serious threat to the environment as regards disposal and reuse challenges. Fly ash and ground granulated blast furnace slag (GGBS) commonly known as slag, both are extensively used as an effective SCM in concrete due to their pozzolanic – hydraulic ability.

Fly ash and GGBS can be directly used to replace OPC in concrete. The maximum replacement for fly ash is found to be around 35%, whereas for GGBS the maximum effective replacement is identified as up to 85% from literature (Giergiczny, 2019). Fly ash and slag based concrete results in better fresh and hardened properties (Musaddiq Laskar and Talukdar, 2017; Sengul and Tasdemir, 2009). The major limitation lies with use of fly ash and slag are in terms of compromised early strength and durability properties (Choi et al., 2012; Coppola et al., 2018). Fly ash and slag both are slow reactant and imparts strength to concrete at later ages. In order to overcome this limitation of slow reactivity and compromised durability, more reactive pozzolana such as silica fume, rice hush ash, ultra-fine fly ash or ultra-fine slag are used as SCM (Krishnaraj and Ravichandran, 2021; Kara De Maeijer et al., 2020; Musaddiq Laskar and Talukdar, 2017). Performance of concrete depends on chemical composition, particle size distribution, fineness and pozzolanic activity of SCMs/binders.

Ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) are two such materials that demonstrate better filler effects resulting in durable concrete. Particle size distribution and specific surface area of binders plays an important role in early strength gain as the reaction takes place at the surface itself. In the case of ultra-fine materials like UFS and UFFA, as the surface area available for reaction is comparatively large, the reaction is rapid and better early strength is achievable. Due to smaller particle size, the density of concrete improves which result in less capillary pores and voids, thus results in more durable concrete.

Significant research is available on use of fly ash and slag as cement replacement. Research on use of ultra-fine fly ash and ultra-fine slag with Portland cement in binary combination is scanty. However, the use of ultra-fine fly ash and ultra-fine slag with OPC - fly ash based concrete forming a ternary mixture is not studied in literature. The present study, uses fly ash as primary replacement for OPC, i.e as binary component. Thereafter, OPC is replaced by UFFA or UFS to form ternary blended concrete. In the present study, OPC – FA – UFFA/UFS ternary blend is used to investigate the fresh, mechanical and durability properties of concrete mixtures.

Use of UFFA/UFS in ternary concrete combinations are expected to affect the workability due to different shapes of UFFA and UFS. The early and long term strength of ternary concrete are expected to improve due to ultra-fine content in UFFA/UFS, which would compact the concrete by filling the finer pores/voids in concrete. Similarly, resistance offered by concrete to chloride migration and water permeability are also expected to improve for ternary concrete mixes. Rate of water absorption (sorptivity) and volume of permeable void in ternary concrete mixes are expected to reduce due to use of UFFA/UFS. However, this hypothesis needs to be confirmed experimentally before its use in the construction industry. Ultra-fine fly ash and ultra-fine slag are used in concrete mixes in various combinations to study their effect on mechanical and durability properties of concrete and their effectiveness is compared. This will give a scientific basis while choosing one among UFFA or UFS for making ternary concrete.

The present study examines flow and strength properties of reference, 21 binary and 30 ternary mortar blends at the preliminary investigation stage. This is done to obtain the feasible range of replacement percentages of different binders. Thereafter, reference/control, 3 binary and 27 ternary concrete mixes were tested for fresh, mechanical and durability properties. The properties of all binary and ternary mixtures are compared with properties of reference mix to understand the effect of binders. Cost aspect is also studied for all concrete mixtures and economic mix is suggested. Three optimization techniques are used to optimize the proportions of binders with regards to measured parameters and cost to get the best alternative concrete proportion from the present study.

1.2 Objectives of the present study

Based on detailed literature review (presented in chapter 2), the major objectives of the present research work are identified as the investigation of properties of concrete produced using fly ash, ultra-fine fly ash and ultra-fine slag in OPC – FA binary combination and OPC – FA – UFFA/UFS ternary combinations. Following are the objectives of the present study.

1. To study the physical and chemical properties of fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) for assessing their suitability for use as supplementary cementitious material.
2. To perform Scanning Electron Microscope (SEM) analysis, and chemical composition examinations using Energy Dispersive X-Ray Spectroscopy (EDS) analysis to understand the micro structure properties of binders.
3. To investigate the possible range of replacement percentages for binders in mortar and assess the compressive strength and particle packing density. Measured properties of binary and ternary mortar mixes are compared with that of reference mortar.
4. To investigate the workability and mechanical properties such as compressive strength, split tensile strength and flexural strength of OPC – FA – UFFA/UFS concrete mixtures in different binary and ternary mixes.
5. To investigate durability properties such as chloride migration/penetration, water permeability, initial and secondary sorptivity, and volume of permeable voids of concrete mixtures.
6. To investigate the cost aspect of different binders and subsequent concrete combinations as regards market price/rate of binders.
7. To optimize the different concrete combination with regards to compressive strength, tensile strength, chloride migration, water permeability, sorptivity, permeable voids and cost parameters. It is proposed to use three multiple response optimization methods namely, a) Grey Relational Analysis (GRA),

b) Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and c) Desirability function approach (DFA) in order to rank the investigated concrete mixtures, and to obtain the best alternate concrete combination with improved performance.

1.3 Scope and limitations

The scope of the study is limited to concrete mixes which are considered as medium strength concrete, as usage of this type of concrete is higher compared to high strength or high performance concrete in Indian construction industry. Ordinary Portland cement has become obsolete from the market in order to encourage utilization of industrial wastes as partial replacement of OPC. Fly ash is used as primary replacement considering its wide availability, spherical shape and cost in addition to its pozzolanic property. Presently, around 20% of fly ash generated remains un-utilized. Ultra-fine fly ash and ultra-fine slag are the two other binders which are used in the present study as ternary binders. UFFA and UFS both poses similar trend in terms of particle size distribution, availability and cost.

The microstructural analysis/tests conducted are limited to SEM and EDS analysis to understand the particle size, shape and chemical characteristics of binders. The tests conducted on concrete are related to workability, compressive strength at early and later ages (up to 90 days), tensile and flexural strength. The durability tests selected for the study are related to chloride migration, water permeability, sorptivity, and permeable voids. To study the economic benefits, the cost of all concrete mixtures were evaluated. Three multi-response optimization methods are used for optimizing the mixture proportions with regards to measured properties and cost of concrete mixtures. The scope of the present work is to assess the material potential alone with regards to mechanical and durability aspects.

1.4 Methodology

In order to achieve the above objectives following step by step methodology is adopted:

1. Perform tests to identify chemical and physical characteristics of ordinary Portland cement, fly ash, ultra-fine fly ash, and ultra-fine slag.

2. Perform SEM and EDS analysis to understand shape, size and chemical properties of OPC, FA, UFFA and UFS as part of characterization of binders.
3. Perform tests to ascertain suitability of FA, UFFA and UFS to be used as supplementary cementitious material.
4. Investigate packing density and compressive strength of reference, binary and ternary mortars to identify range of replacement percentage for different binders.
5. Design the mix and perform fresh, mechanical and durability tests on control/reference, OPC – FA binary and OPC – FA – UFFA/UFS ternary concrete mixtures.
6. Perform cost analysis of all concrete mixtures using prevailing rates of binders.
7. Perform optimization analysis to obtain best alternate concrete combination with regards to investigated properties.

1.5 Novelty of the present work

This research is focussed on following important aspects:

i. Although the construction industry have shifted to Portland slag or Portland pozzolana cement in concrete making, OPC blended with SCM is preferred in ready mix concrete plants/units to produce high strength concrete. Findings of this study with ternary blended concrete composed of OPC, FA and UFFA/UFS will be meaningful to all big and small producers of concrete across all construction sites.

ii. The effect of ultra-fine fly ash and ultra-fine slag on fresh, mechanical and durability parameters in ternary combination with OPC and FA. This research fills this gap with an extensive study.

iii. Few independent studies on ultra-fine materials exists in literature, however detailed comparison of UFFA and UFS presented here under similar testing conditions makes this research meaningful.

iv. Ranking and optimization of different concrete mixtures using three established optimization methods provides series of alternate concrete combinations with regards to measured properties and cost for UFFA or UFS blended OPC – FA – UFFA/UFS ternary concrete.

1.6 Organization of the thesis

The study undertaken in this thesis is organized into seven chapters as detailed below.

Chapter 1 deals with the introduction of SCM with emphasis on ultra-fine materials in concrete, explicit objectives, scope and methodology of the present study.

Chapter 2 presents exhaustive review of available literature on use of key industrial by-products or wastes viz. fly ash (FA) and ground granulated blast furnace slag (GGBS) as supplementary cementitious materials in concrete. Literature study focuses on mechanical and durability properties of binary and/or ternary concrete mixtures composed of cement with fly ash, ultra-fine fly ash or ultra-fine slag. Chapter 2 also presents critical appraisal of the literature and identifies the available gaps.

Chapter 3 presents characterization of OPC, FA, UFFA and UFS in terms of physical and chemical properties. This chapter also presents the test results performed to ascertain the use of FA, UFFA and UFS as SCM in concrete. The material characteristics and micro structure analysis observed for binders are compared with data from literature.

Chapter 4 deals with investigation of packing density of binders, flow and compressive strength results of reference, binary and ternary mortars. To understand the effect of replacement of binders a wide range of replacement (up to 70%) is chosen for any individual binder in binary combinations. In ternary combinations, the FA replacement up to 30% and UFFA/UFS replacement up to 50% is used in ternary combinations. The results are compared with mortars made using 100% OPC. The results of mortars were adopted as basis of appropriate range of binder content in concrete testing.

Chapter 5 presents the experimental results of reference mix, OPC – FA binary and OPC – FA – UFFA/UFS ternary concrete combinations. The investigated fresh and mechanical properties include workability, compressive strength at early and later ages, flexural and split tensile strengths. Results of durability properties such as chloride migration test, water penetration test, sorptivity and volume of voids are presented in this chapter.

Chapter 6 deals with methodology and implementation of optimizations method and cost analysis used in the present study. Three methods namely i. Grey Relational Analysis (GRA), ii. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and iii. Desirability function approach (DFA) are used to find the optimal solution based on investigated properties of concrete.

The summary and conclusions drawn from the present study with major contributions and scope for future research are presented in **Chapter 7**.

Experimental results of mortar and concrete are shown in **Annexures** followed by **References** and **Publications** from the present study.

Chapter 2

Literature Review

2.1 General

Effective utilization of industrial wastes in cement and concrete helps to overcome disposal issues of wastes and will result in less cement production. By reducing the cement production, carbon di oxide emission in the environment will reduce significantly. Present literature survey aims at accumulating and critically reviewing the available data on utilization of selected supplementary cementitious materials i.e. fly ash (FA), ultra - fine fly ash (UFFA) and ultra - fine slag (UFS) as partial replacement for ordinary Portland cement. The literature survey focus on reviewing the studies conducted on cement paste, cement mortar and cement concrete incorporating these supplementary cementitious materials (SCMs). Cement or binder combination is known as binary or ternary mixture when OPC is replaced with one or two SCMs, respectively. The present review focuses on limitations and advantages of binary and ternary mixtures. The present review observes fresh, mechanical and durability properties of concrete incorporating FA, UFFA and UFS. For presentation purpose the literature review is divided in three broad segments such as (i) studies in mortar and concrete using FA (ii) studies in mortar and concrete using UFFA and UFS (iii) review of experimental methods used in the present study.

2.2 Studies in mortar and concrete using fly ash (FA)

Supplementary cementitious materials are used in construction industry to partially substitute OPC. This leads to significant reduction of CO_2 emission as cement production reduces and also it is an effective means to utilize by-products from industrial manufacturing process. Fly ash (FA) derived during coal combustion and granulated blast furnace slag derived from pig iron production are successfully used in concrete. Blast furnace slag, after grinding is used as replacement of cement and is commonly called as ground granulated blast furnace slag (GGBS) or slag. FA has also been effectively used in the past as a substitute of OPC.

2.2.1 General

Fly ash (FA) is an industrial waste generated by exhaust gases of coal fired power plants. FA has been successfully used in different sectors such as in cement, bricks and tiles, ceramics and glass, mine filling, roads and flyovers, reclamation of low lying areas etc. As per annual report (2019-20) by Ministry of Power, Government of India, 197 thermal power stations with an installed capacity of over two lakh MW consumes 678 million tons of coal for generating power. During this power generation process, 226 million tons of fly ash is generated as an industrial waste. With constant encouragement and policies regarding utilization of fly ash, in the year 2019-20, 187 million tons, i.e. 83% of fly ash is re-utilized in different sectors. The fly ash generation and utilization of major contributing states are shown in the Table 2.1.

Table 2.1. State wise fly ash generation and utilization during the year 2019-20 (Source: Report on fly ash generation, Ministry of Power, Govt. of India, November 2020).

Sl. No.	Name of state	Fly ash generation (Million tonne)	Fly ash utilization (Million tonne)	Percentage utilization (%)
1.	Andhra Pradesh	16.28	16.69	102.52
2.	Chhattisgarh	34.82	26.85	77.12
3.	Madhya Pradesh	25.02	13.75	54.95
4.	Maharashtra	25.01	22.14	88.51
5.	Odisha	24.91	21.06	84.56
6.	Uttar Pradesh	24.12	13.85	54.41
7.	West Bengal	17.82	16.01	89.84
8.	Jharkhand	7.67	7.91	103.05
9.	Rajasthan	8.98	8.76	97.52
10.	Tamil Nadu	8.82	9.63	109.2
11.	Telangana	7.13	5.02	70.5
	Others	25.55	26.13	102.0
	Grand Total	**226.13**	**187.80**	**83.05**

Five states namely Chhattisgarh, Madhya Pradesh, Maharashtra, Odisha and Uttar Pradesh have generated about 60% of total fly ash across the country. Highest contribution was observed by Chhattisgarh state with 34.82 million tons during the year 2019-20. Fly ash utilization by most of the states are more than 75%, however for states like Madhya Pradesh, Uttar Pradesh, Telangana and Assam, fly ash utilization is comparatively less. Few states like Andhra Pradesh, Gujarat, Haryana, Jharkhand, Punjab and Tamil Nadu have achieved fly ash utilization level of more than 100%. Table 2.2 indicates the mode of utilization of FA across India based on annual report 2019-20, Ministry of Power, Govt. of India. Maximum utilization of 25.6% is shown in cement industry, however about 17% of fly ash remains unutilized and adversely affect the environment.

Table 2.2. Mode of fly ash utilization during the year 2019-20 (Source: Report on fly ash generation, Ministry of Power, Govt. of India, November 2020).

Sl. No.	Mode of FA utilization	Quantity of utilization (million tonne)	Percentage (%)
1.	Cement	57.88	25.60
2.	Reclamation of low lying areas	35.06	15.50
3.	Ash dyke raising	22.16	9.80
4.	Bricks and tiles	21.38	9.64
5.	Roads and flyovers	20.96	9.27
6.	Mine filling	10.61	4.69
7.	Concrete	1.66	0.74
8.	Agriculture	0.14	0.06
9.	Others	17.91	7.92
10.	Unutilized ash	38.32	16.96
	Grand Total	**226.13**	**100.00**

2.2.2 Properties of fly ash

Fly ash is generally classified as class F or Class C fly ash. Class F fly ash are obtained from burning of harder and older bituminous coal having low calcium (Ca) content (less than 20%). The total content of silicon dioxide + aluminium oxide + iron oxide in this type is greater than 70% (Vassilev and Vassileva, 2007). These fly ash are pozzolanic in nature as it hardens when reacted with calcium hydroxide and water. Class C fly ash are results of burning of younger lignite or subbituminous coal in thermal power plants. They possess high calcium and magnesium content (more than 20%). The total content of silicon dioxide + aluminium oxide + iron oxide is less than 70%. These fly ash show pozzolanic as well as some self-cementing characteristics (Panda and Dash, 2020).

The chemical and physical characteristics of fly ash differs depending on the source and type of coal being burnt, boilers and its operating conditions and process during combustion (Li et al., 2021). The collection and storage of fly ash also affects its physical and chemical characteristics. Depending on the amount of unburnt carbon the colour of fly ash varies from tan to grey to black. Table 2.3 provides summary of different chemical and physical properties of fly ash (Kaur et al., 2017; Panda and Dash, 2020).

Table 2.3 Chemical and physical characteristics of fly ash (Kaur et al., 2017; Panda and Dash, 2020).

Chemical characteristics (oxides) of FA		
1.	Silicon dioxide (SiO_2)	50.00 – 70.00 %
2.	Aluminium oxide (Al_2O_3)	15.00 – 30.00 %
3.	Iron Oxide (Fe_2O_3)	2.00 – 8.00 %
4.	Calcium oxide (CaO)	0.20 – 20.00 %
5.	Sulphur trioxide (SO_3)	0.05 – 2.00 %
6.	Magnesium oxide (MgO)	0.02 – 2.00 %
Physical Properties of FA		
7.	Average Particle Size (µm)	18.00 – 24.00
8.	Specific gravity	2.1 – 2.6
9.	Blaine specific surface area (m^2/kg)	250 – 500
10	Loss on ignition (%)	0.5 – 5.0

2.2.3 Effect of fly ash on properties of mortar and concrete

Fly ash has been found to be useful for cement and concrete industry in multiple ways. FA can be used as raw material in cement production, as mineral admixture in blended cement concrete, as partial replacement of natural sand, as light weight aggregate in concrete when used in low to medium volumes. FA also finds application as in sub-base or base course in road way construction, as structural fill in embankments or dams. A replacement of 35% of OPC with FA is reported as optimum replacement from available literature. However, it is also found in literature that, replacing OPC with FA results in longer setting time, lower early strength development and reduced durability (Wilińska and Pacewska, 2018). The effect of fly ash as SCM in concrete performance is discussed further.

2.2.4 Effect of fly ash on fresh properties of mortar and concrete

Incorporation of fly ash results in reduction of fresh density and improvement in workability of concrete (Samad and Shah, 2017). The spherical shape of fly ash reduces the inter particle as well as aggregate friction thereby improving the workability of concrete. Also, the pump-ability of concrete gets improved due to reduction in friction. Fly ash reduces the water demand for a given workability as it increases the fine content in concrete. This increment in fine volume reduces the water content which in turn prevents bleeding of concrete. Hannesson et al., (2012) have found that the initial and final setting time of FA based mixture is generally greater than that of OPC mixture. Shaikh et al., (2014) have reported increment in workability with use of FA in mortars. They reported flow diameter of control mortar as 135mm, whereas the flow diameter of mortar with 40%, 50%, 60% and 70% FA as replacement of OPC was found to be 140, 150, 175 and 195 mm, respectively.

Padavala et al., (2021) have observed increment in slump value when OPC was replaced with increasing quantity of fly ash. They concluded the increment was in the range of 45% to 55% with 20%, 30% and 40% of FA. It was also observed that, FA was able to give better workability as compared to silica fume. Sadrmomtazi et al., (2018) showed that the concrete with 10%, 20% and 30% of FA demonstrate 127, 140 and 145 mm of slump value, whereas the slump of control concrete is reported as 100 mm. The requirement of superplasticiser for producing a similar flow for FA blended mixtures are examined by Chindaprasirt et al., (2008). They found reduction in superplasticiser requirement with increment in FA content. In comparison to 1.9% of superplasticiser in control mixture, 0.4% and 0.1% of superplasticiser was required to produce the same flow with 20% and 40% of FA usage. This was associated with ball-bearing effect of small spherical shaped FA particles. Paliwal and Maru, (2017) investigated compaction factor of control and FA based concrete. They found increment in compaction factor with increment in FA content. The observed value of compaction factor of control mixture was found as 0.883, whereas factor ranges from 0.894 to 0.931 for 5% to 20% FA content in concrete mixture. They also observed the reduction in fresh density of concrete with increment in FA content due to lower specific gravity of FA. The observed fresh density of control concrete was 2404 kg/m^3, whereas for concrete with 20 % FA, is has reduced to 2381 kg/m^3. As regards the available literature, workability enhancement was attributable to spherical shaped FA particles. Hence for mixtures with fly ash, lower water content and less superplasticizer will be required to obtain the desired workability which can result in cost saving.

With the addition of FA in the concrete, OPC content reduces which in turn decrease the rate of production of hydrates. This is responsible for delayed setting and hardening of mixture. Hence, FA based mixtures shows prolonged initial and final setting time. Mounanga et al., (2011), found a rising trend with FA based concrete on initial and final setting time. The initial setting time of FA based concrete with 25% and 50% replacement level were 340min and 381min, respectively as compared to 251min for OPC concrete. Similarly, final setting time was observed as 657min and 681min for FA concrete as compared to 537min for OPC concrete. Rate of setting is stated to be directly related to initial porosity and early age reactivity of binders (Mounanga et al., 2011). Delay in initial and final setting time of FA based mixtures was similarly observed by (Güneyisi and Gesoğlu, 2008). They found 30% to 70% increment in setting time with replacement of OPC with 20%, 40% and 60% of FA. Overall it is observed that, FA delays the overall setting time in mortars and concrete.

2.2.5 Effect of fly ash on mechanical and durability properties of mortar and concrete

Fly ash is known to be slow reactive SCM and hence compressive strength of FA based mortars and concrete are reported to be lower, specifically at early ages (<28 days) (Li et al., 2006). However, FA is found to provide better compressive strength at later ages (>28 days). Replacement of OPC by FA results in dilution, hence less OPC is available for hydration at an early age. FA does not react directly with water, whereas it chemically bonds with $Ca(OH)_2$, which is produced due to formation of calcium silicate hydrate gel (CSH gel) resulting from hydration of OPC. Reduction in OPC content due to replacement, diminishes the hydration, which in turn reduces the primary CSH formation. This results in reduced gain in strength with FA. However, with time, due to pozzolanic activity of FA, secondary CSH gels are formed resulting in enhanced compressive strength at later ages (Papadakis, 2000).

Paliwal and Maru, (2017) found reduction in 7 day compressive strength for FA based mixtures as compared to reference mixture. The 7 day strength was observed to reduce consistently by increasing the fly ash content from 5% to 20%. Maximum reduction of 13.6% was observed for 20% FA mixture. However, at 28 days, the compressive strength have shown an increasing trend. The maximum increment of 11.4% was observed for 10% FA as compared to control mixture. Similar improvement in flexural strength was observed by FA based mixtures with maximum improvement in 10% FA mixture. Water penetration depth of FA based mixture have been observed to reduce consistently with increment in FA content. Reference concrete shows a water penetration depth of 33 mm, whereas least depth is observed as 25 mm for 20% FA mixture. They attributed the strength gain at 28 days and improved durability to pozzolanic action of FA which resulted in additional formation of CSH gels and to refinement of pore structure.

Bagheri et al., (2021) found, strength of mix, with 30% FA replacement is significantly low as compared to reference concrete. However, with the progress of pozzolanic reaction, the difference in compressive strength of binary and reference concrete becomes smaller. The strength at 90 and 180 days are marginally less, whereas strength at 360 day is better for FA concrete (73.4 MPa) as compared to that of reference concrete (69.0 MPa). Higher chloride migration coefficient is observed for FA based concrete mix up to the age of 28 days as compared to control mix. However, due to progress in pozzolanic reactions the diffusion coefficient show a significant declining trends at ages from 180 to 360 days. The diffusion coefficient of FA concrete is observed to reduce over 50% and 60% at 180 and 360 days, respectively as compared to diffusion coefficient of reference concrete.

The compressive strength shows reducing trend at all ages with increment in quantity of FA as replacement of OPC (Hashmi et al., 2020). Compressive strength gets reduced by 13%, 27% and 42% as compared to that of reference concrete for 25%, 40% and 60% replacement by fly ash, respectively. They concluded that, the lower strength is due to slow pozzolanic reactivity of FA. Isaia et al., (2003) have studied the effect of addition of 12.5%, 25% and 50% of FA in concrete with regards to compressive strength at 28 and 91 days. They observed marginal improvement in 28 day compressive strength for 12.5% and 25% FA concrete, whereas for 50% FA replacement, the strength is significantly low as compared reference concrete. Significant improvement in compressive strength is noticed at 91 days by 12.5% and 25% FA replacement mixtures. However the mixture with 50% replacement demonstrate lower strength as compared to reference concrete at all ages.

Shaikh et al., (2014) investigated compressive strength at 7 and 28 days for high volume fly ash replacement in concrete. They observed substantial reduction in 7 day strength of mortar and concrete with 40%, 50%, 60% and 70% replacement by fly ash. Similar reduction was observed for 28 day, where except for 40% FA concrete, remaining all higher replacement mix shows less strength as compared to control mixture. Wang, (2018) investigated concrete with 5% - 35% replacement by FA, and reported significant reduction in strength at 1, 7 and 28 days. They observed marginal increment in compressive strength at 90 and 180 days. Maximum improvement was observed for concrete with 20% of FA as compared to control mixture. Dąbrowski et al., (2016) observed similar compressive strength at 28 day in the mix with 29% FA replacement. However an increment of 20% in 90 day compressive strength is seen for the same binary concrete as compared to control mixture. Chloride migration coefficient values have observed to reduce for FA based concrete. They observed a reduction of about 15% and 55% in chloride migration coefficient at 28 day and 90 day, respectively for FA based mixture as compared to control concrete. They concluded that, fly ash based concrete demonstrated good resistance to chloride migration.

Franco-Luján et al., (2021) tested control and binary concrete with 20% replacement by FA, they concluded marginal improvement in compressive strength at all ages. They observed 28 day and 90 day strength as 45.0 MPa and 57.5 MPa, respectively for blended mixture as compared to 45 MPa and 48 MPa for control concrete. The improvement in compressive strength of FA based mixture after 28 days was due to secondary CSH formation and pozzolanic activity of fly ash.

Chindaprasirt et al., (2008) observed equal and marginal (2% and 3%) increment at 7, 28 and 90 day compressive strength of mixture with 20% of FA as compared to that of OPC mortar. The mixture with 40% of FA shows 25% and 6% less compressive strength at 7 day and 28 day, respectively, whereas it showed 2% increment at 90 days. Chloride penetration depth at 28 days for reference concrete is observed as 16.0 mm, whereas a substantial reduction in penetration is observed in fly ash based mixtures. The chloride penetration depth observed was 10.0 mm and 8.0 mm for 20% FA and 40% FA based mix, respectively. Similar reduction in permeability was observed, which was attributable to reduction in capillary pores and segmentation of large pores due to inclusion of fly ash. Dispersing and synergic effect of fly ash resulted in improved mechanical and durability properties. Similar results related to low early strengths (<28day) due to 20%, 25%, 40%, 50% and 60% replacement by fly ash as compared to control mortar was observed (Güneyisi and Gesoğlu, 2008; Mounanga et al., 2011).

Delay in formation of CSH gels with use of FA and lower CaO content in FA results in low strength gain in FA based concrete as reported by Hannesson et al., (2012). All concrete combinations reported lesser early age (<28 days) strength as compared to reference concrete. Concrete with 40% replacement by FA was able to give better later age (>28 days) strength. However, 60% and higher replacement have been seen to reduce the compressive strength at later ages. Also, with increment in FA content, the compressive strength have been observed to reduce. They observed best improvement in 40% replacement with 28 day strength as 83.5 MPa compared to 80.0 MPa for reference concrete. For the same replacement, 168 day strength was noted as 102.2 MPa, whereas for reference concrete, it is 85.1 MPa. This observation confirms the ability of fly ash to impart later age strength.

Sadrmomtazi et al., (2018) have examined compressive and tensile strength for control and binary concrete with 10%, 20% and 30% of fly ash as replacement of OPC. They observed reduction in compressive strength for all binary concrete at 7 and 28 days, however the compressive strength increased marginally at 90 days. Split tensile strength for concrete with 10% of FA have shown slight increment. Other mixtures shows reduced tensile strength as compared to control mixture. The split tensile strength at 28 days was observed as 2.3 MPa and 2.4 MPa for control and 10% FA blended concrete, respectively. They examined water sorptivity, chloride migration, electrical resistivity and porosity of

FA based concrete as part of durability parameters. Water sorptivity and water penetration depth have shown an increasing trend by addition of 10%, 20%, and 30% FA in binary mixtures as compared to control concrete. Chloride migration at 28 days have observed to increase with FA content, however at 90 days, the chloride migration rate have decreased due to progress in pozzolanic reactions. Maximum reduction in rate of chloride migration is observe for 30% FA concrete. Electrical resistivity and porosity results show similar trend in binary concrete, where durability properties enhance marginally by addition of FA.

It is observed in literature that, replacement of OPC with FA have potential to improve the later age strength (>28 days) and durability performance of concrete. Inability of FA based mixture to provide early age strength (<28 days) is observed by all researchers. Therefore it is necessary to use and develop ternary mixtures which will be composed of OPC, FA and some other finer pozzolanic material. The beneficial effects of OPC and FA at later age and effects of finer material at early age can be ascertained in ternary combinations. Previous studies have investigated the effects of ternary mixtures by using fly ash as binary component, and lime stone, silica fume, rice husk ash, ultra-fine fly ash or ultra-fine slag as ternary component.

Wang, (2018) have investigated effect of fly ash and lime stone addition in ternary concrete. They found marginal increment in compressive strength at early age and significant improvement at later ages. Early age strength was attributable to fineness of lime stone and later age strength was due to slow pozzolanic reaction capacity of fly ash. Ternary combination with fly ash and lime stone was suggested to satisfy early as well as later age strength requirements. Isaia et al., (2003) have observed compressive strength of binary concrete with FA as well as with ternary concrete with FA and rice husk ash (RHA). They observed 19.1% and 14.8% increment at 28 day and 91 day strength when OPC is replaced with 25% FA and 25% RHA in ternary mix as compared to binary concrete with 50% of FA. Improvement of 2.9% and 4.6% was observed in compressive strength for the same ternary mix as compared to that of control concrete. Whereas for the same 50% replacement with FA in binary concrete, the compressive strength have reduced by 13.6% and 8.8%, respectively. Therefore the addition of fine material such as lime stone or rice husk ash have proved to effectively enhance the compressive strength in concrete.

Bagheri et al., (2021) have investigated the effects of usage of 5% silica fume (SF), 15% FA and 80% OPC to form a ternary concrete. The compressive strength at 7 day was found to be equal to that of control concrete. Significant improvement is observed at 28 days and longer in ternary concrete. Up to 20% improvement was noticed in ternary concrete till 360 days of curing. The 28 day compressive strength of ternary mix was 66.1 MPa, whereas for reference concrete it was 55.4 MPa. This improvement in strength at later age was attributable to pozzolanic reaction of fly ash and silica fume. They found similar trend in chloride diffusivity, where the diffusion coefficient of ternary mix was greater till 7 days, thereby the coefficient has reduced with progress in pozzolanic reactions. Chloride diffusion coefficient was improved up to 72.7% in ternary mixture as compared to reference concrete.

From the literature it was found that mechanical strength and durability properties are enhanced by using fly ash as supplementary cementitious material in mortars and concrete. Due to slow pozzolanic reaction of fly ash, concrete has demonstrated compromised early strength properties in binary combinations. Hence the ultra-fine material usage was investigated to validate the property enhancement at early age. It was evidenced that, due to smaller or finer particle sizes of binders such as SF, MK, RHA, UFFA and UFS, the early age properties are considerably enhanced. The later age compressive strength as well as durability properties are also improved due to finer materials attributable to compactness of microstructure.

Although much research is available on usage of FA, UFFA and UFS in binary combinations, the study of properties of concrete in ternary concrete with FA as primary replacement and UFS/UFFA as secondary replacement of OPC are not found. The presented work focus on using ultra-fine fly ash and ultra-fine slag as secondary replacement. Following sections of literature discuss the effects of ultra-fine fly ash and ultra-fine slag in mortars and concrete.

2.3 Studies in mortar and concrete using ultra-fine fly ash (UFFA) and ultra-fine slag (UFS)

2.3.1 General

Ultra-fine fly ash and ultra-fine slag can be produced by mechanical grinding of raw fly ash or ground granulated blast furnace slag in ball mill. Air classification process is used to separate the ultra-fine particles from the coarser particles. In this process the coarser particles are removed based on their weight and size, resulting in retaining the finer fractions. The physical characteristics such as particle size and shape changes as a result of grinding. This mechanical grinding or activation is found to improve pozzolanic reactivity of UFFA and UFS.

The particle size of fly ash and ground granulated blast furnce slag are comparebale to that of ordinary portland cement. However, grinding of FA or GGBS produce UFFA or UFS with significantly smaller particle size. It is observed that, particle size plays an important role in early pozzolanic reaction. Fig 2.1 shows particle size of raw fly ash and ultra-fine fly ash produced after grinding (Sengul and Tasdemir, 2009)..

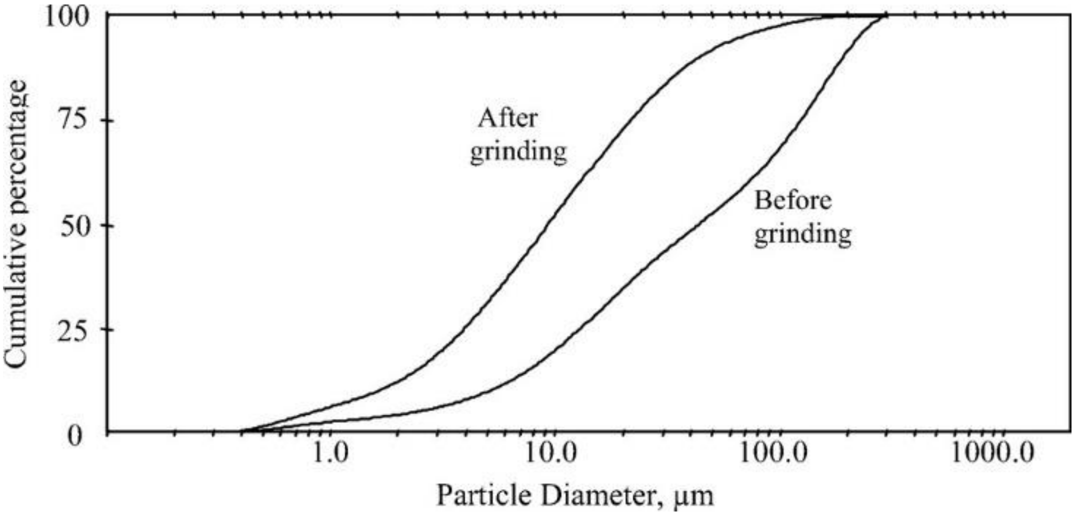


Figure 2.1. Particle size distribution of fly ash before and after grinding (Sengul and Tasdemir, 2009).

Fig. 2.2 shows the reduced particle size distribution of UFS and that of cement (Teng et al., 2013). It is observed that, both UFS and UFFA demonstrates smaller particle size as compared to OPC and hence demonstrate better reactivity.

With regards to micro-structure analysis it is observed that fly ash are spherical in shape with smooth surface finish whereas slag demonstrate angular shaped particles. Fig 2.3 and Fig 2.4 shows SEM analysis of raw fly ash and ultra-fine fly ash (Han et al., 2019).

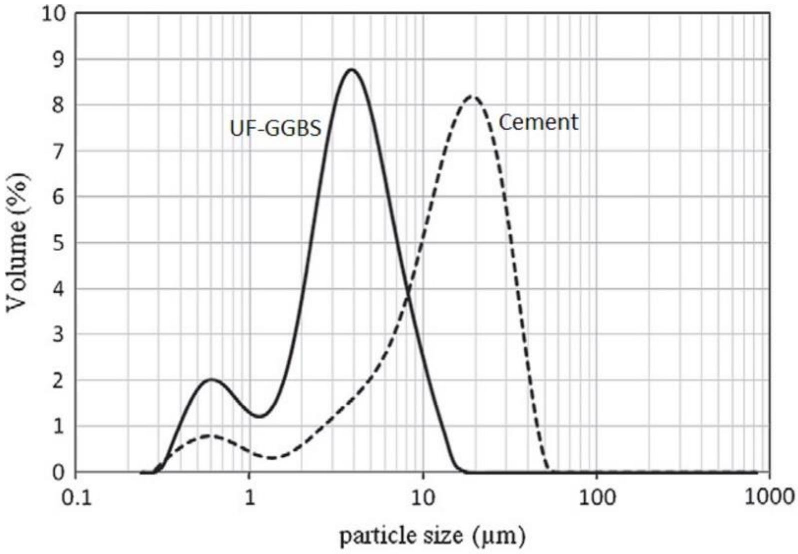


Figure 2.2. Particle size distribution of ultra fine slag and cement (Teng et al., 2013).

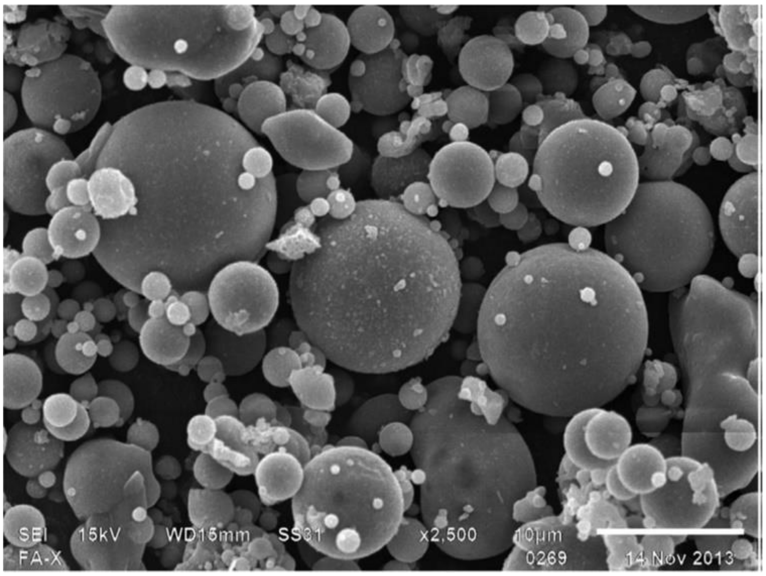


Figure 2.3. SEM image of raw fly ash (Han et al., 2019).

It is observed that the raw fly ash contains spherical shaped particles whereas UFFA show smaller sized particle which are majorly spherical with few broken irregular shaped particles due to grinding are also observed.

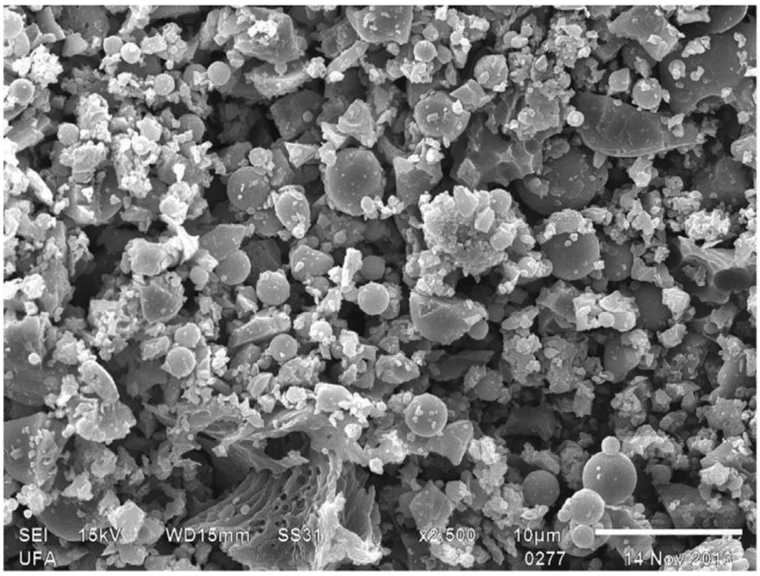


Figure 2.4. SEM image of ultra-fine fly ash (Han et al., 2019).

Spherical shape of FA and UFFA have resulted in improvement of workability with their additions. UFS on the other hand, demonstrate angular shaped particles as shown in Fig. 2.5 (Musaddiq Laskar and Talukdar, 2017). These angular shaped particles resists the flows and reduces the workability when used in concrete.

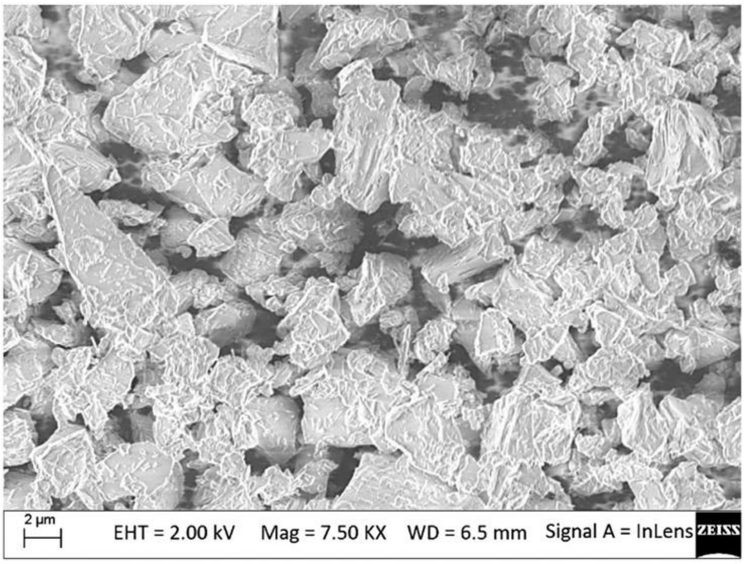


Figure 2.5. SEM image of ultra-fine slag (Musaddiq Laskar and Talukdar, 2017).

Table 2.4. Chemical and physical characteristics of UFFA and UFS from literature.

Characteristics	UFFA (Choi et al., 2012; Han et al., 2019)	UFS (Musaddiq Laskar and Talukdar, 2017; Teng et al., 2013)
Chemical analysis (oxides)		
Silicon dioxide (SiO_2)	50.00 – 55.00 %	30.00 – 35.00 %
Aluminium oxide (Al_2O_3)	22.00 – 28.00 %	10.00 – 25.00 %
Iron Oxide (Fe_2O_3)	6.00 – 12.00 %	0.50 – 2.00 %
Calcium oxide (CaO)	3.00 – 10.00 %	30.00 – 35.00 %
Sulphur trioxide (SO_3)	0.10 – 2.00 %	0.10 – 2.00 %
Magnesium oxide (MgO)	0.50 – 4.00 %	6.00 – 12.00 %
Physical Properties		
Average Particle Size (µm)	Less than 5 µm	Less than 5 µm
Specific gravity	2.1 – 2.6	2.4 – 2.9
Blaine specific surface area (m^2/kg)	400 – 900	700 – 1200
Loss on ignition (%)	Less than 2%	Less than 2%

Chemical properties of UFFA and UFS are dependent on raw fly ash and raw GGBS used to manufacture ultra-fine material. The physical characteristic such as particle size varies on extent of grinding. It was observed in literature that, the particle size of UFFA and UFS are significantly finer than ordinary Portland cement but were coarser than silica fume or metakaolin. UFS and UFFA differs considerably in CaO content, which plays an important role in imparting strength. CaO content of UFFA is very less as compared to that of UFS. The chemical characteristics of UFFA and UFS are shown in Table 2.4.

2.3.2 Effect of UFFA and UFS on properties of mortar and concrete

Ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) have been used in concrete to investigate its suitability as an effective SCM. Most of the researchers have investigated the effects of UFFA and UFS in binary combinations with OPC. Han et al., (2019) have compared mechanical strength of UFFA based binary mixture. They compared the results with FA based binary mixture with same binder content and reference concrete. 7 day and 28 day compressive strength of UFFA mixtures are marginally less than that of control mixture but have significantly improved as compared to FA based mixtures. They found significant improvement in 90 and 360 day compressive strength of UFFA based mixture as compared to FA and OPC based mixture. Similar observation was noted for flexural strength as well. They concluded that, the use of UFFA in place of FA can be beneficial for high early strength without compromising the later age strength. They concluded that, effective utilization of UFFA can improve the physical filling and chemical action in hydration which can result in compact microstructure. Coppola et al., (2018) have confirmed high early strength (compressive and flexural) for UFFA based binary mixtures as compared to FA based mixtures. The maximum compressive strength increment of about 45% at 3 days was achieved by mix with 35% UFFA as compared to control mixture. General observation was increment in compressive strength at all ages regardless of percentage of replacement with UFFA.

Obla et al., (2003) have investigated binary concrete with 8%, 12% and 16% of UFFA. Due to spherical shaped UFFA particles, the water requirement to produce similar slump has reduced, which confirms the improvement in workability with inclusion of UFFA. They found significant improvement at early as well as later ages due to UFFA addition. They observed 23% and 34% increment in compressive strength for 12% UFFA based concrete at 3 and 180 days as compared to control concrete. Significant improvement in resistance to chloride penetration was observed with UFFA concrete tested up to 2 years. The improvement in mechanical and durability characteristics were attributable to smaller particle size of UFFA which accelerates the pozzolanic reaction resulting in early strength and improvement in microstructure of concrete. Han et al., (2019) have investigated mechanical properties of concrete with 25% and 50% of UFFA. They observed marginally reduced values of compressive strength at 3 and 28 days, but significantly high values at 90 and 360 days as compared to control concrete. They observed highest improvement by 25% UFFA based concrete. Similar trend was observed in flexural strength as well. They experimentally compared the observation with similar replacement with raw fly ash. They observed improved properties of UFFA based mixtures as compared to control or FA based mixtures which was attributable to higher pozzolanic and filling effect of UFFA as compared to FA or OPC.

Hossain et al., (2009) have investigated effect of 9% and 15% UFFA based concrete. They observed low water demand resulting in higher workability due to UFFA. The compressive strength, measured up to 28 days have shown increasing trend as compared to control concrete, however, the increment was meagre. The UFFA have also demonstrated increased resistance to chloride penetration as compared to control mixture. Kara De Maeijer et al., (2020) have replaced OPC by 15%, 25%, 35% and 50% of UFFA to investigate the fresh and hardened properties of mortar and concrete. They reported increment in workability with inclusion of UFFA in mixture attributable to spherical shaped UFFA. They found increment in 7 day compressive strength by 15% UFFA based mixture. Higher replacement mixtures have shown marginally less strength as compared to control mixture at 7 days. All mixtures have shown significant improvement in compressive strength at 28 days and 57 days, the maximum improvement was shown by 15% UFFA based mixture. Mixtures with UFFA have shown better resistance against chloride migration and electrical resistivity at all ages. They attributed fineness and higher pozzolanic reactivity of UFFA and its ability to densely pack the matrix as the reasons for improved mechanical and durability properties.

Ting et al., (2019) have found reduced workability of paste with addition of UFS due to angular shaped particle of UFS. They also observed reduction in setting time for UFS based mixtures attributable to acceleration of hydration due to fineness and availability of high calcium oxide content in UFS. Sharmila and Dhinakaran, (2016) have investigated the effects of 5%, 10%, and 15% usage of ultra-fine slag (UFS) in binary concrete mixture. They observed significant improvement of 23.5% at 7 days for UFS based concrete as compared to control concrete. Continuous improvement in compressive strength was observed until the age of 90 days for UFS based concrete, with the maximum strength of 63.2 MPa observed by 10% UFS mixture as compared to 59.3 MPa of control concrete at 90 days. As part of durability tests, they observed reduction in water absorption and pore volume for UFS based mixture as compared to control concrete. Maximum reduction of 14.2% and 13.0% in water absorption and pore volume, respectively was observed for 10% UFS based concrete as compared to control mixture. Similar reduction in water sorptivity for all UFS based mixtures was observed. The initial and secondary sorptivity for 10% UFS mixture was found as 0.0019 mm and 0.0023 mm, respectively as compared to 0.0024 mm and 0.0034 mm for control mixture. Overall they observed improvement in mechanical and durability properties by addition of UFS in binary concrete.

Teng et al., (2013) have investigated mechanical and durability properties in concrete made with 30% of UFS in binary combination. They observed significant improvement in compressive strength at early age (<28days). The observed improvement in compressive strength of UFS based concrete as compared to control concrete was about 12.6%, 7.8% and 4.1% at 3, 28, and 90 days, respectively. Similar trend of improvement was noted in flexural strength as well. Chloride migration coefficient of UFS mixture have reduced by 46% and 25% at 3 and 28 days, respectively as compared to control mixture. Similarly, the reduction of 35% and 54% at 56 and 90 days, respectively was observed for chloride migration coefficient of UFS mixture as compared to control concrete. They classified UFS based mixture as high to very high resistant to chloride migration, whereas the control concrete shows low to moderate resistance to chloride migration as regards their coefficients. They attributed this improvement in mechanical and durability aspects to densification of microstructure due to UFS and to formation of additional CSH gels leading to high reactivity in early ages.

2.4 Gaps in literature

From the available literature it was observed that, fly ash and ground granulated blast furnace slag have a good potential of replacing ordinary Portland cement in mortar and concrete. Fly ash being spherical, imparts better workable mix, on the contrary, GGBS show reduction in workability due to its angular shaped particles. Use of FA and GGBS imparts satisfactory compressive strength at later ages and comparable durability properties, however they show low early strength due to their slow pozzolanic reaction time. Binary combinations of OPC – FA or OPC – GGBS does not promise high early strength and improved workability, therefore use of some other finer materials in mortar and concrete are essential.

Ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) are two such material which are comparable in cost and physical properties. Binary combinations such as OPC – UFFA and OPC – UFS have been studied in the past and resulted in satisfactory results. Use of UFFA and UFS have potential to impart comparable early strength due to their smaller sized particles. Smaller particles results in large surface area exposed for hydration in early days and hence pozzolanic reaction takes place at a faster rate. Later age strength of UFFA and UFS based mixtures are also found to be comparable with that of only OPC mixtures. The durability properties of binary mixtures with UFFA and UFS are also observed to enhance due to better particle packing and compactness of microstructure. Hence, the effectiveness of UFFA and UFS in OPC – FA based concrete mixes are proposed to be examined.

2.5 Objective of the present work

Most of the available research is on binary combinations such as OPC – FA, OPC – UFFA and OPC – UFS. The binary combination of OPC – FA in not investigated with ternary replacement of UFFA or UFS in the past. The present study, therefore aims to develop understanding on ternary mixture such as OPC – FA – UFFA and OPC – FA – UFS. The study aims to compare the results of ternary mix with UFFA and UFS, to identify the best alternative material. The study also compares properties of concrete with UFFA/UFS addition with OPC – FA binary mixture and with reference (100% OPC) concrete. The present study aims to identify the best alternative concrete combinations with regards to three well established optimization methods in accordance with observed mechanical and durability properties.

