EFFECT OF FIBRE SYNERGY ON MECHANICAL AND DURABILITY PROPERTIES OF PERFORMANCE BASED CONCRETE USING COPPER SLAG

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MOHIT GUPTA
(2K17/PHD/CE/29)

Under the Supervision of

(Dr. Ritu Raj) **(Prof. Anil Kumar Sahu)**

Delhi Technological University, Delhi

Department of Civil Engineering

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-110042. India

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(MOHIT GUPTA)

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-42

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I Mohit Gupta hereby certify that the work which is being presented in the thesis entitled "Effect of Fibre Synergy on Mechanical and Durability Properties of Performance Based Concrete using Copper Slag" in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Civil Engineering, Delhi Technological University, is an authentic record of my own work carried out during a period from August, 2017 to June, 2024 under the supervision of Dr Ritu Raj and Prof. Anil Kumar Sahu, Department of Civil Engineering, Delhi Technological University, Delhi, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree or any other Institution.

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(Dr. Ritu Raj)
Supervisor

(**Prof. Anil Kumar Sahu)**
Joint-Supervisor

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-42

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Joint-Supervisor	Supervisor
(Professor)	(Assistant Professor)

Date:

Effect of Fibre Synergy on Mechanical and Durability Properties of Performance Based Concrete using Copper Slag

Mohit Gupta

ABSTRACT

The distinct fibre addition to concrete can improve weak performance in tension. Due to its higher performance, fibre hybridization is becoming increasingly competitive. In this study, the hardened and durability characteristics of performance-based concrete reinforced with polypropylene, basalt and hooked-end steel fibres are investigated. A total of 13 mixes are prepared to evaluate the different characteristics of performance-based concrete. The influence of basalt fibres (BFs 0, 0.25, 0.5, 0.75 %), polypropylene fibres (PFs 0, 0.25, 0.5, 0.75 %), hooked end steel fibres (HES 0, 0.25, 0.5, 0.75 %) to explore the effect of fibre synergy & maximum volume fraction of 1% is used. The Copper slag is used as a partial replacement of 20% & 40 % by the weight of fine aggregate. The test investigation on the hardened characteristics includes; compressive strength, flexural strength, and splitting tensile strength. In addition, durability properties, including; Sorptivity (water absorption), electrical Resistivity, and water permeability tests for high-performance concrete, are also conducted. In addition, previously published high-performance concrete literature is predicted by Enhanced Deep Neural Network (EDNN) algorithm. Performance analysis of already published high-performance concrete is also examined based on the RMSE, MAE, and MAPE, along with R^2 metrics, with the already available DNN, CNN, ANN, and SVM algorithms. The proposed EDNN attains better performance. Out of the 13 mixes considered for this study, PP0.5B0HES0.5CS40 performs better and exhibits excellent performance in terms of strength and durability.

Keywords: High-*Performance Concrete, fibre synergy, mechanical property, durability property, hybrid fibre high-performance concrete.*

LIST OF PUBLICATIONS

1. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2022). EDNN based prediction of strength and durability properties of HPC using fibres & copper slag. Advances in concrete construction 2022-09-25 DOI: 10.12989/ACC.2022.14.3.185
2. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2022). Mechanical properties of high strength concrete incorporating Chopped Basalt fibers: Experimental and Analytical Study. Materials Research Express. Volume 9, Number 12. DOI 10.1088/2053-1591/aca644
3. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2023). Effect of fiber synergy on strength & durability of high-performance concrete. Materials Research Express. 10. 10.1088/2053-1591/acb75a.
4. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2021). Effect of Rice Husk Ash, silica fume & GGBFS on compressive strength of performance-based concrete. 10.1016/j.matpr.2021.06.343
5. **Mohit Gupta et al.** (2023) Elimination of global warming gas emissions by utilizing high reactive metakaolin in high-strength concrete for eco-friendly protection. Materials Research Express.10 (2023) https://doi.org/10.1088/2053-1591/acead8
6. **Mohit Gupta et al.** (2021) Experimental investigation on mechanical property of concrete with the hybrid supplementary cementitious material.
   Materials Today: Proceedings 2022 | Journal article DOI: 10.1016/j.matpr.2022.03.377
7. **Mohit Gupta et al.** (2022) Experimental investigation on mechanical property of concrete with the hybrid supplementary cementitious material. International Conference on Advances in Materials and Mechanical Engineering on 18th & 19th February 2022.
8. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2020). Effect of Rice Husk Ash, silica fume & GGBFS on compressive strength of performance-based concrete. International Conference on Integration of Advanced Technologies 4.0 (ICIATI) sponsored by AICTE, New Delhi on 27th and 28th March 2020
9. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2024). Indian Patent Publication on the invention “Sustainable Concrete Mix Design for Reduced Environmental Impact and Increased Durability” with Application Number: 202421012566, Date of filing: 22/02/2024, Date of Publication: 15/03/2024.

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LIST OF ABBREVIATIONS AND NOMENCLATURE

HyFRC: Hybrid fibre-Reinforced concrete

FRHPC: Fibre Reinforced high-performance concrete

FRC**:** Fiber Reinforced Concrete

w/b ratio: Water to binder ratio

SFRC: Steel fibre reinforced concrete

HES: Hooked end Steel fibres

CS: Compressive strength

STS: Split tensile strength

FS: Flexural Strength

OPC: Ordinary Portland Cement

FA: Fly ash

PP: Polypropylene fibre

BF: Basalt fibre

ST: Split tensile

MS: Micro steel

SCC: Self-compacting concrete:

ACI: American Concrete Institute:

IS: Indian standard

CTM: Compression testing machine

ASTM: American Society of Testing and Materials:

HPC: High-Performance Concrete

BCMO: Balancing Composite Motions

GEP: Gene expression programming

RFR: Random Forest Regression

GS-SVR: Grid Search- Support Vector Regression

SHAP: Shapley additive explanation

GWO: Grey Wolf Optimizer

PSO: Particle Swarm Optimization

GA: Genetic algorithm

JO: Jellyfish Optimization

FV: Fitness Value

EDNN: Enhanced Deep Neural Network

DNN: Deep Neural Network

CNN: Convolutional Neural Network

ANN: Artificial Neural Network

SVM: Support Vector Machine

SMOJO: Switched Multi-Objective Jellyfish Optimization

RMSE: Root Mean Square Error

MAE: Mean Absolute Error

MAPE: Mean Absolute Percentage Error

R^2: Coefficient of Determination

CHAPTER 1
INTRODUCTION

1.1 Research Background

Fiber-Reinforced High-Performance Concrete (HPC) is an advanced construction material that combines the superior mechanical properties of HPC with the enhanced durability and crack resistance provided by fibers. HPC itself is characterized by its high strength, durability, and resistance to environmental stresses, making it ideal for demanding structural applications. By incorporating fibers—such as steel, glass, or synthetic materials—into the mix, Fiber-Reinforced HPC exhibits improved tensile strength, reduced shrinkage cracking, and increased impact resistance. This synergy between the high-performance matrix and the reinforcing fibers leads to a composite material capable of withstanding significant loads and harsh conditions. Fiber-Reinforced HPC is particularly beneficial in applications requiring long-term durability and resilience, such as bridges, high-rise buildings, and marine structures. Its development represents a significant advancement in construction technology, offering enhanced performance and longevity for critical infrastructure projects.

In 1930, paste strength was as high as D. A. Abram obtained 276 MPa. The W/C ratio used was 0.08 with applied high pressure. This high strength is due to dense packing or minimum air voids. The maximum strength of 40MPa was achieved in the historical scenario. About 1970 maximum of 45 MPa strength was noticed; never more than 50 MPa. Because it is easy to modify concrete qualities using ordinary elements to match the requirements of each specific situation, it has become quite popular. Even though concrete is used in most structures, there are still significant issues with its use.

Compressive strength values up to 60 MPa after 28 days of curing are typically indicative of normal concrete. So, above 60 MPa, that is high-strength concrete – HSC. Now, IS 456 2000 – and its later amendments have recognized M60 to M80 grade of concrete as high-strength concrete. On the other hand, when compressive strength is greater than 120 MPa after the same curing period, it is classified as very high-strength concrete. Some of this special concrete is referred to as cement-based matrices (CBM) because some of the ingredients of the concrete may not be there. For instance, in very high-strength concrete, some of the concrete ingredient i.e., coarse aggregate, is missing, which makes it cement-based matrices.

High Performance Concrete is defined by some set of performances. For example, strength performance, fresh state performance, hardened long-term performance, and hardened state performance. In fresh state performance, flowability, and workability i.e., ease of compaction of concrete, should be considered.

There could be several concrete performances, such as; bleeding, shrinkage, creep, the heat of hydration, and early strength gain; durability could be long-term and hardening stage property.

High-strength concrete is the requirement of today's era as number of high-rise structures require advanced materials to inculcate the need of the structure, as discussed by I Nováková et al. (2019) The use of high-strength concrete in modern structures is increasing day by day due to reduced dead load of the structural columns which in turns reduce the cost Z Algin et al. (2020) High strength concrete possesses high compressive strength greater than 60 MPa as per Indian standard code. The material requirement for the high-strength concrete includes silica fume and fly ash as mineral admixture, which combines with chemical admixture to attain the required workability with a low w/c ratio. Silica Fume (SF) plays a prominent role in the hydration process of high-strength concrete. As the concrete has high strength, which results in brittle behaviour so, to reduce the brittleness, the fibers are added together with the concrete.

Concrete is the most consumable building material that is usually utilized worldwide. Zhang et al. (2020) and Asteris et al. (2021) have both discussed concrete properties such as high strength, high elasticity modulus, significant plasticity, and excellent workability. In recent years, the performance requirements for underground structures have not been met by conventional strength concrete addressed by Junwei et al. (2021) , Dadmand et al. (2020) . A very high amount of energy is required for concrete production as reported by Selvadurai . As noted by Federowicz et al., concrete often incorporates industrial waste and by-products such as slag, fly ash, and silica fume. In the construction sector, they have been effectively utilized as a fine aggregate substitute discussed by K. Khan et al. (2020), Eisa et al. (2021) Copper slag is incorporated by high-strength concrete (HSC) as a fine aggregate. Fediuk et al. (2020) reported that high-strength concrete (HSC) can be achieved with a fine aggregate replacement level of less than 40% using copper slag. The properties of such exhibit a considerable enhancement concretes over those of conventional concrete as reported by Afroughsabet & Ozbakkaloglu , Turk et al. (2015) Paving blocks using steel slag powder (SSP) was investigated by Iqrar Hussain et al. (2021) On addition of coir waste compressive strength of HSC reduced while other mechanical properties significantly enhanced by using silica fume and coir waste addressed by Ali et al. (2022) and Rasheed et al. (2022)

Construction projects frequently involve the usage of concrete. Further improvements to concrete's durability, flexibility, impact resistance, and energy absorption are advised given the current building standards reported by R Yu et al. (2015) and DY Yoo et al. (2017). To make concrete stronger and more durable, fibers are added to the mix. Its key benefits include preventing macro crack formation and micro crack expansion to microscopic and macroscopic levels. Low tensile strength and tensile strain capacity are combined with significant brittleness in concrete. Every day, there is a greater requirement for concrete to be more resilient and long-lasting in challenging situations. The material qualities and fiber geometry of a specific type of fiber will determine how well it can accomplish this task. A technique for maximizing the enhancements provided by fiber reinforcement is to incorporate two or more types of fiber that contribute in complementary and additive ways to performance in a concrete mix addressed by L Xu et al. (2019) The greatest difficulty resulting from the industrial revolution is environmental conservation.

Large amounts of Portland cement, silica fume (SF), and small aggregates with steel fibers for reinforcement are typical characteristics of (UHPC) Ultra high-performance concrete. UHPC also exhibits exceptional flowability and a close-packed condition while having a very less w/b ratio. By adding fiber, cracks can be bridged and prevented from spreading, which considerably lessens the characteristics of dry shrinkage. When fibers are added, the stress-strain relationship of cured concrete performs better. To improve performance and reduce the life cycle costs of concrete structures, engineers must continue to face a formidable challenge: obtaining acceptable concrete durability levels. The advantages of utilizing additional binder components for concrete durability are well recognized addressed by N Banthia et al. (2014)

High-performance concrete is a concrete made with appropriate materials, combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give an excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subjected for its design.

Table 1.1 Categorization of different types of concrete.

Parameter	Conventional	High Strength	Very high Strength	Ultra-high Strength
Compressive Strength (MPa)	<50	50-100	100-200	>200
Water-binder Ratio(typical)	0.45-0.55	0.30-0.45	0.24-0.30	<0.24
Chemical Admixture	Not necessary	WRA necessary	HRWRA essential	HRWRA Essential
Mineral binder Addition	Not necessary	Fly ash/slag/ Metakaolin/rice Husk ash	Silica fume	Silica fume And fly ash
Aggregate type	Gravel/crushed Stone/light weight aggregate	Crushed stone	Crushed stone/ Artificial aggregate	Artificial Aggregate
Maximum size of Aggregate(mm)	Any size	15	10	5
Fibres	Optional	Beneficial	Beneficial	Essential
Air entertainment (AE)	Necessary	Necessary	Necessary	Not Necessary
Processing	Conventional	Conventional	Conventional	Heat and pressure required
Permeability Coefficient(cm^2/s)	10^{-10}	10^{-11}	10^{-12}	$<10^{-14}$
Chloride Diffusivity(cm^2/s)	10^{-10}	10^{-9}	10^{-8}	10^{-7}

1.2 Microstructure of High-Strength Concrete

Several microstructure investigations compared high-strength concrete to regular concrete and found dense dispersion of particles. Figure 1.1 and Figure 1.2 represents the microstructure of ordinary concrete and high strength concrete microstructure.

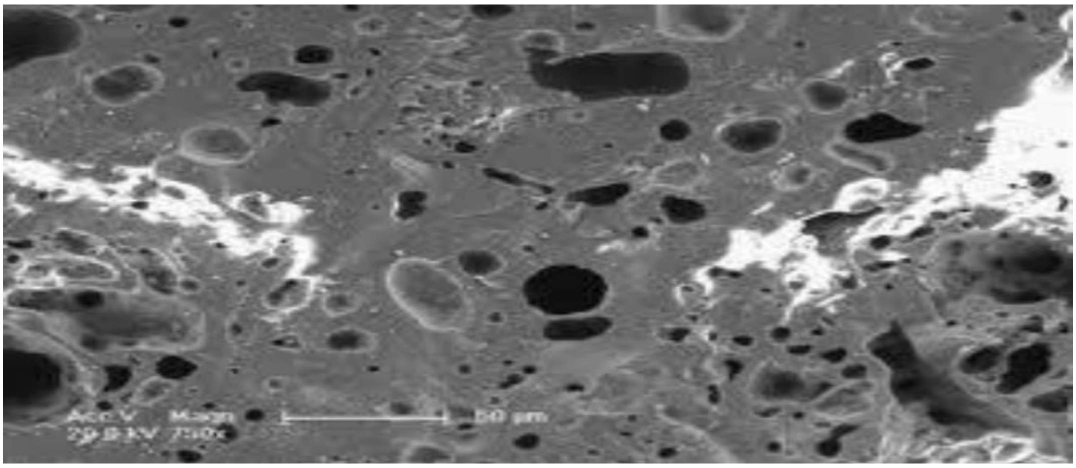

Figure 1.1 HSC Micro structure

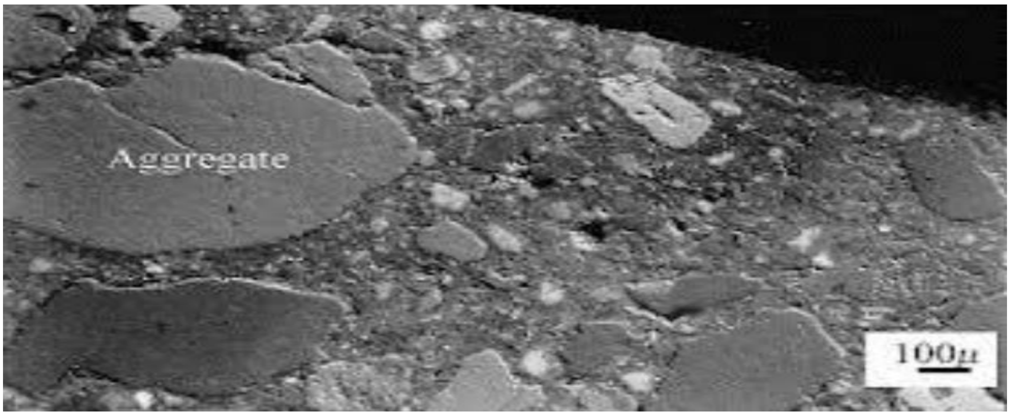

Figure 1.2 Less Dense Micro structure of ordinary concrete

1.3 Historical Development of HPC

HPC deals with a situation, where a set of performance requirement is specified and it must satisfy those requirements. For example, if lower strength self-compacting concrete is developed, this could be also termed as the high-performance concrete. Basically, the prime parameter is not the high strength, but it could be high performance.

O Abraham (1919) suggests that strength is a function of the water-cement ratio and for a low water-cement ratio, strength will increase. Moreover, dense packing could be result in very high strength. This was the understanding from O Abraham et al. (1919) work. This can be seen that lower the porosity, higher is the durability as well as strength for hardened concrete.

To get higher strength, porosity must be reduced. These inferences came through over the years that result in high performance concrete, densified with small particle system; micro defect-free matrices, reactive powder concrete, etc. To get high strength concrete, pore refinement and porosity must be reduced because this is the main section for the crack's development. Achieving high-strength concrete relies on two crucial factors: the incorporation of a fine pozzolanic material, such as silica fume, and maintaining a low water-cement ratio. The reduction of the water-cement ratio can be accomplished through the use of water-reducing agents. And, in addition to this, the aggregate size and packing must be appropriate.

Since ancient historical period Pozzolana were used even Roman empire used the pozzolanic material. They are the volcanic ashes; the lime and silica combinations were also used in various structures. Later on, Surkhi was also used in various part of the world including India. But in recent time cement is utilized everywhere in the world.

By mixing various ingredients normal concrete is formed. After that, Normal strength concrete is also modified and some mineral admixtures were added to enhance the strength property and which led to development of high strength concrete. The special concrete is categorized as SCC, FRC, HSC, HPC etc.

HPC posses' high strength, workability and durability in natural environment. The key ingredients necessary for creating high-performance concrete include silica fume, fly ash, and high-range water-reducing admixtures, all combined in specific proportions, in addition to the materials typically used in standard concrete production.

1.4 Effect of Copper Slag on HPC

The addition of reinforcing fibers can enhance both the mechanical and durability properties of high-performance concrete (HPC) containing copper slag (CS), leading to a synergistic effect.

The fiber synergy effect refers to the enhancement of two or more reinforcing fibers with distinct features on the properties of a material. In HPC, the fibers improve the tensile strength, toughness, and ductility, while copper slag boosts durability by shrinking the porosity and enhancing the microstructure.

Multiple types of fibers can be used in copper slag-based HPC such as steel, glass, carbon, and polypropylene fibers. Several investigations have confirmed that copper slag and steel fibers, when combined, significantly elevate the mechanical characteristics of HPC.

Moreover, the fiber-copper slag composite HPC exhibited outstanding durability properties. The durability developments are attributed to the reduction in the pore size and the generation of a denser, more uniform microstructure resulting from the fiber-copper slag synergy effect.

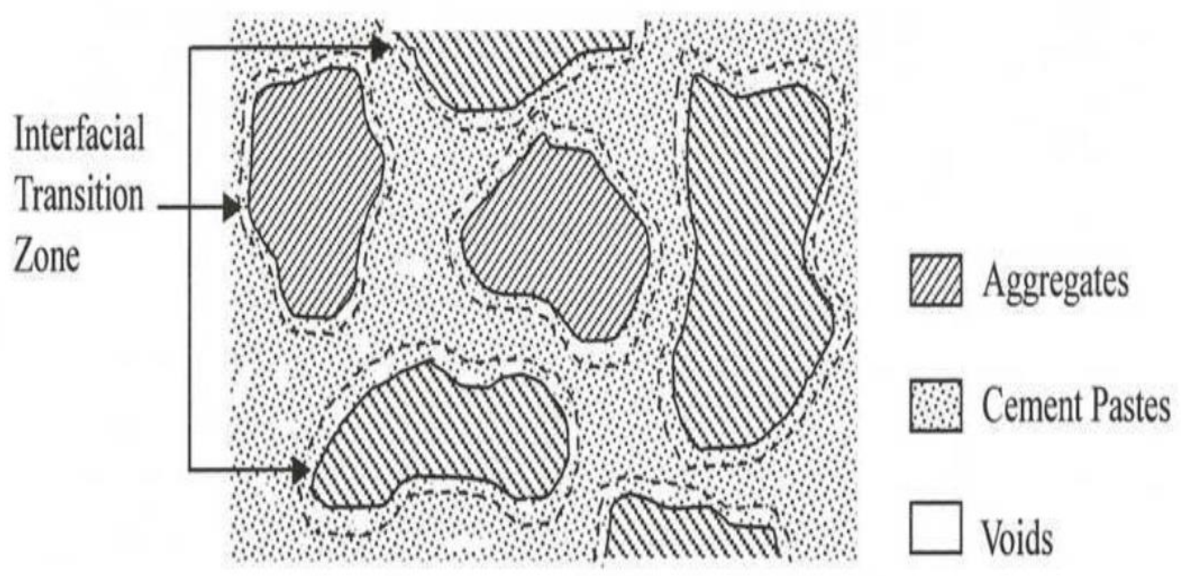

Figure 1.3 Microstructure of Normal strength concrete

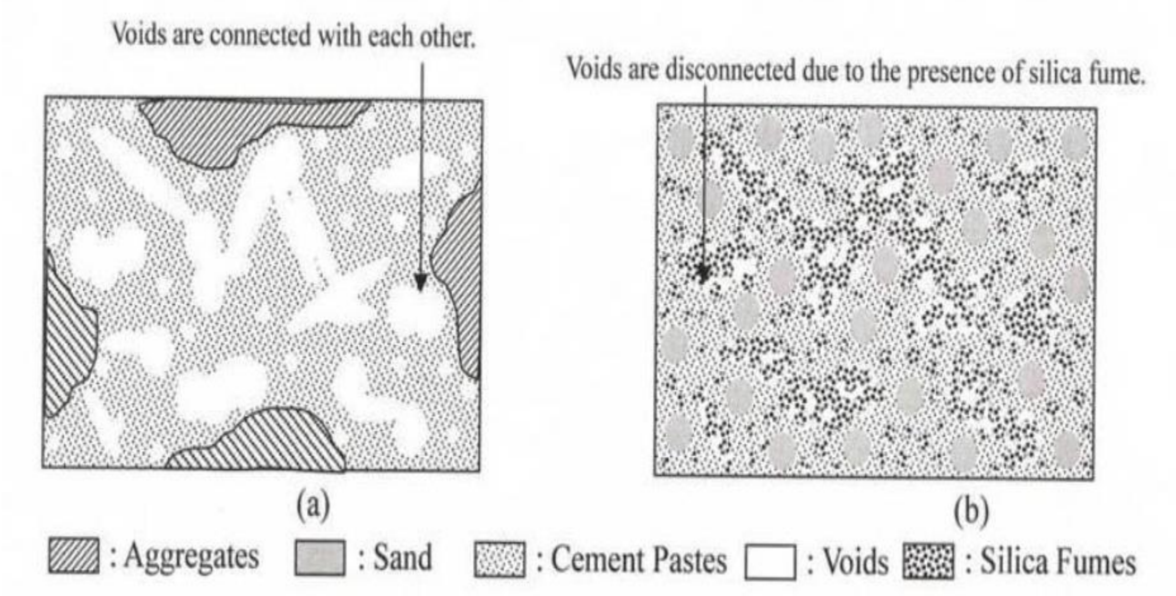

Figure 1.4 Pores connectivity in HSC and NSC

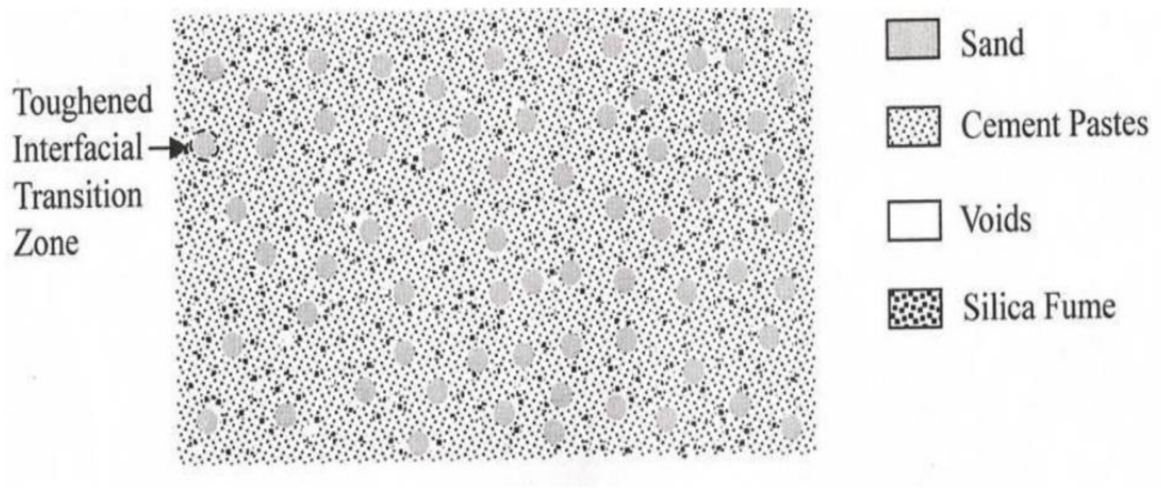

Figure 1.5 Microstructure of HPC

1.5 Need of The Study

The present study undertaken is very important in the field of concrete composites. The study focussed the special concrete i.e., High-Performance concrete. In real life situation, all the structural elements are designed and intended to behave as ductile behaviour so that at the time of collapse, occupants are having sufficient time to escape. In this context, this study emphasizes on the addition/ incorporation of hybrid fibres and their effect on high performance concrete’s hardened property and durability property. In this ongoing study, hybrid fibers are utilized to enhance the characteristics of high-performance concrete, aiming to address the inherent brittleness and tension weakness of concrete. By incorporating both micro fibers and macro fibers, the synergy between them is ensured, resulting in improved strength and durability parameters for high-performance concrete.

It is worth noting that civil engineering structures often experience impact loads throughout their lifespan, making it crucial to consider strength criteria in their design. As the pavements are subjected to heavy impact load therefore for satisfactory performance the concrete used must possess high flexural strength along with high compressive strength. To achieve this objective hybrid fibres are added in HPC. This is the prime motivation of doing this research. The proposed research is limited to design of M65 grade of concrete as per IS 10262:2019 and the hybrid fibres are incorporated in variation by the volume fraction of total concrete mix.

