INFLUENCE OF USING INDUCTION FURNACE SLAG AS PARTIAL REPLACEMENT FOR SAND ON THE PROPERTIES OF UHPC

Name and IDs

FAHIM FAISAL, 190051207

MD. AL ABRAR MAHIR, 190051228

TAYAF MAHAMUD, 190051234

A THESIS SUBMITTED FOR THE DEGREE OF BACHELOR OF SCIENCE IN CIVIL ENGINEERING (STRUCTURE)

Department of Civil and Environmental Engineering

Islamic University of Technology (IUT)

Board Bazar, Gazipur – 1704

Dhaka, Bangladesh.

PROJECT APPROVAL

This is to certify that the thesis entitled "INFLUENCE OF USING INDUCTION FURNACE SLAG AS PARTIAL REPLACEMENT FOR SAND ON THE PROPERTIES OF UHPC" submitted by Fahim Faisal, Md. Al-Abrar Mahir and Tayaf Mahamud has been approved as partial fulfillment of the requirement for the Degree Bachelor of Science in Civil Engineering at the Islamic University of Technology (IUT).

Supervisor

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Dr. Tanvir Ahmed

Assistant Professor

Department of Civil and Environmental Engineering (CEE)

Islamic University of Technology (IUT)

Board Bazar, Gazipur-1704, Bangladesh.

DECLARATION

We hereby declare that the undergraduate research work detailed in this thesis was conducted by us under the expert supervision of Dr. Tanvir Ahmed. Rigorous cautionary measures were implemented to ensure the originality and authenticity of our work. We confirm that the material presented in this thesis is entirely our own and has not been copied, plagiarized, or submitted elsewhere for any purpose other than publication. We have adhered to the highest standards of academic integrity throughout the research process.

Names and IDs

Fahim Faisal, 190051207

Md. Al Abrar Mahir, 190051228

Tayaf Mahamud, 190051234

DEDICATION

We dedicate this thesis to our parents, whose unwavering support, time, and effort have been instrumental in shaping our achievements. Their profound dedication and belief in our abilities have enabled us to pursue our technical goals with confidence and determination. We express our deepest gratitude for their immeasurable sacrifices and steadfast support.

We also wish to convey our sincere appreciation to Dr. Tanvir Ahmed, our esteemed supervisor, for his relentless encouragement, insightful guidance, and motivational support. His expert supervision has been pivotal to the success of this research project, and without his dedicated assistance, this endeavour would not have been possible.

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ABSTRACT

This thesis investigates the utilization of Induction Furnace Slag (IFS) as a replacement for sand in Ultra-High-Performance Concrete (UHPC), aiming to enhance mechanical properties, durability, and sustainability. The research encompasses a comprehensive series of experimental formulations where sand is replaced with IFS at varying proportions (0%, 5%, 10%, 20%, and 30%). Key mechanical properties assessed include compressive strength, tensile strength, and flexural strength. The durability characteristics focus on resistance to environmental degradation, such as freeze-thaw cycles, chloride ion penetration, and sulphate attack. The findings reveal that moderate IFS replacement (10% and 20%) maintains high compressive strengths and significantly improves drying shrinkage characteristics due to enhanced particle packing and reduced pore connectivity. Furthermore, the study includes an environmental impact assessment through a detailed life-cycle analysis, quantifying reductions in carbon footprint and resource consumption. The incorporation of IFS not only promotes the recycling of industrial waste but also contributes to the reduction of the environmental footprint of concrete production. Practical recommendations are provided for the construction industry, emphasizing the use of UHPC with IFS for sustainable and resilient infrastructure development. This research underscores the potential of IFS as a valuable resource in UHPC, aligning with global efforts to achieve more sustainable construction practices.

Keywords: Ultra-High-Performance Concrete, Induction Furnace Slag, Mechanical Properties, Durability, Environmental Impact, Sustainable Construction, Industrial By-products.

Chapter 1: Introduction

1.1 General

Ultra-High-Performance Concrete (UHPC) is a pioneering advancement in the field of construction materials, known for its superior mechanical properties, durability, and longevity. The unique composition of UHPC, characterized by a low water-to-cement ratio, high cement content, and the inclusion of fine particles such as silica fume and quartz sand, often supplemented with steel fibres, results in a material with outstanding compressive and tensile strengths, reduced permeability, and enhanced durability[12]. These attributes make UHPC an ideal choice for demanding structural applications, including bridge construction, rehabilitation, and other infrastructure projects that require long-lasting and resilient materials [12, 13].

The exceptional performance of UHPC is largely attributed to its dense microstructure, which significantly reduces porosity and enhances the material's resistance to environmental degradation. This makes UHPC particularly suitable for structures exposed to harsh conditions, such as marine environments and areas subjected to freeze-thaw cycles. The use of steel fibres further enhances the ductility and impact resistance of UHPC, providing additional safety margins for structural applications. Despite these advantages, the production of UHPC is associated with high costs and significant environmental impacts, primarily due to the extraction and processing of its raw materials. As the construction industry increasingly adopts sustainable practices, there is a growing interest in incorporating industrial by-products and waste materials into UHPC formulations. This approach not only mitigates the environmental footprint of concrete production but also offers a sustainable solution for managing industrial waste. Among the various potential materials, Induction Furnace Slag (IFS), a by-product of the steel manufacturing process, has emerged as a promising alternative to natural sand in UHPC.

1.2 Background

The idea of utilizing industrial waste materials in UHPC is not new. Numerous studies have demonstrated the feasibility and benefits of incorporating such materials into UHPC without compromising its performance. For example, Ahmad et al. explored the development of UHPC mixtures utilizing natural and industrial waste materials as partial replacements for silica fume and sand. Their findings indicated that such substitutions could enhance the mechanical properties and environmental sustainability of UHPC [14]. Similarly, Ahmed et al. developed Eco-UHPC using gold mine tailings as a quartz sand alternative, underscoring the potential for sustainable material substitution without sacrificing performance [15].

Induction Furnace Slag (IFS) is particularly promising as a sand replacement in UHPC due to its favourable chemical composition and physical properties. IFS is rich in silica and alumina, which are critical components for the strength and durability of UHPC. Additionally, the angular particle shape and rough texture of IFS can enhance the interfacial bond between the cement matrix and aggregate, leading to improved mechanical properties[16]. Previous research on the use of alternative aggregates, such as glass sand and waste foundry sand, supports the viability of IFS as a suitable replacement material [17,18].

The integration of waste materials like IFS into UHPC aligns with broader goals of sustainable construction and resource efficiency. Studies have shown that the use of recycled and industrial by-products can significantly reduce the carbon footprint of concrete production while maintaining or even enhancing the performance characteristics of the final product[19]. However, the incorporation of IFS into UHPC requires comprehensive research to fully understand its impacts on the fresh and hardened properties of UHPC, as well as its long-term durability and environmental performance.

1.3 Objectives

This thesis aims to investigate the impacts of using IFS as a sand replacement in UHPC. The specific objectives of the study are:

1. **Evaluate Mechanical Properties**: To assess the mechanical properties of UHPC with varying proportions of IFS as a sand replacement, including compressive strength, tensile strength, and flexural strength. This evaluation will provide insight into the potential benefits and drawbacks of incorporating IFS in terms of structural performance.

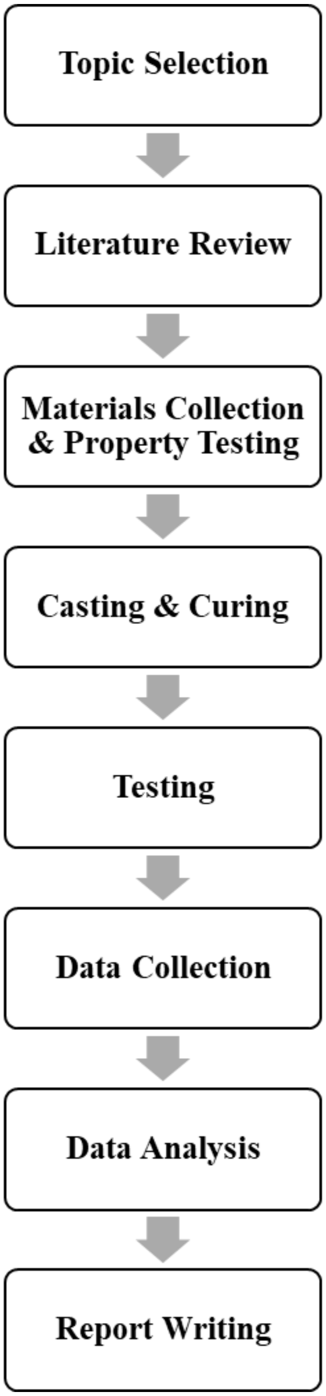
2. **Assess Durability Characteristics**: To evaluate the durability characteristics of UHPC incorporating IFS, focusing on resistance to environmental degradation. This includes analysing the material's performance under freeze-thaw cycles, chloride ion penetration, and sulphate attack, which are critical for ensuring long-term durability in various environmental conditions.
3. **Optimize Mix Design**: To optimize the mix design of UHPC with IFS to achieve a balance between mechanical performance and sustainability. This objective aims to ensure that the material meets or exceeds current performance standards for UHPC while maintaining a focus on sustainable practices by reducing the reliance on traditional sand.
4. **Environmental Impact Assessment**: To compare the environmental impact of UHPC with and without IFS through a detailed life-cycle assessment. This will involve quantifying reductions in carbon footprint and resource consumption, highlighting the environmental benefits of using IFS as a sustainable alternative to sand.
5. **Practical Recommendations**: To provide practical recommendations for the use of IFS in UHPC for structural applications, particularly in bridge construction and other infrastructure projects. These recommendations will ensure that the material is both economically viable and environmentally friendly, promoting wider adoption of IFS in the construction industry. The demand for UHPC in the construction industry has been driven by its ability to address many of the shortcomings of conventional concrete. Traditional concrete, while widely used, often suffers from issues related to durability and maintenance, particularly in severe environmental conditions. UHPC, with its dense matrix and enhanced mechanical properties, offers solutions to these problems by providing a longer service life and reduced maintenance requirements. This is particularly advantageous in critical infrastructure applications, where the cost and difficulty of repairs can be substantial [20].

Incorporating IFS into UHPC is not only an environmental imperative but also a technical challenge that necessitates comprehensive investigation. IFS is produced in significant quantities globally, and its disposal poses considerable environmental issues. By integrating IFS into UHPC, this study aims to transform a waste product into a valuable resource, thereby contributing to both waste reduction and resource efficiency. This approach not only addresses the environmental burden associated with IFS disposal but also leverages its potential benefits in enhancing the performance characteristics of UHPC. Consequently, the use of IFS can significantly improve the sustainability profile of UHPC, positioning it as a more attractive and responsible option for modern construction practices, aligning with the industry's move towards greener and more sustainable building materials.

Previous studies have demonstrated that industrial by-products such as fly ash, slag, and glass sand can be effectively utilized as replacements for traditional aggregates in concrete. These by-products not only offer a sustainable alternative to natural resources but also contribute to enhanced material properties. Fly ash, for instance, improves the workability and durability of concrete, while slag can enhance its compressive strength and resistance to chemical attacks. Similarly, the inclusion of glass sand has been found to improve the concrete's strength and thermal stability. By incorporating these industrial by-products, researchers have been able to reduce the environmental impact associated with concrete production, promote resource conservation, and achieve superior performance characteristics in concrete materials. These materials have been found to improve various properties of concrete, such as compressive strength, workability, and durability [21]. The successful incorporation of these materials into UHPC formulations suggests that IFS, with its similar properties, could offer similar or even superior benefits.

In conclusion, the integration of IFS as a sand replacement in UHPC represents a promising approach to advancing sustainable construction practices. By leveraging industrial by-products, this research aligns with global efforts to reduce the environmental impact of construction activities and promote resource efficiency. The outcomes of this study will contribute to the development of next-generation UHPC materials that combine superior performance with environmental sustainability, thereby offering practical solutions for the future challenges of the construction industry. This study aims to demonstrate the feasibility of using IFS in UHPC, providing a foundation for future research and applications in sustainable construction materials. Furthermore, it paves the way for the development of more sustainable and resilient infrastructure, addressing both current and future demands for environmentally responsible building practices.

1.4 Research Flow Diagram



1.5 Layout of the Thesis

The thesis consists of the following layout.

Chapter 1: Introduction - This chapter provides a comprehensive overview of the theoretical framework and background pertinent to the study. It delineates the objectives and scope of the research and includes a detailed research flow diagram to guide the reader through the study's structure.

Chapter 2: Literature Review - This chapter offers an in-depth review of existing literature related to the field of study. It systematically examines the research conducted by previous authors, critically analysing their findings and highlighting their relevance to the current study.

Chapter 3: Methodology - This chapter meticulously describes the research design, procedures, and methodologies employed in conducting the study. It details each step of the research process, ensuring transparency and reproducibility of the study.

Chapter 4: Results and Discussion - This chapter presents the data collected during the study and explains the processes used to analyse this data. It discusses the results in detail, interpreting the findings in the context of the research objectives and existing literature.

Chapter 5: Conclusion and Recommendations - This chapter provides a thorough discussion of the study's conclusions, identifying the key findings and their implications. It addresses the limitations encountered during the research and offers well-considered recommendations for future studies and practical applications.