2.6 Experimental methods as per code provisions

The experimental work conducted in the present study are based on Indian, American and European standards. This section briefly describes the method used for conducting experiments.

2.6.1 Chemical and physical characteristics

Chemical characterization of ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag are identified based on IS 4032:1985 and IS 1727:2015. The results of chemical analysis are validated in accordance with requirement of IS 269:2015, IS 3812:2003 and 12089:1987. The physical characteristics such as specific gravity and fineness of all binders were investigated as per IS 4031:1996 and IS 1727:2015. Consistency and setting time of cement is investigated as per IS 4031:1996 and validated with requirement of IS 269:2015. In order to confirm the suitability of fly ash, ultra-fine fly ash and ultra-fine slag as pozzolanic material, the compressive strength of 50 mm cube is casted and tested as per IS 1727:2015 and validated in accordance with IS 455:1989 and IS 3812:2003.

2.6.2 SEM and EDS micrographs

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) observations were performed in order to understand the microstructure of ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag. The binder samples were sputter coated with platinum to increase the conductivity and further examined using JEOL-JSM-6360 L V SEM instrument for SEM and EDS micrographs. During the examination, the accelerating voltage is maintained at 10kV and observation are noted at a scale of 2µm, 5 µm and 10 µm.

2.6.3 Particle size distribution

Particle size distribution (PSD) observations were performed for ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag. The particle size distribution was obtained by laser diffraction using Malvern Mastersizer 2000 fitted with Scirocco sample handling unit. During the examination, the observations of sample volume are measured within a range from 0.010 µm to 10000 µm.

2.6.4 Particle packing density

Particles packing density for binary and ternary combinations of binders such as fly ash, ultra-fine fly ash and ultra-fine slag with ordinary Portland cement are conducted as per Puntke particle packing density test method. The binary and ternary combinations are mixed as per desired ratios by volume and are initially dry mixed. Water is added to the mixture until the paste becomes saturated. The amount of water added to completely saturate the mixture is observed. Particle packing density is calculated as ratio of dry volume to saturated volume of mixture.

2.6.5 Flow of mortar

The flow of mortars were examined using mini slump cone with bottom and top diameter as 100 mm and 50 mm, respectively. The height of mini slump cone is 150 mm. Mini slump cone is filled with mortar and lifted. The spread of mortar is measured along four diameters and an average diameter is reported as flow value of mortar.

2.6.6 Compressive strength of mortar

The compressive strength of mortars were examined as per provision of IS 4031: 1988. Compressive strength is determined using cube moulds of size 70.6 mm after 1, 3, 7, 28, 56, and 90 days of water curing at room temperature. The cube moulds were tested under laboratory scale compression testing machine. Three identical samples are tested for a typical category and the calculated mean value is noted as compressive strength of that specified category.

2.6.7 Workability of concrete

The workability of concrete is measured in terms of slump value in mm. Standard slump cone test procedure is followed as per IS 1199:2018. Top and bottom diameter of slump cone is 100 mm and 200 mm, respectively, and height as 300 mm. The subsidence of concrete immediately after raising the cone is measured as slump value in millimetre.

2.6.8 Compressive strength of concrete

The compressive strength of concrete is determined based on provisions of IS 516:2018 after 3, 7, 28, 56 and 90 days of curing. The standard mould used for testing the compressive strength is 150 mm cube. The cube moulds were tested under laboratory scale compression testing machine. Three identical samples are tested for a typical category and the calculated mean value is noted as compressive strength of that specified category.

2.6.9 Split Tensile strength of concrete

The tensile strength of concrete is determined based on provisions of IS 5816:1999 after 28 days. Standard cylindrical mould with 150 mm in diameter and 300 mm in length is casted. The cylindrical specimen were tested under laboratory scale compression testing machine. Three identical samples are tested for a typical category and the calculated mean value is noted as split tensile strength of that specified category.

2.6.10 Flexural strength of concrete

The flexural strength of concrete is determined based on provisions of IS 516:2018 after 28 days. Beams of standard size i.e. 150 mm × 150 mm × 700 mm is casted and tested for flexural strength. The specimen were kept above two steel rollers and tested in universal testing machine as per code guidelines. Three identical samples are tested for a typical category and the calculated mean value is noted as flexural strength of that specified category.

2.6.11 Rapid chloride migration test (RCMT) of concrete

The rapid chloride migration test of concrete is determined based on provisions of NT Build 492:1999 after 7, 28 and 90 days. Specimens of desired size i.e. 50 mm thick slice of 100 mm diameter cylinder is cut from cast cylinder (200 mm cylinder with 100 mm diameter). The test is performed as per standard to obtain the chloride penetration depth. Further, non-steady state migration coefficient is computed in accordance with observed values. Three identical samples are tested for a typical category and the calculated mean value is noted as chloride migration coefficient of that specified category.

2.6.12 Water permeability of concrete

The water permeability test of concrete is determined based on provisions of EN 12390:2009 after 28 and 90 days. Specimens of size 150 mm cube is pressurized under water pressure of 500 kPa for 72 hours. The maximum depth of water penetration in mm is noted after splitting the specimen. Three identical samples are tested for a typical category and the calculated mean value is noted as depth of water penetration of that specified category.

2.6.13 Water sorptivity of concrete

The initial and secondary sorptivity of concrete is determined based on provisions of ASTM C 1585 – 13. Specimens of desired size i.e. 50 mm thick slice of 100 mm diameter cylinder is cut from cast cylinder (200 mm cylinder with 100 mm diameter). Samples are conditioned in the environmental chamber at 50°C and 80% relative humidity for 3 days. Thereafter, specimen are sealed and stored at room temperature for 15 days. Absorption procedure is commenced and increase in mass is recorded until 7 days. Initial and secondary sorptivity is then calculated as per procedure recommended by code. Two identical samples are tested for a typical category and the calculated mean value is noted as sorptivity of that specified category.

2.6.14 Volume of permeable voids of concrete

The volume of permeable voids of concrete is determined based on provisions of ASTM C 642 – 13. Specimens of desired size i.e. 50 mm thick slice of 100 mm diameter cylinder is cut from cast cylinder (200 mm cylinder with 100 mm diameter). Specimen is observed for oven dry mass, saturated mass after immersion, saturated mass after boiling and immersed apparent mass. Volume of permeable voids is then calculated as per procedure recommended by code. Two identical samples are tested for a typical category and the calculated mean value is noted as volume of permeable voids of that specified category.

2.7 Summary

The present chapter reviews the research on mortar and concrete made with different supplementary cementitious materials such as fly ash, ground granulated blast furnace slag, ultra-fine fly ash and ultra-fine slag. The chapter presents detailed review of properties of mortar and concrete made with fly ash as binary mixtures. The need of ultra-fine material for enhancement of mechanical and durability properties is addressed. Two important ultra-fine material i.e. ultra-fine fly ash and ultra-fine slag is reviewed in available literature. The effect of UFFA and UFS in binary mixtures are presented. The chapter summarizes the critical appraisal of the literature where the use of ultra-fine material in ternary mixtures are proposed to be objective of the present study. The chapter also briefly describes various methods for assessing characteristics of binders and mechanical and durability properties of mortar and concrete.

Chapter 3

Characterization of Materials

3.1 General

Ordinary Portland cement (OPC), fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) are used as binders in the presented study. OPC is considered as primary binder, FA as binary and UFFA/UFS as ternary binder in mortar and concrete. This chapter presents physical and chemical characteristics of all binders. The chemical and physical parameters are validated with respect to relevant code requirements. This chapter presents the scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDS) results of OPC, FA, UFFA and UFS. The findings of SEM and EDS results are compared with findings of chemical characteristics and particle size of binders. In order to ascertain/validate the use of pozzolana such as fly ash, ultra-fine fly ash and ultra-fine slag as supplementary cementation materials, the mechanical strength with regards to IS 1727:2013 and IS 16715:2018 are performed and are presented in this chapter.

3.2 Chemical characteristics of OPC, FA, UFFA and UFS

As part of chemical analysis, the oxide compositions of all binders are investigated. The chemical composition of ordinary Portland cement (OPC) 53 grade is investigated as per IS 4032:1985.

Table 3.1 Chemical characteristics (oxide) of OPC, FA, UFS and UFFA

Oxide compositions	OPC (%)	FA (%)	UFS (%)	UFFA (%)
SiO_2	21.36	56.41	33.62	51.25
Al_2O_3	5.39	24.90	17.2	27.61
Fe_2O_3	3.81	7.99	1.25	6.14
CaO	62.25	4.12	35.5	8.05
SO_3	2.33	0.50	0.45	0.80
MgO	2.15	1.47	8.1	2.28

The chemical compositions of pozzolanic materials i.e. fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) are identified as per IS1727:2015 and IS 4032:1985. The results of chemical investigation show typical bulk oxide contents for all the binder as presented in Table 3.1. The findings of oxide composition are also validated with regards to results of EDS in the subsequent section

3.2.1 Cement

Cement is the primary binding material used in the present study. Ordinary Portland cement of 53 grade, confirming to IS 12269:2013 and IS269:2015 was used in the preparation of reference and blended mixtures of mortar and concrete. The OPC used in the present study was OPC 53 grade (ACC brand). The supply of cement was in bags with net weight of 50 kg. Figure 3.1 shows sample of ordinary Portland cement used in the present study.

Figure 3.1. Ordinary Portland cement used in the present study.

The results of chemical analysis of 53 grade OPC are validated with requirement of IS 269:2015. As per IS code the ratio of percentage of lime to that of silica, alumina and iron oxide calculated as per Eq. 3.1 should be within range of 0.80 – 1.02. The observed value of this ratio for 53 grade OPC used in the present study is found to be 0.88, is within the acceptable range.

$$\frac{CaO - 0.7\,SO_3}{2.8\,SiO_2 + 1.2\,Al_2O_3 + 0.65Fe_2O_3} \qquad 3.1$$

For OPC, the ratio of percent of alumina to that of iron oxide is found to be 1.44 which is greater than required minimum value of 0.66 as per IS 269:2015. Magnesia and sulphur content were identified as 2.15% and 2.33%, respectively, these are within maximum permissible limit of 6.0% and 3.5%, respectively. Insoluble residue (IR) and loss on ignition (LoI) permitted are maximum of 5% and 4%, respectively, the chemical analysis have found 1.7% and 2.4% as IR and LoI, respectively. The results of chemical analysis and validation are presented in Table 3.2.

Table 3.2 Chemical characteristics of OPC in accordance with code regulations.

Characteristics	**Observed Values**	**Recommendation as per IS 269:2015**	**Remarks**
	OPC		
Lime saturation factor $\frac{CaO - 0.7\,SO_3}{2.8\,SiO_2 + 1.2\,Al_2O_3 + 0.65Fe_2O_3}$	0.88	0.80 – 1.02	Acceptable
Ratio of alumina (Al_20_3)to that of iron oxide (Fe_2O_3)	1.44	Min, 0.66 %	Acceptable
Insoluble residue	1.70 %	Max, 5.0 %	Acceptable
Loss on Ignition	2.40 %	Max, 4.0 %	Acceptable
Sulphuric Anhydride (SO_3)	2.33 %	Max, 3.5 %	Acceptable
MgO	2.15 %	Max, 6.0 %	Acceptable
Chloride content	0.01 %	Max, 0.1%	Acceptable

3.2.2 Fly ash

Fly ash confirming to IS 3812: 2013 used in the present study was procured from Dirk India Private limited, a subsidiary of Ambuja Cements Ltd. Nashik, Maharashtra, India. Fly ash used is available commercially as POZZOCRETE 60 supplied in bags of 30kg as shown in Figure 3.2.

The chemical composition of fly ash is investigated as per IS 1727:2015 and is validated in accordance with IS 3812:2013. The observed and permitted values as per codes are presented and validated as shown in Table 3.3.

Figure 3.2. Fly ash (POZZOCRETE 60) used in the present study.

Table 3.3. Chemical characteristics of FA in accordance with code regulations.

Characteristics	Observed Values	Recommendation as per IS 3812:2013	Remarks
	FA		
$SiO_2 + Al_2O_3 + Fe_2O_3$	89.30 %	Min, 70 %	Acceptable
SiO_2	56.41 %	Min, 35 %	Acceptable
MgO	1.47 %	Max, 5 %	Acceptable
SO_3	0.50 %	Max, 3 %	Acceptable
Loss on Ignition	1.04 %	Max, 5 %	Acceptable

3.2.3 Ultra-fine fly ash

Ultra-fine fly ash confirming to IS 3812: 2013 used in the present study was procured from Dirk India Private limited, a subsidiary of Ambuja Cements Ltd. Nashik, Maharashtra, India. Ultra-fine fly ash used is available commercially as POZZOCRETE 100 supplied in bags of 25 kg as shown in Figure 3.3.

The chemical composition of UFFA is investigated as per IS 1727:2015 and validated in accordance with IS 3812:2013. The observed and permitted values as per codes are presented and validated as shown in Table 3.4.

Figure 3.3. Ultra-Fine fly ash (POZZOCRETE 100) used in the present study.

Table 3.4. Chemical characteristics of UFFA in accordance with code regulations.

Characteristics	**Observed Values**	**Recommendation as per IS 3812:2013**	**Remarks**
	UFFA		
$SiO_2 + Al_2O_3 + Fe_2O_3$	85.00 %	Min, 70 %	Acceptable
SiO_2	51.25 %	Min, 35 %	Acceptable
MgO	2.28 %	Max, 5 %	Acceptable
SO_3	0.80 %	Max, 3 %	Acceptable
Loss on Ignition	1.01 %	Max, 5 %	Acceptable

3.2.4 Ultra-fine slag

Ultra-fine slag confirming to IS 16715: 2018 used in the present study was procured from Counto Microfines Products Pvt. Ltd. Goa, India. Ultra-fine slag used is available commercially as ALCCOFINE 1203 supplied in bags of 25 kg as shown in Figure 3.4.

The chemical characteristics of UFS is investigated as per IS 4032:1985 and validated in accordance with IS 16715:2018. The observed and permitted values as per codes are presented and validated as shown in Table 3.5

Figure 3.4. Ultra-fine slag (ALCCOFINE 1203) used in the present study.

Table 3.5. Chemical characteristics of UFS in accordance with code regulations.

Characteristics	**Observed Values**	**Recommendation as per IS 16715:2018**	**Remarks**
	UFS		
MgO	8.1 %	Max, 17 %	Acceptable
SO_3	0.45 %	Max, 3 %	Acceptable
MnO	1.20 %	Max, 5.5 %	Acceptable
Sulphide Sulphur (S)	0.51 %	Max, 2.0 %	Acceptable
Loss on Ignition	0.95 %	Max, 3 %	Acceptable
$\frac{CaO + MgO + \frac{1}{3}Al_2O_3}{SiO_2 + \frac{2}{3}Al_2O_3}$	1.09	Min, 1.0	Acceptable
$\frac{CaO + MgO + Al_2O_3}{SiO_2}$	1.80	Min, 1.0	Acceptable

3.3 Physical characteristics of OPC, FA, UFFA and UFS

Physical analysis of OPC (53 grade) is investigated as per IS 4031:1996. The observed physical characteristics of OPC is validated as per IS 269:2015. The observed values and permissible values are presented in Table 3.6.

In case of FA and UFFA, their physical properties are investigated as per IS 1727:2015 and are validated in accordance with IS 3812:2013. The observed and permitted values as per codes are presented and validated as shown in Table 3.7.

The physical characteristics of UFS is investigated and validated in accordance with IS 16715:2018. The Blaine's specific surface area of UFS is found as 1050 m^2/kg. The observed and permitted values as per codes are presented and validated as shown in Table 3.8.

Table 3.6. Physical characteristics of OPC in accordance with code requirement

Characteristics	Observed Values	Recommendation as per IS 269:2015	Remarks
	OPC		
Blaine's specific surface area	265 m^2/kg	Min, 225 m^2/kg	Acceptable
Initial setting time	180 min	Min, 30 min	Acceptable
Final setting time	230 min	Min, 600 min	Acceptable
Normal Consistency	28 %	-	-
Soundness by Le-Chatelier expansion	0.26 mm	Max, 10 mm	Acceptable
3 Day compressive strength	39.18	Min, 27.00 MPa	Acceptable
7 Day compressive strength	47.24	Min, 37.00 MPa	Acceptable
28 Day compressive strength	56.22	Min, 53.00 MPa	Acceptable

Table 3.7. Physical characteristics of FA and UFFA in accordance with code regulations.

Characteristics	Observed Values		Recommendation as per IS 3812:2013	Remarks
	FA	UFFA		
Blaine's specific surface area	377 m^2/kg	642 m^2/kg	Min, 320 m^2/kg	Acceptable
Residue over sieve of 45 μm	15.59 %	3.02 %	Max, 34 %	Acceptable
28 Day compressive strength	54.40 MPa	60.37 MPa	Minimum 80 % strength of plain cement mortar	Acceptable

Table 3.8. Physical characteristics of UFS in accordance with code regulations.

Characteristics	Observed Values	Recommendation as per IS 16715:2018	Remarks
	UFS		
Particle Size, D_{50}	4.3 μm	Max, 5 μm	Acceptable
Particle Size, D_{95}	12.8 μm	Max, 15 μm	Acceptable
Slag activity index at 7 days	110.9 %	Min, 60 %	Acceptable
Slag activity index at 28 days	104.3 %	Min, 75 %	Acceptable

3.4 Particle size analysis of OPC, FA, UFFA and UFS

Particle size analysis is conducted for all binders by laser diffraction using a MALVERN MasterSizer 2000 fitted with Scirocco sample handling unit. The graphical representation of particle size distribution (PSD) of all binders are presented in Figure 3.5.

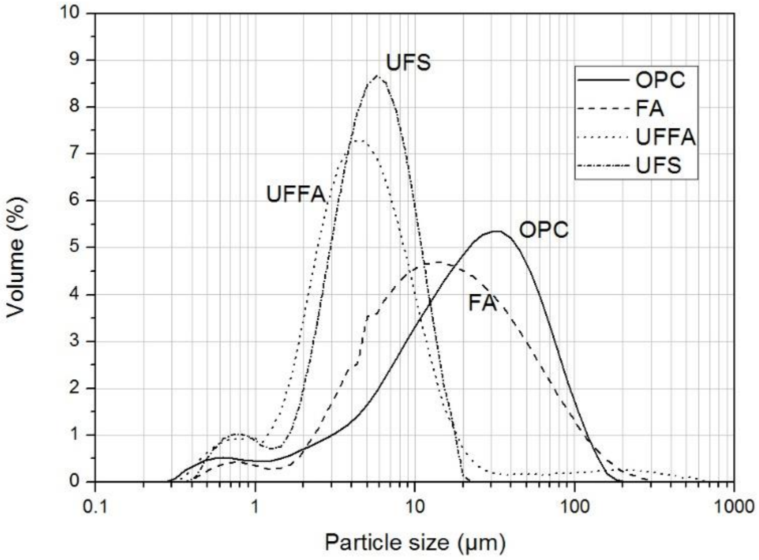


Figure 3.5. Particle size distribution of OPC, FA, UFS and UFFA examined by laser diffraction method.

It is observed from Figure 3.5 that particle size of OPC and FA are similar to each other but are coarser than that of UFFA or UFS. Similarly, the particle size distribution of UFS and UFFA are almost same. Table 3.9 presents specific gravity, surface area, and results of PSD for all binders.

Table 3.9. Physical characteristics of OPC, FA, UFS and UFFA.

Parameter	OPC	FA	UFS	UFFA
Specific gravity	3.15	2.28	2.86	2.36
Blaine's surface area (m^2/kg)	265	377	1050	642
Residue on 45 µm sieve (%)	21.50	15.62	-	4.15
Particle size, D_{50} (µm)	22.9	15.13	5.02	4.36
Particle size, D_{95} (µm)	91.2	91.2	13.18	19.9

3.5 Compressive strength requirement of OPC, FA, UFFA and UFS

Suitability of pozzolanic materials i.e. FA, UFFA and UFS are investigated as per provisions of IS 1727:2013. Pozzolana mortar is prepared according to the specified ratio of pozzolana: cement: standard sand in ratio of $0.2N$:0.8:3.0, where N is the ratio of specific gravity of pozzolana to cement. For the preparation of only OPC mortar the specified ratio is 1:3 with 500 gm of cement and 1500 gm of standard sand. Whereas in case of Pozzolana mortars, the quantity of pozzolana is $100 \times N$ gm, cement as 400 gm, and standard sand as 1500 gm. Quantity of water is identified in order to satisfy the flow requirement of 105 ± 5 % increase in base diameter of mortar mass with 25 drops in 15 seconds. The cubes of 50 mm size are casted and tested for compressive strength after 3, 7 and 28 days of curing. The results of cube compressive strength are presented in Fig. 3.6 and Table 3.10.

Table 3.10. Compressive strength of OPC, OPC – FA, OPC – UFFA and OPC – UFS mortars.

Type of mortar	Compressive strength of 50 mm mortar cube (MPa)		
	3 Day	7 Day	28 Day
OPC	39.18	47.24	56.22
OPC - FA	32.63	37.71	54.40
OPC - UFFA	40.71	53.32	60.37
OPC - UFS	42.61	52.39	58.64

It was observed from the results of compressive strength of mortars that, the strength at 3 and 7 days have reduced substantially due to addition of fly ash due to slow pozzolanic reaction at early age. However, at 28 days the strength of OPC – FA is 96.7% of the strength of OPC mortar. As per IS 3812:2013, compressive strength at 28 days for OPC pozzolana mortar should have been more than 80% of strength of control mortar. The observed values are greater than the minimum requirement, and hence fly ash is found to be suitable as supplementary cementitious material.

With regards to compressive strength of OPC – UFFA and OPC – UFS, the compressive strength at all ages are higher than that of OPC mortar. The early age compressive strength of ultra-fine mortars are higher than OPC mortar, which shows acceleration in pozzolanic activity due to ultra-fine particle size. As per IS 3812:2013, the 28 day strength of OPC – pozzolana mortar should be 80% of control mixture. The observed value of 28 days compressive strength for OPC-UFFA is 107.3% of control mortar. The code requirement as per IS 16715:2018, the slag activity index at 7 and 28 days must be 60% and 75%, respectively. The observed value of slag activity index of OPC – UFS mortar at 7 and 28 days are 110.9 % and 104.3%, respectively. Hence the ultrafine materials UFFA and UFS comply for use as SCM in mortar and concrete as per physical and chemical requirements.

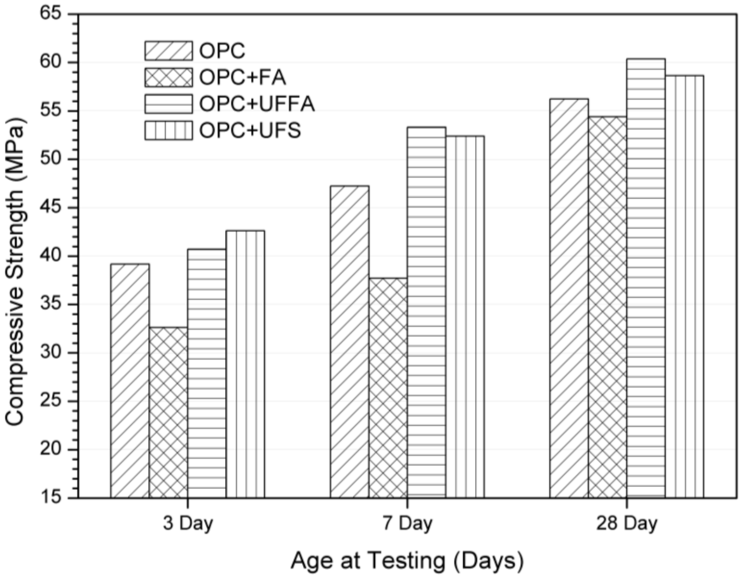


Figure 3.6. Compressive strength of 50 mm cube for OPC, OPC – FA, OPC – UFFA and OPC – UFS mortars.

3.6 SEM and EDS analysis of OPC, FA, UFFA and UFS

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) observations were performed in order to understand the microstructure of ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag. The binder samples are sputter coated with platinum to increase the conductivity and further examined using JEOL-JSM-6360 L V SEM for SEM and EDS micrographs. During the examination, the accelerating voltage is maintained at 10kV – 15kV and observation are noted at a scale of 2µm, 5 µm and 10 µm.

3.6.1 SEM and EDS analysis of OPC

The results of SEM and EDS analysis of OPC are presented in Figs. 3.7 to 3.10. It is observed from the SEM images that, the particles of OPC are generally angular and irregular. The size of particles are generally greater than 5 µm with many particles greater than 10 µm as well, the same is observed from the PSD analysis also.

The EDS analysis confirms the presence of calcium and silica oxides in abundance, with traces of alumina, ferrous, magnesium and sulphur oxides, which confirms the findings from chemical analysis of OPC.

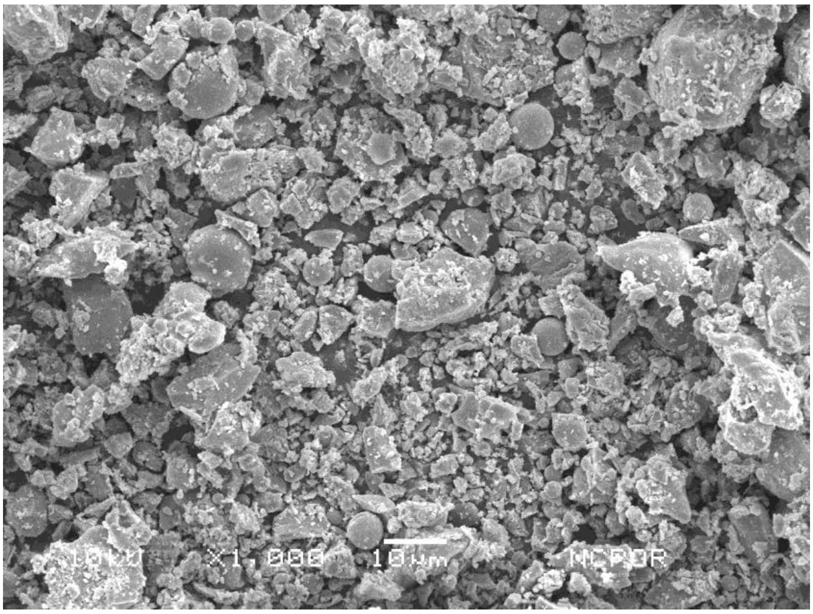


Figure 3.7. SEM analysis of Ordinary Portland Cement (10 µm)

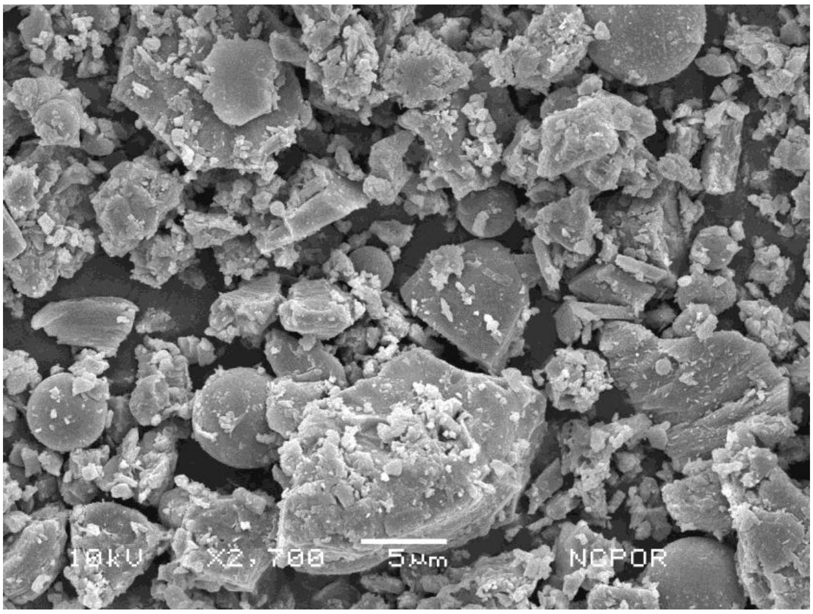


Figure 3.8. SEM analysis of OPC (5 µm).

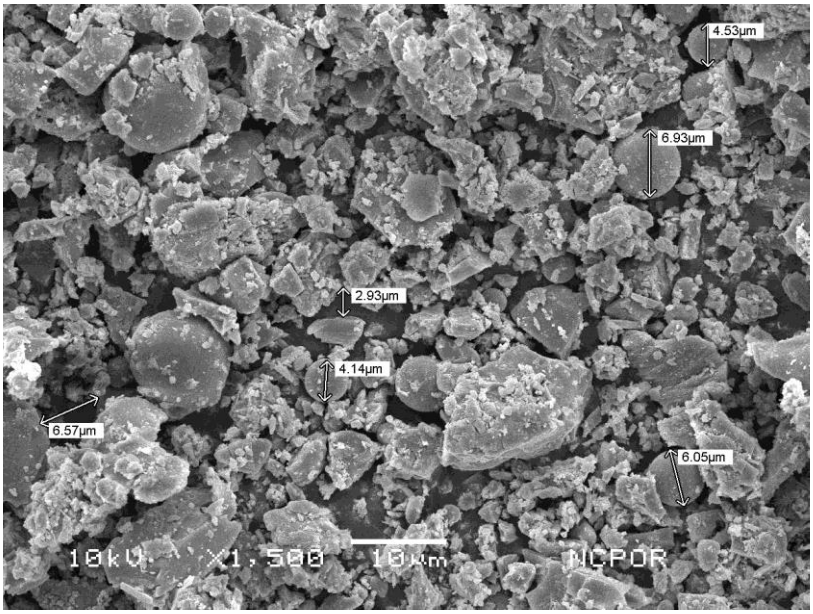


Figure 3.9. SEM analysis of OPC with particle size measurement (2 µm).

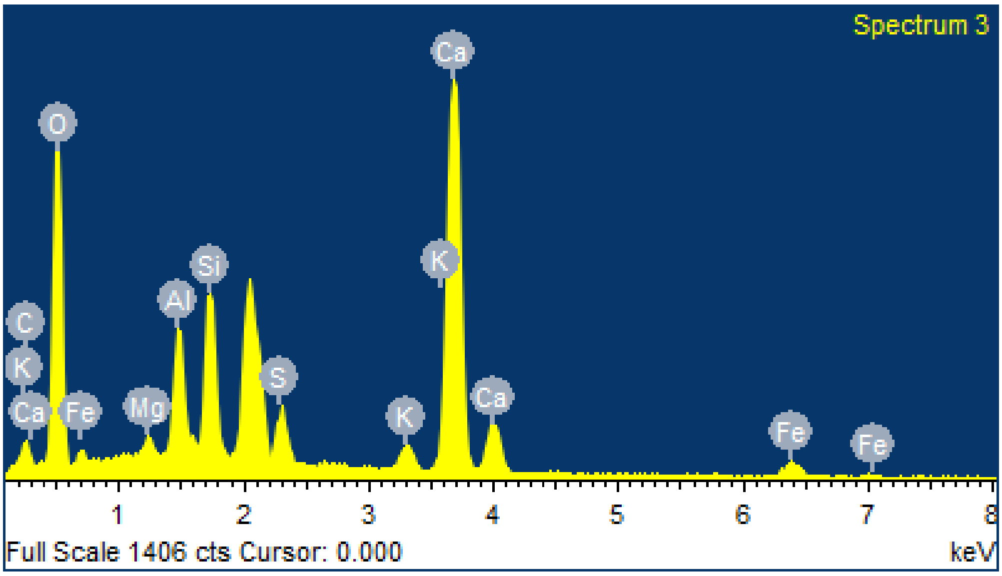


Figure 3.10. EDS analysis of OPC.

3.6.2 SEM and EDS analysis of FA

The results of SEM and EDS analysis of FA are presented in Figs. 3.11 to 3.14. It is observed from the SEM images that, the particles of FA are spherical. The size of particles are generally greater than 4 µm with many particles greater than 10 µm as well, the same is observed from the PSD analysis also. The particle sizes of FA are almost similar to that of OPC.

The spherical shape of fly ash imparts better flow and workability properties in mortar and concrete. The EDS analysis confirms the presence of silica and alumina oxides in abundance as shown by peaks, with traces of ferrous, magnesium and sulphur oxides, which confirms the findings from chemical analysis of fly ash.

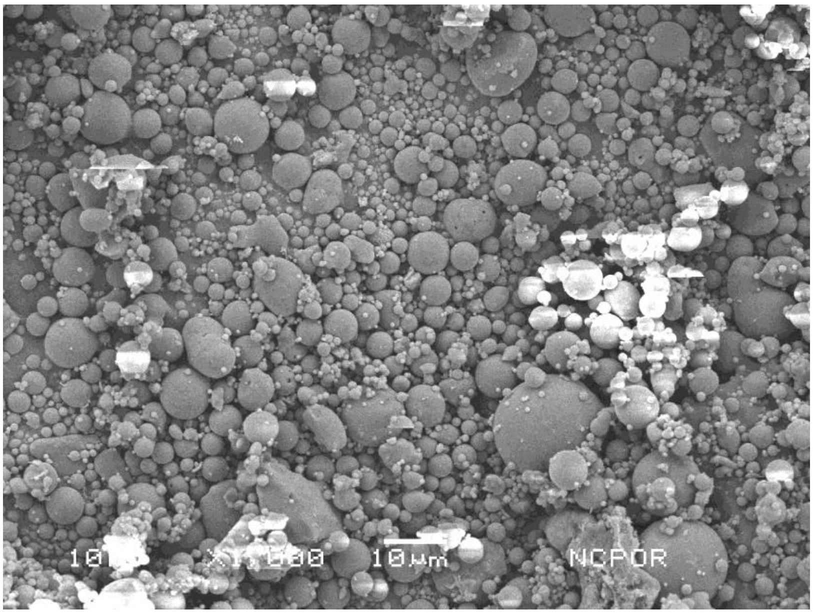


Figure 3.11. SEM analysis of fly ash (10 µm).

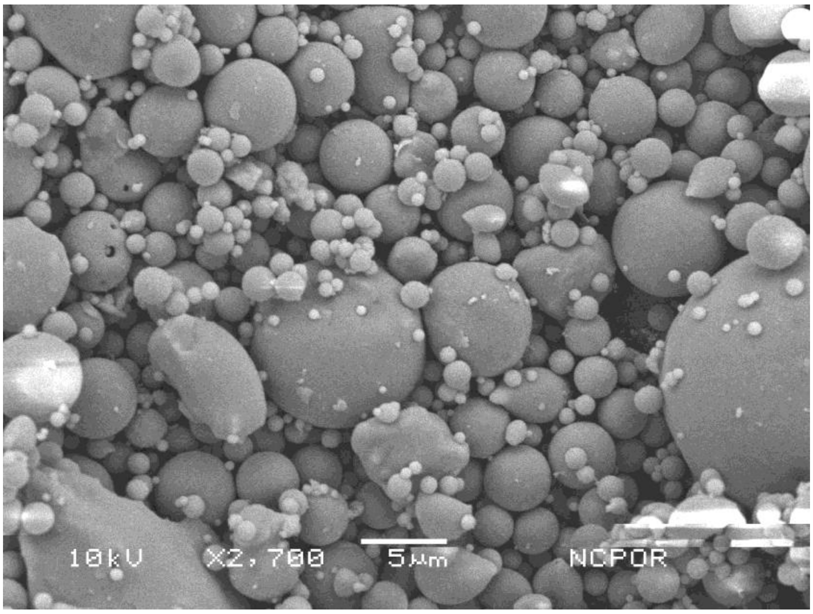


Figure 3.12. SEM analysis of fly ash (5 µm).

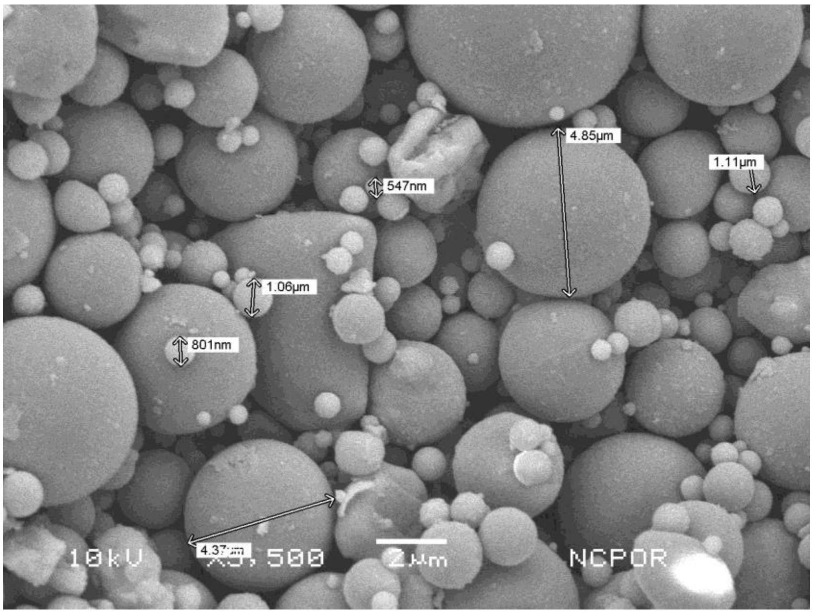


Figure 3.13. SEM analysis of fly ash with particle size measurement (2 µm).

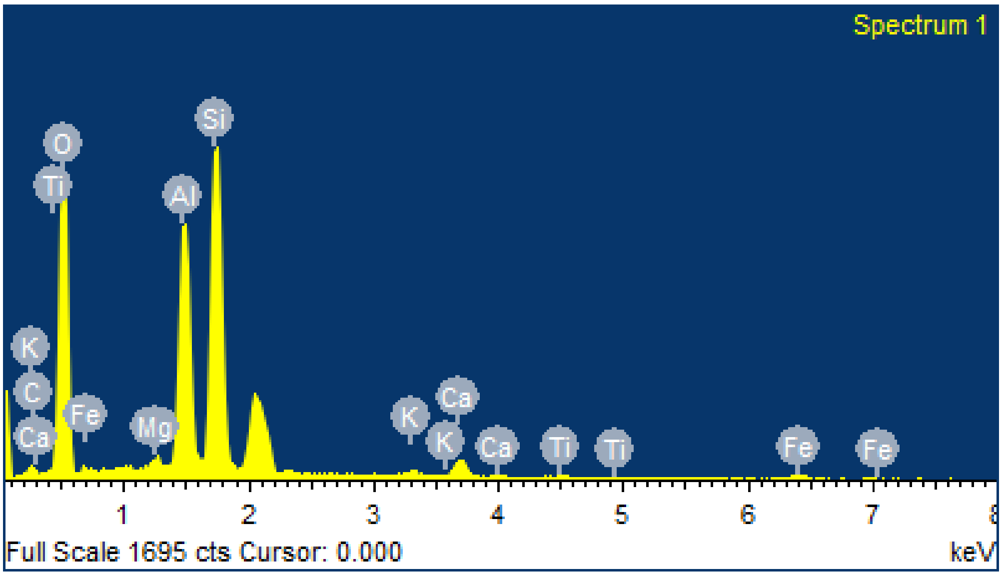


Figure 3.14. EDS analysis of fly ash.

3.6.3 SEM and EDS analysis of UFFA

The results of SEM and EDS analysis of UFFA are presented in Figs. 3.15 to 3.18. It is observed from the SEM images that, the particles of UFFA are spherical like FA. The size of particles are generally smaller than 5 µm with majority of particles under 10 µm, the same is observed from the PSD analysis also. The size of UFFA is much smaller as compared to FA or OPC. This small sized UFFA particles improves their reactivity and responsible for high early strength.

The spherical shape of UFFA imparts better flow and workability properties in mortar and concrete. The EDS analysis confirms the presence of silica and alumina oxides in abundance as shown by peaks, with traces of ferrous, magnesium and sulphur oxides, which confirms the findings from chemical analysis of ultra-fine fly ash.

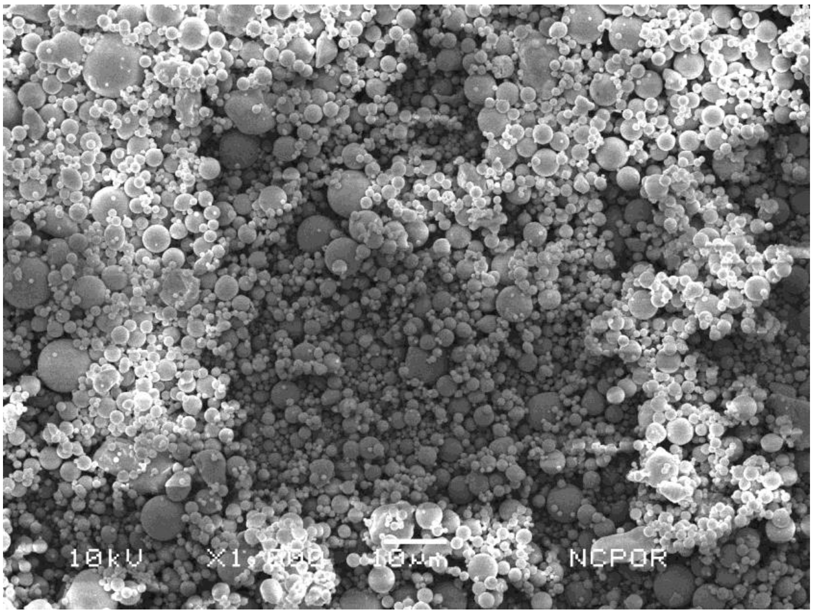


Figure 3.15. SEM analysis of ultra-fine fly ash (10 µm).

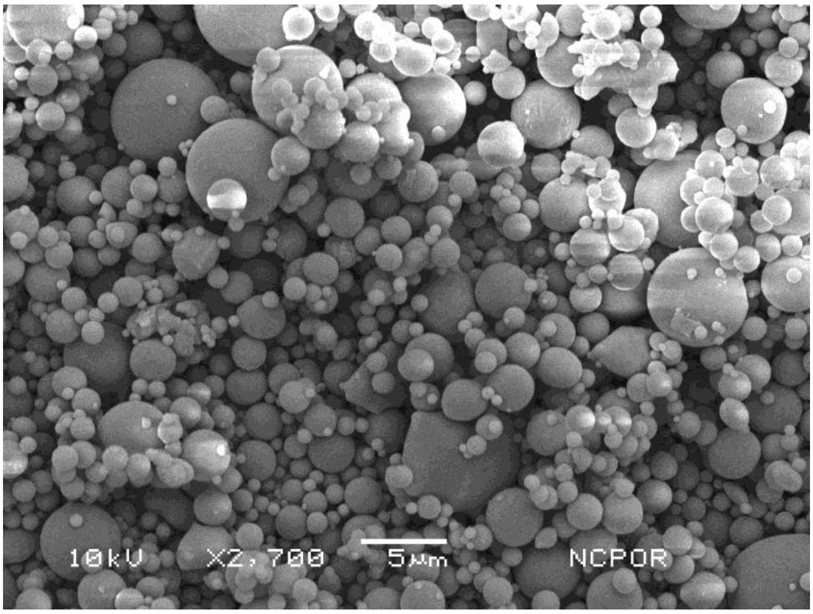


Figure 3.16. SEM analysis of ultra-fine fly ash (5 µm).

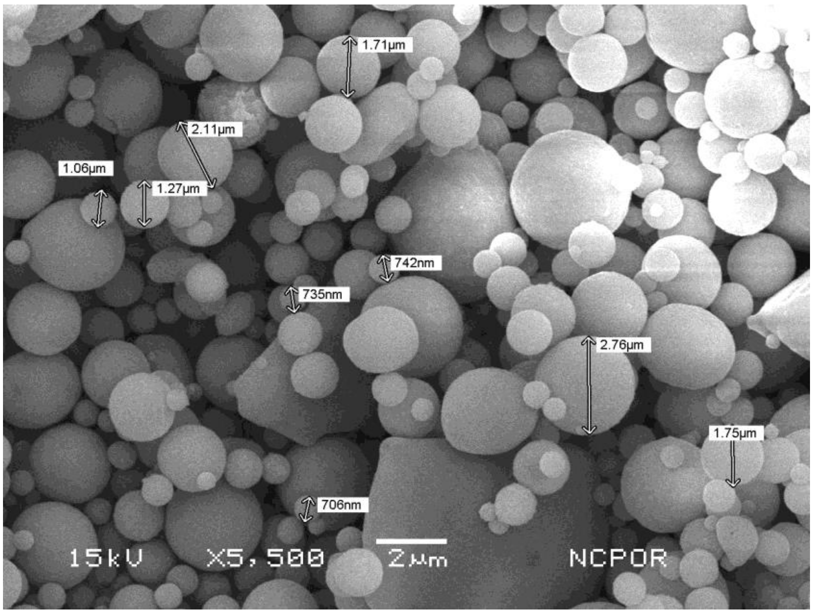


Figure 3.17. SEM analysis of UFFA with particle size measurement (2 µm).

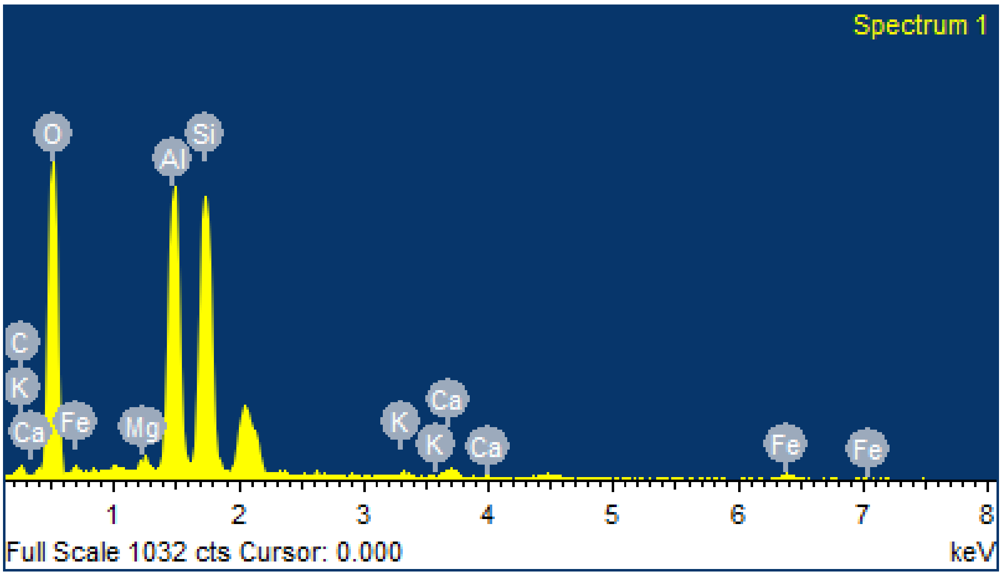


Figure 3.18. EDS analysis of ultra-fine fly ash.

3.6.4 SEM and EDS analysis of UFS

The results of SEM and EDS analysis of UFS are presented in Figs. 3.19 to 3.22. It is observed from the SEM images that, the particles of UFS are angular unlike FA. The size of particles are generally smaller than 5 µm with majority of particles under 10 µm, the same is observed from the PSD analysis also. The size of UFS is much smaller as compared to FA or OPC, however, it is comparable to size of UFFA.

This small sized UFS particles improves their reactivity and are responsible for high early strength. The angular shape of UFS results in less flow and workability properties in mortar and concrete. The EDS analysis confirms the presence of silica and calcium oxides in abundance as shown by peaks, with traces of ferrous, magnesium, sulphur and alumina oxides, which confirms the findings from chemical analysis of ultra-fine slag.

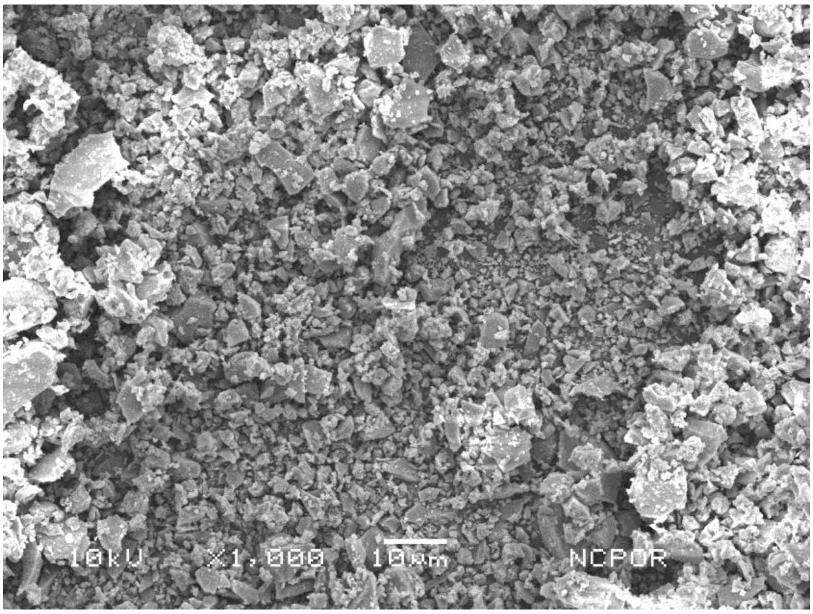


Figure 3.19. SEM analysis of ultra-fine slag (10 μm).