1.5.1 Hybridisation is based on following important parameters;

Fibre constitutive response

High modulus & high strength + Low modulus & high strain

Fibre Dimensions

Micro fibres+ Macro fibres

Fibre Functions

Micro synthetic + Macro high strength

Fibre Performances

Short terms+ Long terms

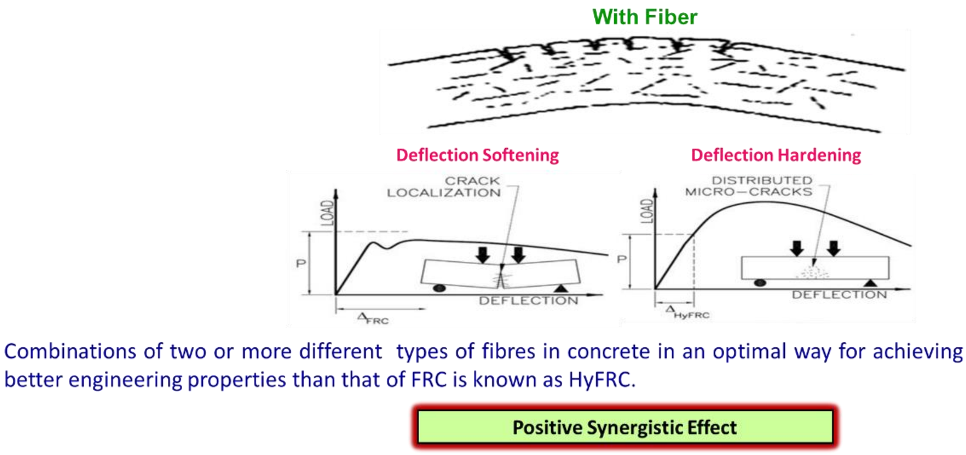

Figure 1.6 Comparison of Concrete

1.6 Problem Statement

Concrete stands as a highly prevalent construction material, renowned for its adaptability, cost-effectiveness, and ready availability. Nevertheless, conventional concrete exhibits constraints regarding its mechanical strength and resilience, particularly when confronted with severe environmental conditions and substantial loads. In response to these issues, it is imperative to employ High-Performance Concrete (HPC) that integrates diverse supplementary materials, including copper slag, to augment its characteristics.

Copper slag, derived from the process of copper refining, has emerged as a prospective substitute for conventional aggregates in concrete, thanks to its pozzolanic and granular attributes. When integrated into concrete mixtures, copper slag can enhance specific characteristics like compressive strength, workability, and resistance to corrosive chemical surroundings. Nonetheless, relying solely on copper slag may fall short of meeting the rigorous requirements of contemporary construction projects. To further elevate the mechanical and durability aspects of High-Performance Concrete (HPC) incorporating copper slag, the inclusion of various types of fibers becomes imperative. Extensive research has demonstrated that fiber reinforcement can substantially elevate tensile and flexural strength, diminish the likelihood of cracking, and fortify the concrete's capacity to withstand impact and fatigue loads.

The current study seeks to investigate the collaborative impact of fiber synergy, involving various fiber types, in conjunction with the use of copper slag as a partial substitute for conventional aggregates within high-performance concrete. This research endeavors to address the following inquiries:

1. What is the optimal proportion of copper slag that can be employed as a substitute for traditional aggregates to strike the most favorable equilibrium between mechanical strength, workability, and durability in high-performance concrete?
2. How does the inclusion of fibers influence both the fresh and hardened characteristics of high-performance concrete containing copper slag, encompassing attributes such as slump, compressive strength, tensile strength, flexural strength, and durability properties?

Addressing these questions will provide valuable insights into the synergy between copper slag and fibers in HPC, potentially paving the way for the creation of construction materials that are not only more environmentally friendly but also longer-lasting.

1.7 Limitation of the study

The materials procured in the present research are purchased from nearby vicinity of NCR, India. Basalt fibers and polypropylene microfibers and hooked end steel macro fibers are the two different types of fibres used in this investigation. These micro and macro fibres, when combined properly, may have the desired qualities. Properties of fibers used in the study is made available from the supplier and is refereed in the experimental design process. The water permeability of hybrid fibre high-performance concrete is determined for 28 and 56 days only.

1.8 Objective of Study

The current research is centered on assessing the mechanical and durability characteristics of High-Performance Concrete that integrates hybrid fibers and employs copper slag to partially replace fine aggregates. The specific objectives of this study include the following:

1. To determine the mechanical properties of High-Performance Concrete at various percentage substitution of hybrid fibre and Copper Slag.
2. To determine the optimum dosage of hybrid fibre with and without substitution of Copper Slag in High Performance Concrete.
3. To determine the physical property of newly developed High-Performance Concrete.
4. To determine the durability properties of High-Performance Concrete at various percentage substitution of hybrid fibre and Copper Slag.

1.9 Outline of thesis

The current research work is explained in 5 chapters in this thesis.

Chapter 1 provides a concise introduction to high-performance concrete, encompassing its research background, microstructure of high-strength concrete, the significance of employing copper slag in high-performance concrete, the historical development of high-performance concrete, the identified need, the problem statement, limitations of the study, and the objectives of the current investigation.
Chapter 2 offers a comprehensive review of high-performance concrete, hybrid fiber-reinforced concrete, and summarizes the existing research gaps.
Chapter 3 is dedicated to materials characterization and the methodology adopted to assess the impact of fiber synergy on high-performance concrete.
Chapter 4 focuses on presenting and discussing the results, including workability, mechanical properties such as compressive strength, flexural strength, and split tensile strength, as well as durability properties like water absorption, electrical resistivity, sorptivity, and water permeability of high-performance concrete.
Chapter 5 outlines the conclusions drawn from the research and outlines potential areas for future research, research contribution.
In the end, references, appendix, list of Publication and curriculum vitae is mentioned.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This section critically reviews the literature from past published online journals and conferences of high repute to address the current research gap in high-performance concrete using hybrid fibres. This section provides numerous previous literatures exhibiting special concrete connected to high-performance concrete. The literature examined various aspects, including high-strength concrete, high-performance concrete, fiber-reinforced high-strength concrete, and techniques for optimizing strength in high-performance concrete (HPC).

2.2 Critical review of literature

HPC is a material that attracts attention because of its exceptional strength, long-lasting properties, and its ability to withstand a range of environmental conditions. Researchers have explored the use of HFR-HPC, which involves the utilisation of two or more fibres with different features to enhance the properties of HPC.

Smith, J. A., & Liu, Y. (2024) explore the advancements, applications, and performance characteristics of High-Performance Fiber-Reinforced Concrete (HPFRC). The incorporation of fibers into high-performance concrete significantly enhances its mechanical properties and durability, making it a versatile material for various structural applications.

Kumar, S., & Patel, R. (2024) addressed HPHFRC that exhibits outstanding mechanical properties, surpassing those of both HPC and single-fiber-reinforced concrete. Studies have demonstrated significant improvements in compressive strength, tensile strength, flexural strength, and energy absorption.

According to the data, C Wen et al. (2022) revealed that the tensile and fracture strengths of Ultra-High-Performance Concrete (UHPC) saw enhancements with the introduction of fibers, and these improvements were influenced by factors such as fiber volume fraction (Vf) and the specific type of fibers used.. The aspect ratio does not considerably impact the properties of UHPC. However, hybrid fibre combinations' impact appears unpredictable and depends on the synergistic interaction of various fibre types.

Guosheng Ren et al. (2022) investigated the effects of elevated temperatures on Ultra-High-Performance Concrete (UHPC) when hybridizing sisal and steel fibers. The outcome demonstrates that sisal and steel fibre hybridization exhibit a superb synergistic impact on enhancing hardened properties of UHPC when temperature rises. Sisal fibres considerably preventing the material from spalling at high temperatures. The best sisal fibre content for enhancing the remaining mechanical characteristics was

0.6 vol%. According to sorptivity data, sisal fibres can improve the porosity of UHPC when exposed to elevated temperature, which affects the remaining hardened properties.

W Abbass et al. (2022) found that using polyvinyl alcoholic/ steel fibre load-bearing capacity was found to be increased by 5% to 50%. The numerical model's findings were consistent. It can be deduced that the use of hybrid fibers in HSC has the potential to be employed in the construction industry, leading to reduced structural weight and increased open space.

Jie Wei et al. (2021) studied how 6, 10, and 15mm straight fibres affected the UHPC mechanical property along with multiple & single impact tests. The diameter and dosage of fibre volume were kept constant during the study. The results reported that hybrid fibres performed better flexural performance even though longer fibres improved hardened properties. In addition, the flexural strength and fracture energy of blends reinforced with a combination of long and short fibers exhibited an increase of 21.83% and 20.14%, respectively, compared to those reinforced solely with long fibers. The impact resistance also improved when UHPC beam samples were tested during the study.

Yanfei Niu et al. (2021) reported that total debonding strain and maximum strain for cracks generation were 0.32% and 3.25%, respectively, among steel fibers and UHPC composite. Moreover, they concluded that as the proportion of longer fibers used for replacement increased, samples containing hybrid fibers exhibited a more rapid decrease in the crack initiation strain rate. An exponential function model was developed to establish the correlation between temporal crack & length of crack.

S. R. R. Teja Prathipati et al. (2020) studied hybrid Fibre Reinforced-HSC and Graded fibre-HSC specimens. Compared to examine how fibre grading affected the strength characteristics and uniaxial compressive behaviour of HSC with hybrid fibres. Glass fibers improved the performance before reaching the peak, while steel fibers improved the behavior after the peak in both hybrid Fiber-Reinforced HSC and hybrid Graded Fiber-HSC mixtures, indicating a positive interaction resulting from the combination of glass and steel fibers in the concrete. Hybrid Graded fibre-HSC excelled hybrid Fibre Reinforced-HSC among the two-hybrid FRCs, showing a sizable improvement in strength and ductility.

Doo-Yeol Yoo et al. (2020) studied various half hooked and straight smooth steel fibres to assess the hardened property of ultra HPC. The hybrid fibre specimens showed superior cracking characteristics as compared to normal HPC.

Mohamed Said et al. (2020) focussed on the performance of flexural strength & flexural rigidity with Polyvinyl alcohol (PVA) and steel bars as fibres addition in different proportions. Their conclusion is that the introduction of steel bars and PVA delayed the initiation of the initial crack. Moreover, the mix's strain ductility also improved throughout the study along with the ductility factor.

Fangqian Deng et al. (2020) demonstrated that the mixed polypropylene & steel fibres cocktail strengthens interfaces in UHPC and modifies the failure pattern. The toughness property of the mixture gets enhanced with the inclusion of a single steel fibre. With the more robust "skeleton" and increased packing density, adding coarse aggregate increases strength and modulus while lowering toughness and deformability.

MR Ahmad et al. (2019) discussed that Basalt Fibres (BF) could replace steel fibre since they can make lightweight cement compounds. BF dramatically increases the ductility of Fly ash/ Magnesium Phosphate Cement (FA/MPC) composites. The composites with 1% of BF showed the highest compressive strength (CS) at roughly 77.6 MPa at 28 days, which was a relative increase of 25% over the standard control sample, according to J Qin et al. (2018) they showed that mixtures with more than 1% BF incorporation showed the compressive strength started to decline, which was caused by the increased development of pores within these solid compounds, and splitting tensile strength, Flexural Strength (FS), and Flexural Tension (FT) found to increase with increase of BF contents. 59% & 108% split tensile strength was increased by adding 0.75% and 1.5% basalt fibres. Additionally, MR Ahmad et al. (2019) showed that the Magnesium Phosphate Cement (MPC) matrix 0.5% BF provided the highest compressive and flexural strength at 28 days, with values of 49.42 MPa and 5.31 MPa, respectively. Even yet, they also noted an important point: there was a slight loss of strength for MPC mixtures with 0.75% BF as opposed to 0.5% BF. The answer for this reduced strength containing 0.75% BF was related to the flocculation tendency of BF at higher dosages. This is consistent with AB Kizilkanat et al. (2015) research work. 12 mm & 24 mm basalt fibres length were investigated and tested for fresh and mechanical properties of concrete, and the results were verified with ANOVA (statistical tool) to validate the results. It revealed that on changing the length of basalt fibres, the workability, air content and compressive strength of concrete reduced, as reported by S Elshafie et al. (2016). The basalt fibres and Polyvinyl alcohol (PVA) fibres were taken to determine the mechanical properties of concrete, and the results revealed that PVA fibres improved the property as compared to basalt fibre due to the bridging ability of PVA, as reported by N Shafiq et al. (2016) There is a more significant change in the post-peak residual strength of flexural performance of basalt fibre concrete as compared to control concrete showed by V Mohanavel et al. (2019) Basalt fibre reinforcement for geopolymer concrete was researched by J Xu et al. The findings demonstrated that basalt fibre could improve the pores and raise geopolymer concrete's compressive and flexural strengths when basalt fibre content was increased. The fibre-matrix transition zone benefited from the addition of basalt fibres. The right amount of basalt fibres increased the concrete's setting time and strength. SA Mostafa et al. (2022) studied their work on self-compacting concrete with basalt fibre addition for ultra-high-performance concrete, and the behaviour of (Ultra high-performance basalt fibre- self-compacting concrete) UHPBF-SCC is also examined in this work about increased temperatures of 300°C and 600°C. Studies were done on the physical characteristics, such as segregation resistance and flowability. They found that when nanoparticles are present, mechanical properties dramatically improve—by more than 18% in CS, 32% in TS, and 28% in FS compared to the reference mix.

PC Chiadighikaobi et al. (2022) worked on basalt fibres with lightweight expanded clay composite. They found that porosity index, CS, and elastic modulus were improved when 1.6 % BF was added to the mix. This paper is written to understand the characterisation of chopped basalt fibres composite on high-strength concrete in varying proportions by keeping the volume fraction of fibres limited to 3%

of the total volume of concrete. Other fibres such as steel, polypropylene, and carbon fibres were used to study the behaviour of fibre-reinforced concrete of normal strength & still, there is ample scope to utilize the chopped basalt fibres in high-strength concrete and work in its analytical study.

According to research by A Khaloo et al. (2014) on the mechanical and rheological characteristics of steel fibre reinforced concrete (SFRC), adding silica fume decreased the compressive strengths and workability of SCC. Otherwise, it might improve the energy absorption capability, rupture modulus, and splitting tensile strength.

Afroughsabet and Ozbakkaloglu (2015) revealed that including steel and polypropylene fibres increased the concrete's compressive, splitting tensile, and flexural strengths. The electrical resistivity did, however, drop when steel fibres were present, as opposed to rising when polypropylene fibres were included.

Ye Li et al. (2019) investigated PP fibre at a rate of 4 kg/m3 addition inhibited explosive spalling of UHPC, Steel fibre (SF) incorporation alone offered no protection against it. Due to a significant increase in permeability, mixed PP and SF fibres entirely avoided explosive spalling even at low fibre doses. Spalling-induced weight loss decreases proportionately as UHPC permeability increases.

According to Estela O. Garcez et al. (2011), all the mixtures had an ideal flow of 560 mm in 4 seconds. Regarding elastic modulus and compressive strength during 28 days, (Forta ferro- low density) FF-LD had the highest values. Among all the combinations, (Forta ferro- medium density) FF-MD fibre displayed the highest splitting tensile strength, measuring 5 MPa. The fact that residual flexural strength improved dramatically from 36% to 79% is undoubtedly evidence of the contribution of fibres to concrete's post-cracking behavior. The mix design with the lowest Forta Ferro and RheoShore fibre dosages appears to be the most appropriate for the intended application of the four.

In their research, Emad A.H. Alwesabi et al. (2020) showed that hybrid fibres (0.1% PP + 0.9% MS) had greater elastic modulus, CS, STS, and other mechanical properties. The FS of concrete was significantly increased by the mixes containing 1.0% MS. The 1% PP mixes negatively impacted the mechanical characteristics of concrete.

According to research by B Masood et al. (2020), the workability of recycled aggregate concrete (RAC) is higher than that of natural aggregate concrete (NAC) because RAC contains more free water. Comparatively speaking, RAC mixes have more air content than NAC mixes. The fresh density of concrete mixes was decreased by substituting NCA for RCA. Comparing RAC to its NAC mix competitors, the compressive strength of RAC dropped.

PP and BF both attain the best mechanical performance at a content of 0.1%, according to research by X Hu et al. (2019). The workability of concrete is not significantly affected by PP and BF hybridization compared to single fibres at the same concentration.

D Wang et al. (2019) discovered that the highest synergy effect of hybrid fibres occurred when the volume percentage of basalt fibre was 0.15% and the volume fraction of polypropylene fibre was 0.033%.

I Sadrinejad et al. (2018) investigated how hybridizing poly-olefin (PO) with PP fibres might increase mixtures' compressive and splitting tensile strengths by up to 7.5% and 23%, respectively, compared to control mixtures. These fibres' hybridization did not have a beneficial impact on the post-cracking behavior during the flexural test. significant volume fibre content, the detrimental effects of PO and PP fibre hybridization were evident. It is advised to use PO and PP fibres at volume fractions of 0.9% and 0.1%, respectively.

In their study, DY Yoo et al. (2017) discovered that the flexural performance suffered when short fibres length of fibre to the diameter of fibre (l_f/d_f of 13/0.2) were used in place of long fibres (l_f/d_f of 30/0.3). Long fibres were used, which significantly enhanced complimentary energy.

In structures, the HPC's usage has been raised significantly recently by (Kumar & Rai (2018), Haido et al. (2021) (Maharishi et al. (2020), Mazloom et al. (2020). Considerable buildings must have higher strength, enhanced ductility and durability, suitable workability, and volume stability (Deng et al., Raj et al. (2020). But, the brittleness of concrete was more apparent with the higher strength, as discussed by Teng et al. (2018) For improving the concrete structure's ductility and strength against constant loading, impact, and fatigue, along with earthquakes, the fibres are mixed with the concrete (Zahiri & Eskandari-naddaf (2018). For stress transferring, fibres are helpful and serve as a bridge between the cracked sections (Sankar & Ramadoss , Prumal & Prabakaran (2021). The incorporation of mineral admixtures and fibers led to synergistic enhancements in both the splitting tensile and flexural strength of recycled aggregate concrete, as observed in studies by Alyousef et al. (2021) and Babar et al. (2021).

Zhang et al. (2020) conclude that for improving ductility along with impact resistance, steel and synthetic fibres are the various sorts of fibres that are extensively utilized. For higher performance, steel fibre was slowly added into concrete recently by Yan et al. (2021) A comparatively new construction material is Polypropylene fibre (PF) presented by Singh & Rai (2018) Currently, owing to their eco-friendly manufacturing method along with outstanding mechanical properties in concrete, basalt fibres (BF) have gained popularity as investigated by M. Khan et al. (2018) HPC is offered by hybrid fibres. Fu et al. studied the concrete's dynamic compressive behaviour and addressed that numerous advantages over traditional concrete are offered by the HPC's high compressive quality, and it could be valuably employed in compression members, namely piles along with columns that could be attained by the fibres. The strength and also durability of HPC are predicted by this research paper via fibre synergy.

Zemei Wu et al. (2018) found that the hybrid fibre's integration; the compression properties were significantly improved, showing higher strength and toughness. The best compressive behavior was observed in a UHPC mixture containing 1.5% long fibers and 0.5% short fibers, while those with 2% short fibers exhibited the least favorable properties.

Sivakumar et al. (2014) discussed that fibres in hybrid form work together to boost bond tension and decrease slide. They found that steel and polypropylene fibres regulate cracks at the macro- and micro-scales, respectively.

Thang Le-Duc et al. (2020) addressed that based on balancing composite motions (BCMO), they suggested a unique population-based optimization approach. Four test suites were chosen from the literature to demonstrate the effectiveness of BCMO, ranging from numerical benchmarks to real-world issues. The statistical findings show that BCMO has a promising track record when applied to various optimization and real-world problems involving confined and unknown search areas. Additionally, BCMO's exceptional performance compared to all other methods was highly praised when it came to solving high-dimensional classical functions.

Iftikhar et al. (2022) proposed GEP and RFR methods to use in their work. The models were created using 192 data points from a trustworthy database. In terms of robustness, the GEP model outperforms the RFR ensemble model. The GEP model shows a substantial improvement with an average error reduction of 37.33 percent, resulting in an average error of 2.35 MPa.

An M5P model tree approach was proposed by Ali Behnood et al. (2017) to forecast the compressive strength of normal concrete (NC) and High-Performance Concrete (HPC). Model trees provided two key advantages over other soft computing techniques: (a) they could produce mathematical equations and provide more profound understanding of the results, and (b) they were easier to create and use. 1912 unique data records were gathered from worldwide existing literature to create the model tree. Overall, the findings indicate that the M5P model tree was a more practical alternative method for predicting the compressive strength of NC and HPC.

Gupta et al. (2022) The fibres used were mico fibre and macro fibre. The mico fibre was Polypropylene, PVA, polyester, polyethylene or steel. The macro fibre was steel fibre. Hence studies on different micro fibres such as steel and polyethylene for controlling the micro crack and hooked-end steel fibres for handling the macro cracks are limited. The direct tensile strength of HFRC is also little. The studies used were investigated with steel fibres of various geometries, and hence studies related to the use of synthetic micro fibre, steel micro fibre, and steel macro fibre are also limited. Up-to-date studies on the development of HFRC with High-Performance Concrete using micro steel, polyethylene and macro steel only limited, and only a little work has been done so far.

The direct shear strength of concrete is studied using notched cylindrical specimens with a single type of fibre. The study includes fibre in conjunction with steel stirrups as reinforcement. Hence combining various kinds of fibres in hybrid form to study the direct shear is limited. High-performance concrete played a vital role in the above combinations. In structures, the tensile cracking is seen in pure flexure members and a combination of flexure and shear in members. Studies on the shear behavior of High-Performance concrete together with fibres are scanty and limited and warrant further research in this direction.

Therefore, there is ample scope to introduce all these fibres in concrete, and it is needed to investigate further essential properties for developing High-Performance Concrete for different grades of concrete which can be used in actual practice.

2.3 Summary of Other Previous published work on High-performance Concrete

High-performance concrete (HPC) is a popular construction material thanks to its exceptional strength, durability, and resistance to environmental degradation. At the same time, researchers have given the material a boost by investigating the use of hybrid fibre-reinforced HPC, which involves using two or more fibres with differing characteristics, to effect a synergistic result.

Several types of fibres can be introduced to HPC to improve its tensile strength, toughness, and ductility, including steel, polypropylene, glass, carbon, and natural fibres. The combination of these fibres magnifies the mechanical properties of HPC, leading to superior qualities.

Research studies have looked into the effects of hybrid fibre reinforcement on the mechanical properties of HPC. One study found that combining steel and polypropylene fibres significantly improved the compressive strength, tensile strength, and toughness of the material.

In a separate study, researchers found that the combination of steel and glass fibres led to a substantial escalation in the material's flexural strength, energy absorption, and ductility compared to a single fibre-reinforced HPC.

Additionally, the durability properties of HPC can also experience improvements by introducing a combination of fibres. A study investigated the effect of hybrid fibre reinforcement on the chloride ion permeability of HPC and found that an HPC reinforced with polypropylene and steel fibres significantly reduced chloride ion penetration compared to HPC reinforced with only one fibre.

Table 2.1 Previously published work on High-performance concrete

S.No	**Author Name**	**Materials used in Investigation**	**Methodology**	**Conclusion**
1.	R. Yu et al. (2015)	Long Steel Fibre, Length=13 mm, D=0.2 mm; Short Steel Fibre (SSF), Length = 6 mm, D = 0.16 mm; Hooked Fibre (HF), Length = 35 mm, D=0.55mm	Flowability, Mechanical properties and Flexural Toughness	(1) All fibres showed relatively good flowability. (2) HF can notably enhance flexural toughness. (3) On the other hand, SSF exhibit comparatively limited effectiveness in enhancing flexural toughness.