Chapter 2: Literature Review

UHPC is widely recognized for its exceptional mechanical properties, durability, and longevity. Its composition, characterized by a low water-to-cement ratio, high cement content, and the inclusion of fine particles such as silica fume and quartz sand, often supplemented with steel fibres, results in a material with outstanding compressive and tensile strengths, reduced permeability, and enhanced durability[1]. Given the environmental concerns and high costs associated with the traditional components of UHPC, there has been significant research into the use of industrial by-products and waste materials as substitutes. However, the specific application of IFS as a sand replacement in UHPC remains largely unexplored. This literature review examines the development and performance of UHPC with various industrial waste materials, highlighting the research gap related to IFS.

Ahmad et al. (2014) conducted a study on the development of UHPC mixtures using natural and industrial waste materials as partial replacements for silica fume and sand. Their research demonstrated that incorporating these materials could enhance the mechanical properties and environmental sustainability of UHPC. They found that the compressive and flexural strengths of UHPC improved with the addition of waste materials, while also reducing the overall environmental impact of the concrete production process[2]. This foundational work has paved the way for further exploration into other industrial by-products as potential UHPC components.

Ahmed et al. (2021) developed Eco-UHPC using gold mine tailings as an alternative to quartz sand. Their study highlighted the potential for sustainable material substitution in UHPC without compromising its performance. The mechanical properties of the Eco-UHPC were comparable to those of traditional UHPC, demonstrating the viability of using waste materials in high-performance concrete formulations[3]. In a subsequent study, Ahmed et al. (2022) explored the use of high-volume Class-F fly ash in Eco-UHPC, providing new insights into the mechanical and durability properties of the material. They concluded that high-volume fly ash could significantly enhance the durability of UHPC, particularly in terms of resistance to chloride ion penetration and sulphate attack[4]. These studies underscore the importance of developing environmentally friendly UHPC formulations.

Soliman and Tagnit-Hamou (2017) investigated the use of glass sand as an alternative to quartz sand in UHPC. Their research demonstrated that glass sand could be effectively used in UHPC, improving both the mechanical properties and environmental sustainability of the material. They found that the incorporation of glass sand resulted in a denser microstructure, which enhanced the durability of UHPC[5]. This study contributes to a growing body of evidence supporting the use of recycled materials in UHPC formulations.

The mechanical properties of UHPC are significantly influenced by the type and proportion of waste materials used. Farzad et al. (2019) conducted an experimental and numerical study on the bond strength between conventional concrete and UHPC. Their research showed that the addition of waste materials, such as foundry sand, could enhance the bond strength and overall mechanical properties of UHPC. They concluded that the optimized mix designs incorporating waste materials could achieve superior performance compared to conventional UHPC[6]. This finding is critical as it demonstrates the potential for industrial by-products to improve the structural integrity of UHPC.

Marzewski (2020) studied the mechanical properties of UHPC with partial utilization of waste foundry sand. The results indicated that the incorporation of waste foundry sand could improve the compressive and tensile strengths of UHPC, making it a viable alternative to natural sand. The study also highlighted the environmental benefits of using waste materials, reducing the carbon footprint of concrete production[7]. Marzewski's work aligns with global sustainability goals by promoting the use of industrial waste in high-performance construction materials.

Zhu et al. (2022) examined the mechanical properties of UHPC with coal gasification coarse slag as a replacement for river sand. Their findings demonstrated that coal gasification slag could enhance the compressive strength and durability of UHPC, particularly in harsh environmental conditions. The study emphasized the potential of using industrial by-products to develop high-performance and sustainable concrete materials[8]. This research highlights the versatility of UHPC formulations and the potential for significant performance improvements through the use of alternative materials.

Chen et al. (2021) provided insights into the mechanical performance of UHPC repaired cementitious composite systems after exposure to high temperatures. Their research highlighted the importance of understanding the long-term durability and environmental performance of UHPC with waste materials, particularly in extreme conditions. They found that UHPC incorporating industrial by-products could maintain its mechanical properties and durability even after exposure to high temperatures[9]. This study is particularly relevant for applications where UHPC is subjected to severe thermal stresses, such as in fire-prone areas.

The environmental impact of UHPC production is a critical consideration in the development of sustainable construction materials. Graybeal et al. (2020) discussed the international perspective on UHPC in bridge engineering, highlighting the importance of sustainability in the development and application of UHPC. They emphasized the need for incorporating industrial by-products and waste materials to reduce the environmental footprint of UHPC[10]. Their work illustrates the global commitment to sustainable construction practices and the role of UHPC in achieving these goals.

Miraldo et al. (2021) reviewed the advantages and shortcomings of utilizing recycled wastes as aggregates in structural concretes[26]. Their study provided a comprehensive overview of the potential environmental benefits and challenges associated with using waste materials in concrete. They concluded that while recycled aggregates could enhance the sustainability of concrete, careful consideration must be given to the quality and performance of the resulting material[11]. This review is essential for understanding the broader implications of using industrial by-products in UHPC and the need for rigorous quality control.

Despite the extensive research on the use of various waste materials in UHPC, the specific application of Induction Furnace Slag (IFS) as a sand replacement remains largely unexplored. IFS is a by-product of the steel manufacturing process and is produced in significant quantities globally. Its disposal poses environmental challenges, making it an attractive candidate for sustainable construction materials. IFS is rich in silica and alumina, essential components for the strength and durability of UHPC. Additionally, its angular particle shape and rough texture can enhance the interfacial bond between the cement matrix and aggregate, leading to improved mechanical properties[8].

Brühwiler discussed the rehabilitation and strengthening of concrete structures using Ultra-High-Performance Fibre Reinforced Concrete (UHPFRC). Their work highlighted the potential of using industrial by-products, such as IFS, to enhance the performance and sustainability of UHPFRC. They emphasized the need for comprehensive research to fully understand the impacts of IFS on the fresh and hardened properties of UHPC, as well as its long-term durability and environmental performance[12]. This gap in the research represents a significant opportunity for innovation in UHPC formulations.

Previous studies have primarily focused on the use of waste materials like fly ash, foundry sand, and glass sand, but the potential benefits of IFS have not been fully explored. The unique chemical and physical properties of IFS could offer distinct advantages in UHPC applications. For instance, the high silica content in IFS can contribute to the pozzolanic reaction, enhancing the strength and durability of the concrete. Additionally, the angular shape of IFS particles can improve the packing density and interfacial transition zone in UHPC, leading to better mechanical performance.

The literature reveals a significant gap in the research on the use of IFS as a sand replacement in UHPC. While there is substantial evidence supporting the use of various industrial by-products in UHPC, the specific benefits and challenges of incorporating IFS remain underexplored. This gap presents an opportunity for future research to develop a deeper understanding of the potential of IFS in UHPC applications.

Future research should focus on comprehensive experimental studies to evaluate the fresh and hardened properties of UHPC with IFS. Key areas of investigation should include the mechanical properties (compressive, tensile, and flexural strengths), durability (resistance to environmental degradation, such as freeze-thaw cycles and chloride ion penetration), and long-term performance of UHPC incorporating IFS. Additionally, life-cycle assessments should be conducted to quantify the environmental benefits of using IFS in UHPC, including reductions in carbon footprint and resource consumption.

Another important aspect of future research is the optimization of mix designs to achieve the best possible performance with IFS. This involves determining the optimal proportion of IFS to replace natural sand, as well as understanding the interactions between IFS and other components of the UHPC mix. By optimizing the mix design, researchers can develop UHPC formulations that not only meet performance standards but also offer significant environmental benefits.

Finally, practical applications of UHPC with IFS should be explored in real-world construction projects. Pilot projects can provide valuable insights into the feasibility and performance of UHPC with IFS in different environmental conditions and structural applications. These projects can also help identify any practical challenges in the use of IFS and provide feedback for further refinement of the mix designs.

The integration of industrial by-products and waste materials into UHPC formulations offers significant potential for enhancing the sustainability and performance of concrete materials. Research has demonstrated that materials such as gold mine tailings, fly ash, glass sand, foundry sand, and coal gasification slag can improve the mechanical properties and durability of UHPC while reducing its environmental footprint. However, the use of IFS as a sand replacement in UHPC has not been extensively studied, indicating a significant research gap in this area. This study aims to address this gap by investigating the feasibility and performance of UHPC incorporating IFS. The outcomes will contribute to the development of next-generation UHPC materials that combine superior performance with environmental sustainability, offering practical solutions for the future challenges of the construction industry.

Chapter 3: Methodology

3.1 General

In this chapter, the experimental methodology of the study is comprehensively detailed, providing an extensive overview of the research process. It begins with an in-depth description of the mixture proportions of concrete, outlining the specific cases investigated within this research. The chapter then elaborates on the procedures for collecting and preparing materials, including a thorough discussion of the methods and standards employed for testing the constituent materials. This section ensures that all materials used in the experiments meet the required specifications and are prepared consistently.

Furthermore, the protocols for preparing testing samples are meticulously described, ensuring that the experimental process is both accurate and replicable. The chapter also covers the curing methods utilized, detailing the various techniques applied to optimize the properties of the UHPC. The different testing procedures used to evaluate the mechanical and durability properties of UHPC are explained in detail, highlighting the importance of each test in assessing the performance of the concrete.

Additionally, this chapter provides a critical discussion on the relevance of these methods to the overall study objectives, ensuring that the experimental framework is thoroughly aligned with the research goals. This discussion emphasizes the significance of each methodological step and its contribution to achieving the study's aims. By providing a detailed and critical overview of the experimental methodology, this chapter ensures a comprehensive understanding of the research framework and its alignment with the objectives of evaluating the performance and sustainability of UHPC incorporating IFS.

3.2 Collection of Materials

To produce the concrete mixtures, natural river sand obtained from Durgapur was employed. The binding materials consisted of CEM Type 1 (Ordinary Portland Cement, OPC) and CEM Type II A-M, conforming to BDS EN 197 standards [containing 80%-94% clinker, 6%-20% mineral admixture, and 5% gypsum], along with silica fume, all sourced from a local manufacturer. The induction furnace slag utilized in this study was acquired from a cement manufacturing facility in Chittagong. Two different admixtures were evaluated to identify the most appropriate one, with both admixtures being procured from a local manufacturing company.

3.3 Material Properties

The utilization of industrial by-products and sustainable materials in concrete technology has gained significant attention in recent years, primarily driven by the dual objectives of enhancing material performance and minimizing environmental impact. UHPC exemplifies these advancements with its superior mechanical properties and durability, making it ideal for high-demand structural applications such as bridges, buildings, and other critical infrastructure.

The unique composition of UHPC, typically characterized by a low water-to-cement ratio, high cement content, and the inclusion of fine particles such as silica fume and quartz sand, is often further optimized with supplementary materials to improve its sustainability and performance. This study aims to investigate the potential of using various sustainable materials as replacements for traditional components in UHPC, focusing on the integration of industrial by-products such as slag and fly ash.

A comprehensive experimental program was designed to evaluate the performance of these materials in UHPC mixtures. The study encompasses the detailed preparation of the constituent materials, including the collection and characterization of aggregates, cementitious materials, and water. Specific attention is given to the properties of these materials before their incorporation into the concrete mix, ensuring that they meet the necessary standards for high-performance concrete applications. The following sections outline the methods and standards employed in testing material properties, the mixture proportions for both mortar and concrete, the curing procedures, and the various testing protocols adopted to assess the mechanical and durability characteristics of the resulting UHPC. This approach not only aims to enhance the understanding of the potential of UHPC but also seeks to contribute to the development of more sustainable construction practices.

3.3.1 Fine Aggregates

In this study, four types of natural river sands were utilized as fine aggregates. The sands were sieved through 450 micrometre and 600 micrometre meshes to obtain the finest particles for concrete casting. Based on the compressive strength test results, the natural river sand collected from Durgapur and sieved through the 600-micrometre mesh was selected for the main concrete mixes.

