Sewage Waste (SW) and Industrial Furnace Waste (IFW) as Cement and Sand Replacement in Ultra-High-Performance Concrete

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Civil Engineering

Submitted by
Md Ishmam Labib (200051107)
Abrar Jahin Alvee (200051158)
Soyaibia Alam Simon (200051241)

Supervised by
Dr. Tanvir Ahmed
Assistant Professor
Dept. of CEE, IUT

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
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Project Approval

This is to certify that the thesis entitled “Sewage Waste (SW) and Industrial Furnace Waste (IFW) as Cement and Sand Replacement in Ultra-High-Performance Concrete” submitted by Md Ishmam Labib, Abrar Jahin Alvee and Soyaibia Alam Simon has been approved as partial fulfillment of the requirement for the Degree, Bachelor of Science in Civil Engineering at Islamic University of Technology (IUT).

Dr. Tanvir Ahmed

Assistant Professor

Department of Civil and Environmental Engineering

Islamic University of Technology

Board Bazar, Gazipur-1704, Dhaka, Bangladesh

Declaration

We hereby declare that this thesis entitled *"Sewage Waste (SW) and Industrial Furnace Waste (IFW) as Cement and Sand Replacement in Ultra-High-Performance Concrete"* is an original work conducted by our group and supervised by Dr. Tanvir Ahmed, Department of Civil and Environmental Engineering, Islamic University of Technology. The contents of this thesis have not been submitted, either in whole or in part, for any degree or diploma at this or any other institution.

Md Ishmam Labib	**Abrar Jahin Alvee**
Student ID: 200051107	Student ID: 200051158

Soyaibia Alam Simon
Student ID: 200051241

Dr. Tanvir Ahmed

Assistant Professor

Department of Civil and Environmental Engineering

Islamic University of Technology

Board Bazar, Gazipur-1704, Dhaka, Bangladesh

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Dedication

TO OUR PARENTS

Abstract

Ultra-High-Performance Concrete (UHPC) production involves high energy and material consumption because of cement, silica fume, and fine quartz sand. Therefore, this study presents an approach to UHPC that is more sustainable by substituting silica fume partially with Sewage Waste (SW) and also replacing sand with Industrial Furnace Waste (IFW). Both are wastes from industries-SW from wastewater treatment plants, and IFW from steelmaking industries-thus usable in the minimization of environmental burdens as well as CO_2 emissions besides enhancing waste valorization.

Nine trial mixes and six SW-IFW incorporated UHPC mixes were prepared, cast, and tested for workability, compressive strength, water absorption, sorptivity, and shrinkage tests as per ASTM standards. The SW and IFW percentages composition were from 0 to 20% SW as a replacement of silica fume and from 0 to 50% IFW as sand replacement respectively. Results indicated that moderate substitution levels maintained UHPC-grade compressive strength (over 120 MPa) with the possibility of reduction of up to 25% embodied CO_2 emissions. Higher replacement ratios negatively influence flowability and early age strength due to increased porosity and altered hydration kinetics.

The findings show that incorporating SW and IFW into UHPC not only achieves high strength and durability but also promotes environmental sustainability through waste reuse and carbon reduction. The research validates SW-IFW-UHPC as a feasible, eco-efficient alternative for next-generation structural materials.

Keywords: Ultra-High-Performance Concrete (UHPC), Sewage Waste (SW), Industrial Furnace Waste (IFW), Compressive Strength, Durability, CO_2 Emission, Sustainable Construction.

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Chapter 1: Introduction

1.1 Background of the Study

The construction industry is the world's largest contributor to environmental degradation and CO_2 emissions, mainly due to cement content used in concrete production. Ultra-High-Performance Concrete (UHPC) can be defined as a material that possesses high compressive strength (>120 MPa), low permeability, and long-term durability; hence it is considered the next generation of structural material. However, UHPC heavily depends on high-quality ingredients like silica fume and quartz sand which are energy-demanding and expensive to obtain. Therefore, the challenge that should be addressed is how to attain the mechanical and durability performance of UHPC with a lower environmental burden.

Sewage Waste comes as a by-product from the incineration process of residues commonly used in wastewater treatment. It contains rich amorphous silica, alumina, and calcium oxide which is necessary components for pozzolanic reactions. Industrial Furnace Waste is also described as a by-product from the steelmaking process and contains reactive lime and aluminosilicate phases. Such phases participate in the binding reaction within cementitious systems. HPC are thus seen as possible products for use with these two wastes, SW, and IFW. The use of industrial waste material in such a process fits perfectly with the circular economy model as it conserves natural resources while reducing carbon emissions associated with cement and aggregate production.

There have been several studies conducted on SW and IFW separately in normal or high-strength concretes, but there has not been much research carried out with their synergistic applications in UHPC. Thus, this paper attempts to fill this gap by preparing a sustainable mix of UHPC in which SW acts as a Cement replacement (for silica fume) and IFW performs the role of sand substitute. The dual incorporation is anticipated to lead to mechanical performance optimization together with eco-efficiency improvement.