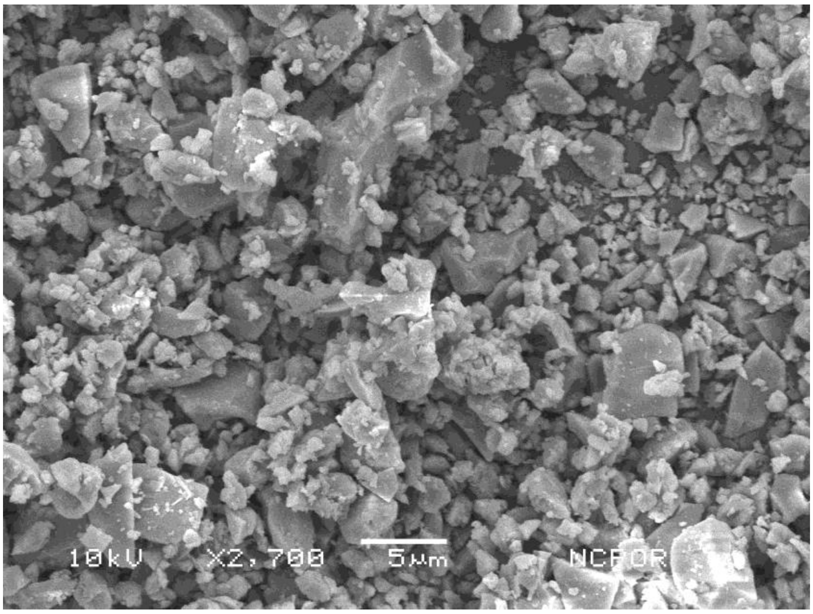


Figure 3.20. SEM analysis of ultra-fine slag (5 μm).

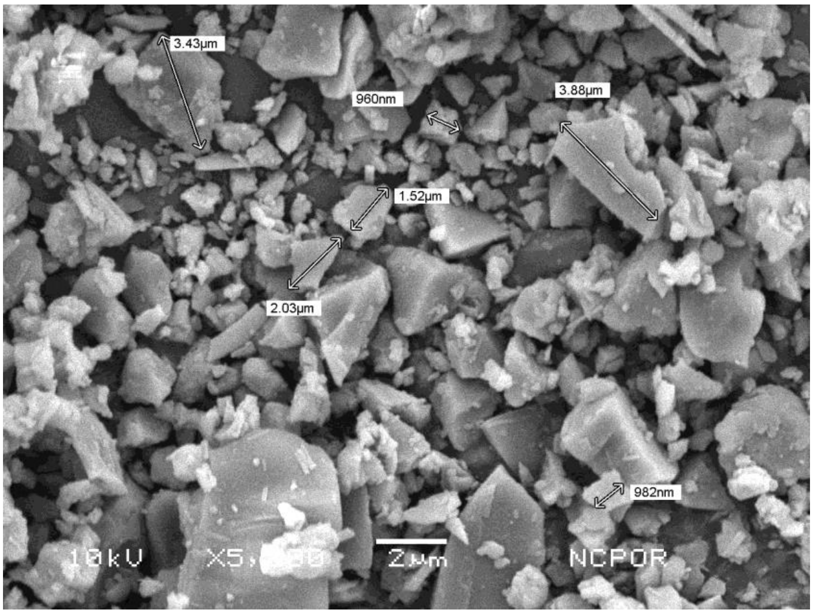


Figure 3.21. SEM analysis of UFS with particle size measurement (2 µm).

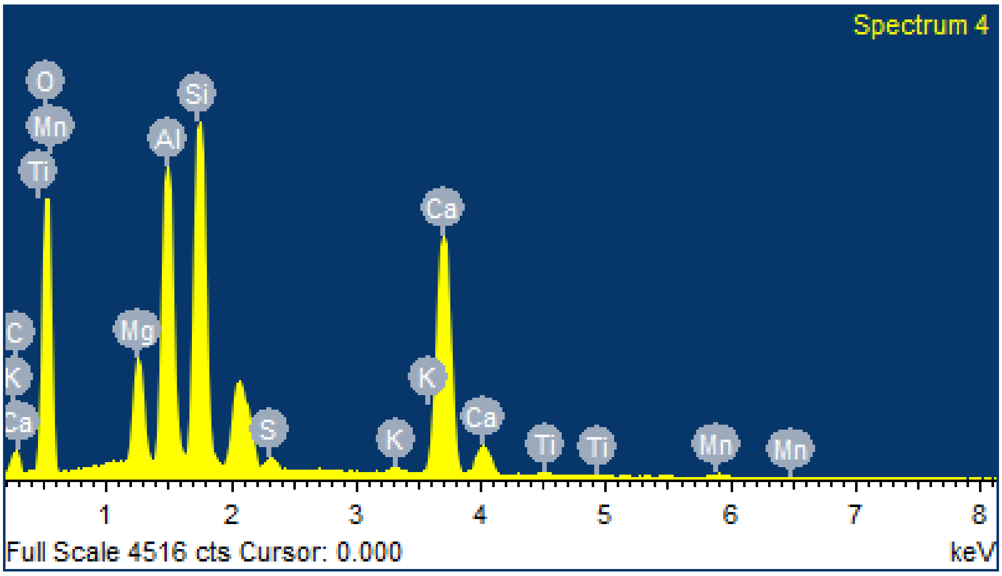


Figure 3.22. EDS analysis of ultra-fine slag.

3.7 Tests on aggregates

Fine and coarse aggregate used for the present study are procured from local sources. Coarse aggregate is of 20 mm maximum nominal size. The fine aggregate used is manufactured sand (M-sand) confirming to Indian standards. The specific gravity and water absorption of coarse aggregate was 2.83 and 0.6%, respectively. The specific gravity and water absorption of fine aggregate is found to be 2.80 and 1.65%. The results of sieve analysis of fine and coarse aggregate are presented in Table 3.11 and 3.12, respectively. Fine aggregate confirms to grading Zone II as per IS 383:2016.

Table 3.11. Results of sieve analysis of coarse aggregate.

IS Sieve designation	Percentage passing	IS 383:2016 Requirement	Remarks
40 mm	100	100	Coarse aggregate satisfies requirement of IS 383:2016
20 mm	92.3	90 – 100	
10 mm	45.5	25 – 55	
4.75 mm	3.2	0 – 10	

Table 3.12. Results of sieve analysis of fine aggregate.

IS Sieve designation	Percentage passing	IS 383:2016 Requirement of Zone II	Remarks
10 mm	100	100	Fine aggregate used satisfies requirement of IS 383:2016 and confirms Zone II
4.75 mm	98.5	90 – 100	
2.36 mm	88.2	75 – 100	
1.18 mm	65.3	55 – 90	
600 µm	45.7	35 – 59	
300 µm	16.2	8 – 30	
150 µm	2.1	0 – 10	

3.8 Water used in mortar and concrete.

Tap water available in the laboratory is used for preparation of mortar and concrete. Tap water is used for curing of mortar and concrete specimens maintaining an ambient temperature of 25 – 27 °C. Water used for curing is replaced with fresh tap water every seven days.

3.9 Admixture

Workability of concrete is maintained by addition of commercially available Poly - Carboxylic Ethers (PCE) based super plasticizer as shown in Figure 3.23.

The admixture satisfy requirements as per IS 9103:1999, and is suitable for mixture containing fly ash and ground granulated blast furnace slag. The properties of admixture are presented in Table 3.13.

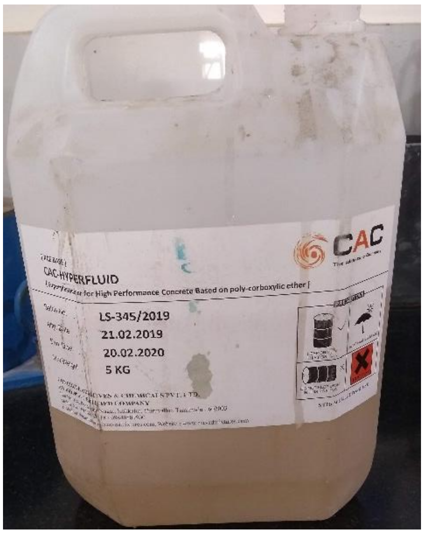


Figure 3.23. Superplasticizer used in the present study.

Table 3.13. Properties of superplasticizer.

Type of Admixture	Poly – carboxylic Ether based Superplasticizer
Company	Concrete Additives & Chemicals Pvt. Ltd. (CAC)
Specific gravity	1.145
Chloride content	Nil
pH	6.0
Dosage	0.5% - 1.5% of binder content
Appearance	Light brown liquid

3.10 Summary

This chapter presents chemical and physical characteristics of ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag. The findings of chemical and physical characteristics are validated as regards to Indian Standards. The results of particle size distribution of all binders are presented in this chapter. SEM and EDS observations of binders are presented and compared with findings of chemical and physical characteristics. It was observed that, OPC and fly ash are of similar average particle size. Similarly, the average particle size of UFFA and UFS are similar and are significantly smaller as compared to FA or OPC. The shape of OPC and UFS are angular, whereas the shape of FA and UFFA are spherical. The suitability of FA, UFFA and UFS as supplementary cementitious material is ascertained as per code provisions in terms of physical, chemical and mechanical strength parameters. Sieve analysis results of fine and coarse aggregate are presented. Overall this chapter comprise characterisation of materials used in the present study. The subsequent chapters focus on results and discussion on mortars and concrete made with fly ash, ultra – fine fly ash and ultra – fine slag.

Chapter 4

Studies on Mechanical Properties of Mortar Mixes

4.1 General

The present chapter investigates the properties of binders and mortar in different combinations. This chapter discusses the particle packing density of binders in different binary and ternary combinations. With regards to mortars, the flow properties and compressive strength of reference (100% OPC), 21 binary mixtures and 30 ternary mixtures were investigated. Ordinary Portland cement (OPC) is replaced by fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) to make binary and ternary combinations. FA, UFFA and UFS are replaced in the range of 10% - 70% each to form binary combinations. In case of ternary combinations, the FA replacement is from 10% to 30%, whereas for UFFA and UFS, the replacement percentage is up to 50%. The results of mortars tests have been used to identify the feasible range of replacement for each binder corresponding to compressive strengths. These identified replacement dosage of FA, UFFA and UFS are used in concrete mixes to analyse its mechanical and durability properties.

4.2 Binder proportions of mortars

OPC, FA, UFFA and UFS are mixed in different proportions to investigate the particle packing density of paste, flow and compressive strength of mortars. Control mixture containing 100% OPC is chosen as reference mix. 21 binary combinations with varying percentage of binders in OPC – FA, OPC – UFFA and OPC – UFS are investigated. The results of binary mixtures are analysed and used for choosing feasible range of replacement in ternary combinations. 30 ternary mixtures of mortar with varying percentage of binders in OPC – FA – UFFA and OPC – FA – UFS are investigated.

The details of binder proportions of reference and binary mixtures are presented in Table 4.1. Mix ID 'R' represents reference or control mixture with 100% ordinary

Portland cement. The properties of binary and ternary combinations are compared with reference mixture ‘R’. Binary combinations in terms of OPC – FA, OPC – UFFA and OPC – UFS have replacement of binders in range of 10% to 70%.

Table 4.1. Binder proportions of reference and binary mortar mixes with FA, UFFA and UFS.

Sr. No.	Mix ID	OPC (%)	FA (%)	UFFA (%)	UFS (%)	Remarks
1	R	100	-	-	-	Reference mix
2	B10F	90	10	-	-	Binary mix of OPC – FA
3	B20F	80	20	-	-	
4	B30F	70	30	-	-	
5	B40F	60	40	-	-	
6	B50F	50	50	-	-	
7	B60F	40	60	-	-	
8	B70F	30	70	-	-	
9	B10UF	90	-	10	-	Binary mix of OPC – UFFA
10	B20UF	80	-	20	-	
11	B30UF	70	-	30	-	
12	B40UF	60	-	40	-	
13	B50UF	50	-	50	-	
14	B60UF	40	-	60	-	
15	B70UF	30	-	70	-	
16	B10US	90	-	-	10	Binary mix of OPC – UFS
17	B20US	80	-	-	20	
18	B30US	70	-	-	30	
19	B40US	60	-	-	40	
20	B50US	50	-	-	50	
21	B60US	40	-	-	60	
22	B70US	30	-	-	70	

Mix ID of binary combinations starts with letter ‘B’. The number followed by ‘B’ represents the percent of replacement of OPC by FA, UFFA or UFS. Letter followed by number represents fly ash as ‘F’, ultra-fine fly ash as ‘UF’ and ultra-fine slag as ‘US’. For example, B20F represents, binary combination with 20% of fly ash and remaining 80% as OPC. B60UF represents, binary combination with 60% of ultra-fine fly ash and remaining 40% as OPC. Similarly, B40US represents, binary combination with 40% of ultra-fine slag and remaining 60% as OPC.

Table 4.2. Binder proportions of reference and ternary mixes with FA, UFFA and UFS.

Sr. No.	Mix ID	OPC (%)	FA (%)	UFFA (%)	UFS (%)	Remarks
1	R	100	-	-	-	Reference mix
2	10T10UF	80	10	10	-	Ternary mix of OPC – FA – UFFA
3	10T20UF	70	10	20	-	
4	10T30UF	60	10	30	-	
5	10T40UF	50	10	40	-	
6	10T50UF	40	10	50	-	
7	20T10UF	70	20	10	-	
8	20T20UF	60	20	20	-	
9	20T30UF	50	20	30	-	
10	20T40UF	40	20	40	-	
11	20T50UF	30	20	50	-	
12	30T10UF	60	30	10	-	
13	30T20UF	50	30	20	-	
14	30T30UF	40	30	30	-	
15	30T40UF	30	30	40	-	
16	30T50UF	20	30	50	-	
17	10T10US	80	10	-	10	Ternary mix of OPC – FA – UFS
18	10T20US	70	10	-	20	
19	10T30US	60	10	-	30	
20	10T40US	50	10	-	40	
21	10T50US	40	10	-	50	
22	20T10US	70	20	-	10	
23	20T20US	60	20	-	20	
24	20T30US	50	20	-	30	
25	20T40US	40	20	-	40	
26	20T50US	30	20	-	50	
27	30T10US	60	30	-	10	
28	30T20US	50	30	-	20	
29	30T30US	40	30	-	30	
30	30T40US	30	30	-	40	
31	30T50US	20	30	-	50	

The details of binder proportions of ternary mixtures are presented in Table 4.2. Mix ID ‘R’ represents reference or control mixture with 100% ordinary Portland cement. 30 different ternary combinations in terms of OPC – FA – UFFA and OPC – FA – UFS have been studied in mortar.

The range of replacement of binders was identified based on preliminary investigation and observation of reference and binary mortar mixes. The replacement range for FA was 10%, 20% and 30% along with replacement percentage of UFFA and UFS range from 10% to 50%.

Mix ID of ternary combinations starts with percent of fly ash in the respective combination. The letter followed by FA percentage is ‘T’ and it represents ternary. The number followed by ‘T’ represents the percent of replacement of OPC by either UFFA or UFS. Letter followed by this particular replacement percentage represents ultra-fine fly ash as ‘UF’ and ultra-fine slag as ‘US’. For example, 10T20UF represents ternary combination with 10% of fly ash, 20% of UFFA and remaining 70% as OPC. Similarly, 30T40US represents ternary combination with 30% of fly ash, 40% of UFS and remaining 30% as OPC.

4.3 Particle packing density

Particle packing density (PPD) of pastes are determined using Puntke particle packing density method. The binders such as OPC, FA, UFFA and UFS are combined in different proportions to form 21 binary and 30 ternary mixtures. Binders are dry mixed in desired proportion and then water required to completely saturate this dry mixture is observed. Ratio of dry volume to saturated volume of mixture is noted as particle packing density. The higher value of particle packing density resembles the mixture with better packing. Particle packing also represents the volume of voids available for water to fill, hence lower particle density represents more voids in the mixture. Particle size of binders and their proportions play an important role in filling the voids of smaller binder created by coarser binder. Figure 4.1 shows step by step procedure for determination of particle packing density. The results of particle packing density of all binder combinations are presented in Table 4.3.

The particle packing density of reference mix was found to be 0.605. The particle packing density have improved for initial substitution up to 30% replacement of all binders. Thereafter, the particle packing density have been observed to reduce. The maximum PPD was observed as 0.622, 0.653 and 0.662 for B20F, B20UF and B20US, respectively. Similar results were noticed in ternary mixes where the PPD have shown an increasing trend up to 30% of UFFA or UFS content, thereby PPD have shown reduced values. The maximum value of PPD for UFFA ternary mix was observed as 0.668 for 30T20UF. Similarly, the maximum value of PPD for UFS ternary mix was observed as 0.671 for 30T20US.

(a) Dry mixing of binders (b) Addition of water and mixing

(c) saturated mix of binders

Figure 4.1. Investigation of particle packing density of binders.

Particle packing density of mix depends on the particle size of binders. As the particle size distribution of fly ash are similar to that of OPC, marginal improvement is noted in PPD for FA based mix. Whereas, the particle size of UFFA and UFS are significantly smaller than that of OPC and FA, hence improvement in particle packing density was observed with UFFA and UFS binder mixers. The improvement in PPD is attributable to better packing density which has resulted from filler effect of UFFA or UFS. The particle packing density is determined based on quantity of water required to produce a saturated mix. Hence for mixes with more than 30% replacement, the water was absorbed by particles of binders having higher surface area due to increased fineness. Hence, PPD of ternary mixes with higher UFFA/UFS are less as compared to that of reference mixture. Overall it was observed that particle packing density of binary and ternary mixes were in the range of 0.44 – 0.662 and 0.485 – 0.671, respectively as compared to 0.605 for reference mix.

4.4 Flow of mortar

The workability of mortar is measured in terms of flow (in mm). The flow of reference mortar is found to be 175 mm. The flow properties of mortar have been observed to increase due to addition of fly ash with a maximum flow of 210 mm for B70F mortar mix. Similar increasing trend in flow value was observed in case of binary mortars with ultra-fine fly ash. The maximum increment in flow was observed for the mortar with maximum percent of UFFA, i.e. B70UF with a flow of 220 mm. The flow of mortar have been generally observed to increase with increment in fly ash and/or ultra-fine fly ash in mortar. This increment in flow properties are attributable to spherical shape of fly ash and ultra-fine fly ash. The spherical shaped particles reduces the inter particle friction and imparts mobility of the mixture. The spherical shape of fly ash and ultra-fine fly ash is evidently observed by SEM observation. Increment in workability of mortar due to fly ash and ultra-fine fly ash was observed by many researchers (Choi et al., 2012; Fang et al., 2018; Nguyen et al., 2018).

The flow properties of mortar have been observed to reduce due to addition of ultra-fine slag in mortars. The UFS based binary mortars show reduced workability as compared to reference mortar. The maximum workability was observed by mortar with minimum UFS content i.e. B10US, with a flow value of 165 mm. The workability was observed to reduce with increment of UFS content in binary mortars.

Table 4.3. Particle Packing Density (PPD) and flow of mortar mixes.

Sr. No.	Mix ID	Flow (mm)	PPD	Sr. No.	Mix ID	Flow (mm)	PPD
1	R	175	0.605	1	R	175	0.605
Binary Mixes				**Ternary Mixes**			
2	B10F	180	0.610	2	10T10UF	185	0.632
3	B20F	190	0.622	3	10T20UF	195	0.641
4	B30F	195	0.610	4	10T30UF	195	0.639
5	B40F	195	0.524	5	10T40UF	210	0.585
6	B50F	200	0.520	6	10T50UF	215	0.523
7	B60F	210	0.450	7	20T10UF	190	0.638
8	B70F	210	0.440	8	20T20UF	200	0.645
9	B10UF	195	0.623	9	20T30UF	205	0.641
10	B20UF	195	0.653	10	20T40UF	215	0.552
11	B30UF	200	0.595	11	20T50UF	220	0.510
12	B40UF	210	0.553	12	30T10UF	190	0.645
13	B50UF	215	0.525	13	30T20UF	205	0.668
14	B60UF	215	0.485	14	30T30UF	205	0.650
15	B70UF	220	0.450	15	30T40UF	215	0.510
16	B10US	165	0.635	16	30T50UF	225	0.485
17	B20US	160	0.662	17	10T10US	175	0.635
18	B30US	150	0.621	18	10T20US	170	0.656
19	B40US	150	0.584	19	10T30US	165	0.642
20	B50US	145	0.536	20	10T40US	165	0.584
21	B60US	135	0.508	21	10T50US	150	0.534
22	B70US	135	0.482	22	20T10US	180	0.639
				23	20T20US	175	0.642
				24	20T30US	170	0.647
				25	20T40US	170	0.567
				26	20T50US	160	0.515
				27	30T10US	185	0.653
				28	30T20US	180	0.671
				29	30T30US	175	0.656
				30	30T40US	170	0.526
				31	30T50US	170	0.490

The reduction in flow properties are attributable to angular shaped ultra-fine slag particles. The angular shaped particles increases the inter particle friction and restricts mobility of the mixture. The angular shape of ultra-fine slag is evidently observed by SEM observation. Reduction in workability of mortar due to ultra-fine slag was observed by many researchers (Bhushan Jindal et al., 2020; Laskar and Talukdar, 2017; Narender Reddy and Meena, 2018).

In the case of ternary mortars, the flow of mortars with ultra-fine fly ash have been observed to improve with increment in FA and/or UFFA content. The maximum improvement in flow was observed by mortar with maximum FA and UFFA, i.e. 30T50UF with flow value of 225 mm as compared to 175 mm for reference mixture. Ternary mortars have shown an improved workability over a range of 185 – 225 mm for different mixes incorporating FA and UFFA in different proportions. Over all it was observed that with increment in FA or UFFA content, the workability have seen an improvement in all ternary mixtures. This improvement in workability of ternary mixtures is due to spherical shaped FA and UFFA particles.

The flow of mortars with ultra-fine slag have been observed to reduce with increment in UFS content. The maximum reduction in flow was observed by mortar with minimum FA and maximum UFFA content i.e. 10T50US with a flow value of 150 mm as compared to 175 mm for reference mixture. UFS have reduced the workability, whereas FA content in the same ternary mortar tend to improve the workability, finally resulting in improved workability. Hence, the reduction of workability due to UFS is compensated by ability of FA to improve the workability. Improvement in workability was observed by combinations where the FA content are comparatively higher than UFS content. Over all it was observed that with increment in UFS content, the workability have reduced in all ternary mixtures. However, the workability is improved if the FA percentage in increased in UFS based ternary mixtures. This reduction in workability of ternary mixtures is due to angular shaped UFS particles.

4.5 Compressive strength of mortar for binary and ternary mixes

The compressive strength is determined for all mortar mixes prepared with 1:3 binder to fine aggregate proportions. The water to binder ratio is maintained at 0.40 for all mortar mixes. The standard cubes of 70.6 mm size are cased and water cured until the test duration. The compressive strength of mortar at 1 day, 3 day, 7 day, 28 day, 56 day, and 90 days are observed under laboratory scale compression testing machine as shown in Figure 4.2. The results of compressive strengths of binary and ternary mortars are compared with that of reference mortar ‘R’. The compressive strength of reference mortar was observed as 23.18 MPa, 40.49 MPa, 53.46 MPa, 64.73 MPa, 71.59 MPa and 74.21 MPa at 1, 3, 7, 28, 56 and 90 days, respectively.

(a) Casting of 70.6 mm mortar cubes (b) Mortar cubes ready for testing

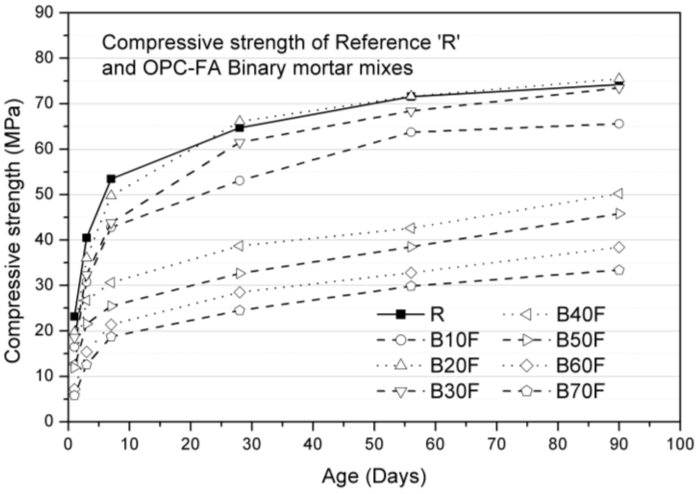
(c) Testing of mortar cube for compressive strength (d) Cube after compressive strength test

Figure 4.2. Testing of compressive strength of mortar cubes

4.5.1 Compressive strength of OPC – FA binary mortar mixes

The results of compressive strength of reference and binary mortars with 10% to 70% of fly ash is presented in Figure 4.3 and Annexure A.1. The compressive strength of all binary mixes at early age (<28 days) is lower than the strength of reference mortars at same age. For binary mixes, the highest strength achieved at early age was observed for B20F at 7 day, and is 7% less than the strength of reference mortar at the same age. Compressive strength at 28 days was also less for all binary mortars except for B20F, where the strength is 2% higher as compared to that of reference mortar. Similarly, the later age strength (> 28 days) was also less for all binary mortars except for B20F, where the 90 day strength is 2% higher as compared to that of reference mortar attributable to prolonged pozzolanic reaction of fly ash.

Overall it is observed that mortar combinations with fly ash up to 30% can provide comparable strengths. Whereas, mortars with replacements of more than 30% of fly ash reduces the strength considerably and hence they may not satisfy the requirements. The slow pozzolanic reactivity of fly ash have reduced the early strength requirement in binary combinations.



Note: R - Reference Mix - 100% OPC
B'x'F - Binary Mix of OPC - x% FA

Figure 4.3. Compressive strength of reference and binary mortars with fly ash (F).

4.5.2 Compressive strength of OPC – UFFA binary mortar mixes

The results of compressive strength of reference and binary mortars with 10% to 70% of ultra-fine fly ash is presented in Figure 4.4 and Annexure A.1. The compressive strength at early age (<28 days) of all binary mixes except for B20UF is lower than the strength of reference mortars at same age. The 7 day strength of B20UF is 7% higher as compared to that of reference mix. Compressive strength at 28 days was also less for all binary mortars except for B10UF and B20UF, where the strength is 5% and 9% higher as compared to that of reference mortar. Similarly, the later age strength (> 28 days) was also less for all binary mortars except for B10UF and B20UF, where the 90 day strength is 4% and 9% higher as compared to that of reference mortar attributable to prolonged pozzolanic reaction of ultra-fine fly ash.

Overall it is observed that mortar combinations with ultra-fine fly ash up to 20% can provide comparable strengths. Whereas, mortars with replacements of more than 20% of ultra-fine fly ash reduces the strength considerably and hence they may not satisfy the strength requirements. Hence, the ternary combinations of concrete investigated in the present study have maximum of 20% as ultra-fine fly ash content. Due to ultra-fine particle size of UFFA, the early age strength have improved in binary combinations as compared to OPC or FA based binary mixes. Ultra-fine fly ash particles reacts faster as compared to fly ash or OPC resulting in high early strengths.

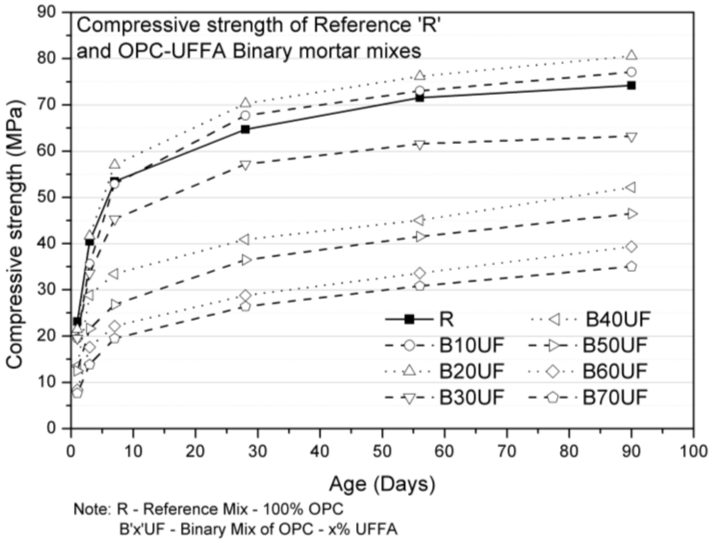


Figure 4.4. Compressive strength of reference and binary mortars with ultra-fine fly ash (UF).

4.5.3 Compressive strength of OPC – UFS binary mortar mixes

The results of compressive strength of reference and binary mortars with 10% to 70% of ultra-fine slag is presented in Figure 4.5 and Annexure A.1. The compressive strength at early age (<28 days) of all binary mixes except for B10US and B20US is lower than the strength of reference mortars at same age. The 7 day strength of B10US and B20US is 4% and 9% higher as compared to that of reference mix. Compressive strength at 28 days was also less for all binary mortars except for B10US and B20US where the strength is 7% and 13% higher as compared to that of reference mortar. Similarly, the later age strength (> 28 days) was also less for all binary mortars except for B10FS and B20FS, where the 90 day strength is 6% and 9% higher as compared to that of reference mortar attributable to prolonged pozzolanic reaction of ultra-fine slag.

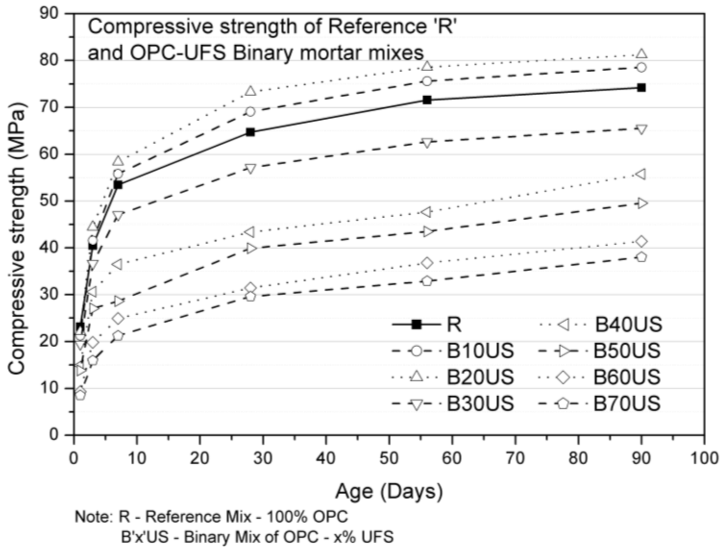
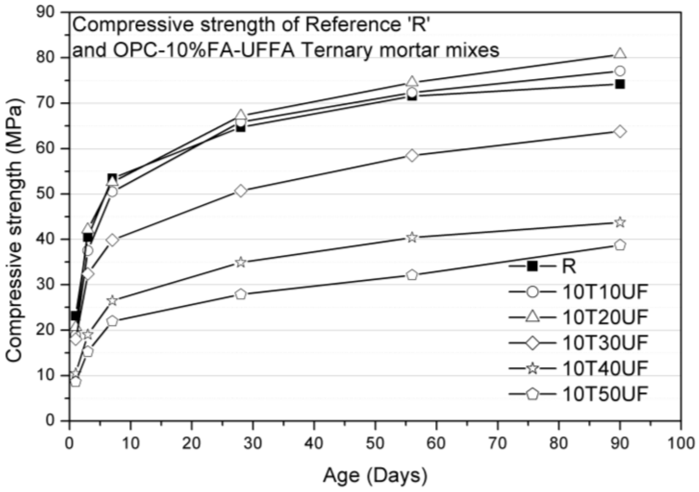


Figure 4.5. Compressive strength of reference and binary mortars with ultra-fine slag (US).

Overall it is observed that mortar combinations with ultra-fine slag up to 20% can provide higher strengths as compared to reference mortar mix. Whereas, mortars with replacements of more than 20% of ultra-fine slag reduces the strength considerably and hence they may not satisfy the strength requirements. Hence, the ternary combinations of concrete investigated in the present study have maximum of 20% as ultra-fine slag content. Due to ultra-fine particle size of UFS the early age strength have improved in binary combinations as compared to OPC or FA based binary mixes. Ultra-fine slag particles reacts faster as compared to OPC, UFFA or FA resulting in highest early strengths.

4.5.4 Compressive strength of OPC – 10%FA – UFFA ternary mortar mixes

The results of compressive strength of reference and ternary mortars with 10% of FA and 10 – 50% of ultra-fine fly ash is presented in Figure 4.6 and Annexure A.2. The compressive strength at early age (<28 days) of all ternary mixes except for 10T20UF is lower than the strength of reference mortars at same age. The 3 day strength of 10T20UF is 4% higher as compared to that of reference mix. The strengths at early age of 10T10UF and 10T20UF are marginally less than that of reference mix. Compressive strength at 28 days was 2% and 4% higher for 10T10UF and 10T20UF as compared to reference mortar. However for mixes with 30% to 50% UFFA, compressive strengths are significantly less as compared to that of reference mortar. Similarly, the later age strength (> 28 days) was also less for all ternary mortars except for 10T10UF and 10T20UF, where the 90 day strength is 4% and 9% higher as compared to that of reference mortar attributable to formation of compact and dense microstructure as compared to other mixes.



Note: R - Reference Mix - 100% OPC
10T'n'UF - Ternary Mix of OPC - 10%FA - n%UFFA

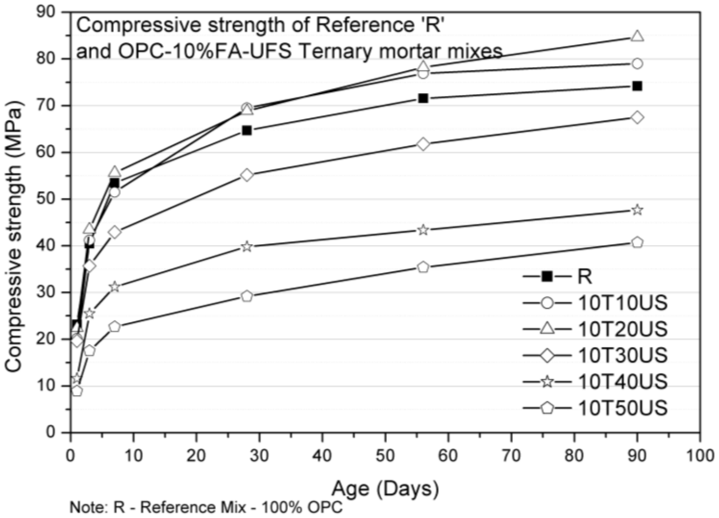
Figure 4.6. Compressive strength of reference and ternary mortars with 10% FA and ultra-fine fly ash (UF).

Overall it is observed that mortar combinations with ultra-fine fly ash up to 20% with 10% of FA in ternary combinations can provide higher strengths as compared to reference mortar mix at all ages. Whereas, mortars with replacements of more than 20%

of ultra-fine fly ash reduces the strength considerably and hence they may not satisfy the strength requirements. Hence, the ternary combinations of concrete investigated in the present study have maximum of 20% as ultra-fine fly ash content. Due to ultra-fine particle size of UFFA the early age strength have improved in ternary combinations as compared to OPC or FA based binary mixes. Ultra-fine fly ash particles reacts faster as compared to OPC or FA resulting in high early strengths.

4.5.5 Compressive strength of OPC – 10%FA – UFS ternary mortar mixes

The results of compressive strength of reference and ternary mortars with 10% of FA and 10 – 50% of ultra-fine slag is presented in Figure 4.7 and Annexure A.2. The compressive strength at early age (<28 days) of all ternary mixes except for 10T10US and 10T20US is lower than the strength of reference mortars at same age.



Note: R - Reference Mix - 100% OPC
10T'n'US - Ternary Mix of OPC - 10%FA - n%UFS

Figure 4.7. Compressive strength of reference and ternary mortars with 10% FA and ultra-fine slag (US).

The 3 day strength of 10T20US is 7% higher as compared to that of reference mix. The strengths at 7 days of 10T10US and 10T20US are marginally less than that of reference mix. Compressive strength at 28 days was less for all ternary mortars except for 10T10US and 10T20US where the strength is 7% and 6% higher as compared to that of reference mortar. Similarly, the later age strength (> 28 days) was also less for all ternary mortars except for 10T10US and 10T20US, where the 90 day strength is 6% and 14%

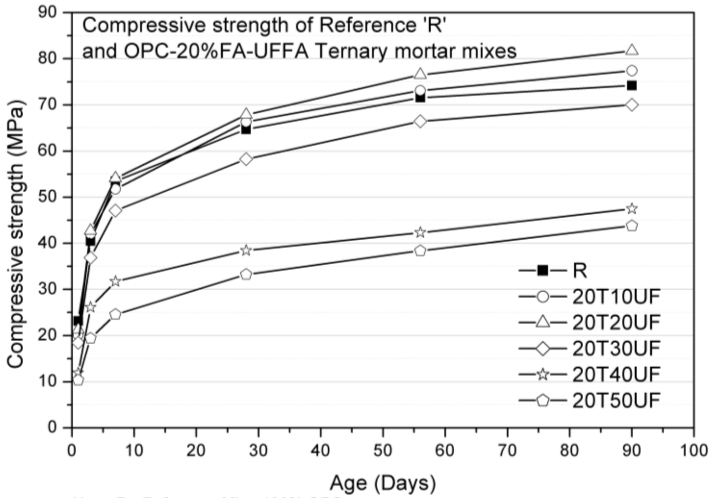
higher as compared to that of reference mortar attributable to formation of compact and dense microstructure as compared to other mixes.

Overall it is observed that mortar combinations with ultra-fine slag up to 20% with 10% of FA in ternary combinations can provide higher strengths as compared to reference mortar mix at all ages. Whereas, mortars with replacements of more than 20% of ultra-fine slag reduces the strength considerably and hence they may not satisfy the strength requirements. Hence, the ternary combinations of concrete investigated in the present study have maximum of 20% as ultra-fine slag content. Due to ultra-fine particle size of UFS the early age strength have improved in ternary combinations as compared to OPC or FA based binary mixes. Ultra-fine slag particles reacts faster as compared to OPC or FA resulting in high early strengths. UFS based mortars have been found to show higher compressive strength as compared to UFFA based mortars for similar replacement percentages

4.5.6 Compressive strength of OPC – 20%FA – UFFA ternary mortar mixes

The results of compressive strength of reference and ternary mortars with 20% of FA and 10 – 50% of ultra-fine fly ash is presented in Figure 4.8 and Annexure A.3. The compressive strength at early age (<28 days) for 20T10UF and 20T20UF are higher as compared to reference mortar. The 3 day strength of 20T10UF and 20T20UF is 4% and 6% higher as compared to that of reference mix. However, the early age strength of mortars with 30 – 50% UFFA are comparatively low. Compressive strength at 28 days for 20T10UF and 20T20UF is 2% and 5% higher as compared to that of reference mortar. For other mixes, the 28 day strength has been found to be lower. Similarly, the later age strength (> 28 days) for 20T10UF and 20T20UF was 4% and 9% higher as compared to that of reference mortar attributable to formation of compact and dense microstructure as compared to other mixes.

Overall it is observed that mortar combinations with ultra-fine fly ash up to 20% with 20% of FA in ternary combinations can provide higher strengths as compared to reference mortar mix at all ages. Whereas, mortars with replacements of more than 20% of ultra-fine fly ash reduces the strength considerably and hence they may not satisfy the strength requirements.



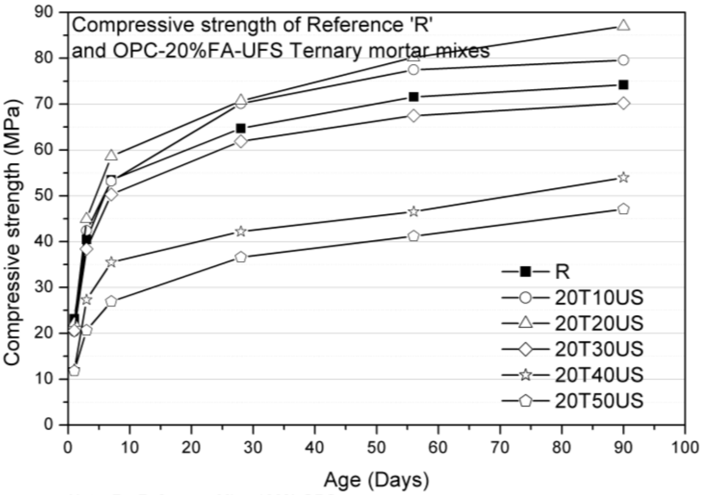
Note: R - Reference Mix - 100% OPC
20T'n'UF - Ternary Mix of OPC - 20%FA - n%UFFA

Figure 4.8. Compressive strength of reference and ternary mortars with 20% FA and ultra-fine fly ash (UF).

4.5.7 Compressive strength of OPC – 20%FA – UFS ternary mortar mixes

The results of compressive strength of reference and ternary mortars with 20% of FA and 10 – 50% of ultra-fine slag is presented in Figure 4.9 and Annexure A.3. The compressive strength at early age (<28 days) for 20T10US and 20T20US are higher as compared to reference mortar. The 3 day strength of 20T10US and 20T20US is 5% and 11% higher as compared to that of reference mix. However, the early age strength of mortars with 30 – 50% UFS are comparatively low. Compressive strength at 28 days for 20T10US and 20T20US is 8% and 9% higher as compared to that of reference mortar. For other mixes, the 28 day strength has been found to be lower. Similarly, the later age strength (> 28 days) for 20T10US and 20T20US was 8% and 17% higher as compared to that of reference mortar attributable to formation of compact and dense microstructure as compared to other mixes.

Overall it is observed that mortar combinations with ultra-fine slag up to 20% with 20% of FA in ternary combinations can provide higher strengths as compared to reference mortar mix at all ages. Whereas, mortars with replacements of more than 20% of ultra-fine slag reduces the strength considerably and hence they may not satisfy the strength requirements. UFS based mortars have been found to show higher compressive strength as compared to UFFA based mortars for similar replacement percentages.



Note: R - Reference Mix - 100% OPC
20T'n'US - Ternary Mix of OPC - 20%FA - n%UFS

Figure 4.9. Compressive strength of reference and ternary mortars with 20% FA and ultra-fine slag (US).

4.5.8 Compressive strength of OPC – 30%FA – UFFA ternary mortar mixes

The results of compressive strength of reference and ternary mortars with 30% of FA and 10 – 50% of ultra-fine fly ash is presented in Figure 4.10 and Annexure A.4. The compressive strength at early age (<28 days) for 30T20UF is higher as compared to reference mortar. The 3 day strength of 30T20UF is 2% higher as compared to that of reference mix. Early strength of 30T10UF is marginally lower, however, the early age strength of mortars with 30 – 50% UFFA are significantly low as compared to reference mortar. Compressive strength at 28 days for 30T20UF is 3% higher as compared to that of reference mortar. For other mixes, the 28 day strength has been found to be lower. The later age strength (> 28 days) for 30T10UF and 30T20UF was 7% and 9% higher as compared to that of reference mortar attributable to formation of compact and dense microstructure as compared to other mixes.

Overall it is observed that mortar combinations with ultra-fine fly ash up to 20% with 30% of FA in ternary combinations can provide marginally higher strengths as compared to reference mortar mix at all ages. Whereas, mortars with replacements of more than 20% of ultra-fine fly ash reduces the strength considerably and hence they may not satisfy the strength requirements.

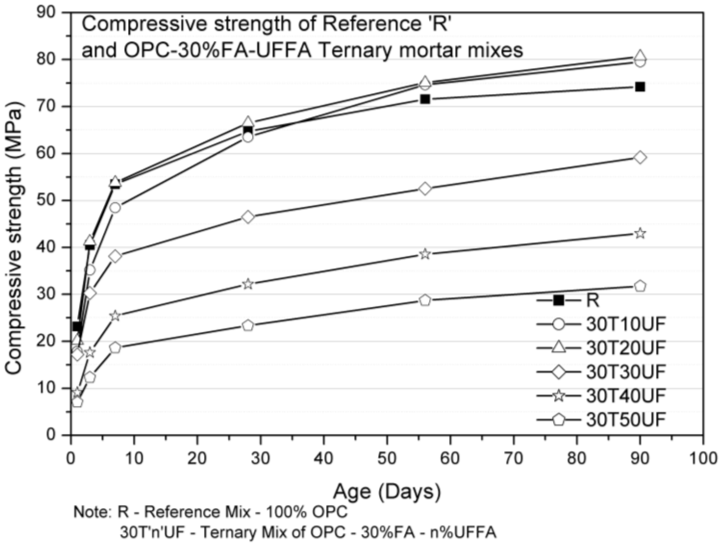
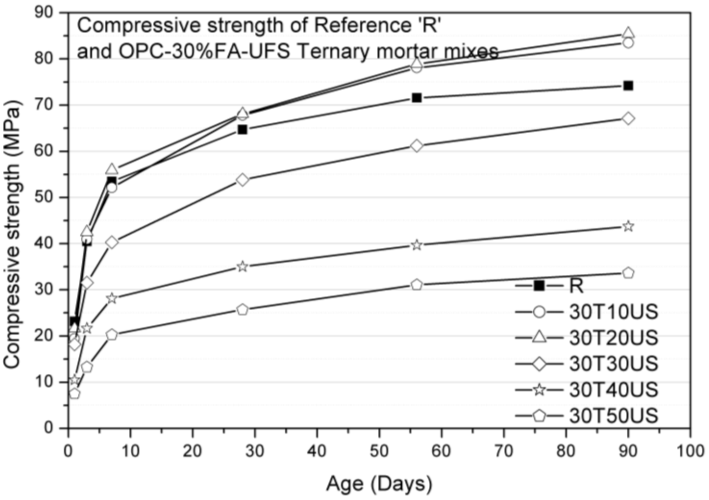


Figure 4.10. Compressive strength of reference and ternary mortars with 30% FA and ultra-fine fly ash (UF).

4.5.9 Compressive strength of OPC – 30%FA – UFS ternary mortar mixes

The results of compressive strength of reference and ternary mortars with 30% of FA and 10 – 50% of ultra-fine slag is presented in Figure 4.11 and Annexure A.4. The compressive strength at early age (<28 days) for 30T10US and 30T20US are higher as compared to reference mortar. The 3 day strength of 30T10US and 30T20UF is 1% and 5% higher as compared to that of reference mix. However, the early age strength of mortars with 30 – 50% UFS are comparatively low. Compressive strength at 28 days for 20T10US and 20T20US is 5% and 6% higher as compared to that of reference mortar. For other mixes, the 28 day strength has been found to be lower. Similarly, the later age strength (> 28 days) for 30T10US and 30T20US was 13% and 15% higher as compared to that of reference mortar attributable to formation of compact and dense microstructure as compared to other mixes.

Overall it is observed that mortar combinations with ultra-fine slag up to 20% with 30% of FA in ternary combinations can provide higher strengths as compared to reference mortar mix at all ages. Whereas, mortars with replacements of more than 20% of ultra-fine slag reduces the strength considerably and hence they may not satisfy the strength requirements. UFS based mortars have been found to show higher compressive strength as compared to UFFA based mortars for similar replacement percentages.



Note: R - Reference Mix - 100% OPC
30T'n'UF - Ternary Mix of OPC - 30%FA - n%UFS

Figure 4.11. Compressive strength of reference and ternary mortars with 30% FA and ultra-fine slag (US).

4.6 Summary

The presented chapter discuss the results of reference, 21 binary and 30 ternary mixes with regards to measured properties of particle packing density, flow and compressive strength at 1, 3, 7, 28, 56 and 90 days. It was observed that, the particle packing density have improved marginally for mortars with 10 – 30 % of FA, UFFA or UFS in binary and ternary combinations. In case of workability, UFFA and FA blended mixtures have shown an increment due to its spherical shape, while UFS blended have shown reduction in flow properties due to angular shape.

Compressive strength of mortar have improved for combinations with 20% of replacement of UFFA or UFS. Early age strength have been observed to improve due to UFFA and UFS. Maximum improvement in compressive strength up to 17% was observed by UFS blended mix. UFS have observed to provide marginally better strength as compared to UFFA based mixtures. The results of mortar studies have suggested to use up to 30% of fly ash and up to 20% of UFFA/UFS in concrete. With regards to these observations, the binary and ternary blended concrete mixes were prepared and tested in the present study.

Chapter 5

Studies on Mechanical and Durability Properties of Concrete Mixes

5.1 General

The present chapter investigates the properties of concrete in different binary and ternary combinations. This chapter discusses the fresh, mechanical and durability properties of concrete made using different combinations of ordinary Portland cement (OPC), fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS). Workability in terms of slump value is measured as part of fresh concrete properties. With regards to mechanical properties, compressive strength up to 90 days, split tensile and flexural strength of concrete are observed. Chloride migration, water permeability, water sorptivity and permeable voids are measured as durability parameters for all concrete combinations. Ordinary Portland cement (OPC) is replaced by fly ash (FA) to make binary mixes. OPC is further replaced by either ultra-fine fly ash (UFFA) or ultra-fine slag (UFS) to make ternary concrete combinations. Concrete combinations investigated include one reference (100% OPC), 3 binary (OPC – FA) and 27 ternary mix (OPC – FA – UFFA/UFS).

Results and analysis of the preliminary study on mortars, as presented in the previous chapter suggested the use of ultra-fine fly ash and ultra-fine slag with a maximum of up to 20% in ternary combinations. Similarly, results of mortar study suggest the use of up to a maximum of 30% fly ash in different combinations. In order to investigate the properties of concrete, the fly ash content in binary and ternary combinations was set as 20%, 30% and 40%. As 10% of FA in concrete will provide very little benefit to sustainability and economy, it is not included in the present study. In order to validate the effect of usage of higher FA content (40%) in ternary combinations, up to 40% of FA was also used in ternary concrete mixes. Therefore, in binary concrete mixes, OPC is replaced by 20%, 30% and 40% of fly ash to form three binary combinations. Ternary combinations are composed of OPC – FA – UFFA/UFS mixture, where, fly ash replacement is 20%, 30% or 40% with 5%, 10%, 15% or 20% of ultra-fine fly ash or ultra-fine slag, respectively.

5.2 Binder proportions of concrete mixes

OPC, FA, UFFA and UFS are mixed in different proportions to investigate the fresh, mechanical and durability properties of concrete. Control mixture containing 100% OPC is chosen as reference mix. Three binary combinations with 20%, 30% and 40% of FA in OPC – FA mix was investigated. Combinations such as, OPC – FA – UFFA and OPC – FA – UFS forms 24 ternary mixtures of concrete with 20 – 40% of FA with 5 – 20% of UFFA/UFS. In order to validate the effect of 50% of FA with 5 – 15% of UFS, three additional ternary combinations are investigated.

