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Mechanical and Durability Properties of High Strength Mortar with Construction Waste and Recycled Wastewater

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A THESIS SUBMITTED FOR THE PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF BACHELORS OF SCIENCE IN CIVIL ENGINEERING

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PROJECT APPROVAL

This is to certify that the thesis entitled “Mechanical and Durability Properties of High Strength Mortar with Washed Waste Fines and Washed Waste Water” submitted by Nakib Mujtaba, Nusrat Kamal and Shafinur Hasan has been approved as partial fulfillment of the requirement for the Degree, Bachelor of Science in Civil Engineering at Islamic University of Technology (IUT).

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DECLARATION

We hereby declare that the undergraduate research work presented in this thesis has been conducted by Nakib Mujtaba, Nusrat Kamal and Shafinur Hasan under the guidance and supervision of Assistant Professor Dr.
Tanvir Ahmed. We assure you that the findings and conclusion presented in this work are the result of our own investigation and have not been duplicated or submitted previously for any other purpose.

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DEDICATION

We would like to highlight that the completion of this study is dedicated to our parents, who over time assisted us by the means of time support and labor so that we can achieve what we wish to. They have inspired us to develop ourselves and supported us wherever they could, enabling us to pursue our technical goals without ever looking back.

We also want to convey our sincere appreciation to Dr. Tanvir Ahmed, our esteemed supervisor, for his continuous encouragement and motivation.

Without his consistent upliftment, this endeavor would have not been possible.

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"In the name of Allah, Most Gracious, Most Merciful"

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ABSTRACT

This study explores the combined use of two industrial by-products, Concrete Waste (CW) and Recycled Water (RW) as sustainable alternatives in High-Strength Mortar (HSM). The goal of this study is to reduce the environmental impact of cement production and sand extraction in the construction industry. We addressed the research gap by testing seven mixtures with 100% RW and varying amounts of CW as a replacement for cement or sand.

We evaluated mechanical and durability properties using standardized tests for compressive strength (ASTM C 109), sorptivity (ASTM C1585), and drying shrinkage (ASTM C596). The results showed that using 100% RW is a practical option, with the control mix achieving 91.3 MPa. The replacement strategies were important, such as- substituting cement with CW led to a decrease in compressive strength (down to 60.3 MPa) and reduced durability. On the other hand, replacing sand with CW produced excellent results. The 40SRW mix, which replaced 40% of the sand, maintained compressive strength at 91.7 MPa and sorptivity at 0.0036 /√s, similar to the control mix. It also shows better dimensional stability, reducing drying shrinkage by 15.6%. The study concludes that the 40SRW formulation is an ideal sustainable mixture. It also supports a circular economy approach by delivering high mechanical performance and durability while maintaining structural integrity.

Keywords: Sustainable Construction, High-Strength Mortar (HSM), Construction Waste (CW), Recycled Wastewater (RW), Sand Replacement, Circular Economy, Mechanical Properties, Durability.

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Chapter 1: Introduction

1.1 Background

One of the biggest users of natural resources worldwide and also a major cause of environmental pollution is the structural sector. Large-scale extraction of natural sand damages the environment, reduces limited resources and the production of Portland cement. This results in significant emissions of Carbon Dioxide (CO_2). This has led to an increasing demand for environmentally friendly building methods and the creation of substitute materials that can satisfy contemporary structural performance requirements without compromising the environmental impact of this industry (Gholampour et al. 2020). A fundamental idea of the circular economy is the integration of industrial by-products into building materials, which is one of the most practical solutions (Dwivedi et al. 2024).To check this point, a viable substitute is Construction Waste (CW)- which are made from industrial and construction waste. CW can help preserve resources and shield ecosystems from the damaging effects of sand mining when used in part as a replacement for natural sand. CW can reduce the carbon footprint of mortar and possibly improve its strength, durability and water-absorption resistance when used in place of some of the cement as well (Dwivedi et al. 2024). Reusing wastewater from building operations offers an additional chance for sustainable development in addition to solid waste. When compared to ordinary water, Recycled Wastewater (RW) has a higher pH and more alkalinity (Ranaweera et al., 2023). These characteristics might help concrete and mortar mixtures last longer.