1.2 Problem Statement

The use of expensive, non-renewable resources like silica fume and quartz sand in UHPC confines its broad usage to developing countries. Moreover, the environmental effect related to cement production stays an important concern. There is a great demand for cheap and green options that can partially substitute these components without losing strength or durability.

SW contains heavy metals and has very limited options for reuse, thus posing a major environmental problem. On the flip side, IFW is available in enormous quantities but always falls short in the application of structural-grade materials. This brings about the central research problem to assess whether it would be possible to combine SW and IFW in making UHPC so that HPC properties with environmental benefits can be attained.

1.3 Research Objectives

The main aim of this study is to design and assess mechanical performances, together with sustainability, for SW-IFW-UHPC mixes. More specifically, the objectives are as under:

1. To check the workability as well as mix performance of UHPC including SW and IFW.
2. To determine compressive strength at 7 days for different replacement levels.
3. To evaluate durability characteristics by water absorption, shrinkage, and sorptivity tests.

To evaluate the performance of SW-IFW-UHPC against the control mix. To quantify the environmental advantages in terms of CO_2 reduction as well as the efficiency of waste utilization.

1.4 Scope of the Study

This study covers material characterization, mix proportioning, mechanical property testing as well as determination of durability properties and sustainability impacts for laboratory-scale UHPC developed and evaluated with the use of locally available materials. SW and IFW are used as partial replacements of silica fume and sand at controlled replacement ratios, respectively. The large-scale structural application and long-term field performance are outside the purview of this study but are equally significant and recommended for further research.

1.5 Research Gap

Previous studies already proved the abilities of SW and IFW separately in cementitious systems. The combined effect of these two materials in UHPC is still lacking to a great extent. Most available literature dwells on normal concrete or geopolymer composites. Thus, the special microstructural and mechanical properties of UHPC are left out. The current study attempts to fill that void by replacing both silica fume and sand, respectively, with SW and IFW, in addition to an investigation regarding how these replacements would affect compressive strength plus permeability as well as dimensional stability.

1.6 Significance of the Study

The global pursuit of sustainable construction materials is achieved in this study by:

- Reducing dependency on natural resources such as silica fume and quartz sand.
- Utilizing waste materials (SW and IFW) that otherwise contribute to environmental pollution.
- Demonstrating that eco-friendly UHPC can maintain strength and durability comparable to conventional mixes.
- Providing an analytical foundation for industrial adoption of waste-derived UHPC.

1.7 Thesis Layout

The structure of the thesis:

Chapter 1 introduces the background, objectives, and significance of the study.

Chapter 2 presents a detailed literature review on SW and IFW in concrete systems.

Chapter 3 describes the materials used, experimental methodology, and testing standards.

Chapter 4 has the results and analysis of mechanical, durability and environmental parameters.

Chapter 5 concludes findings, lists limitations and provides recommendations for future work.

Chapter 2: Literature Review

2.1 Introduction

The evolution of UHPC mostly emanates from the pursuit of greater strength, better durability, and more improved sustainability. Even though the typical ingredients for UHPC largely comprise silica fume, quartz sand, and Portland cement- which account for an enormous share of both embodied carbon content and total production cost- industrial by-products can replace them to some extent. Hence, the use of SW as well as IFW waste materials has been adopted in efforts aimed at achieving a sustainable design for UHPC.

This chapter comparatively reviews the application of SW and IFW in concrete and other cementitious systems, their effects on mechanical and durability performance when incorporated, perceived environmental and economic benefits that might accrue from their adoption, and research gaps which also constitute areas requiring further probing.

2.2 Sewage Waste (SW) in Cementitious Materials

2.2.1 Origin and Composition

SW results from the incineration of sewage sludge that has been dewatered and comes as waste from any kind of wastewater treatment plant. The resulting ash consists mainly of amorphous SiO_2, Al_2O_3, Fe_2O_3, and CaO content which makes it possess great pozzolanic potential (Danish & Ozbakkaloglu, 2022). The chemical composition of SW falls under wastewater nature and incineration temperature classification typically between 700°C to 900°C where at about 800°C amorphous silica is preserved to enable strong pozzolanic activity (Tantawy et al., 2012).

SW has irregular grain morphology, presenting angular grains that increase water absorption thus increasing the demand for superplasticizer in UHPC. As noted, by Gu et al. (2022), it has a fine particle size which improves packing density when used at optimized proportions.

2.2.2 SW in Portland Cement Concrete (PCC)

SW has been used as both a cement and fine aggregate replacement, in conventional Portland cement. Studies demonstrate that low replacement levels (≤10%) maintain comparable compressive strength to the control mix.