The details of binder proportions of reference, binary and ternary mixtures are presented in Table 5.1. Reference or control concrete is composed of 100% OPC. Three combinations as OPC – FA with 20%, 30% and 40% of FA content forms binary concrete mix. In ternary mixture OPC – FA – UFFA/UFS, FA is used in 20%, 30% and 40% with UFFA or UFS as 5%, 10%, 15% and 20% forming 24 ternary mixtures. Three additional OPC – FA – UFS ternary mix is investigated with 50% of FA and 5%, 10%, and 15% of UFS. Overall, one reference, 3 binary and 27 ternary concrete mixtures are tested for mechanical and durability properties.

Mix ID of control or reference concrete with 100% OPC is designated as ‘R’. Mix ID of binary combinations starts with letter ‘B’. The number followed by ‘B’ represents the percent of replacement of OPC by FA. Letter followed by number represents Fly ash as ‘F’. For example, B20F represents, binary combination with 20% of fly ash and remaining 80% as OPC.

Mix ID of ternary combinations starts with percent of fly ash in the respective combination. The letter followed by FA percentage is ‘T’ and it represents ternary. The number followed by ‘T’ represents the percent of replacement of OPC by either UFFA or UFS. Letter followed by this particular replacement percentage represents ultra-fine fly ash as ‘UF’ or ultra-fine slag as ‘US’. For example, 20T15UF represents ternary combination with 20% of fly ash, 15 % of UFFA and remaining 65% as OPC. Similarly, 40T5US represents ternary combination with 40% of fly ash, 5% of UFS and remaining 55% as OPC.

Table 5.1. Binder proportions of reference and binary mixes with FA, UFFA and UFS.

Sr. No.	Mix ID	OPC (%)	FA (%)	UFFA (%)	UFS (%)	Remarks
1	R	100	-	-	-	Reference Mix
2	B20F	80	20	-	-	Binary mix of OPC – FA
3	B30F	70	30	-	-	
4	B40F	60	40	-	-	
5	20T5UF	75	20	5	-	Ternary mix of OPC – 20%FA – UFFA
6	20T10UF	70	20	10	-	
7	20T15UF	65	20	15	-	
8	20T20UF	60	20	20	-	
9	30T5UF	65	30	5	-	Ternary mix of OPC – 30%FA – UFFA
10	30T10UF	60	30	10	-	
11	30T15UF	55	30	15	-	
12	30T20UF	50	30	20	-	
13	40T5UF	55	40	5	-	Ternary mix of OPC – 40%FA – UFFA
14	40T10UF	50	40	10	-	
15	40T15UF	45	40	15	-	
16	40T20UF	40	40	20	-	
17	20T5US	75	20	-	5	Ternary mix of OPC – 20%FA – UFS
18	20T10US	70	20	-	10	
19	20T15US	65	20	-	15	
20	20T20US	60	20	-	20	
21	30T5US	65	30	-	5	Ternary mix of OPC – 30%FA – UFS
22	30T10US	60	30	-	10	
23	30T15US	55	30	-	15	
24	30T20US	50	30	-	20	
25	40T5US	55	40	-	5	Ternary mix of OPC – 40%FA – UFS
26	40T10US	50	40	-	10	
27	40T15US	45	40	-	15	
28	40T20US	40	40	-	20	
29	50T5US	45	50	-	5	Ternary mix of OPC – 50%FA – UFS
30	50T10US	40	50	-	10	
31	50T15US	35	50	-	15	

5.3 Concrete Mix Design

The mix design of concrete is established as per procedure recommended by IS 10262:2019. The grade of concrete is M35. The binder proportion was kept as 375 kg/m^3 of concrete. Ordinary Portland cement (OPC) was used as primary binder in concrete. OPC was partially replaced by fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag

(UFS) in different combinations to form binary and ternary concrete mixers. The replacement of OPC by FA, UFFA or UFS is done as per weight. The replacement of OPC by FA, UFFA or UFS tends to increase the volume of paste due to their lower densities as compared to OPC. Hence, the proportioning of concrete is achieved by appropriately modifying fine and coarse aggregate content in the mixture. The binder to aggregate ratio for all concrete combinations are maintained as 0.18. The water to binder ratio of 0.38 is kept constant for all concrete combinations. The admixture dosage of 0.4% is kept to ensure the desired minimum workability. The fine and coarse aggregate used in the concrete mix were in saturated surface dry condition. The mix proportion of M35 concrete is as shown in the Table 5.2. The mix proportion of all binary and ternary concrete combinations are presented in Annexure B.1 to B.3.

Table 5.2. Concrete mix proportion of reference/control mix 'R'.

Grade of concrete	M35
Ordinary Portland cement (53 Grade)	375 kg/m^3
Water	142.5 kg/m^3
Fine aggregate (SSD)	715 kg/m^3
Coarse aggregate (SSD)	1375 kg/m^3
Admixture	1.5 kg/m^3
Admixture dosage	0.4% of binder
Water to binder ratio	0.38

5.4 Workability of concrete

The workability of concrete is measured for reference, binary and ternary concrete mixes in terms of their slump value. Standard procedure for slump cone test is followed as per IS 1199:2018. Top and bottom diameter of slump cone are 100 mm and 200 mm, respectively with the height of cone as 300 mm. The subsidence of concrete immediately after raising the slump cone is measured as slump value in millimetre. Figure 5.1 shows typical steps for measurement of workability in terms of slump value.

(a) standard slump cone (b) tamping of concrete

(c) removal of slump cone (d) measurement of slump value

Figure 5.1. Measurement of workability by slump cone.

5.4.1 Workability of OPC – FA binary concrete mixes

The workability of reference concrete ‘R’ made with 100% OPC was observed as 125 mm. The slump value of OPC – FA binary mixes have shown improvement in workability as compared to reference mix as shown in Fig. 5.2. The observed workability of binary mix with 20% FA was similar to that of reference concrete. The workability of mix with 30% FA and 40% FA was 130 mm and 140 mm, respectively. This improvement in workability is due to addition of fly ash. Spherical shaped fly ash particles impart less resistance to flow resulting in better workability in the mixture.

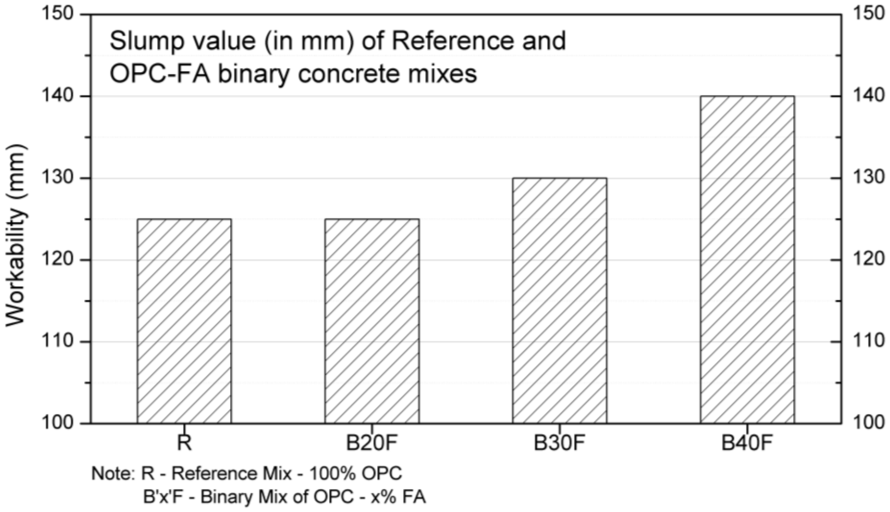
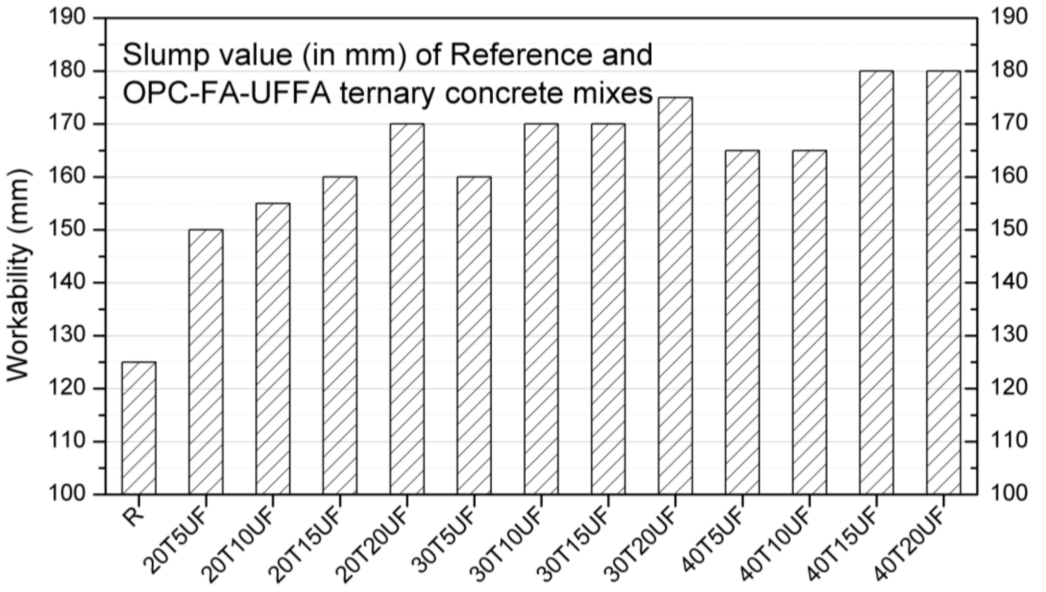


Fig. 5.2. Workability of reference and OPC – FA binary concrete mixes.

5.4.2 Workability of OPC – FA – UFFA ternary concrete mixes

The workability of OPC – FA – UFFA ternary mixtures are presented in Fig 5.3. It is observed that the workability of mixtures improves with inclusion of ultra-fine fly ash in ternary concrete mix. The workability of ternary mixtures have improved with increment in ultra-fine fly ash content from 5% to 20% in all cases. The highest improvement in workability was observed by mixtures with maximum quantity of ultra-fine fly ash. The highest workability of 180 mm was observed by ternary mixtures 40T15UF and 40T20UF, and is 44% higher as compared to workability of reference concrete. The concrete mix was stable and did not segregate or bleed while handling and placing. This increment in workability is attributable to spherical shape of fly ash and ultra-fine fly ash. The spherical shaped particles reduces the inter particle friction and imparts mobility to the mixture. The spherical shape of fly ash and ultra-fine fly ash is evidently observed by SEM observation presented in chapter 3.



Note: R - Reference Concrete Mix - 100% OPC
'a'T'b'UF - Ternary Concrete Mix of OPC - a%FA - b%UFFA

Fig. 5.3. Workability of reference and OPC – FA – UFFA ternary concrete mixes.

5.4.3 Workability of OPC – FA – UFS ternary concrete mixes

The workability of OPC – FA – UFS ternary mixtures are presented in Fig 5.4. It is observed that the workability of mixtures generally increase in ternary concrete mix with fly ash and ultra-fine slag as compared to reference mix. The workability of ternary mixtures have reduced with increment in ultra-fine slag content from 5% to 20% in all cases. The highest workability of 165 mm was observed by ternary mixtures 50T5UF and is 32% higher as compared to workability of reference concrete. 20T20US have shown the workability of 125 mm, which is similar to that of reference concrete. 20% FA in 20T20US mix tend to improve the workability, while 20% of UFS have tend to reduce the workability, resulting in similar workability as of reference concrete.

The availability of fly ash in ternary mixtures tends to improve the workability, whereas the ultra-fine slag particles result in reduction of workability. Therefore, the blend of FA and UFS with higher proportion of FA results in improved workability. Increment in workability is attributable to spherical shape of fly ash. The angular shaped ultra-fine slag particles however reduce the workability. The spherical shape of fly ash and angular shape of ultra-fine slag is evidently observed by SEM observation presented in chapter 3.

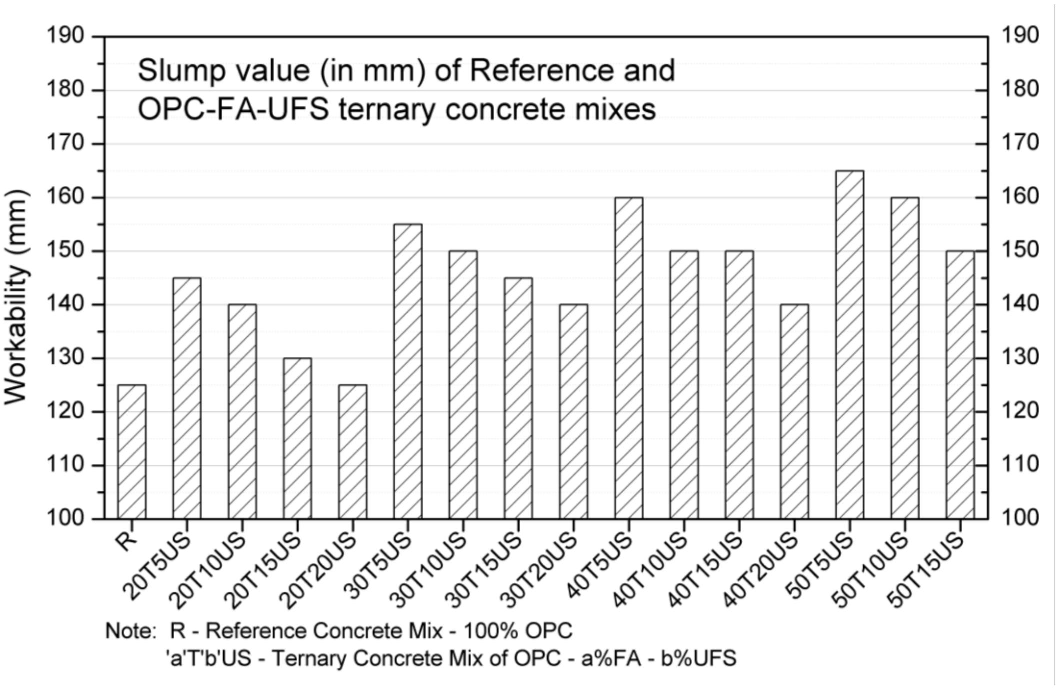


Fig. 5.4. Workability of reference and OPC – FA – UFS ternary concrete mixes.

Workability was observed to increase in the range of 4% to 12% for OPC – FA binary concrete mixes. In the case of OPC – FA – UFFA ternary concrete mixtures the workability have improved in the range of 20% to 44%. In the case of OPC – FA – UFS ternary concrete mixtures the workability have improved in the range of 0% to 32%. The slump value of reference mix, OPC – FA binary mixes and OPC – FA – UFFA/UFS ternary concrete mixes are presented in Table 5.3.

The workability of UFFA blended ternary mixtures have been observed to be higher as compared to similar UFS blended ternary mixtures. The resistance offered by UFS was observed to be compensated by presence of fly ash in ternary mixture. Therefore the combination of OPC – FA – UFS or OPC – FA – UFFA in ternary mixtures can be preferred as they tend to increase the overall workability as compared to reference concrete.

5.4.4 Discussion on workability of concrete mixes

The workability of reference concrete mix was found to be 125 mm in terms of slump value. It was observed that the workability has improved with addition of fly ash and ultra-fine fly ash in binary or ternary concrete mixes. The improvement in workability is attributable to spherical shaped particles of fly ash and ultra-fine fly ash. The spherical shaped particle reduces the inter particle friction, resulting in higher mobility and improved slump. Similar observation was reported by many researchers (Cheah et al., 2017; Ikotun et al., 2017; Laskar and Talukdar, 2017; Nguyen et al., 2018).

The workability of concrete reduces with addition of ultra-fine slag in ternary concrete mixes. This is attributable to angular shaped particles of UFS which offers resistance to flow of concrete (Cheah et al., 2017; Nath and Sarker, 2014; J. Zhang et al., 2020; P. Zhang et al., 2020). Due to high calcium content in UFS, the formation of primary CSH gels accelerates rapidly, which leads to mobility loss (Fang et al., 2018; Puertas et al., 2014; P. Zhang et al., 2020).

Table 5.3. Workability of reference, binary and ternary concrete mixes.

Mix ID	Slump in mm	Mix ID	Slump in mm	Mix ID	Slump in mm
Reference Mix		Ternary Mix of OPC – FA – UFFA		Ternary Mix of OPC – FA – UFS	
R	125	20T5UF	150	20T5US	145
Binary Mix		20T10UF	155	20T10US	140
B20F	125	20T15UF	160	20T15US	130
B30F	130	20T20UF	170	20T20US	125
B40F	140	30T5UF	160	30T5US	155
		30T10UF	170	30T10US	150
		30T15UF	170	30T15US	145
		30T20UF	175	30T20US	140
		40T5UF	165	40T5US	160
		40T10UF	165	40T10US	150
		40T15UF	180	40T15US	150
		40T20UF	180	40T20US	140
				50T5US	165
				50T10US	160
				50T15US	150

5.5 Compressive strength of concrete

The compressive strength of all concrete mixes are determined based on provisions of IS 516:2018. The standard mould used for testing the compressive strength is 150 mm cube. Compressive strength is evaluated at the age of 3, 7, 28, 56 and 90 days. The cube moulds were tested under laboratory scale compression testing machine at desired age. Three identical samples are tested for a typical category and the calculated mean value is noted as compressive strength of that specified category. Figure 5.5 shows typical steps for measurement of compressive strength of concrete. The results of compressive strengths of binary and ternary concrete are compared with compressive strength of reference concrete. The compressive strength of reference concrete 'R' was observed as 27.0 MPa, 37.7 MPa, 47.2 MPa, 51.9 MPa and 55.0 MPa at 3, 7, 28, 56 and 90 days, respectively.

5.5.1 Compressive strength of OPC – FA binary concrete mixes

The results of compressive strength of reference and binary concrete with 20%, 30% and 40% of fly ash is presented in Figure 5.6 and Appendix B.4. The compressive strength of binary mixes at early age (<28 days) is marginally lower than the strength of reference concrete at same age. For B30F, the 3 day strength is 1% greater than that of 3 day strength of reference concrete. For OPC – FA binary mixes, the highest strength achieved at early age was observed for B30F at 7 day, and is 11% less than the strength of reference concrete at the same age.

Compressive strength at 28 days was marginally less for all binary concrete. The 28 day strength of B20F and B40F was found to be 89% and 83% of strength of reference concrete at 28 days. In the case of B30F binary mix the compressive strength at 28 day is only 1% lower as compared to that of 28 day strength of reference concrete.

The later age strength (> 28 days) was observed to be higher for B20F and B30F, but was marginally lower for B40F as compared to compressive strength of reference concrete at same age. An improvement of 4% and 7% in compressive strength at 56 days was observed by B20F and B30F, respectively as compared to 56 day strength of reference concrete. Similarly, an improvement of 4% and 9% in compressive strength at 90 days was observed by B20F and B30F, respectively as compared to 90 day strength of reference concrete.

(a) Mixing of concrete (b) Casting 150 mm cubes of concrete

(c) Curing of concrete cubes (d) Testing of cube under CTM

(e) Compressive strength reading (f) Cubes after testing

Figure 5.5. Procedure for measurement of compressive strength of concrete.

Overall it is observed that concrete combinations with fly ash up to 30% can provide better strength, specifically at later ages. Whereas, concrete with replacements of more than 30% of fly ash could marginally reduce the strength. The slow pozzolanic reactivity of fly ash have reduced the early strength development in binary combinations. However at later ages the pozzolanic reactivity of fly ash has improved resulting in better later age strengths.

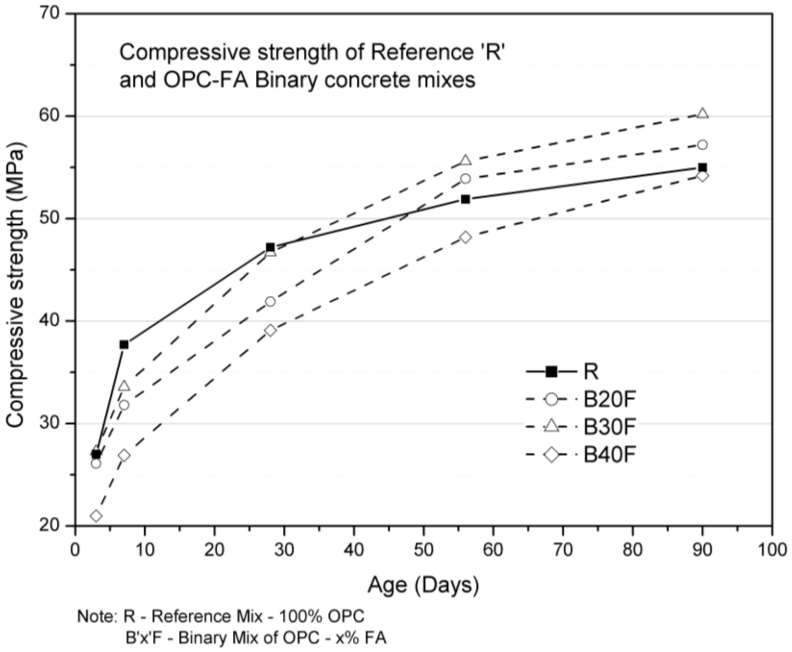


Figure 5.6. Compressive strength of reference and OPC – FA binary concrete.

5.5.2 Compressive strength of OPC – 20% FA – UFFA ternary concrete mixes

The results of compressive strength of reference concrete 'R' and ternary concrete with 20% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.7 and appendix B.5. The compressive strength of ternary mixes at early age (<28 days) is marginally lower than the strength of reference concrete at same age. The compressive strength at 3 day for OPC – 20% FA – UFFA ternary concrete are in the range of 83% to 89% of that of 3 day strength of reference concrete. The compressive strength at 7 day for OPC – 20% FA – UFFA ternary concrete are in the range of 87% to 101% of that of 7 day strength of reference concrete. For 20T15UF, the 7 day strength is 1% greater than that of 7 day strength of reference concrete. For OPC – 20% FA – UFFA ternary mixes, the highest strength at early age was observed for 20T15UF at 3 and 7 day as compared to strength of reference concrete at the same age.

Compressive strength at 28 days was higher for 20T10UF and 20T15UF as compared to strength of reference concrete at same age. The 28 day strength of 20T10UF and 20T15UF was found to be 0.01% and 3% higher than that of strength of reference concrete at 28 days. The 28 day strength for 20T5UF and 20T20UF is marginally less as compared to 28 day strength of reference concrete. In the case of 20T5UF and 20T20UF ternary mix the compressive strength at 28 day is 4% and 2% lower as compared to that of 28 day strength of reference concrete.

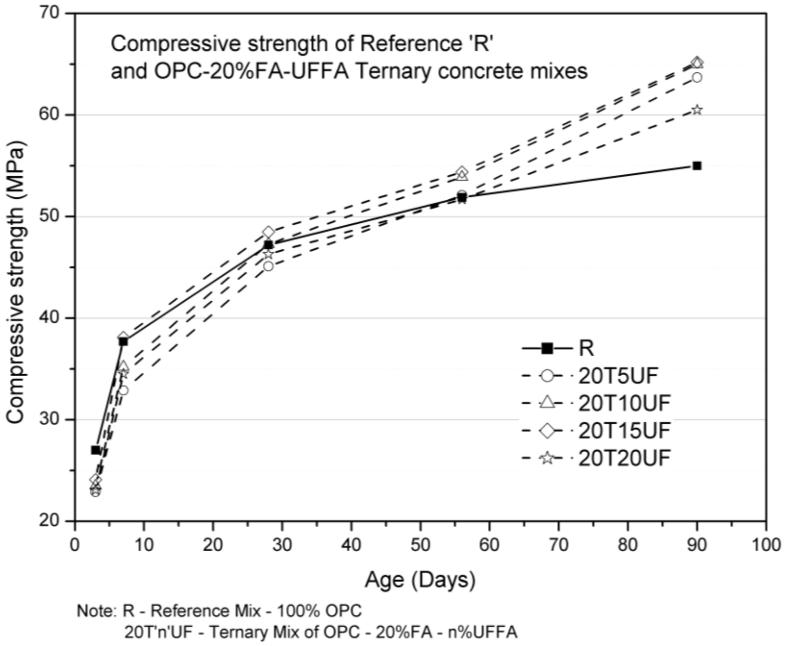


Figure 5.7. Compressive strength of reference and OPC – 20% FA – UFFA ternary concrete mixes.

The later age strength (> 28 days) was observed to be higher for all OPC – 20% FA – UFFA ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength of 20T5UF and 20T20UF was found to be 0.01% higher than that of strength of reference concrete at 56 days. The 56 day strength of 20T10UF and 20T15UF was found to be 4% and 5% higher than that of strength of reference concrete at 56 days. An improvement of 16% and 10% in compressive strength at 90 days was observed by 20T5UF and 20T20UF, respectively as compared to 90 day strength of reference concrete. Similarly, an improvement of 18% and 19% in compressive strength at 90 days was observed by 20T10UF and 20T15UF, respectively as compared to 90 day strength of reference concrete.

Overall it is observed that OPC – 20% FA – UFFA ternary concrete mixture can provide better strengths specifically at later ages. Among all the ternary mix examined, 20T15UF has shown improved compressive strength as compared to reference mix. Compressive strength at early age has enhanced due to ultra-fine particle of UFFA which reacts rapidly. The pozzolanic activity of UFFA is higher as compared to that of OPC or FA, hence early age requirements are met in OPC – FA – UFFA ternary mixtures. The pozzolanic reaction of fly ash prolongs for a longer duration and hence is able to provide significant improvement in compressive strength at 90 days.

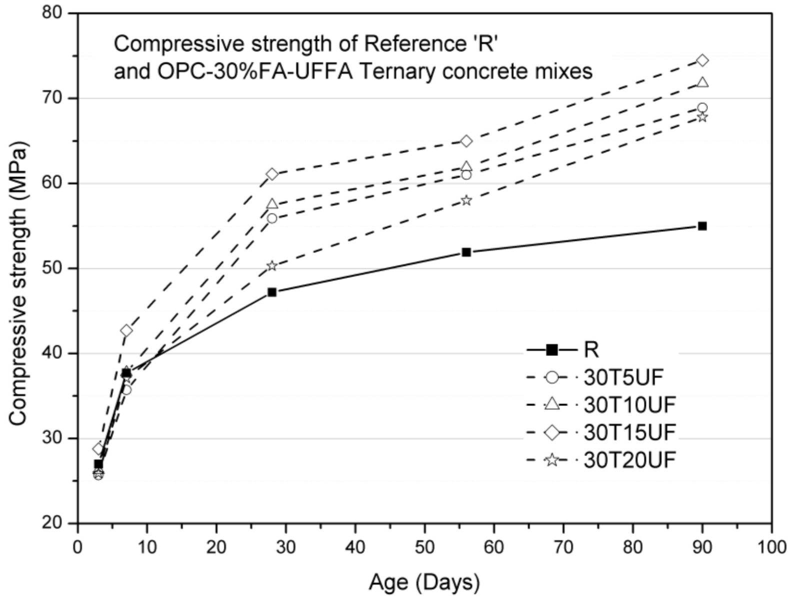
5.5.3 Compressive strength of OPC – 30% FA – UFFA ternary concrete mixes

The results of compressive strength of reference concrete ‘R’ and ternary concrete with 30% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.8 and appendix B.5. The compressive strength of ternary mixes at early age (<28 days) is marginally lower than the strength of reference concrete at same age for all ternary mixes except 30T15UF. The compressive strength at 3 day for OPC – 30% FA – UFFA ternary concrete are in the range of 95% to 107% of that of 3 day strength of reference concrete. For 30T15UF, the 3 day strength is 7% greater than that of 3 day strength of reference concrete. The compressive strength at 7 day for OPC – 30% FA – UFFA ternary concrete are in the range of 95% to 113% of that of 7 day strength of reference concrete. For 30T15UF, the 7 day strength is 13% greater than that of 7 day strength of reference concrete. For OPC – 30% FA – UFFA ternary mixes, the highest strength at early age was observed by 30T15UF at 3 and 7 day as compared to strength of reference concrete at the same age.

Compressive strength at 28 days was higher for all OPC – 30% FA – UFFA ternary concrete mixes as compared to strength of reference concrete at same age. The 28 day strength of 30T10UF and 30T15UF was found to be 22% and 29% higher than that of strength of reference concrete at 28 days. In the case of 30T5UF and 30T20UF ternary mix the compressive strength at 28 day is 18% and 7% lower as compared to that of 28 day strength of reference concrete.

The later age strength (> 28 days) was observed to be higher for all OPC – 30% FA – UFFA ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength of 30T5UF and 30T20UF was found to be 18% and 12% higher than that of strength of reference concrete at 56 days. The 56 day strength of 30T10UF and 30T15UF was found to be 19% and 25% higher than that of strength of reference concrete at 56 days. An improvement of 25% and 23% in compressive strength at 90 days was observed by 30T5UF and 30T20UF, respectively as compared to 90 day strength of reference concrete. Similarly, an improvement of 31% and 35% in compressive strength at 90 days was observed by 20T10UF and 20T15UF, respectively as compared to 90 day strength of reference concrete.

Overall it is observed that OPC – 30% FA – UFFA ternary concrete mixture can provide better strengths specifically at later ages. Among all the ternary mix examined, 30T15UF has shown improved compressive strength as compared to reference mix. Compressive strength at early age has enhanced due to ultra-fine particle of UFFA which reacts rapidly. The pozzolanic activity of UFFA is higher as compared to that of OPC or FA, hence early age requirements are met in OPC – FA – UFFA ternary mixtures. The pozzolanic reaction of fly ash prolongs for a longer duration and hence is able to provide significant improvement in compressive strength at 90 days.

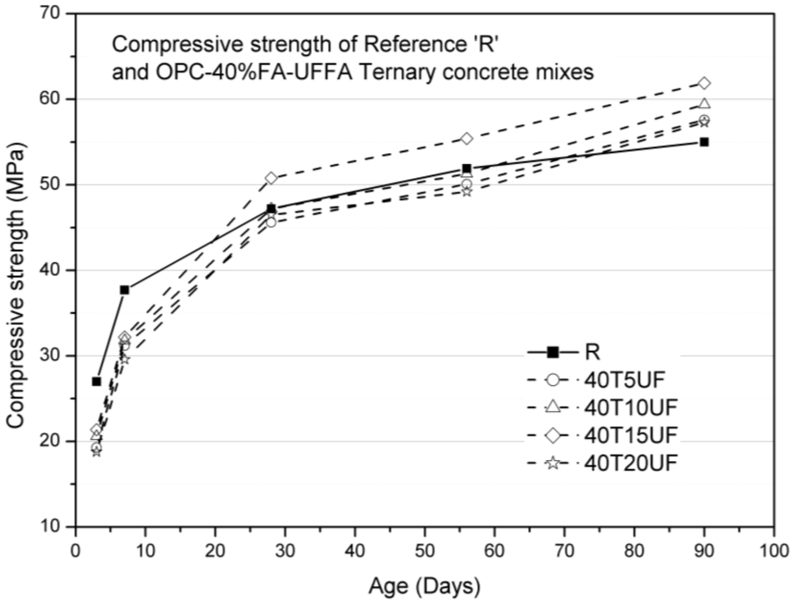


Note: R - Reference Mix - 100% OPC
30T'n'UF - Ternary Mix of OPC - 30%FA - n%UFFA

Figure 5.8. Compressive strength of reference and OPC – 30% FA – UFFA ternary concrete mixes.

5.5.4 Compressive strength of OPC – 40% FA – UFFA ternary concrete mixes

The results of compressive strength of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.9 and appendix B.5. The compressive strength of ternary mixes at early age (<28 days) is significantly lower than the strength of reference concrete at same age for all ternary mixes. The compressive strength at 3 day for OPC – 40% FA – UFFA ternary concrete are in the range of 70% to 79% of that of 3 day strength of reference concrete. For 40T15UF, the 3 day strength is 21% lower than that of 3 day strength of reference concrete. The compressive strength at 7 day for OPC – 40% FA – UFFA ternary concrete are in the range of 79% to 85% of that of 7 day strength of reference concrete. For 40T15UF, the 7 day strength is 15% lower than that of 7 day strength of reference concrete. Among all OPC – 30% FA – UFFA ternary mixes, the highest strength at early age was observed by 40T15UF at 3 and 7 day but are less than the strength of reference concrete at the same age.



Note: R - Reference Mix - 100% OPC
40T'n'UF - Ternary Mix of OPC - 40%FA - n%UFFA

Figure 5.9. Compressive strength of reference and OPC – 40% FA – UFFA ternary concrete mixes.

Compressive strength at 28 days was higher for 40T10UF and 40T15UF as compared to strength of reference concrete at same age. The 28 day strength of 40T10UF and 40T15UF was found to be 0.01% and 8% higher than that of strength of reference concrete at 28 days. The 28 day strength for 40T5UF and 40T20UF is marginally less as compared to 28 day strength of reference concrete. In the case of 40T5UF and 40T20UF ternary mix the compressive strength at 28 day is 3% and 1% lower as compared to that of 28 day strength of reference concrete.

The later age strength (> 28 days) was observed to be marginally lower at 56 days and marginally higher at 90 days for OPC – 40% FA – UFFA ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength of 40T5UF and 40T20UF was found to be 3% and 5% lower than that of strength of reference concrete at 56 days. The 56 day strength of 50T10UF and 50T15UF was found to be 1% lower and 7% higher than that of strength of reference concrete at 56 days. An improvement of 5% and 4% in compressive strength at 90 days was observed by 40T5UF and 40T20UF, respectively as compared to 90 day strength of reference concrete. Similarly, an improvement of 8% and 13% in compressive strength at 90 days was observed by 40T10UF and 40T15UF, respectively as compared to 90 day strength of reference concrete.

Overall it is observed that OPC – 40% FA – UFFA ternary concrete mixture can provide marginally better strengths specifically at later ages but not at early ages . Among all the ternary mix examined, 40T15UF has shown improved compressive strength as compared to reference mix only after 56 days. The pozzolanic reaction of fly ash prolongs for a longer duration and hence is able to provide significant improvement in compressive strength at 90 days.

5.5.5 Compressive strength of OPC – 20% FA – UFS ternary concrete mixes

The results of compressive strength of reference concrete ‘R’ and ternary concrete with 20% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.10 and appendix B.6. The compressive strength of ternary mixes at early age (<28 days) are marginally lower or higher as compared to strength of reference concrete at same age. The compressive strength at 3 day for OPC – 20% FA – UFS ternary concrete are in the range of 97% to 101% of that of 3 day strength of reference concrete. The 3 day strength of 20T10US and 20T15US was found to be 0.01% and 1% higher than that of strength of reference concrete at 3 days. In the case of 20T5US and 20T20US ternary mix the compressive strength at 3 day is 3% lower as compared to that of 3 day strength of reference concrete. The compressive strength at 7 day for OPC – 20% FA – UFFA ternary concrete are in the range of 94% to 103% of that of 7 day strength of reference concrete.

For 20T15US, the 7 day strength is 3% greater than that of 7 day strength of reference concrete. For OPC – 20% FA – UFS ternary mixes, the highest strength at early age was observed for 20T15US at 3 and 7 day as compared to strength of reference concrete at the same age.

Compressive strength at 28 days was higher for all OPC – 20% FA – UFS ternary concrete mixes as compared to strength of reference concrete at same age. The 28 day strength of 20T10USand 20T15US was found to be 6% and 9% higher than that of strength of reference concrete at 28 days. In the case of 20T5US and 20T20US ternary mix the compressive strength at 28 day is 3% higher as compared to that of 28 day strength of reference concrete.

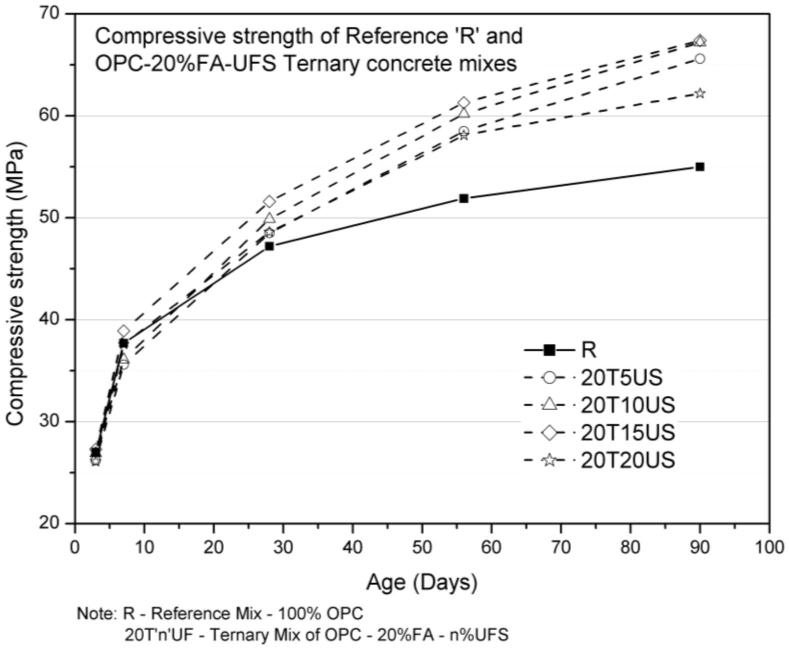


Figure 5.10. Compressive strength of reference and OPC – 20% FA – UFS ternary concrete mixes.

The later age strength (> 28 days) was observed to be higher for all OPC – 20% FA – UFS ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength of 20T5US and 20T20US was found to be 13% and 12% higher than that of strength of reference concrete at 56 days. The 56 day strength of 20T10US and 20T15US was found to be 16% and 18% higher than that of strength of reference concrete at 56 days. An improvement of 19% and 13% in compressive strength at 90 days was observed by 20T5US and 20T20US, as compared to 90 day strength of reference concrete. Similarly, an improvement of 22% and 23% in compressive strength at 90 days was observed by 20T10US and 20T15US, respectively as compared to 90 day strength of reference concrete.

Overall it is observed that OPC – 20% FA – UFS ternary concrete mixture can provide better strengths. Among all the ternary mix examined, 20T15US has shown improved compressive strength at early and later ages as compared to reference mix. Compressive strength at early age has enhanced due to ultra-fine particle of UFS which reacts rapidly. The pozzolanic reaction of fly ash prolongs for a longer duration and hence is able to provide significant improvement in compressive strength at 90 days.

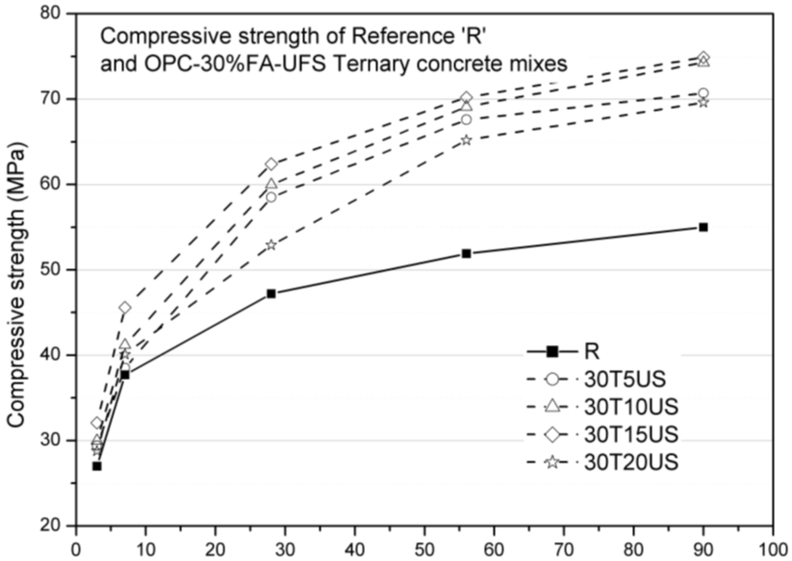
5.5.6 Compressive strength of OPC – 30% FA – UFS ternary concrete mixes

The results of compressive strength of reference concrete 'R' and ternary concrete with 30% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.11 and appendix B.6. The compressive strength of ternary mixes at early age (<28 days) are higher as compared to strength of reference concrete at same age. The 3 day strength of 30T10US and 30T15US was found to be 11% and 19% higher than that of strength of reference concrete at 3 days. In the case of 30T5US and 30T20US ternary mix the compressive strength at 3 day is 9% and 7% higher as compared to that of 3 day strength of reference concrete. The 7 day strength of 30T10US and 30T15US was found to be 9% and 21% higher than that of strength of reference concrete at 7 days. In the case of 30T5US and 30T20US ternary mix the compressive strength at 7 day is 2% and 6% higher as compared to that of 7 day strength of reference concrete. For OPC – 30% FA – UFS ternary mixes, the highest strength at early age was observed for 30T15US at 3 and 7 day as compared to strength of reference concrete at the same age.

Compressive strength at 28 days was higher for all OPC – 30% FA – UFS ternary concrete mixes as compared to strength of reference concrete at same age. The 28 day strength of 30T10US and 30T15US was found to be 27% and 32% higher than that of strength of reference concrete at 28 days. In the case of 30T5US and 30T20US ternary mix the compressive strength at 28 day is 24% and 12% higher as compared to that of 28 day strength of reference concrete.

The later age strength (> 28 days) was observed to be higher for all OPC – 30% FA – UFS ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength of 30T5US and 30T20US was found to be 30% and 26% higher than that of strength of reference concrete at 56 days. The 56 day strength of 30T10US and 30T15US was found to be 33% and 35% higher than that of strength of reference concrete at 56 days. An improvement of 29% and 27% in compressive strength at 90 days was observed by 30T5US and 30T20US, respectively as compared to 90 day strength of reference concrete. Similarly, an improvement of 35% and 36% in compressive strength at 90 days was observed by 30T10US and 30T15US, respectively as compared to 90 day strength of reference concrete.

Overall it is observed that OPC – 30% FA – UFS ternary concrete mixture can provide better strengths. Among all the ternary mix examined, 30T15US has shown improved compressive strength at early and later ages as compared to reference mix. Compressive strength at early age has enhanced due to ultra-fine particle of UFS which reacts rapidly. The pozzolanic reaction of fly ash prolongs for a longer duration and hence is able to provide significant improvement in compressive strength at 90 days.



Note: R - Reference Mix - 100% OPC
30T'n'UF - Ternary Mix of OPC - 30%FA - n%UFS

Figure 5.11. Compressive strength of reference and OPC – 30% FA – UFS ternary concrete mixes.

5.5.7 Compressive strength of OPC – 40% FA – UFS ternary concrete mixes

The results of compressive strength of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.12 and appendix B.6. The compressive strength of ternary mixes at early age (<28 days) are lower as compared to strength of reference concrete at same age. The 3 day strength of 40T10US and 40T15US was found to be 13% and 11% lower than that of strength of reference concrete at 3 days. In the case of 40T5US and 40T20US ternary mix the compressive strength at 3 day is 19% and 22% lower as compared to that of 3 day strength of reference concrete. The 7 day strength of 40T10US and 40T15US was found to be 10% and 8% lower than that of strength of reference concrete at 7 days. In the case of 40T5US and 40T20US ternary mix the compressive strength at 7 day is 11% and 15% lower as compared to that of 7 day strength of reference concrete.

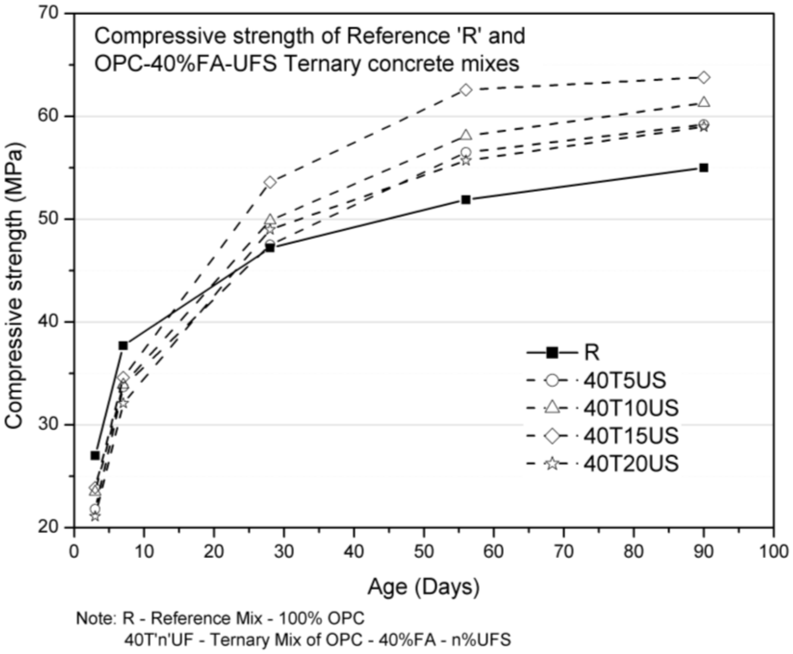


Figure 5.12. Compressive strength of reference and OPC – 40% FA – UFS ternary concrete mixes.

Compressive strength at 28 days was higher for all OPC – 40% FA – UFS ternary concrete mixes as compared to strength of reference concrete at same age. The 28 day strength of 40T10US and 40T15US was found to be 6% and 14% higher than that of strength of reference concrete at 28 days. In the case of 40T5US and 40T20US ternary mix the compressive strength at 28 day is 1% and 4% higher as compared to that of 28 day strength of reference concrete.

The later age strength (> 28 days) was observed to be higher for all OPC – 40% FA – UFS ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength of 40T5US and 40T20US was found to be 9% and 7% higher than that of strength of reference concrete at 56 days. The 56 day strength of 40T10US and 40T15US was found to be 12% and 21% higher than that of strength of reference concrete at 56 days. An improvement of 8% and 7% in compressive strength at 90 days was observed by 40T5US and 40T20US, respectively as compared to 90 day strength of reference concrete. Similarly, an improvement of 11% and 16% in compressive strength at 90 days was observed by 40T10US and 40T15US, respectively as compared to 90 day strength of reference concrete.

Overall it is observed that OPC – 40% FA – UFS ternary concrete mixture can provide better strengths at later ages but not at early age. Among all the ternary mix examined, 40T15US has shown improved compressive strength at later ages as compared to reference mix. The pozzolanic reaction of fly ash prolongs for a longer duration and hence is able to provide significant improvement in compressive strength at 90 days.

5.5.8 Compressive strength of OPC – 50% FA – UFS ternary concrete mixes

The results of compressive strength of reference concrete ‘R’ and ternary concrete with 30% fly ash and 5 – 15% ultra-fine slag is presented in Figure 5.13 and appendix B.6. The compressive strength of ternary mixes at early age (<28 days) are lower as compared to strength of reference concrete at same age. The 3 day strength of OPC – 50% FA – UFS are 31% to 57% lower as compared to 3 day strength of reference concrete. Similarly The 7 day strength of OPC – 50% FA – UFS are 26% to 48% lower as compared to 7 day strength of reference concrete

Compressive strength at 28 days was lower for all OPC – 50% FA – UFS ternary concrete mixes as compared to strength of reference concrete at same age. The 28 day strength was found to be 26% to 40% lower than that of strength of reference concrete at 28 days. The later age strength (> 28 days) was also observed to be lower for all OPC – 50% FA – UFS ternary concrete mixture as compared to compressive strength of reference concrete at same age. The 56 day strength was 18% to 36% lower than that of strength of reference concrete at 56 days. Similarly, the 90 day strength was 17% to 27% lower than that of strength of reference concrete at 90 days. Overall it is observed that OPC – 50% FA – UFS ternary concrete mixture does not provide better strengths at any age.

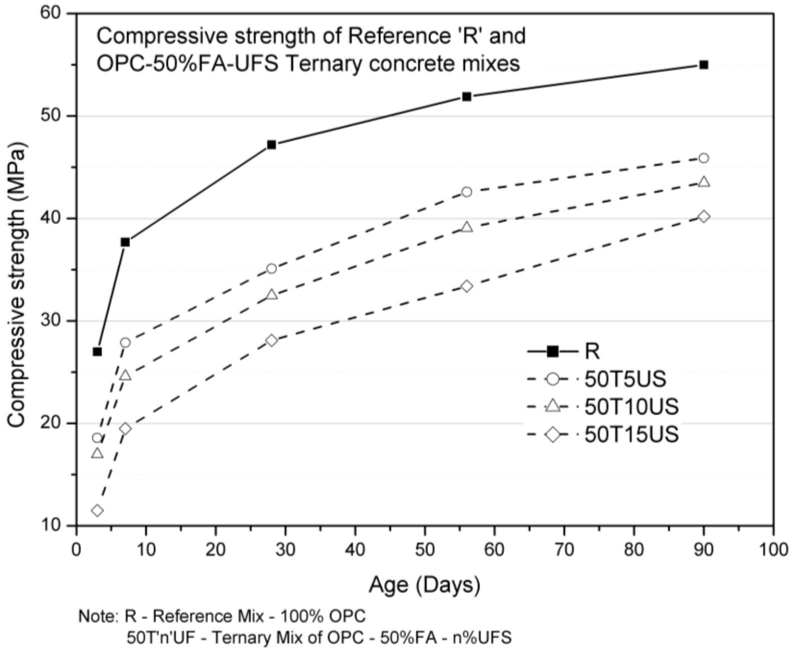


Figure 5.13. Compressive strength of reference and OPC – 50% FA – UFS ternary concrete mixes.

5.5.9 Discussion on compressive strength of concrete mixes

The results of compressive strength show reduced early strength due to addition of fly ash in binary concrete mixes. The compressive strengths has improved marginally after 28 days of curing. Low early strength of fly ash based binary concrete are attributable to slow pozzolanic reactivity of fly ash (Ashish et al., 2016; Choi et al., 2012; Hosan and Shaikh, 2020; Jeong et al., 2015). However, as the pozzolanic reaction prolongs for fly ash, the later age strength development of FA based concrete are comparable to reference concrete. The use of ultra-fine fly ash and ultra-fine slag has demonstrated better compressive strength at early and later ages.