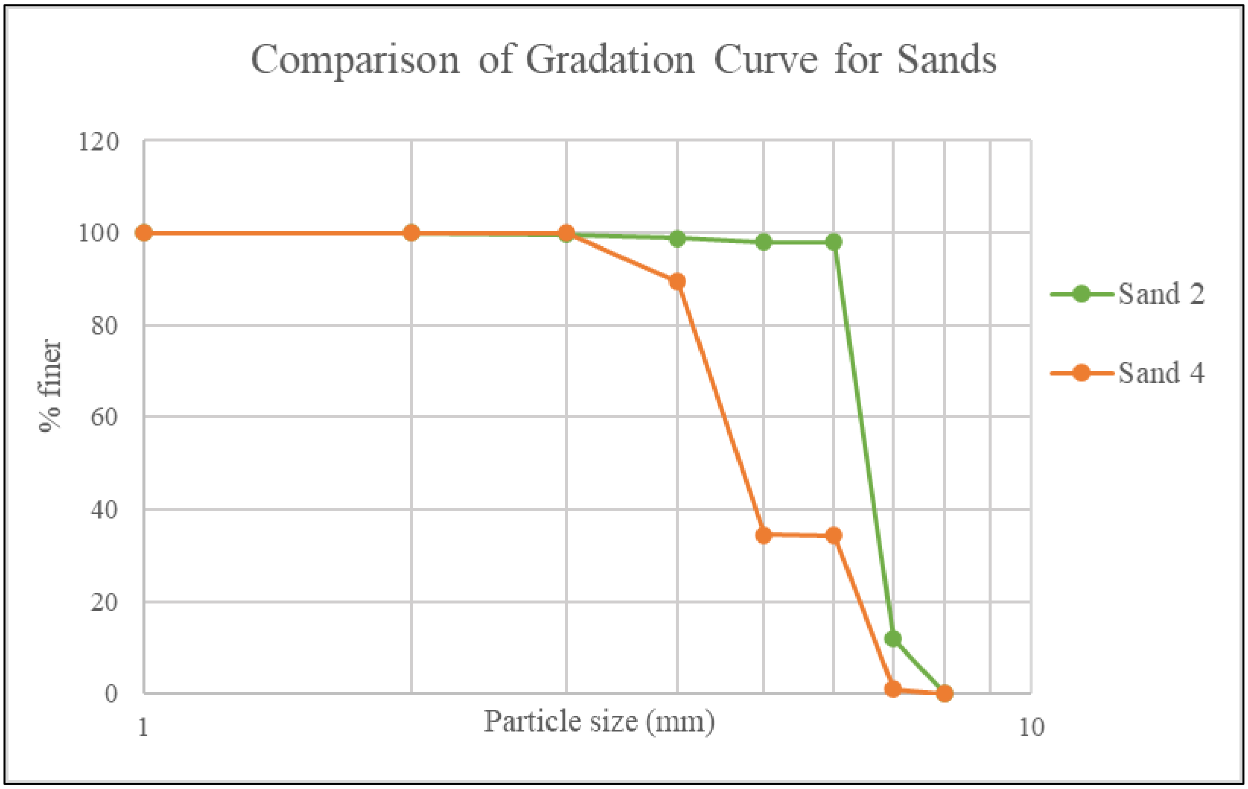


Figure 3.1: Gradation Comparison of Sands

Figure 3.1 provides a visual representation of the gradation comparison among the different sands utilized in this research. This figure effectively illustrates the particle size distribution and highlights the differences in granularity between the sands. Complementing this visual data, Table 3.2 offers a detailed account of the material properties of the sands employed in the study. This table includes critical parameters such as specific gravity, absorption capacity, and other relevant physical properties, providing a comprehensive overview of the characteristics of each type of sand. Together, these visual and tabulated data form a robust foundation for understanding the behaviour and suitability of the sands in the context of the experimental investigation.

Table 3.1: Material Properties of Sands

	Test	Specification	Result
Sand	Specific Gravity of Sand 2	ASTM C 128	2.54
	Specific Gravity of Sand 4	ASTM C 128	2.63

3.3.2 Binder Material

CEM Type I (Ordinary Portland Cement), CEM Type II A-M, and silica fume were utilized as binding materials in this project. Silica fume, also known as micro silica, is an ultrafine byproduct of silicon and ferrosilicon alloy production, primarily composed of amorphous silicon dioxide (SiO_2). In UHPC, silica fume is essential for enhancing strength, durability, and density. Its high surface area and pozzolanic reactivity fill voids between cement particles, forming additional calcium silicate hydrate (C-S-H) gel[27]. The composition of the mineral properties of the cements is provided in Table 3.2, and the mineral properties of the silica fume is detailed in Table 3.3.

Table 3.2: Material Properties of Cements

Material	Material Type	Test	Result
Cement	CEM I	Specific Gravity	3.15
		Clinker %	95%
		Gypsum %	5%
	CEM II/A-M	Specific Gravity	2.90
		Clinker %	80-94%
		Mineral Admixture	6-20%
		Gypsum %	0-5%

Table 3.3: Material Properties of Silica Fume

	Test	Specification	Result
Silica Fume	Specific Gravity	ASTM C 188-17	2.25

3.3.3 Induction Furnace Slag (IFS) as Sand Replacement Material

For this study, induction furnace slag (IFS) was used as a sand replacement in the Ultra-High-Performance Concrete (UHPC) mixes. The IFS was sourced from a cement factory in Chittagong, and its specific gravity was measured prior to its use as a replacement, as specified in Table 3.4.

Table 3.4: Material Properties of Induction Furnace Slag

Induction Furnace Slag	Test	Specification	Result
	Specific Gravity	ASTM C 128	2.63

The gradation curve of the induction furnace slag is depicted in Figure 3.2.

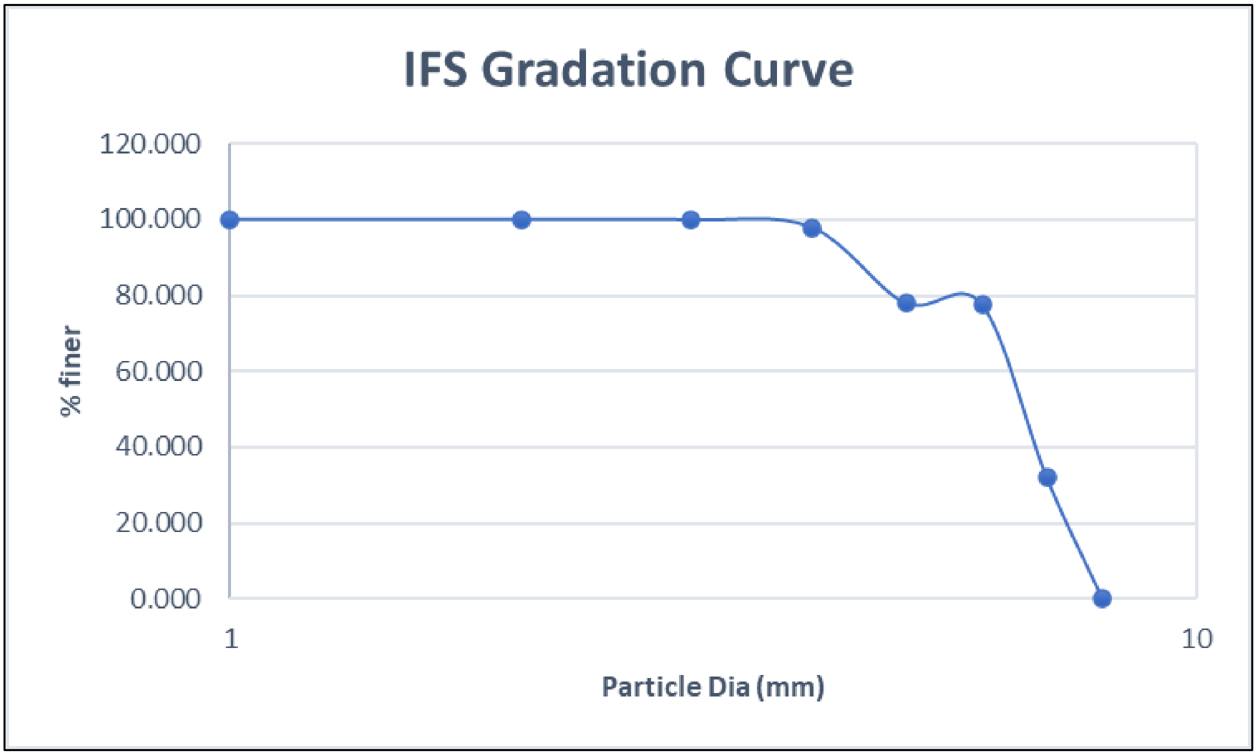


Figure 3.2: Gradation Curve of IFS

Additionally, Figure 3.3 presents a comparison of the gradation curves between Sand 3 and the induction furnace slag.

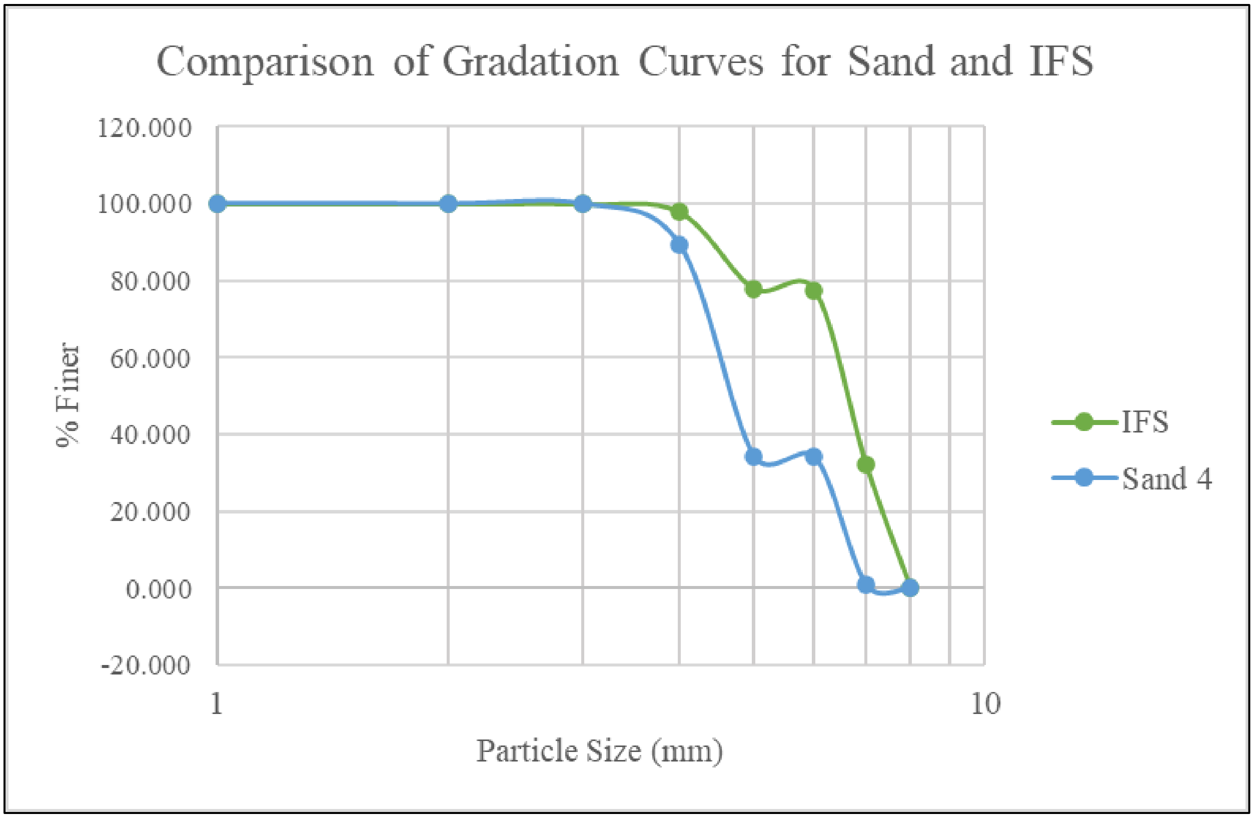


Figure 3.2: Gradation Curve Comparison between Sand 4 & IFS

3.3.4 Water

In this study, water with a unit weight of 1000 kg/m³ was utilized for both the mixing and curing of the concrete specimens. This water was carefully selected to be uncontaminated and free from any harmful pollutants, thereby ensuring its compliance with the stringent standards required for concrete production. By adhering to these quality specifications, the study guarantees that the integrity and performance of the concrete specimens are not compromised by impurities or contaminants in the water.

3.3.5 Admixture

Here, two admixtures were tested in the trial mixes to determine the most suitable one for the control mix of UHPC. The two admixtures used were AURAMIX 500 and ARMIX Emmecrete PC 10. The properties of these admixtures are detailed in Table 3.5.

Table 3.5: Chemical Properties of Admixtures

Chemical Properties		
Characteristics	Admixture 1 (Armix Emmecrete PC 10)	Admixture 2 (Auramix 500)
Chemical Type	Based on Polycarboxylic Ether Polymer	Based on Polycarboxylic Ether Polymer
Appearance	Clear to Light Brown Liquid	Light Yellow coloured Liquid
pH	Minimum 6.0	Minimum 6.0
Volumetric mass at 20 ^{O}C	-	1.1 ± 0.2 kg/litre
Alkali Content	-	Typically, less than 1.5 g Na_2O equivalent / litre of admixture
Chloride Content	Nil	-

3.4 Mortar Mix Design

The mix proportions utilized in this study were calculated on volumetric basis. The individual ingredient contents of the mortar were designed such that their combined volume equated to 1 m^3 of mortar. This approach ensures accurate scaling and can be expressed by the following equation:

$$\frac{S}{G_S\gamma_W}+\frac{C}{G_C\gamma_W}+\frac{W}{G_W\gamma_W}+Air(\%)=1 \ldots\ldots (3.1)$$

Where,

C = Unit content of cement (kg/m^3 of mortar)

S = Unit content of fine aggregate (kg/m^3 of mortar)

W = Unit content of water (kg/m^3 of mortar)

γ_W = Unit weight of water (kg/m^3)

G_C = Specific gravity of cement

G_S = Specific gravity of fine aggregate (SSD)

G_W = Specific gravity of water

Air (%) = Percentage of air in mortar (assumed at 0% without air entraining agent)

3.5 Details of Specimens of Trial Mixes

UHPC is broadly defined as a cementitious, composite material that exhibits superior strength, durability, and tensile ductility compared to High-Performance Concretes (HPC). UHPC often incorporates fibres for post-cracking ductility, features a specified compressive strength of at least 120 MPa at 28 days, and is formulated with a modified multi-scale particle packing of inorganic materials with diameters less than 0.6 mm (although larger sizes can also be used) [Canadian Standards Association CSA A23.1/2 Annex S on Ultra-High-Performance Concrete, Rexdale, ON, Canada 2018 (Draft)]. To achieve a strength greater than 120 MPa, a total of eight trial mixes were conducted to identify the optimal control mix. The test specimens, cubic in shape (25 mm * 25 mm * 25 mm), were prepared using potable water.