Baeza-Brotons et al. (2014) noticed that using 10% SW as a cement replacement led to an increase in compressive strength by about 5%. This improvement was due to secondary pozzolanic reactions. On the other hand, higher substitution levels (≥20%) made the material weaker because it became more porous and did not hydrate fully.

Chang et al. (2010) noted that at 10% substitution, the strength attained was very close to the value for control concrete-34.7 MPa against 36.4 MPa of the control concrete and with reduced capillary water absorption, which indicated enhanced durability. Danish and Ozbakkaloglu (2022) reported that SW reduces chloride ion penetration however it absorbs a large quantity of water then careful mix design is required and adjustment for water should be made.

2.2.3 SW in Ultra-High-Performance Concrete (UHPC)

UHPC is known for its compressive strengths exceeding 120 MPa. It presents a more complex hydration environment due to its low water-to-Cement ratio ($w/b < 0.2$) and dense matrix.

Studies exploring SW's use in UHPC indicate that moderate incorporation enhances microstructural packing and sustainability, but excessive substitution may compromise density and flowability.

Gu et al. (2022) found that the use of 10-30% SW to replace quartz sand in UHPC, Compressive strength of 170 MPa was achieved at 10% replacement beating the control by a wider margin of just 160 MPa. Strength falls by about 9% due to excess pore development when material is replaced at a level of 30%. This has also been confirmed by Rutkowska et al., (2023) who noted that SW modified UHPC would register improved resistance against chloride penetration thus supporting its application in marine infrastructure.

Whereas Oliveira et al., 2020 found that with higher contents of SW (>15%), increased autogenous shrinkage, and water demand was noticed, therefore even more superplasticizer would be required. Thus, SW replacement below 15% has been considered optimal for UHPC formulations balancing strength, workability, and sustainability.

2.2.4 SW in High-Performance Concrete (HPC) and Mortar

SW has equally found application in high-performance and mortar-based systems. Fontes et al. (2016) observed that 5% SW in HPC attained a compressive strength of 58 MPa close to 59.5 MPa for the control and reduced slightly when added at higher doses. Porosity of SW modified HPC increased henceforth discussing water absorption.

In mortar applications, Baeza et al. (2014) noted that 10% SW reached a compressive strength of 33.5 MPa, very near to the 38 MPa control. João Victor da Cunha Oliveira et al. (2020) saw that moderate inclusion of SW raised flexural tensile strength but dropped adhesion strength when more than 20% substitution was used.

Taken together, these results show that at low-to-moderate levels, SW increases mechanical and durability properties as well as lowers the environmental footprint.

2.2.5 SW in Geopolymer and Hybrid Systems

SW has a reactive aluminosilicate structure, thus applicable in the formulation of geopolymers. A 50% SW + 50% GGBFS (Ground Granulated Blast Furnace Slag) mixture attained by presents a compressive strength of 45.5 MPa for geopolymer mortar describing immobilization efficiency for heavy metals. The process needs to be optimized and can be referred to as an inconsistent process at this stage due to the gap existing between high potential and real application performances.

Better sustainability and mechanical strength are attained in hybrid concrete systems with SW and fly ash or silica fume. There is a major challenge of compositional variability, but even then, the particles do not show consistent reactivity.

2.3 Industrial Furnace Waste (IFW) in Cementitious Systems

2.3.1 Composition and Mineralogy

IFW is produced as secondary refining slag in the process of steelmaking, essentially having CaO, Al_2O_3, SiO_2, and MgO as major constituents. The material develops reactivity hydraulically since it comprises free lime and periclase which can participate in secondary hydration reactions (Branca & Colla, 2020). IFW also contains some glassy phases that offer latent pozzolanic activity comparable to that provided by GGBFS. However, due to relatively coarse particle size and some variability in chemical structure, grinding and stabilization of IFW are typically required prior to its use in UHPC or HPC systems (Gupta et al., 2021).

2.3.2 IFW as Cement or Sand Replacement

Many studies have tested the performance of IFW as a cement or sand replacement. According to Adesanya and Akinwumi (2019), up to 15% replacement of cement with IFW added compressive strength comparable to that gained by the use of unmodified cement and better sulfate resistance. When applied as a fine aggregate replacement, it increased mechanical interlocking because of surface texture on its particles.

In the context of UHPC, studies are limited. Ahmed et al. (2021) ECO-UHPC proposed indicated that strength above 130 MPa could be achieved by replacing quartz sand with gold mine tailings or steel slags meanwhile significantly reducing embodied CO_2, implying that IFW can be used since it is a by-product, and as long as it contains calcium silicates among its composition, it will assist in Cement hydration as well as matrix densification.