The improvement in early age strength is attributable to finer particle sizes of UFFA and UFS, which accelerates the pozzolanic reactions (Sengul and Tasdemir, 2009; Shaikh and Supit, 2015; Teng et al., 2013; Ting et al., 2019). The filler and pozzolanic effect are dominant in UFS and UFFA which accelerates the hydration and reduces the pores at the microstructure of concrete (Faheem et al., 2021; Goldman and Bentur, 1993; Lim et al., 2016). Calcium content in UFFA is lesser (<10%) as compared to higher quantity present in UFS (>35%).

The significant improvement in compressive strength of UFS blended concrete mixes are also attributable to presence of abundant CaO, which enhances the compactness of concrete by producing additional CSH and ASH gels (Fang et al., 2018; Lee and Lee, 2013; Venu and Gunneswara Rao, 2017). The UFFA based ternary concrete also demonstrate better mechanical strength at later age but the improvement are less due to availability of limited compounds of Ca in UFFA (Coppola et al., 2018; Guo et al., 2020). Overall, the compressive strength has improved significantly at all ages due to addition of ultra-fine fly ash and ultra-fine slag in ternary concrete. The improvement is attributable to filler and pozzolanic effect of UFS and thus resulting in compact and denser microstructure.

5.6 Tensile strength of concrete

The tensile strength of concrete is determined after 28 days of curing based on provisions of IS 5816:1999. Standard cylindrical mould with 150 mm in diameter and 300 mm in length is casted. The cylindrical specimen were tested under laboratory scale compression testing machine. Three identical samples are tested for a typical category and the calculated mean value is noted as split tensile strength of that specified category.

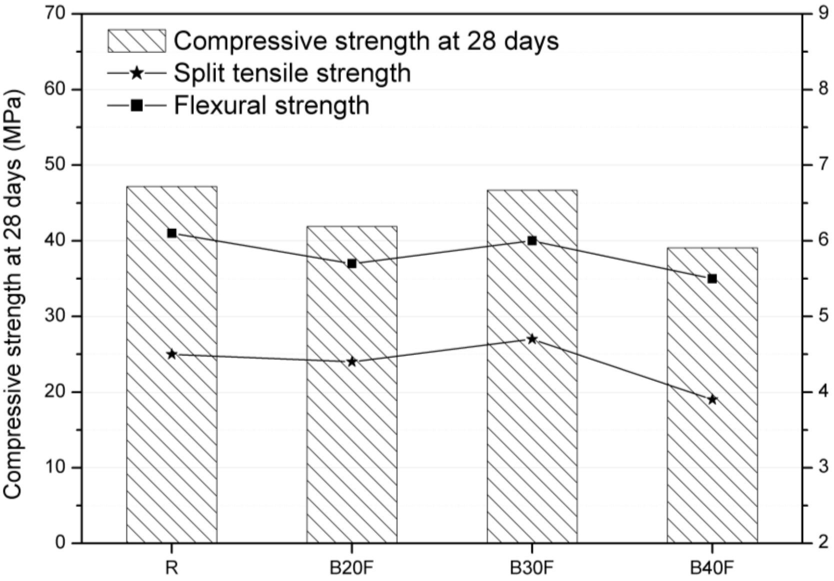
The flexural strength of concrete is determined based on provisions of IS 516:2018 after 28 days. Beams of standard size i.e. 150 mm × 150 mm × 700 mm is casted and tested for flexural strength. The specimen were kept above two steel rollers and tested in universal testing machine as per code guidelines. Three identical samples are tested for a typical category and the calculated mean value is noted as flexural strength of that specified category.

The split tensile strength (STS) and flexural strength (FS) of reference concrete ‘R’ is observed to be 4.5 MPa and 6.1 MPa, respectively. The ratio of split tensile strength to that of 28 day compressive strength is 0.095 for reference concrete ‘R’.

5.6.1 Tensile strength of OPC – FA binary concrete mixes

The results of split tensile strength (STS) and flexural strength (FS) of reference and binary concrete with 20%, 30% and 40% of fly ash is presented in Figure 5.14 and appendix B.4. The experimental results shows reduction in FS and STS when fly ash is added in binary mixtures. The flexural strength have reduced in the range of 2% to 10% as compared to flexural strength of reference concrete. The split tensile strength of binary mix is found to reduce by 2% and 13% for B20F and B40F, respectively. An improvement of 4% was observed in split tensile strength of B30F binary mix.

Overall it was observed that, the pattern or trend of split tensile and flexural strength generally follows the trend of compressive strength of respective mix. The ratio of split tensile strength to that of compressive strength at 28 days for OPC – FA binary mixes have been found as 0.102 which is closer to similar ratio of reference mix.

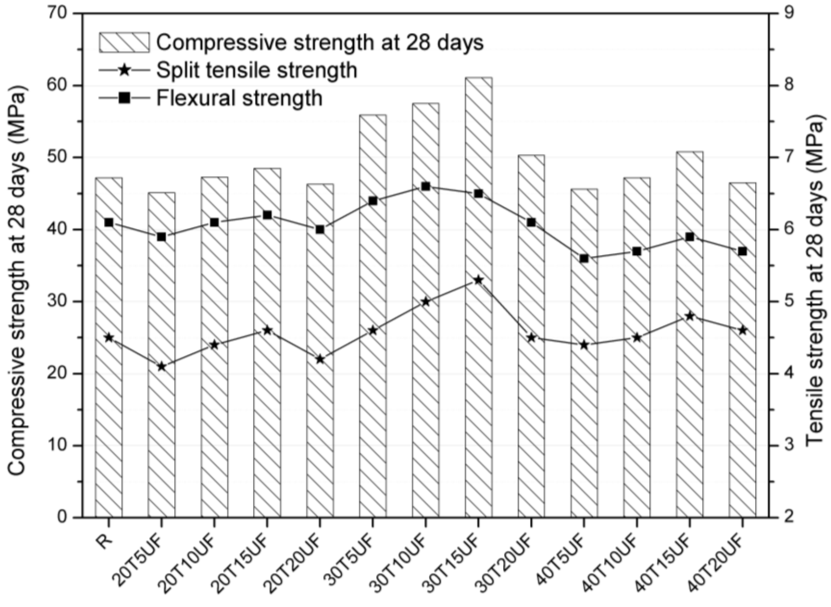


Note: R - Reference Concrete Mix - 100% OPC
B'x'F - Binary Concrete Mix of OPC - x%FA

Figure 5.14. Tensile strength of reference and OPC – FA binary concrete mixes.

5.6.2 Tensile strength of OPC – FA – UFFA ternary concrete mixes

The results of split tensile strength (STS) and flexural strength (FS) of reference and OPC – (20 – 40%) FA – (5 – 20%) UFFA ternary concrete mixes is presented in Figure 5.15 and appendix B.5. The experimental results shows increment in FS and STS for ternary mixtures with up to 15% of UFFA. Thereafter, the FS and STS have shown to reduce for ternary mix with 20% UFFS. For ternary mixtures with 20% of constant FA, i.e. OPC – 20% FA – UFFA mixes, variation is in the range of -3% to 2% in flexural strength as compared to FS of ‘R’. In the similar combinations, the variation of -9% to 2% in split tensile strength was observed as compared to STS of reference concrete. The highest improvement of 2% in FS and STS was shown by 20T15UF.



Note: R - Reference Concrete Mix - 100% OPC
'a'T'b'UF - Ternary Concrete Mix of OPC - a%FA - b%UFFA

Figure 5.15. Tensile strength of reference and OPC – FA – UFFA ternary concrete mixes.

For ternary mixtures with 30% of constant FA, i.e. OPC – 30% FA – UFFA mixes, variation is in the range of 0% to 8% in flexural strength as compared to FS of ‘R’. In the similar combinations, the variation of 0% to 18% in split tensile strength was observed as compared to STS of reference concrete. The highest improvement of 8% in FS was shown by 30T10UF as compared to reference concrete. The FS of 30T15UF was found to be 7% higher as compared to ‘R’. The highest improvement of 18% in STS was shown by 30T15UF.

For ternary mixtures with 40% of constant FA, i.e. OPC – 40% FA – UFFA mixes, variation is in the range of -3% to -8% in flexural strength as compared to FS of ‘R’. In the similar combinations, the variation of -2% to 7% in split tensile strength was observed as compared to STS of reference concrete. The highest improvement of 7% in STS was shown by 40T15UF as compared to 'R'.

Overall it was observed that, the pattern or trend of split tensile and flexural strength generally follows the trend of compressive strength of respective mix. The ratio of split tensile strength to that of compressive strength at 28 days for OPC – FA – UFFA ternary mixes varies from 0.082 – 0.099 with an average of 0.092, which is closer to similar ratio of reference mix 'R'.

5.6.3 Tensile strength of OPC – FA – UFS ternary concrete mixes

The results of split tensile strength (STS) and flexural strength (FS) of reference and OPC – (20 – 40%) FA – (5 – 20%) UFS ternary concrete mixes is presented in Figure 5.16 and appendix B.6. The experimental results shows increment in FS and STS for ternary mixtures with up to 15% of UFS. Thereafter, the FS and STS have shown to reduce for ternary mix with 20% UFS. For ternary mixtures with 20% of constant FA, i.e. OPC – 20% FA – UFS mixes, variation is in the range of 0% to 3% in flexural strength as compared to FS of 'R'. In the similar combinations, the variation of -2% to 9% in split tensile strength was observed as compared to STS of reference concrete. The highest improvement of 3% and 9% in FS and STS was shown by 20T15US.

For ternary mixtures with 30% of constant FA, i.e. OPC – 30% FA – UFS mixes, variation is in the range of 5% to 11% in flexural strength as compared to FS of 'R'. In the similar combinations, the variation of 7% to 22% in split tensile strength was observed as compared to STS of reference concrete. The highest improvement of 11% and 22% in FS and STS, respectively was shown by 30T15US as compared to reference concrete 'R'.

For ternary mixtures with 40% of constant FA, i.e. OPC – 40% FA – UFS mixes, variation is in the range of 0% to 7% in flexural strength as compared to FS of 'R'. In the similar combinations, the variation of 7% to 16% in split tensile strength was observed as compared to STS of reference concrete. The highest improvement of 7% and 16% in FS and STS was shown by 40T15US as compared to 'R'.

For ternary mixtures with 50% of constant FA, i.e. OPC – 50% FA – UFS mixes, variation is in the range of -15% to -41% in flexural strength as compared to FS of 'R'. In the similar combinations, the variation of -22% to -38% in split tensile strength was observed as compared to STS of reference concrete.

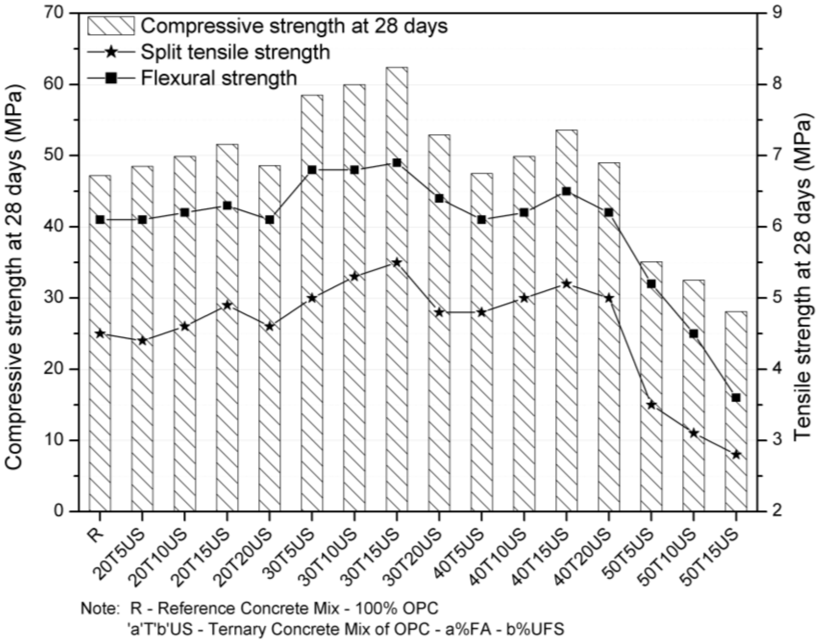


Figure 5.16. Tensile strength of reference and OPC – FA – UFS ternary concrete mixes.

Overall it was observed that, the pattern or trend of split tensile and flexural strength generally follows the trend of compressive strength of respective mix. The ratio of split tensile strength to that of compressive strength at 28 days for OPC – FA – UFS ternary mixes varies from 0.085 – 0.102 with an average of 0.095, which is closer to similar ratio of reference mix ‘R’

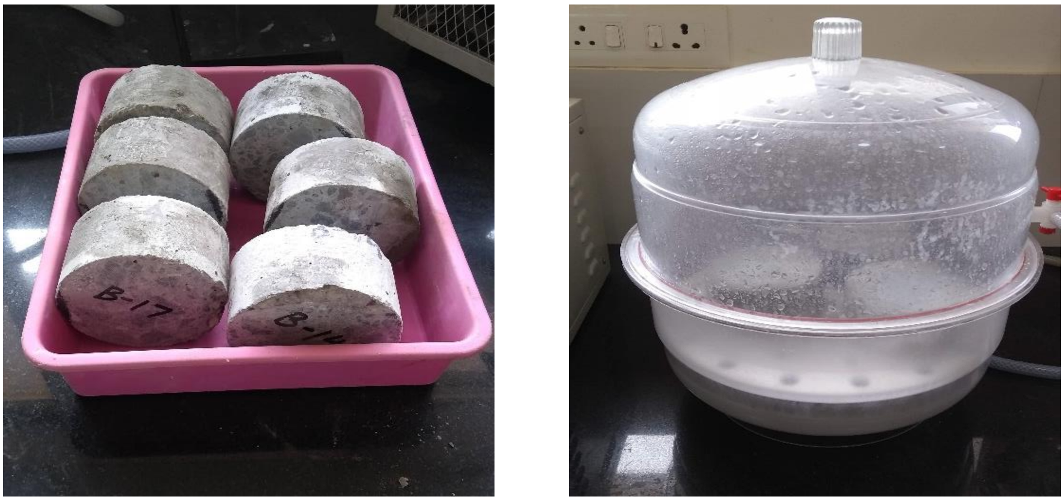
5.6.4 Discussion on tensile strength of concrete mixes

The split tensile strength (STS) and flexural strength (FS) of binary and ternary concrete mixes follow the similar pattern as their 28 day compressive strength. STS and FS have improved with inclusion of ultra-fine fly ash or ultra-fine slag in ternary concrete mixtures. This improvement is attributable to formation of secondary CSH gels and compactness of microstructure of concrete in ternary mixes (Nath and Sarker, 2017; Shamanth Gowda and Ranganath, 2020). The observed ratio of split tensile strength to 28 day compressive strength of concrete for binary and ternary mixtures are 0.095. This closely agrees with the findings in the available literature (Parveen et al., 2019) .

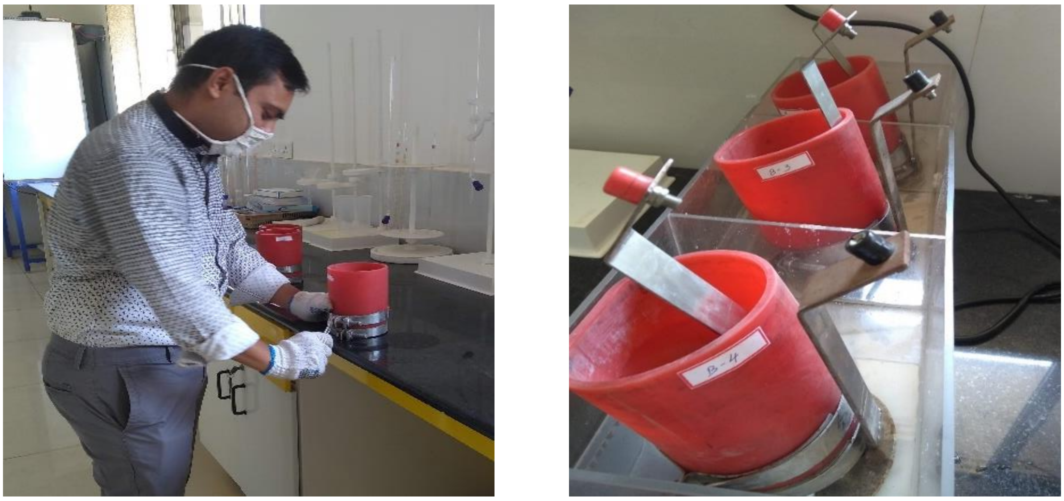
5.7 Rapid chloride migration test of concrete

The rapid chloride migration test (RCMT) of concrete is performed based on provisions of NT Build 492:1999 at the age of 7, 28 and 90 days. Specimens of desired size i.e. 50 mm thick slice of 100 mm diameter cylinder is cut from cast cylinder (200 mm cylinder with 100 mm diameter). The test is performed as per standards to obtain the chloride penetration depth. Further, non-steady state migration coefficient (D_{nssm}) is computed in accordance with observed values. Three identical samples are tested for a typical category and the calculated mean value is noted as chloride migration coefficient of that specified category. Figure 5.17 shows typical steps for measurement of rapid chloride migration coefficient of concrete.

The results of chloride migration of binary and ternary concrete are compared with chloride migration coefficient of reference concrete. The chloride migration coefficient (D_{nssm}) of reference concrete ‘R’ was observed as 15.65×10^{-12} m^2/s, 10.61×10^{-12} m^2/s and 9.28×10^{-12} m^2/s at 7, 28 and 90 days, respectively. Concrete can be classified in accordance with computed chloride migration coefficient (D_{nssm}) values as presented in Table 5.3 (Teng et al., 2013).

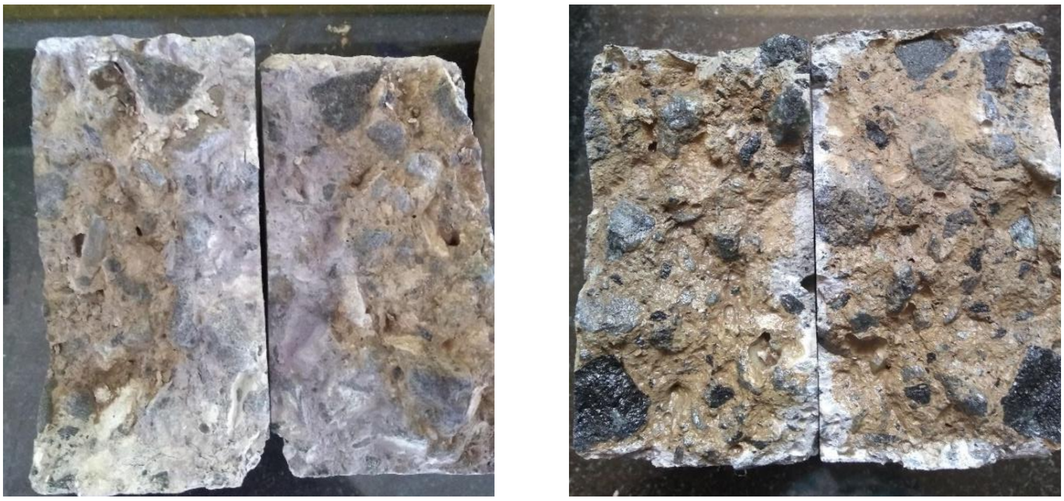


(a) test specimen (b) preconditioning in vacuum container



(c) fitting of rubber sleeve on specimen (d) placement of specimen for test

(e) RCMT test apparatus (f) spray of silver nitrate after splitting



(g) depth of chloride penetration in specimens

Figure 5.17. Measurement of chloride penetration of concrete using RCMT.

Table 5.4. Classification of concrete as per chloride migration coefficient.

Non steady state chloride migration coefficient ($D_{nssm} \times 10^{-12}$ m^2/s)	Classification of resistance of concrete against chloride migration
Greater than 15	Low
10 – 15	Moderate
5 – 10	High
2.5 – 5	Very high
Less than 2.5	Extremely high

As regards the above classification, reference mixture ‘R’ made with 100% of OPC shows ‘low’ resistance to chloride migration at the age of 7 days. Reference concrete show ‘moderate’ and ‘high’ resistance to chloride migration at 28 and 90 days, respectively.

5.7.1 Chloride migration of OPC – FA binary concrete mixes

The results of rapid chloride migration test (RCMT) of reference and binary concrete with 20%, 30% and 40% of fly ash is presented in Figure 5.18 and appendix B.7. The experimental results shows reduction in rapid chloride migration coefficient when fly ash is added to form binary mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – FA binary concrete have reduced in the range of 63 – 69% as compared to that of reference concrete. B20F and B30F have shown ‘high’ resistance to chloride migration at 7 days. The binary concrete B40F show ‘very high’ resistance to chloride migration at 7 days. Among all binary mixes, the maximum reduction of 69% in chloride migration coefficient was observed for B40F mix as compared to reference concrete at the same age.

The rapid chloride migration coefficient at the age of 28 days for OPC – FA binary concrete have reduced in the range of 77 – 79% as compared to that of reference concrete. All the binary mixes have shown ‘extremely high’ resistance to chloride migration at 28 days. Among all binary mixes, the maximum reduction of 79% in chloride migration coefficient for B40F mix was observed as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – FA binary concrete have reduced in the range of 81 – 86% as compared to that of reference concrete. All the binary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all binary mixes, the maximum reduction of 86% in chloride migration coefficient was observed for B40F mix as compared to reference concrete at the same age.

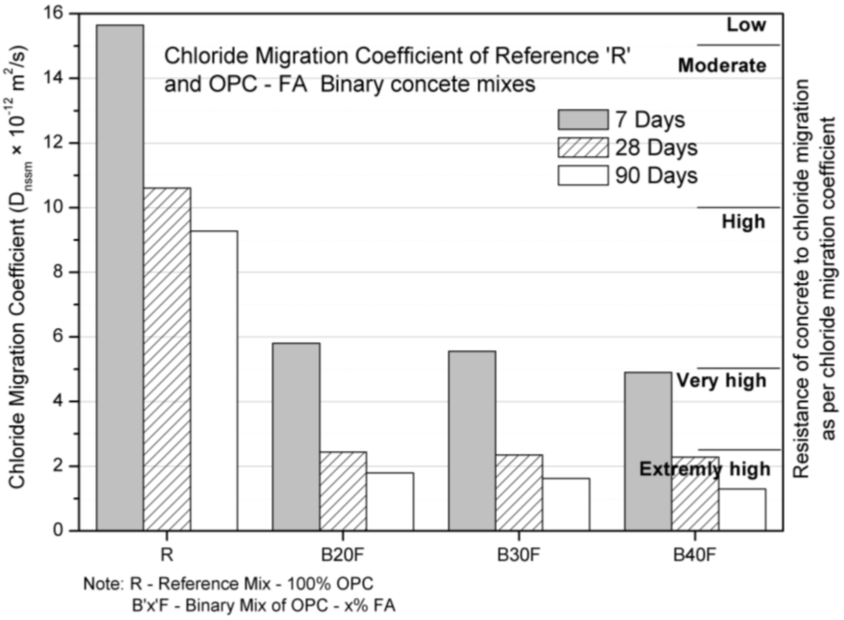


Figure 5.18. Chloride migration coefficient of reference and OPC – FA binary concrete mixes.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash in binary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash.

5.7.2 Chloride migration of OPC – 20% FA – UFFA ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 20% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.19 and appendix B.8. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine fly ash are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 20% FA – UFFA ternary concrete have reduced in the range of 64 – 85% as compared to that of reference concrete. Mix 20T5UF and 20T10UF has shown ‘high’ and ‘very high’ resistance to chloride migration, respectively at 7 days. The ternary concrete

20T15UF and 20T20UF shows ‘extremely high’ resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 85% in chloride migration coefficient was observed for 20T15UF mix as compared to reference concrete at the same age.

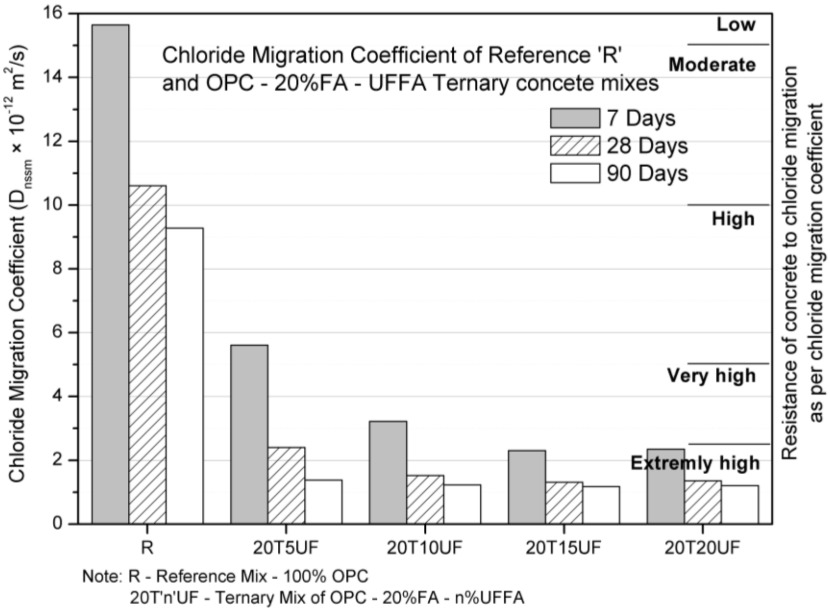


Figure 5.19. Chloride migration coefficient of reference and OPC – 20% FA – UFFA ternary concrete mixes.

The rapid chloride migration coefficient at the age of 28 days for OPC – 20% FA – UFFA ternary concrete has reduced in the range of 77 – 87% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 28 days. Among all ternary mixes, the maximum reduction of 87% in chloride migration coefficient was observed for 20T15UF mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 20% FA – UFFA ternary concrete have reduced in the range of 85 – 87% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 86% in chloride migration coefficient was observed for 20T15UF mix as compared to reference concrete at the same age.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash.

5.7.3 Chloride migration of OPC – 30% FA – UFFA ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 30% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.20 and appendix B.8. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine fly ash are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 30% FA – UFFA ternary concrete have reduced in the range of 80 – 87% as compared to that of reference concrete. Mix 30T5UF and 30T20UF has shown ‘very high’ resistance to chloride migration at 7 days. The ternary concrete 30T10UF and 30T10UF shows ‘extremely high’ resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 87% in chloride migration coefficient was observed for 30T15UF mix as compared to reference concrete at the same age.

The rapid chloride migration coefficient at the age of 28 days for OPC – 30% FA – UFFA ternary concrete has reduced in the range of 86 – 91% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 28 days. Among all ternary mixes, the maximum reduction of 91% in chloride migration coefficient was observed for 30T15UF mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 30% FA – UFFA ternary concrete have reduced in the range of 86 – 90% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 90% in chloride migration coefficient was observed for 30T15UF mix as compared to reference concrete at the same age.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash.

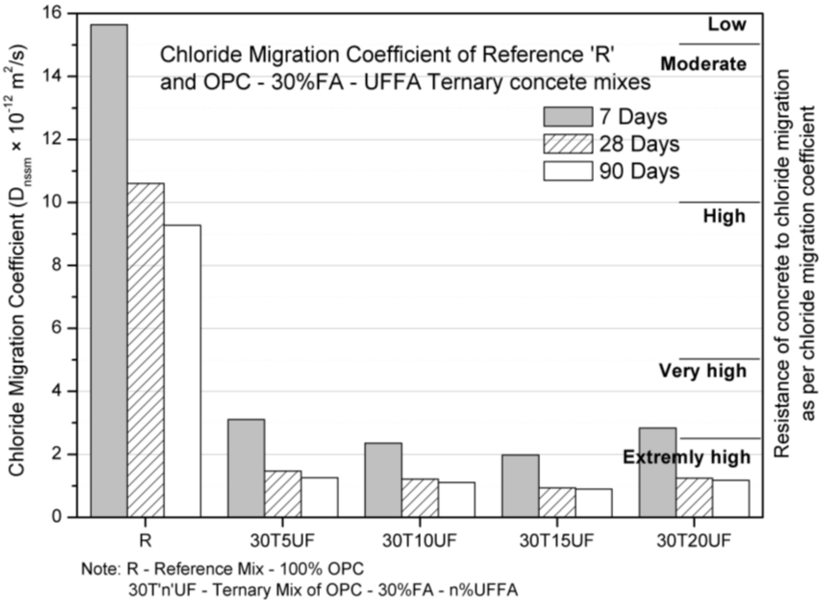
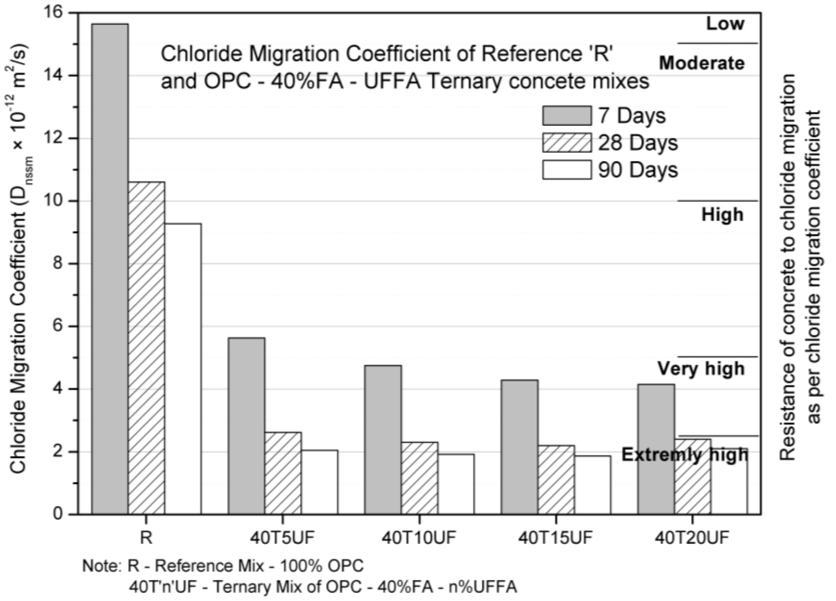


Figure 5.20. Chloride migration coefficient of reference and OPC – 30% FA – UFFA ternary concrete mixes.

5.7.4 Chloride migration of OPC – 40% FA – UFFA ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.21 and appendix B.8. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine fly ash are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 40% FA – UFFA ternary concrete have reduced in the range of 64 – 73% as compared to that of reference concrete. Mix 40T5UF has shown ‘high’ resistance to chloride migration at 7 days. The ternary concrete 40T10UF, 40T15UF and 40T20UF shows ‘extremely high’ resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 73% in chloride migration coefficient was observed for 40T15UF mix as compared to reference concrete at the same age.

The rapid chloride migration coefficient at the age of 28 days for OPC – 40% FA – UFFA ternary concrete has reduced in the range of 75 – 79% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 28 days, except 40T5UF which shows ‘very high’ resistance. Among all ternary mixes, the maximum reduction of 79% in chloride migration coefficient was observed for 40T15UF mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 40% FA – UFFA ternary concrete have reduced in the range of 77 – 80% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 90% in chloride migration coefficient was observed for 40T15UF mix as compared to reference concrete at the same age.



Note: R - Reference Mix - 100% OPC
40T'n'UF - Ternary Mix of OPC - 40%FA - n%UFFA

Figure 5.21. Chloride migration coefficient of reference and OPC – 40% FA – UFFA ternary concrete mixes.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash.

5.7.5 Chloride migration of OPC – 20% FA – UFS ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 20% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.22 and appendix B.9. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine slag are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 20% FA – UFS ternary concrete have reduced in the range of 69 – 89% as compared to that of reference concrete. Mix 20T5US and 20T10US has shown ‘very high’ resistance to chloride migration at 7 days. The ternary concrete 20T15US and 20T20US shows ‘extremely high’ resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 89% in chloride migration coefficient was observed for 20T15US mix as compared to reference concrete at the same age.

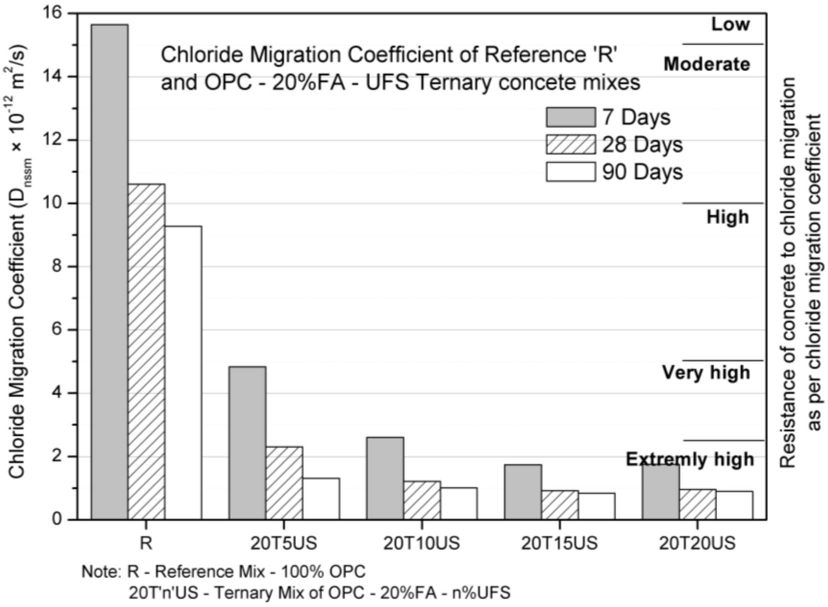


Figure 5.22. Chloride migration coefficient of reference and OPC – 20% FA – UFS ternary concrete mixes.

The rapid chloride migration coefficient at the age of 28 days for OPC – 20% FA – UFS ternary concrete has reduced in the range of 78 – 91% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 28 days. Among all ternary mixes, the maximum reduction of 91%

in chloride migration coefficient was observed for 20T15US mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 20% FA – UFS ternary concrete have reduced in the range of 86 – 91% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 91% in chloride migration coefficient was observed for 20T15US mix as compared to reference concrete at the same age.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

5.7.6 Chloride migration of OPC – 30% FA – UFS ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 30% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.23 and appendix B.9. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine slag are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 30% FA – UFS ternary concrete have reduced in the range of 85 – 90% as compared to that of reference concrete. All the ternary concrete mixes show ‘extremely high’ resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 90% in chloride migration coefficient was observed for 30T15US mix as compared to reference concrete at the same age.

The rapid chloride migration coefficient at the age of 28 days for OPC – 30% FA – UFS ternary concrete has reduced in the range of 89 – 93% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 28 days. Among all ternary mixes, the maximum reduction of 93% in chloride migration coefficient was observed for 30T15US mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 30% FA – UFS ternary concrete have reduced in the range of 88 –

92% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 92% in chloride migration coefficient was observed for 30T15US mix as compared to reference concrete at the same age.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

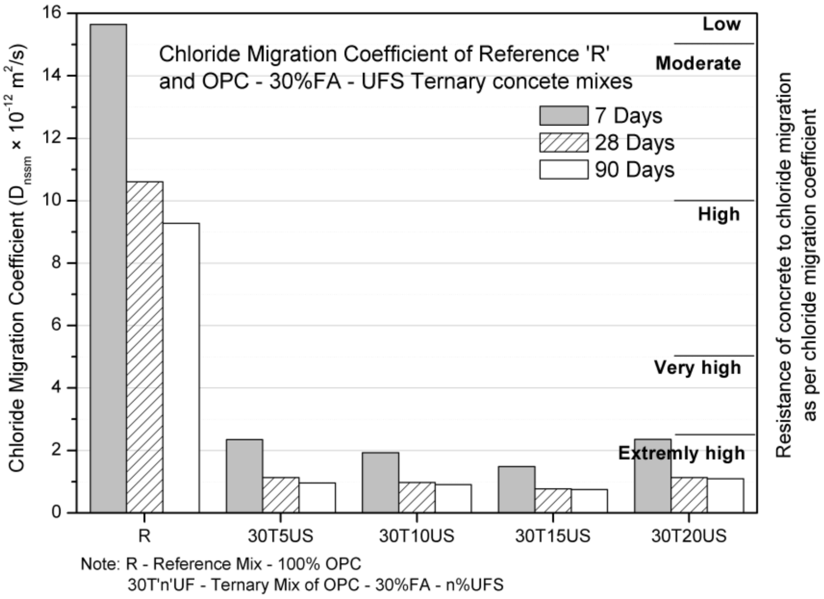


Figure 5.23. Chloride migration coefficient of reference and OPC – 30% FA – UFS ternary concrete mixes.

5.7.7 Chloride migration of OPC – 40% FA – UFS ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.24 and appendix B.9. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine slag are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 40% FA – UFS ternary concrete have reduced in the range of 71 – 80% as compared to that of reference concrete. All the ternary concrete mixes show 'very high' resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 80% in chloride migration coefficient was observed for 40T15US mix as compared to reference concrete at the same age.

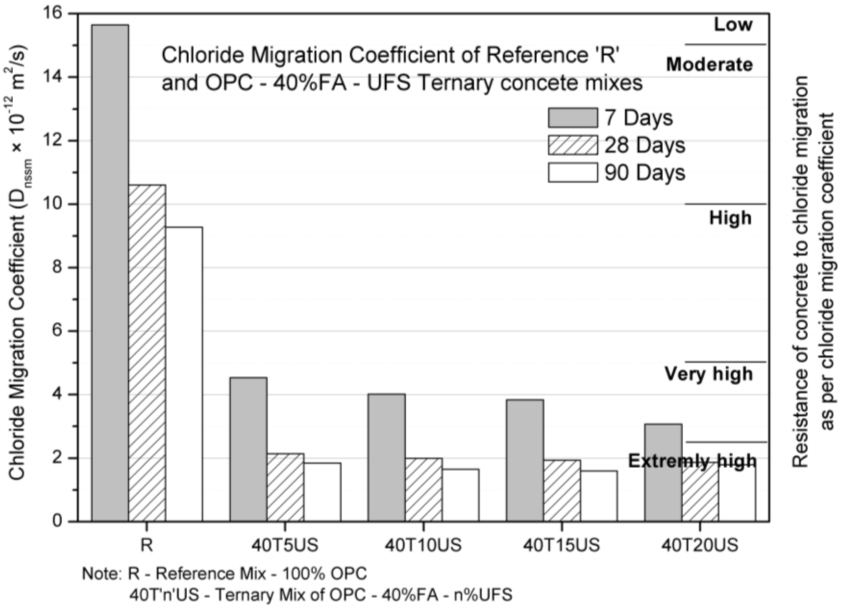


Figure 5.24. Chloride migration coefficient of reference and OPC – 40% FA – UFS ternary concrete mixes.

The rapid chloride migration coefficient at the age of 28 days for OPC – 40% FA – UFS ternary concrete has reduced in the range of 80 – 82% as compared to that of reference concrete. All the ternary mixes have shown 'extremely high' resistance to chloride migration at 28 days. Among all ternary mixes, the maximum reduction of 82% in chloride migration coefficient was observed for 40T15US mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 40% FA – UFS ternary concrete have reduced in the range of 80 – 83% as compared to that of reference concrete. All the ternary mixes have shown 'extremely high' resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 83% in chloride migration coefficient was observed for 40T15US mix as compared to reference concrete at the same age.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

5.7.8 Chloride migration of OPC – 50% FA – UFS ternary concrete mixes

The results of rapid chloride migration test (RCMT) of reference concrete ‘R’ and ternary concrete with 50% fly ash and 5 – 15% ultra-fine slag is presented in Figure 5.25 and appendix B.9. The experimental results shows significant reduction in rapid chloride migration coefficient when fly ash and ultra-fine slag are added to form ternary concrete mixtures. The rapid chloride migration coefficient at the age of 7 days for OPC – 50% FA – UFS ternary concrete have reduced in the range of 69 – 74% as compared to that of reference concrete. All the ternary concrete mixes show ‘very high’ resistance to chloride migration at 7 days. Among all ternary mixes, the maximum reduction of 74% in chloride migration coefficient was observed for 50T15US mix as compared to reference concrete at the same age.

The rapid chloride migration coefficient at the age of 28 days for OPC – 50% FA – UFS ternary concrete has reduced in the range of 73 – 75% as compared to that of reference concrete. All the ternary mixes have shown ‘very high’ resistance to chloride migration at 28 days. Among all ternary mixes, the maximum reduction of 75% in chloride migration coefficient was observed for 50T15US mix as compared to reference concrete at the same age. The rapid chloride migration coefficient at the age of 90 days for OPC – 50% FA – UFS ternary concrete have reduced in the range of 78 – 81% as compared to that of reference concrete. All the ternary mixes have shown ‘extremely high’ resistance to chloride migration at 90 days. Among all ternary mixes, the maximum reduction of 81% in chloride migration coefficient was observed for 50T15US mix as compared to reference concrete at the same age.

Overall it was observed that, the resistance to chloride migration have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to chloride migration increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to chloride migration is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

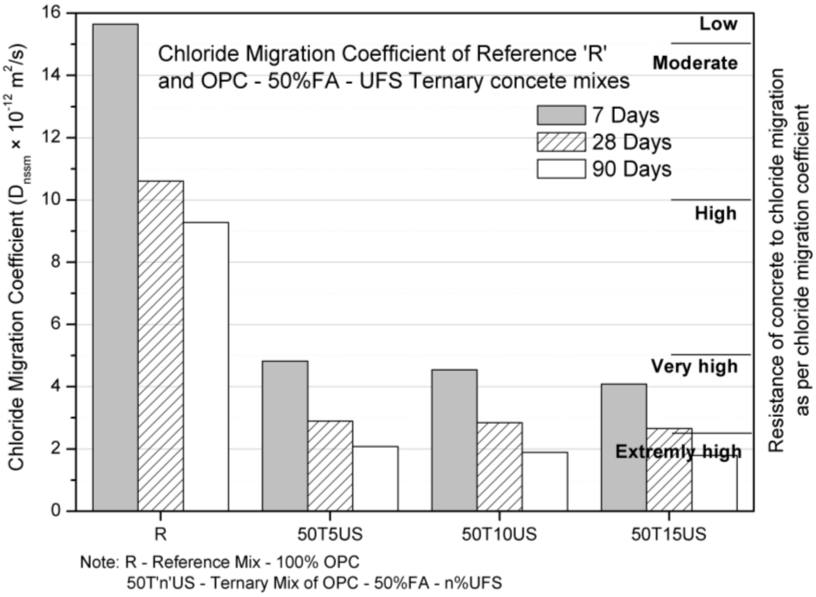


Figure 5.25. Chloride migration coefficient of reference and OPC – 50% FA – UFS ternary concrete mixes.

5.7.9 Discussion on chloride migration of concrete mixes

The concrete made with ultra-fine fly ash and ultra-fine slag has shown significant improvement in resistance against chloride migration (Dąbrowski et al., 2016; Ismail et al., 2013; Li et al., 2020; Papadakis, 2000; Rukzon and Chindaprasirt, 2013; Sengul and Tasdemir, 2009). The ultra-fine particle size of UFFA and UFS has resulted in refinement of pore structure resulting in denser and compact microstructure (Chindaprasirt et al., 2008; Mehta and Siddique, 2018; Rattanashotinunt et al., 2018; Yang et al., 2014). This compactness is a result of formation of denser secondary CSH and ASH gels due to ultra-fine pozzolanic materials (Ismail et al., 2013; Lim et al., 2016; Rukzon and Chindaprasirt, 2013). The resistance to chloride migration has also improved due to improvement in particle packing and reduction of interconnected voids in ternary concrete mixes (Sengul and Tasdemir, 2009).

5.8 Depth of penetration of water under pressure in concrete

The depth of penetration of water under pressure in concrete is determined based on provisions of EN 12390:2009 after 28 and 90 days. Specimens of size 150 mm cube is pressurized under water pressure of 500 kPa for 72 hours. The maximum depth of water penetration in mm is noted after splitting the specimen. Three identical samples are tested for a typical category and the calculated mean value is noted as depth of water penetration of that specified category.

(a) placement of specimen in apparatus (b) specimen under water pressure

(c) splitting of specimen (d) measurement of penetration depth

Figure 5.26. Measurement of depth of penetration of water under pressure in concrete.

Figure 5.26 shows typical steps for measurement of depth of penetration of water in concrete. The depth of penetration of water is observed as 38 mm and 32 mm at 28 days and 90 days, respectively for reference concrete ‘R’. The observed values of water penetration for binary and ternary mixtures are compares with that of reference concrete.

5.8.1 Depth of penetration of water for OPC – FA binary concrete mixes

The results of depth of water penetration of reference and binary concrete with 20%, 30% and 40% of fly ash is presented in Figure 5.27 and appendix B.7. The experimental results shows reduction in depth of water penetration when fly ash is added to form binary mixtures. The water penetration depth at the age of 28 days for OPC – FA binary concrete have reduced in the range of 58 – 71% as compared to that of reference concrete. Among all binary mixes, the maximum reduction of 71% in water penetration depth was observed for B40F mix as compared to reference concrete at the same age.

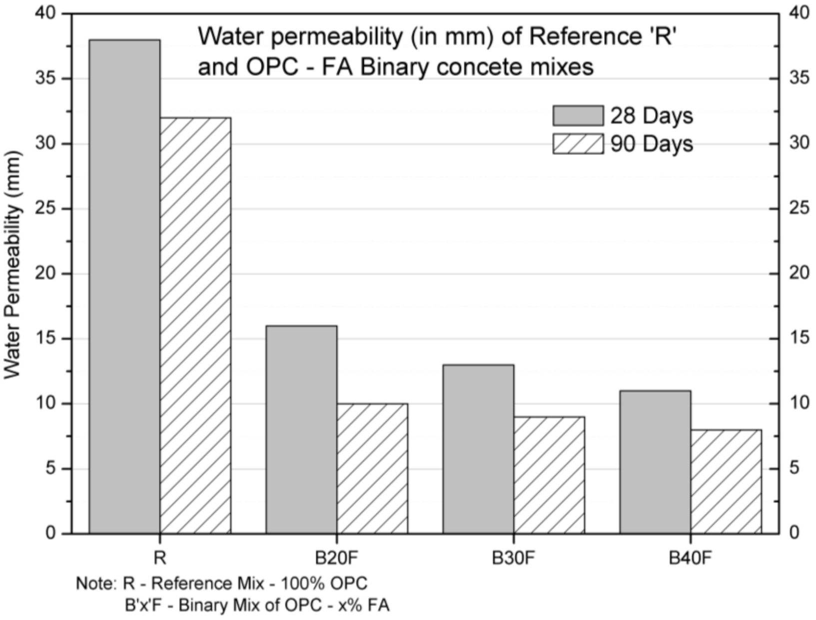


Figure 5.27. Water permeability of reference and OPC – FA binary concrete mixes.

The water penetration depth at the age of 90 days for OPC – FA binary concrete have reduced in the range of 69 – 75% as compared to that of reference concrete. The maximum reduction of 75% in water penetration depth was observed for B40F mix as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash in binary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash.

5.8.2 Depth of penetration of water for OPC – 20% FA – UFFA ternary concrete mixes

The results of depth of water penetration of reference concrete 'R' and ternary concrete with 20% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.28 and appendix B.8. The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine fly ash are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 20% FA – UFFA ternary concrete have reduced in the range of 61 – 74% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 74% in water penetration depth was observed for 20T20UF ternary mix as compared to reference concrete at the same age.

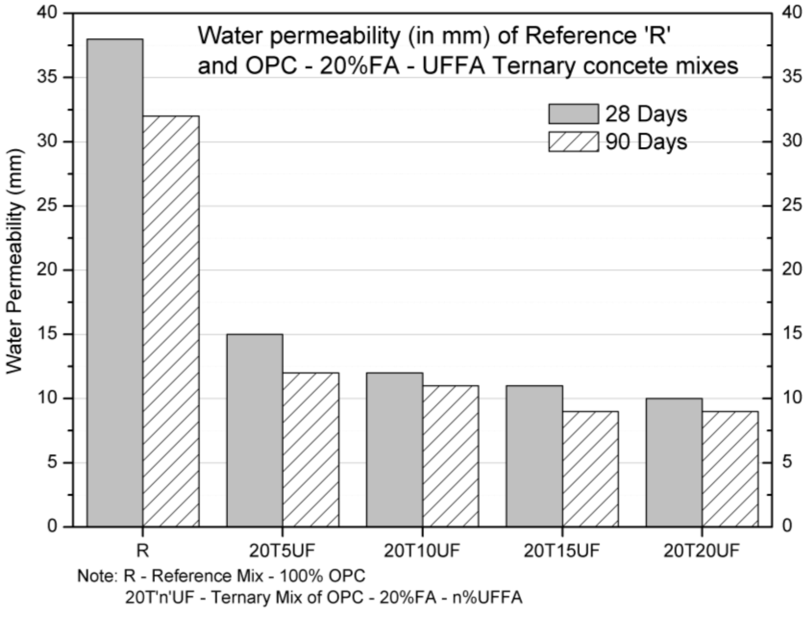


Figure 5.28. Water permeability of reference and OPC – 20% FA – UFFA ternary concrete mixes.

The water penetration depth at the age of 90 days for OPC – 20% FA - UFFA ternary concrete have reduced in the range of 63 – 72% as compared to that of reference concrete. The maximum reduction of 72% in water penetration depth was observed for 20T20UF mix as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash in ternary concrete.

5.8.3 Depth of penetration of water for OPC – 30% FA – UFFA ternary concrete mixes

The results of depth of water penetration of reference concrete 'R' and ternary concrete with 30% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.29 and appendix B.8. The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine fly ash are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 30% FA – UFFA ternary concrete have reduced in the range of 76 – 87% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 87% in water penetration depth was observed for 30T15UF ternary mix as compared to reference concrete at the same age.

The water penetration depth at the age of 90 days for OPC – 30% FA - UFFA ternary concrete have reduced in the range of 78 – 91% as compared to that of reference concrete. The maximum reduction of 91% in water penetration depth was observed for 30T15UF mix as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash in ternary concrete.