Both CEM Type I and CEM Type II A-M cements were tested to determine the more suitable option for the control mix. In the second trial, CEM Type I demonstrated better performance due to its finer particle size compared to CEM Type II A-M. Consequently, subsequent trial mixes were conducted with CEM Type I. Four types of sands were evaluated to establish the control mix. Sand 1 is natural river sand passed through a 450 µm sieve. Sand 2 is natural sand passed through a 600 µm sieve. Sand 3 is natural river sand from Durgapur passed through a 2.3 mm sieve. Sand 4 is the same sand as Sand 3, but passed through a 600 µm sieve.

Two superplasticizers were tested, with AURAMIX 500 yielding better results. Compressive strength tests were conducted at 7 and 28 days to determine the control mix. A combination of water curing and increased temperature curing was employed. The specimens were initially submerged in water at room temperature for 72 hours, followed by increased temperature curing in an oven at 70°C for 96 hours. The implementation of this mixed curing process significantly improved the compressive strength of the concrete specimens. By combining different curing methods, the process optimized the hydration and hardening phases, leading to superior mechanical properties. The specific mix designs used in the trial mixes, detailing the proportions and components, are comprehensively presented in Table 3.6 and Table 3.7. These tables provide a clear and structured overview of the experimental formulations, facilitating an understanding of the relationship between mix composition and performance outcomes.

Table 3.6: Mix Proportions of Trial Mixes without IFS replacements

Mix →		**C_2WB_{20}**	**$C_1WB_{20}^1$**	**$C_1WB_{20}^2$**	**C_1WB_{23}**	**$C_1WB_{18}^1$**
Contents	CEM I		823	876	884	930
	CEM II	923				
	Silica Fume	231	206	219	221	232
	Sand 1	969	905			
	Sand 2			964	928	976
	Sand 3					
	Sand 4					
	IFS					
	Water	221	291	221	234	184
	Superplasticizer 1	15	12	-	-	-
	Superplasticizer 2	-	-	37	34	46

Table 3.7: Mix Proportions of Trial Mixes without IFS replacements

Mix →		**$C_1WB_{18}^2$**	**$C_1WB_{18}^3$**	**$C_1WB_{18}^4$**	**$C_1WB_{17}^1$**	**$C_1WB_{17}^2$**
Contents	CEM I	930	930	930	941	941
	CEM II					
	Silica Fume	232	232	232	235	235
	Sand 1					
	Sand 2	976	976			
	Sand 3				988	
	Sand 4			976		988
	IFS					
	Water	184	184	184	174	174
	Superplasticizer 1	-	-	-	-	-
	Superplasticizer 2	46	46	46	47	47

[Notes on Nomenclature: Here, C_1 = Cem I, C_2 = Cem II, WB = Water-binder ratio, Sand 1=Old Sand, Sand 2= New Sand, Sand 3 = Durgapur(2.3mm), Sand 4 = Durgapur (600 micron)]

3.6 Details of Specimens of IFS Replacement Mixes

Following the investigation of eight trial mixes, the highest compressive strength was observed for the mix ratio designated as $C_1WB_{17}SP_2$. In this instance, the water to binder ratio was 0.17, and CEM Type I cement was utilized. The superplasticizer employed in this mix was AURAMIX 500. This mix underwent a combined curing process, where the cubic specimens were initially cured in water for 72 hours and subsequently subjected to increased temperature curing in an oven at 70°C for 96 hours. Due to its superior strength compared to all other trial mixes, $C_1WB_{17}SP_2$ was identified as the "control mix" for the study. Thereafter, replacement mixes were introduced to examine the effects of IFS on the mechanical and durability properties of UHPC. In this experimental study, sand was replaced with IFS at proportions of 5%, 10%, 20%, and 30% by volume of the sand in the control mix. The proportions of the replacement mixes are detailed in Table 3.8.

Table 3.8: Mix Proportions of Trial Mixes with IFS replacements

Mix →		**$C_1WB_{17}IFS_5$**	**$C_1WB_{17}IFS_{10}$**	**$C_1WB_{17}IFS_{20}$**	**$C_1WB_{17}IFS_{30}$**
Contents	CEM I	941	941	941	941
	CEM II				
	Silica Fume	235	235	235	235
	Sand 1				
	Sand 2				
	Sand 3				
	Sand 4	939	889	790	692
	IFS	49	99	198	296
	Water	174	174	174	174
	Superplasticizer 1	-	-	-	-
	Superplasticizer 2	47	47	47	47

[Notes on Nomenclature: Here, C_1 = Cem I, C_2 = Cem II, WB = Water-binder ratio, $IFS_{5/10/20/30}$ = Induction Furnace Slag percentage]

3.7 Specimen Mould Preparation

For this study, two types of specimens were cast: 50 mm * 50 mm * 50 mm cube-shaped concrete specimens and 25 mm * 25 mm * 285 mm prism-shaped concrete specimens. These moulds are available at the CEE Concrete Lab of the Islamic University of Technology (IUT). Prior to casting, the moulds were ensured to be airtight by adjusting the available screws, and the inner surfaces were lubricated with grease in accordance with ASTM C 31-03. The moulds are depicted in Figure. After ensuring proper preparation of the moulds, the concrete was carefully poured and compacted to avoid any air pockets. This meticulous process was critical to achieving uniformity and integrity in the test specimens.

Figure 3.3: Prepared Moulds for UHPC mix

3.8 Casting Procedure of UHPC

The casting process started by setting up the mixer machine. First, cement and silica fume were mixed slowly for 90 seconds. Then, sand was added and mixed for another 90 seconds. Next, water and superplasticizer were added and blended at a medium speed for 5 minutes. Finally, the mixture was mixed at a high speed until it was workable, taking about 18 to 20 minutes in total. The concrete was then transferred to a non-absorbent sheet for casting. Care was taken to keep the mixture even, ensuring any leftover material was scraped from the bowl for consistency. This careful process was essential for making high-quality concrete specimens.

Figure 3.4: Casting of UHPC mix

3.8.1 Moulding of Concrete Cube Specimens

Initially, cement and silica fume were added to the mixing bowl and mixed at a slow pace (140 ± 5 r/min) for 90 seconds. Subsequently, sand in a saturated surface dry (SSD) condition was introduced into the mixing bowl and mixed at a slow pace for another 90 seconds. Following this, water and superplasticizer were added, and the mixture was blended at a medium pace (285 ± 10 r/min) for 5 minutes. The machine was then set to a high pace and the mixture was allowed to mix until it achieved standard workability. The entire mixing procedure typically took 18 to 20 minutes. Upon completion of mixing, the concrete was transferred to a non-absorbent sheet to proceed with the casting operation concurrently. Care was taken to ensure that the mixture remained homogeneous throughout the process, and any residual material was thoroughly scraped from the sides of the mixing bowl to maintain consistency. This meticulous approach was essential for producing high-quality UHPC specimens.

Figure 3.5: Moulding of UHPC mix

3.8.2 Moulding of Concrete Shrinkage Specimen

To measure the drying shrinkage of UHPC, shrinkage specimens were cast. The control mix and the replacement mixes with proportions of 5%, 10%, 20%, and 30% of sand replaced with Induction Furnace Slag (IFS) were tested for drying shrinkage. For a total of five cases, three prism specimens of size 25 mm * 25 mm * 285 mm were cast, resulting in a total of 15 prisms for this study. The casting of the shrinkage specimens adhered to ASTM C 490 specifications. Before moulding the specimens, the outside joints of the moulds, the contact line, and the base plate were sealed to prevent the loss of mixing water from the moulded specimens. Subsequently, gauge studs were fixed at the ends of the moulds. For tamping, an initial layer of approximately 12.5 mm was cast and tamped using a non-absorbent tamper.

Figure 3.6: Moulding of UHPC mix for Shrinkage

To ensure homogeneous distribution over the entire specimen, a scale was used near the gauge stud areas. After tamping the first layer, the remaining compartments were filled with concrete, and the tamping method described above was repeated. The top layer was then smoothened using the flat side of a trowel to remove any excess mixture. Finally, a steel scale was used to level the top surface, ensuring a smooth and even finish.

3.9 Curing of Specimens

The curing method employed in this study combined water curing and increased temperature curing[24]. After demoulding, the cube specimens were first placed in water at room temperature for 72 hours to ensure initial hydration and strength development. Subsequently, the specimens were transferred to an oven for increased temperature curing at a temperature of 70°C for 96 hours, which facilitated further hydration and enhanced the mechanical properties of the concrete. This combination of curing methods aimed to optimize the strength and durability of the UHPC specimens. After completing the increased temperature curing process, the specimens were carefully removed from the oven and subjected to a series of mechanical tests to evaluate their performance.

Figure 3.7: Curing of Specimens

3.10 Conducted Tests

3.10.1 Compressive Strength Test

Compressive strength is defined as the maximum stress a concrete or mortar specimen can withstand when loaded axially. This parameter is crucial because both concrete and mortar predominantly experience compressive stresses in most structural applications. In this study, the compressive strength of the cubic concrete blocks, with dimensions of 50 mm * 50 mm * 50 mm, was tested in accordance with ASTM C 109 specifications. This testing ensured that the specimens met the required standards for evaluating their performance under compressive loads, providing essential data for assessing the material's suitability for structural applications.

Figure 3.8: Setup for Compressive Strength testing

3.10.2 Sorptivity Measurement

Sample Conditioning

The absorption of UHPC specimens was measured in terms of the sorptivity coefficient following the ASTM C 1585-20 specification. A well-defined method was used for sample conditioning to determine the absorption of the specimens. In this study, the specimens underwent a combination of water curing and thermal curing. During the increased temperature curing process, the test specimens were placed in an oven at 70°C for 96 hours to remove any free water present in the cubic specimens. After thermal curing, the test specimens were cooled and prepared for the subsequent stages of the absorption test. This conditioning process ensured that the specimens were in a consistent state, minimizing the variability in test results. By following this rigorous methodology, the study aimed to accurately assess the absorption characteristics of the UHPC, providing valuable insights into its performance in real-world applications.

Sample Preparation and Test Conduction

After the conditioning of the test samples was completed, four faces of the specimens were sealed using duct tape, leaving two sides exposed. The top surface of each specimen was then covered with a plastic sheet and secured with a rubber band to ensure that no water evaporation occurred. The sample weight was measured at specified time intervals using an airtight weighing machine, as described in the ASTM C 1585-20 specification.

Figure 3.8: Specimen Setup for Sorptivity testing

The sorptivity coefficient was subsequently determined using the relevant equations provided in the specification. The experimental setup is illustrated in Figure 3.7. This meticulous preparation and measurement process ensured the accuracy and reliability of the absorption data obtained for the UHPC specimens.

$I = S_i + B$ ....(3.2)

$S_i = I / \sqrt{t}$ ....(3.3)

$I = m/(d*A)$ ....(3.4)

Here,

I = water absorption, mm

S_i = Sorptivity coefficient, mm/$\sqrt{sec}$

t = time, sec

m= change in specimen mass in grams as a specific time,

t = time, sec

A = area of the exposed specimen in mm^2,

d = density of water in g/mm^3,

B = y- intercept of the best fitted line.

3.11 Drying Shrinkage of UHPC

The drying shrinkage of UHPC specimens was measured in accordance with ASTM C 596-07 specifications. For this test, prism-shaped specimens were prepared with dimensions of 25 mm * 25 mm * 285 mm, as per ASTM C 490-07. At the end points of each prism bar, two-gauge studs were fixed to measure the change in length of the specimens at pre-specified ages. The specimens underwent a combination of water curing and thermal curing. For each replacement case, three prism specimens were prepared to ensure consistency and reliability of the results. The procedure for taking compactor readings of the specimens is illustrated in Figure 3.9. This rigorous testing protocol provided accurate measurements of the drying shrinkage behaviour of the UHPC specimens under different curing conditions and material compositions.

Figure 3.9: Setup for measuring Shrinkage

Chapter 4: Results and Discussion

4.1 General

In this chapter, the results of the conducted tests are presented, along with an analysis of the findings. The analysis includes the compressive strength of the trial mixes to identify the control mix for the study. Additionally, the test results and analysis of the sand replacement mixes are discussed.

4.2 Compressive Strengths

4.2.1 Trial Mix Results and Analysis

Figure 4.1: Sample Specimen after going through Compression

The aim of these trial mixes was to establish a control mix for Ultra-High-Performance Concrete (UHPC) to serve as a baseline for further experiments involving the partial replacement of sand with Induction Furnace Slag (IFS). This section provides an analysis of the trial mixes based on cement type, water to binder ratio, and sand type, identifying the mixture with the highest overall performance. The compressive strength test results at 7 and 28 days are shown in Figure 4.1.

4.2.1.1 Analysis of Cement Types

CEM Type II-A/M was tested in two mixtures ($C_2WB_{20}SP_1$ and $C_1WB_{29}SP_1$), both of which exhibited relatively lower compressive strength. The composition of CEM Type II-A/M, designed for moderate sulphate resistance, may contribute to its lower performance in UHPC applications where higher early and long-term strengths are critical. Conversely, CEM Type I was used in the majority of the mixtures and demonstrated superior performance characteristics. Mixtures with

CEM Type I generally showed higher strength and better overall properties, with its higher early strength and durability making it more suitable for UHPC.