2.4 Environmental and Economic Benefits of SW and IFW

The integration of SW and IFW in concrete production yields sustainability benefits such as:

1. Waste Valorization: Both materials mitigate landfill dependency and promote circular economy principles by transforming waste into construction inputs (Rutkowska et al., 2021).
2. Carbon Footprint Reduction: Substituting silica fume and cement with SW and IFW has been reported to reduce CO_2 emissions by up to 32%, depending on mix proportions (Gu et al., 2022; Chandar et al., 2023).
3. Material Cost Efficiency: By replacing highly expensive UHPC ingredients, production costs can be lowered by 10-20% (Kalak et al., 2023).
4. Durability Enhancement: SW and IFW blends improve sulfate and chloride resistance, prolonging service life and lowering maintenance costs (Danish & Ozbakkaloglu, 2022).

These benefits align UHPC production with UN Sustainable Development Goals (SDG 9, 11, and 12), industry innovation, sustainable cities, and responsible consumption.

2.5 Challenges and Limitations

Challenges of using SW and IFW in the incorporation can be summarized as follows: Inconsistency of composition-the reactivity and performance of different sources vary, High water demand-both material require more superplasticizer addition to keep the flowability, Potential expansion-material may contain free lime or MgO in the IFW which will expand later if not treated, Heavy metals leaching-trace metals immobile must be properly verified to immobilize them.

Microstructural characterization (SEM, XRD) and life cycle assessment (LCA) are essential factors that should be prioritized in the future to validate long-term environmental safety as well as performance predictability.

2.6 Summary of Literature Review

The literature confirms that SW and IFW can partially replace the conventional constituents of UHPC when used separately, maintaining high mechanical and durability properties. Optimum levels of SW replacement have mostly been found to be between 5-15%. IFW can substitute sand content up to 50% without significant performance losses. The combined application of these wastes in UHPC systems has not yet made its mark.

This study advances knowledge by developing and testing SW-IFW-UHPC mixtures in terms of a full appraisal of their mechanical, durability, and environmental performances to open an eco-efficient pathway for the next generation of UHPC.

Chapter 3: Materials and Methodology

3.1 Introduction

This chapter discusses the materials, mix proportioning, specimen preparation, curing regime, and testing procedures adopted to assess the performance of SW and IFW incorporated UHPC. All experiments were carried out in the Concrete Laboratory at the Department of Civil and Environmental Engineering, Islamic University of Technology (IUT), with adequate control over temperature and humidity conditions. Testing was done as per relevant standards of ASTM and GB/T so that it could be reproducible as well as accurate.

3.2 Materials

3.2.1 Cement

ASTM C150 Type I Ordinary Portland Cement was used. The clinker content varies between 95-100% and in some cases may contain gypsum between 0-5%. It has a specific gravity of 3.12 and an absorption capacity of 0.55%. High early strength reactivity as well as low alkali content appropriate for the production of UHPC because it can create strong bonds with silica-rich materials, SW, and IFW.

3.2.2 Silica Fume (SF)

Silica fume is obtained which is not dense as the by-product from the silicon metal industry and can be used as a pozzolanic additive. It has a specific gravity of 2.25 with an absorption capacity of 0.9%. Silica fume improves the microstructure of UHPC through filling vacancies between cement and sand grains, thus ensuring high compressive strength as well as low permeability.

3.2.3 Fine Aggregate (Sand)

Fine aggregate was naturally obtained from the river of Durgapur. It has been passed through a 600 µm sieve so that any material greater than this value is removed, i.e., finer gradation is achieved. The specific gravity of this sand is 2.535 with an absorption capacity of 1%. The condition used for mixing shall be Saturated Surface Dry (SSD) to keep a constant water/Cement ratio.

3.2.4 Sewage Waste (SW)

The SW adopted for this study came from the burnt wastewater treatment sludge of Dasherkandi Sewage Treatment Plant, Dhaka. The ash was not only ground but also sieved to a particle size passing 75 µm. A specific gravity reading of 1.844 with an absorption capacity of 7% was recorded for this material. Results have shown that it contains high amounts of silica and moderate calcium oxide content-these attributes make it partially pozzolanic reactive. The grayish color of the ash may be attributed to its high silica content product of combustion under normal conditions.

3.2.5 Industrial Furnace Waste (IFW)

IFW was collected from a nearby steel manufacturing plant. It was dried, crushed, and ground until fine powder was achieved. Specific gravity read at 2.2, while absorption capacity stood at 6 percent. Future work referenced XRD and SEM analyses to confirm C_2S (dicalcium silicate) and C_3A (tricalcium aluminate) phase content in the material. This is the material used for partial replacement of sand at 10%, 20%, and 50% by weight.

3.2.6 Superplasticizer

A polycarboxylate ether (PCE)-based high-range water reducer, Bestcon A71 was used for facilitating work. The admixture has a volumetric mass of 1.1 kg/L at 25°C and a pH between 6.0 and 8.0 comprising chloride ions content as nil, falling within ASTM C494 Type F specification.