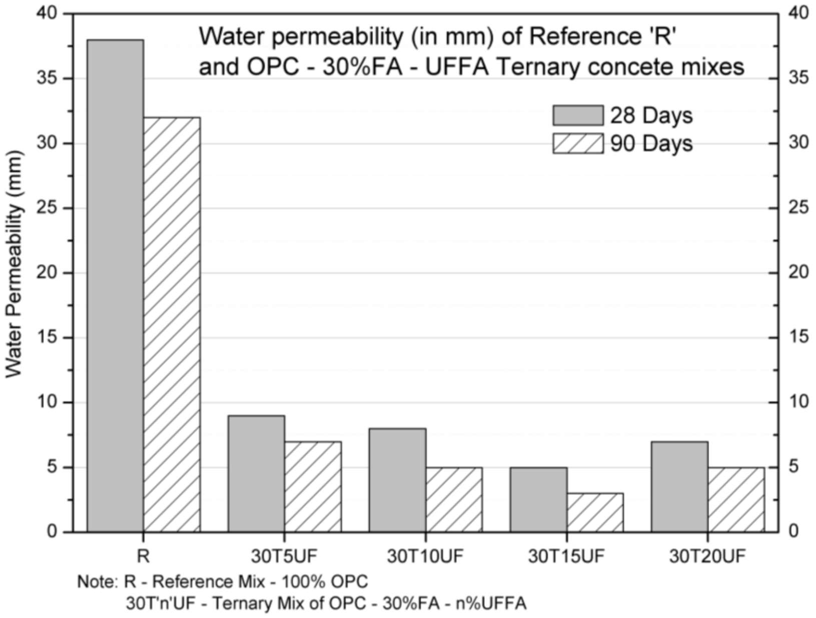


Figure 5.29. Water permeability of reference and OPC – 30% FA – UFFA ternary concrete mixes.

5.8.4 Depth of penetration of water for OPC – 40% FA – UFFA ternary concrete mixes

The results of depth of water penetration of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.30 and appendix B.8. The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine fly ash are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 40% FA – UFFA ternary concrete have reduced in the range of 71 – 79% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 79% in water penetration depth was observed for 40T15UF ternary mix as compared to reference concrete at the same age.

The water penetration depth at the age of 90 days for OPC – 40% FA - UFFA ternary concrete have reduced in the range of 75 – 84% as compared to that of reference concrete. The maximum reduction of 84% in water penetration depth was observed for 40T15UF mix as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash.

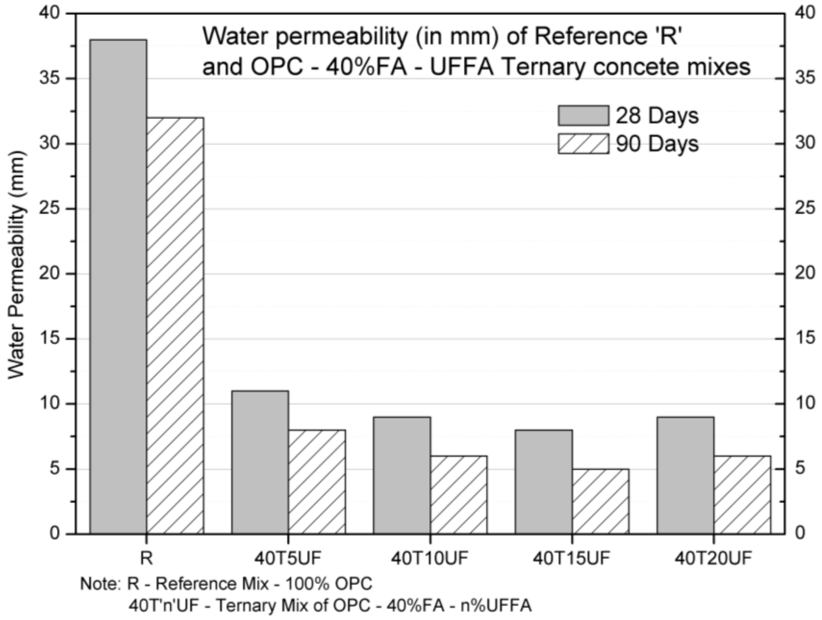


Figure 5.30. Water permeability of reference and OPC – 40% FA – UFFA ternary concrete mixes.

5.8.5 Depth of penetration of water for OPC – 20% FA – UFS ternary concrete mixes

The results of depth of water penetration of reference concrete ‘R’ and ternary concrete with 20% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.31 and appendix B.9.

The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine slag are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 20% FA – UFS ternary concrete have reduced in the range of 74 – 84% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 84% in water penetration depth was observed for 20T15US ternary mix as compared to reference concrete at the same age.

The water penetration depth at the age of 90 days for OPC – 20% FA - UFS ternary concrete have reduced in the range of 81 – 88% as compared to that of reference concrete. The maximum reduction of 88% in water penetration depth was observed for 20T15US mix as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

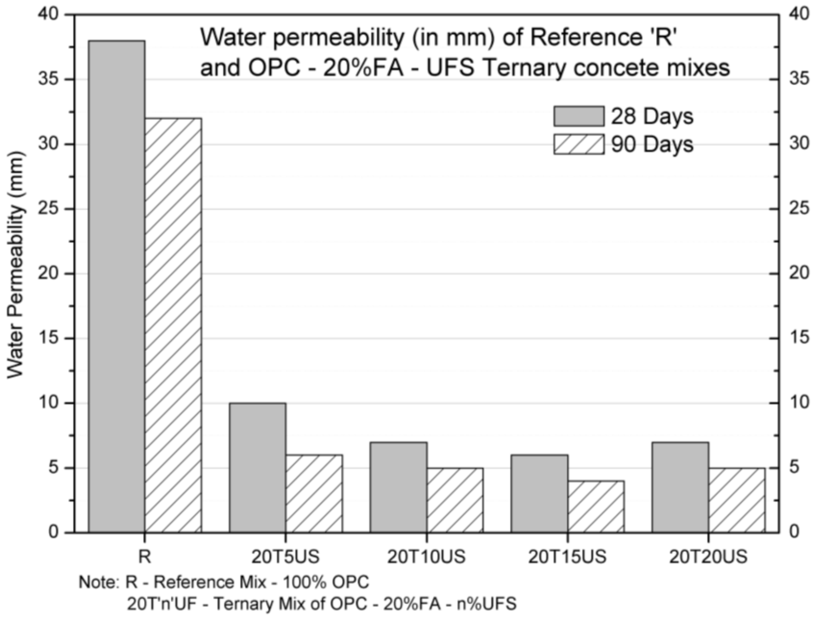


Figure 5.31. Water permeability of reference and OPC – 20% FA – UFS ternary concrete mixes.

5.8.6 Depth of penetration of water for OPC – 30% FA – UFS ternary concrete mixes

The results of depth of water penetration of reference concrete ‘R’ and ternary concrete with 30% fly ash and 5 – 30% ultra-fine slag is presented in Figure 5.32 and appendix B.9.

The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine slag are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 30% FA – UFS ternary concrete have reduced in the range of 84 – 92% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 92% in water penetration depth was observed for 30T15US ternary mix as compared to reference concrete at the same age.

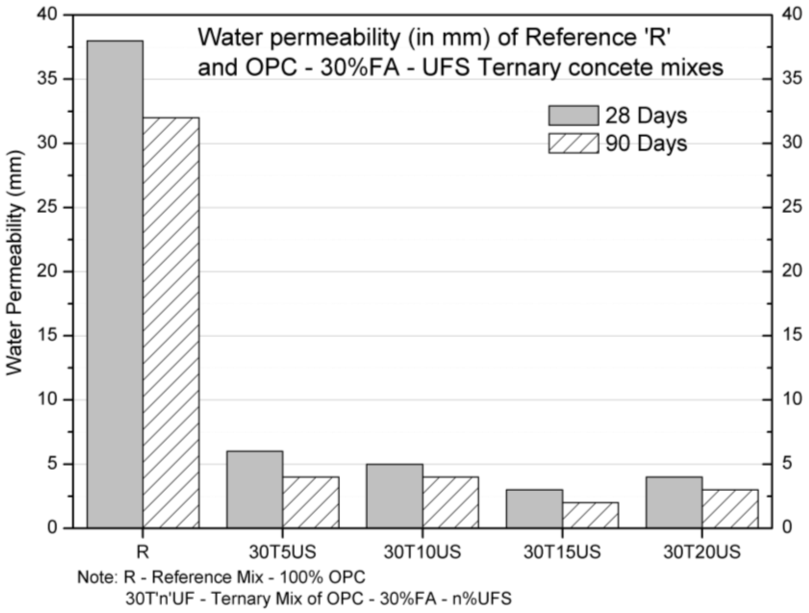


Figure 5.32. Water permeability of reference and OPC – 30% FA – UFS ternary concrete mixes.

The water penetration depth at the age of 90 days for OPC – 30% FA - UFS ternary concrete have reduced in the range of 88 – 94% as compared to that of reference concrete. The maximum reduction of 94% in water penetration depth was observed for 30T15US mix as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

5.8.7 Depth of penetration of water for OPC – 40% FA – UFS ternary concrete mixes

The results of depth of water penetration of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.33 and appendix B.9. The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine slag are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 40% FA – UFS ternary concrete have reduced in the range of 82 – 84% as compared to that of reference concrete. Ternary mixes 40T10UF, 40T15US and 40T20US show the maximum reduction of 84% in water penetration depth as compared to reference concrete at the same age.

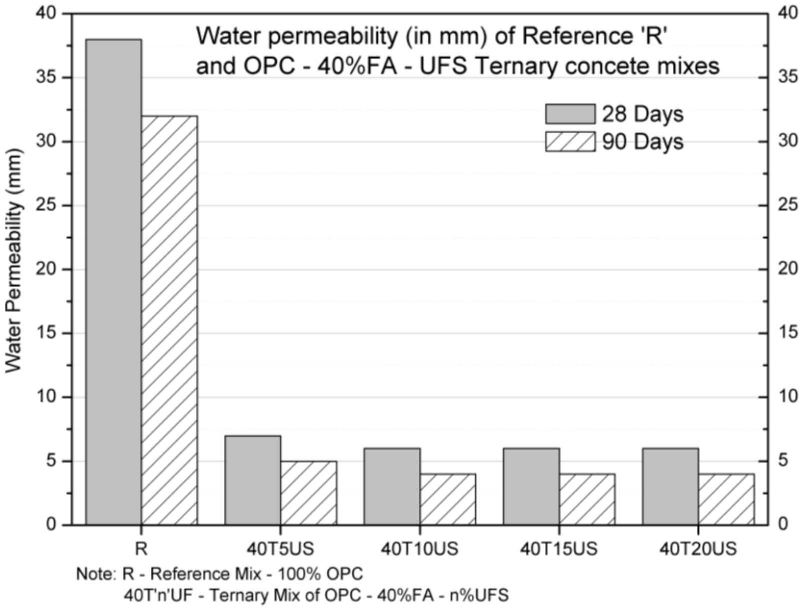


Figure 5.33. Water permeability of reference and OPC – 40% FA – UFS ternary concrete mixes.

The water penetration depth at the age of 90 days for OPC – 40% FA - UFS ternary concrete have reduced in the range of 84 – 88% as compared to that of reference concrete. Ternary mixes 40T10US, 40T15US and 40T20US show the maximum reduction of 88% in water penetration depth as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

5.8.8 Depth of penetration of water for OPC – 50% FA – UFS ternary concrete mixes

The results of depth of water penetration of reference concrete 'R' and ternary concrete with 50% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.34 and appendix B.9. The experimental results shows reduction in depth of water penetration when fly ash and ultra-fine slag are added to form ternary mixtures. The water penetration depth at the age of 28 days for OPC – 50% FA – UFS ternary concrete have reduced in the range of 76 – 79% as compared to that of reference concrete. Ternary mixes 50T15US show the maximum reduction of 79% in water penetration depth as compared to reference concrete at the same age.

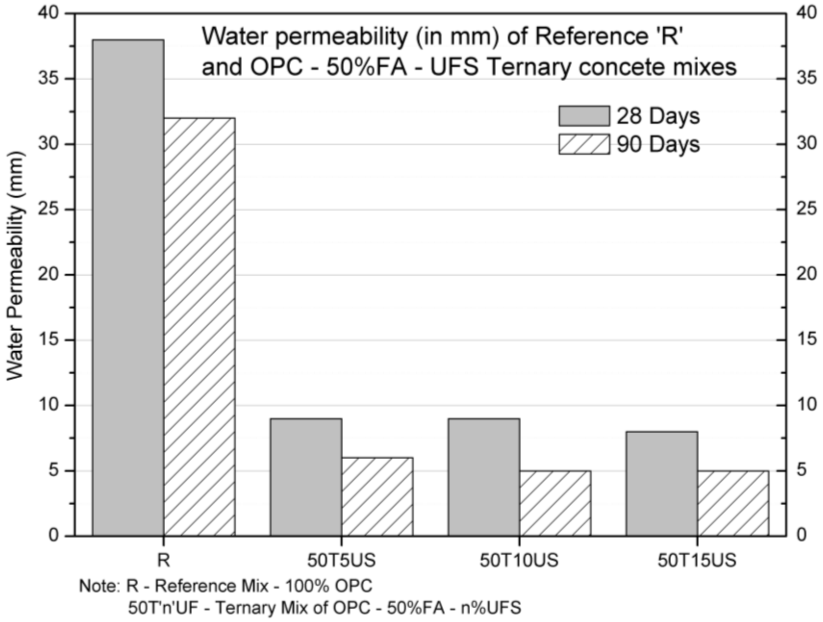


Figure 5.34. Water permeability of reference and OPC – 50% FA – UFS ternary concrete mixes.

The water penetration depth at the age of 90 days for OPC – 50% FA - UFS ternary concrete have reduced in the range of 81 – 84% as compared to that of reference concrete. Ternary mixes 50T10US and 50T15US show the maximum reduction of 84%

in water penetration depth as compared to reference concrete at the same age. Overall it was observed that, the resistance to water permeability have improved significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The resistance to water permeability increases with the age of concrete and is found to be maximum at 90 days. The improvement in resistance to water permeability is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag.

5.8.9 Discussion on depth of penetration of water of concrete mixes

The depth of water penetration has reduced for all binary and ternary concrete mixes using ultra-fine fly ash and ultra-fine slag. Previous research (Bhushan Jindal et al., 2020; Chusilp et al., 2009; Muthadhi and Kothandaraman, 2013; Rattanachu et al., 2019; Rattanashotinunt et al., 2018; Somna et al., 2012; Yu et al., 2018) have confirmed the reduction in water permeability due to addition of pozzolanic materials. UFFA and UFS in ternary mixture has refined the pore structure resulting in dense and compact microstructure. The improvement in resistance to water penetration is also due to formation of denser secondary CSH gels in ternary concrete (Muthadhi and Kothandaraman, 2013).

5.9 Sorptivity or rate of water absorption of concrete

The initial and secondary sorptivity of concrete is determined based on provisions of ASTM C 1585 – 13. Specimens of desired size i.e. 50 mm thick slice of 100 mm diameter cylinder is cut from cast cylinder (200 mm cylinder with 100 mm diameter). Samples are conditioned in the environmental chamber at 50°C and 80% relative humidity for 3 days. Thereafter specimen are sealed and stored at room temperature for 15 days. Absorption procedure is commenced and increase in mass is recorded until 7 day. Initial and secondary sorptivity is then calculated as per procedure recommended by code. Two identical samples are tested for a typical category and the calculated mean value is noted as sorptivity of that specified category. Figure 5.35 shows typical steps for measurement of sorptivity of concrete.

(a) test specimen ready for conditioning

(b) environmental chamber for conditioning of specimen

(c) specimen in sealable container

(d) side and top sealing of specimen

(e) placement of specimen for water absorption at different intervals

Figure 5.35 Measurement of sorptivity of concrete.

The results of water sorptivity of binary and ternary concrete are compared with water sorptivity of reference concrete. The initial and secondary sorptivity of reference concrete ‘R’ was observed as 16.85 × 10^{-4} mm/$s^{1/2}$ and 4.14 × 10^{-4} mm/$s^{1/2}$.

5.9.1 Sorptivity of OPC – FA binary concrete mixes

The results of initial and secondary sorptivity of reference and binary concrete with 20%, 30% and 40% of fly ash is presented in Figure 5.36 and appendix B.7. The experimental results shows reduction in water sorptivity when fly ash is added to form binary mixtures. The initial sorptivity for OPC – FA binary concrete have reduced in the range of 10 – 19% as compared to that of reference concrete. Among all binary mixes, the maximum reduction of 19% in initial sorptivity was observed for B40F mix as compared to reference concrete.

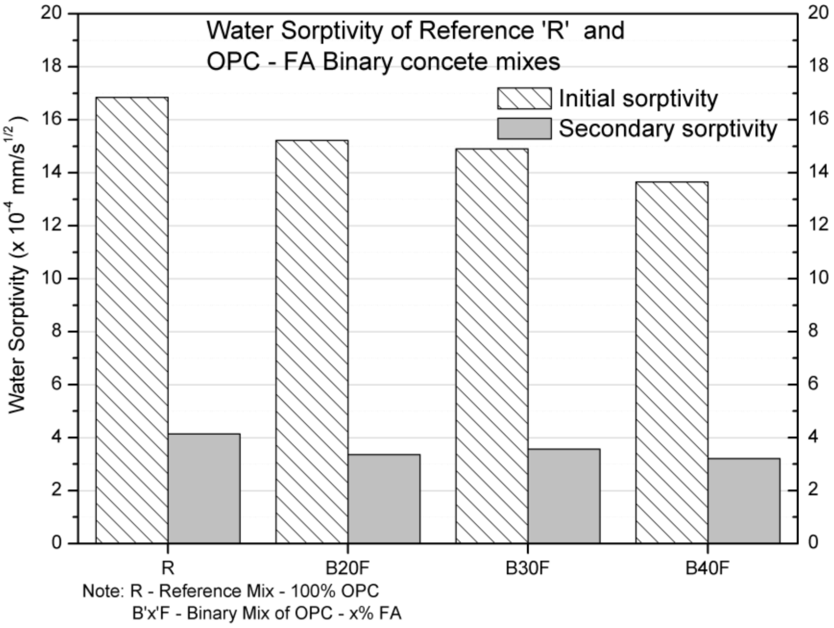


Figure 5.36. Sorptivity of reference and OPC – FA binary concrete mixes.

The secondary water sorptivity for OPC – FA binary concrete have reduced in the range of 14 – 22% as compared to that of reference concrete. The maximum reduction of 22% in secondary sorptivity was observed for B40F mix as compared to reference concrete. Overall it was observed that, the rate of water absorption or sorptivity of concrete have reduced due to addition of fly ash in binary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash.

5.9.2 Sorptivity of OPC – 20% FA – UFFA ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete ‘R’ and ternary concrete with 20% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.37 and appendix B.8. The experimental results shows reduction in sorptivity when fly ash and ultra-fine fly ash are added to form ternary mixtures. The initial sorptivity of OPC – 20% FA – UFFA ternary concrete have reduced in the range of 12 – 37% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 37% in initial sorptivity was observed for 20T15UF ternary mix as compared to reference concrete.

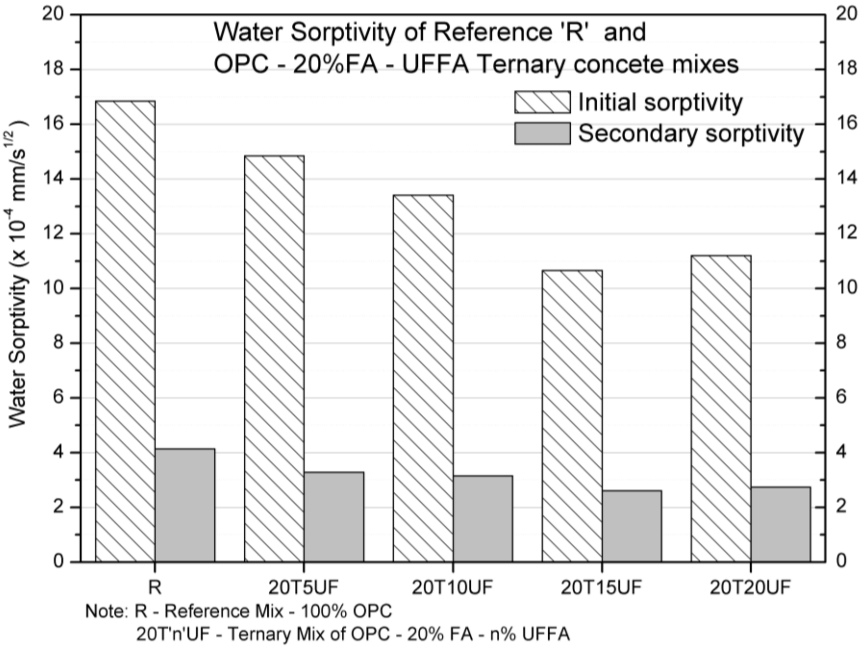


Figure 5.37. Sorptivity of reference and OPC – 20% FA – UFFA ternary concrete mixes.

The secondary sorptivity of OPC – 20% FA - UFFA ternary concrete have reduced in the range of 21 – 37% as compared to that of reference concrete. The maximum reduction of 37% in secondary sorptivity was observed for 20T15UF mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete.

The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash in ternary concrete.

5.9.3 Sorptivity of OPC – 30% FA – UFFA ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete 'R' and ternary concrete with 30% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.38 and appendix B.8. The experimental results shows reduction in sorptivity when fly ash and ultra-fine fly ash are added to form ternary mixtures. The initial sorptivity of OPC – 30% FA – UFFA ternary concrete have reduced in the range of 32 – 56% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 56% in initial sorptivity was observed for 30T15UF ternary mix as compared to reference concrete.

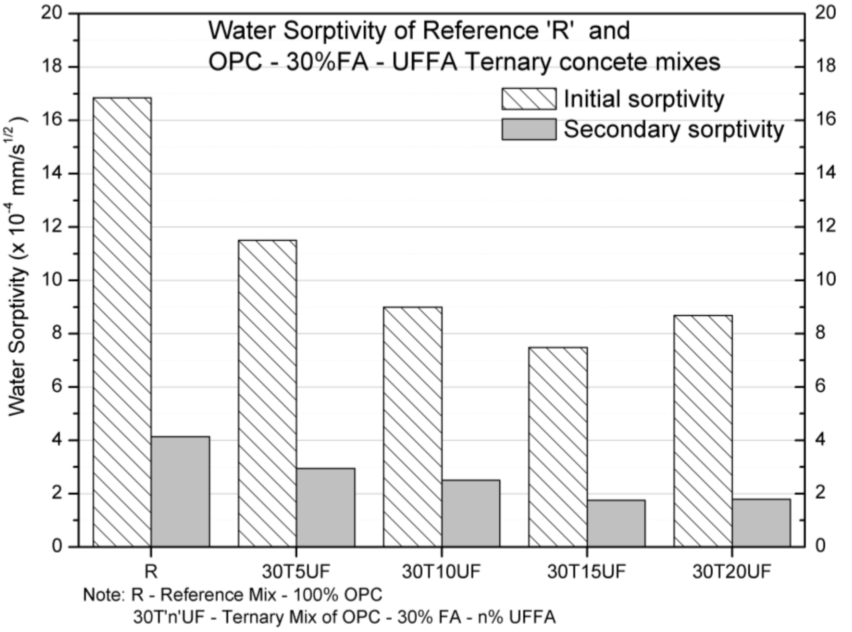


Figure 5.38. Sorptivity of reference and OPC – 30% FA – UFFA ternary concrete mixes.

The secondary sorptivity of OPC – 20% FA - UFFA ternary concrete have reduced in the range of 29 – 58% as compared to that of reference concrete. The maximum reduction of 58% in secondary sorptivity was observed for 30T15UF mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash in ternary concrete.

5.9.4 Sorptivity of OPC – 40% FA – UFFA ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete 'R' and ternary concrete with 40% fly ash and 5 – 20% ultra-fine fly ash is presented in Figure 5.39 and appendix B.8. The experimental results shows reduction in sorptivity when fly ash and ultra-fine fly ash are added to form ternary mixtures. The initial sorptivity of OPC – 40% FA – UFFA ternary concrete have reduced in the range of 28 – 51% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 51% in initial sorptivity was observed for 40T15UF ternary mix as compared to reference concrete.

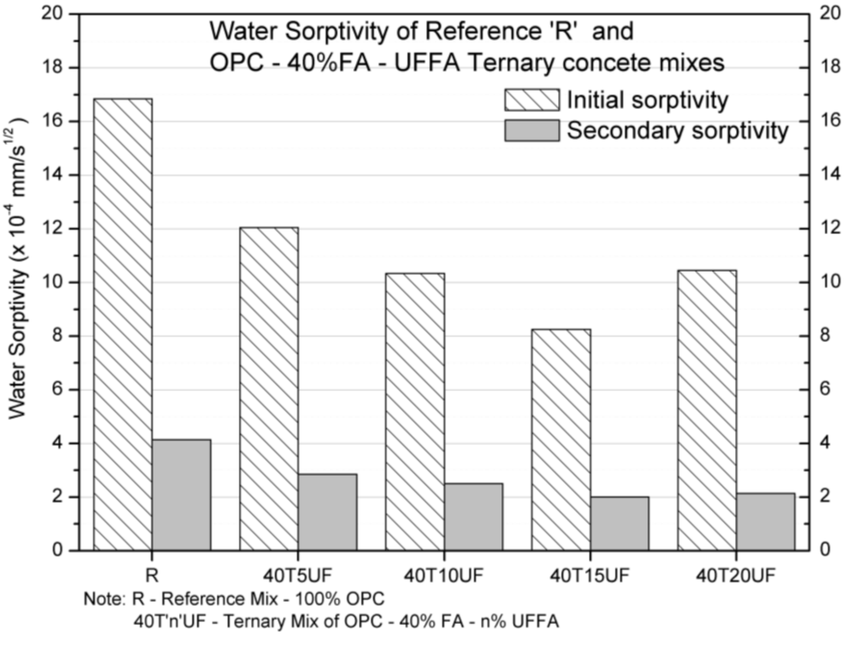


Figure 5.39. Sorptivity of reference and OPC – 40% FA – UFFA ternary concrete mixes.

The secondary sorptivity of OPC – 40% FA - UFFA ternary concrete have reduced in the range of 31 – 51% as compared to that of reference concrete. The maximum reduction of 51% in secondary sorptivity was observed for 40T15UF mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine fly ash in ternary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine fly ash in ternary concrete.

5.9.5 Sorptivity of OPC – 20% FA – UFS ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete 'R' and ternary concrete with 20% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.40 and appendix B.9. The experimental results shows reduction in sorptivity when fly ash and ultra-fine slag are added to form ternary mixtures. The initial sorptivity of OPC – 20% FA – UFS ternary concrete have reduced in the range of 19 – 39% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 39% in initial sorptivity was observed for 20T15US ternary mix as compared to reference concrete.

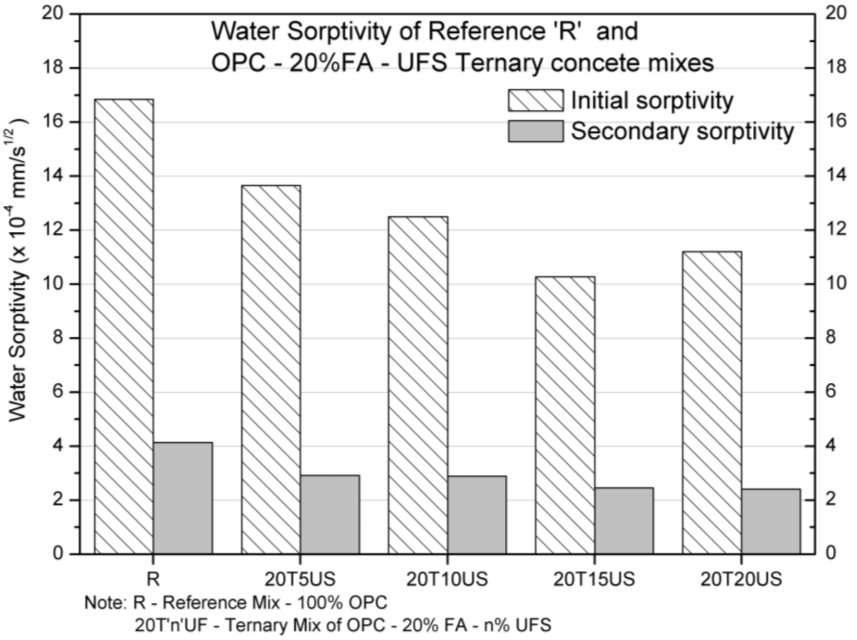


Figure 5.40. Sorptivity of reference and OPC – 20% FA – UFS ternary concrete mixes.

The secondary sorptivity of OPC – 20% FA - UFS ternary concrete have reduced in the range of 29 – 42% as compared to that of reference concrete. The maximum reduction of 42% in secondary sorptivity was observed for 20T20US mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag in ternary concrete.

5.9.6 Sorptivity of OPC – 30% FA – UFS ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete 'R' and ternary concrete with 30% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.41 and appendix B.9. The experimental results shows reduction in sorptivity when fly ash and ultra-fine slag are added to form ternary mixtures. The initial sorptivity of OPC – 30% FA – UFS ternary concrete have reduced in the range of 36 – 61% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 61% in initial sorptivity was observed for 30T15US ternary mix as compared to reference concrete.

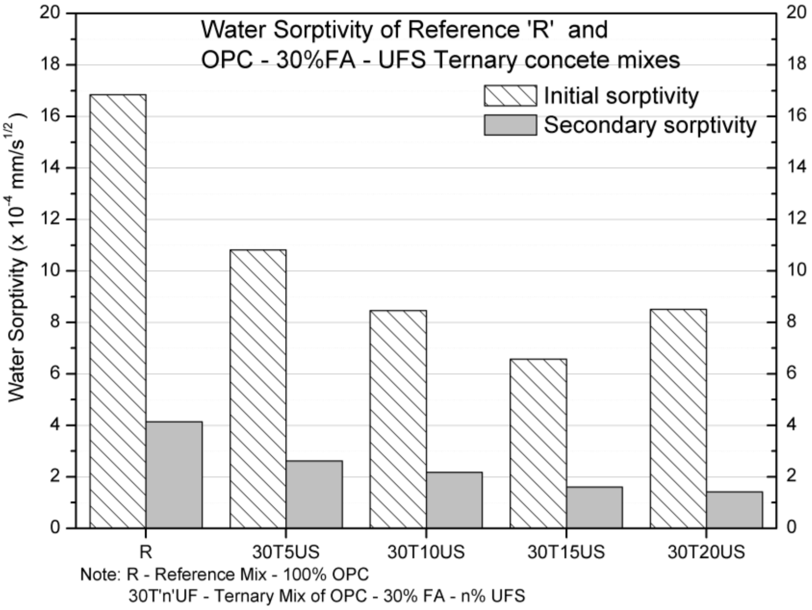


Figure 5.41. Sorptivity of reference and OPC – 30% FA – UFS ternary concrete mixes.

The secondary sorptivity of OPC – 30% FA - UFS ternary concrete have reduced in the range of 37 – 66% as compared to that of reference concrete. The maximum reduction of 66% in secondary sorptivity was observed for 30T20US mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag in ternary concrete.

5.9.7 Sorptivity of OPC – 40% FA – UFS ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete ‘R’ and ternary concrete with 40% fly ash and 5 – 20% ultra-fine slag is presented in Figure 5.42 and appendix B.9. The experimental results shows reduction in sorptivity when fly ash and ultra-fine slag are added to form ternary mixtures.

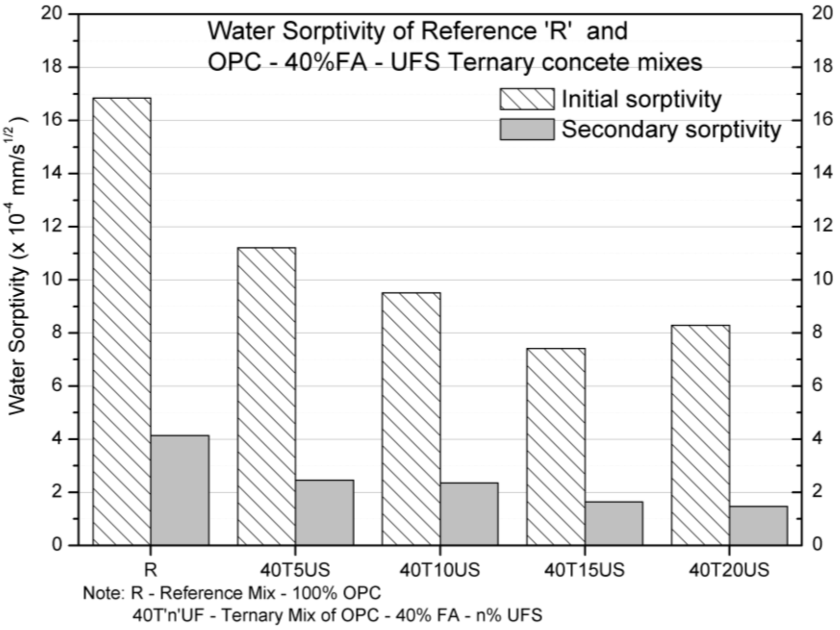


Figure 5.42. Sorptivity of reference and OPC – 40% FA – UFS ternary concrete mixes.

The initial sorptivity of OPC – 40% FA – UFS ternary concrete have reduced in the range of 33 – 56% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 56% in initial sorptivity was observed for 40T15US ternary mix as compared to reference concrete.

The secondary sorptivity of OPC – 40% FA - UFS ternary concrete have reduced in the range of 41 – 64% as compared to that of reference concrete. The maximum reduction of 64% in secondary sorptivity was observed for 40T20US mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag in ternary concrete.

5.9.8 Sorptivity of OPC – 50% FA – UFS ternary concrete mixes

The results of initial and secondary sorptivity of reference concrete ‘R’ and ternary concrete with 50% fly ash and 5 – 15% ultra-fine slag is presented in Figure 5.43 and appendix B.9.

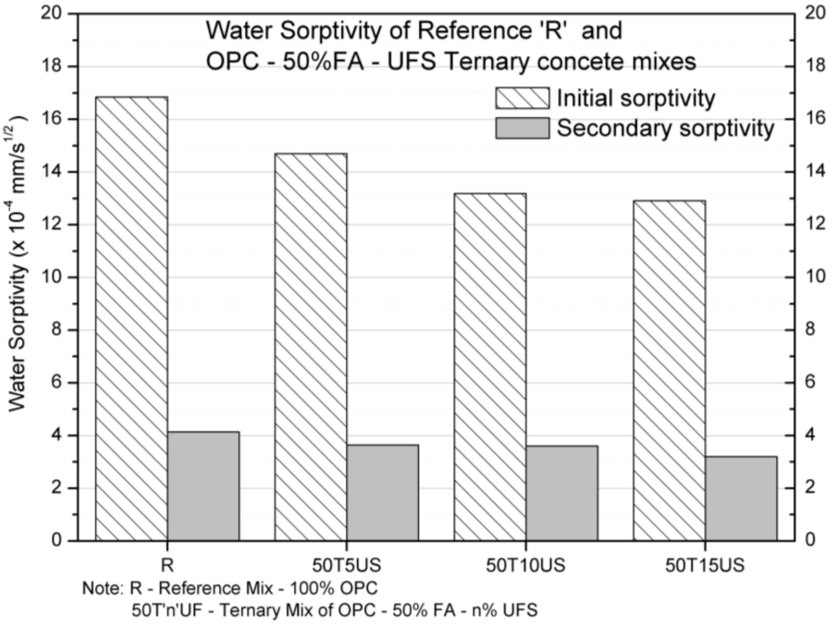


Figure 5.43. Sorptivity of reference and OPC – 50% FA – UFS ternary concrete mixes.

The experimental results shows reduction in sorptivity when fly ash and ultra-fine slag are added to form ternary mixtures. The initial sorptivity of OPC – 50% FA –

UFS ternary concrete have reduced in the range of 13 – 23% as compared to that of reference concrete. Among all ternary mixes, the maximum reduction of 23% in initial sorptivity was observed for 50T20US ternary mix as compared to reference concrete.

The secondary sorptivity of OPC – 50% FA - UFS ternary concrete have reduced in the range of 12 – 23% as compared to that of reference concrete. The maximum reduction of 23% in secondary sorptivity was observed for 50T20US mix as compared to reference concrete. Overall it was observed that, the initial and secondary sorptivity have reduced significantly due to addition of fly ash and ultra-fine slag in ternary concrete. The improvement in resistance to water absorption is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash and ultra-fine slag in ternary concrete.

5.9.9 Discussion on sorptivity of concrete mixes

The initial and secondary sorptivity has reduced for all binary and ternary concrete mixes using ultra-fine fly ash and ultra-fine slag. Previous research (Alaghebandian et al., 2020; Mehta and Siddique, 2018; Muthadhi and Kothandaraman, 2013; Sharmila and Dhinakaran, 2016) have also observed the reduction in water sorptivity due to addition of pozzolanic materials. UFFA and UFS in ternary mixture has refined the pore structure resulting in dense and compact microstructure. The refinement of pore structure have resulted in less inter connected voids and capillaries. This has collectively reduced the sorptivity of ternary concrete mixes.

5.10 Volume of permeable voids in concrete

The volume of permeable voids of concrete is determined based on provisions of ASTM C 642 – 13. Specimens of desired size i.e. 50 mm thick slice of 100 mm diameter cylinder is cut from cast cylinder (200 mm cylinder with 100 mm diameter). Specimen is observed for oven dry mass, saturated mass after immersion, saturated mass after boiling and immersed apparent mass. Volume of permeable voids is then calculated as per procedure recommended by code. Two identical samples are tested for a typical category and the calculated mean value is noted as volume of permable voids of that specified category. The volume of void in reference concrete ‘R’ was observed as 14.5%. Figure 5.44 shows typical steps for measurement of volume of permeable voids in concrete.

(a) Specimen ready for drying in oven (b) Specimen being dried in oven

(c) saturated specimens under boiling condition

(d) saturated specimen after boiling (e) immersed apparent mass

Figure 5.44. Measurement of volume of voids in concrete.

5.10.1 Volume of voids in OPC – FA binary concrete mixes

The volume of voids of reference and binary concrete with 20%, 30% and 40% of fly ash is presented in Figure 5.45 and appendix B.7.

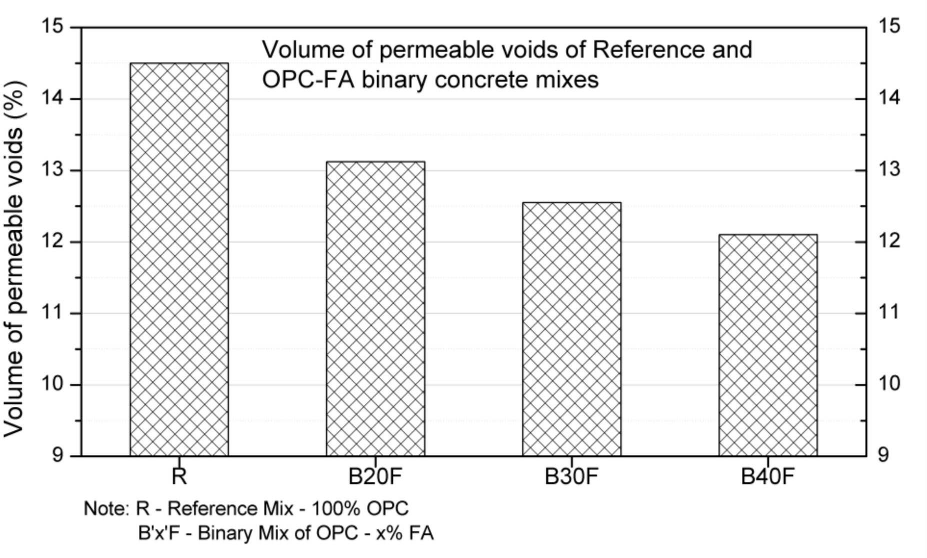


Figure 5.45. Volume of voids in reference and OPC – FA binary concrete mixes.

The experimental results shows reduction in void volume when fly ash is added in binary mixtures. The volume of voids of binary mix is found to reduce by 10 – 17% as compared to volume of voids of reference concrete. A maximum improvement of 17% was observed by B40F binary mix in void volume.

Overall it was observed that the volume of voids have reduced with the use of fly ash in binary mixes. The reduction in volume of voids is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash in binary concrete.

5.10.2 Volume of voids in OPC – FA – UFFA ternary concrete mixes

The volume of voids in reference mix ‘R’ and OPC – (20 – 40%) FA – (5 – 20%) UFFA ternary concrete mixes is presented in Figure 5.46 and appendix B.8. The experimental results shows reduction in void volume for UFFA based ternary mixtures.

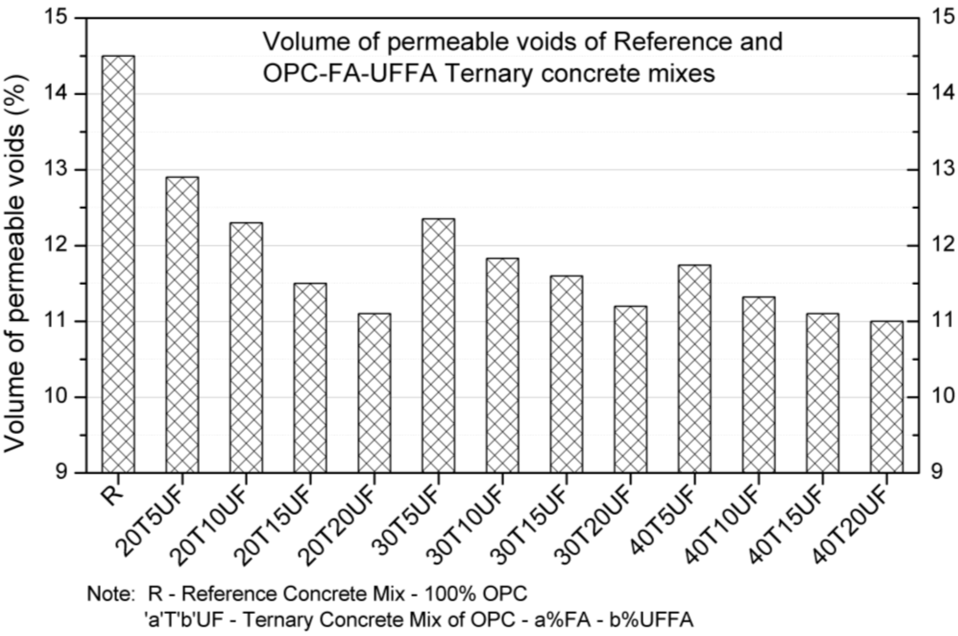


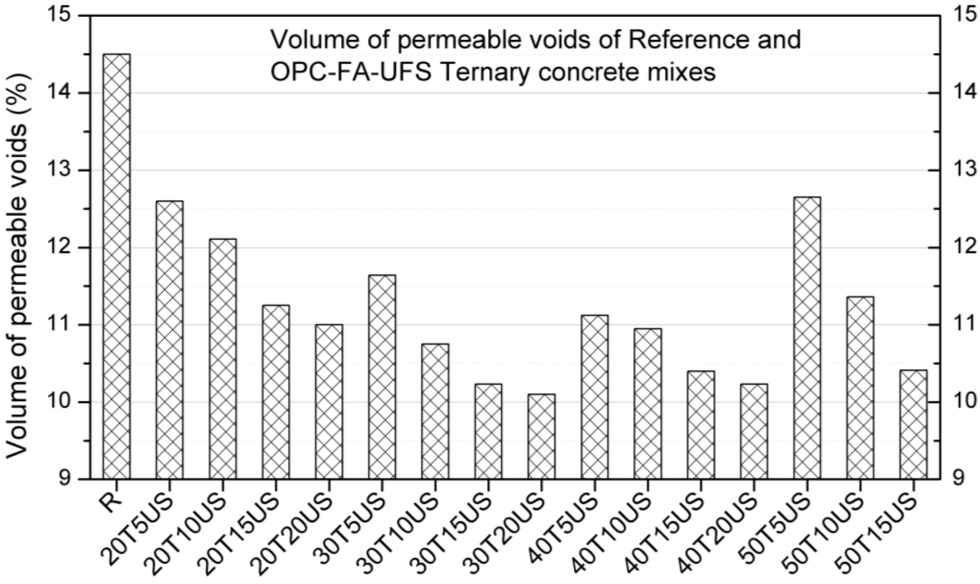
Figure 5.46. Volume of voids of reference and OPC – FA – UFFA ternary concrete mixes.

For ternary mixtures with 20% of constant FA, i.e. OPC – 20% FA – UFFA mixes, reduction in volume of voids is 11 - 23% as compared to that of reference concrete. The highest reduction of 23% in volume of voids was shown by 20T20UF. For ternary mixtures with 30% of constant FA, i.e. OPC – 30% FA – UFFA mixes, reduction in volume of voids is 15 - 23% as compared to that of reference concrete. The highest reduction of 23% in volume of voids was shown by 30T20UF.

For ternary mixtures with 40% of constant FA, i.e. OPC – 40% FA – UFFA mixes, reduction in volume of voids is 19 - 24% as compared to that of reference concrete. The highest reduction of 24% in volume of voids was shown by 40T20UF. Overall it was observed that the volume of voids have reduced with the use of fly ash in binary mixes. The reduction in volume of voids is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash in binary concrete.

5.10.3 Volume of voids in OPC – FA – UFS ternary concrete mixes

The volume of voids in reference mix ‘R’ and OPC – (20 – 50%) FA – (5 – 20%) UFS ternary concrete mixes is presented in Figure 5.47 and appendix B.9. The experimental results shows reduction in void volume for UFS based ternary mixtures. For ternary mixtures with 20% of constant FA, i.e. OPC – 20% FA – UFS mixes, reduction in volume of voids is 13 - 24% as compared to that of reference concrete. The highest reduction of 24% in volume of voids was shown by 20T20US. For ternary mixtures with 30% of constant FA, i.e. OPC – 30% FA – UFS mixes, reduction in volume of voids is 20 - 30% as compared to that of reference concrete. The highest reduction of 30% in volume of voids was shown by 30T20US.



Note: R - Reference Concrete Mix - 100% OPC
'a'T'b'US - Ternary Concrete Mix of OPC - a%FA - b%UFS

Figure 5.47. Volume of voids of reference and OPC – FA – UFFA ternary concrete mixes.

For ternary mixtures with 40% of constant FA, i.e. OPC – 40% FA – UFS mixes, reduction in volume of voids is 23 - 29% as compared to that of reference concrete. The highest reduction of 29% in volume of voids was shown by 40T20US. For ternary mixtures with 50% of constant FA, i.e. OPC – 50% FA – UFS mixes, reduction in volume of voids is 13 - 28% as compared to that of reference concrete. The highest reduction of 28% in volume of voids was shown by 50T15US.

Overall it was observed that the volume of voids have reduced with the use of fly ash in binary mixes. The reduction in volume of voids is attributable to refinement in pore structure resulting in denser and compact microstructure due to addition of fly ash in binary concrete.

5.10.4 Discussion on volume of permeable voids of concrete mixes

The volume of permeable voids has reduced for all binary and ternary concrete mixes using ultra-fine fly ash and ultra-fine slag. Previous research (Chen et al., 2020; Saloni et al., 2020) have also observed the reduction in water sorptivity due to addition of pozzolanic materials. UFFA and UFS in ternary mixture has refined the pore structure resulting in dense and compact microstructure. The refinement of pore structure have resulted in less inter connected voids and capillaries. This has collectively reduced the voids in ternary concrete mixes.

5.11 Summary

This chapter presents the results of mechanical and durability properties of binary and ternary concrete mixes. Three binary mixes and 27 ternary mixes were investigated in different binder combinations. Workability, compressive strength at 3, 7, 28, 56 and 90 days, split tensile strength and flexural strength were examined as part of mechanical parameters. With regards to durability characteristics, the chloride migration coefficients at 7, 28 and 90 days, water permeability at 28 and 90 days, initial and secondary sorptivity and volume of permeable voids are investigated for all 31 concrete mixes.

The workability of concrete was found to increase with addition of fly ash and ultra-fine fly ash in binary and ternary concrete. However the workability have reduced in ultra-fine slag based concrete mixes. The compressive strength, flexural strength and split tensile strength has improved due to addition of UFFA and UFS in ternary mixes. Similar improvement was observed in all durability characteristics for ternary mixes. The enhancement in properties of concrete is attributable to ultra-fine particle size of UFFA and UFS. The high pozzolanic reactivity of UFFA and UFS imparts better mechanical strength. The filler and pozzolanic effect of UFFA and UFS has resulted in denser and compact microstructure of ternary concrete. For all the measured properties, UFS blended mixtures have shown better results as compared to UFFA blended mixtures.

Chapter 6

Cost Analysis and Optimization of Concrete Mixes

6.1 General

The present chapter discuss the cost analysis of reference, binary and ternary concrete mixes. The analysis is performed based on commercial rates of different binders, aggregates and admixtures. Optimization of concrete mixes are performed in order to get the best concrete mix with regards to performance criteria. The multi criteria optimization techniques were used in the present study are 1. Grey Relational Analysis (GRA), 2. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and 3. Desirability Function Approach (DFA). The measured properties such as compressive strength, tensile strength, chloride migrations coefficient, water permeability, sorptivity, volume of voids and cost are the performance indicators used in the optimization methods.

6.2 Cost analysis of concrete mixes

The cost of concrete for reference, OPC – FA binary mixes and OPC – FA – UFFA/UFS ternary mixes are computed based on prevailing market rates of materials. The cost of different binders such as ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag, coarse and fine aggregates, admixtures and water are presented in Table 6.1.

Table 6.1. Cost of binders, aggregates, admixture and water used in analysis.

Ingredient	Cost
Ordinary Portland Cement (ACC 53 Grade)	Rs. 7500 per MT
Fly ash (Dirk P60)	Rs. 2500 per MT
Ultra-fine fly ash (Dirk P100)	Rs. 12500 per MT
Ultra-fine slag (Alccofine 1203)	Rs. 12500 per MT

Coarse aggregate	Rs. 1400 per MT
Fine aggregate	Rs. 1000 per MT
Admixtures (CAC superplasticizer)	Rs. 150 per kg
Water	Rs. 25 per 1000 litres

The cost of concrete is obtained by considering the market rates of ingredients and their respective proportion in concrete mix design. The cost of reference concrete ‘R’ is found to be Rs. 5639.1 per m^3 as presented in Table 6.2.