2.	Doo-Yeol Yoo et al. (2020)	Three straight steel fibres with different lengths at various Vf. Short fibre L=13mm Medium fibre L= 19.5mm Long fibre L=30 mm	Flexural Performance; post-cracking strength, deflection capacity, toughness, and cracking behavior.	(1) Replacing Long fibres with short fibres produced a deterioration & replacing long fibres with medium fibres improved the flexural performance, (2) Also The concurrent application of extended and short fibers resulted in a decline in these metrics when the substitution ratio exceeded 1%.
3.	Emad A.H. Alwesabi et.al (2020)	Crumb rubber (CR) aggregate (20%), micro steel (MS) and polypropylene (PP) fibre.	Workability, bulk density, elastic modulus and compressive, splitting tensile and flexural strength.	(1) Hybrid fibers, comprising 0.1% polypropylene (PP) and 0.9% (MS) fibers, exhibited superior hardened properties. (2) Mixes containing 1.0% (MS) fibers notably improved the flexural strength. (3) Conversely, mixes containing 1% polypropylene (PP) had an adverse effect on the hardened properties.
4.	Estela O. Garcez et.al (2011)	Forta-Ferro fibres and ReoShore fibres.	Fresh and Mechancial Properties test.	(1) All the mixes observed an Ideal flow of 560 mm in 4

				seconds. (2) FF-LD showed the highest compressive strength of 69.6 MPa and modulus of elasticity on 28 days. (3) FF-MD fibre showed the highest splitting tensile strength of 5 MPa among all the combinations. (4) Residual flexural strength was increased significantly from 36% to 79%
5.	Bilal Masood et al. (2020)	Low calcium bentonite, recycled concrete aggregates (RCA)	Workability, Air content, fresh density, Compressive strength, Split tensile strength, water absorption, chloride migration coefficient, and sulfuric acid attack resistance.	(1) Workability of RAC is more than that of the NAC due to more free water in RAC. (2) Addition of bentonite improved the resistance to chloride penetration in both NAC and RAC mixes. (3) At 15% replacement of Bentonite, Maximum reduction up to 8% in water absorption and increase in Compressive and tensile strength.
6.	Yu Wang et al. (2020)	Nickel-titanium (NiTi) shape memory alloy (SMA), steel and polypropylene (PP) fibre.	Slump flow and J-Ring tests, Flexural strength, Pull-out test.	(1) The pull-out force for the NiTi SMA fibre was 55.08% lower than steel

				fibre and 29.1% higher than PP fibre. (2) The flexural strength of NiTi SMAFRSCC increased from 15 kN to 17.5 kN. (3) The NiTi SMA fibre showed tensile strength 60% of that of the steel fibre & 155% of PP fibre but had the most significant strain(0.32) in comparison with the steel fibre (0.23) and PP fibre (0.15)
7.	Lihua Xu et al. (2019)	Four steel fibre volume dosages (0%, 1%, 2% and 3%).	Compressive strength, splitting tensile strength, flexural behavior & synergistic effect between coarse aggregate and steel fibre were studied.	Both the compressive and splitting tensile strength demonstrated an increase when the coarse aggregate replacement level went from 0% to 28%. However, they exhibited a decrease with a subsequent rise in coarse aggregate content up to 38%.
8.	Dehong Wang et al. (2019)	Single basalt fibres (BFs), Single Polypropylene fibres (PF) and hybrid fibres.	Compressive, Flexural, Splitting Tensile Strength, stress-strain curve of HPC, Development of formula for calculating	The most effective synergistic effect of hybrid fibers was observed when the volume fraction of basalt fiber was 0.15% and the

			Flexural strength.	polypropylene fiber was 0.033%.
9.	Iman Sadrinejad, Rahmat Madandoust , Malek Mohammad Ranjbar (2018)	Some of the PO fibres of 0.5,1 & 1.5% were replaced with PP fibres at volume fractions of 0.1% and 0.2%.	Fresh Concrete; Slump & Inverted Slump Flow Test. Mechanical Properties; Compressive strength, Splitting tensile strength and flexural strength. Durability Properties; Water absorption, electrical resistivity and chloride penetration tests.	(1) Hybridization of PO with PP fibres can improve the CS & ST strength of mixtures up to 7.5% and 23% the hybridization of these fibres did not show a positive effect on post-cracking behavior at the flexural test. (2) High volume fraction of fibres, the hybridization of PO with PP fibres showed an adverse effect. PO and PP fibres at the volume fraction of 0.9% and 0.1%, respectively, can be recommended for practical usage.
10.	Vahid Afroughsabet , Togay Ozbakkaloglu (2015)	1.Hooked-end steel fibres of 60 mm length & various Vf (0.25%, 0.50%, 0.75%, and 1.0%.) 2. PP fibre of 12mm length & various Vf (0.15%, 0.30%, and 0.45%.)	Mechanical Properties; Compressive strength, Splitting tensile strength and flexural strength. Durability Properties; Water absorption, electrical resistivity.	(1) At 1%, steel fibre significantly enhanced the splitting tensile and flexural strength. (2) Best performance was attained at 0.85% steel and 0.15% PP fibre, decreasing WA & ER.
11.	Guncheol Lee et al. (2012)	Polypropylene (PP) and Nylon (NY) fibres.	Fresh concrete;	(1) Combination of the two fibres

			Slump flow & Air content. Compressive strength, Tensile Strength. Fire Resistance; Spalling, Weight loss ratio, Residual Compressive Strength.	can improve spalling protection by providing connections between pores with low fibre content. No explosion occurred at 0.05% of NY and PP 0.025% fibre content.
12.	Valeria Corinaldesi , Alessandro Nardinocchi (2016)	A total of five kinds of fibres include Three hooked metallic: steel, zinc-coated and brass-coated; Two plastic corrugated: polypropylene (PP) and hooked polyethene terephthalate (PET) fibres.	Fresh consistency, compressive and flexural strength, and drying shrinkage strains were studied.	About 6-12% CS increased for polymeric fibres and 26-40% for metallic fibres. Adding CaO produced a loss of CS to 40% and FS to 30%. A large amount of metallic fibres reduces the final shrinkage (35%). Plastic fibres were less effective, even at 13%, due to lower elastic modulus.
13.	N. Banthia et al. (2014)	Macro-steel fibres and a Micro-cellulose fibre.	Flexure and direct shear tests were conducted.	(1) there was a positive Synergy between steel and cellulose fibres for flexure. The Hooked End fibre (HE) was the more efficient. (2) For shear, two steel fibres, when present all by themselves, the DD was seen to elicit greater Synergy in combination

				with cellulose fibres.
14.	Xinyu Hu, Yihong Guo (2019)	Polypropylene fibre (PP) and basalt fibre (BF)	Slump, compressive, splitting tensile, flexural and rapid chloride permeability (RCP), scanning electron microscopy (SEM) and (MIP) test.	(1) Optimum combination is 0.1% PP and 0.1% BF (Vf), and the CS, ST & Flex. Strength was improved by 4.74, 43.65 and 18.98%. (2) Fibres reduced the chloride resistance of concrete, and reduction was observed when adding PP compared to adding BF. (3) Hybridization increases the cumulative pore volume and porosity of concrete.
15.	M.Velumani et al. (2014)	Fly ash and copper slag.	Workability, Ultrasonic pulse velocity test and water absorption test.	(1) Average pulse velocity is above 5 km/sec for 40% copper slag replacement with fine aggregate and 30% replacement with cement. (2) CS increase at 40% copper slag. (3) At 40% replacement, the density of the mix is high and free from pores. (4) . Beyond 40%, the segregation and bleeding effect of copper slag and fly ash mixed concrete

				increases, thereby increasing water absorption value.
16.	Mohamed A.E.M. Ali et al. (2016)	2% polyvinyl-alcohol (PVA) and 0.5%, 1%, and 1.5% NiTi-SMA fibres by volume fraction.	Flow table test for workability, Compressive strength, splitting tensile strength, and flexural strength.	(1) Combination of these fibres can enhance the tensile capacity of ECC by up to 39% with a slight to no increase in compressive strength. (2) At 2% PVA and 1% NiTi-SMA presents the best mechanical performance.
17.	Safeer Abbas et al. (2015)	Steel fibre lengths 8 mm, 12 mm and 16 mm and dosages (1%, 3% and 6%) by mixture volume.	Mechanical Properties, Resistance to chloride ions penetration and mechanical degradation under various chloride exposures.	(1) Fibre length had an insignificant effect on CS. (2) Increase CS of 3%,9%,13% for 1%,3% & 6% for 8mm steel fibres. (3) At a higher fibre dosage of 6%, the 28 days splitting tensile strength was approximately four times greater than that of the control mixture.
18.	Ye Li et al. (2019)	Polypropylene (PP) and steel fibres.	Permeability test.	(1) Steel fibre alone did not provide any protection, while the inclusion of 4 kg/m3 of PP fibre suppressed the explosive spalling of UHPC. (2) Hybrid PP and

				steel fibres completely prevented explosive spalling even at low fibre dosage due to a significant increase in permeability.
19.	Mojtaba Tabatabaeian et al. (2017)	Hooked-end steel fibres and polypropylene fibres.	Slump flow, J-ring and V-funnel tests compressive strength, splitting tensile strength, modulus of rupture and flexural toughness tests, ultrasonic pulse velocity electrical resistivity test.	(1) PP fibres(0.2% & 0.3%) drop the slump flow of hybrid fibre reinforced mixtures. (2) In the J-Ring test, steel fibres in greater percentage reduced workability due to long length. (3) All V-funnel flow time was within the allowable range(6-12 sec) for SCC. (4) Based on the Analysis of Variance, CS slightly increased with the addition of steel fibres at 28 days. (5) Replacement of steel fibres with PP fibres led to reduced CS compared to the Control mix up to 38%.

2.4 Summary of some other past reviews of Literature on FRC and HyFRC

The durability of HPC can also be enhanced considerably by using hybrid fibre reinforcement. A study revealed that using polypropylene and steel fibres significantly reduced chloride ion penetration compared to single fibre-reinforced HPC.

In conclusion, hybrid fibre reinforcement in HPC significantly enhances the material's strength, toughness, and durability. The combination of different fibres can be customised to meet specific design requirements, producing high-quality and sustainable construction materials.

Table 2.2 Past Review of Literature before year 2000 on FRC and HyFRC

Authors	Fibres Investigated	Major Findings	Observation
Wimal Suaris et al. (1983)	S, PP, G	FRC structures with loads coming from impact and impulsive loading are studied. Energy absorbed by Steel FRC (100%) is higher than unreinforced specimens.	The energy absorbed by steel FRC is higher than PP FRC and Glass FRC.
Gopalaratnam et al. (1986)	S	Steel FRC subjected to impact load is studied. The comp. strength of FRC is higher (34%) rather than normal concrete.	Concrete with less bound matrices, higher fibre dosage and more significant aspect ratio are more rate-sensitive than those with more robust matrices, with low fibre dosage and small aspect ratio.
Narayanan et al. (1987)	S	When compressive strength enhanced from 42 MPa to 62 MPa (about 50 per cent), an increase in shear strength from 1.97 MPa to 3.23 MPa (about 64 per cent) was observed.	The beam was reinforced with conventional stirrups and fibres in concrete.
Barr (1987)	S, PP, G	The influence of the shear performance of FRC materials is studied. The matrix had shear strength of 8 MPa for 1 per cent addition, while 10 MPa for 4 per cent addition of fibres	The inclusion of fibres in the matrix increased the shear performance of concrete.

Swamy et al. (1987)	S	The results show that the crack width varied from 0.15 mm to 0.53 mm with about 75 per cent of the values in the range of 0.15 mm to 0.30 mm.	Fibres in conjunction with steel stirrups are studied.
Gopalaratnam et al. (1991)	S, PP	The behavior of fracture toughness of fibre-reinforced concrete is studied. The concrete mixes were designed for the compressive strength of 34.48 to 41.37 MPa.	The stress at the first crack was observed to be relatively independent of the fibre volume fraction.
Banthia et al. (1995)	S	The toughness characterization of SFRC using deformed steel fibres is studied. It was found that no significant improvements in strengths or moduli were possible at a low fibre dosage of 40 kg/m3. Deformed fibres, in general, brought substantial progress in the toughness of concrete.	A strong influence of fibre geometry and matrix strength on the toughness characteristics of fibre-reinforced concrete was observed.
Ali R Khaloo et al. (1997)	S	A study is done on the direct shear behaviour of SFRC from low-strength to high-strength concrete. The SFRC specimens showed a comparatively ductile type of failure, whereas failure in plain specimens occurred in a very brittle manner with little warning before the collapse.	Steel fibres were used to study the direct shear properties with conventional stirrups.
Mirsayah A.Amir et al. (2002)	S (various geometry)	The shear behaviour of FRC.	Shear tests were conducted using JSCE-SF6 standard test method.
Senthil Kumaran (2012)	waste tyre fibre	The development of a ―New Generation Rubberised Concrete (NGRC)‖ is studied. The shear behavior of NGRC is studied using direct shear with slits. The distance between the slits was 30mm, 60mm, 90mm, 120mm and 150mm.	It was observed that from 30mm slit to 60mm slit, the reduction in shear stress was around 68% for NGRC and Control Specimen.

Ramanalingam et al. (2001)	PVA (micro and macro), S	Concrete reinforced with steel (1.5%) and PVA (0.5%) showed a flexural strain –hardening behavior accompanied by multiple cracking when a large amount of cement in the composite (50%) was replaced by fly ash.	The resulting composite had high flexural strength, toughness, and ductility. Hybridization provided significant increases to both ultimate load and post-peak ductility.

2.5 Research Gap

There is ample scope to work with different fibre hybridization such as PP, B & HES fibres in various combinations on high-performance concrete. The utilization of Copper slag in fibre-reinforced high-performance concrete is significantly restricted. Lack of Mechanical and Durability properties with PP, B & HES fibres with substitution of copper slag was seen throughout the literature review. No work was reflected in the literature regarding PP, B & hooked end steel fibre combination for high-performance concrete with copper slag. The outcome is solely confined to various types of fibers, without replacing the Fine aggregate. Therefore, there is ample scope to introduce all these fibres in combination (PP-B-HES) in concrete. It is required to investigate further essential properties for developing high-performance concrete of M65 grade, which can be used in actual practice. Based on the fibre constitutive response, fibre dimensions, fibre functions and fibre performances, hooked-end steel fibre, polypropylene fibre and basalt fibre are selected for this research. Silica fume and fly ash are the essential constituents for making high-strength concrete, and to prevent depletion of fine aggregate, other waste material, such as copper slag, is used in this research to make the environment ecologically sustainable.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 General

This section discusses the complete research process, including materials used to conduct the study and comprehensive research methodology. Moreover, the experimental procedure is also elaborated in the subsequent section to understand the research methodology in detail.

3.2 Materials Used in mix design

As per ACI Committee 363R-92, the main raw ingredients used to develop the concrete mix design for HSC were cement, fly ash, silica fume, coarse aggregates, fine aggregates, Polypropylene fibres, basalt fibres, hooked end steel fibres, polycarboxylate ether (PCE) based superplasticizer, and water.

3.2.1 Cement

OPC of 53-grade Ultratech cement with minimum compressive strength of 53 MPa was used. The cement met the requirements of IS 8112-2013. Table 3.1 displays the cement test results of the 53-grade cement used in OPC. All required cement tests have been completed before casting and compared to OPC 53 grade standards.

Figure 3.1 Ultratech Ordinary Portland Cement of 53 Grade

Table 3.1 Cement Test Results

S. No	Test	Laboratory results	Suggested values as per I.S 12269 - 1987 specification
1	Fineness of Cement*		
	a) Sieve test	4.52%	< 10.0 %
	b) Specific surface Area	315 m^2/kg	--
2	Specific gravity	3.10	--
3	Normal consistency	33%	--
4	Setting time		
	Initial setting time	75 min	Min 30 min
	Final setting time	235 min	Max 440min
5	Compressive Strength at		
	Three days	30.4 N/mm^2	27.0 N/mm2
	Seven days	42.7 N/mm^2	37.0 N/mm2
	Twenty Eight days	57.8 N/mm^2	53.0 N/mm2

*Ultratech OPC cement is used throughout the research work.

3.2.2 Admixtures

A pozzolan substance called fly ash admixture was acquired from manufacturer Azure India, Delhi. According to IS 456-2000, FA is typically used as a partial substitution for cement. The widely used mineral additive silica fume, according to IS 5388: 2003, was employed in the mix design to create high-strength concrete. Silica fume was purchased from Advance Chemical Sales Corporation Pitam Pura, Delhi. An excellent water content reduction, slump retention admixture, and polycarboxylate ether (PCE) chemical admixture was used and the optimum dose was obtained from Marsh Cone.

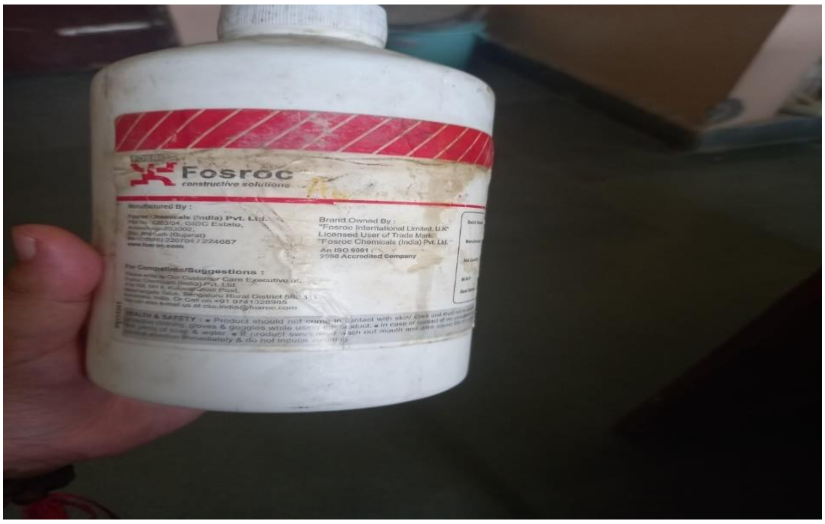

Figure 3.2 FOSROC chemical Admixture

3.2.3 Aggregates

Natural Sand was purchased from company M. K Traders in Gurugram, Haryana, India; Zone II sand, under IS 383: 2016, was identified based on the sieve analysis test results, along with the fineness modulus of sand utilized in the experiment was determined. The fine aggregate (FA) was subjected to sieve analysis to produce the particle size distribution curve depicted in Figure 3.3; for the design mix, coarse aggregates (CA) with a maximum size of aggregate of 20 mm are used. Coarse aggregate was purchased from Sani Builder, Noida, Gautam Buddh Nagar.

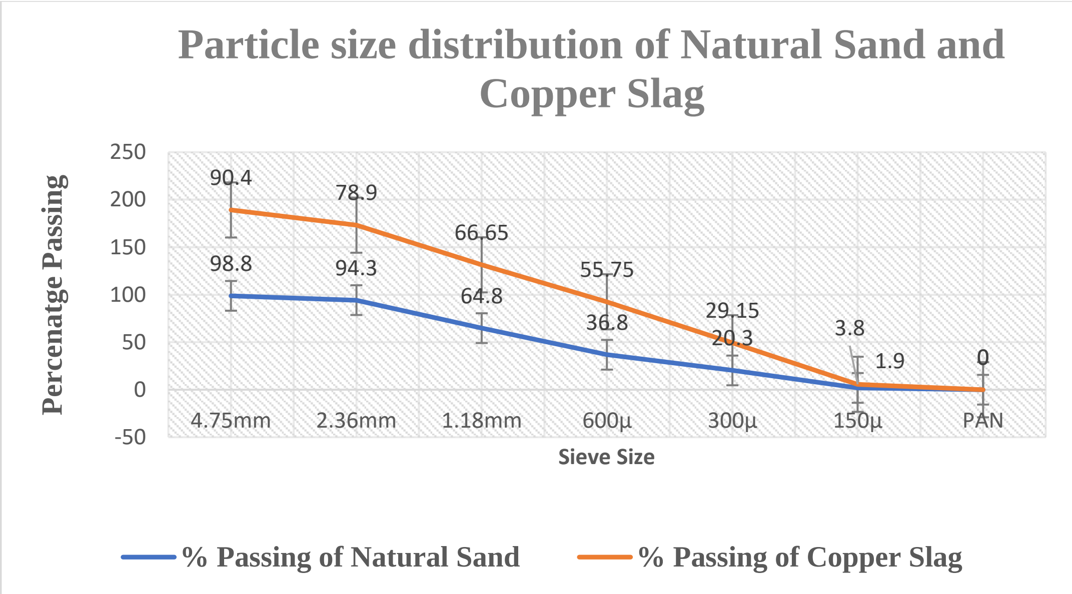

Figure 3.3 Particle size gradation Curve of Natural Sand and Copper Slag.

Table 3.2: Sieve Analysis of Natural Sand

IS Sieve Size in mm	Retained in gms	% Retained	Cumulative % Retained	% Passing	Acceptable Limit	Remarks
4.75mm	12	1.2	1.2	98.8	90-100	Confirming to Grading Zone II
2.36mm	45	4.5	5.7	94.3	75-100	
1.18mm	295	29.5	35.2	64.8	55-90	
600μ	280	28	63.2	36.8	35-59	
300μ	165	16.5	79.7	20.3	8 to 30	
150μ	184	18.4	98.1	1.9	0-10	
PAN	19	1.9	100			

Table 3.3: Sieve Analysis of Copper Slag

IS Sieve Size in mm	Retained in gms	% Retained	Cumulative % Retained	% Passing	Acceptable Limit	Remarks
4.75mm	96	9.6	9.6	90.4	90-100	Confirming to Grading Zone II
2.36mm	115	11.5	21.1	78.9	75-100	
1.18mm	122.5	12.25	33.35	66.65	55-90	
600µ	109	10.9	44.25	55.75	35-59	
300µ	266	26.6	70.85	29.15	8 to 30	
150µ	253.5	25.35	96.2	3.8	0-10	
PAN	38	3.8	100			

Table 3.4: Physical properties of Fine Aggregate (Natural Sand)

S. No.	Property	Values Obtained
1	Specific gravity	2.69
2	Fineness modulus	2.75 as per (IS 383:2016)
3	Grading	Zone – II as per (IS 383:1970)

Table 3.5: Physical properties of coarse aggregate

S.NO	Property	Values obtained
1	Specific gravity	2.759 as per (IS 2386: Part III -1963)
2	Water absorption	0.70% as per (IS 2386: Part III -1963)
3	Crushing value	21.43% as per (IS 2386: Part IV-1963)
4	Impact value	15.50% as per (IS 2386: Part IV-1963)

3.2.4 Polypropylene, Basalt and Hooked End Steel Fibres

The polypropylene fibre, Basalt Fibre and Hooked End Steel fibres were taken from MF Composites, Dilshad Garden, Ghaziabad and are utilized throughout the research work. Hooked-end steel fibre has a 60mm length and 0.75mm diameter, polypropylene fibre has a 12 mm length and 0.022mm diameter, and basalt fibre has a 12 mm length and 12-micrometre diameter.

3.2.5 Copper Slag

Figure 3.4 Copper Slag

3.3 Mix Design Proportion of Concrete

Thirteen mix proportion compositions are established to comprehend the mechanical behavior of high-strength concrete and the viability of hybrid fibres. Table 3.7 displays the numerous mixed-design compositions that are developed. Basalt fibre, polypropylene fibre, and hooked-end steel fibre were hybrid fibres.

Table 3.7 focuses on various mix proportions PP0B0HES0CS0 shows the control mix. Mix PP0B0HES0CS20 and PP0B0HES0CS40 represents 0% Polypropylene, 0% Basalt, 0% Hooked End Steel fibres and Copper Slag of 20% and 40%, respectively. Similarly, PP0.25B0.5HES0.25CS40 represents 0.25% Polypropylene, 0.5% Basalt, 0.25% Hooked End Steel fibres and Copper Slag of 40%. Similarly, all the remaining mix designations were nomenclature.

Initially, Coarse aggregate (CA) and Fine Aggregate (FA) were introduced to the concrete mixer for batching, and the mixer received automated revolutions for roughly a minute. At this point, mineral additive silica fume, fly ash, and cement were added. The determined amount of water and Superplasticizer (SP) was added, and the mixture was homogenized correctly before being slowly added to the mixer. Finally, the appropriate dose of hybrid fibres was equally distributed throughout the dry mixer, and the mixer once more received automatic revolutions for another minute. All the mix components received enough revolutions for around three minutes to produce a satisfactory blend.

The mixing process was now halted, and the prepared concrete mixture was poured into moulds with the dimensions 150*150*150mm and 500*100*100mm, respectively, for the manufacture of cubic and prismatic beam samples for subsequently conducting compressive and flexure tests. Using a shaking table to create a dense mixture for generating a high-strength concrete mix, the prepared concrete mix was poured into three layers to achieve enough compaction. The set samples were also demolded after 24 hours and then cured in water for 28 days. The samples were ready for testing for ultrasonic pulse velocity tests after 28 days of water curing before flexure and compressive strength test by IS 516-1959 and IS 456-2000 these tests were conducted.

Figure 3.5 Hooked End steel fibres

Figure 3.6 Polypropylene Fibres

Figure 3.7 Basalt Fibres

Table 3.6 Properties of Hybrid fibres used

Properties of Fibres	**Polypropylene Fibre**	**Basalt Fibre**	**Hooked End Steel Fibre**
Density (Kg/m^3)	910	2650	7850
Tensile Strength (MPa)	310-540	2800-3100	1140
Elastic Modulus (GPa)	3.72	85-87	210
Melting Point (ºC)	160-170	-200 to +900(Operative Temp.)	400-500
Failure Strain (%)	19-20	3.1	3-4

Table 3.7 Concrete mix design for HFRC (kg m^{-3}) (As per IS 10262:2019)

S.No.	Mix Designation	Cement	Fine Aggregate	Coarse aggregate	Water	Chemical admixture	Fly ash	SF	PP (Vf%)	B (Vf%)	HES (Vf%)	CS
1	Control Mix PP0B0HES0CS0	441	578	1169	142	1.12	105	43	-	-	-	-
2	PP0B0HES0CS20								-	-	-	20%
3	PP0B0HES0CS40								-	-	-	40%
4	PP0.25B0.5HES0.25CS40								0.25	0.50	0.25	40%
5	PP0.5B0.25HES0.25CS40								0.50	0.25	0.25	40%
6	PP0B0.75HES0.25CS40								-	0.75	0.25	40%
7	PP0.75B0HES0.25CS40								0.75	-	0.25	40%
8	PP0.25B0.25HES0.5CS40								0.25	0.25	0.50	40%
9	PP0B0.5HES0.5CS40								-	0.50	0.50	40%
10	PP0.5B0HES0.5CS40								0.50	-	0.50	40%
11	PP0.25B0HES0.75CS40								0.25	-	0.75	40%
12	PP0B0.25HES0.75CS40								-	0.25	0.75	40%
13	PP0.125B0.125HES0.75CS40								0.125	0.125	0.75	40%

3.4 Experimental Program and Challenges

This section deals with the research methodology conducted to achieve the desired objectives to determine high-performance concrete's mechanical and durability properties. Material Variability and Selection: One of the primary challenges is the inherent variability in the materials used. The quality and properties of cement, aggregates, and fibers can differ significantly between batches, affecting the consistency of the concrete mix. Mixing and Homogeneity, Workability and Compaction, Curing Conditions and testing procedures also act as challenges.

3.4.1 Compressive Strength

To determine the CS of various mix compositions, 36 cubes as samples with dimensions of 150* 150* 150 mm were cast, cured, and tested at 28 days by the IS Code [IS-456:2000]. Standard equipment with a capacity of 2000 kN for strength estimation was used. The loading rate was 5.18 kN s^{-1} for the samples. Three cubes average strength of every mix was considered as compressive strength.

3.4.2 Flexural Strength

36 beam samples having 150*150*700 mm in size, with 12 various mix proportions, were cast and subjected to flexure testing. According to ASTM C1609 requirements, four-point loading was used to calculate the specimen's flexural strength incorporated hybrid fibres. A load of 0.035 to 0.1 mm per minute was applied to the specimen. Under displacement control, a 0.6 mm min^{-1} deflection rate was performed. This test method and residual loads that take into consideration the L/600 and L/150 deflection were used to calculate the peak load (P) because aggregate can only be 20 mm in size, and the size of the beam specimen that was taken is 150 mm x 150 mm x

700 mm. This flexural strength test was conducted in UTM & with a loading rate of 400 kg/min till failure. The modulus of rupture is used in Equation 2 to calculate strength.

$$f = PL/Bd^2 \tag{1}$$

Where "L" stands for the beam's length, "d" for its depth, "P" for its failure load, and "f" for its flexural strength.

3.4.3 Split Tensile Strength

Three cylinders for each mix type were subjected to STS testing by ASTM C39 specifications. Every minute, 12 MPa of loading occurs. For testing, 36 cylinders of hybrid fibres in varied proportions were put into each sample. The specimen is 150mm x 300mm in size. From 0.7 to 1.4 MPa/min of the load was applied to the ST test until failure. STS was Determined using the formula provided in the Indian standard, by ASTM C496 standards.

$$fst = 2P/\pi DL \tag{2}$$

In this formula, L denotes the cylinder's length, D its diameter, P its failure load, and fst, its split tensile strength.