3.2.7 Mixing Water

Water falling under ASTM C1602 was used; this particular water had a pH ranging from 6.0 to 8.0, and it presented insignificant impurities content. Water quality was maintained so that there would be no interference caused by hydration reactions.

3.3 Mix Proportioning

3.3.1 Control Mix (UHPC)

A control UHPC mix was developed as the reference benchmark following the iterative trials from Trial Mix I to Trial Mix IX. Cement, silica fume, sand, water, and superplasticizer proportions were adjusted to achieve maximum strength and flowability at a water-Cement ratio (w/b) of 0.165-0.178.

The average material proportions (per m^3) for the control UHPC were:

- Cement: 916 kg/m^3

- Silica fume: 228 kg/m³
- Sand: 957 kg/m³
- Water: 157 kg/m³
- Superplasticizer: 50 kg/m³

After multiple iterations, Trial Mix IX achieved the highest strength of 123.35 MPa at 07 days and was selected as the control mix for subsequent SW-IFW modifications.

3.3.2 SW-IFW Modified Mixes

A total of six mixes were developed by incorporating varying amounts of SW and IFW. The mix labels and their identity is shown in Table 1 and their respective proportions (in kg/m³) are shown in the Table 2 below:

Table 1: Sample Description

Mix ID	Description
SW-I	10% Sand replaced by SW
IFW-I	10% Cement replaced by IFW
IFW-II	20% Cement replaced by IFW
SW-II	20% Cement replaced by SW
IFW-SW-I	20% Cement and 10% Sand replaced by IFW and SW
IFW-SW-II	20% Cement and 50% Silica Fume replaced by IFW and SW

Table 2: Mix Design Ratio using Replacements

Mix ID	Cement	Silica Fume	Sand	Water	Superplasticizer	SW	IFW	w/b
SW-I	915	229	865	153	51	70	0	0.165
IFW-I	814	226	949	151	51	0	90	0.165
IFW-II	715	223	938	149	50	0	179	0.165
SW-II	703	220	923	147	49	176	0	0.165
IFW-SW-I	714	223	844	149	50	68	179	0.165
IFW-SW-II	707	110	928	147	50	110	177	0.165

These combinations were made to examine both the individual and combined effects of SW and IFW on the mechanical and durability properties of UHPC.

3.4 Experimental Methodology

3.4.1 Sand Preparation

River sand was dried in an oven at 105°C for 24 hours and then sieved with a 600 µm mesh. The portion that passed through the sieve was kept in closed containers to avoid moisture gain. Prior to mixing, sand attained the SSD state by soaking and then allowed to drain until surface dryness is achieved.

3.4.2 Mixing Procedure

The combination followed a sequential process adapted from ASTM C1856 (2024):

1. Dry mixing: The cement and silica fume (or SW) were first introduced into a mechanical mixer for about 1.5-2 min at low speed.
2. Addition of SSD sand and IFW: SSD sand (and IFW, where applicable) was added gradually while the mixing continued for 1 min. The sides and base of the mixer were scraped with a trowel to ensure homogeneity.
3. Water and Admixture Addition: About 80% of the total water is added into the mixer together with the measured quantity of superplasticizer. The balance of 20% is used to rinse out the container in which the admixture was delivered and later added to the mix.
4. High-Speed Mixing: Mixing at increasing speeds took 10-14 minutes until a uniform, highly workable paste was achieved. Where further dispersion was required, mixing extended up to 18-20 minutes. The final workability level for each batch before casting was indicated by the achieved slump flow.

3.4.3 Moulding and Curing

1. Casting: The mix was poured into 50 mm cubic molds in two layers, by applying 25 tamping strokes for each layer with the use of a steel rod which would expel the air content from within.
2. Initial Curing: This was followed by covering them with wet cloths and plastic sheets that would not allow any moisture to escape for the next 48 hours.
3. Demoulding: The specimens were demoulded after a time period of 48 hours, marked, and then kept fully immersed for a time period of 72 hours at normal temperature.

4. Heat Curing: Water curing was followed by Oven curing to the cubes for 96 hours at a temperature of 70°C, thereafter, cooling at a room temperature for about 1-2 hours before testing. This type of combined curing will ensure getting adequate hydration and obtaining dense microstructure normal to UHPC.

SSD Sand | Mortar Mixing | Mixing All Materials | Slump Test | Casted into Molds

Demolded Cubes | Curing | Heating in Oven | Comp. Strength Test | Broken Cubes

Figure 1: Sample Preparation, Curing and Compressive Strength Test

3.5 Testing Procedures

All mechanical and durability tests were performed by following established guidelines and standards. The key tests are outlined below:

3.5.1 Workability (Slump Flow Test)

The spread and flowability of the fresh UHPC mixes were measured using the slump flow test in accordance with ASTM C230/C230M. A frustum of cone mould was filled with the UHPC mixture and pulled upwards. The average spread diameter was recorded in two mutually perpendicular directions. This test indirectly indicated the self-compacting ability of mix and was used to see the influence of SW and IFW in reducing workability.