Table 6.2. Mix proportion and cost analysis of reference concrete ‘R’.

Ingredient	Quantity	Cost
OPC	375 kg/m^3	375 kg × Rs. 7.5 per kg = Rs. 2812.5 per m^3
Coarse aggregate	1345 kg/m^3	1345 kg × Rs. 1.4 per kg = Rs. 1883 per m^3
Fine aggregate	715 kg/m^3	715 kg × Rs. 1.0 per kg = Rs. 715 per m^3
Admixtures	1.5 kg/m^3	1.5 kg × Rs. 150 per kg = Rs. 225 per m^3
Water	142.5 kg/m^3	142.5 kg × Rs. 0.025 per kg = Rs. 3.56 per m^3
Total		Rs. 5639.1 per cubic metre of concrete

6.2.1 Cost analysis of OPC – FA binary concrete mixes

The cost of concrete for reference mix ‘R’ and OPC – FA binary mixes with 20%, 30% and 40% of fly ash as OPC replacement are presented in annexure B.1. The cost of all OPC – FA binary mixes is found to be less as compared to reference mix. The cost of binary mixtures are normalized with respect to cost of reference concrete and are presented in Figure 6.1. The relative cost of reference concrete ‘R’ is 1.00 and the relative cost of all binary concrete mixes are less than one. The reduction in cost of OPC – FA concrete mixtures are due to cheaper cost of fly ash as compared to OPC.

The cost of binary mixtures are 7.2 – 14.4% cheaper as compared to reference mix. The lowest cost is achieved by B40F, which is 14.4% cheaper as compared to cost of reference mix.

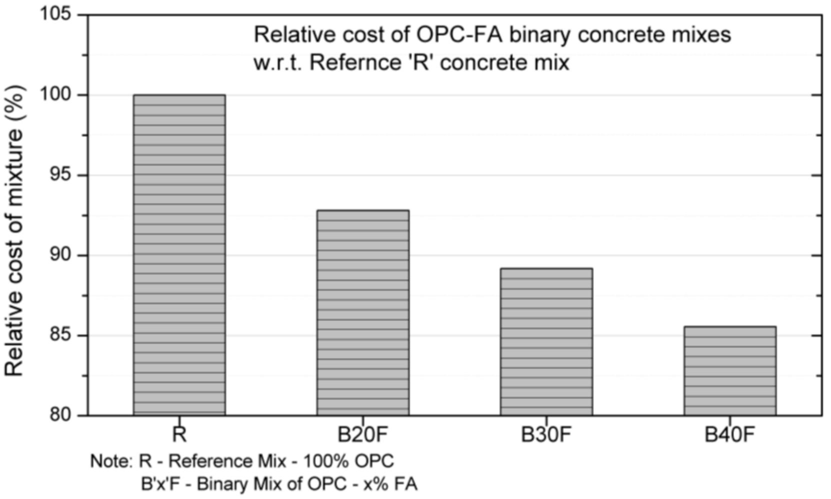


Figure 6.1. Relative cost of reference and OPC – FA binary concrete mixes.

6.2.2 Cost analysis of OPC – FA – UFFA ternary concrete mixes

The cost of concrete for reference and OPC – (20 – 40%) FA – (5 – 20%) UFS ternary concrete mixes is presented in appendix B.2. The cost of all OPC – FA – UFFA ternary mixes are found to be less as compared to reference mix. The cost of all ternary mixtures are normalized with respect to cost of reference concrete and are presented in Figure 6.2. The relative cost of reference concrete 'R' is 1.00 and the relative cost of all ternary concrete mixes are less than one. The reduction in cost of OPC – FA concrete mixtures are due to cheaper cost of fly ash as compared to OPC. however as the cost of UFFA is more as compared to that of OPC, the cost of concrete increases when UFFA content is increased.

The cost of ternary mix OPC – 20% FA – UFFA are 1.1 – 5.7% cheaper as compared to reference mix. The lowest cost is shown by 20T5UF with a reduction of 5.7%. In the case of OPC – 30% FA – UFFA, the cost have reduced in the range of 4.7 – 9.3% as compared to reference mix. The lowest cost is shown by 30T5UF with a reduction of 9.3%. In the case of OPC – 40% FA – UFFA, the cost have reduced in the range of 8.3 – 12.9% as compared to reference mix. The lowest cost is shown by 40T5UF with a reduction of 12.9%. Overall the cost of concrete reduces with increment in fly ash as it is cheaper than OPC. Also, for a constant FA content, the cost of concrete increases with the increment in UFFA content, as it is expensive than OPC.

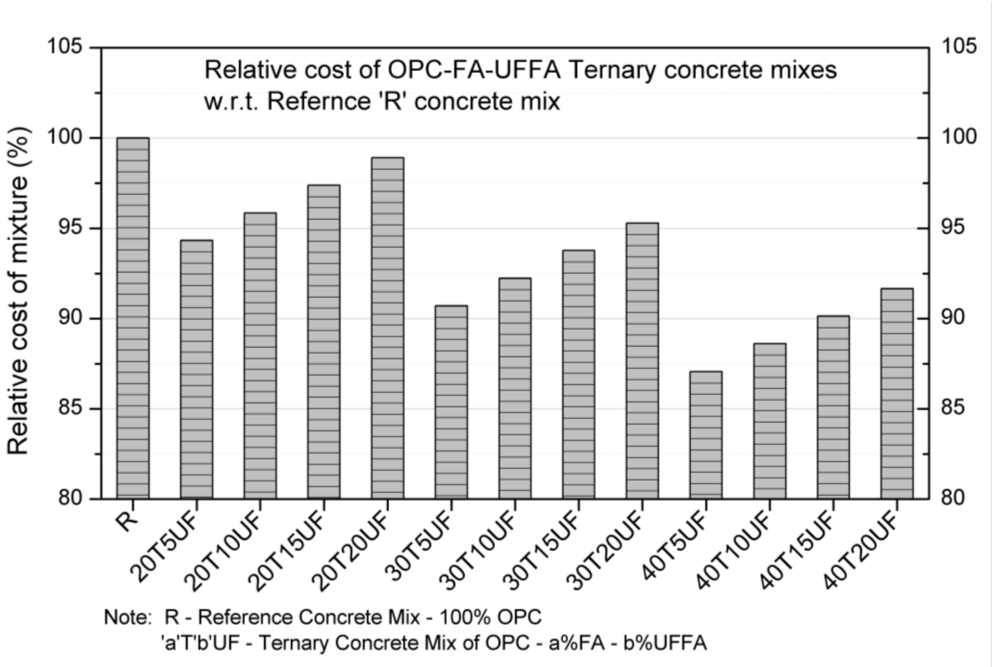


Figure 6.2. Relative cost of reference and OPC – FA – UFFA ternary concrete mixes.

6.2.3 Cost analysis of OPC – FA – UFS ternary concrete mixes

The cost of concrete for reference and OPC – (20 – 50%) FA – (5 – 20%) UFS ternary concrete mixes is presented in appendix B.3. The cost of all OPC – FA – UFS ternary mixes are found to be less as compared to reference mix. The cost of all ternary mixtures are normalized with respect to cost of reference concrete and are presented in Figure 6.3. The relative cost of reference concrete ‘R’ is 1.00 and the relative cost of all ternary concrete mixes are less than one. The reduction in cost of OPC – FA concrete mixtures are due to cheaper cost of fly ash as compared to OPC. However as the cost of UFS is more as compared to that of OPC, the cost of concrete increases when UFFA content is increased.

The cost of ternary mix OPC – 20% FA – UFS are 0.7 – 5.6% cheaper as compared to reference mix. The lowest cost is shown by 20T5US with a reduction of 5.6%. In the case of OPC – 30% FA – UFS, the cost have reduced in the range of 4.3 – 9.2% as compared to reference mix. The lowest cost is shown by 30T5US with a reduction of 9.2%. In the case of OPC – 40% FA – UFS, the cost have reduced in the range of 8.0 – 12.8% as compared to reference mix. The lowest cost is shown by 40T5US with a reduction of 12.8%. In the case of OPC – 50% FA – UFS, the cost have reduced in the range of 13.2 – 16.5% as compared to reference mix. The lowest cost is shown by 50T5US with a reduction of 16.5%. Overall the cost of concrete reduces with increment in fly ash as it is cheaper than OPC. Also, for a constant FA content, the cost of concrete increases with the increment in UFS content, as it is expensive than OPC.

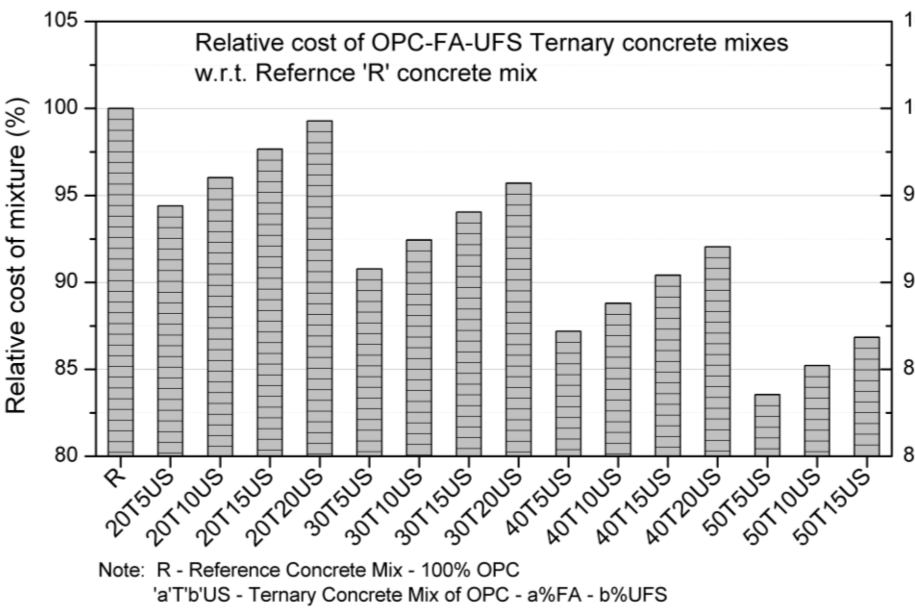


Figure 6.3. Relative cost of reference and OPC – FA – UFS ternary concrete mixes.

6.3 Optimization of concrete

The optimization methods are used to rank the alternatives based on multiple responses. In the present study there are 31 different concrete mix proportions studied for various responses. The responses include, compressive strength, split tensile strength, flexural strength as part of mechanical properties. Durability properties include coefficient of chloride migrations, water permeability, water sorptivity and volume of voids in concrete. Another important aspect considered in the present investigation is cost of concrete. In order to rank different concrete mixes with regards to these observed parameters, three optimization methods are used. Measured mechanical and durability properties and cost are the input parameters in these methods.

The measured parameter or response are desired to be higher or lower depending on its feature. The parameter/response and their desired target values are as shown in

Table 6.3. The compressive strengths at 3 days, 7 days, 28 days, 56 days, and 90 days are designed as C3, C7, C28, C56 and C90. The flexural strength and split tensile strengths are symbolised as FS and STS. Compressive strength, flexural strength and split tensile strengths are desired to be higher for any concrete mix and hence are under ‘higher the better’ criteria.

Table 6.3. Selected response, symbol and their target criteria for optimization.

Sr. No.	Symbol	Selected response	Criteria
Mechanical Properties			
1	C3	Compressive strength at 3 days (MPa)	Higher the better
2	C7	Compressive strength at 7 days (MPa)	Higher the better
3	C28	Compressive strength at 28 days (MPa)	Higher the better
4	C56	Compressive strength at 56 days (MPa)	Higher the better
5	C90	Compressive strength at 90 days (MPa)	Higher the better
6	FS	Flexural strength (MPa)	Higher the better
7	STS	Split tensile strength (MPa)	Higher the better
Durability Properties			
8	WP28	Water permeability at 28 days (mm)	Lower the better
9	WP90	Water permeability at 90 days (mm)	Lower the better
10	CM7	Chloride migration coefficient, D_7 x 10^{-12} m^2/s	Lower the better
11	CM28	Chloride migration coefficient, D_{28} x 10^{-12} m^2/s	Lower the better
12	CM90	Chloride migration coefficient, D_{90} x 10^{-12} m^2/s	Lower the better
13	IS	Initial Sorptivity (× 10^{-4} mm/$s^{1/2}$)	Lower the better
14	SS	Secondary Sorptivity (× 10^{-4} mm/$s^{1/2}$)	Lower the better
15	PV	Volume of permeable voids (%)	Lower the better
Cost			
16	CO	Cost of concrete	Lower the better

Depth of water penetration or water permeability at 28 days and 90 days are designated as WP28 and WP 90, respectively. The coefficient of chloride migration at 7 days, 28 days and 90 days are symbolised as CM7, CM28 and CM90, respectively. Initial sorptivity and secondary sorptivity are designated as IS and SS, respectively. The volume of permeable voids and cost of concrete are symbolised as PV and CO, respectively. All the durability parameters and cost are desired to be lower for any concrete mix and hence are under ‘lower the better’ criteria. The measured properties/responses are tabulated in appendix C.1 for reference, binary and ternary concrete mixes. These responses are common input parameter for all three optimization methods discussed in the subsequent sections.

6.3.1 Taguchi - Grey relational analysis (GRA)

To determine the optimum combination for 16 observed parameters, grey relational analysis (GRA) can be used as it have evolved to be one of the highest influential method for multi objective optimization problems. The multi-characteristic objective problem can be transformed into a single objective problem through GRA, and then the optimum setting of parameters can be determined. The steps involved in GRA are well documented in available literature (Arıcı et al., 2021; Arıcı and Keleştemur, 2019; Gopal and Soorya Prakash, 2018a; Lai et al., 2012; Ramu et al., 2018; Singh et al., 2016; Suji et al., 2021) and are as follows:

a) Normalization of the measured responses

The measured parameters or responses are to be normalised depending on its feature. Normalisation is done in order to distribute and scale the response in an acceptable range (Mercy et al., 2017). The normalization of the responses are performed based on Eq. (1) and Eq. (2) presented below (Ajith Arul Daniel et al., 2019; Chang et al., 2011; Narong et al., 2018; Prusty and Pradhan, 2020).

$$Z_{uv} = \frac{x_{uv} - min(x_{uv})}{max(x_{uv}) - min(x_{uv})} \tag{1}$$

$$Z_{uv} = \frac{max(x_{uv}) - x_{uv}}{max(x_{uv}) - min(x_{uv})} \tag{2}$$

Where, where, Z_{uv} is the normalised ratio of the uth experiment for vth response, i.e. for x_{uv}, and is obtained from experimental results. $min(x_{uv})$ and $max(x_{uv})$ are the minimum and maximum values from the experiment, respectively.

Equation (1) is used when the criteria for response is ‘higher the better’. Mechanical strengths such as compressive, split tensile and flexural strength are desired to be higher for any combination, hence they follow ‘higher the better’ criteria. Therefore, normalization of CS3, CS7, CS28, CS56, CS90, FS and STS are computed based on Eq. (1). For example, in a particular case, B20F represents as uth experiment, and CS3 is one of the measured vth response of this concrete combination. The normalised value for this will be computed based on x_{uv} as equal to 26.1, i.e. CS3 of B20F, $min(x_{uv})$ as equal to 11.5 i.e. minimum value all CS3 considering all concrete mixes, and $max(x_{uv})$ as equal to 32.1 i.e. maximum value all CS3 considering all concrete mixes. Computing the value of Z_{uv} as 0.71 as per Eq. (1). Hence, the normalized value of CS3 for B20F is 0.71. The normalized values for any response will have values between 0 and 1. Zero is for least desirable combination and 1 is for most desirable combination as regards the chosen response.

Similarly, Eq. (2) is used when the criteria for response is 'lower the better'. Cost of concrete and durability properties such as chloride migration coefficient, water penetration depth, sorptivity, volume of voids are desired to be lower for any combination, hence they follow 'lower the better' criteria. Therefore, normalization of WP28, WP90, CM7, CM28, CM90, IS, SS and CO are computed based on Eq. (2). For example, in a particular case, B30F represents as uth experiment, and SS is one of the measured vth response of this concrete combination. The normalised value for this will be computed based on x_{uv} as equal to 3.57, i.e. SS of B30F, $min(x_{uv})$ as equal to 1.41 i.e. minimum value all SS considering all concrete mixes, and $max(x_{uv})$ as equal to 4.14 i.e. maximum value all SS considering all concrete mixes. Computing the value of Z_{uv} as 0.21 as per Eq. (2). Hence, the normalized value of SS for B30F is 0.21. The normalized values for any response will have values between 0 and 1. Zero is for least desirable combination and 1 is for most desirable combination as regards the chosen response. The normalised value of all concrete mixes for all measured parameters are computed and presented in appendix C.2.

b) Computation of Grey relational coefficient

The next step is to compute the Grey Relational Coefficient (GRC) from the normalised responses using Eq. (3) (Prusty and Pradhan, 2020).

$$GRC_{uv} = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{0uv} + \xi \Delta_{max}} \tag{3}$$

Where, GRC_{uv} represents the grey relational coefficient of uth experiment for vth response. Δ_{0uv} is the difference between idealised value of normalised ratio (Z_{0v}) i.e 1.0 and the computed normalised ratio (Zuv) of a particular response. Δ_{max} and Δ_{min} are the maximum and minimum values of Δ. ξ is defined as a distinguishing coefficient. Its values lie anywhere between 0 and 1. The value of ξ is chosen as 0.5 (Chang et al., 2011; Kuo et al., 2008; Narong et al., 2018; Prusty and Pradhan, 2020).

For example, in order to compute the grey relational coefficient of B30F for the selected response SS, Δ_{0uv} will be equal to 1.00 – 0.21 = 0.79, Δ_{max} and Δ_{min} are 1.0 and 0.0, respectively. The computed value of GRC for this response using Eq. (3) will equal to 0.39. The grey relational coefficients (GRC) of all concrete mixes for all measured parameters are computed and presented in appendix C.3.

c) Computation of Grey relational grade

The final step is to compute grey relational grade (GRG) of each concrete mixture corresponding to all measured parameter. GRG is calculated using Eq. (4) Shown below.

$$GRG_u = \sum_{v=1}^{n} \omega_v GRC_{uv} \tag{4}$$

Where, GRG_u is the grey relational grade of uth experiment, ω_v is normalised weight of vth response. Additionally, $\sum_{v=1}^{n} \omega_v$ is equal to one. In this study, equal weight was assigned to all the selected parameters and hence the value of ω_v is equal to 1/16 (Kuo et al., 2008; Narong et al., 2018; Prusty and Pradhan, 2020). The grey relational grade of all concrete mixes are accordingly computed and are presented in Table 6.4.

The higher value of grey relation grade represents desirable mixture combination with regards to selected parameters. Hence, ranking of mixtures are done as per value of GRG. The ranking of all concrete mixtures are also presented in Table 6.4. Rank 1 is awarded to the 30T15US as the best mixture combination with the highest GRG of 0.954. In this particular combination, OPC is 55%, FA is 30% and UFS is 15%. This 30T15US combination saves 45% of OPC and is able to give significantly better mechanical and durability results as compared to any of the tested concrete mixes. The reference concrete ‘R’ has the least rank as 31, with lowest GRG of 0.440.

The 2nd and 3rd rank is achieved by 30T10US and 30T15UF with a GRG of 0.840 and 0.833, respectively. The 4th and 5th rank is achieved by 30T20US and 30T5UF with a GRG of 0.803 and 0.770, respectively. It is generally observed that OPC – FA – UFS ternary mixes have performed better as compared to OPC – FA – UFFA ternary mixes for any common replacement proportions.

Table 6.4. Grey relational grade and GRA ranking of all concrete mixes.

Sl. No.	Mix ID	Grey Relational Grade (GRG)	Rank
1	R	0.440	31
2	B20F	0.550	28
3	B30F	0.592	23
4	B40F	0.571	25
5	20T5UF	0.555	26
6	20T10UF	0.603	22
7	20T15UF	0.649	17
8	20T20UF	0.621	18
9	30T5UF	0.673	13
10	30T10UF	0.736	7
11	**30T15UF**	**0.833**	**3**
12	30T20UF	0.703	10
13	40T5UF	0.580	24
14	40T10UF	0.614	20
15	40T15UF	0.661	15
16	40T20UF	0.610	21
17	20T5US	0.616	19
18	20T10US	0.669	14
19	20T15US	0.724	8
20	20T20US	0.685	11
21	**30T5US**	**0.770**	**5**
22	**30T10US**	**0.840**	**2**
23	**30T15US**	**0.954**	**1**
24	**30T20US**	**0.803**	**4**
25	40T5US	0.649	16
26	40T10US	0.681	12
27	40T15US	0.748	6
28	40T20US	0.710	9
29	50T5US	0.551	27
30	50T10US	0.544	29
31	50T15US	0.542	30

6.3.2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method of optimization is used to find out the best alternate mix satisfying all 16 observed parameters. The steps involved in TOPSIS are well documented in available literature and are as follows (Byun and Lee, 2005; Çakır and Dilbas, 2021;

Gopal and SooryaPrakash, 2018; Hong and Su, 2012; Şimşek et al., 2013; Şimşek and Uygunoğlu, 2016; Su et al., 2010):

a) Computation of normalized values of the measured responses

The measured parameters or responses are normalized with regards to Eq. (5) shown below.

$$s_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} \left(r_{ij}\right)^2}} \tag{5}$$

Where, s_{ij} is the normalized value of j^{th} response of i^{th} experiment. r_{ij} is the j^{th} response of i^{th} experiment. The normalized value of all responses are computed based on this equation. For example, the normalised value of flexural strength of 20T5UF will be computed based on r_{ij} as equal to 5.9, and $\sum_{i=1}^{m}\left(r_{ij}\right)^2$ is the sum of squares of flexural strengths for all concrete mixes, i.e. 1127.73. After computation using Eq. (5), the normalised value of FS for 20T5UF will be equal to 0.18. The normalised value of all responses for each concrete mixes are calculated using Eq. (3) and are presented in appendix C.4.

b) Computation of weighted normalized values of the measured responses

The measured parameters or responses are multiplied with equal weights to compute the weighted normalized responses using Eq. 6.

$$v_{ij} = s_{ij} \times W_j \tag{6}$$

Where, v_{ij} is the normalized value of j^{th} response of i^{th} experiment. W_{ij} is the weight of response. In the present study all responses are assigned an equal weight. The weighted normalized value of all responses are computed based on this equation and are presented in appendix C.5.

c) Computation of positive ideal V^+ and negative ideal V^- solution

The positive ideal and negative ideal solution are identified based on maximum and minimum values of a particular response with regards to all concrete mixes. The positive ideal solution is denoted by V^+ and negative ideal solution by V^-. The positive ideal solution for mechanical strengths are the ones which shows maximum value as the desirable value is higher. Accordingly, the negative ideal solution for mechanical properties are the one with minimum value as lower responses are not desirable. For example V^+ and V^- of CS90 is 0.013 and 0.007, respectively.

In the case of cost and durability parameters, the positive ideal solution are ones which shows minimum value as the desirable value is lower. Accordingly, the negative ideal solution for cost and durability properties are the one with maximum value as higher responses are not desirable in this category of responses. For example V^+ and V^- of WP28 is 0.003 and 0.038, respectively. The positive ideal and negative ideal solution in terms of V^+ and V^- are computed and tabulated in appendix C.5.

d) Closeness of each response from positive ideal and negative ideal solution

The closeness of each response from their positive and negative ideal solution is computed. The closeness of response from positive ideal solution is known as positive solution distance represented by d^+. The closeness of response from negative ideal solution is known as negative solution distance represented by d^-. The values of d^+ and d^- are computed based on Eq. (7) and Eq. (8).

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \tag{7}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \tag{8}$$

The computed values of positive solution distance and negative solution distance in terms of d^+ and d^- are presented in Table 6.5.

e) Computation of closeness coefficient

The closeness coefficient of each concrete mix is computed based on d+ and d- using Eq. (9) as shown below.

$$CC_i = \frac{d^-}{d^+ + d^-} \tag{9}$$

Where, CC_i is the closeness coefficient of the concrete mix. The higher value of closeness coefficient resembles to the alternative as near the desirable responses. The computed values of closeness coefficient of all concrete mixes are accordingly calculated and are presented in Table 6.5.

Table 6.5. Closeness coefficient and TOPSIS ranking of all concrete mixes.

Sl. No.	Mix ID	d^+	d^-	Closeness coefficient (CC)	Rank
1	R	0.0885	0.0128	0.126	31
2	B20F	0.0263	0.0681	0.721	30
3	B30F	0.0235	0.0709	0.751	25
4	B40F	0.0222	0.0732	0.767	23
5	20T5UF	0.0262	0.0688	0.724	29
6	20T10UF	0.0205	0.0751	0.786	22
7	20T15UF	0.0160	0.0784	0.830	16
8	20T20UF	0.0168	0.0782	0.823	18
9	30T5UF	0.0145	0.0789	0.845	14
10	30T10UF	0.0101	0.0826	0.891	8
11	**30T15UF**	0.0044	0.0871	**0.951**	**2**
12	30T20UF	0.0100	0.0822	0.892	7
13	40T5UF	0.0225	0.0702	0.758	24
14	40T10UF	0.0182	0.0743	0.803	20
15	40T15UF	0.0153	0.0766	0.833	15
16	40T20UF	0.0184	0.0742	0.801	21
17	20T5US	0.0182	0.0754	0.806	19
18	20T10US	0.0125	0.0823	0.868	11
19	**20T15US**	0.0088	0.0855	**0.907**	**5**
20	20T20US	0.0108	0.0840	0.886	9
21	30T5US	0.0089	0.0845	0.905	6
22	**30T10US**	0.0057	0.0863	**0.938**	**3**
23	**30T15US**	0.0015	0.0903	**0.984**	**1**
24	**30T20US**	0.0058	0.0861	**0.936**	**4**
25	40T5US	0.0161	0.0765	0.826	17
26	40T10US	0.0133	0.0791	0.856	13
27	40T15US	0.0114	0.0803	0.875	10
28	40T20US	0.0125	0.0802	0.865	12
29	50T5US	0.0247	0.0716	0.744	27
30	50T10US	0.0246	0.0730	0.748	26
31	50T15US	0.0257	0.0744	0.744	28

The higher value of closeness coefficient represents desirable mixture combination with regards to selected parameters. Hence, ranking of mixtures are done as per value of closeness coefficient. The ranking of all concrete mixtures are also presented in Table 6.5.

Rank 1 is awarded to the 30T15US as the best mixture combination with the highest closeness coefficient of 0.984. In this particular combination, OPC is 55%, FA is 30% and UFS is 15%. This 30T15US combination saves 45% of OPC and is able to give significantly better mechanical and durability results as compared to any of the tested concrete mixes. The reference concrete ‘R’ has the least rank as 31, with lowest closeness coefficient of 0.126.

The 2nd and 3rd rank is achieved by 30T15UF and 30T10US with a closeness coefficient of 0.951 and 0.938, respectively. The 4th and 5th rank is achieved by 30T20US and 20T15US with a closeness coefficient of 0.936 and 0.907, respectively. It is generally observed that OPC – FA – UFS ternary mixes have performed better as compared to OPC – FA – UFFA ternary mixes for any common replacement proportions.

6.3.3 Desirability Function Approach (DFA)

To optimize several responses in the present study, a multi criteria optimization technique named Desirability Function Approach is used in the present study. The approach computes a desirability function over a range from 0 to 1. The steps involved in desirability function approach are well documented in the available literature and are as follows (Das and Mishra, 2017; Mesa et al., 2017; Sengul and Tasdemir, 2009a; Şimşek et al., 2018, 2013b; Şimşek and Uygunoğlu, 2018):

a) Computation of desirability function of an individual response

The individual desirability of any response is computed using Eq. (10) and Eq. (11), respectively as shown below (Sengul and Tasdemir, 2009b).

$$d_i = \left[\frac{Y_i - \min f_i}{\max f_i - \min f_i}\right]^t \qquad (10)$$

$$d_i = \left[\frac{\max Y_i - Y_i}{\max f_i - \min f_i}\right]^t \qquad (11)$$

Where d_i, Y_i, $\min f_i$ and $\max f_i$ are individual desirability function, the measured, the lowest, and the highest value of the ith response included in the optimization, respectively (Sengul and Tasdemir, 2009). The power value t is the weighting factor of the i^{th} response. The value of t in the present study is equal to one for all measured response.

Eq. (10) is used for parameters which follows ‘higher the better’ criteria. Compressive strength, split tensile strength and flexural strengths are expected to be higher and hence Eq. (10) is used to compute the desirability of these responses. For example, the desirability function of CS28 for 40T15US is calculated using Y_i = 53.6, *min* f_i = 28.1 and *max* f_i = 62.4. The computed desirability value of CS28 for 40T15US from Eq. (10) is 0.74. Similarly, the desirability of CS3, CS7, CS28, CS56, CS90, FS and STS are calculated and presented in appendix C.6.

Eq. (11) is used for parameters which follows 'lower the better' criteria. Cost and durability parameters are expected to be lower and hence Eq. (11) is used to compute the desirability of these responses. For example, the desirability function of PV for 20T10UF is calculated using Y_i = 12.3, *min* f_i = 10.1 and *max* f_i = 14.5. The computed desirability value of PV for 20T10UF from Eq. (11) is 0.50. Similarly, the desirability of WP28, WP90, CM7, CM28, CM90, IS, SS, PV and CO are calculated and presented in appendix C.6.

b) Computation of overall desirability function

The overall desirability function (D) for all concrete mixes are computed using Eq. (12). This computation is a geometric mean of individual desirability functions d_i. The optimal solution will be the one with maximum value of D which ranges between 0 and 1.

$$D = (d_1 \times d_2 \times d_3 \times \ldots \times d_n)^{1/n} \tag{12}$$

Where, n = number of responses. The higher value of overall desirability function resembles to the alternative as near the desirable responses. The computed values of overall desirability function of all concrete mixes are accordingly calculated and are presented in Table 6.6. The higher value of desirability function represents desirable mixture combination with regards to selected parameters. Hence, ranking of mixtures are done as per value of overall desirability function. The ranking of all concrete mixtures are also presented in Table 6.6.

Rank 1 is awarded to the 30T15US as the best mixture combination with the highest overall desirability function of 0.932. In this particular combination, OPC is 55%, FA is 30% and UFS is 15%. This 30T15US combination saves 45% of OPC and is able to give significantly better mechanical and durability results as compared to any of the tested concrete mixes. The reference concrete 'R' has the least rank as 30, with lowest overall desirability function of 0.000.

Table 6.6. Overall desirability function and DFA ranking of all concrete mixes.

Sl. No.	Mix ID	Overall desirability function (D)	Rank
1	R	0.000	30
2	B20F	0.509	27
3	B30F	0.573	24
4	B40F	0.522	26
5	20T5UF	0.522	25
6	20T10UF	0.590	22
7	20T15UF	0.650	16
8	20T20UF	0.574	23
9	30T5UF	0.709	13
10	30T10UF	0.782	7
11	**30T15UF**	**0.857**	**3**
12	30T20UF	0.736	9
13	40T5UF	0.593	21
14	40T10UF	0.647	17
15	40T15UF	0.710	12
16	40T20UF	0.622	20
17	20T5US	0.622	19
18	20T10US	0.668	15
19	20T15US	0.718	11
20	20T20US	0.627	18
21	**30T5US**	**0.807**	**5**
22	**30T10US**	**0.872**	**2**
23	**30T15US**	**0.932**	**1**
24	**30T20US**	**0.815**	**4**
25	40T5US	0.693	14
26	40T10US	0.737	8
27	40T15US	0.800	6
28	40T20US	0.730	10
29	50T5US	0.411	28
30	50T10US	0.351	29
31	50T15US	0.000	30

The 2nd and 3rd rank is achieved by 30T10US and 30T15UF with a closeness coefficient of 0.872 and 0.857, respectively. The 4th and 5th rank is achieved by 30T20US and 30T5US with a closeness coefficient of 0.815 and 0.807, respectively. It is generally observed that OPC – FA – UFS ternary mixes have performed better as compared to OPC – FA – UFFA ternary mixes for any common replacement proportions.

6.4 Spearman’s rank order correlation method

The results from all three optimization methods (GRA, TOPSIS and DFA) indicate ranks for different concrete mixes with regards to observed cost, mechanical and durability properties. All these optimization methods are well established but steps and methodology are different in all three methods. Hence, the comparison of ranks cannot be made among the results of these methods. Therefore, spearman’s rank correlation coefficient is computed in order to understand the distribution of ranking obtained from GRA, TOPSIS and DFA methods of optimization (Ashok and Abarami, 2018; Sadhukhan et al., 2015). Spearman rank correlation establishes the comparison between obtained ranks of GRA, TOPSIS and DFA. The observed value of spearman’s correlation coefficients are as presented in Table 6.7.

Table 6.7. Spearman’s correlation coefficient of GRA, TOPSIS and DFA.

Sl. No:	Optimization Methods	Spearman’s Coefficient	Confidence Value
1.	GRA and TOPSIS	0.980	99%
2.	TOPSIS and DFA	0.939	99%
3.	DFA and GRA	0.972	99%

Spearman’s rank order correlation coefficient between GRA and TOPSIS is 0.980 with 99% confidence value. Spearman’s rank order correlation coefficient between TOPSIS and DFA is 0.939 with 99% confidence value. Spearman’s rank order correlation coefficient between DFA and GRA is 0.972 with 99% confidence value. All the ranking from optimization methods show high spearman’s coefficient with high confidence value of 99%. GRA gives higher coefficient value either with TOPSIS or DFA, hence GRA can be a preferred ranking method. However, though the results of any of these methods are acceptable, GRA could be preferred over the others as regards higher spearman’s correlation coefficient.

6.5 Summary

The presented chapter elaborates on cost analysis of all concrete mixes. It was observed that the cost of concrete reduces with increment in fly ash content as it is cheaper than ordinary Portland cement. However, with addition of ultra-fine fly ash and ultra-fine slag, the cost of concrete increases, as they are expensive than OPC.

This chapter presents three methods of optimization, namely Grey Relational Analysis (GRA), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Desirability Function Approach (DFA). All the optimization methods are used for solving multiple criteria decision making problem. The measured responses such as compressive, split tensile and flexural strengths, chloride migration coefficient, water penetration depth, water sorptivity, volume of voids and cost of concrete are chosen as responses for optimization.

In accordance with optimization methods the ranking for most desirable concrete mix with regards to each optimization technique is identified and presented. Spearman's rank order correlation method is used to find the preferred optimization method. Grey relational analysis is found to be preferred method of optimization. Ternary concrete combination 30T15US i.e. 55% OPC – 30% FA – 15% UFS, has been found to be the best alternative concrete mix.

Chapter 7

Summary and Conclusions

7.1 Summary

In the present thesis, an attempt has been made to investigate the properties of mortar and concrete made with industrial wastes such as fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) which could be effectively used as supplementary cementitious material. The major objectives of the present study include 1. Characterization and microstructural study of binders with the help of SEM and EDS analysis. 2. Study of binary and ternary mortars for their mechanical properties in order to understand the feasible replacement proportions which could be adopted in concrete mixes. 3. Study of mechanical and durability properties of 3 OPC – FA binary and 27 OPC – FA – UFFA/UFS ternary concrete mixes. 4. Study the cost aspect and perform optimization methods to obtain best concrete mix.

The properties of all binary and ternary concrete mixes are compared with reference concrete made with only OPC. Workability, compressive strength, flexural strength and split tensile strengths are measured as part of fresh and mechanical parameters in concrete. The durability properties such as chloride migration, water permeability, water sorptivity and volume of permeable voids are examined for all concrete mixes. The cost of concrete is computed as part of economic consideration. Overall, 27 ternary mixes were examined for their 15 engineering properties in the present study with concrete. Three optimization methods viz. Grey relational analysis, Technique of order of preference by similarity to ideal solution (TOPSIS) and Desirability function approach (DFA) are conducted to identify the best concrete mix with regards to cost, and measured mechanical and durability properties. Also, Spearman’s rank order correlation methods has been performed on all three optimization techniques.

7.2 Important conclusions

Based on the present investigation carried out and reported in this thesis, the following important conclusions are drawn:

7.2.1 Characterization of binders

1. It is found that, physical and chemical characteristics of ordinary Portland cement (OPC), fly ash (FA), ultra-fine fly ash (UFFA) and ultra-fine slag (UFS) used in the present study complies the relevant code recommendations for their usage as pozzolanic material or supplementary cementitious material (SCM) in cement mortar/concrete.
2. The average particle size (D_{50}) of OPC and FA are 22.9 µm and 15.1 µm, respectively. The average particle size (D_{50}) of UFFA and UFS are 4.36 µm and 5.02 µm, respectively. The smaller particle size of UFFA and UFS results in early activation during hydration.
3. It is observed from the scanning electron microscopy (SEM) images that, the particle of OPC and UFS are angular and that of FA and UFFA are spherical. The energy dispersive x-ray spectroscopy (EDS) analysis performed on all binders confirms the chemical characteristics found in analysis.
4. The strengths of OPC – UFFA and OPC – UFS mortars at all ages are significantly higher as compared to only OPC mortars, due to high pozzolanic reactivity of UFS and UFFA. All the binders (FA, UFFA and UFS) satisfy the minimum strength requirements for their use as SCM.

7.2.2 Mechanical properties of binary and ternary mortar mixes with OPC, FA, UFFA and UFS

1. The compressive strength of OPC – FA mortar with 20% - 40% of FA has demonstrated comparable results at later ages (>28 days) but not at early age. Therefore an ultra-fine material is used to form ternary mixes to enhance early strengths.
2. The compressive strength at all ages for OPC – UFFA and OPC – UFS binary mixes are found to be improved for mixes with 10% and 20% of UFFA as compared to OPC mortar. The proportion of UFFA and UFS in concrete is therefore, in the range of 5 - 20% for ternary concrete mixes.
3. The ternary mortar mix OPC – FA – UFFA/UFS have shown increment in early and later age compressive strength with usage of up to 20% of UFFA or UFS. Therefore, maximum of 20% of UFFA or UFS was used in concrete mixes.

4. UFFA and UFS reacts faster due to greater surface area resulting in improved early age strength. The pozzolanic reactivity of fly ash is prolonged resulting in improved later age strength in ternary mixes.
5. It is observed that, UFS based mortars has demonstrated better mechanical strength as compared to UFFA based mortars for any common replacement mixture.
6. Workability of mortar mixes increases due to spherical shaped FA and UFFA particles, which reduces the inter particle friction and imparts fluidity to mix. Workability of mortars reduces with inclusion of ultra-fine slag due to angular shaped particles which offers resistance to flow.

7.2.3 Fresh and mechanical properties of binary and ternary concrete mixes with OPC, FA, UFFA and UFS

1. The workability of concrete improves with addition of fly ash and ultra-fine fly ash due to their spherical shaped particles. Whereas, workability reduces with use of ultra-fine slag due to angular shaped particles.
2. The compressive strength of OPC – FA binary concrete mixes has shown reduced early age strength due to slow pozzolanic reactivity of fly ash. The later age strength has shown marginal improvement in OPC – FA binary mixes
3. In the case of OPC – FA – UFFA based ternary concrete mixes, the early age strength and later age strength has improved up to 13% and 35% as compared to reference concrete.
4. In the case of OPC – FA – UFS based ternary concrete mixes, the early age strength and later age strength has improved up to 21% and 36% as compared to reference concrete.
5. The high pozzolanic reactivity of UFFA and UFS imparts better early age strength. The high later age strength is due to prolonged pozzolanic reaction of FA in ternary mix. The improved mechanical strength is a result of better packing density, reduction in pore volume and densification of mixture due to addition of finer particle of UFFA and UFS.
6. Flexural strength and split tensile strength of ternary concrete mixes showed an improvement of up to 13% and 22%, respectively. The improvement in tensile

strengths are attributable to densification of ternary concrete due to addition of UFFA and UFS.

7.2.4 Durability properties of binary and ternary concrete mixes with OPC, FA, UFFA and UFS

1. The resistance against chloride migration of OPC – FA, OPC – FA – UFFA and OPC – FA – UFS concrete mixes has increased in the range of 63 – 86%, 64 – 90% and 69 – 92%, respectively as compared to reference concrete.
2. The resistance to water permeability of OPC – FA, OPC – FA – UFFA and OPC – FA – UFS concrete mixes has increased in the range of 58 – 75%, 61 – 91% and 74 – 94%, respectively as compared to reference concrete.
3. The resistance to water sorptivity of OPC – FA, OPC – FA – UFFA and OPC – FA – UFS concrete mixes has increased in the range of 10 – 22%, 12 – 58% and 13 – 66%, respectively as compared to reference concrete.
4. The volume of permeable voids of OPC – FA, OPC – FA – UFFA and OPC – FA – UFS concrete mixes has reduced in the range of 10 – 17%, 11 – 24% and 13 – 30%, respectively as compared to reference concrete.
7. The durability improvement is attributable to addition of UFFA and UFS which refines the pore structure, resulting in denser and compact microstructure. The compactness is due to formation of secondary CSH gels due to ultra-fine pozzolanic material (UFFA and UFS).
8. The durability has also enhanced due to reduction in inter connected capillaries and voids in ternary mixes. Overall, the ternary concrete with UFFA and UFS have demonstrated superior mechanical and durability properties as compared to reference concrete.

7.2.5 Cost analysis and optimization of concrete mixes with OPC, FA, UFFA and UFS

1. The cost of concrete reduces with addition of cheaper fly ash. The cost of concrete increases with addition of ultra-fine slag or ultra-fine fly ash as it is expensive than OPC. The cost of binary and ternary mixtures are cheaper in the range of 0.7 – 16.5% as compared to cost of reference concrete.

2. GRA, TOPSIS and DFA methods were used to optimize different concrete mixes as per observed cost, mechanical and durability properties. The concrete mix with rank 1 was observed to be 30T15US (55% OPC – 30% FA – 15% UFS) as per optimization methods.
3. Spearman’s rank order correlation methods is used to find the preferred method among GRA, TOPSIS and DFA. It was observed from spearman’s rank order correlation method that, the rankings of GRA could be preferred over rankings of DFA or TOPSIS.
4. Based on optimization of different concrete mixes, the ternary combination 30T15US (55% OPC – 30% FA – 15% UFS) have demonstrated best results as regards cost, mechanical and durability properties.
5. The saving of OPC in 30T15US (55% OPC – 30% FA – 15% UFS) is 45% which will substantially reduce the carbon footprint.

7.3 Major contributions from the study

1. Characterization of binders such as ordinary Portland cement, fly ash, ultra-fine fly ash and ultra-fine slag in terms of oxide composition, particle size distributions, packing density, microstructure study using SEM and EDS observations.
2. Identification of feasible replacement range of fly ash, ultra-fine fly ash, and ultra-fine slag in accordance with observed mechanical properties of binary and ternary mortar mixes.
3. Identification of compressive strength, flexural strength and split tensile strength of different binary and ternary concrete mixes made in OPC – FA – UFFA/UFS combinations in different proportions.
4. Identification of durability parameters such as chloride migration, water permeability, sorptivity and permeable voids of different binary and ternary concrete mixes made in OPC – FA – UFFA/UFS combinations in different proportions.
5. Analysis of cost of different binary and ternary concrete mixes as part of economic analysis.
6. Optimization techniques under taken to identify best alternate concrete mixes as regards cost, mechanical and durability properties using three optimization techniques (GRA, TOPSIS and DFA).

7. Application of Spearman’s rank order correlation method to identify the preferred method of optimization as regards observed ranking from GRA, TOPSIS and DFA.

7.4 Scope of future work

The following are the scope for the extension of future work:

1. The present study can be extended to design the methodology of concrete mix design when ultra-fine materials such as UFFA and UFS are used.
2. The present study used single source and single fineness of UFFA and UFS. The present study can be extended to develop the understanding on ultra-fine fly ash or ultra-fine slags with variable fineness.
3. The fly ash replacement in the present study is limited to 50%. The present study can be extended to use high volume replacement (more than 70%) of fly ash.
4. The present study show high workability with OPC – FA – UFFA ternary concrete mixes. The suitability of this combination can be studied in self compacting concrete.
5. The advanced properties such as alkali silica reaction, resistance to freeze and thaw, electrical resistivity, chloride induced corrosion, plastic shrinkage cracking can be thought as an extension of present study.
6. Silica fume, metakaolin or rice husk ash can be used to further replace OPC in ternary concrete to form quaternary concrete mixes. Mechanical and durability study can be done for quaternary blended concrete.
7. Additional methods of optimization such as Relative to an identified distribution (RIDIT) or simple additive weighing (SAW) can be used in addition to GRA, TOPSIS and DFA in the present study.

Annexure A.1. Results of compressive strength of reference and binary mortars with FA, UFFA and UFS.

Sr. No.	Mix ID	Compressive Strength in MPa					
		1 d	3 d	7 d	28 d	56 d	90 d
Reference mix							
1	R	23.18	40.49	53.46	64.73	71.59	74.21
Binary mix of OPC – FA							
2	B10F	16.45	30.77	42.77	53.08	63.72	65.6
3	B20F	19.7	36.04	49.72	66.1	71.65	75.46
4	B30F	18.54	32.39	43.84	61.5	68.4	73.5
5	B40F	12.75	26.72	30.65	38.71	42.6	50.2
6	B50F	11.91	21.55	25.45	32.65	38.5	45.8
7	B60F	7.18	15.39	21.39	28.5	32.8	38.4
8	B70F	5.79	12.55	18.71	24.5	29.85	33.4
Binary mix of OPC – UFFA							
9	B10UF	19.51	35.65	52.93	67.69	73.03	77.12
10	B20UF	21.49	41.64	57.01	70.29	76.19	80.59
11	B30UF	19.54	33.61	45.32	57.19	61.58	63.25
12	B40UF	13.54	28.87	33.46	40.91	45.06	52.15
13	B50UF	12.49	21.64	26.83	36.49	41.55	46.47
14	B60UF	8.4	17.61	22.17	28.82	33.62	39.37
15	B70UF	7.67	13.88	19.5	26.39	30.84	35.07
Binary mix of OPC - UFS							
16	B10US	21.26	41.56	55.81	69.09	75.62	78.55
17	B20US	22.13	44.47	58.36	73.29	78.59	81.25
18	B30US	19.46	36.68	47.09	57.12	62.64	65.53
19	B40US	14.91	30.65	36.47	43.36	47.64	55.74
20	B50US	13.83	22.07	28.62	39.92	43.51	49.55
21	B60US	9.3	19.81	24.92	31.46	36.78	41.39
22	B70US	8.51	15.95	21.24	29.61	32.89	38.05

Annexure A.2. Results of compressive strength of reference and ternary mortars with 10% FA and 10 – 50% UFFA/UFS.

Sr. No.	**Mix ID**	**Compressive Strength in MPa**					
		1 d	**3 d**	**7 d**	**28 d**	**56 d**	**90 d**
Reference mix							
1	R	23.18	40.49	53.46	64.73	71.59	74.21
Ternary mix of OPC – 10%FA – UFFA							
2	10T10UF	18.92	37.54	50.48	65.85	72.34	77.1
3	10T20UF	20.66	42.18	52.62	67.2	74.55	80.73
4	10T30UF	18.02	32.43	39.84	50.71	58.49	63.82
5	10T40UF	10.46	19.03	26.49	34.91	40.4	43.74
6	10T50UF	8.6	15.26	21.96	27.88	32.12	38.73
Ternary mix of OPC – 10%FA – UFS							
7	10T10US	20.14	41.22	51.49	69.5	76.87	79
8	10T20US	22.43	43.51	55.67	68.87	78.19	84.69
9	10T30US	19.66	35.73	42.91	55.18	61.8	67.52
10	10T40US	11.62	25.49	31.22	39.81	43.36	47.67
11	10T50US	8.9	17.52	22.66	29.19	35.41	40.73

Annexure A.3. Results of compressive strength of reference and ternary mortars with 20% FA and 10 – 50% UFFA/UFS.

Sr. No.	Mix ID	Compressive Strength in MPa					
		1 d	3 d	7 d	28 d	56 d	90 d
Reference mix							
1	R	23.18	40.49	53.46	64.73	71.59	74.21
Ternary mix of OPC – 20%FA – UFFA							
2	20T10UF	20.11	42.05	51.78	66.3	73.12	77.41
3	20T20UF	21.3	42.75	54.09	67.88	76.51	81.72
4	20T30UF	18.46	36.91	47.1	58.25	66.46	70.03
5	20T40UF	11.88	26.12	31.73	38.43	42.32	47.47
6	20T50UF	10.35	19.42	24.56	33.25	38.37	43.79
Ternary mix of OPC – 20%FA – UFS							
7	20T10US	20.4	42.4	53.2	70.1	77.5	79.6
8	20T20US	22.2	44.9	58.6	70.7	80.2	87
9	20T30US	20.6	38.4	50.3	61.9	67.5	70.2
10	20T40US	12.09	27.3	35.49	42.21	46.54	53.96
11	20T50US	11.81	20.64	26.95	36.6	41.22	47.08

Annexure A.4. Results of compressive strength of reference and ternary mortars with 30% FA and 10 – 50% UFFA/UFS.

Sr. No.	Mix ID	Compressive Strength in MPa					
		1 d	3 d	7 d	28 d	56 d	90 d
Reference mix							
1	R	23.18	40.49	53.46	64.73	71.59	74.21
Ternary mix of OPC – 30%FA – UFFA							
2	30T10UF	17.85	35.19	48.46	63.51	74.65	79.52
3	30T20UF	20.15	41.27	53.78	66.51	75.07	80.66
4	30T30UF	17.18	30.27	38.15	46.52	52.54	59.18
5	30T40UF	9.13	17.61	25.4	32.18	38.55	42.98
6	30T50UF	7.05	12.3	18.64	23.35	28.71	31.75
Ternary mix of OPC – 30%FA – UFS							
7	30T10US	19.43	40.99	52.12	67.81	78.08	83.5
8	30T20US	21.63	42.51	55.94	68.1	78.88	85.47
9	30T30US	18.22	31.56	40.29	53.81	61.2	67.11
10	30T40US	10.5	21.65	28.11	35	39.66	43.73
11	30T50US	7.46	13.28	20.3	25.71	31.08	33.65

Appendix B.1. Mix proportion details of reference and OPC – FA binary concrete mixes.