3.4.4 Specific Electrical Resistivity and Water Absorption.

An electrical resistivity test is conducted on a 100mm x 200mm cylinder. An AC-Impedance spectroscopic technique determined the electrical resistivity using a 1.0 kHz frequency and 1.0 Ω-m ultimate capacity. According to BS 1881-122, cubic specimens were subjected to water absorption tests. In water, samples were cured for 27 days at 22 degrees centigrade. After that, the samples were dried for at least 14 days in an oven set at 45 degrees Celsius. If the values obtained from two successive mass measures differed by more than 0.5% of the smaller value, the specimens were put back in the oven for an additional 24-hour drying period. The weights of the samples were then measured over a more extended period until there was a 0.5% variation between any two successive measurements. The cured specimens were then wiped with a dry paper towel, submerged in a tank filled with water for half an hour and 168 hours, and weighed on a 0.01 g balance. The early and final water absorptions are referred to in the current study as occurring at 0.5 hours and seven days, respectively. The remaining tests were conducted at 7, 28, and 91 days. ASTM C642-21 conducts the water absorption test.

Figure 3.8 Cement before casting

Figure 3.9 Coarse Aggregate

Figure 3.10 Casted Cubes of size 150mm x 150mm x150 mm

Figure 3.11 Demoulded Cubes

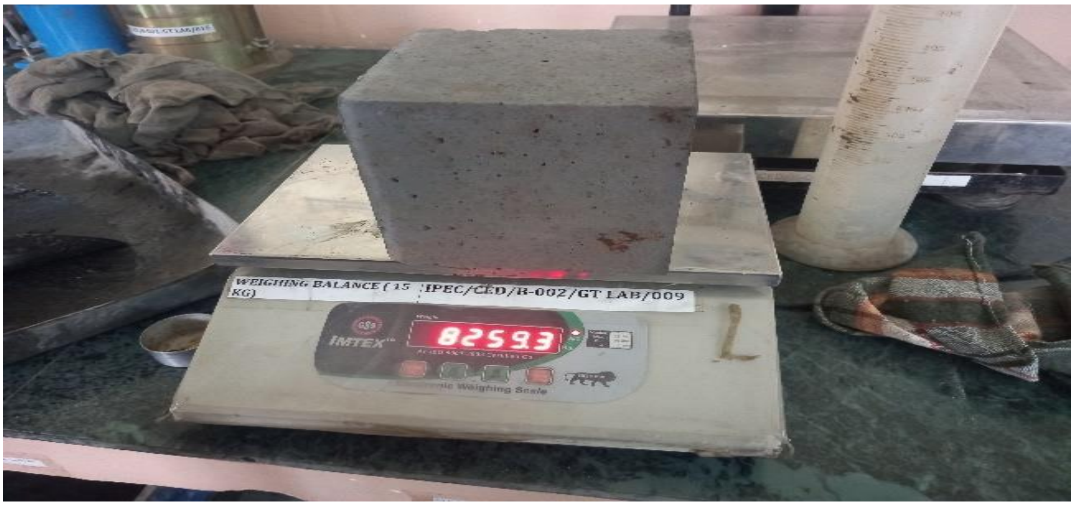

Figure 3.12 Cube Weight after demoulding

Figure 3.13 Sorptivity Samples for a Durability Test

Figure 3.14 Cube under test experiment.

Figure 3.15 Cylinder under test experiment

Figure 3.16 Samples for sorptivity test

Figure 3.17 Samples prepared for the test experiment

Figure 3.18 Casted beams, cylinders and cubes

Figure 3.19 Casted samples under the curing tank

Figure 3.20 Some more casted and prepared samples

Figure 3.21 Casted cubes of size 150mm x 150 mm x 150mm for water permeability test

Figure 3.22 Cylinder samples are cured under a water tank.

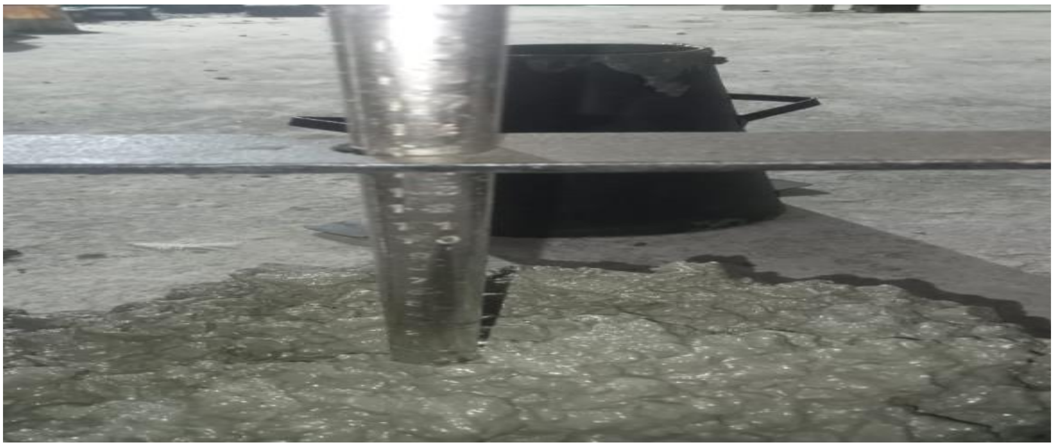

Figure 3.23 Workability Test (Slump Test)

Figure 3.24 Demolition waste of tested samples.

3.4.5 Water Permeability Test

In structures that are meant to hold water or that come into touch with water, cement mortar or concrete's permeability is particularly important. In addition to functional factors, permeability is closely linked to concrete's durability, especially its resistance to gradual loss under exposure to harsh climatic factors and leaching because of extended water seepage, primarily when it includes aggressive gases or minerals in the solution. So, it becomes extremely important to determine the permeability properties of concrete.

This test is conducted on a 150mm size cube by DIN 1048. The weight of the sample is noted initially. After that, fix the sample onto the permeability test setup and fix it. Keep the pressure of 5 kg/cm^2 constant for three days or 472+/- 2 hours. Then, after three days, split the sample into two halves, measure the penetration depth along the length, and take the maximum penetration depth. An average of 3 samples are taken as the water permeability. Generally, if the penetration depth is less, the sample is good. Due to the addition of fibres, the penetration depth is less and a 30-35 mm clear cover is achieved.

3.4.6 Sorptivity test

This experiment is carried out to determine how vulnerable unsaturated concrete is to water penetration. With capillary suction, it gauges how quickly water and other liquids are absorbed into unsaturated concrete. A concrete mixture is used to cast moulded cylinder samples, which are then water cured for 28 days. A 2-inch (50-mm) slice of the cylinder is taken, put in an evaporation cell for three days at 122 °F (50 °C) and 80% relative humidity, and then covered for at least 15 days. It is submerged in water after applying epoxy to the slice's outside and top. Over the period, the slice's change in mass is monitored.

This test is conducted following ASTM C 1585 on 100mm x 200mm cylinders. In this test, the cylinder sample is cut into three pieces and a cut of 50mm interval is achieved after leaving the space from the top and bottom of the cylinder. The sample is cut with the cutter blade of thickness 3-4mm and in that case approximate 15mm portion remains waste. One piece of sample weighs around 1 kg, and the total weight of the cylinder is 3-3.5kg. The dry weight or constant weight of the sample is initially noted down. After three days, the sample is kept in the environmental chamber or oven at 50 degrees, +/- 5 degrees centigrade and a Relative Humidity of 65 is maintained. Potassium Bromide powder is added to the tray to maintain the relative humidity. After three days, samples are kept in an airtight container for at least 15 days. The sides of the samples are coated with epoxy to inhibit moisture or water ingress into the sample. After that, the samples are covered with polythene with a rubber band. After that, the tray is taken and adjusted to keep samples over a corrosion-free pipe of thickness 4-15mm. The samples are immersed 2-3mm in water. The weight taken before the coating of epoxy is considered as W1. After coating epoxy and applying polythene (before dipping into water), the weight considered at 0 seconds is W2. After that, 60 seconds, 5 minutes, 10 minutes, 20 minutes, 30 minutes, 60 minutes, 2 hours,3 hours, 4 hours, 5 hours and 6 hours weights are noted down and considered as initial absorption. At 24 hours up to 6 days, weights are noted down and are referred to as secondary absorption.

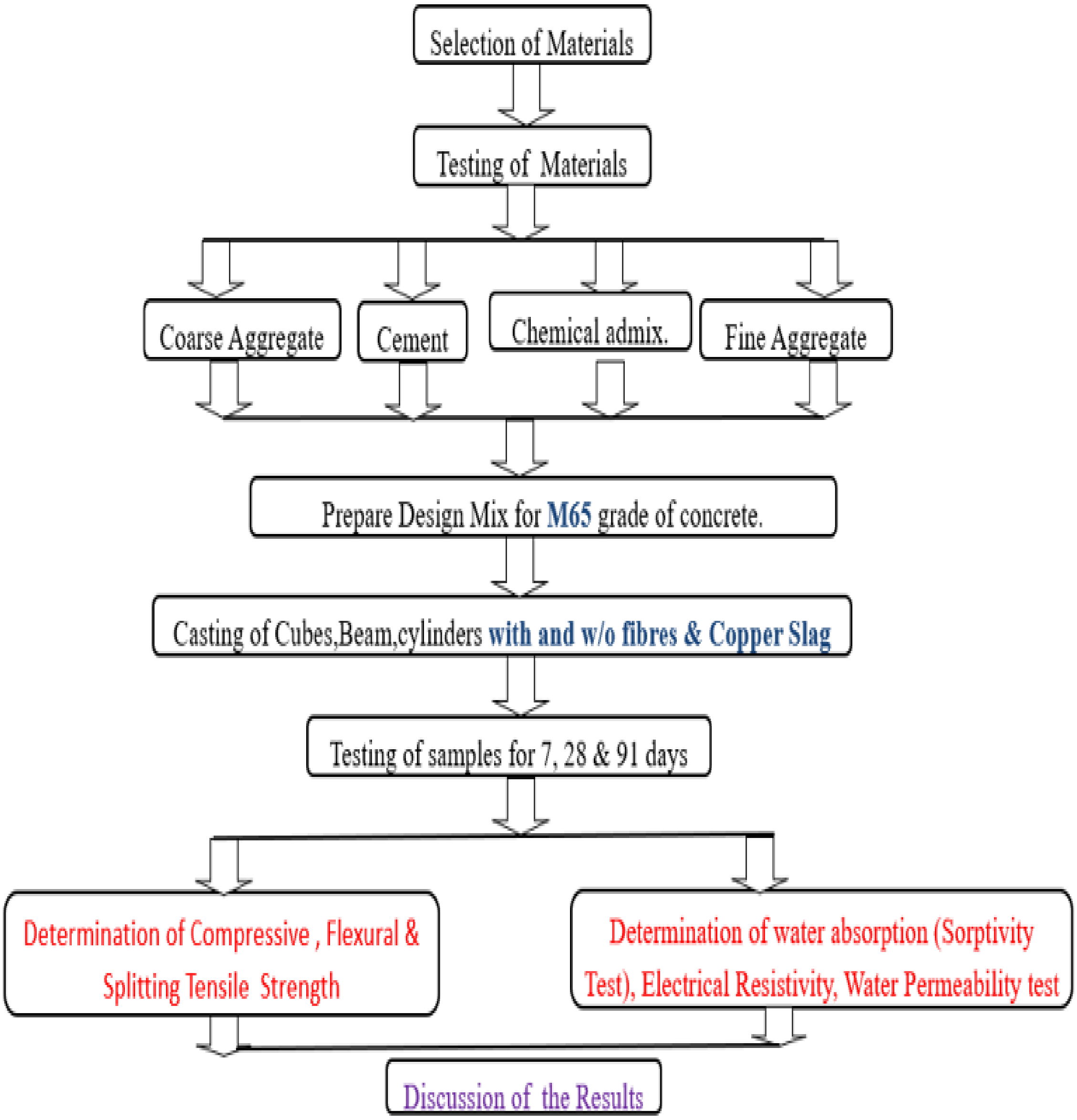

Figure 3.25 Flow Diagram of Research Methodology

Table 3.8 Fibre % and Copper Slag % in different concrete Mixes.

S No	Mix Designation	Fibres (Vf%)			Fine Aggregate Replacement (%)
		PP	B	S	Copper Slag
1	Control Mix PP0B0HES0CS0	-	-	-	-
2	PP0B0HES0CS20	-	-	-	20%
3	PP0B0HES0CS40	-	-	-	40%

4	PP0.25B0.5HES0.25CS40	0.25	0.50	0.25	40%
5	PP0.5B0.25HES0.25CS40	0.50	0.25	0.25	40%
6	PP0B0.75HES0.25CS40	-	0.75	0.25	40%
7	PP0.75B0HES0.25CS40	0.75	-	0.25	40%
8	PP0.25B0.25HES0.5CS40	0.25	0.25	0.50	40%
9	PP0B0.5HES0.5CS40	-	0.50	0.50	40%
10	PP0.5B0HES0.5CS40	0.50	-	0.50	40%
11	PP0.25B0HES0.75CS40	0.25	-	0.75	40%
12	PP0B0.25HES0.75CS40	-	0.25	0.75	40%
13	PP0.125B0.125HES0.75CS40	0.125	0.125	0.75	40%

NOTE: PP- Polypropylene fibre, B-Basalt fibre, HES- Hooked End Steel Fibre, CS- Copper Slag. The total fibre volume fraction of 1% by Volume of concrete to study the effect of fibre hybridization.

Table 3.9 Number of Specimens for Various Tests

S.No.	Test	Specimen Description	Age (Days)	Nos.	Total No. of Samples
1	Compressive Strength	Cube: 150x150x150(mm)	7,28	12	13*6=78
2	Flexural Strength	Beam: 100x100x500(mm)	28	3	13*3=39
3	Splitting Tensile Strength	Cylinder: 100x200 (mm)	7,14,28	12	13*9=117
4	Water Permeability Test	Cube: 150x150x150(mm)	28,56	6	13*6=78
5	Water Absorption (Sorptivity test)	Cylinder: 150x300 (mm)	28	3	13*3=39
6	Specific Electrical Resistivity	Cube:100mm	7,28,91	9	13*9=117

The age of testing for Water Permeability and Water Absorption (Sorptivity test) is based on the published literature and this is also the limitation of the study.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

This section deals with the results and discussion of various characteristics of High-Performance concrete, which includes hardened properties as well as durability properties. Moreover, the results are also supporting other published researcher's contributions to high-performance concrete.

4.2 Results and Discussion on Mechanical Property

The mechanical properties of high-performance concrete incorporating hybrid fibres are addressed in the subsequent section, and its validation with other researchers' work in high-performance concrete is shown.

4.2.1 Effect of hybrid fibres on the fresh property of Concrete

Figure 4.1 shows the Slump test of different hybrid mixes with controlled concrete. The Mix PP0B0.25HES0.75CS40 offers the lowest slump value of 130 mm compared to Control Mix PP0B0HES0CS0, reported as a 170 mm slump. PP0B0HES0CS0 signifies 0% polypropylene fibre, 0% basalt fibre, 0% hooked-end steel fibre, and 0% copper slag and the same nomenclature with different percentages of all other mixes with fibres is addressed.

The varying proportions of fibres, the methods used to assess, and the results align with the trends observed by the other authors for fresh properties used in this study. The observed slump value (130 mm) is consistent with what has been reported in previous studies. There is a similarity in the context of slump patterns for concrete mixes with different fibre and slag content. The observed pattern of slump value aligns with the other authors despite factors such as variations in materials, mix design, testing methods, and environmental conditions.

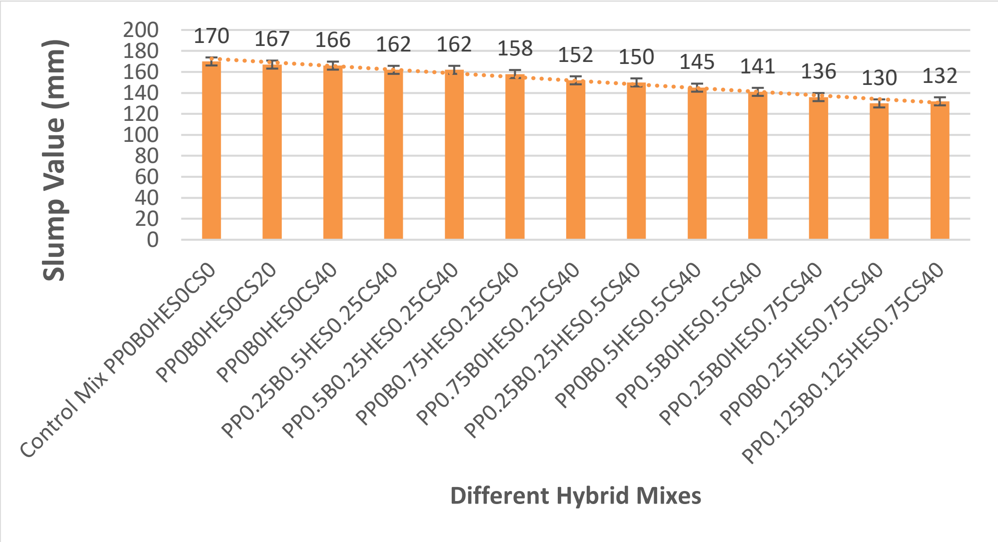

Figure 4.1 Slump test of different hybrid mix with reference to controlled concrete.

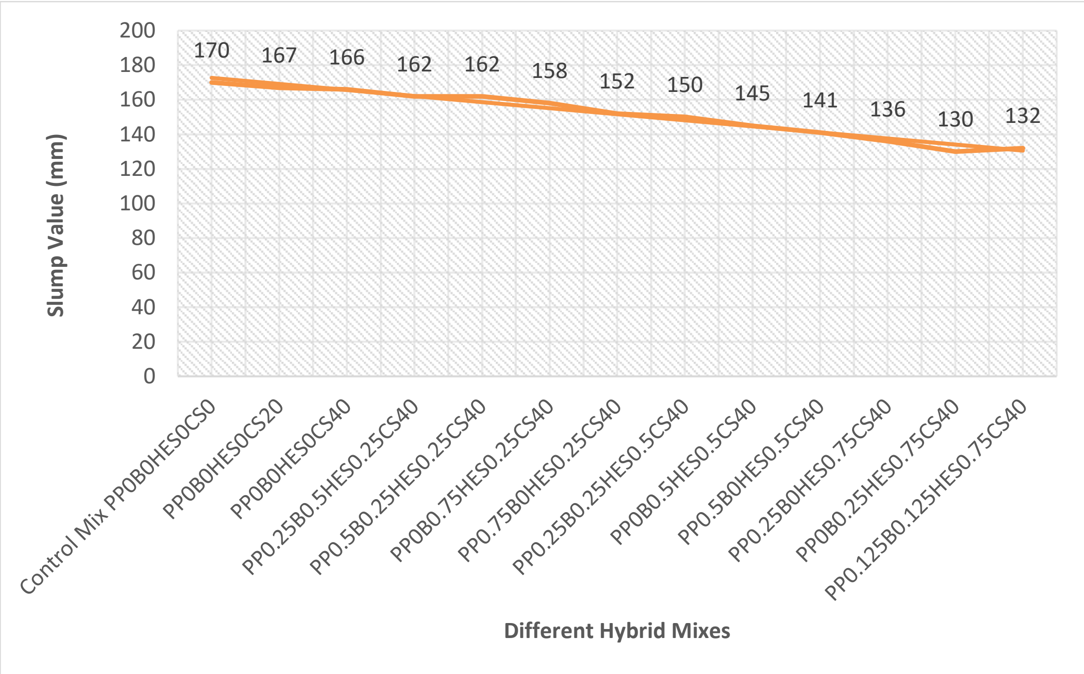

Figure 4.2 Slump value of hybrid mix with reference to controlled concrete.

4.2.1 Effect of hybrid fibres on compressive strength of Concrete

As it is very clear from Figure 4.3 and Table 4.1, the compressive strength of hybrid fibres of 13 mixes has different strengths at seven days and 28 days of curing. After minute monitoring of tested cubes in CTM, the findings reveal that the control mix PP0B0HES0CS0 has a compressive strength of 76.5 MPa. In addition to this, on increasing the dosage of hybrid fibres, the behaviour of tested samples changed, and maximum compressive strength is reported for mix PP0.5B0HES0.5CS40, i.e., 78 MPa, which is 1.96% greater but insignificant as compared with the control mix

PP0B0HES0CS0. After that, all the mixes strength starts decreasing with a similar trend. The lower compressive strength is because the failure is due to compressive loading and not due to fracture; the concentration of fibres in compression does not significantly increase. Although compressive strength in terms of capacity to carry loads does not satisfy the criteria, the increased fibre dosage in cubes indicates that the fracture width has decreased. Table 4.1 also demonstrates that depending on the replacement amount of steel, polypropylene fibre, and basalt fibre PP0.5B0HES0.5CS40 mix shows maximum strength. The mix of 0.5% PP and 0.5% hooked-end steel fibres produced the maximum compressive strength out of all the steel, PP fibre and basalt fibre combinations considered in this investigation.

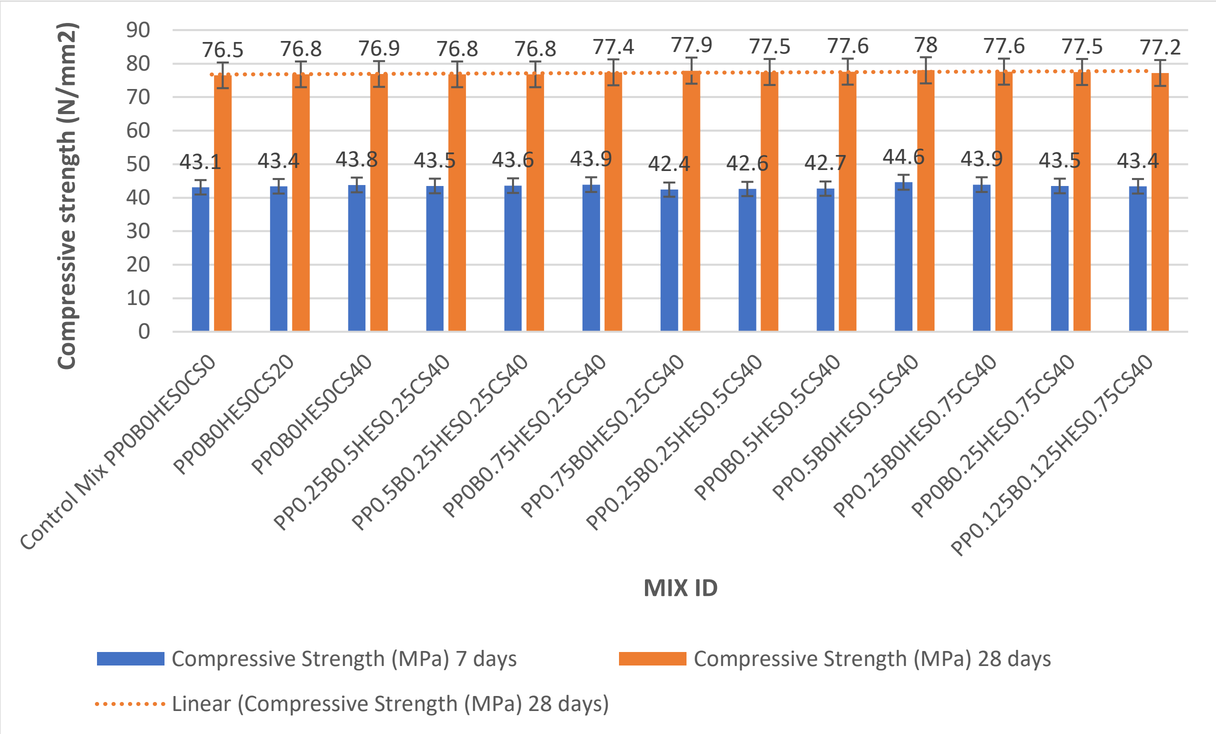

Figure 4.3 Comparison of compressive strength of hybrid fibre HPC with reference to controlled concrete.

Table 4.1 Compressive strength of hybrid fibre HPC.

Mix Designation	Compressive Strength (MPa)	
	Seven days	**28 days**
Control Mix PP0B0HES0CS0	43.1	76.5
PP0B0HES0CS20	43.4	76.8
PP0B0HES0CS40	43.8	76.9
PP0.25B0.5HES0.25CS40	43.5	76.8
PP0.5B0.25HES0.25CS40	43.6	76.8

PP0B0.75HES0.25CS40	43.9	77.4
PP0.75B0HES0.25CS40	42.4	77.9
PP0.25B0.25HES0.5CS40	42.6	77.5
PP0B0.5HES0.5CS40	42.7	77.6
PP0.5B0HES0.5CS40	44.6	78
PP0.25B0HES0.75CS40	43.9	77.6
PP0B0.25HES0.75CS40	43.5	77.5
PP0.125B0.125HES0.75CS40	43.4	77.2

PP0B0HES0CS0 signifies 0% polypropylene fibre, 0% basalt fibre, 0% hooked-end steel fibre, and 0% copper slag and the same nomenclature with different percentage of all other mixes with fibres are addressed.

In Summary, the control mix (PP0B0HES0CS0) achieved a compressive strength of 76.5 MPa, serving as the baseline reference. Increasing the dosage of hybrid fibres resulted in changes in the compressive strength of tested samples. Mix PP0.5B0HES0.5CS40 demonstrated the highest compressive strength among the tested mixes, reaching 78 MPa, which is 1.96% greater but insignificant as compared with the control mix PP0B0HES0CS0 the control mix. This finding suggests that this particular mix, with 0.5% polypropylene (PP) fiber and 0.5% hooked-end steel (HES) fiber along with 40% copper slag (CS) replacement, was the most effective in enhancing compressive strength. Subsequent to the peak strength (PP0.5B0HES0.5CS40), all other mixes exhibited a decreasing trend in compressive strength. This decrease may be attributed to factors such as fiber concentration and the specific behavior of these fibres in compression. The influence of hooked end steel, polypropylene fiber, and basalt fiber on compressive strength is relatively minimal. This conclusion aligns with the observation that the highest compressive strength was achieved with a combination of 0.5% PP and 0.5% HES fibres, indicating that steel, polypropylene fiber, and basalt fiber do not have a pronounced impact together on compressive strength. Although the increased fiber dosage didn't significantly enhance compressive strength in terms of load-carrying capacity, it did lead to a decrease in fracture width. This finding suggests that the primary role of the hybrid fibres may be related to improving the concrete's crack control capacity rather than solely increasing compressive strength. The observed trends in this research align with other authors' despite of different fibre types and dosages on concrete compressive strength.