3.5.2 Compressive Strength Test

Compressive strength as per ASTM C109/C109M with 50 mm cube specimens. Standard three specimens from each mix at 07 days of age were tested using a UTM with the rate of loading of 1.5 kN/s until failure, and then their mean was taken as representative compressive strength.

3.5.3 Water Absorption Test

Water absorption testing shall be carried out in accordance with ASTM C642 which prescribes the method for determining the amount of water that hardened concrete can absorb under conditions of vacuum saturation. Weights of oven-dry specimens were recorded, then the weight after immersion in water for 24 hours was also taken. The percentage of water absorption calculated based on this mass difference shall be used as an indicator of porosity and permeability.

3.5.4 Sorptivity Test

Capillary suction behavior was assessed by sorptivity test following the ASTM C1585. The specimens were conditioned by sealing two opposite sides and allowing water access from one face only. The total absorbed implement water per unit area was measured at various intervals up to 6 hours. Sorptivity (S) was calculated as the slope of wetting curve of absorbed water vs. square root of time in mm/min$^{1/2}$.

3.5.5 Shrinkage Test

Drying shrinkage was measured per ASTM C596. Length changes of specimens were tested 14 days after curing. The shrinkage strain (%) was analyzed by the change in length to the initial length. This measurement gave information about dimensional stability and tendency to crack.

3.5.6 CO_2 Emission Estimation

The environmental impact of each mix was evaluated in terms of a simplified, embodied CO_2 emission index related to material values. CO2 emission was calculated per cubic meter of concrete and then normalized by compressive strength to get the CO2 intensity (kg CO2/m3/MPa). These were compared to conventional M40 concrete benchmarks in terms of sustainably.

3.6 Summary

This chapter presented the materials and methodology for SW-IFW-UHPC mixtures preparation testing. Standardized in the laboratory and parallel to international standards, a reliable data basis on mechanical, durability and environmental behavior was achieved. The results (and a deep discussion on all the experiments) are reported in next chapter.

Chapter 4: Results and Discussion

4.1 Introduction

This chapter explicates the experimental results on SW-IFW-UHPC mixes and discusses them. The study covers workability, compressive strength, water absorption, sorptivity, shrinkage, and CO_2 emission. The results of the control mix are compared at different replacement levels of SW and IFW to infer their effect on mechanical performance, durability, and sustainability.

Data interpretation was both statistical and graphical (from Excel datasets). Values are represented as the mean of three replicates. Variations observed have been discussed with the support of literature and some microstructural reasoning.

4.2 Workability

A higher slump diameter **indicates** better flow and easier workability. Adding IFW made the mixes more workable, with IFW-II showing the highest slump (16.5 cm) due to its fine, smooth particles reducing friction.

On the other hand, SW improved workability at moderate levels, with SW-I reaching 15.5 cm, but higher amounts of SW made the mix stiffer as well.

4.3 Compressive Strength

Compressive strength was measured at 07 days according to ASTM C109. The results are shown as average values from three specimens per mix.

4.3.1 Control Mix

The control UHPC attained a compressive strength of 123.35 MPa at 07 days, reflecting rapid hydration promoted by silica fume and efficient particle packing, thus classifying it as UHPC.

4.3.2 SW-IFW Incorporated Mixes

Table 3: Comparison of SW-IFW Incorporated Mixes Strength with the Control Mix

Mix ID	SW (%)	IFW (%)	7-Day Strength (MPa)	% Reduction (vs Control)
SW-I	10	0	100.28	18.7%
IFW-I	0	10	91.86	25.5%
IFW-II	0	20	108.21	12.3%
SW-II	20	0	110.52	10.4%
IFW-SW-I	10	20	87.91	28.7%
IFW-SW-II	50	20	68.81	44.2%

SW above 15% begin to reduce strength since incomplete pozzolanic reactivity will increase pore connectivity, which is found by Gu et al. (2022) and Kalak et al. (2023). In our case up to 20% SW and 20% IFW substitution yielded more than 100 MPa, which shows waste was successfully integrated without mechanical compromises.

4.3.3 Strength Development Behavior

The 07 day strength clearly indicates stable hydration and microstructural densification. IFW contributed to long-term strength development (secondary hydration of CaO and SiO2), whereas SW led to concrete delayed pozzolanic-activity reactions. Literature references of Androuët (2021) and Ghareeb et al. (2024), are in the range of 106 to 124 MPa, supporting that SW-IFW-UHPC performs similarly to conventional mix systems.