Sl. No.	Mix ID	Binders (Kg/m^3)				Aggregates (Kg/m^3)		Water (Kg/m^3)	Admixture (Kg/m^3)	Cost of concrete (Rs./m^3)	Remarks
		OPC	FA	UFFA	UFS	Fine	Coarse				
1	R	375	-	-	-	715	1345	142.5	1.5	5639.1	Reference Mix
2	B20F	300	75	-	-	705	1330	142.5	1.5	5233.1	Binary mix of OPC – FA
3	B30F	262.5	112.5	-	-	701	1321	142.5	1.5	5029.0	
4	B40F	225	150	-	-	698	1311	142.5	1.5	4824.5	

Appendix B.2. Mix proportion details of reference and OPC – FA – UFFA ternary concrete mixes.

Sl. No.	Mix ID	Binders (Kg/m^3)				Aggregates (Kg/m^3)		Water (Kg/m^3)	Admixture (Kg/m^3)	Cost of concrete ($Rs./m^3$)	Remarks
		OPC	FA	UFFA	UFS	Fine	Coarse				
1	R	375	-	-	-	715	1345	142.5	1.5	5639.1	Reference Mix
2	20T5UF	281.25	75	18.75	-	703	1326	142.5	1.5	5319.2	Ternary mix of OPC – 20%FA – UFFA
3	20T10UF	262.5	75	37.5	-	702	1321	142.5	1.5	5405.0	
4	20T15UF	243.75	75	56.25	-	701	1317	142.5	1.5	5492.1	
5	20T20UF	225	75	75	-	700	1312	142.5	1.5	5577.9	
6	30T5UF	243.75	112.5	18.75	-	700	1316	142.5	1.5	5114.7	Ternary mix of OPC – 30%FA – UFFA
7	30T10UF	225	112.5	37.5	-	698	1312	142.5	1.5	5200.9	
8	30T15UF	206.25	112.5	56.25	-	697	1308	142.5	1.5	5288.0	
9	30T20UF	187.5	112.5	75	-	696	1303	142.5	1.5	5373.8	
10	40T5UF	206.25	150	18.75	-	699	1304	142.5	1.5	4909.4	Ternary mix of OPC – 40%FA – UFFA
11	40T10UF	187.5	150	37.5	-	697	1301	142.5	1.5	4997.0	
12	40T15UF	168.75	150	56.25	-	696	1296	142.5	1.5	5082.7	
13	40T20UF	150	150	75	-	694	1292	142.5	1.5	5168.9	

Appendix B.3. Mix proportion details of reference and OPC – FA – UFS ternary concrete mixes.

Sl. No.	Mix ID	Binders (Kg/m^3)				Aggregates (Kg/m^3)		Water (Kg/m^3)	Admixture (Kg/m^3)	Cost of concrete (Rs./m^3)	Remarks
		OPC	FA	UFFA	UFS	Fine	Coarse				
1	R	375	-	-	-	715	1345	142.5	1.5	5639.1	Reference Mix
2	20T5US	281.25	75	-	18.75	707	1326	142.5	1.5	5323.2	Ternary mix of OPC – 20%FA – UFS
3	20T10US	262.5	75	-	37.5	706	1325	142.5	1.5	5414.6	
4	20T15US	243.75	75	-	56.25	705	1325	142.5	1.5	5507.3	
5	20T20US	225	75	-	75	704	1324	142.5	1.5	5598.7	
6	30T5US	243.75	112.5	-	18.75	703	1317	142.5	1.5	5119.1	Ternary mix of OPC – 30%FA – UFS
7	30T10US	225	112.5	-	37.5	701	1318	142.5	1.5	5212.3	
8	30T15US	206.25	112.5	-	56.25	700	1317	142.5	1.5	5303.6	
9	30T20US	187.5	112.5	-	75	698	1318	142.5	1.5	5396.8	
10	40T5US	206.25	150	-	18.75	699	1309	142.5	1.5	4916.4	Ternary mix of OPC – 40%FA – UFS
11	40T10US	187.5	150	-	37.5	699	1307	142.5	1.5	5007.4	
12	40T15US	168.75	150	-	56.25	698	1306	142.5	1.5	5098.7	
13	40T20US	150	150	-	75	696	1306	142.5	1.5	5190.5	
14	50T5US	168.75	187.5	-	18.75	695	1299	142.5	1.5	4710.9	Ternary mix of OPC – 40%FA – UFS
15	50T10US	150	187.5	-	37.5	693	1301	142.5	1.5	4805.5	
16	50T15US	131.25	187.5	-	56.25	691	1301	142.5	1.5	4897.2	

Appendix B.4. Workability, compressive strength and tensile strength of reference and OPC – FA binary concrete mixes.

Sl. No.	Mix ID	Slump (mm)	Compressive strength (MPa)					Flexural strength (MPa)	Split tensile strength (MPa)	Remarks
			3 d	7 d	28 d	56 d	90 d			
1	R	125	27.00	37.70	47.20	51.90	55.00	6.1	4.5	Reference Mix
2	B20F	125	26.10	31.80	41.90	53.90	57.20	5.7	4.4	Binary mix of OPC – FA
3	B30F	130	27.30	33.60	46.70	55.60	60.20	6.0	4.7	
4	B40F	140	21.00	26.90	39.10	48.20	54.20	5.5	3.9	

Appendix B.5. Workability, compressive strength and tensile strength of reference and OPC – FA – UFFA ternary concrete mixes.

Sl. No.	Mix ID	Slump (mm)	Compressive strength (MPa)					Flexural strength (MPa)	Split tensile strength (MPa)	Remarks
			3 d	7 d	28 d	56 d	90 d			
1	R	125	27.00	37.70	47.20	51.90	55.00	6.1	4.5	Reference Mix
2	20T5UF	125	26.10	31.80	41.90	53.90	57.20	5.9	4.1	Ternary mix of OPC – 20%FA – UFFA
3	20T10UF	130	27.30	33.60	46.70	55.60	60.20	6.1	4.4	
4	20T15UF	140	21.00	26.90	39.10	48.20	54.20	6.2	4.6	
5	20T20UF	150	22.90	32.90	45.10	52.10	63.70	6.0	4.2	
6	30T5UF	155	23.50	35.20	47.30	53.90	65.00	6.4	4.6	Ternary mix of OPC – 30%FA – UFFA
7	30T10UF	160	24.10	38.10	48.50	54.40	65.20	6.6	5.0	
8	30T15UF	170	23.10	34.50	46.30	51.70	60.50	6.5	5.3	
9	30T20UF	160	25.70	35.70	55.90	61.00	68.90	6.1	4.5	
10	40T5UF	170	26.30	37.80	57.50	61.90	71.80	5.6	4.4	Ternary mix of OPC – 40%FA – UFFA
11	40T10UF	170	28.80	42.70	61.10	65.00	74.50	5.7	4.5	
12	40T15UF	175	25.90	37.10	50.30	58.00	67.80	5.9	4.8	
13	40T20UF	165	19.30	31.20	45.60	50.10	57.60	5.7	4.6	

Appendix B.6. Workability, compressive strength and tensile strength of reference and OPC – FA – UFS ternary concrete mixes.

Sl. No.	Mix ID	Slump (mm)	Compressive strength (MPa)					Flexural strength (MPa)	Split tensile strength (MPa)	Remarks
			3 d	7 d	28 d	56 d	90 d			
1	R	125	27.00	37.70	47.20	51.90	55.00	6.1	4.5	Reference Mix
2	20T5US	145	26.20	35.60	48.50	58.50	65.60	6.1	4.4	Ternary mix of OPC – 20%FA – UFS
3	20T10US	140	26.90	36.10	49.90	60.20	67.20	6.2	4.6	
4	20T15US	130	27.30	38.90	51.60	61.30	67.40	6.3	4.9	
5	20T20US	125	26.10	37.60	48.60	58.10	62.20	6.1	4.6	
6	30T5US	155	29.40	38.50	58.50	67.60	70.70	6.8	5.0	Ternary mix of OPC – 30%FA – UFS
7	30T10US	150	30.00	41.20	60.00	69.10	74.30	6.8	5.3	
8	30T15US	145	32.10	45.60	62.40	70.20	74.90	6.9	5.5	
9	30T20US	140	28.80	40.10	52.90	65.20	69.60	6.4	4.8	
10	40T5US	160	21.80	33.70	47.50	56.50	59.20	6.1	4.8	Ternary mix of OPC – 40%FA – UFS
11	40T10US	150	23.50	33.90	49.90	58.10	61.30	6.2	5.0	
12	40T15US	150	23.90	34.60	53.60	62.60	63.80	6.5	5.2	
13	40T20US	140	21.10	32.10	49.00	55.70	59.00	6.2	5.0	
14	50T5US	165	18.60	27.90	35.10	42.60	45.90	5.2	3.5	Ternary mix of OPC – 50%FA – UFS
15	50T10US	160	17.00	24.60	32.50	39.10	43.50	4.5	3.1	
16	50T15US	150	11.50	19.50	28.10	33.40	40.20	3.6	2.8	

Appendix B.7. Rapid chloride migration coefficient, depth of water penetration, water sorptivity and volume of voids of reference and OPC – FA binary concrete mixes.

Sl. No.	Mix ID	Chloride migration coefficient (D_{nssm} × 10^{-12} m^2/s)			Depth of water penetration (mm)		Water sorptivity (× 10^{-4} $mm/s^{1/2}$)		Vol. of permeable voids (%)	Remarks
		7 d	28 d	90 d	28 d	90 d	Initial	Secondary		
1	R	15.65	10.61	9.28	38	32	16.85	4.14	14.50	Reference Mix
2	B20F	5.81	2.44	1.80	16	10	15.22	3.36	13.12	Binary mix of OPC – FA
3	B30F	5.56	2.35	1.62	13	9	14.90	3.57	12.55	
4	B40F	4.91	2.28	1.30	11	8	13.65	3.21	12.10	

Appendix B.8. Rapid chloride migration coefficient, depth of water penetration, water sorptivity and volume of voids of reference and OPC – FA – UFFA ternary concrete mixes.

Sl. No.	Mix ID	Chloride migration coefficient (D_{nssm} × 10^{-12} m^2/s)			Depth of water penetration (mm)		Water sorptivity (× 10^{-4} $mm/s^{1/2}$)		Vol. of permeable voids (%)	Remarks
		7 d	28 d	90 d	28 d	90 d	Initial	Secondary		
1	R	15.65	10.61	9.28	38	32	16.85	4.14	14.50	Reference Mix
2	20T5UF	5.61	2.40	1.38	15	12	14.84	3.28	12.90	Ternary mix of OPC – 20%FA – UFFA
3	20T10UF	3.22	1.52	1.23	12	11	13.41	3.15	12.30	
4	20T15UF	2.31	1.32	1.18	11	9	10.66	2.61	11.50	
5	20T20UF	2.35	1.36	1.21	10	9	11.20	2.74	11.10	
6	30T5UF	3.11	1.47	1.26	9	7	11.50	2.95	12.35	Ternary mix of OPC – 30%FA – UFFA
7	30T10UF	2.36	1.22	1.11	8	5	9.00	2.51	11.83	
8	30T15UF	1.98	0.94	0.90	5	3	7.48	1.75	11.60	
9	30T20UF	2.84	1.25	1.18	7	5	8.69	1.79	11.20	
10	40T5UF	5.63	2.62	2.05	11	8	12.05	2.85	11.74	Ternary mix of OPC – 40%FA – UFFA
11	40T10UF	4.75	2.31	1.92	9	6	10.34	2.51	11.32	
12	40T15UF	4.29	2.20	1.87	8	5	8.26	2.01	11.10	
13	20T20UF	4.15	2.40	2.10	9	6	10.45	2.14	11.00	

Appendix B.9. Rapid chloride migration coefficient, depth of water penetration, water sorptivity and volume of voids of reference and OPC – FA – UFS ternary concrete mixes.

Sl. No.	Mix ID	Chloride migration coefficient ($D_{nssm} \times 10^{-12}$ m^2/s)			Depth of water penetration (mm)		Water sorptivity ($\times 10^{-4}$ mm/s$^{1/2}$)		Vol. of permeable voids (%)	Remarks
		7 d	28 d	90 d	28 d	90 d	Initial	Secondary		
1	R	15.65	10.61	9.28	38	32	16.85	4.14	14.50	Reference Mix
2	20T5US	4.84	2.31	1.32	10	6	13.66	2.92	12.60	Ternary mix of OPC – 20%FA – UFS
3	20T10US	2.61	1.22	1.01	7	5	12.50	2.89	12.11	
4	20T15US	1.74	0.92	0.84	6	4	10.27	2.46	11.25	
5	20T20US	1.76	0.96	0.90	7	5	11.20	2.41	11.00	
6	30T5US	2.35	1.13	0.96	6	4	10.82	2.62	11.64	Ternary mix of OPC – 30%FA – UFS
7	30T10US	1.93	0.98	0.91	5	4	8.46	2.18	10.75	
8	30T15US	1.49	0.77	0.75	3	2	6.58	1.60	10.23	
9	30T20US	2.36	1.13	1.10	4	3	8.51	1.41	10.10	
10	40T5US	4.54	2.14	1.85	7	5	11.21	2.46	11.12	Ternary mix of OPC – 40%FA – UFS
11	40T10US	4.02	2.00	1.65	6	4	9.51	2.36	10.95	
12	40T15US	3.84	1.94	1.60	6	4	7.42	1.65	10.40	
13	40T20US	3.07	1.87	1.79	6	4	8.29	1.48	10.23	
14	50T5US	4.82	2.90	2.08	9	6	14.69	3.65	12.65	Ternary mix of OPC – 50%FA – UFS
15	50T10US	4.55	2.85	1.89	9	5	13.18	3.61	11.36	
16	50T15US	4.09	2.66	1.80	8	5	12.91	3.20	10.41	

Appendix C.1. Measured response with regards to reference, binary and ternary concrete mixes.

S. No.	Mix ID	CS3	CS7	CS28	CS56	CS90	FS	STS	WP28	WP90	CM7	CM28	CM90	IS	SS	PV	CO
1	R	27.0	37.7	47.2	51.9	55.0	6.1	4.5	38	32	15.65	10.61	9.28	16.85	4.14	14.50	5639.1
2	B20F	26.1	31.8	41.9	53.9	57.2	5.7	4.4	16	10	5.81	2.44	1.80	15.22	3.36	13.12	5233.1
3	B30F	27.3	33.6	46.7	55.6	60.2	6.0	4.7	13	9	5.56	2.35	1.62	14.90	3.57	12.55	5029.0
4	B40F	21.0	26.9	39.1	48.2	54.2	5.5	3.9	11	8	4.91	2.28	1.30	13.65	3.21	12.10	4824.5
5	20T5UF	22.9	32.9	45.1	52.1	63.7	5.9	4.1	15	12	5.61	2.40	1.38	14.84	3.28	12.90	5319.2
6	20T10UF	23.5	35.2	47.3	53.9	65.0	6.1	4.4	12	11	3.22	1.52	1.23	13.41	3.15	12.30	5405.0
7	20T15UF	24.1	38.1	48.5	54.4	65.2	6.2	4.6	11	9	2.31	1.32	1.18	10.66	2.61	11.50	5492.1
8	20T20UF	23.1	34.5	46.3	51.7	60.5	6.0	4.2	10	9	2.35	1.36	1.21	11.20	2.74	11.10	5577.9
9	30T5UF	25.7	35.7	55.9	61.0	68.9	6.4	4.6	9	7	3.11	1.47	1.26	11.50	2.95	12.35	5114.7
10	30T10UF	26.3	37.8	57.5	61.9	71.8	6.6	5.0	8	5	2.36	1.22	1.11	9.00	2.51	11.83	5200.9
11	30T15UF	28.8	42.7	61.1	65.0	74.5	6.5	5.3	5	3	1.98	0.94	0.90	7.48	1.75	11.60	5288.0
12	30T20UF	25.9	37.1	50.3	58.0	67.8	6.1	4.5	7	5	2.84	1.25	1.18	8.69	1.79	11.20	5373.8
13	40T5UF	19.3	31.2	45.6	50.1	57.6	5.6	4.4	11	8	5.63	2.62	2.05	12.05	2.85	11.74	4909.4
14	40T10UF	20.6	31.8	47.2	51.3	59.4	5.7	4.5	9	6	4.75	2.31	1.92	10.34	2.51	11.32	4997.0
15	40T15UF	21.4	32.2	50.8	55.4	61.9	5.9	4.8	8	5	4.29	2.20	1.87	8.26	2.01	11.10	5082.7
16	40T20UF	18.8	29.6	46.5	49.2	57.3	5.7	4.6	9	6	4.15	2.40	2.10	10.45	2.14	11.00	5168.9
17	20T5US	26.2	35.6	48.5	58.5	65.6	6.1	4.4	10	6	4.84	2.31	1.32	13.66	2.92	12.60	5323.2
18	20T10US	26.9	36.1	49.9	60.2	67.2	6.2	4.6	7	5	2.61	1.22	1.01	12.50	2.89	12.11	5414.6
19	20T15US	27.3	38.9	51.6	61.3	67.4	6.3	4.9	6	4	1.74	0.92	0.84	10.27	2.46	11.25	5507.3
20	20T20US	26.1	37.6	48.6	58.1	62.2	6.1	4.6	7	5	1.76	0.96	0.90	11.20	2.41	11.00	5598.7
21	30T5US	29.4	38.5	58.5	67.6	70.7	6.8	5.0	6	4	2.35	1.13	0.96	10.82	2.62	11.64	5119.1
22	30T10US	30.0	41.2	60.0	69.1	74.3	6.8	5.3	5	4	1.93	0.98	0.91	8.46	2.18	10.75	5212.3
23	30T15US	32.1	45.6	62.4	70.2	74.9	6.9	5.5	3	2	1.49	0.77	0.75	6.58	1.60	10.23	5303.6
24	30T20US	28.8	40.1	52.9	65.2	69.6	6.4	4.8	4	3	2.36	1.13	1.10	8.51	1.41	10.10	5396.8
25	40T5US	21.8	33.7	47.5	56.5	59.2	6.1	4.8	7	5	4.54	2.14	1.85	11.21	2.46	11.12	4916.4
26	40T10US	23.5	33.9	49.9	58.1	61.3	6.2	5.0	6	4	4.02	2.00	1.65	9.51	2.36	10.95	5007.4
27	40T15US	23.9	34.6	53.6	62.6	63.8	6.5	5.2	6	4	3.84	1.94	1.60	7.42	1.65	10.40	5098.7
28	40T20US	21.1	32.1	49.0	55.7	59.0	6.2	5.0	6	4	3.07	1.87	1.79	8.29	1.48	10.23	5190.5
29	50T5US	18.6	27.9	35.1	42.6	45.9	5.2	3.5	9	6	4.82	2.90	2.08	14.69	3.65	12.65	4710.9
30	50T10US	17.0	24.6	32.5	39.1	43.5	4.5	3.1	9	5	4.55	2.85	1.89	13.18	3.61	11.36	4805.5
31	50T15US	11.5	19.5	28.1	33.4	40.2	3.6	2.8	8	5	4.09	2.66	1.80	12.91	3.20	10.41	4897.2
	Max	11.5	19.5	28.1	33.4	40.2	3.6	2.8	3	2	1.49	0.77	0.75	6.58	1.41	10.1	4710.9
	Min	32.1	45.6	62.4	70.2	74.9	6.9	5.5	38	32	15.65	10.61	9.28	16.85	4.14	14.5	5639.1

Appendix C.2. Normalised values of individual responses with regards to reference, binary and ternary concrete mixes in GRA.

S. No.	Mix ID	CS3	CS7	CS28	CS56	CS90	FS	STS	WP28	WP90	CM7	CM28	CM90	IS	SS	PV	CO
1	R	0.75	0.70	0.56	0.50	0.43	0.76	0.63	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
2	B20F	0.71	0.47	0.40	0.56	0.49	0.64	0.59	0.63	0.73	0.69	0.83	0.88	0.16	0.29	0.31	0.44
3	B30F	0.77	0.54	0.54	0.60	0.58	0.73	0.70	0.71	0.77	0.71	0.84	0.90	0.19	0.21	0.44	0.66
4	B40F	0.46	0.28	0.32	0.40	0.40	0.58	0.41	0.77	0.80	0.76	0.85	0.94	0.31	0.34	0.55	0.88
5	20T5UF	0.55	0.51	0.50	0.51	0.68	0.70	0.48	0.66	0.67	0.71	0.83	0.93	0.20	0.32	0.36	0.34
6	20T10UF	0.58	0.60	0.56	0.56	0.71	0.76	0.59	0.74	0.70	0.88	0.92	0.94	0.33	0.36	0.50	0.25
7	20T15UF	0.61	0.71	0.59	0.57	0.72	0.79	0.67	0.77	0.77	0.94	0.94	0.95	0.60	0.56	0.68	0.16
8	20T20UF	0.56	0.57	0.53	0.50	0.59	0.73	0.52	0.80	0.77	0.94	0.94	0.95	0.55	0.51	0.77	0.07
9	30T5UF	0.69	0.62	0.81	0.75	0.83	0.85	0.67	0.83	0.83	0.89	0.93	0.94	0.52	0.44	0.49	0.56
10	30T10UF	0.72	0.70	0.86	0.77	0.91	0.91	0.81	0.86	0.90	0.94	0.95	0.96	0.76	0.60	0.61	0.47
11	30T15UF	0.84	0.89	0.96	0.86	0.99	0.88	0.93	0.94	0.97	0.97	0.98	0.98	0.91	0.88	0.66	0.38
12	30T20UF	0.70	0.67	0.65	0.67	0.80	0.76	0.63	0.89	0.90	0.90	0.95	0.95	0.79	0.86	0.75	0.29
13	40T5UF	0.38	0.45	0.51	0.45	0.50	0.61	0.59	0.77	0.80	0.71	0.81	0.85	0.47	0.47	0.63	0.79
14	40T10UF	0.44	0.47	0.56	0.49	0.55	0.64	0.63	0.83	0.87	0.77	0.84	0.86	0.63	0.60	0.72	0.69
15	40T15UF	0.48	0.49	0.66	0.60	0.63	0.70	0.74	0.86	0.90	0.80	0.85	0.87	0.84	0.78	0.77	0.60
16	40T20UF	0.35	0.39	0.54	0.43	0.49	0.64	0.67	0.83	0.87	0.81	0.83	0.84	0.62	0.73	0.80	0.51
17	20T5US	0.71	0.62	0.59	0.68	0.73	0.76	0.59	0.80	0.87	0.76	0.84	0.93	0.31	0.45	0.43	0.34
18	20T10US	0.75	0.64	0.64	0.73	0.78	0.79	0.67	0.89	0.90	0.92	0.95	0.97	0.42	0.46	0.54	0.24
19	20T15US	0.77	0.74	0.69	0.76	0.78	0.82	0.78	0.91	0.93	0.98	0.98	0.99	0.64	0.62	0.74	0.14
20	20T20US	0.71	0.69	0.60	0.67	0.63	0.76	0.67	0.89	0.90	0.98	0.98	0.98	0.55	0.63	0.80	0.04
21	30T5US	0.87	0.73	0.89	0.93	0.88	0.97	0.81	0.91	0.93	0.94	0.96	0.98	0.59	0.56	0.65	0.56
22	30T10US	0.90	0.83	0.93	0.97	0.98	0.97	0.93	0.94	0.93	0.97	0.98	0.98	0.82	0.72	0.85	0.46
23	30T15US	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	0.93	0.97	0.36
24	30T20US	0.84	0.79	0.72	0.86	0.85	0.85	0.74	0.97	0.97	0.94	0.96	0.96	0.81	**1.00**	**1.00**	0.26
25	40T5US	0.50	0.54	0.57	0.63	0.55	0.76	0.74	0.89	0.90	0.78	0.86	0.87	0.55	0.62	0.77	0.78
26	40T10US	0.58	0.55	0.64	0.67	0.61	0.79	0.81	0.91	0.93	0.82	0.88	0.89	0.71	0.65	0.81	0.68
27	40T15US	0.60	0.58	0.74	0.79	0.68	0.88	0.89	0.91	0.93	0.83	0.88	0.90	0.92	0.91	0.93	0.58
28	40T20US	0.47	0.48	0.61	0.61	0.54	0.79	0.81	0.91	0.93	0.89	0.89	0.88	0.83	0.97	0.97	0.48
29	50T5US	0.34	0.32	0.20	0.25	0.16	0.48	0.26	0.83	0.87	0.76	0.78	0.84	0.21	0.18	0.42	**1.00**
30	50T10US	0.27	0.20	0.13	0.15	0.10	0.27	0.11	0.83	0.90	0.78	0.79	0.87	0.36	0.19	0.71	0.90
31	50T15US	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.90	0.82	0.81	0.88	0.38	0.34	0.93	0.80
Max		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Min		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Appendix C.3. Grey relational coefficient (GRC) of individual responses with regards to reference, binary and ternary concrete mixes in GRA.

S. No.	Mix ID	CS3	CS7	CS28	CS56	CS90	FS	STS	WP28	WP90	CM7	CM28	CM90	IS	SS	PV	CO
1	R	0.67	0.62	0.53	0.50	0.47	0.67	0.57	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**
2	B20F	0.63	0.49	0.46	0.53	0.50	0.58	0.55	0.57	0.65	0.62	0.75	0.80	0.37	0.41	0.42	0.47
3	B30F	0.68	0.52	0.52	0.56	0.54	0.65	0.63	0.64	0.68	0.63	0.76	0.83	0.38	0.39	0.47	0.59
4	B40F	0.48	0.41	0.42	0.46	0.46	0.54	0.46	0.69	0.71	0.67	0.77	0.89	0.42	0.43	0.52	0.80
5	20T5UF	0.53	0.51	0.50	0.50	0.61	0.62	0.49	0.59	0.60	0.63	0.75	0.87	0.38	0.42	0.44	0.43
6	20T10UF	0.54	0.56	0.53	0.53	0.64	0.67	0.55	0.66	0.63	0.80	0.87	0.90	0.43	0.44	0.50	0.40
7	20T15UF	0.56	0.64	0.55	0.54	0.64	0.70	0.60	0.69	0.68	0.90	0.90	0.91	0.56	0.53	0.61	0.37
8	20T20UF	0.53	0.54	0.52	0.50	0.55	0.65	0.51	0.71	0.68	0.89	0.89	0.90	0.53	0.51	0.69	0.35
9	30T5UF	0.62	0.57	0.73	0.67	0.74	0.77	0.60	0.74	0.75	0.81	0.88	0.89	0.51	0.47	0.49	0.53
10	30T10UF	0.64	0.63	0.78	0.69	0.85	0.85	0.73	0.78	0.83	0.89	0.92	0.92	0.68	0.55	0.56	0.49
11	30T15UF	0.76	0.82	0.93	0.78	0.98	0.80	0.87	0.90	0.94	0.94	0.97	0.97	0.85	0.80	0.59	0.45
12	30T20UF	0.62	0.61	0.59	0.60	0.71	0.67	0.57	0.81	0.83	0.84	0.91	0.91	0.71	0.78	0.67	0.41
13	40T5UF	0.45	0.48	0.51	0.48	0.50	0.56	0.55	0.69	0.71	0.63	0.73	0.77	0.48	0.49	0.57	0.70
14	40T10UF	0.47	0.49	0.53	0.49	0.53	0.58	0.57	0.74	0.79	0.68	0.76	0.78	0.58	0.55	0.64	0.62
15	40T15UF	0.49	0.49	0.60	0.55	0.57	0.62	0.66	0.78	0.83	0.72	0.77	0.79	0.75	0.69	0.69	0.56
16	40T20UF	0.44	0.45	0.52	0.47	0.50	0.58	0.60	0.74	0.79	0.73	0.75	0.76	0.57	0.65	0.71	0.50
17	20T5US	0.64	0.57	0.55	0.61	0.65	0.67	0.55	0.71	0.79	0.68	0.76	0.88	0.42	0.47	0.47	0.43
18	20T10US	0.66	0.58	0.58	0.65	0.69	0.70	0.60	0.81	0.83	0.86	0.92	0.94	0.46	0.48	0.52	0.40
19	20T15US	0.68	0.66	0.61	0.67	0.70	0.73	0.69	0.85	0.88	0.97	0.97	0.98	0.58	0.57	0.66	0.37
20	20T20US	0.63	0.62	0.55	0.60	0.58	0.67	0.60	0.81	0.83	0.96	0.96	0.97	0.53	0.58	0.71	0.34
21	30T5US	0.79	0.65	0.81	0.88	0.81	0.94	0.73	0.85	0.88	0.89	0.93	0.95	0.55	0.53	0.59	0.53
22	30T10US	0.83	0.75	0.88	0.94	0.97	0.94	0.87	0.90	0.88	0.94	0.96	0.96	0.73	0.64	0.77	0.48
23	30T15US	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	0.88	0.94	0.44
24	30T20US	0.76	0.70	0.64	0.79	0.77	0.77	0.66	0.95	0.94	0.89	0.93	0.92	0.73	**1.00**	**1.00**	0.40
25	40T5US	0.50	0.52	0.54	0.57	0.52	0.67	0.66	0.81	0.83	0.70	0.78	0.79	0.53	0.57	0.68	0.69
26	40T10US	0.54	0.53	0.58	0.60	0.56	0.70	0.73	0.85	0.88	0.74	0.80	0.83	0.64	0.59	0.72	0.61
27	40T15US	0.56	0.54	0.66	0.71	0.61	0.80	0.82	0.85	0.88	0.75	0.81	0.83	0.86	0.85	0.88	0.54
28	40T20US	0.48	0.49	0.56	0.56	0.52	0.70	0.73	0.85	0.88	0.82	0.82	0.80	0.75	0.95	0.94	0.49
29	50T5US	0.43	0.42	0.39	0.40	0.37	0.49	0.40	0.74	0.79	0.68	0.70	0.76	0.39	0.38	0.46	**1.00**
30	50T10US	0.41	0.38	0.36	0.37	0.36	0.41	0.36	0.74	0.83	0.70	0.70	0.79	0.44	0.38	0.64	0.83
31	50T15US	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	0.78	0.83	0.73	0.72	0.80	0.45	0.43	0.88	0.71

Appendix C.4. Normalised response with regards to reference, binary and ternary concrete mixes in TOPSIS.

S. No.	Mix ID	CS3	CS7	CS28	CS56	CS90	FS	STS	WP28	WP90	CM7	CM28	CM90	IS	SS	PV	CO
1	R	0.20	0.19	0.17	0.17	0.16	0.18	0.18	0.61	0.67	0.60	0.71	0.75	0.26	0.27	0.22	0.19
2	B20F	0.19	0.16	0.15	0.17	0.16	0.17	0.17	0.26	0.21	0.22	0.16	0.15	0.24	0.22	0.20	0.18
3	B30F	0.20	0.17	0.17	0.18	0.17	0.18	0.18	0.21	0.19	0.21	0.16	0.13	0.23	0.24	0.19	0.17
4	B40F	0.15	0.14	0.14	0.15	0.16	0.16	0.15	0.18	0.17	0.19	0.15	0.11	0.21	0.21	0.19	0.17
5	20T5UF	0.17	0.17	0.16	0.17	0.18	0.18	0.16	0.24	0.25	0.22	0.16	0.11	0.23	0.22	0.20	0.18
6	20T10UF	0.17	0.18	0.17	0.17	0.19	0.18	0.17	0.19	0.23	0.12	0.10	0.10	0.21	0.21	0.19	0.19
7	20T15UF	0.18	0.20	0.18	0.17	0.19	0.18	0.18	0.18	0.19	0.09	0.09	0.10	0.17	0.17	0.18	0.19
8	20T20UF	0.17	0.18	0.17	0.16	0.17	0.18	0.16	0.16	0.19	0.09	0.09	0.10	0.17	0.18	0.17	0.19
9	30T5UF	0.19	0.18	0.20	0.19	0.20	0.19	0.18	0.15	0.15	0.12	0.10	0.10	0.18	0.20	0.19	0.18
10	30T10UF	0.19	0.19	0.21	0.20	0.21	0.20	0.20	0.13	0.10	0.09	0.08	0.09	0.14	0.17	0.18	0.18
11	30T15UF	0.21	0.22	0.22	0.21	0.21	0.19	0.21	0.08	0.06	0.08	0.06	0.07	0.12	0.12	0.18	0.18
12	30T20UF	0.19	0.19	0.18	0.18	0.19	0.18	0.18	0.11	0.10	0.11	0.08	0.10	0.14	0.12	0.17	0.19
13	40T5UF	0.14	0.16	0.17	0.16	0.17	0.17	0.17	0.18	0.17	0.22	0.18	0.17	0.19	0.19	0.18	0.17
14	40T10UF	0.15	0.16	0.17	0.16	0.17	0.17	0.18	0.15	0.13	0.18	0.16	0.16	0.16	0.17	0.17	0.17
15	40T15UF	0.16	0.17	0.19	0.18	0.18	0.18	0.19	0.13	0.10	0.16	0.15	0.15	0.13	0.13	0.17	0.18
16	40T20UF	0.14	0.15	0.17	0.16	0.16	0.17	0.18	0.15	0.13	0.16	0.16	0.17	0.16	0.14	0.17	0.18
17	20T5US	0.19	0.18	0.18	0.19	0.19	0.18	0.17	0.16	0.13	0.19	0.16	0.11	0.21	0.19	0.19	0.18
18	20T10US	0.20	0.19	0.18	0.19	0.19	0.18	0.18	0.11	0.10	0.10	0.08	0.08	0.19	0.19	0.19	0.19
19	20T15US	0.20	0.20	0.19	0.20	0.19	0.19	0.19	0.10	0.08	0.07	0.06	0.07	0.16	0.16	0.17	0.19
20	20T20US	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.11	0.10	0.07	0.06	0.07	0.17	0.16	0.17	0.19
21	30T5US	0.22	0.20	0.21	0.22	0.20	0.20	0.20	0.10	0.08	0.09	0.08	0.08	0.17	0.17	0.18	0.18
22	30T10US	0.22	0.21	0.22	0.22	0.21	0.20	0.21	0.08	0.08	0.07	0.07	0.07	0.13	0.14	0.17	0.18
23	30T15US	0.24	0.23	0.23	0.22	0.21	0.21	0.22	0.05	0.04	0.06	0.05	0.06	0.10	0.11	0.16	0.18
24	30T20US	0.21	0.21	0.19	0.21	0.20	0.19	0.19	0.06	0.06	0.09	0.08	0.09	0.13	0.09	0.16	0.19
25	40T5US	0.16	0.17	0.17	0.18	0.17	0.18	0.19	0.11	0.10	0.17	0.14	0.15	0.17	0.16	0.17	0.17
26	40T10US	0.17	0.17	0.18	0.18	0.18	0.18	0.20	0.10	0.08	0.15	0.13	0.13	0.15	0.16	0.17	0.17
27	40T15US	0.18	0.18	0.20	0.20	0.18	0.19	0.20	0.10	0.08	0.15	0.13	0.13	0.12	0.11	0.16	0.18
28	40T20US	0.16	0.17	0.18	0.18	0.17	0.18	0.20	0.10	0.08	0.12	0.13	0.15	0.13	0.10	0.16	0.18
29	50T5US	0.14	0.14	0.13	0.14	0.13	0.15	0.14	0.15	0.13	0.19	0.19	0.17	0.23	0.24	0.20	0.16
30	50T10US	0.12	0.13	0.12	0.12	0.12	0.13	0.12	0.15	0.10	0.17	0.19	0.15	0.21	0.24	0.18	0.17
31	50T15US	0.08	0.10	0.10	0.11	0.12	0.11	0.11	0.13	0.10	0.16	0.18	0.15	0.20	0.21	0.16	0.17

Appendix C.5. Weighted normalised response and ideal solutions of reference, binary and ternary concrete mixes in TOPSIS.

S. No.	Mix ID	CS3	CS7	CS28	CS56	CS90	FS	STS	WP28	WP90	CM7	CM28	CM90	IS	SS	PV	CO
1	R	0.012	0.012	0.011	0.010	0.010	0.011	0.011	0.038	0.042	0.038	0.045	0.047	0.016	0.017	0.014	0.012
2	B20F	0.012	0.010	0.010	0.011	0.010	0.011	0.011	0.016	0.013	0.014	0.010	0.009	0.015	0.014	0.013	0.011
3	B30F	0.013	0.011	0.011	0.011	0.011	0.011	0.012	0.013	0.012	0.013	0.010	0.008	0.015	0.015	0.012	0.011
4	B40F	0.010	0.009	0.009	0.010	0.010	0.010	0.010	0.011	0.010	0.012	0.010	0.007	0.013	0.013	0.012	0.010
5	20T5UF	0.011	0.011	0.010	0.010	0.011	0.011	0.010	0.015	0.016	0.013	0.010	0.007	0.014	0.014	0.012	0.011
6	20T10UF	0.011	0.011	0.011	0.011	0.012	0.011	0.011	0.012	0.014	0.008	0.006	0.006	0.013	0.013	0.012	0.012
7	20T15UF	0.011	0.012	0.011	0.011	0.012	0.012	0.011	0.011	0.012	0.006	0.006	0.006	0.010	0.011	0.011	0.012
8	20T20UF	0.011	0.011	0.011	0.010	0.011	0.011	0.010	0.010	0.012	0.006	0.006	0.006	0.011	0.011	0.011	0.012
9	30T5UF	0.012	0.011	0.013	0.012	0.012	0.012	0.011	0.009	0.009	0.007	0.006	0.006	0.011	0.012	0.012	0.011
10	30T10UF	0.012	0.012	0.013	0.012	0.013	0.012	0.012	0.008	0.007	0.006	0.005	0.006	0.009	0.010	0.011	0.011
11	30T15UF	0.013	0.014	0.014	0.013	0.013	0.012	0.013	0.005	0.004	0.005	0.004	0.005	0.007	0.007	0.011	0.011
12	30T20UF	0.012	0.012	0.011	0.012	0.012	0.011	0.011	0.007	0.007	0.007	0.005	0.006	0.008	0.007	0.011	0.012
13	40T5UF	0.009	0.010	0.010	0.010	0.010	0.010	0.011	0.011	0.010	0.014	0.011	0.010	0.012	0.012	0.011	0.011
14	40T10UF	0.009	0.010	0.011	0.010	0.011	0.011	0.011	0.009	0.008	0.011	0.010	0.010	0.010	0.010	0.011	0.011
15	40T15UF	0.010	0.010	0.012	0.011	0.011	0.011	0.012	0.008	0.007	0.010	0.009	0.009	0.008	0.008	0.011	0.011
16	40T20UF	0.009	0.010	0.011	0.010	0.010	0.011	0.011	0.009	0.008	0.010	0.010	0.011	0.010	0.009	0.011	0.011
17	20T5US	0.012	0.011	0.011	0.012	0.012	0.011	0.011	0.010	0.008	0.012	0.010	0.007	0.013	0.012	0.012	0.011
18	20T10US	0.012	0.012	0.011	0.012	0.012	0.012	0.011	0.007	0.007	0.006	0.005	0.005	0.012	0.012	0.012	0.012
19	20T15US	0.013	0.013	0.012	0.012	0.012	0.012	0.012	0.006	0.005	0.004	0.004	0.004	0.010	0.010	0.011	0.012
20	20T20US	0.012	0.012	0.011	0.012	0.011	0.011	0.011	0.007	0.007	0.004	0.004	0.005	0.011	0.010	0.011	0.012
21	30T5US	0.014	0.012	0.013	0.013	0.013	0.013	0.012	0.006	0.005	0.006	0.005	0.005	0.011	0.011	0.011	0.011
22	30T10US	0.014	0.013	0.014	0.014	0.013	0.013	0.013	0.005	0.005	0.005	0.004	0.005	0.008	0.009	0.010	0.011
23	30T15US	0.015	0.015	0.014	0.014	0.013	0.013	0.013	0.003	0.003	0.004	0.003	0.004	0.006	0.007	0.010	0.011
24	30T20US	0.013	0.013	0.012	0.013	0.012	0.012	0.012	0.004	0.004	0.006	0.005	0.006	0.008	0.006	0.010	0.012
25	40T5US	0.010	0.011	0.011	0.011	0.011	0.011	0.012	0.007	0.007	0.011	0.009	0.009	0.011	0.010	0.011	0.011
26	40T10US	0.011	0.011	0.011	0.012	0.011	0.012	0.012	0.006	0.005	0.010	0.008	0.008	0.009	0.010	0.011	0.011
27	40T15US	0.011	0.011	0.012	0.012	0.011	0.012	0.013	0.006	0.005	0.009	0.008	0.008	0.007	0.007	0.010	0.011
28	40T20US	0.010	0.010	0.011	0.011	0.011	0.012	0.012	0.006	0.005	0.007	0.008	0.009	0.008	0.006	0.010	0.011
29	50T5US	0.009	0.009	0.008	0.008	0.008	0.010	0.009	0.009	0.008	0.012	0.012	0.011	0.014	0.015	0.012	0.010
30	50T10US	0.008	0.008	0.007	0.008	0.008	0.008	0.008	0.009	0.007	0.011	0.012	0.010	0.013	0.015	0.011	0.010
31	50T15US	0.005	0.006	0.006	0.007	0.007	0.007	0.007	0.008	0.007	0.010	0.011	0.009	0.013	0.013	0.010	0.011
	V^+	0.015	0.015	0.014	0.014	0.013	0.013	0.013	0.003	0.003	0.004	0.003	0.004	0.006	0.006	0.010	0.010
	V^-	0.005	0.006	0.006	0.007	0.007	0.007	0.007	0.038	0.042	0.038	0.045	0.047	0.016	0.017	0.014	0.012

Appendix C.6. Individual desirability of responses with regards to reference, binary and ternary concrete mixes in DFA.

S. No.	Mix ID	CS3	CS7	CS28	CS56	CS90	FS	STS	WP28	WP90	CM7	CM28	CM90	IS	SS	PV	CO
1	R	0.752	0.697	0.557	0.503	0.427	0.758	0.630	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	B20F	0.709	0.471	0.402	0.557	0.490	0.636	0.593	0.629	0.733	0.695	0.830	0.877	0.159	0.286	0.314	0.437
3	B30F	0.767	0.540	0.542	0.603	0.576	0.727	0.704	0.714	0.767	0.713	0.839	0.898	0.190	0.209	0.443	0.657
4	B40F	0.461	0.284	0.321	0.402	0.403	0.576	0.407	0.771	0.800	0.758	0.847	0.936	0.312	0.341	0.545	0.878
5	20T5UF	0.553	0.513	0.496	0.508	0.677	0.697	0.481	0.657	0.667	0.709	0.834	0.926	0.196	0.315	0.364	0.345
6	20T10UF	0.583	0.602	0.560	0.557	0.715	0.758	0.593	0.743	0.700	0.878	0.924	0.944	0.335	0.363	0.500	0.252
7	20T15UF	0.612	0.713	0.595	0.571	0.720	0.788	0.667	0.771	0.767	0.942	0.944	0.950	0.603	0.560	0.682	0.158
8	20T20UF	0.563	0.575	0.531	0.497	0.585	0.727	0.519	0.800	0.767	0.939	0.940	0.946	0.550	0.513	0.773	0.066
9	30T5UF	0.689	0.621	0.810	0.750	0.827	0.848	0.667	0.829	0.833	0.886	0.929	0.940	0.521	0.436	0.489	0.565
10	30T10UF	0.718	0.701	0.857	0.774	0.911	0.909	0.815	0.857	0.900	0.939	0.954	0.958	0.764	0.597	0.607	0.472
11	30T15UF	0.840	0.889	0.962	0.859	0.988	0.879	0.926	0.943	0.967	0.965	0.983	0.982	0.912	0.875	0.659	0.378
12	30T20UF	0.699	0.674	0.647	0.668	0.795	0.758	0.630	0.886	0.900	0.905	0.951	0.950	0.795	0.861	0.750	0.286
13	40T5UF	0.379	0.448	0.510	0.454	0.501	0.606	0.593	0.771	0.800	0.708	0.812	0.848	0.467	0.473	0.627	0.786
14	40T10UF	0.442	0.471	0.557	0.486	0.553	0.636	0.630	0.829	0.867	0.770	0.843	0.863	0.634	0.597	0.723	0.692
15	40T15UF	0.481	0.487	0.662	0.598	0.625	0.697	0.741	0.857	0.900	0.802	0.855	0.869	0.836	0.780	0.773	0.599
16	40T20UF	0.354	0.387	0.536	0.429	0.493	0.636	0.667	0.829	0.867	0.812	0.834	0.842	0.623	0.733	0.795	0.507
17	20T5US	0.714	0.617	0.595	0.682	0.732	0.758	0.593	0.800	0.867	0.763	0.843	0.933	0.311	0.447	0.432	0.340
18	20T10US	0.748	0.636	0.636	0.728	0.778	0.788	0.667	0.886	0.900	0.921	0.954	0.970	0.424	0.458	0.543	0.242
19	20T15US	0.767	0.743	0.685	0.758	0.784	0.818	0.778	0.914	0.933	0.982	0.985	0.989	0.641	0.615	0.739	0.142
20	20T20US	0.709	0.693	0.598	0.671	0.634	0.758	0.667	0.886	0.900	0.981	0.981	0.982	0.550	0.634	0.795	0.044
21	30T5US	0.869	0.728	0.886	0.929	0.879	0.970	0.815	0.914	0.933	0.939	0.963	0.975	0.587	0.557	0.650	0.560
22	30T10US	0.898	0.831	0.930	0.970	0.983	0.970	0.926	0.943	0.933	0.969	0.979	0.981	0.817	0.718	0.852	0.460
23	30T15US	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.930	0.970	0.361
24	30T20US	0.840	0.789	0.723	0.864	0.847	0.848	0.741	0.971	0.967	0.939	0.963	0.959	0.812	1.000	1.000	0.261
25	40T5US	0.500	0.544	0.566	0.628	0.548	0.758	0.741	0.886	0.900	0.785	0.861	0.871	0.549	0.615	0.768	0.779
26	40T10US	0.583	0.552	0.636	0.671	0.608	0.788	0.815	0.914	0.933	0.821	0.875	0.894	0.715	0.652	0.807	0.681
27	40T15US	0.602	0.579	0.743	0.793	0.680	0.879	0.889	0.914	0.933	0.834	0.881	0.900	0.918	0.912	0.932	0.582
28	40T20US	0.466	0.483	0.609	0.606	0.542	0.788	0.815	0.914	0.933	0.888	0.888	0.878	0.833	0.974	0.970	0.483
29	50T5US	0.345	0.322	0.204	0.250	0.164	0.485	0.259	0.829	0.867	0.765	0.784	0.844	0.210	0.179	0.420	1.000
30	50T10US	0.267	0.195	0.128	0.155	0.095	0.273	0.111	0.829	0.900	0.784	0.789	0.866	0.357	0.194	0.714	0.898
31	50T15US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.857	0.900	0.816	0.808	0.877	0.384	0.344	0.930	0.799

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List of Standards

ASTM C642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
ASTM C 1585	Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes
EN 12390:2009	Testing hardened concrete. Depth of penetration of water under pressure
IS 1199:2018	Methods of sampling and analysis of concrete
IS 1727:2015	Methods of test for pozzolanic materials
IS 12089:2018	Specification for granulated slag for the manufacture of. Portland slag cement
IS 12269:2013	Ordinary Portland cement, 53 grade — specification
IS 16715:2018	Ultrafine ground granulated blast furnace slag — specification
IS 269:2015	Ordinary portland cement, 33 grade — specification
IS 3812:2003	Pulverized fuel ash — specification
IS 383:2002	Coarse and fine aggregates from natural sources for concrete
IS 4031:1996	Methods of physical tests for hydraulic cement
IS 4032:1985	Method of chemical analysis of hydraulic cement
IS 455:2003	Portland Slag Cement - Specification
IS 516:2018	Methods of tests for strength of concrete
IS 5816:1999	Splitting tensile strength of concrete - Method of test
NT Build 492	Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments

List of Publications

From the research works carried out for the current Ph.D. programme and reported in Chapters 2, 3, 4, 5 and 6 of this thesis, the following technical papers have been published.

Published Papers:

In Referred International Journals

1. Agrawal, V. M. and Savoikar, P., (2021), "Optimization of binary and ternary concrete composed of fly ash and ultra-fine slag using GRA." *Advances in Concrete Construction*, Vol. 12, No. 4, pp. 283 – 294.

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DOI: https://doi.org/10.12989/acc.2021.12.4.283

In proceedings of International Conferences

2. Agrawal, V. M. and Savoikar, P., (2021), "Sustainable use of normal and ultra-fine fly ash in mortar as partial replacement to ordinary Portland cement in ternary combinations." *Materials Today: Proceedings.* Vol. 51 (3), pp. 1593 – 1597.

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3. Agrawal, V. M. and Savoikar, P., (2020), "A Comprehensive Review of Ultra-Fine Materials as Supplementary Cementitious Materials in Cement Concrete" *Lecture Notes in Civil Engineering: Recent Trends in Civil Engineering, (Springer Nature Singapore),* Vol. 105, pp. 171 – 176.

ISBN 978-981-15-8292-9; Indexed in Scopus
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4. Agrawal, V. M. and Savoikar, P., (2022), “Effects of Ultra Fine Materials on Workability, Particle Packing Density and Compressive Strength of Mortar.” *Lecture Notes in Civil Engineering: Recent Trends in Civil Engineering, (Springer Nature Singapore),* Vol. 221, pp. 9 – 15.

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5. Agrawal, V. M. and Savoikar, P., (2022), “Effective utilization of fly ash and ultra-fine slag in cement mortar as partial replacement of Ordinary Portland Cement in ternary combinations.” Presented at International Conference on Advances in Structural Mechanics and Applications, Oct 06 – 08, 2021, NIT Silchar, India.