4.2.2 Effect of hybrid fibres on flexural strength of Concrete

As it is very clear from Figure 4.4 and Table 4.2, the flexural strength of hybrid fibres of 13 mixes has different strengths at 28 days of curing. The findings after minute monitoring of tested beams in UTM reveal that the control mix PP0B0HES0CS0 has a flexural strength of 5.96 MPa. In addition to this, on increasing the dosage of hybrid fibres, the behaviour of tested beam samples changed and maximum flexural strength is reported for mix PP0.5B0HES0.5CS40 i.e., 10.3 MPa, which is 72.81 % greater than the control mix PP0B0HES0CS0. After that, all the mixes and strength start decreasing with a similar trend. The combination

PP0.25B0.5HES0.25CS40 shows the lowest flexural strength out of the 13 mixes prepared. The improvement in strength brought on by adding supplementary cementitious materials, including silica fume, is due to the more robust connection between the wet cement matrix and the aggregate. Due to the conversion of calcium hydroxide, which typically occurs on the surface of aggregate particles, into CSH in the presence of reactive silica, the connection is reinforced. The reason for increased flexural strength incorporating hybrid fibres is the densest inter-particle packing in the concrete matrix and strong bond. Table 4.2 also demonstrates that depending on the replacement amount of steel, polypropylene fibre, and basalt fibre PP0.5B0HES0.5CS40 mix shows maximum strength. The mix of 0.5% PP, 0 % Basalt fibre and 0.5% hooked-end steel fibres produced the maximum flexural strength at 28 days of curing out of all the steel, PP fibre and basalt fibre combinations considered in this investigation.

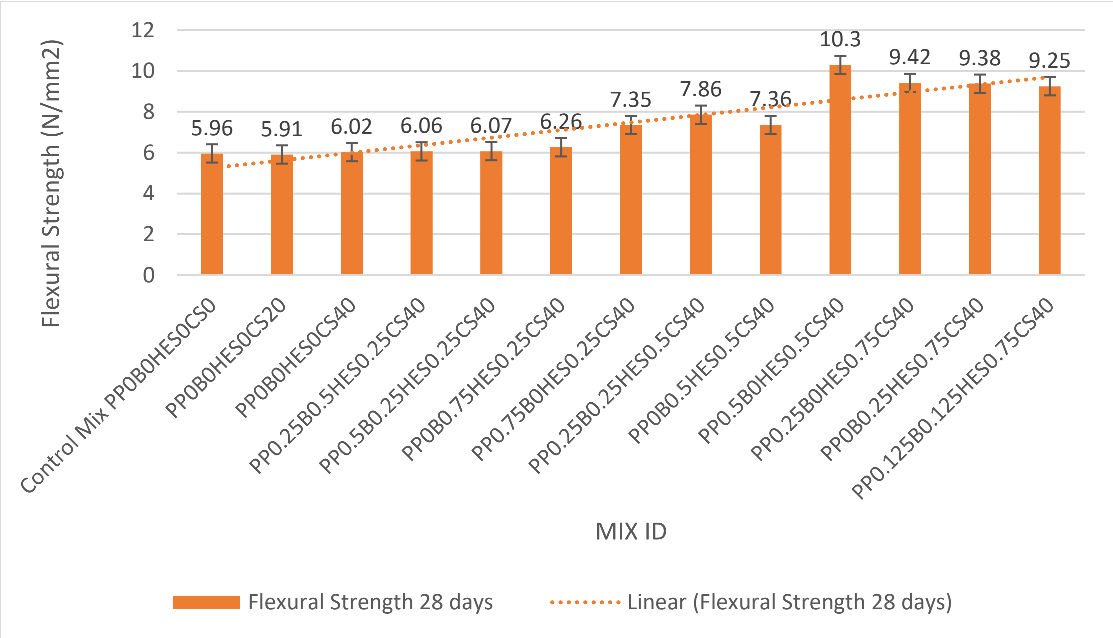

Figure 4.4 Comparison of Flexural strength of hybrid fibre HPC with reference to controlled concrete.

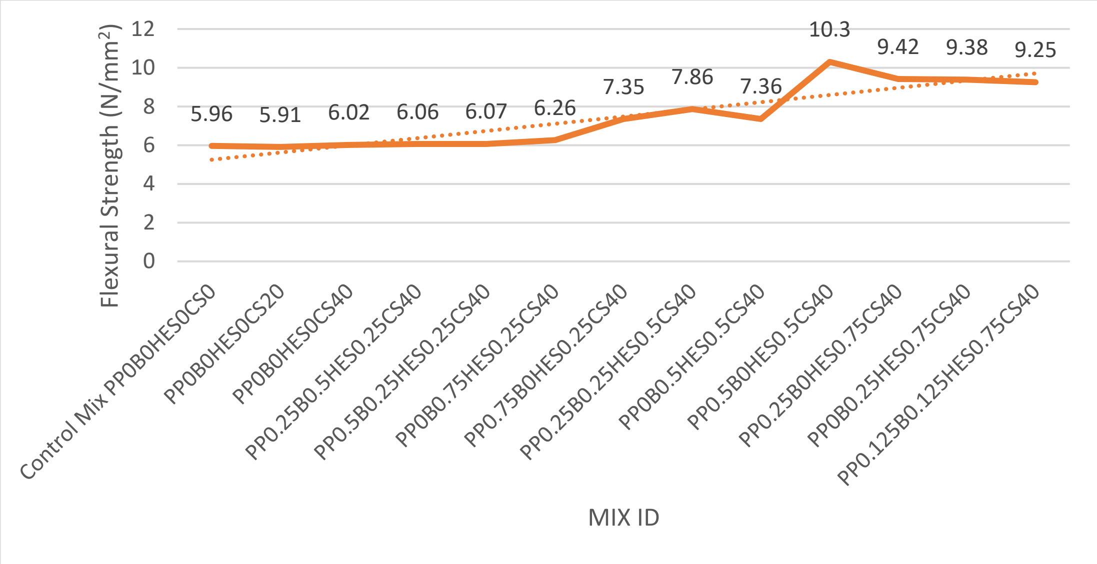

Figure 4.5 Flexural strength of hybrid fibre HPC with reference to controlled concrete.

Table 4.2 Flexural strength of hybrid fibre HPC.

Mix Designation	Flexural Strength (N/mm^2) 28 days
Control Mix PP0B0HES0CS0	5.96
PP0B0HES0CS20	5.91
PP0B0HES0CS40	6.02
PP0.25B0.5HES0.25CS40	6.06
PP0.5B0.25HES0.25CS40	6.07
PP0B0.75HES0.25CS40	6.26
PP0.75B0HES0.25CS40	7.35
PP0.25B0.25HES0.5CS40	7.86
PP0B0.5HES0.5CS40	7.36
PP0.5B0HES0.5CS40	10.3
PP0.25B0HES0.75CS40	9.42
PP0B0.25HES0.75CS40	9.38
PP0.125B0.125HES0.75CS40	9.25

PP0B0HES0CS0 signifies 0% polypropylene fibre, 0% basalt fibre, 0% hooked-end steel fibre, and 0% copper slag and the same nomenclature with different percentages of all other mixes with fibres is addressed.

In Summary, the control mix (PP0B0HES0CS0) had a flexural strength of 5.96 MPa, serving as the reference point. Mix PP0.5B0HES0.5CS40 exhibited the highest flexural strength among the tested mixes, reaching 10.3 MPa. This represents a substantial improvement, 72.81% greater than the control mix's flexural strength. Following the peak flexural strength (PP0.5B0HES0.5CS40), all other mixes showed a decreasing trend in flexural strength, indicating a diminishing return with increasing fibre dosage. Silica fume improves the bond between the cement matrix and aggregate by promoting the conversion of calcium hydroxide into calcium silicate hydrate (CSH), enhancing the connection. The dense inter-particle packing in the concrete matrix and a strong bond contribute to the increase in flexural strength. This finding implies that the presence of hybrid fibres enhances the integrity of the concrete matrix. Once a specific dosage of hybrid fibres is reached (0.5% PP, 0% basalt fibre, and 0.5% HES), the flexural strength starts to decrease. In summary, the findings suggest that for the given set of hybrid fibres, the optimal combination for enhancing flexural strength was the mix with 0.5% polypropylene and 0.5% hooked-end steel fibres (PP0.5B0HES0.5CS40). This blend significantly outperformed the control mix, indicating the potential for improving the concrete's resistance to bending. These findings could be valuable for engineers and builders seeking to enhance concrete's flexural strength in construction applications.

4.2.3 Effect of hybrid fibres on Split tensile strength of Concrete

It is clear from Figure 4.6, Figure 4.7, and Table 4.3 that the split tensile strength of hybrid fibres of 13 mixes has different strengths at 28 days of curing. The findings after minute monitoring of tested beams in CTM reveal that the control mix PP0B0HES0CS0 has a split tensile strength of 5.04 MPa. In addition to this, on increasing the dosage of hybrid fibres, the behaviour of tested cylinder samples changed and maximum split tensile strength is reported for mix PP0.5B0HES0.5CS40, i.e., 5.47 MPa, which is 8.53 % greater than the control mix PP0B0S0CS0. After that, all the mixes and strength start decreasing with a similar trend. The combination PP0B0HES0CS20 shows the lowest split tensile strength of 5.06 MPa. The other researchers also support a similar trend in their research.

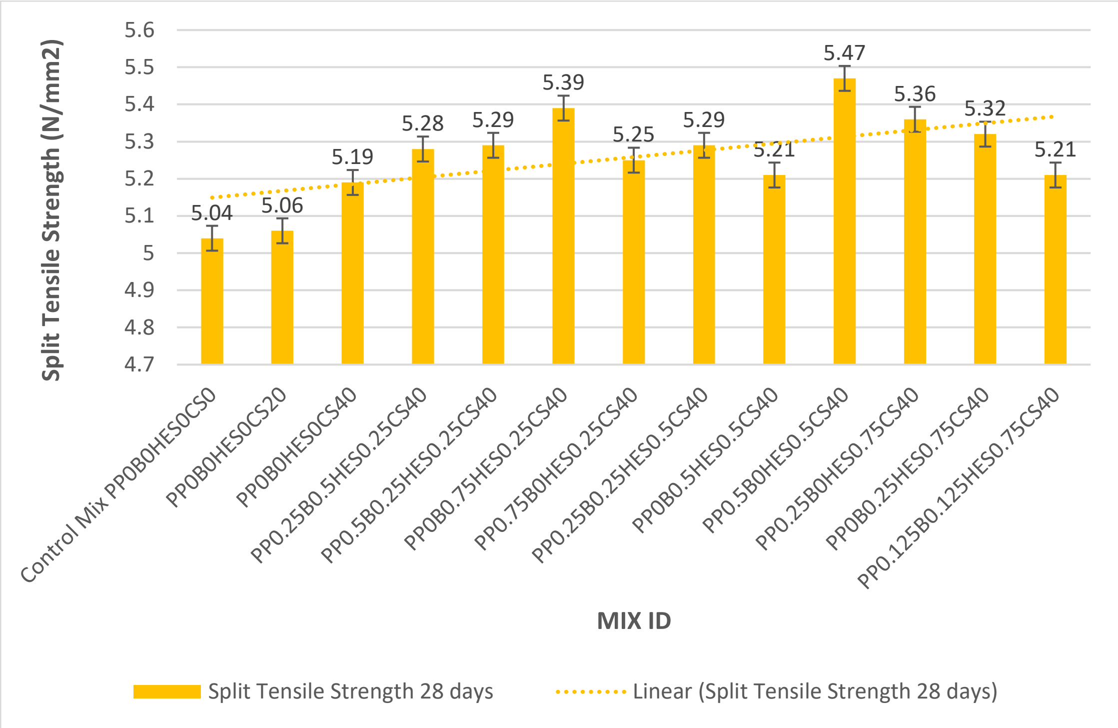

Figure 4.6 Comparison of Split tensile strength of hybrid fibre-reinforced high-performance concrete with reference to controlled concrete.

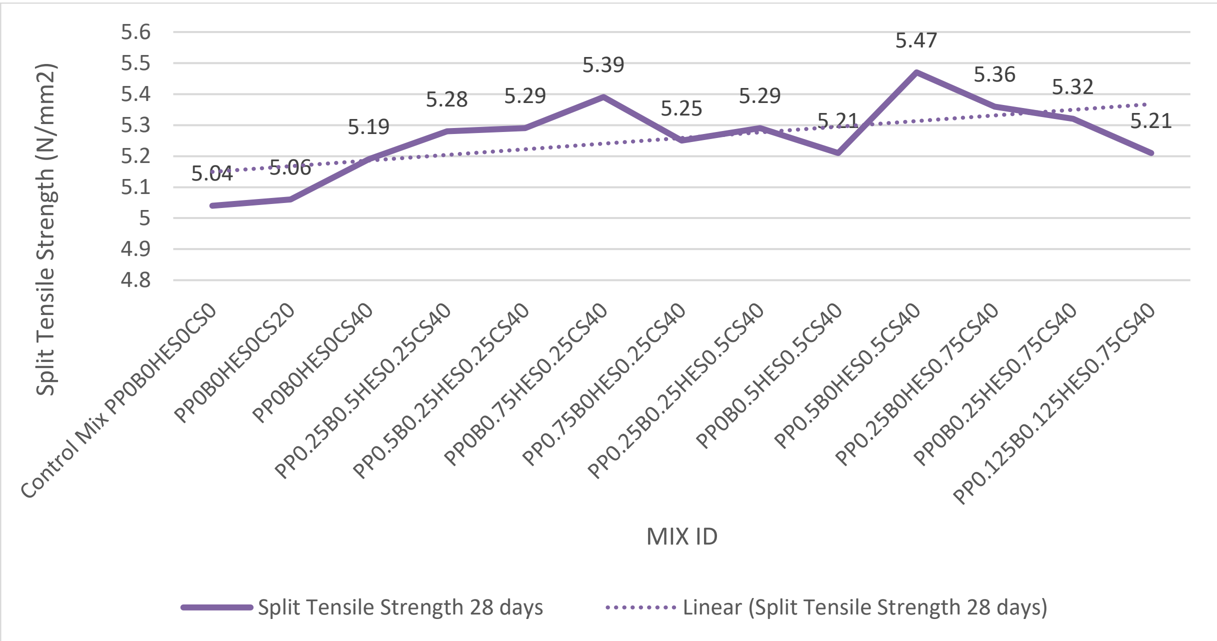

Figure 4.7 Split tensile strength of hybrid fibre-reinforced high-performance concrete with reference to controlled concrete.

Table 4.3 Split Tensile strength of hybrid fibre reinforced high-performance concrete.

Mix Designation	Split Tensile Strength (N/mm^2) 28 days
Control Mix PP0B0HES0CS0	5.04
PP0B0HES0CS20	5.06
PP0B0HES0CS40	5.19
PP0.25B0.5HES0.25CS40	5.28
PP0.5B0.25HES0.25CS40	5.29
PP0B0.75HES0.25CS40	5.39
PP0.75B0HES0.25CS40	5.25
PP0.25B0.25HES0.5CS40	5.29
PP0B0.5HES0.5CS40	5.21
PP0.5B0HES0.5CS40	5.47
PP0.25B0HES0.75CS40	5.36
PP0B0.25HES0.75CS40	5.32
PP0.125B0.125HES0.75CS40	5.21

PP0B0S0CS0 signifies 0% polypropylene fibre, 0% basalt fibre, 0% hooked-end steel fibre, and 0% copper slag and the same nomenclature with different percentages of all other mixes with fibres is addressed.

In Summary, the control mix (PP0B0HES0CS0) had a split tensile strength of 5.04 MPa, serving as the reference point. Mix PP0.5B0HES0.5CS40 exhibited the highest split tensile strength among the tested mixes, reaching 5.47 MPa. This represents a notable improvement, being 8.53% greater than the control mix's split tensile strength. Following the peak split tensile strength (PP0.5B0HES0.5CS40), all other mixes exhibited a decreasing trend in split tensile strength, indicating a diminishing return with increasing fiber dosage. The content mentions that other researchers have observed a similar trend in their research. This suggests that the trend of increasing split tensile strength with the addition of hybrid fibres and subsequent decrease may be a consistent finding in the field. Specific fiber types and dosages used in this study enhancing the split tensile strength of concrete. The observed trends in this research align with what other authors have reported in the literature. These findings could be valuable for engineers and builders seeking to enhance concrete's split tensile strength in construction applications.

4.3 Comparison of optimum dosage of hybrid fibres with reference to controlled concrete.

Table 4.4 Optimum dosage of hybrid fibre-reinforced high-performance concrete.

S.No.	Mechanical Property	Strength (MPa) of Controlled Mix	Strength (MPa) of PP0.5B0HES0.5CS40 at 28 days	% Increase with Controlled Concrete
1	Compressive Strength	76.5	78	1.96 (Insignificant)
2	Flexural Strength	5.96	10.3	72.81
3	Split tensile strength	5.04	5.47	8.53

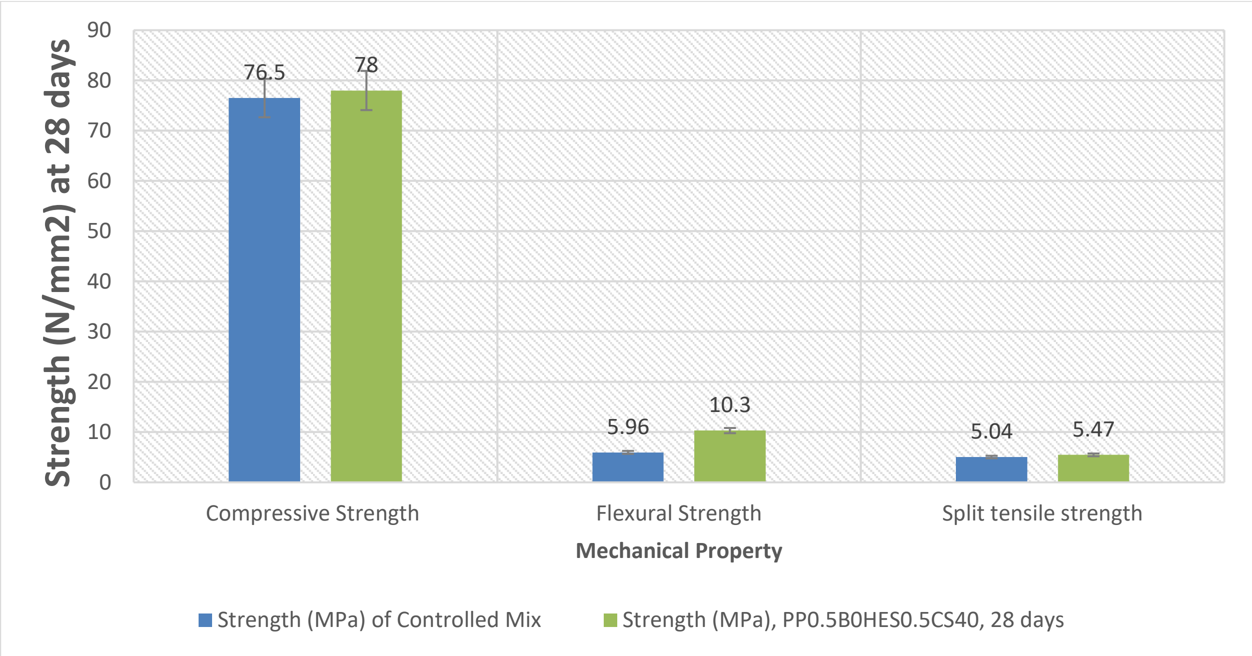

Figure 4.8 Optimum dosage of hybrid fibre-reinforced high performance concrete and comparison with reference to controlled concrete.

4.4 Results and Discussion on Durability Properties

The durability properties of high-performance concrete incorporating hybrid fibres are addressed in the subsequent section, and its validation with other researchers' work in high-performance concrete is shown.

4.4.1 Effect of water absorption (Sorptivity) on hybrid fibres.

Another significant factor that affects concrete longevity is its ability to resist the introduction of hazardous ions. The absorption characteristics of concrete provide crucial information about the number of permeable pores inside the concrete and the connections between them, in addition to acting as an indirect indicator of its porosity. This test is conducted by ASTM C 1585 on 150mm x 300mm cylinders. In this test, the cylinder sample is cut into three pieces and a cut of 50mm interval is achieved after leaving the space from the top and bottom of the cylinder. The sides of the samples are coated with epoxy to inhibit moisture or water ingress into the sample. After that, the samples are covered with polythene with a rubber band. After that, the tray is taken and adjusted so that samples are kept over a corrosion-free pipe of thickness 4-15mm. The samples are immersed 2-3mm in water. The weight taken before the coating of epoxy is considered as W1. After coating epoxy and applying polythene (before dipping into water), the weight considered at 0 seconds is W2. Thereafter, 60 seconds, 5 minutes, 10 minutes, 20 minutes, 30 minutes, 60 minutes, 2 hours,3 hours, 4 hours, 5 hours and 6 hours weights are noted down and considered as initial absorption. At 24 hours up to 6 days, weights are noted down and are referred to as secondary absorption. It was found that the absorption rate of capillary rise for all 13 mixes with hybrid fibres for high-performance concrete is good quality as per the durability aspect.

Figure 4.11 & Table 4.5 provide a visual representation of the absorption (mm) of the numerous hybrid FRC mixes used in the current research. According to the findings, PP0.75B0HES0.25CS40 showed 0.41mm absorption at 0.5 hours (early) and 0.61mm absorption at 168 hours (ultimate) i.e., seven days and significantly reduce concrete's capacity to absorb water than controlled concrete mix PP0B0HES0CS0 which is having 1.53mm (ultimate) absorption. As a result, various mixes examined in this research displayed water absorption values low, which suggested "excellent" concrete quality by standard classifications.

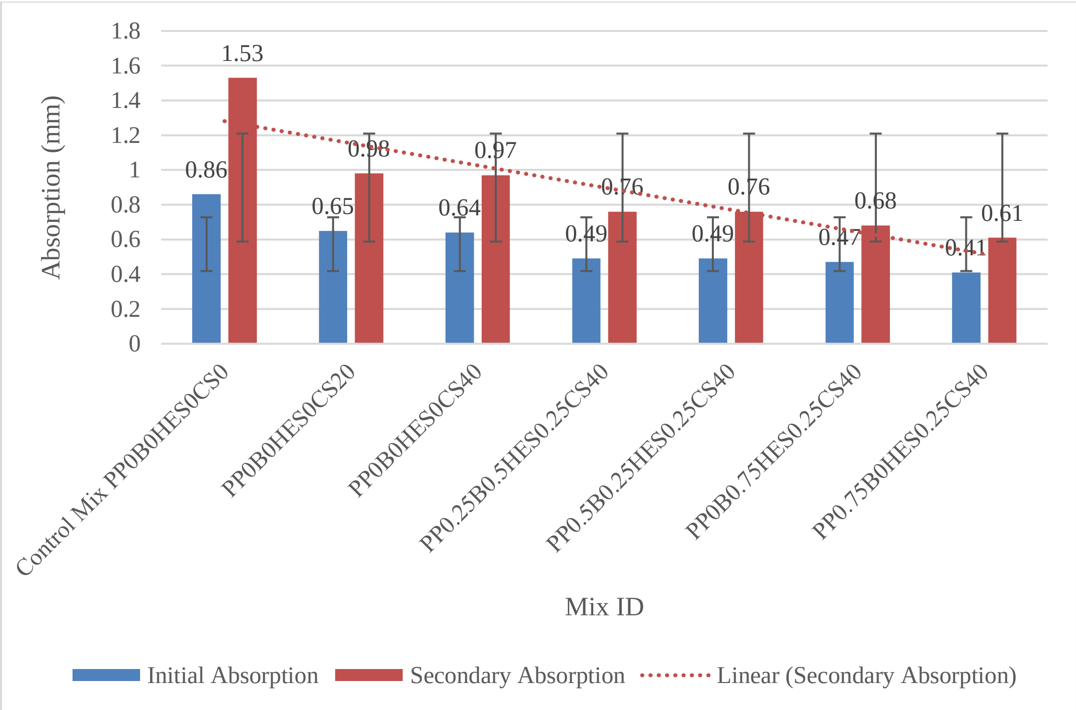

Figure 4.9 Initial and Secondary absorption when HES 0% & 0.25% (Vf) added

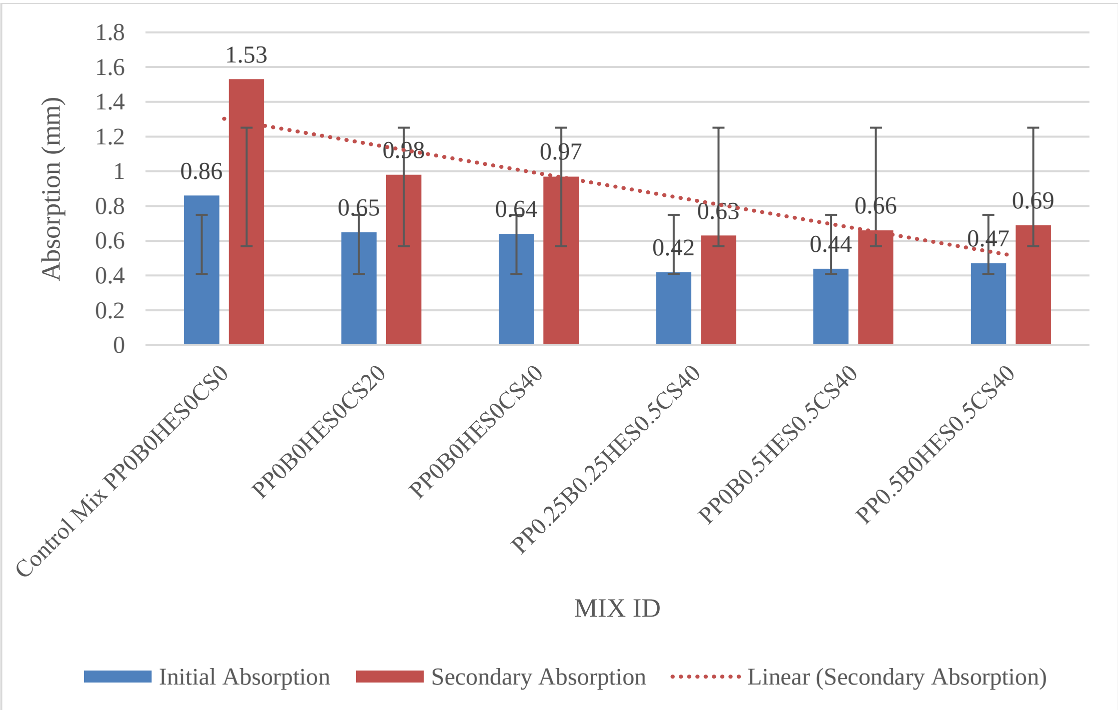

Figure 4.10 Initial and Secondary absorption when HES 0% & 0.5% (Vf) added

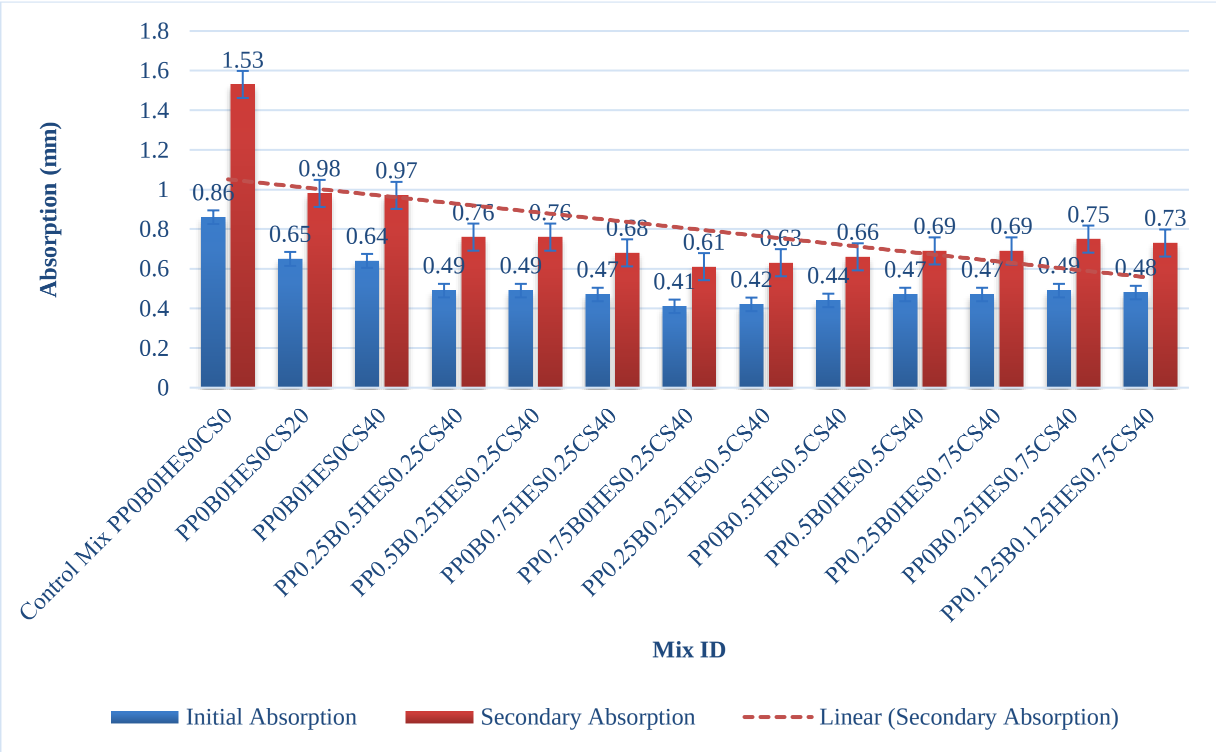

Figure 4.11 Initial and Secondary absorption of hybrid fibre-reinforced high-performance concrete.