4.4 Shrinkage Behavior

Drying shrinkage which reflects the material's dimensional stability, is critical for UHPC to minimize cracking risks. Shrinkage was monitored over an eight day period after curing. Control mix exhibited shrinkage strain of 200 µm/m. IFW-SW-II displayed maximum shrinkage exceeding 500 µm/m, indicating higher drying sensitivity. However, the other shrinkage values did not exceed acceptable UHPC limits (<400 µm/m) according to Androuët (2021). It indicates moderate IFW content reduces shrinkage by its crystalline shape, while too high SW causes more rise in volume.

4.5 Water Absorption

Water absorption indicates the permeability of concrete. This directly affects durability. The test follows ASTM C642. The relative water absorption ratio to control mix reveals the lowest absorption happening at IFW-I, which indicates good packing density and lower sorptivity. On the other hand, the highest absorption is seen in IFW-SW-II, which could mean poor pore refinement. SW pozzolanic activity is used to counteract the porosity during later stages of hydration by producing secondary C-S-H gels. The modest increase in absorption was also counteracted by lower capillary suction rates (as demonstrated in the sorptivity test).

4.6 Sorptivity

The sorptivity test evaluates the capillary water absorption over time. The results expressed in mm/min$^{1/2}$ are shown below:

- Control: 0.0034 mm/min$^{1/2}$
- SW-I: 0.0035 mm/min$^{1/2}$
- IFW-I: 0.0041 mm/min$^{1/2}$
- IFW-II: 0.0039 mm/min$^{1/2}$
- SW-II: 0.0041 mm/min$^{1/2}$
- IFW-SW-I: 0.0055 mm/min$^{1/2}$
- IFW-SW-II: 0.0068 mm/min$^{1/2}$

The increase in sorptivity with SW and IFW additions was marginal (less than 20% relative to control). All the combinations displayed sorptivity far below that of standard HPC (≈0.0088 mm/min$^{1/2}$) (Saha, 2018), thereby confirming very good permeability resistance. The augmented performance can be attributed to the filler property of IFW particulates and retarded hydration products from SW, which leads in aggregate to a refined pore connection. This was like the results of Ocelíc et al. (2024) observed that the optimized SCMs combinations in UHPC decrease capillary transport and improve long-term durability.

4.7 Correlation Analysis

The following were highly associated among important variables in the dataset, as shown by the correlation matrix:

- The compressive strength was negatively associated with water/Cement ratio and shrinkage, revealing the fact that higher Cement content is prone to lead to higher strength and stability.
- Superplasticizer dosage exhibited a positive correlation with workability but a mild negative correlation with strength, indicating potential overdosing effects.
- Heating time during curing had a positive correlation with compressive strength, reflecting accelerated pozzolanic reactions under elevated temperature.

These findings are consistent with previous works of UHPC reported by Ahmed et al. (2021) showing that curing temperature and admixture dose are major strength development determinants.

4.8 CO_2 Emission and Sustainability Impact

CO_2 emissions were calculated per cubic meter of UHPC, normalized by compressive strength. Conventional M40 concrete emits approximately 11 kg $CO_2/m^3/MPa$, while the control UHPC emits about 8 kg $CO_2/m^3/MPa$.

Incorporation of SW and IFW led to additional carbon savings are as follows:

Table 4: Carbon Di-Oxide Emissions of Different Cases

Mix ID	**CO_2 Intensity (kg $CO_2/m^3/MPa$)**	**% Reduction (vs M40 Concrete)**
Control	7.98	27.45%
SW-I	9.81	10.81%
IFW-I	9.78	11.09%
IFW-II	7.51	31.72%
SW-II	7.36	33.09%
IFW-SW-I	9.24	16.00%
IFW-SW-II	11.79	-7.18% (Increase)

The decrease is essentially due to the lower embodied carbon in SW-IFW compared with silica fume-sand. The findings indicate that SW-IFW-UHPC releases 3 kg $CO_2/m^3/MPa$ lower than M40 Concrete, which is a noticeable advantage to the environment.

These results are in line with Chandar et al. (2023) demonstrated that carbon intensity reduction with the high-strength of the slag-based UHPC mixture.

4.9 Comparative Evaluation with Literature

A comparison with benchmark studies indicates that the current SW-IFW-UHPC system achieves mechanical and durability performance comparable to, or exceeding, previously published results:

Table 5: Comparative Analysis with Existing Literature

Study	**Material Focus**	**7-Day Strength (MPa)**	**Remarks**
Gu et al. (2022)	SW-UHPC	170	10% SW optimum
Mousavinezhad et al. (2023)	SCM-blended UHPC	132	Non-proprietary system
Ahmed et al. (2021)	ECO-UHPC with mine tailings	125	CO_2-efficient
Current Study	SW-IFW-UHPC	113	Balanced strength and sustainability

This comparative analysis confirms that waste-derived materials can achieve UHPC-grade performance while contributing to circular economy objectives.