4.2.1.2 Relation of W/B Ratio with Compressive Strength of UHPC

The water to binder (w/b) ratio is a crucial factor in determining the properties of UHPC. The trial mixes explored a range of w/b ratios from 0.17 to 0.29. Mixtures with lower w/b ratios (0.17-0.21) consistently outperformed those with higher ratios. The reduced water content leads to a denser and more compact microstructure, enhancing the mechanical properties and durability of the concrete. Lower w/b ratios result in less pore space, which directly contributes to higher strength and better durability. Mixtures with higher w/b ratios (0.23-0.29) exhibited lower performance due to increased pore space within the concrete matrix, reducing its density and overall strength, despite improved workability.

4.2.1.3 Evaluation of Sand Types

Mixtures utilizing sand passed through a 425 µm sieve showed the lowest performance, as the finer particles can lead to higher water demand and more shrinkage, negatively impacting the concrete's overall strength and durability. Mixtures with sand passed through a 600 µm sieve performed better. The particle size distribution of the 600 µm sand aids in achieving a denser packing and a more optimal particle arrangement, improving the mechanical properties of the UHPC. The balance between particle size and surface area in the 600 µm sand provides the best conditions for high strength and durability. Some mixtures with sand passed through a 2.3 mm sieve were tested for the performance of coarser sand in UHPC, showing average strength but slightly lower than the 600 µm sand. The larger particle size can contribute to better internal bonding and reduced shrinkage, enhancing overall strength, although the 600 µm sand still offered optimal performance due to better particle packing and reduced voids.

4.2.1.4 Assessment of Admixtures and Curing Methods

In normal water curing, the UHPC specimens were kept in water for 72 hours. This method was used in combination with both ARMIX and AURAMIX admixtures. While effective, normal water curing did not achieve the highest performance levels observed in the trial mixes. The method provides adequate moisture for hydration but may not be sufficient for the rapid strength gain required in UHPC. Subsequently, a increased temperature curing method was introduced where the UHPC specimens were cured in water for 72 hours, followed by curing in an oven at 70°C for 96 hours. Increased temperature curing significantly enhanced the performance of the mixtures by accelerating the hydration process, leading to quicker strength gain and improved overall properties. This method was particularly effective in combination with AURAMIX 500 admixture, designed to optimize performance under such conditions.

4.2.1.5 Conclusion

Based on the analysis, $C_1WB_{17}^2$ was selected as the control mix for replacing sand with Induction Furnace Slag (IFS) in UHPC. This mix, featuring CEM Type I, a water to binder ratio of 0.17, sand passed through a 600 µm sieve, and increased temperature curing with AURAMIX 500, achieved the highest compressive strength. This mix demonstrates the optimal balance of material properties and curing methods, making it the ideal candidate for further research involving the partial replacement of sand with IFS. Future work will focus on the performance of this control mix with varying proportions of IFS, aiming to enhance sustainability without compromising the exceptional properties of UHPC.

Table 4.1: Average 7-day and 28-day Strengths for different mix proportions without IFS replacements

	7-day Strength (MPa)	**28-day Strength (MPa)**
C_2WB_{20}	30.4	61.8
$C_1WB_{20}^1$	35.5	62.3
$C_1WB_{20}^2$	62.2	90.2
C_1WB_{23}	65.2	90.9
$C_1WB_{18}^1$	70	95.7
$C_1WB_{18}^2$	73.6	96.4
$C_1WB_{18}^3$	78.3	99.2
$C_1WB_{17}^1$	107.4	105.2
$C_1WB_{18}^4$	119.2	120.2
$C_1WB_{17}^2$	132	122.2

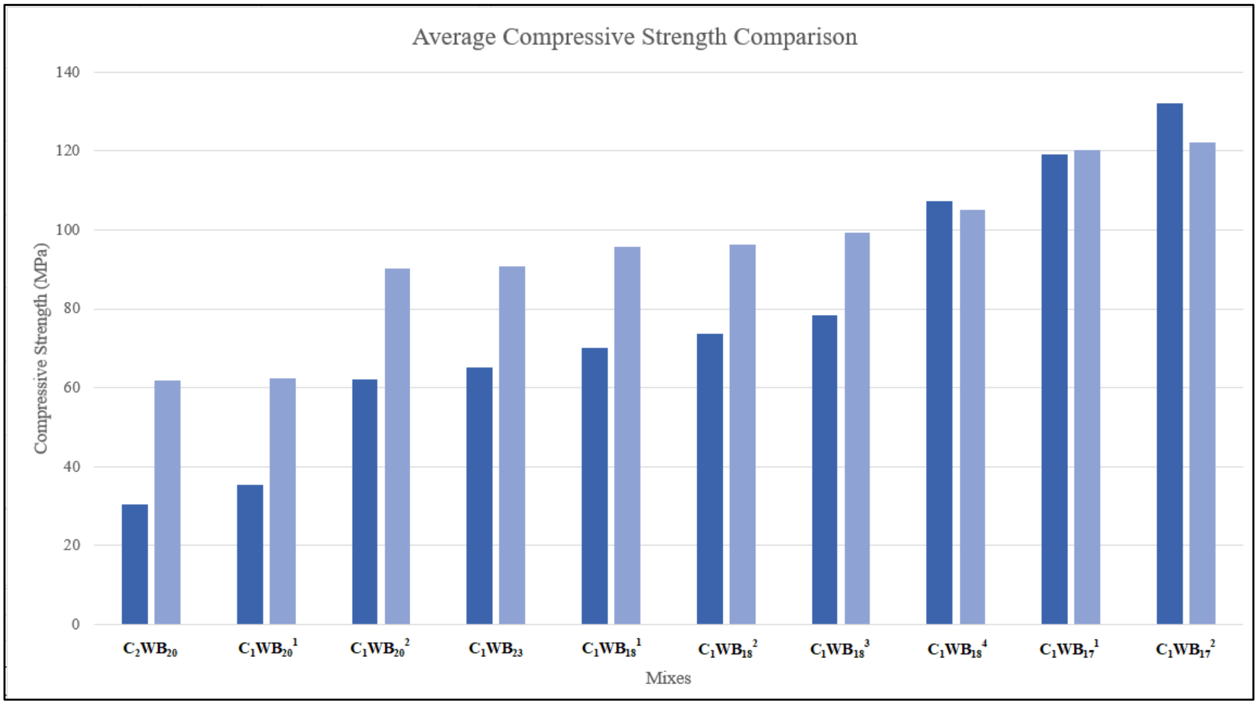


Figure 4.2: Average 7-day and 28-day Strength Comparison for different mix proportions without IFS replacements

4.2.2 Analysis of Sand Replacement Percentages

Four different mixtures were tested with varying percentages of sand replaced by Induction Furnace Slag (IFS): 5%, 10%, 20%, and 30%. The analysis focuses on how these varying replacement levels influenced the performance characteristics of UHPC, specifically the compressive strength at early (7 days) and later (28 days) stages. The compressive strength test results of the replacement mixtures are graphically demonstrated in Figure 4.2.

4.2.2.1 5% Sand Replacement

Replacing 5% of sand with IFS resulted in a noticeable decline in performance compared to the control mix. This decrease suggests that at lower replacement levels, the presence of IFS may interfere with the optimal particle packing density and microstructure. The reduction in compressive strength at both early and later stages indicates that even a small number of IFS can disrupt the cohesion and compactness of the concrete matrix, potentially due to differences in particle shape, size distribution, or chemical composition between sand and IFS.

4.2.2.2 10% Sand Replacement

At a 10% replacement level, the performance shows some decline in performance compared to 5% replacement. This decline implies that at lower levels of replacement, the incorporation of Induction Furnace Slag (IFS) may compromise the optimal particle packing density and microstructural integrity. The reduction in compressive strength observed at both early and later stages suggests that even a minor inclusion of IFS can adversely affect the cohesion and compactness of the concrete matrix, likely due to differences in particle shape and size distribution.

4.2.2.3 20% Sand Replacement

A 20% replacement of sand with IFS results in a further decline in performance. This trend suggests that as the proportion of IFS increases, its negative impact becomes more pronounced. The larger volume of IFS could lead to greater disruptions in the hydration process, possibly due to the different physical and chemical properties of IFS compared to natural sand. The reduced performance indicates that beyond a certain percentage, the detrimental effects of IFS outweigh any potential benefits, leading to lower compressive strength and possibly affecting other mechanical properties and durability.

4.2.2.4 30% Sand Replacement

At the highest replacement level tested (30%), the performance is the lowest among all mixtures. This significant drop underscores the limitations of using IFS as a partial replacement for sand in UHPC. The high proportion of IFS likely causes substantial alterations in the concrete's microstructure, reducing its overall density and strength. The findings suggest that IFS, in larger quantities, disrupts the matrix to an extent that cannot be compensated for by the remaining components, leading to a marked decrease in compressive strength.

4.2.2.5 Implications of Sand Replacement with IFS in UHPC

IFS particles, having different shapes and sizes compared to natural sand, affect the packing density and microstructure of UHPC. Optimal particle packing is crucial for high-performance concrete, and any disruption can lead to increased porosity and reduced strength. The chemical composition of IFS can alter the hydration process of the cementitious matrix. IFS may contain compounds that either react differently or inhibit the formation of the dense hydration products necessary for UHPC. The use of IFS in concrete is driven by sustainability considerations. While the incorporation of industrial by-products like IFS can reduce environmental impact, it is essential to balance this with the performance requirements of UHPC. The findings suggest that a lower percentage of IFS can be integrated without severely compromising the mechanical properties, but higher percentages lead to a significant decrease in compressive strength.

Table 4.2: Average 7-day and 28-day Strengths for different mix proportions with IFS replacements

	7-day Strength (MPa)	**28-day Strength (MPa)**
$C_1WB_{17}IFS_5$	114.13	113
$C_1WB_{17}IFS_{10}$	112.94	110.28
$C_1WB_{17}IFS_{20}$	100.85	104.1
$C_1WB_{17}IFS_{30}$	94.06	99.98

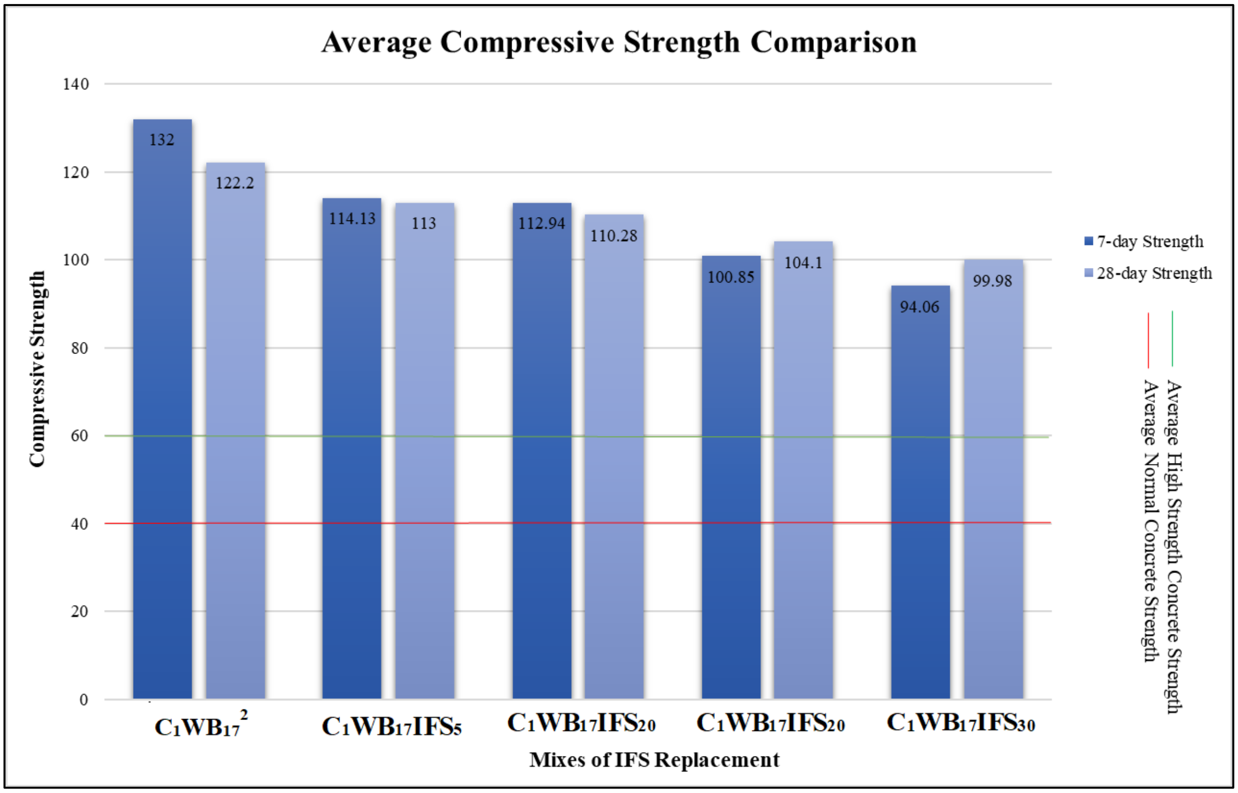


Figure 4.3: Average 7-day and 28-day Strength Comparison for different mix proportions with IFS replacements

4.2.2.6 Compressive Strength Discussion

The comparison of compressive strength for various trial mixes of UHPC reveals insightful trends. The first graph, depicting the average compressive strength of different trial mixes, highlights that mixes without IFS exhibit varying strengths based on the proportions of their components.