Table 4.5 Initial and Secondary absorption of hybrid fibre-reinforced high-performance concrete.

Mix No.	Mix ID	Initial Absorption (mm)	Secondary Absorption (mm)
1	Control Mix PP0B0HES0CS0	0.86	1.53
2	PP0B0HES0CS20	0.65	0.98
3	PP0B0HES0CS40	0.64	0.97
4	PP0.25B0.5HES0.25CS40	0.49	0.76
5	PP0.5B0.25HES0.25CS40	0.49	0.76
6	PP0B0.75HES0.25CS40	0.47	0.68
7	PP0.75B0HES0.25CS40	0.41	0.61
8	PP0.25B0.25HES0.5CS40	0.42	0.63
9	PP0B0.5HES0.5CS40	0.44	0.66
10	PP0.5B0HES0.5CS40	0.47	0.69
11	PP0.25B0HES0.75CS40	0.47	0.69
12	PP0B0.25HES0.75CS40	0.49	0.75
13	PP0.125B0.125HES0.75CS40	0.48	0.73

PP0B0HES0CS0 signifies 0% polypropylene fibre, 0% basalt fibre, 0% hooked-end steel fibre, 0% copper slag and the same nomenclature with different percentages of fibres is addressed.

The research examined the absorption (in millimeters) of various hybrid FRC mixes at different time intervals, including early (0.5 hours) and ultimate (168 hours or seven days) stages. The control mix (PP0B0HES0CS0) had an ultimate absorption of 1.53mm, indicating the standard water absorption capacity of that mix.

Mix PP0.75B0HES0.25CS40 showed notable results in terms of water absorption. It exhibited 0.41mm of absorption at the early stage and 0.61mm of absorption at the ultimate stage.This mix displayed a substantial reduction in water absorption capacity compared to the control mix.The findings suggest that the addition of specific hybrid fibres to the concrete mix, as exemplified by PP0.75B0HES0.25CS40, significantly enhances the concrete's resistance to water absorption. The results demonstrate that the hybrid fiber-reinforced concrete mix (PP0.75B0HES0.25CS40) outperforms the control mix (PP0B0HES0CS0) in terms of water resistance.

In summary, the findings suggest that the inclusion of hybrid fibres in high-performance concrete, as exemplified by mix PP0.75B0HES0.25CS40, significantly reduces the concrete's capacity to absorb water. This reduced water absorption indicates enhanced water resistance, which is a valuable property for concrete used in various construction applications. These findings may be of particular interest to engineers and builders seeking to use high-performance concrete with improved water resistance characteristics.

4.4.2 Effect of hybrid fibres on Specific Electrical Resistivity.

Since corrosion in reinforced concrete is significantly influenced by electrical resistivity, it is one of the most crucial characteristics of concrete durability. It has been demonstrated in the past that corrosion of concrete reinforcement is not likely to occur above an electrical resistance of 120 Ω-m, which is the limit for corrosion propagation in internal steel reinforcing bars. The microstructure of concrete becomes denser due to the presence of supplementary cementitious materials and hybrid fibres, and secondary calcium silicate hydrate is created due to its pozzolanic reaction (C–S–H). The C-S-H gel, a well-known source of concrete strength, increases the volume of solid phases and inhibits the development of capillary pore systems. Concrete resistivity, one of the endurance characteristics of concrete, is improved due to these events. Electrolytes in the pores of composite materials and the presence of conductive materials like steel fibres in fibre-reinforced specimens have a significant impact on the electrical resistance of concrete. The findings show that adding hybrid fibres significantly decreased the electrical resistance of concrete. From Fig. 4.14, it is very clear that Control Mix PP0B0HES0CS0 specific electrical resistivity (Ω m) was 67.8 at 28 days while 104.4 at 91 days. Moreover, PP0.75B0HES0.25CS40 shows 112.4 (Ω m) at 28 days and 215.6 (Ω m) at 91 days. Further, the specific electrical resistivity of PP0.5B0HES0.5CS40 is 219.8 (Ω m) at 91 days. Varying types of fibres added to concrete have different effects on how electrically resistive the concrete is. Polypropylene fibre and basalt fibre addition make mixes more porous and slightly lowers the electrical resistance of concrete. The electrical resistivity of concrete is significantly reduced when all hybrid fibres are added because of the fibres' high conductivity.

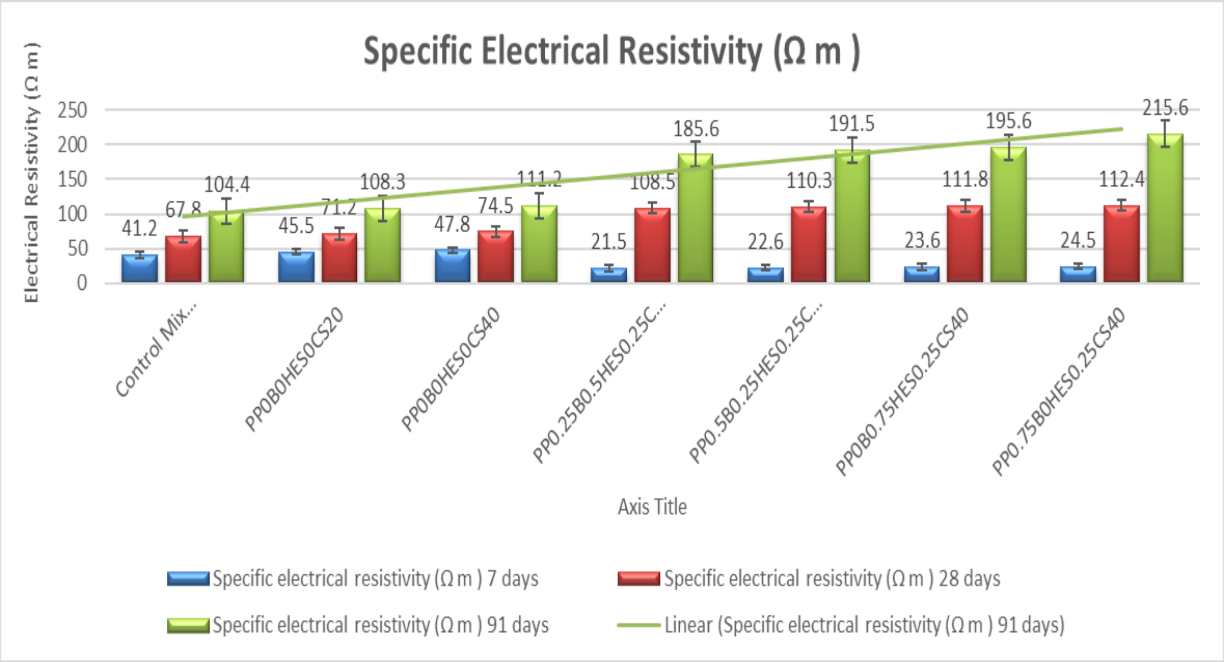

Figure 4.12 Effect of hybrid fibres on Specific Electrical Resistivity when HES 0% & 0.25% (Vf) added

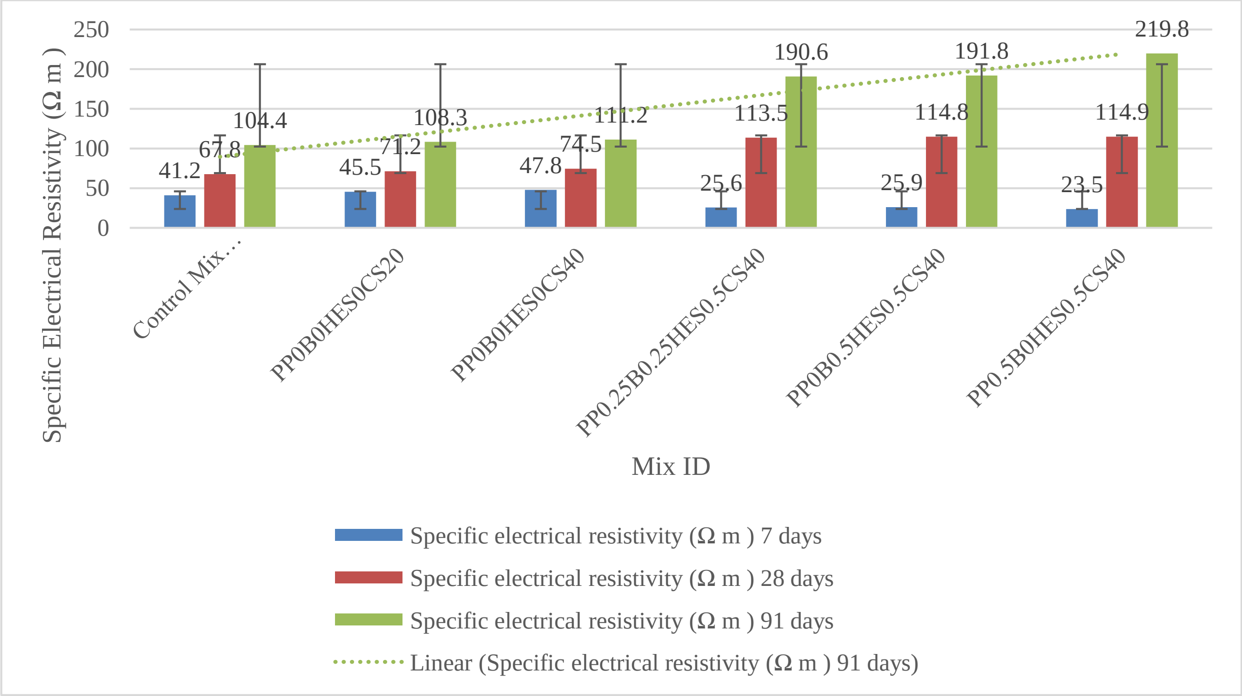

Figure 4.13 Effect of hybrid fibres on Specific Electrical Resistivity when HES 0% & 0.5% (Vf) added

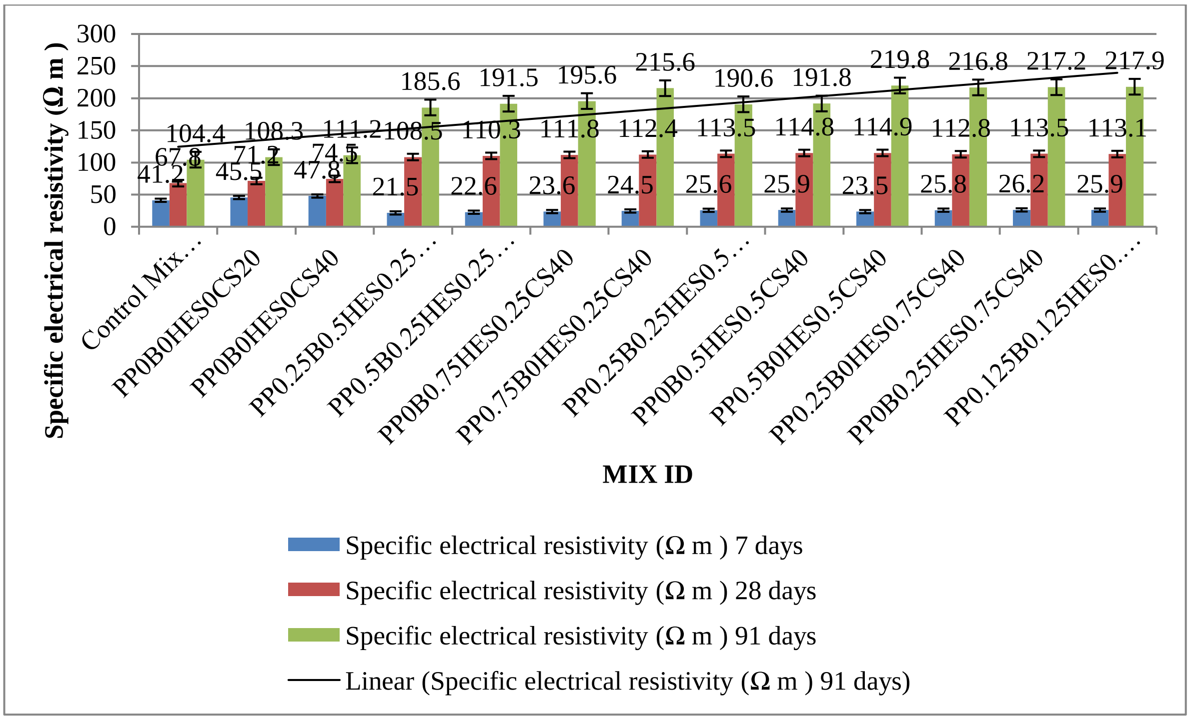

Figure 4.14 Comparison of Specific Electrical Resistivity on different hybrid fibre mixes with Controlled Mix.

The electrical resistance of concrete with and without the addition of hybrid fibres. The specific electrical resistivity of different concrete mixes, including the control mix (PP0B0HES0CS0) and mixes containing hybrid fibres (PP0.75B0HES0.25CS40 and PP0.5B0HES0.5CS40), is compared at two different curing times (28 days and 91 days).

The study demonstrates that adding hybrid fibres significantly decreased the electrical resistance of the concrete. The specific electrical resistivity (in ohm meters, Ω m) of the control mix (PP0B0HES0CS0) at 28 days was 67.8 Ω m, which increased to 104.4 Ω m at 91 days. The control mix serves as a reference point for understanding the electrical resistivity of standard concrete. Mix PP0.75B0HES0.25CS40 had specific electrical resistivity values of 112.4 Ω m at 28 days and 215.6 Ω m at 91 days. Mix PP0.5B0HES0.5CS40 had a specific electrical resistivity of 219.8 Ω m at 91 days. The specific electrical resistivity values of mixes containing hybrid fibres are notably higher than those of the control mix. The trend shows that electrical resistivity tends to increase with longer curing times.

In summary, the findings suggest that the addition of hybrid fibres to concrete leads to a significant decrease in electrical resistance. This can have implications for applications where electrical conductivity or resistance is a key consideration, such as in construction projects that involve the use of electrically conductive or resistive concrete.

4.4.3 Effect of water permeability on hybrid fibres on High-Performance Concrete.

As per IS 516 (Part 2/ Sec 1): 2018 and as per German test method DIN 1048 Part 5, the cubes of size 150mm x 150mm x 150mm for all the hybrid mixes were tested in water permeability test apparatus and it was found that all the high-performance hybrid mixes were durable as the depth of penetration of all the mixes is below 35 mm when measured from scale from the outmost part of cube face to the maximum depth covered by the waterfront. The mix PP0.5B0HES0.5CS40 achieved a depth of penetration of 12 mm as compared to the controlled mix PP0B0HES0CS0, and it was found to be 24mm. Similarly, all other hybrid mixes were found as good quality concrete as per durability point of view.

Table 4.6 Water permeability on hybrid fibres on High-Performance Concrete.

S No.	Mix Designation	Water Permeability (mm)
1	Control Mix PP0B0HES0CS0	24
2	PP0B0HES0CS20	23.5
3	PP0B0HES0CS40	23.1
4	PP0.25B0.5HES0.25CS40	21.5
5	PP0.5B0.25HES0.25CS40	21.3
6	PP0B0.75HES0.25CS40	20.8
7	PP0.75B0HES0.25CS40	20.7
8	PP0.25B0.25HES0.5CS40	19.2
9	PP0B0.5HES0.5CS40	18.7
10	PP0.5B0HES0.5CS40	12
11	PP0.25B0HES0.75CS40	12.7
12	PP0B0.25HES0.75CS40	12.7
13	PP0.125B0.125HES0.75CS40	12.3

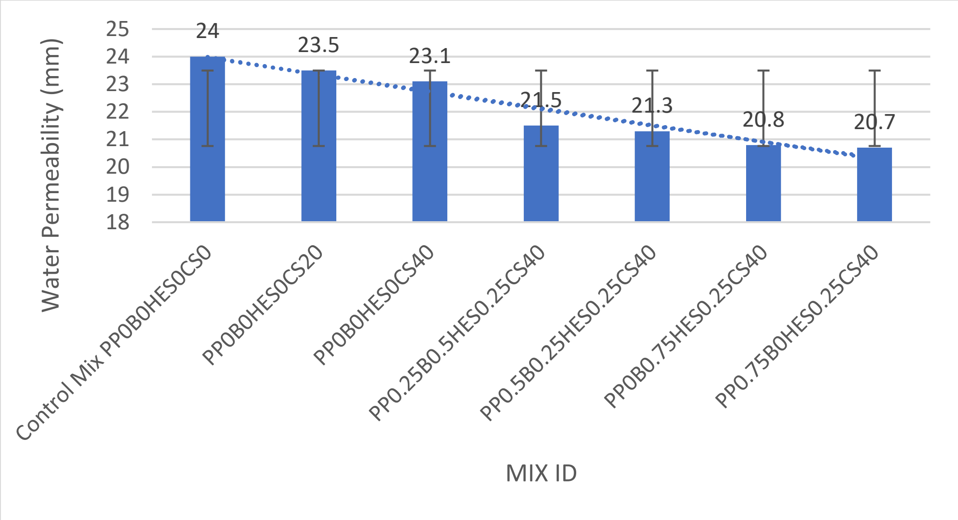

Figure 4.15: Water Permeability (mm) when HES 0% & 0.25 % (Vf) added

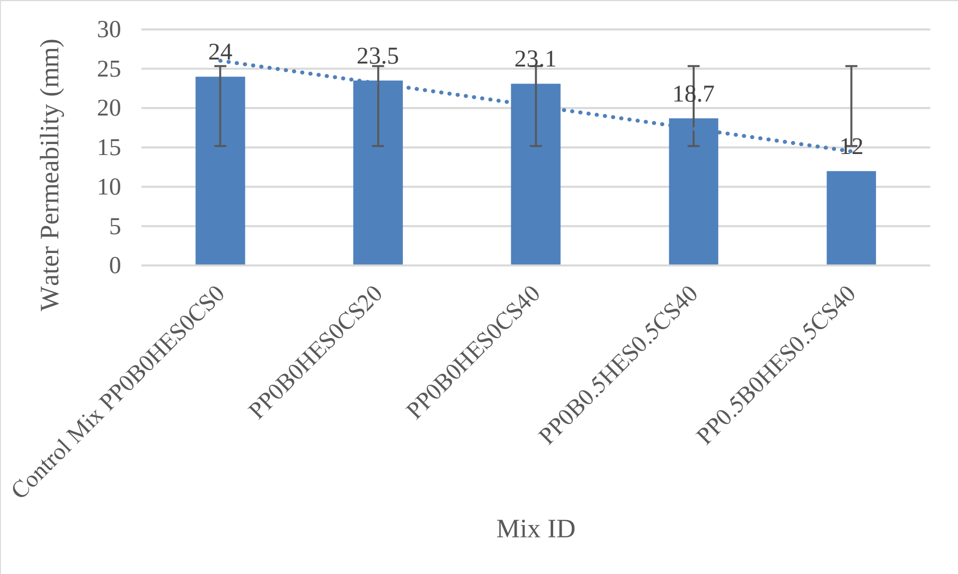

Figure 4.16: Water Permeability (mm) when HES 0% & 0.5% (Vf) added

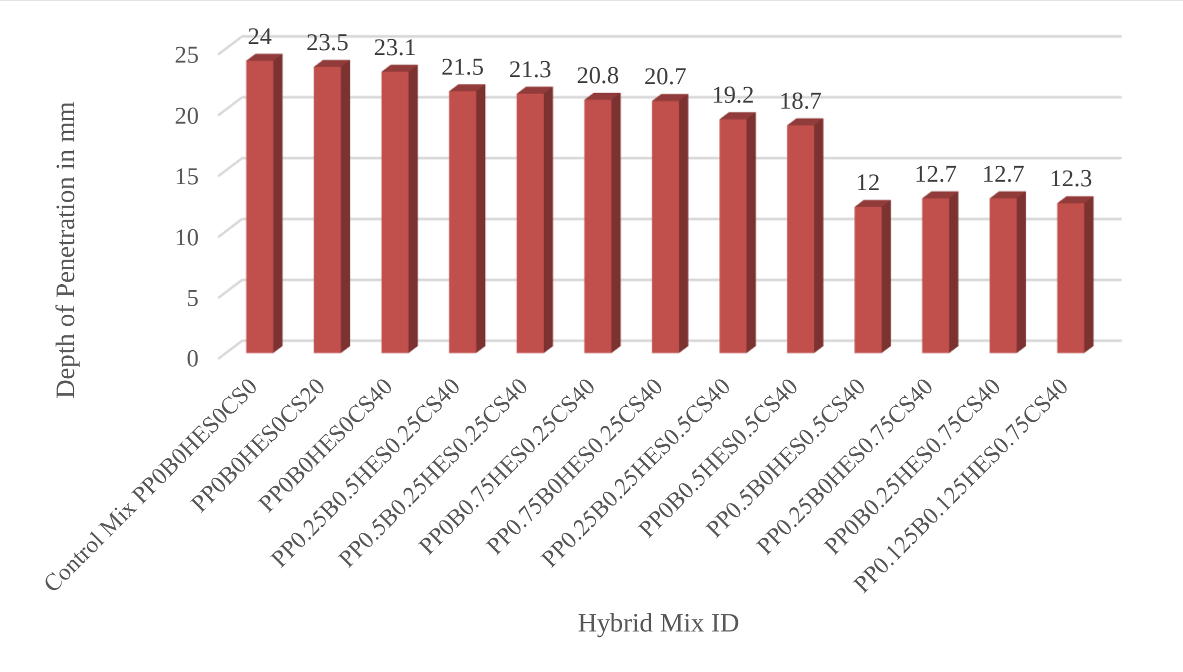

Figure 4.17: Comparison of Water Permeability (mm) with Hybrid Fibres.

The study assessed the durability of various high-performance hybrid concrete mixes by measuring the depth of water penetration. The control mix (PP0B0HES0CS0) had a depth of penetration of 24 mm, indicating a certain level of water ingress. Mix PP0.5B0HES0.5CS40 achieved a notably lower depth of penetration at 12 mm, indicating significantly improved water resistance. All other hybrid mixes exhibited good quality concrete from a durability perspective, with depth of penetration values below 35 mm. This implies that the addition of hybrid fibres to high-performance concrete generally enhanced its resistance to water penetration and improved its durability. These findings may have practical implications for construction projects where durable concrete is essential, such as in structures exposed to environmental moisture or harsh conditions. The presence of hybrid fibres, such as polypropylene, basalt, and hooked-end steel, contributed to the enhanced durability of the concrete mixes.

In summary, the findings suggest that the addition of hybrid fibres to high-performance concrete significantly improved its durability, as evidenced by reduced water penetration depths. The mix PP0.5B0HES0.5CS40 performed particularly well in this regard. These findings are valuable for engineers and builders seeking to use high-performance concrete with enhanced durability in construction applications.

4.5 Performance and Comparative Analysis of Published Literature

The performance of the proposed Extended Deep Neural Network (EDNN) centred HPC prediction by fibre synergy effect is examined in this section based on previous literature published.

4.5.1 Performance analysis of published literature

Based on the RMSE, R^2, MAE, MAPE, accuracy, precision, recall, and F-Measure, the proposed EDNN's performance is examined with the existing DNN, CNN, ANN, and SVM algorithms. Thus, the performance metrics are obtained as,

RMSE: The root mean square error between the concrete's natural strength and durability value with the predicted values (PV) is called RMSE. Thus, it is acquired as,

$$RMSE = \sqrt{\frac{1}{K}\sum[\omega_l - \gamma_l]^2} \tag{15}$$

Where, K specifies the number of samples, ω_l denotes the measured strength and durability values, and γ_l signifies the PV.