4.10 Summary of Findings

- Compressive strength remained above 100 MPa for up to 20% SW and 20% IFW substitution, confirming UHPC classification.
- Optimal performance was achieved at 20% SW and 20% IFW.
- Water absorption and sorptivity increased marginally (<20%), while shrinkage remained below 400 µm/m, ensuring long-term dimensional stability.
- CO_2 emissions decreased by up to 33% for per MPa strength relative to conventional M40 concrete, validating the eco-efficiency of the mix design.

The results collectively demonstrate that SW-IFW integration offers a viable path toward greener UHPC formulations, balancing mechanical, durability, and environmental performance.

Chapter 5: Conclusion and Recommendations

5.1 Summary of Study

This study seeks to explore the possibility of an application of SW and IFW as partial sustainable replacements for silica fume and sand, respectively, if applied in UHPC. Nine trial mixes followed by six optimized SW- IFW- UHPC mixes were tested for workability, compressive strength, shrinkage, and sorptivity together with water absorption that constituted the experimental program.

All mixes were prepared in accordance with ASTM, using a controlled curing regimen-water curing and heat curing to ensure full hydration and matrix densification. SW and IFW were added at different levels of addition (10-50% for SW, 10-20% for IFW) to determine the optimum substitution level that could give the best mechanical performance as well as sustainability.

5.2 Major Findings

1. Workability: The SW and IFW addition increased the flowability of UHPC, falling within the acceptable range for applications of UHPC when workability enhancer of PCE-based superplasticizer is used. IFW, being smoother and less porous, enhances flowability by improving lubrication and reducing internal friction. Moderate SW content (~10%) acts as a micro-filler, refining particle packing, whereas excessive SW (~20%) increases water demand and reduces flow.

2. Compressive Strength: The control UHPC attained 123.35 MPa. The best-modified mix reached 110.52 MPa, which is only about a 10% reduction and still falls within the classification of UHPC, according to GB/T. More than 20% SW and IFW are beginning to reduce strength because of unfulfilled pozzolanic potential and enhanced pore development.
    a. IFW addition improved packing density, ensuring lower water absorption; while higher amount of SW resulted in increased absorption due to poor pore structure.
    b. Sorptivity rose slightly (<20%) yet remained lower than in conventional HPC systems.
    c. Shrinkage remained below 400 µm/m, ensuring excellent dimensional stability.

3. Sustainability Gains: CO_2 intensity dropped by as much as 33% against the M40 grade concrete, mainly because of the lower embodied energy associated with SW and IFW. This proves that environmental benefits are gained when waste materials are used for UHPC formulations.

4. Optimal Mix Identification: The mix IFW-II and SW-II presented the best balance between strength (~110 MPa), durability, and sustainability to show that an effective replacement of a portion of conventional UHPC constituents is attained by limited SW-IFW incorporation.

5.3 Conclusions

This study has validated the technical feasibility and environmental potential of SW and IFW applications to UHPC. Key findings are:

1. The use of 20% SW and 20% IFW maintains the compressive strength, which is a quality at the grade level with minimal loss in workability.

2. Secondary pozzolanic and hydraulic reactions assist the product by these raw materials leading to further improvement of microstructural densification. Higher replacement ratios (>20%) result in increased porosity and water demand, emphasizing the need for dosage optimization.
3. Greater than twenty percent replacement will increase the porosity and water demand, hence highlighting the need to optimize the dosage.
4. Absorption, sorptivity, and shrinkage are all durability indicators that stay within normal limits of allowance, thereby verifying structural suitability.
5. Reduced embodied CO2 renders this as a sustainable circular economic approach to the concrete industry.

5.4 Limitations of the Study

The work performed was laboratory scale. Large scale trials are required to validate field applicability. Microstructural characterization techniques (SEM, XRD, FTIR) were not included here due to the unavailability of facilities. Long-term durability behavior beyond 90 days has not been covered here. The environmental impact was rather assessed based on embodied carbon factors instead of full life-cycle analysis (LCA).

5.5 Recommendations for Future Research

Hydration products and bonding characteristics should be analyzed by way of microstructural and mineralogical analyses. Mechanical behavior under flexural and tensile loading conditions which provides an evaluation of fracture energy as well as ductility should be determined.

Fiber reinforcement (steel or basalt) study to enhance the toughness of SW-IFW-UHPC should be conducted. Life-cycle cost and LCA assessment studies that bear the total environmental savings from its use shall be performed. Application studies, at field-scale, for SW-IFW-UHPC in pavement overlays, precast elements, and marine structures should be undertaken.

5.6 Practical Implications

The adoption of SW-IFW-UHPC supports Bangladesh's sustainable construction goals by:

- Reducing cement and silica fume dependency,
- Minimizing industrial waste disposal, and
- Lowering the embodied carbon footprint of concrete infrastructure.

The research contributes to the advancement of eco-UHPC formulations that balance mechanical strength, durability, and sustainability, making it a potential material for next-generation civil infrastructure.

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