When comparing these results to those of high-strength and normal-strength concrete, it is evident that UHPC significantly outperforms traditional concrete types. Previous studies have shown that high-strength concrete typically achieves compressive strengths ranging from 60 to 100 MPa, while normal-strength concrete generally falls below 40 MPa. The compressive strengths of the trial mixes in this study exceed these values, confirming the superior performance of UHPC. This aligns with findings that suggest UHPC enhanced mechanical properties stem from its dense microstructure and the use of supplementary cementitious materials that refine its internal matrix[30,31].

The second graph focuses on the effect of replacing sand with IFS in the control mix. The control mix with no IFS replacement, $C_1WB_{17}^2$, shows the highest compressive strength at 132 MPa. As IFS content increases, there is a gradual decrease in compressive strength. However, even at 30% IFS replacement, the compressive strength remains above 99 MPa, which is still higher than typical high-strength concrete. This trend suggests that while incorporating IFS slightly reduces the compressive strength, the resulting UHPC still exhibits superior performance compared to conventional high-strength concrete.

The reduction in compressive strength with higher IFS content can be attributed to the increased porosity and potential disruption in the microstructure of the concrete matrix. These findings are consistent with earlier studies that reported similar trends when replacing traditional aggregates with industrial by-products. The studies emphasized the need for optimizing the replacement levels to balance mechanical performance with sustainability[32,30]. The replacement of traditional aggregates with IFS not only promotes sustainable construction practices by recycling industrial waste but also enhances certain durability aspects of UHPC, despite a slight compromise in compressive strength.

Furthermore, the use of IFS in UHPC can lead to economic and environmental benefits. The reduced reliance on natural sand preserves natural resources and minimizes the environmental impact associated with sand extraction. The integration of IFS, an industrial by-product, contributes to waste management solutions by diverting waste from landfills. This dual benefit of environmental sustainability and economic efficiency underscores the potential of IFS in modern construction practices.

In conclusion, the data indicates that UHPC with moderate IFS replacement can achieve high compressive strengths, making it a viable and sustainable alternative to conventional high-strength concrete. These results highlight the importance of carefully designing UHPC mixes to maximize the benefits of incorporating industrial by-products while maintaining superior mechanical properties. Future research should focus on further optimizing IFS content in UHPC mixes to enhance both performance and sustainability, ensuring that UHPC remains at the forefront of advanced construction materials.

4.3 Sorptivity Test Results

Sorptivity measures the capacity of a material to absorb and transmit water through capillary action. In this study, the effect of partially replacing sand with IFS in UHPC on sorptivity was investigated. The sorptivity coefficients for different percentages of sand replacement with IFS were compared to evaluate the impact on the capillary absorption UHPC. Five different replacement levels, including the control mixture, were tested: 0%, 5%, 10%, 20%, and 30%.

Figure 4.4: Average 7-day and 28-day Strength Comparison for different mix proportions with IFS replacements

4.3.1 Overview of the Sorptivity Coefficient

4.3.1.1 Control Mix

The control mix, which contains no IFS, serves as the baseline for comparison. This mixture demonstrated a relatively low sorptivity coefficient, indicative of minimal capillary absorption. The low coefficient suggests a dense, well-compacted concrete matrix with minimal pore connectivity, which is characteristic of high-quality UHPC.

4.3.1.2 5% Sand Replacement

Replacing 5% of sand with IFS resulted in a significant increase in the sorptivity coefficient compared to the control mix. This increase indicates that even a small percentage of IFS can disrupt the optimal particle packing and microstructure of the UHPC. The higher sorptivity coefficient suggests increased porosity and pore connectivity, which could negatively impact the durability and overall performance of the concrete. The introduction of IFS at this level may lead to more capillary channels within the matrix, facilitating higher water absorption.

4.3.1.3 10% Sand Replacement

At a 10% replacement level, there was a slight reduction in the sorptivity coefficient compared to the 5% replacement. This suggests that at this particular replacement level, the IFS particles may be filling voids and contributing to a denser microstructure than 5% replacement. The optimal integration of IFS at this level could enhance the overall packing density, reducing capillary absorption and improving durability. As porosity decreases, the number of interconnected pores within the material is minimized, resulting in less water absorption.

4.3.1.4 20% Sand Replacement

Increasing the content of IFS to 20% yielded a sorptivity coefficient similar to that of the control mix. This suggests that at higher levels of replacement, the beneficial effects of IFS are balanced. The equilibrium between filling voids and creating additional capillary channels appears to be optimal at this level, resulting in a microstructure that exhibits capillary absorption akin to the control mix. This 20% replacement level seems to reach a critical point where the positive effects of IFS, such as enhanced packing density and reduced voids, are offset by the negative effects of increased porosity. Consequently, while this replacement level maintains the durability and water absorption characteristics of the control mix, it underscores the need for a precise balance to optimize UHPC properties with the incorporation of IFS.

4.3.1.5 30% Sand Replacement

At the highest replacement level tested (30%), the sorptivity coefficient increased again compared to 20% replacement, also surpassing the control mix. This suggests that a high proportion of IFS further disrupts the optimal microstructure, increasing porosity and capillary absorption. The increase in the sorptivity coefficient at this level indicates a more open pore structure, which can adversely affect the long-term durability and performance of UHPC. The high percentage of IFS likely creates an excessive number of capillary channels, undermining the concrete's resistance to water ingress and potentially leading to increased deterioration over time.

4.3.2 Analysis of Sorptivity Coefficient Results

The analysis of initial and secondary sorptivity graphs for different proportions of IFS replacement (0%, 5%, 10%, 20%, and 30%) reveals important trends. The initial sorptivity graph shows that the rate of water absorption is highest for the control mix (0% IFS) and decreases with increasing IFS content up to 20%. This indicates that moderate IFS replacement levels improve the microstructural properties of the concrete, reducing capillary pore connectivity and enhancing resistance to water ingress. Specifically, the sorptivity rate for 10% and 20% IFS replacements is significantly lower, reflecting a denser and less permeable matrix.

The secondary sorptivity graph, which measures longer-term water absorption, also shows a similar trend. The control mix continues to exhibit the highest sorptivity, while mixes with 10% and 20% IFS maintain lower sorptivity rates. This aligns with findings from previous studies indicating that the incorporation of industrial by-products like slag reduces permeability and enhances durability by refining the pore structure and improving particle packing density. However, at 30% IFS replacement, the sorptivity increases again, suggesting that excessive IFS content may lead to higher porosity and disrupt the optimal particle packing, thereby increasing water absorption over time.

Comparatively, earlier research demonstrated that moderate levels of slag replacement generally enhance concrete's resistance to water absorption due to improved microstructure and reduced capillary action[30]. This is corroborated by the current findings where 10% and 20% IFS replacements show lower sorptivity. Furthermore, the study by Experimental Investigations[31] highlighted the potential negative impact of excessive supplementary materials on concrete's permeability. The observed increase in sorptivity at 30% IFS replacement supports this, indicating that beyond an optimal level, the benefits of IFS are counterbalanced by increased porosity.

Overall, the data indicates that moderate IFS replacements (10-20%) are effective in reducing both initial and secondary sorptivity, enhancing the durability and performance of the concrete. This underscores the importance of optimizing IFS content to achieve the best balance between enhancing microstructural properties and avoiding increased porosity and permeability. The findings are consistent with broader literature, emphasizing the critical need for careful mix design in utilizing industrial by-products to maximize the benefits while minimizing potential drawbacks.

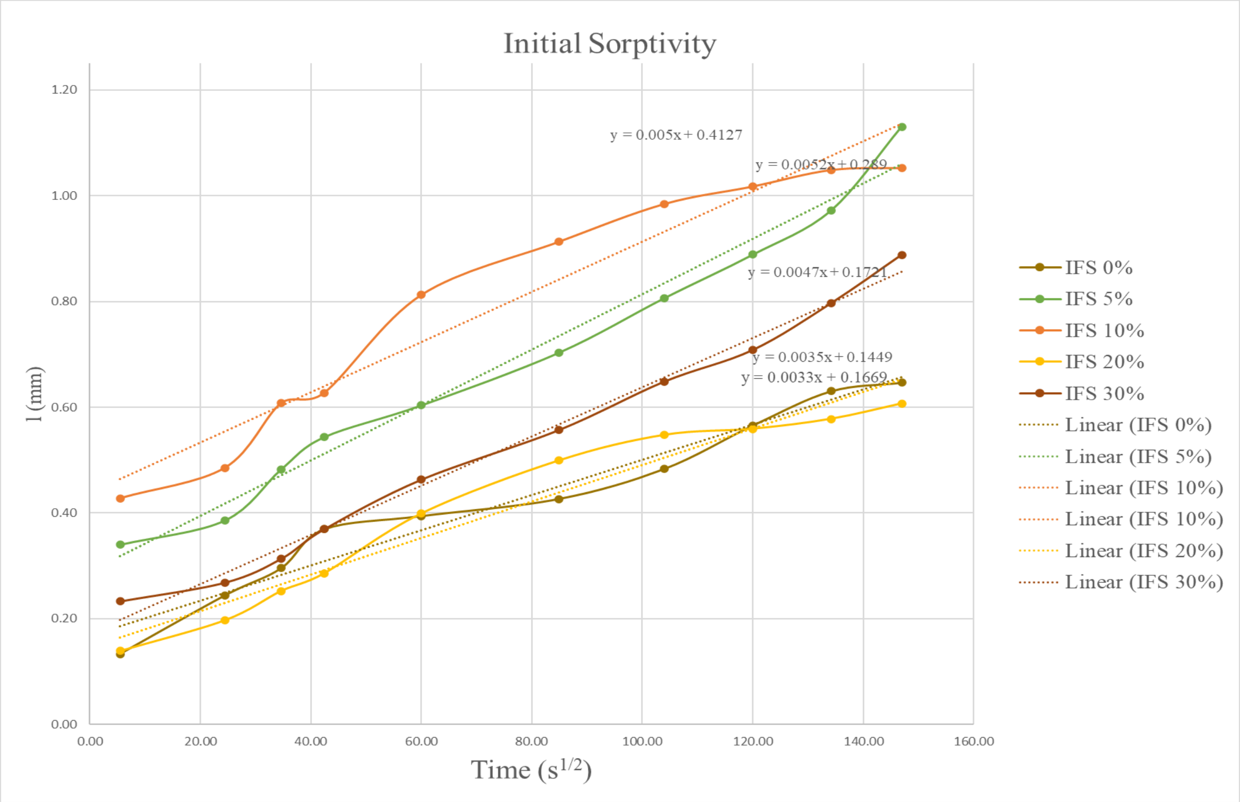


Figure 4.5: Initial Sorptivity Comparison for different mix proportions with IFS replacements

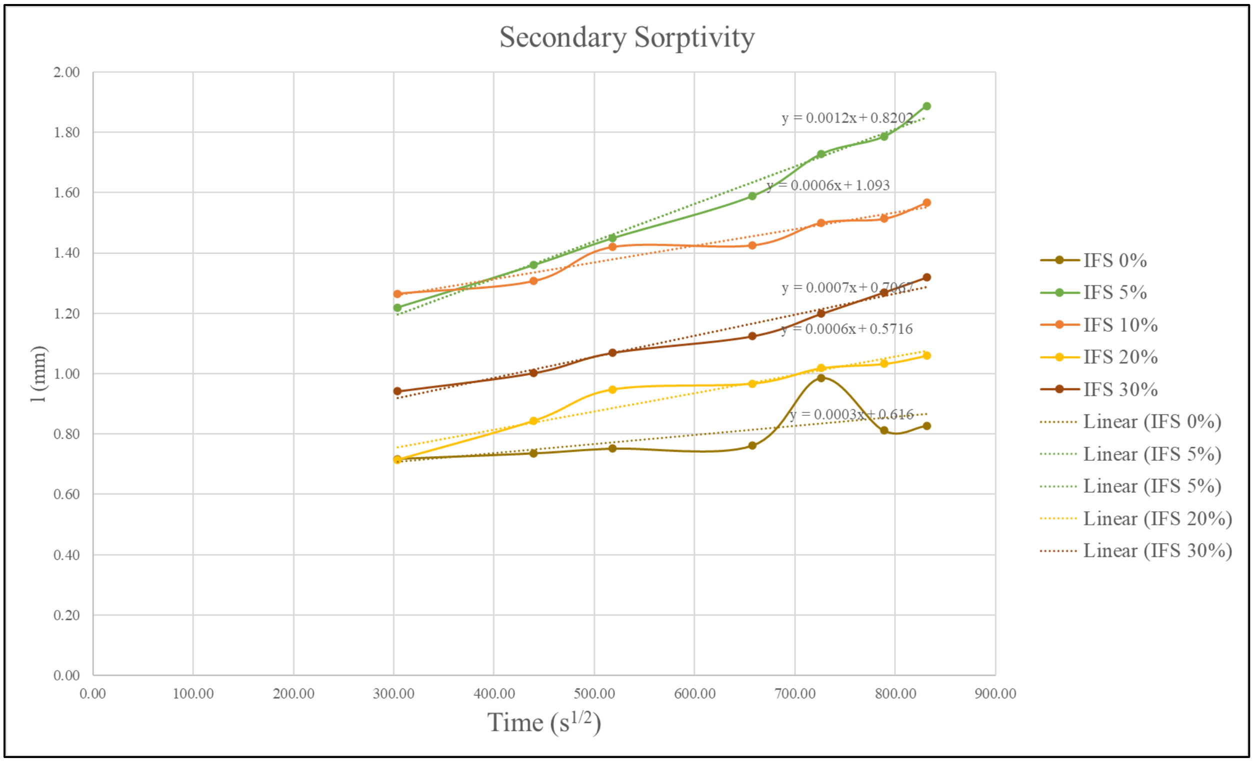


Figure 4.6: Secondary Sorptivity Comparison for different mix proportions with IFS replacements

4.3 Shrinkage Test Results

The shrinkage results for various levels of IFS replacement with sand in the mortar mix reveal notable trends. The study examined five different IFS replacement levels: 0%, 5%, 10%, 20%, and 30%. Each level of replacement exhibited distinct effects on the shrinkage behaviour of the mix.