MAE: It calculates the difference between actual and forecasted values of property. It is specified as,

$$MAE = \frac{1}{K}\sum|\omega_l - \gamma_l| \tag{16}$$

R^2: It estimates the coefficient of several determinations, which is elucidated in equation (17),

$$R^2 = 1 - \frac{\sum(\omega_l - \gamma_l)^2}{\sum(\gamma_l)^2} \tag{17}$$

MAPE: It is a statistical parameter that gauges how accurately predicting techniques perform. It is specified as,

$$MAPE = \frac{100}{K}\sum\left|\frac{\omega_l - \gamma_l}{\omega_l}\right| \tag{18}$$

Accuracy: A fraction of the prediction model that indicates which model got a precise prediction than any other prediction is called accuracy. It is specified as,

$$Accuracy = \frac{a_p + a_n}{a_p + a_n + b_p + b_n} \tag{19}$$

Where, a_p denotes the true positives, a_n indicates the true negatives, b_p signifies the false positives, and b_n denotes the false negative.

Precision: Precision is the proportion of correctly identified positive cases to all positively projected cases.. The formula is,

$$precision = \frac{a_p}{a_p + b_p} \tag{20}$$

Recall: Recall is the proportion of correctly identified positive instances to all real positive cases. The expression is,

$$recall = \frac{a_p}{a_p + b_n} \tag{21}$$

F-Measure: The amalgamation of precision and recall is called F-Measure, which is attained as,

$$F - Measure = 2 * \frac{precision * recall}{precision + recall} \tag{22}$$

Table 4.7 Performance analysis of the proposed and existing methods regarding RMSE, MAE, R^2, and MAPE metrics.

Performance Metrics	**Proposed EDNN**	**DNN**	**CNN**	**ANN**	**SVM**
RMSE (MPa)	3.56	6.23	7.69	12.63	16.23
MAE (MPa)	4.02	6.78	8.71	11	15.03
R2	0.96	0.91	0.89	0.83	0.78
MAPE (MPa)	8.46	11.03	16.95	18.01	21.63

Table 4.7 shows that the RMSE, MAE, and MAPE values are exceptionally high for the SVM algorithm. It deduces that the SVM offers the worst performance. When contrasted to the already available methods, a significantly lower RMSE, MAE, and MAPE value is possessed by the EDNN. It could be stated from the already available algorithm that although it performs less than the suggested EDNN, the DNN method is still far better than the other algorithms that are currently in use. The suggested work, which is based on the R^2 metric, results in better performance.

4.5.1 Comparative Analysis of Published Literature

In this section, the proposed EDNN work is compared with available algorithms. Next, the proposed SMOJO is examined with JO, GWO, PSO, and GA, the fitness is examined.

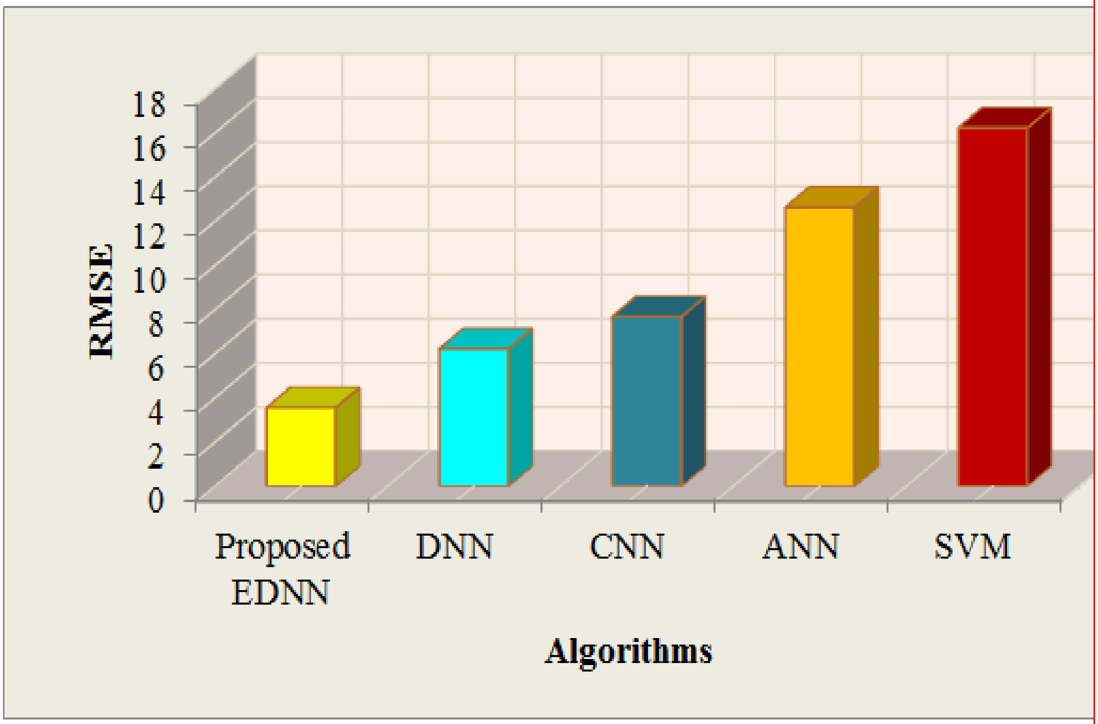

Figure 4.18 RMSE Analysis

The RMSE analysis of the proposed and already available algorithm is depicted in Fig. 4.18 Here, 3.56 MPa is the proposed work RMSE value, which is significantly lower when analogized to the already available algorithms. The RMSE value for already available algorithms is 6.23 MPa, 7.69 MPa, 12.63 MPa, and 16.23 MPa for DNN, CNN, ANN, and SVM, respectively. This signifies that the proposed EDNN algorithm of HPC prediction performs better than already available algorithms.

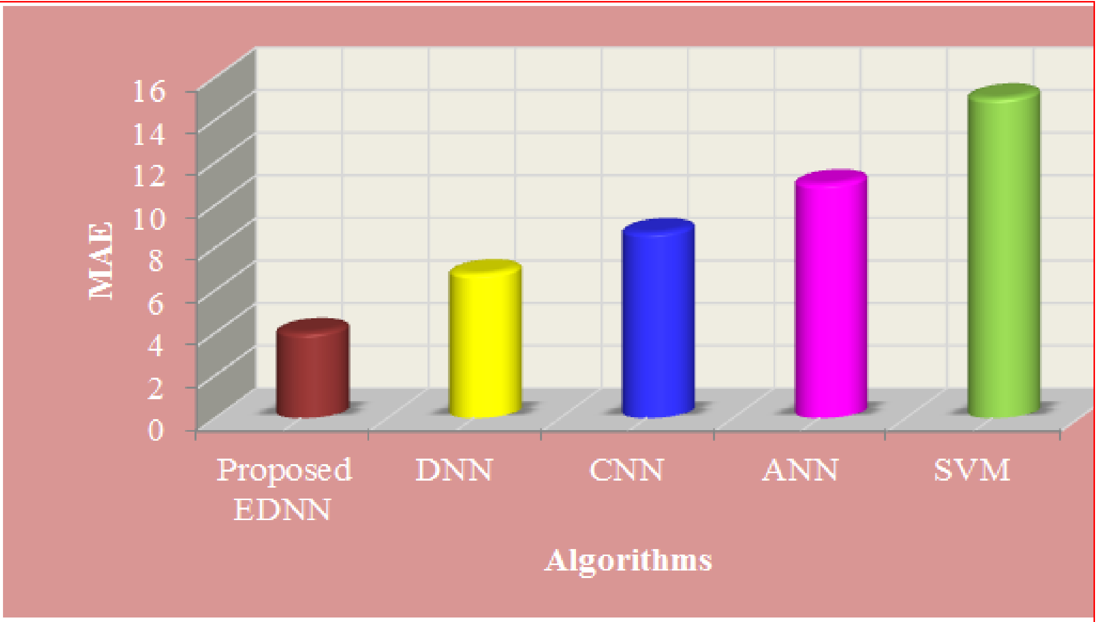

Figure 4.19 MAE Analysis

The MAE value of the proposed EDNN prediction and the prediction of the already available algorithm is depicted in Fig. 4.19 The system is deemed the best system if less MAE is possessed by the system. As of that way, less MAE is possessed by the EDNN is 4.02, which is lower amongst the other prevailing algorithms. 6.78, 8.71, 11, and 15.03 MAE is possessed by the existing DNN, CNN, and ANN, along with SVM. Thus, it is affirmed that better performance is attained via the proposed EDNN model when contrasted with the prevailing algorithms.

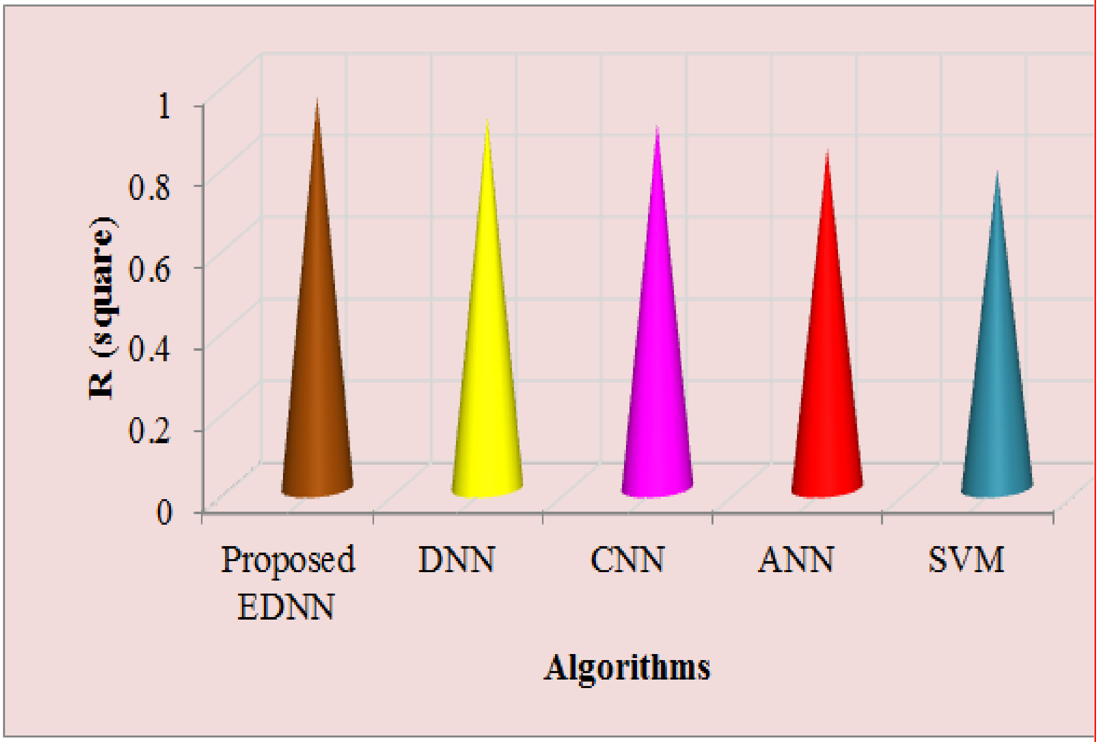

Figure 4.20 EDNN performance based on the R^2 metric

The proposed and existing algorithm R^2 value is exhibited in Fig. 4.20 The proposed EDNN algorithm R^2 value is 0.96, the DNN has 0.91, CNN has 0.89, ANN has 0.83, and SVM has 0.78. In these, the maximum value is possessed by the proposed work-centered system. A very low value is possessed by the already available methods when contrasted with the proposed work. Hence, the proposed EDNN performance is superior when analogized to the already available algorithm.

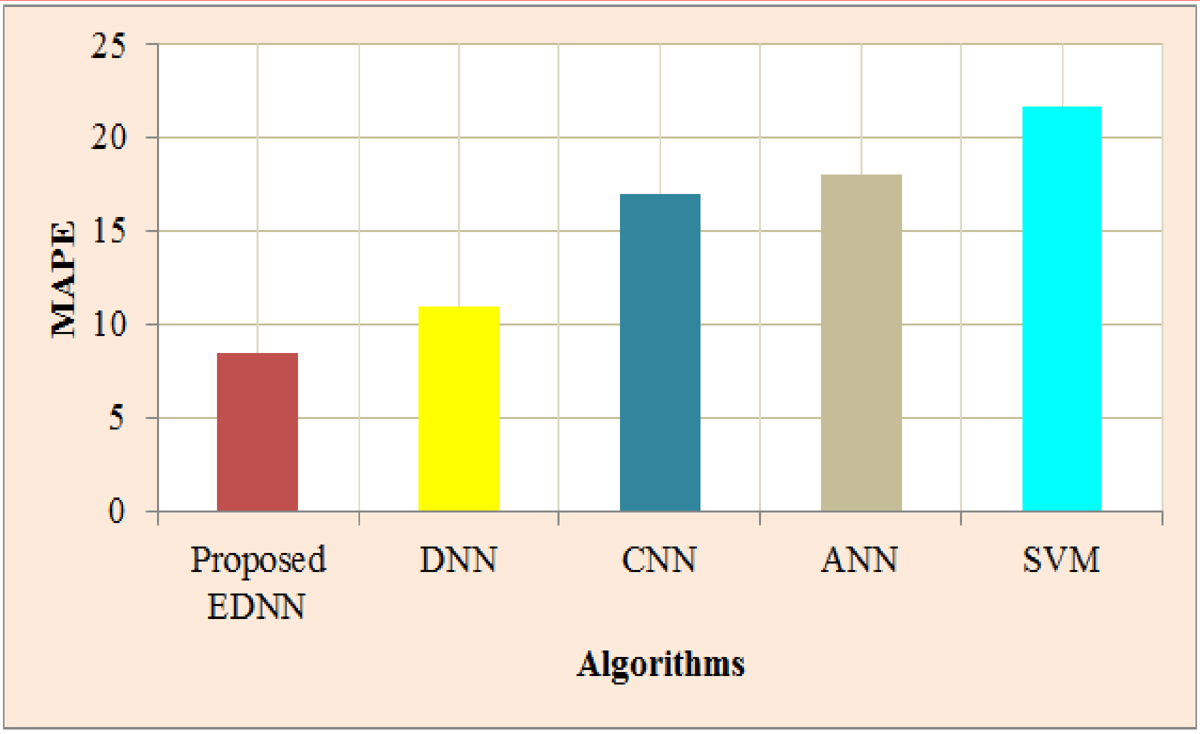

Figure 4.21 MAPE analysis

The MAPE of the proposed EDNN algorithm with the already available DNN, CNN, ANN, and SVM is depicted in Fig. 4.21 A gauge of how precise a forecast system is named the MAPE. The proposed work's MAPE is 8.46, and the 11.03, 16.95, 18.01, and 21.63 MAPE are possessed by the already available DNN, CNN, ANN, and SVM. From that, better performance is attained by the proposed one compared to the existing research methods.

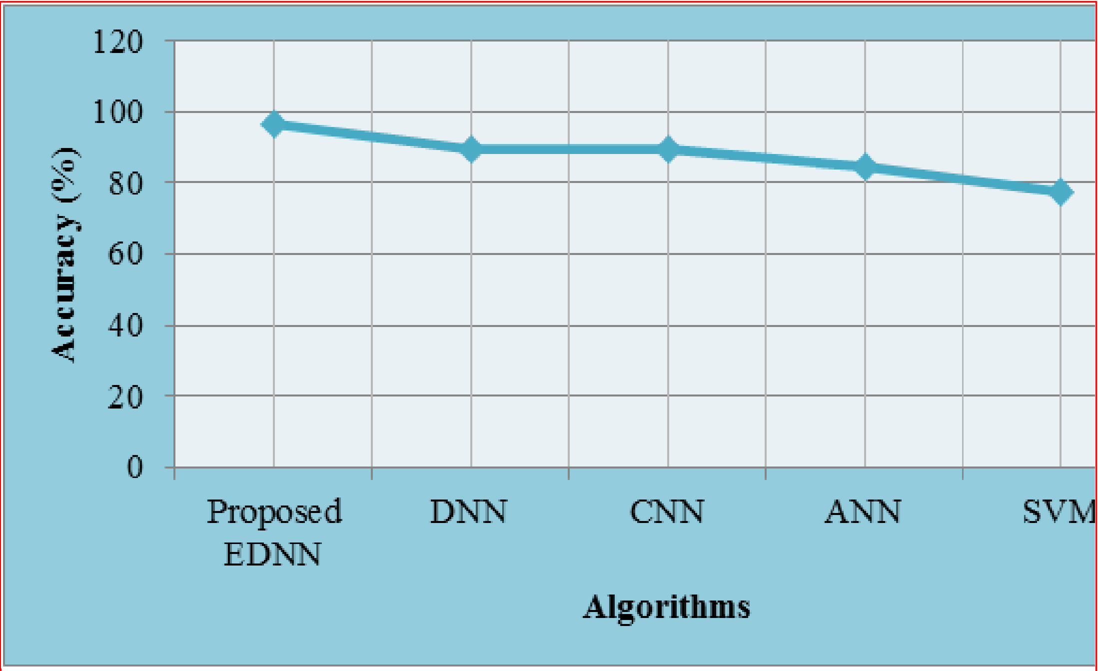

Figure 4.22 Comparative analysis of proposed and existing methods based on accuracy metric

Fig. 4.22 describes how accurately the algorithms anticipate the HPC. The portion of the total number of correct predictions is named the accuracy metric. Here, 96.56% accuracy is attained via the proposed one. Very poor accuracy is acquired by the existing SVM when contrasted to the proposed EDNN i.e., 77.23%. When analogized to the ANN along with SVM algorithms, better performance is possessed by the existing DNN and CNN algorithms. The DNN and CNN's accuracy is 89.65% and 89.25%. However, 84.78% accuracy is possessed by the ANN, which is also lesser when contrasted to the proposed one. Overall, better accuracy is attained by means of the EDNN when contrasted to the existing research methods.

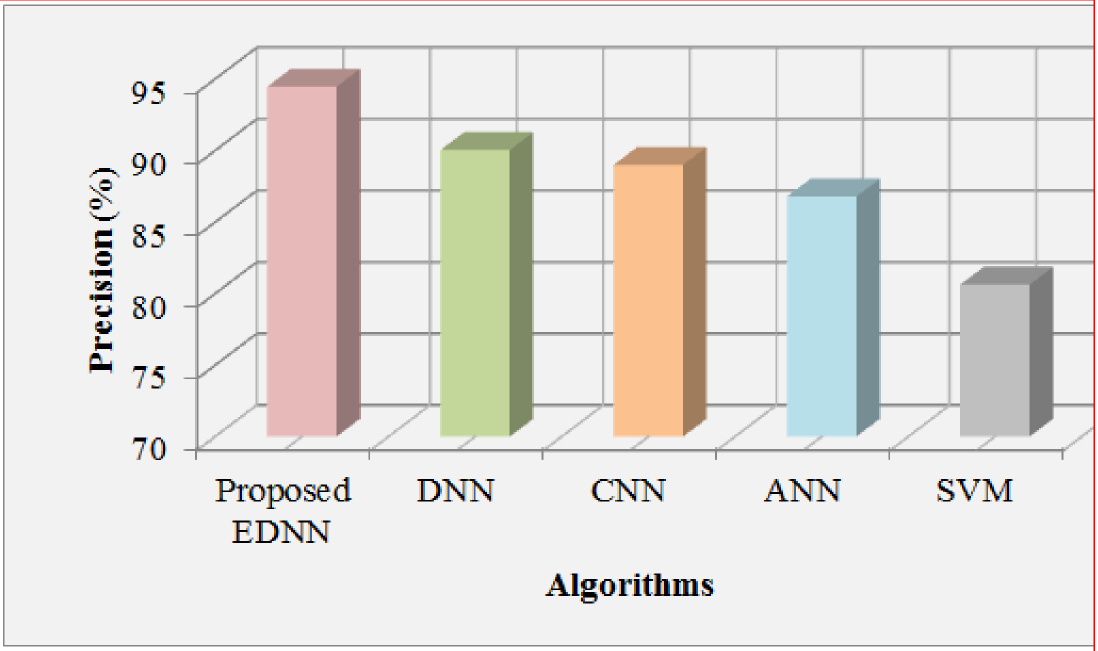

Figure 4.23 Comparative analysis of proposed and existing algorithms based on the precision metric

The comparison of the proposed EDNN with the existing methods based on the precision metric is shown in Figure 4.23 The proposed EDNN's precision value in this case is 94.45%. Compared to other approaches already in use, it is better. The precision of the DNN, CNN, ANN, and SVM is 90.03%, 89%, 86.78%, and 80.62%, respectively. As a result, it indicates that the proposed EDNN achieve a more excellent precision value than the already available techniques.

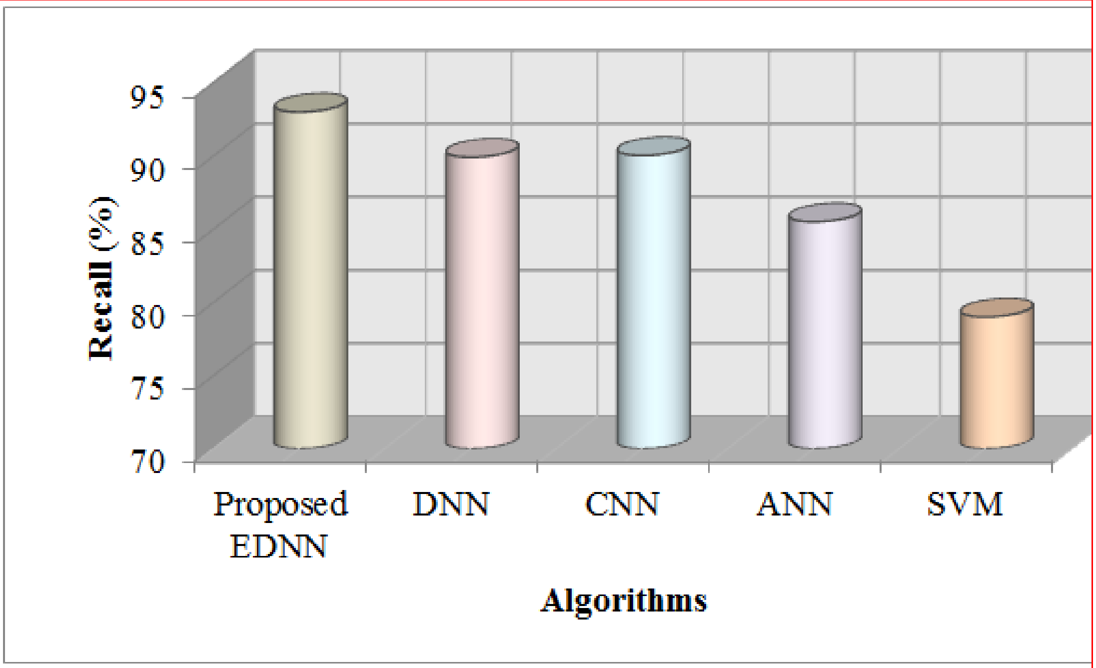

Figure 4.24 Graphical representation of recall analysis

The recall study of the suggested and existing methods was shown in Figure 4.24 The EDNN algorithm performs better, while the SVM algorithm performs worst based on the recall measure. The proposed EDNN's recall value is 93%, while the recall of the SVM is 79%. The remaining DNN, CNN, and ANN had recall values of 89.9%, 90.02%, and 85.5%. Therefore, the analysis exhibits that better performance is attained by the proposed EDNN's performance when contrasted to the already available research method.

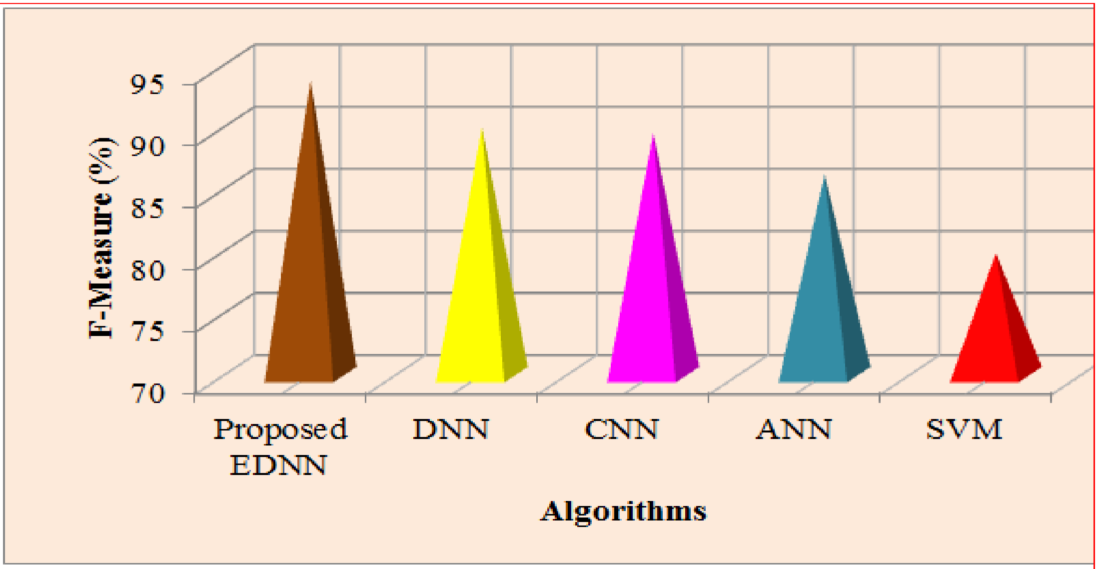

Figure 4.25 F-Measure analysis of proposed and existing algorithms

Concerning the F-Measure metric, Fig. 4.25 exhibits the proposed EDNN's performance with the prevailing DNN, CNN, and ANN, along with SVM algorithms. The amalgamation of the precision and recall metric is called F-measure. Centered on those metrics, better performance is attained via the proposed work. Thus, better performance is attained by the EDNN concerning F-measure also. The maximum F-Measure value is possessed by the proposed EDNN, that is, 93.71%. Less F-Measure is possessed by the prevailing ones when analogized with the proposed work.