Figure 4.7: Sample Specimen after Shrinkage

For the control mix with 0% IFS replacement, the drying shrinkage was observed to be relatively high. This indicates that the absence of IFS did not provide any enhancement in the microstructural properties of the mortar, leading to higher water loss and shrinkage.

At 5% IFS replacement, there was a slight increase in shrinkage compared to the control mix. This suggests that at this low level of replacement, IFS do not significantly contribute to the reduction of shrinkage and may even slightly disrupt the optimal particle packing and microstructure.

Examining the shrinkage data over a seven-day period for various proportions of Induction Furnace Slag (IFS) replacement (0%, 5%, 10%, 20%, and 30%) offers significant insights when contrasted with previous studies. Earlier research demonstrated that incorporating industrial by-products like slag generally reduces early-age shrinkage due to enhanced packing density and internal curing effects. At moderate levels of IFS replacement (10% and 20%), reduce shrinkage compared to the control mix, aligning with these findings. Additionally, studies found that the addition of fine materials in UHPC significantly reduces drying shrinkage by refining the pore structure and reducing water evaporation[28]. These results indicate that at these levels, IFS effectively improves the packing density and reduces pore connectivity within the concrete matrix. This leads to enhanced resistance to water loss and consequently lower shrinkage. The beneficial effects at these replacement levels can be attributed to the optimal balance of fine particle packing and internal curing, which slows the rate of drying shrinkage.

However, the increase in shrinkage at 30% replacement, possibly due to over-saturation of non-cementitious particles leading to higher porosity, reflects other findings[29]. These studies highlighted that while moderate replacements improve properties, excessive use can lead to increased porosity and shrinkage. This data indicates that moderate IFS replacements effectively reduce shrinkage by improving particle packing and reducing pore connectivity, enhancing resistance to water loss. However, higher replacement levels increase shrinkage, underscoring the importance of optimizing IFS content to balance the benefits and mitigate potential risks. This aligns with the broader literature on the use of industrial by-products in concrete, emphasizing the need for careful mix design to maximize performance and sustainability.

Over time, all specimens showed significant increases in shrinkage, reflecting the ongoing evaporation of water and continued hydration processes. The moderate IFS replacement levels (10% and 20%) demonstrated the most favourable outcomes, indicating that these mixes benefit from an optimal balance of fine particle packing and internal curing. In contrast, the higher shrinkage observed at both the control mix and the highest replacement level (30%) suggests less optimal microstructural conditions. The control mix lacks the benefits of IFS-induced packing density, while the highest replacement level suffers from excessive pore connectivity.

Overall, the results highlight the potential of moderate IFS replacement (10-20%) to improve drying shrinkage characteristics in UHPC. Different percentages of IFS replacement yield varying results, underscoring the need for precise formulation to achieve the desired performance. These findings emphasize the importance of balancing IFS content to maintain optimal microstructural properties and achieve enhanced durability in UHPC applications.

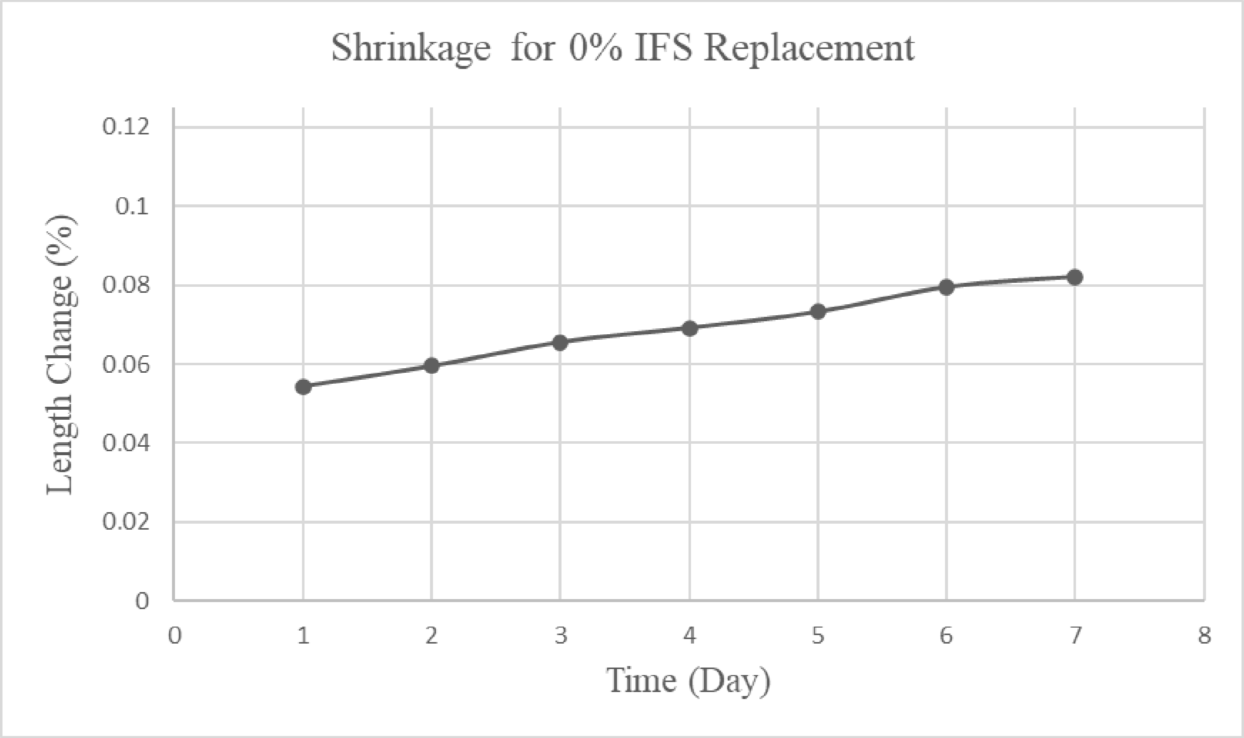


Figure 4.8: Shrinkage Percentage for mix proportion with 0% IFS replacement

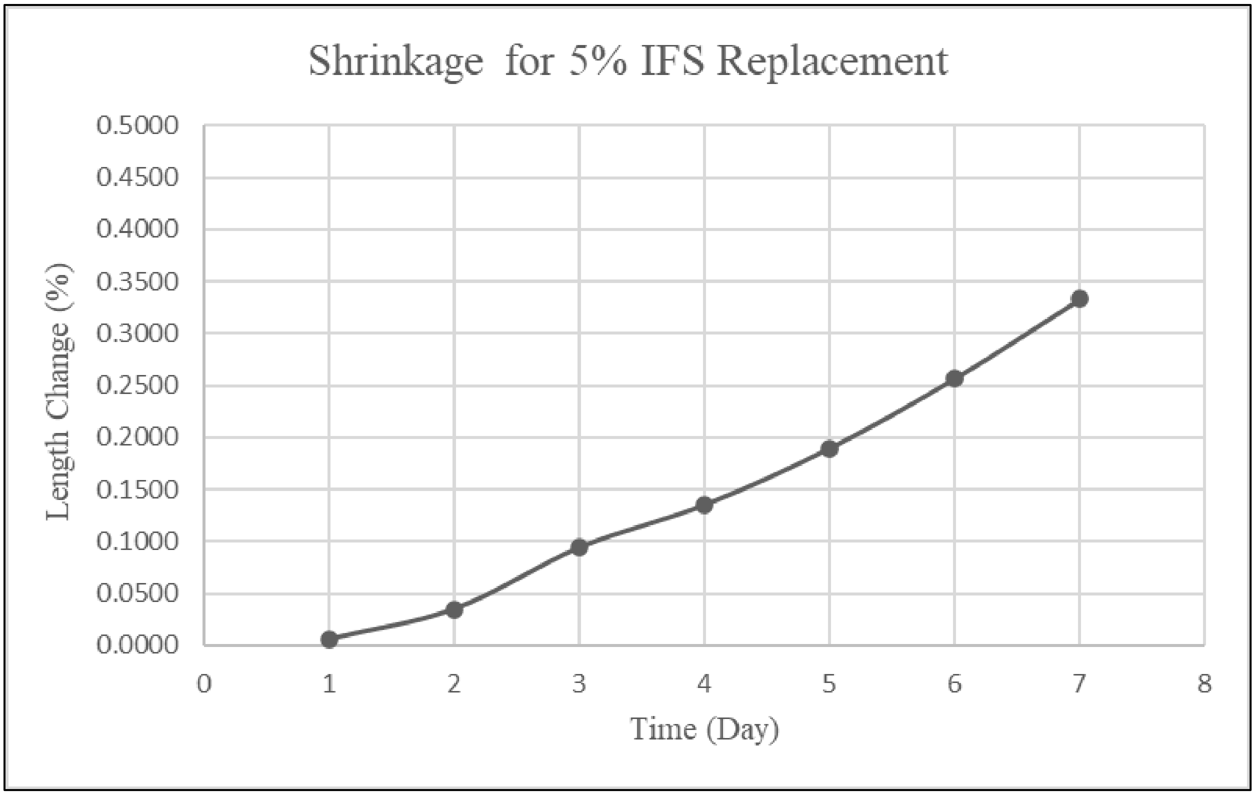


Figure 4.9: Shrinkage Percentage for mix proportion with 5% IFS replacement

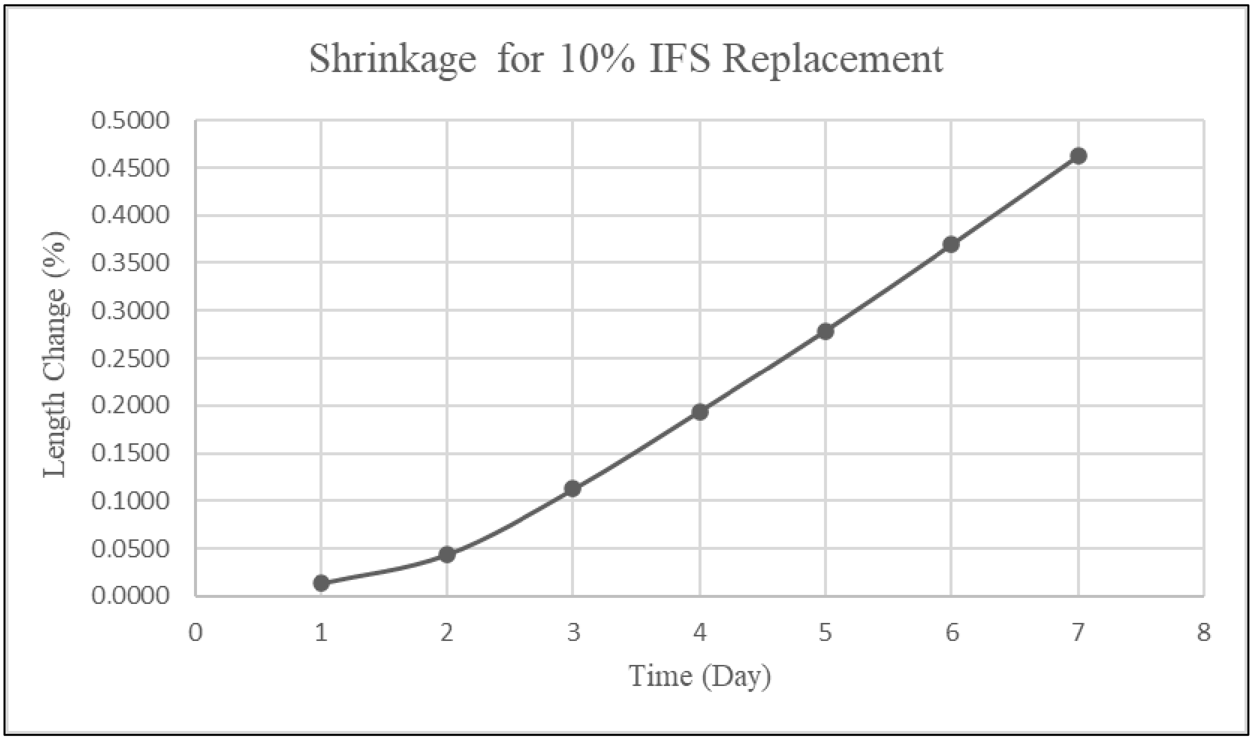


Figure 4.10: Shrinkage Percentage for mix proportion with 10% IFS replacement

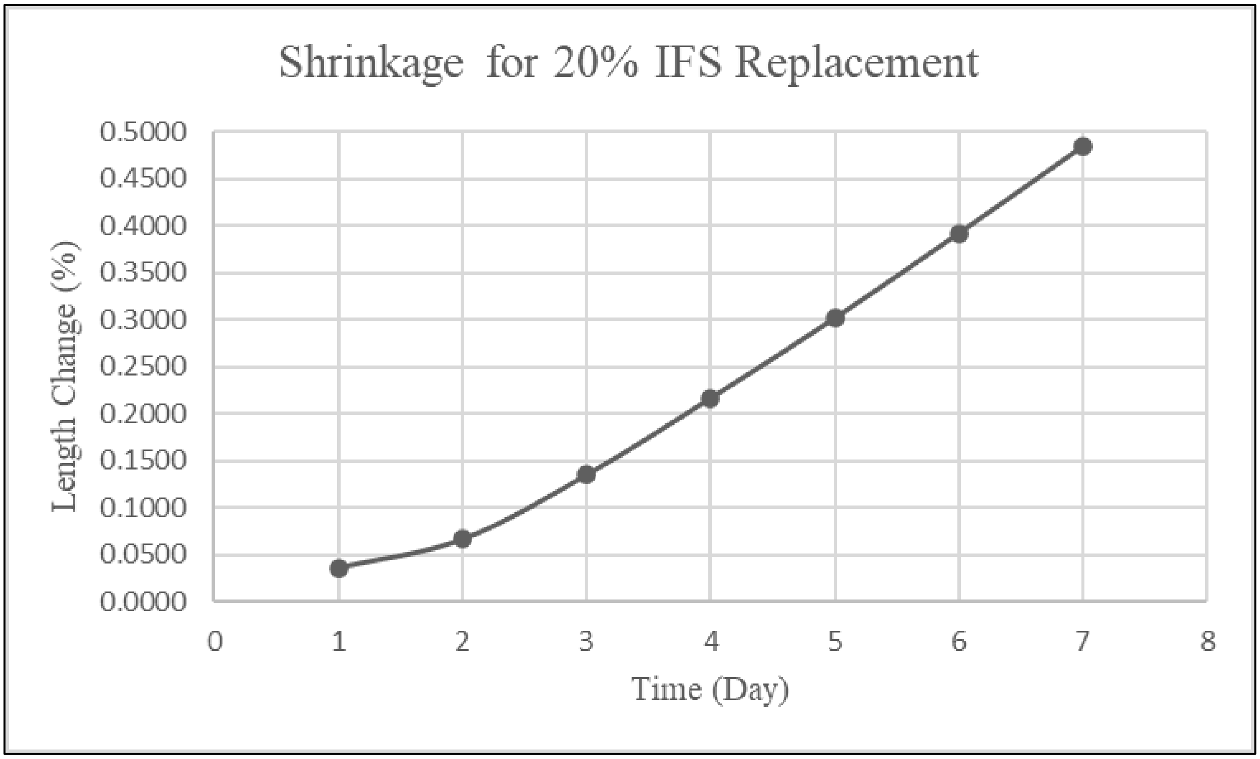


Figure 4.11: Shrinkage Percentage for mix proportion with 20% IFS replacement

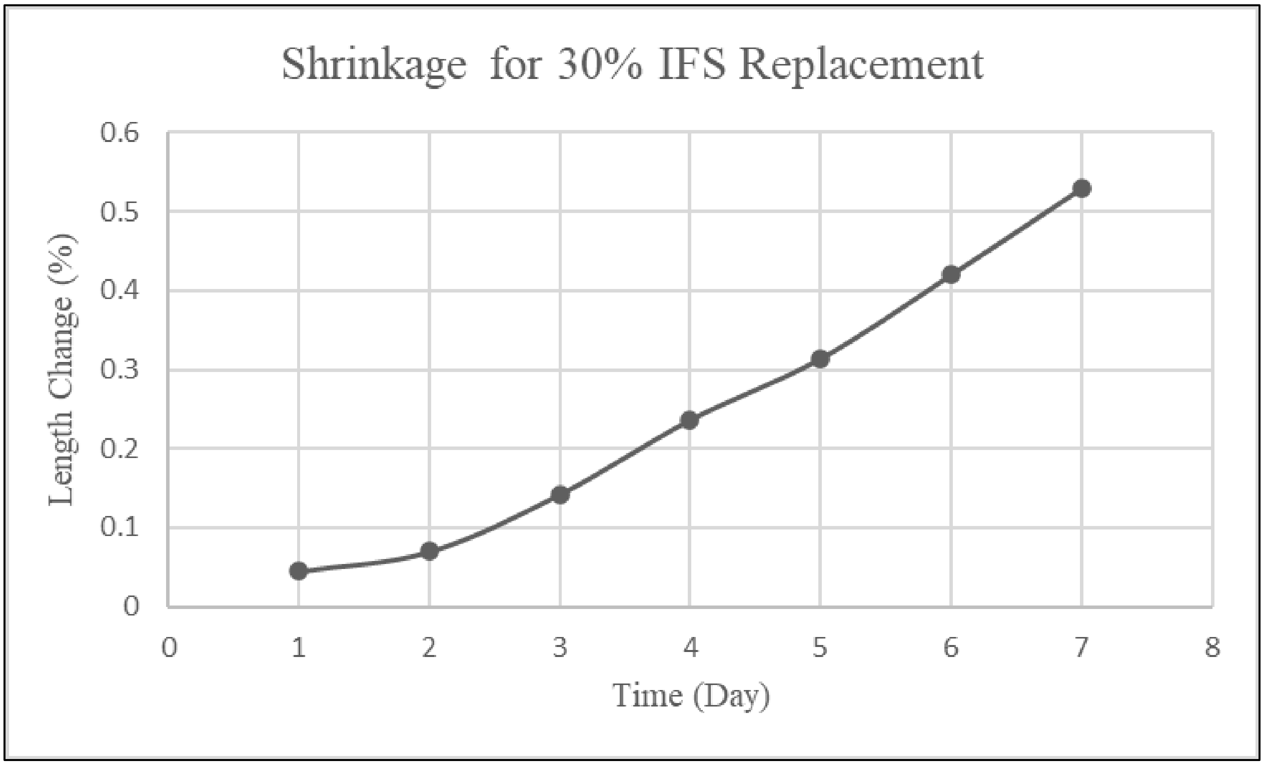


Figure 4.12: Shrinkage Percentage for mix proportion with 30% IFS replacement

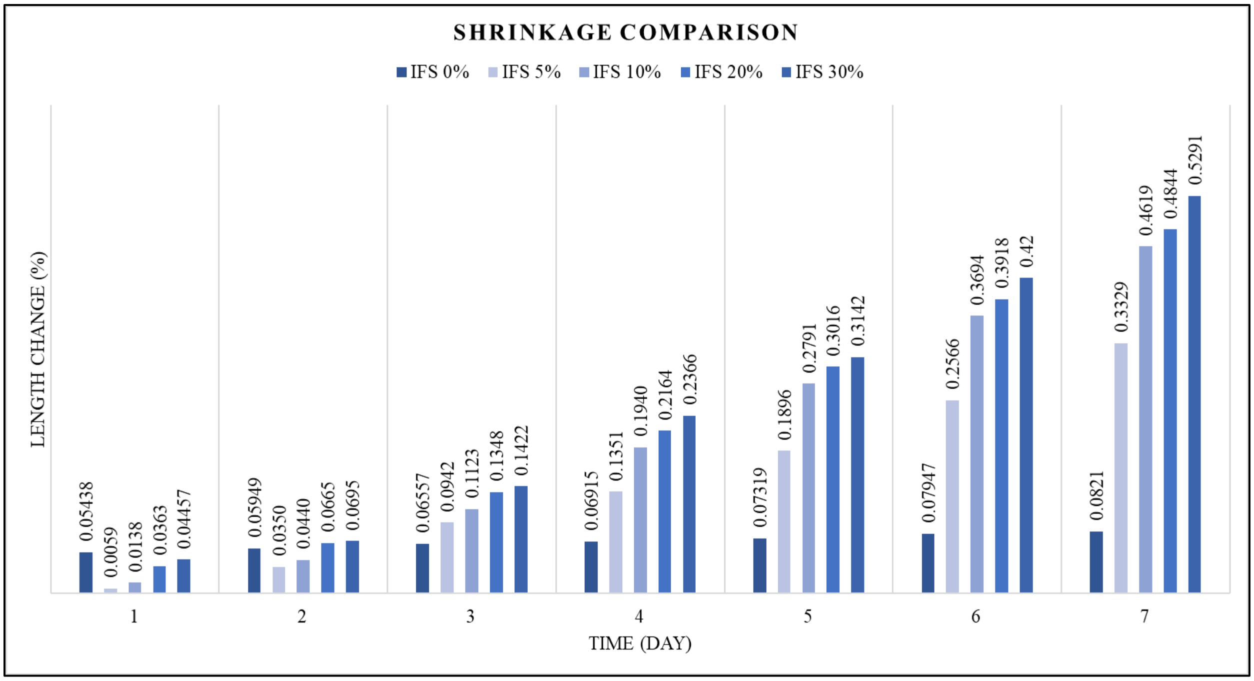


Figure 4.13: Shrinkage Comparison for different mix proportions with IFS replacements

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

The primary objective of this study was to determine the influence of IFS as a replacement for sand in UHPC. This chapter summarizes the research findings based on the results and discussions presented in Chapter 4, providing comprehensive conclusions and detailed recommendations for future research.

According to the experimental findings, several critical conclusions can be drawn. Initially, the use of CEM-I, Auramix 500 admixture, and Sand 4 in the trial mixes significantly improved the compressive strength of UHPC. These components established a robust baseline for assessing the impact of IFS on UHPC properties. The study also highlighted the importance of optimized curing regimes. The control mix subjected to increased temperature curing showed enhanced results compared to normal curing conditions, underscoring the pivotal role of curing techniques in achieving superior mechanical properties in UHPC.

A series of experimental formulations were meticulously developed to explore the influence of IFS on UHPC properties comprehensively. In these formulations, sand was systematically replaced with IFS at incremental proportions of 5%, 10%, 20%, and 30%. The aim was to provide a thorough understanding of how varying levels of IFS affect the concrete's performance. The findings indicated a decrease in compressive strength with increasing percentages of IFS. This reduction is primarily attributed to the lower hardness of IFS particles compared to the quartz particles typically found in traditional sand. Consequently, the substitution of sand with IFS results in a decrease in the overall hardness of the mix, thus impacting its strength.

The outcomes of this study significantly contribute to the body of knowledge on sustainable construction materials. They underscore the necessity for further research into optimizing mix proportions and advanced curing techniques to mitigate the reduction in strength observed with higher IFS content. These findings are pivotal in guiding the construction industry towards more environmentally friendly and resource-efficient practices. While mixes incorporating induction furnace slag can be utilized when only high strength is required, this approach not only reduces dependency on natural sand resources but also promotes the beneficial use of industrial waste materials, thereby enhancing sustainability in construction practices.

Sustained investigative efforts are essential for fully appreciating the potential and limitations of using industrial by-products like IFS in high-performance concrete applications. Future research should focus on further exploring the mechanical properties and practical applications of IFS in UHPC. This includes a comprehensive evaluation of the material's ductility, direct tensile strength, flexural strength, and resistance to carbonation. Such assessments will provide valuable insights into the mechanical properties and potential uses of the material.

Examining the performance of this mix in actual structural components, such as mini-columns and beams, is crucial for understanding its practical application and effectiveness in real-world conditions. Further mechanical testing and real-world application trials will help confirm the material's reliability and efficiency, aiding in its optimization for construction and engineering purposes. This real-world testing is essential for validating the laboratory results and ensuring that the material can meet the demands of practical construction scenarios.

5.2 Recommendations

Moreover, future research should utilize advanced analytical techniques like X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) to thoroughly investigate the material's properties and composition. These techniques can uncover opportunities for further improvements and modifications, leading to enhanced performance and broader applications of UHPC with IFS. Advanced analytical methods will provide a deeper understanding of the material's microstructure and chemical composition, which are critical for optimizing its properties.

Research should also focus on optimizing mix proportions and curing techniques to enhance the mechanical properties of UHPC with IFS. This includes exploring different combinations of materials and curing conditions to achieve the best possible performance. By fine-tuning the mix proportions and curing processes, researchers can develop UHPC formulations that maximize the benefits of IFS while minimizing any potential drawbacks.

Additionally, investigating the long-term performance and durability of UHPC with IFS is essential. This includes assessing its resistance to environmental factors such as freeze-thaw cycles, chemical attacks, and abrasion. Long-term durability studies will provide insights into how UHPC with IFS performs under various environmental conditions, ensuring that it can withstand the rigors of real-world applications over extended periods.

Furthermore, future studies should consider the environmental and economic impacts of using IFS in UHPC. Conducting life cycle assessments (LCAs) and cost-benefit analyses will help evaluate the sustainability and feasibility of this approach. These analyses will quantify the environmental benefits of using industrial by-products like IFS and compare the costs and benefits with traditional construction materials, providing a holistic view of the material's potential impact.

By addressing these recommendations, future research can build upon the findings of this study and further advance the understanding and application of IFS in UHPC. This will ultimately contribute to the development of more sustainable and efficient construction practices, promoting the use of industrial by-products and reducing the environmental impact of construction activities. Through continued research and innovation, the construction industry can move towards more sustainable and resource-efficient practices, benefiting both the environment and society.

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