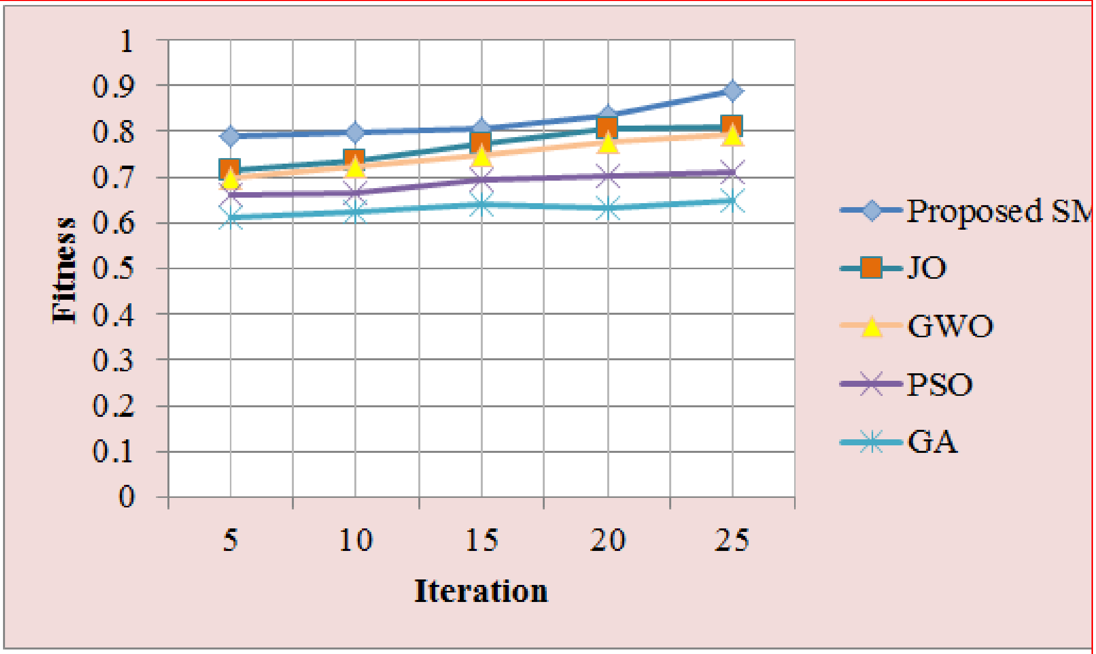

Figure 4.26 Fitness Vs Iteration Analysis

The fitness value (FV) Vs iteration analysis of the proposed SMOJO algorithm with the already available JO, GWO, PSO, and GA algorithms is exhibited in Fig. 4.26 Centered upon the number of iterations, the FV differs. The proposed SMOJO's Fitness value is 0.789 when the iteration count is 5. However, less fitness value is possessed by the prevailing algorithms when contrasted to the proposed one. Thus, the proposed work's better performance is confirmed by the fitness vs iteration analysis.

Chapter 5

Conclusion and Recommendation for Future Study

5.1 Conclusion

Based on the research conducted on HPFRC, this research is helpful for other researchers to utilize the mix design developed for grade M65 with the addition of copper slag at 40%. The present study findings can be used to draw the following conclusions:

1) Increasing the fibre content including basalt, PP, and hooked-end steel fibre enhances the mechanical properties. This improvement is due to the fibres' ability to prevent crack propagation, reduce stress concentration at fissure tips, and slow down crack expansion.
2) The mix PP0B0.25HES0.75CS40 has the lowest slump value at 130 mm, compared to the control mix PP0B0HES0CS0, which has a slump value of 170 mm. This indicates that the addition of fibres maintains concrete workability.
3) With an increased dosage of hybrid fibres, the behaviour of tested samples changed, and the mix PP0.5B0HES0.5CS40 achieved a maximum compressive strength of 78 MPa, which is 1.96% higher but insignificant as compared with the control mix PP0B0HES0CS0. This is probably due to the ineffective dispersion of fibres in concrete or due to the bunching/ sticking of fibres.
4) The behaviour of tested beam samples changed with increased fibre dosage, and the mix PP0.5B0HES0.5CS40 exhibited a maximum flexural strength of 10.3 MPa, which is 72.81% higher than the control mix PP0B0HES0CS0. This indicates that the tested specimen has the highest bending capacity. Since the fibers accommodate the crack face separation by stretching themselves, which provides them additional energy absorbing mechanism.
5) Increasing the dosage of hybrid fibres altered the behaviour of tested cylinder samples, with the mix PP0.5B0S0.5CS40 showing a maximum split tensile strength of 5.47 MPa, which is 8.53% higher than the control mix PP0B0S0CS0. This demonstrates that the tested specimen has the highest split tensile strength. Once the splitting occurred and continued, fibres bridging across the split portion of the matrix acted through the stress transfer from the matrix to the fibers and, thus gradually supported the entire load. The stress transfer improved the tensile strain capacity of the hybrid fibres.
6) The electrical resistivity of concrete varies with the addition of different types of fibres. For the optimal mix, PP0.5B0HES0.5CS40, the electrical resistivity measured 112.4 Ω·m at 28 days and 215.6 Ω·m at 91 days. This means that all the mixes resist the access of aggressive

agents that generally promotes corrosion and considered under the category of negligible risk of corrosion.

7) The mix PP0.5B0HES0.5CS40 achieved a penetration depth of 12 mm, compared to the control mix PP0B0HES0CS0, which had a penetration depth of 24 mm. This indicates that adding hybrid fibres to high-performance concrete significantly enhances its durability by reducing water penetration depth.
8) The mix PP0.75B0HES0.25CS40 showed water absorption of 0.41 mm at 0.5 hours and 0.61 mm at 168 hours (seven days), significantly less than the control mix PP0B0HES0CS0, which had an absorption of 1.53 mm at 168 hours. Compared to ordinary concrete mixtures, initial and ultimate absorption decreased by 45.34% and 54.9%, respectively. The combination of 40% copper slag and hybrid fibres notably reduces water absorption, with the mix containing 0.75% PP, 0% basalt fibres, and 0.25% hooked-end steel fibres showing the lowest absorption among fibre-reinforced concretes.
9) The structures made using this newly developed concrete shall be more durable and require less maintenance over their lifespan, thereby reducing the need for frequent repairs and replacements.
10) The optimal mix (PP0.5B0HES0.5CS40) achieves superior mechanical properties and durability. This high-performance concrete (HPC) can reduce the overall material usage in construction by allowing for thinner and lighter structural elements without compromising strength.
11) The optimal dosage of hybrid fibres for developing high-performance concrete with 40% copper slag replacement of natural sand is 0.5% polypropylene fibres, 0% basalt fibre, and 0.5% hooked-end steel fibre by volume fraction.
12) Out of the 13 mixes tested, the optimized mix was identified as PP0.5B0HES0.5CS40, which excels in both mechanical and durability characteristics. The enhanced performance can be attributed to the high tensile strength and elastic modulus of the steel fibres, which bond effectively with the other fibres. Additionally, the inclusion of mineral admixtures and copper slag in the hybrid fibre-reinforced concrete reduces pore size and densifies the modified concrete.

5.2 Future Scope

The present work focussed on evaluating the optimum dosage of hybrid fibres and its effect on the HPC Properties using copper slag. In continuation with the present work, there are certain areas for future work also to be carried out and research other essential characteristics of high-performance concrete-like, establishing the correlation between strength property and development of regression model. Transporting properties and flowability properties of self-compacting concrete, including L-box, U- box is to be considered in future research as the physical property of special concrete. Furthermore, hardened properties such as; elastic modulus and shear strength of high-performance concrete incorporating hybrid fibres are also considered for future research. In addition, some other durability properties are also to be considered in future, such as; the rapid chloride penetration test and the durability prediction models to be considered in future research.

Some of the other Future Scope for the present investigation are given below:

1. Microstructural analysis to analyze the ITZ between the cement matrix and the copper slag particles to understand the bond strength and potential areas of improvement.
2. Sustainability assessment to evaluate the environmental impact of FRHPC with copper slag compared to conventional concrete. Assess parameters such as embodied energy to demonstrate the sustainability benefits of the proposed material.
3. To determine the economic feasibility of using FRHPC with copper slag. Consider the cost of materials, production, and potential savings from enhanced performance and durability to provide insights for the construction industry.

5.3 Research Contribution

The findings of this research will benefit engineers, construction professionals, and policymakers, contributing to the advancement of innovative concrete technologies and promoting the use of eco-friendly materials in the construction industry. Hybrid FRHPC and copper slag help industries by Combining these materials enhance concrete's mechanical and durability properties while providing sustainable and cost-effective solutions. This study has potential research contributions in the concrete technology field by improving the mechanical properties, durability performance, workability, and sustainability of the material. The findings from such studies can contribute to developing more efficient and sustainable concrete solutions for construction applications.

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APPENDIX- I

Table 1: Sieve Analysis of Natural Sand

IS Sieve Size in mm	Retained in gms	% Retained	Cumulative % Retained	% Passing	Acceptable Limit	Remarks
4.75mm	12	1.2	1.2	98.8	90-100	Confirming to Grading Zone II
2.36mm	45	4.5	5.7	94.3	75-100	
1.18mm	295	29.5	35.2	64.8	55-90	
600µ	280	28	63.2	36.8	35-59	
300µ	165	16.5	79.7	20.3	8 to 30	
150µ	184	18.4	98.1	1.9	0-10	
PAN	19	1.9	100			

Table 2: Sieve Analysis of Copper Slag

IS Sieve Size in mm	Retained in gms	% Retained	Cumulative % Retained	% Passing	Acceptable Limit	Remarks
4.75mm	96	9.6	9.6	90.4	90-100	Confirming to Grading Zone II
2.36mm	115	11.5	21.1	78.9	75-100	
1.18mm	122.5	12.25	33.35	66.65	55-90	
600µ	109	10.9	44.25	55.75	35-59	
300µ	266	26.6	70.85	29.15	8 to 30	
150µ	253.5	25.35	96.2	3.8	0-10	
PAN	38	3.8	100			

LIST OF PUBLICATIONS

1. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2022). EDNN based prediction of strength and durability properties of HPC using fibres & copper slag. Advances in concrete construction 2022-09-25 DOI: 10.12989/ACC.2022.14.3.185
2. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2022). Mechanical properties of high strength concrete incorporating Chopped Basalt fibers: Experimental and Analytical Study. Materials Research Express. Volume 9, Number 12. DOI 10.1088/2053-1591/aca644
3. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2023). Effect of fiber synergy on strength & durability of high-performance concrete. Materials Research Express. 10. 10.1088/2053-1591/acb75a.
4. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2021). Effect of Rice Husk Ash, silica fume & GGBFS on compressive strength of performance-based concrete. 10.1016/j.matpr.2021.06.343
5. **Mohit Gupta et al.** (2023) Elimination of global warming gas emissions by utilizing high reactive metakaolin in high-strength concrete for eco-friendly protection. Materials Research Express.10 (2023) https://doi.org/10.1088/2053-1591/acead8
6. **Mohit Gupta et al.** (2021) Experimental investigation on mechanical property of concrete with the hybrid supplementary cementitious material.
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8. **Mohit Gupta**; Ritu Raj; Anil Kumar Sahu (2020). Effect of Rice Husk Ash, silica fume & GGBFS on compressive strength of performance-based concrete. International Conference on Integration of Advanced Technologies 4.0 (ICIATI) sponsored by AICTE, New Delhi on 27th and 28th March 2020
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EDNN based prediction of strength and durability properties of HPC using fibres & copper slag

Mohit Gupta [a], Ritu Raj* and Anil Kumar Sahu [b]

Civil Engineering Department, Delhi Technological University, Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India

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Abstract. For producing cement and concrete, the construction field has been encouraged by the usage of industrial soil waste (or) secondary materials since it decreases the utilization of natural resources. Simultaneously, for ensuring the quality, the analyses of the strength along with durability properties of that sort of cement and concrete are required. The prediction of strength along with other properties of High-Performance Concrete (HPC) by optimization and machine learning algorithms are focused by already available research methods. However, an error and accuracy issue are possessed. Therefore, the Enhanced Deep Neural Network (EDNN) based strength along with durability prediction of HPC was utilized by this research method. Initially, the data is gathered in the proposed work. Then, the data's pre-processing is done by the elimination of missing data along with normalization. Next, from the pre-processed data, the features are extracted. Hence, the data input to the EDNN algorithm which predicts the strength along with durability properties of the specific mixing input designs. Using the Switched Multi-Objective Jellyfish Optimization (SMOJO) algorithm, the weight value is initialized in the EDNN. The Gaussian radial function is utilized as the activation function. The proposed EDNN's performance is examined with the already available algorithms in the experimental analysis. Based on the RMSE, MAE, MAPE, and R^2 metrics, the performance of the proposed EDNN is compared to the existing DNN, CNN, ANN, and SVM methods. Further, according to the metrices, the proposed EDNN performs better. Moreover, the effectiveness of proposed EDNN is examined based on the accuracy, precision, recall, and F-Measure metrics. With the already-existing algorithms i.e., JO, GWO, PSO, and GA, the fitness for the proposed SMOJO algorithm is also examined. The proposed SMOJO algorithm achieves a higher fitness value than the already available algorithm.

Keywords: copper slag; Enhanced Deep Neural Network (EDNN); fibre synergy; High-Performance Concrete (HPC); Switched Multi-Objective Jellyfish Optimization (SMOJO)

1. Introduction

Concrete is the most consumable building material that is usually utilized in the world. High strength, high elasticity modulus, high plasticity, along with workability are the concrete's properties (Zhang *et al.* 2017, Asteris *et al.* 2021). In recent years, the performance requirements for the growing number of underground structures in difficult geology have not been met by conventional strength concrete (Zhang *et al.* 2021, Dadmand *et al.* 2020). Concrete frequently contains industrial waste and by-products like slag, fly ash, and silica fume as discussed by Federowicz *et al.* (2021). In the construction sector, they have been effectively utilized as a fine aggregate substitute (Khan and Changhode 2021, Eisa *et al.* 2021). Copper slag is incorporated by high-strength concrete (HSC) as a fine aggregate. It is concluded that HSC could be attained by lower than 40% copper slag as sand substitution analogous to or better than the control mix (Fediuk *et al.* 2017, 2020). High strength concrete (HSC), High Performance Concrete (HPC), along with high-performance fiber-reinforced concrete (HPFRC) are examples of new kind of concrete. A considerable enhancement is exhibited by the properties of such concretes over those of conventional concrete (Afroughsabet and Ozbakkaloglu 2015, Turk *et al.* 2020). The impact of steel slag powder (SSP) as a cement substitute material on the structural and mechanical characteristics of paving blocks was investigated by Hussain *et al.* (2021). The compressive strength of HSC is significantly decreased by the addition of coir waste & silica fume; however, the splitting tensile strength and shear strength saw significant gains (Ali *et al.* 2022 and Rasheed *et al.* 2022).

Structural applications, namely buildings, bridges, roads, and dams, and non-structural applications, namely kerbs, pipes, and drains are the uses of concrete. The significance of concrete as a construction material will always stay the same (Maharishi *et al.* 2020, Mazloom *et al.* 2020). It is essential for huge buildings to be equipped with higher strength, enhanced ductility, and durability, suitable workability, along with volume stability (Deng *et al.* 2020, Raj *et al.* 2021). But, the brittleness of concrete was more apparent with the higher strength. Generally, it is understood that the porosity is decreased by the substitution

*Corresponding author, Ph.D., Assistant Professor, E-mail: rituraj@dtu.ac.in
[a] Ph.D., Research Scholar, E-mail: mohit.g@live.com
[b] Professor, E-mail: sahuanilkr@yahoo.co.in

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Mechanical properties of high strength concrete incorporating chopped basalt fibers: experimental and analytical study

Mohit Gupta[1,*], **Ritu Raj**[1] and **Anil Kumar Sahu**[1]

Delhi Technological University, Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India

* Author to whom any correspondence should be addressed.

E-mail: mohit_2k17phdcept029@dtu.ac.in, rituraj@dtu.ac.in and sahuanilkr@yahoo.co.in

Keywords: high strength concrete, flexural strength, chopped basalt fibres, split tensile strength, workability, compressive strength, regression model

Abstract

Many civil engineering structures are constructed in terms of aspect like economy, strength and serviceability requirement. The fibres play a prominent role in bridging the micro cracks at the early stage of crack propagation and makes the structure ductile. The impact of chopped basalt fibre on high-strength reinforced concrete composites is the focus of this research. The chopped basalt fibre hardened property of concrete was investigated and compared it with controlled concrete. Moreover, physical property of concrete i.e. slump cone and compaction factor incorporating chopped basalt fibre volume fraction in variation of 0%,0.75%,1.5%,2.25%,3% to the total volume of concrete mix was also investigated. To analyse the hardened properties of chopped basalt fibre high strength concrete, 135 test samples were made and cured for 7, 14, and 28 days. The test findings show that increasing the volume percentage of fibres reduces slump from 135 mm to 132 mm for BFHS0.75 but does not result in a significant increase in concrete compressive strength of 77.1 MPa for BFHS0.75 However, on addition of chopped basalt fibres at 2.25% (BFHS2.25) the percentage increment of flexural strength increases by 72.8% (10.3 MPa) with control mix (5.96 MPa) and after that it decreases when 3% fibres were incorporated. Similarly, split-tensile strength increases at all fibre dosage and fibre addition of 3% (BFHS3) increases by 12.28% (5.65 MPa) with controlled concrete (5.04 MPa). The analytical results and suggested regression model could be used in real-world situations with fiber reinforced high strength concrete related issues. There is a significant relationship between mechanical property and independent variable through ANOVA in SPSS.

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PAPER

Effect of fiber synergy on strength & durability of high-performance concrete

Mohit Gupta[1], Ritu Raj[2], Anil Kumar Sahu[3] and Sapna Yadav[4,*]

[1] Research Scholar, Delhi Technological University, Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India
[2] Assistant Professor, Delhi Technological University, Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India
[3] Professor, Delhi Technological University, Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India
[4] Assistant Professor, KIET Group of Institutions, Delhi- NCR, Ghaziabad, India
[*] Author to whom any correspondence should be addressed.

E-mail: mohit_2k17phdcept029@dtu.ac.in, rituraj@dtu.ac.in, sahuanilkr@yahoo.co.in and sapna.yadav@kiet.edu

Keywords: performance based concrete, fiber synergy, mechanical property, durability

Abstract

The distinct fiber addition to concrete can improve weak performance in tension. Due to its higher performance, fiber hybridization is becoming more and more competitive. In this study, the hardened and durability characteristics of performance-based concrete reinforced with polypropylene, basalt and hooked end steel fibers are investigated. Total 12 mixes are prepared to evaluate the different characteristics of performance-based concrete. The influence of basalt fibers (0.2, 0.25, 0.5, 0.75 & 1%), polypropylene fibers (0.025, 0.03, 0.035, 0.05 & 1%), hooked end steel fibers (0.225, 0.475, 0.65, 0.75, 0.80 & 1%) to explore the impact of fiber synergy, various hybrid fibers with maximum volume fraction of 1% were used out of total concrete volume with and without copper slag (20% & 40%) replacement with fine aggregate are investigated on the hardened characteristics including; compressive strength, flexural strength, splitting tensile strength. Moreover, durability properties including; water absorption, electrical Resistivity, for performance-based concrete are also conducted.

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Effect of Rice Husk Ash, silica fume & GGBFS on compressive strength of performance based concrete

Mohit Gupta *, Dr. Ritu Raj, Dr. Anil Kumar Sahu

Department of Civil Engineering, Delhi Technological University, Delhi, India

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A B S T R A C T

This investigation exhibits a study on the effect of silica fume, Rice husk ash and Ground granulated blast furnace slag on mechanical property of Performance based concrete. The Performance based concrete with various proportion of different mineral admixtures were tested including compressive strength at 7,14 & 28 days of curing. The ordinary Portland cement by weight was partially replaced with Rice Husk Ash (10%, 15%, 20%), Silica Fume (10%, 15%, 20%) and Ground granulated blast furnace slag (10%, 20%,40%). Estimations were completed subsequent to restoring at 20 °C and 65% relative humidity. Total 90 cubes were casted for different mixes for compressive strength of concrete. The test results reported that optimum % of Rice Husk Ash is for the Mix(C90RHA10) and the compressive strength increases by 6.62% compare to control mix at 28 days. Also, the optimum % of Silica Fume is for the Mix (C80SF20) and the compressive strength increases by 13.4%. Similarly, the optimum % of GGBFS is for the Mix (C60GGBFS40) and the compressive strength increases by 6.81%.

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1. Introduction

Concrete is the most broadly utilized development material everywhere throughout the world taking into account its strength aspect, deformed ability in any shape & stability against structural loads. In the present study the main focus is to determine the optimum use of different mineral admixtures with partial replacement of ordinary Portland cement in various proportions to assess the effect on performance based concrete. Industry across the world, concrete has major role in the effects of construction to our environment. High performance concrete is generally having a high strength comparative to the normal strength concrete. The most prominent characteristics of HPC is modulus of elasticity is very high along with durability i.e long lasting service life in built environment. Admixtures are generally classified as chemical admixture and mineral admixture. The chemical admixture further classified as Napthalene based water reducing admixture and polycarboxylate Ether based superplasticizer. Moreover, mineral admixtures are RHA, Metakaolin, SF, FA etc. When GGBFS content silicon industry and it is noncrystalline or amporphous powder form. Rice husk ash contains 85–90% of silica in it obtained from rice milling industry. GGBFS is having lower heat of hydration when used in concrete. The optimal content of GGBFS should not exceed 20% to assess early-age cracking and the proportion of GGBFS including is 0%, 20%, 35%, 50% and early-age cracking of HPC goes on increasing upto 20% under adiabatic condition [1]. By using local materials available U-HPC was developed and there was no increase in compressive strength by using silica fume and fine sand [2]. Resistance to sea water was accessed by influencing different mineral admixtures and microstructure paste is denser than without mineral admixture cement paste [3]. Max. compressive strength at 28 days increases by 0.1% when 20% SF & 10% glass fibre added with 70% natural sand [4]. As compared to flyash; ground granulated blast furnace showed superior mechanical performance at 28 and 91 days [5]. Flyash is generated from industry like thermal power plant as a waste which is generally used in concrete to reduce the carbon dioxide emission as it is replaced with cement and also improves the workability of concrete. Flyash is

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Experimental investigation on mechanical property of concrete with the hybrid supplementary cementitious material

Mohit Gupta [a,*], Akash Yadav [a], Sapna Yadav [b]

[a] Department of Civil Engineering, Inderprastha Engineering College, Plot No 63, Site IV, Surya Nagar Flyover Road, Sahibabad, Ghaziabad,201010, India
[b] KIET School of Management, KIET Group of Institutions, Delhi, NCR Delhi-NCR, Meerut Road (NH-58), Ghaziabad-201206, India

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ABSTRACT

This experimental study was undertaken to examine the combined effect of Silica fume (SF),Metakaolin (MK), and Ground granulated blast furnace slag (GGBFs)on the mechanical property (compressive strength) of concrete. The test on compressive strength, for curing days 7,14 & 28 days was performed in this study. The ordinary Portland cement of grade 43 was replaced by Silica Fume (SF), Metakaolin (MK)& Ground granulated blast furnace slag (GGBFs) at 15%, 20% & 25% in different proportions. The casting and testing of 243 cubes were performed for compressive strength of concrete on 27 Mix IDs. It wasobserved that maximum strength for 28 curing days, was achieved for the Mix (SF25MK15GF25), which was 19% more than that of normal concrete without SCM's. For the Mix (SF20MK15GF25) the strength was 18.25% higher than ordinary concrete which is quite similar to the Mix (SF25MK15GF25). This study conveys that the usage of cement can be reduced to 60% of SCM's (Silica Fume, Metakaolin & Ground granulated blast furnace slag) by weight without compromising the strength. Hence, it reduces the need for cement for the modern construction industry.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Materials and Mechanical Engineering. (ICAMME-2022).

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This is to certify that Dr. / Mr. / Ms. **Mohit Gupta of Delhi Technological University, Delhi** has participated / presented the paper titled **Effect of different mineral admixture on Compressive strength of Performance based concrete** in the **International Conference on Integration of Advanced Technologies for Industry 4.0 (ICIATI)** held on 27 & 28 March 2020 at KCG College of Technology, Chennai, India

General Chair

Dr. G. Prabhakaran
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Advances in Materials and Mechanical Engineering

(ICAMME - 2022)

18TH-19TH FEBRUARY ' 2022

CERTIFICATE OF PARTICIPATION

Mohit Gupta

of *Delhi Technological University, Delhi*

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Experimental investigation on mechanical property of high performance concrete with hybrid supplementary cementitious materials.

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PAPER

Elimination of global warming gas emissions by utilizing high reactive metakaolin in high strength concrete for eco-friendly protection

K Naveen Kumar[1,*], R Divahar[2], Mohit Gupta[3], P S Aravind Raj[2], S P Sangeetha[2] and P S Joanna[4]

[1] Research Scholar, Department of Civil Engineering, Vinayaka Missions Research Foundation, Salem, Tamil Nadu, India
[2] Department of Civil Engineering, Aarupadai Veedu Institute of Technology, Chennai, India
[3] Department of Civil Engineering, Raj Kumar Goel Institute of Technology, Ghaziabad, India
[4] Department of Civil Engineering, Hindustan Institute of Technology and Science, Chennai, India
[*] Author to whom any correspondence should be addressed.

E-mail: naveen.civil@avit.ac.in

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Abstract

The manufacturing process of cement emits one metric ton of carbon dioxide greenhouse gas. Considering the situation reducing the gas emission without affecting cement production, industrial wastes like metakaolin (MK) can be partially replaced with cement due to high pozzolanic reactivity to arrive the high-strength concrete. This present examination attentions on the obtaining optimum percentage of metakaolin to be substituted for cement proportion and aims to determine the concrete sample's mechanical characteristics, equivalent CO_2 emissions, and energy factor for environmental advantages through comparison with metakaolin varied from 0% to 20% at 5% incremental rate was determined and compared with the conventional control mix. Concrete samples are tested at the periodical interval of 7, 14, and 28 days in addition results, 5% of metakaolin is the optimum percentage to be replaced for cement in concrete. The negative sign implies that replacing binder with MK gradually decreases energy requirements (−2.16% to −7.74%) as well as carbon dioxide emissions (−4.17% to −15.41%). The use of mineral admixture like high reactive metakaolin additional cementitious elements has a considerable effect and may have an impact on the creation of

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CURRICULUM VITAE

Mohit Gupta
B. Tech, M. Tech, PhD in Structural Engineering (DTU, Delhi)
Contact No: +91-9919938815, +91-7007100356
E-mail: *civilengineeringelearning@gmail.com*, *mohit.g@live.com*

Profile Highlights/ Experience:

- **10 Years of Working experience (9 years in academics & 1 year in Industry)**
- **Research Publication:**

a) Research Paper: 20 (Out of which 04 SCIE Indexed, 09 SCOPUS Indexed, 07 Refereed Journals)

b) Patents: 35 (Out of which one Utility Patent Granted on Development of advanced prosthetic device for blind amputees, Patent No. 530306)

c) Indian Design & UK Design Grant: 10

d) Books: 06

e) Conferences: 07

f) Research Paper reviewed SCI Indexed Journals: 05

g) Project Submitted to CSTUP of 15.36 lakhs for 3 years.

h) Google Scholar Link: Dr. Mohit Gupta - Google Scholar

i) ORCID Link: https://orcid.org/my-orcid?orcid=0000-0002-4100-9525

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