Figure 1.1:- Sample of Construction Waste (CW)

1.2 Problem Statement

Construction and building industry faces significant environmental pressure due to high consumption of natural resources and substantial carbon footprint.The production of ordinary Portland cement is one of the key reasons of CO2 emission and production of natural sand in the manufacturing of mortar and concrete mortar drains scarce resources and destroys nature. The production of regular Portland cement is one of the primary sources of CO2 emissions(Wong et al. 2025). Besides, the mining of vast natural sand to make mortar and concrete is exhaustive and harmful to the environment.

Construction and industrial waste can be used as a viable way to a sustainable building. The benefits of such materials such as Construction Waste (CW) include:

- Lower carbon emissions
- Resource conservation and
- Efficient waste recycling

These have been effective as half cement and sand replacements. Moreover, it is possible to increase the life of concrections by the increased pH and alkaline of Recycled Waste Water (RW) that is usually disposed of during construction works. Such waste materials could be used in the form of high-strength mortar to promote the idea of a circular economy because a waste could be transformed into useful resources (Dwivedi et al. 2024).

1.3 Objectives

This thesis is targeted to investigate mechanical performance and durability properties of High Strength Mortar with washed waste fines and washed waste water. The specific objectives are listed below-

Evaluation of Mechanical Properties

This evaluation will provide insight into the potential benefits and drawbacks of incorporating

Washed Waste Fines and Washed Waste Water in terms of structural performance.

Assessing Durability Characteristics

Vital tests, such as sorptivity and drying shrinkage, were used to evaluate the high-strength mortar's durability. According to ASTM C 1585-20, the sorptivity test measured water absorption and demonstrated that substituting Construction Waste (CW) for sand had no effect on water transport, with results that were comparable to the control mix. Dimensional stability was assessed using the drying shrinkage test in accordance with ASTM C 157. According to this test, CW substituted for sand produced stable or decreased shrinkage, suggesting good long-term durability.

Optimization of Mix Design

To determine the best way to use Construction Waste (CW) and Recycled Wastewater (RW) in high-strength mortar, a number of scenarios were created and tested as part of the mix design optimization process. Both cement and sand were substituted with varying percentages of CW. The use of CW for partial sand replacement was determined to be the best course of action following performance analysis.

Practical Recommendations

For specific uses, we advise investigating this high-strength mortar with Construction Waste (CW). More research should be done to determine its potential as an efficient and sustainable repair material. Furthermore, future studies should evaluate how well it performs as a structural overlay on typical concrete substrates, paying particular attention to how it bonds, how it improves durability, and how it affects overall structural performance.

1.4 Layout of the Thesis

Chapter 1: Introduction

The background and context of the research are established in this chapter. It describes the main goals of the study, establishes its parameters, and provides a flowchart to show how the research was conducted.

Chapter 2: Literature Review

This section provides a thorough analysis of earlier research on the subject. It evaluates earlier researchers' findings critically and determines how applicable they are to the current study.

Chapter 3: Methodology

This chapter offers a thorough explanation of the research strategy, steps, and techniques used. To ensure that the study is transparent and reproducible, it describes each step of the experimental procedure.

Chapter 4: Results and Discussion

The experimental data gathered during the study is shown in this section along with the techniques used to analyze it. The findings are thoroughly examined, with their importance being interpreted in light of the study's objectives and body of existing literature.

Chapter 5: Conclusion and Recommendations

The main findings from the study are outlined in the last chapter along with implications. It also discusses the limitations of the study and makes thoughtful suggestions for additional research and real-world uses.

Chapter 2 : Literature Review

Due to the substantial environmental impact of its essential components, the global construction industry is coming under increasing pressure to adopt sustainable practices. While the massive quarrying of natural sand depletes limited resources and causes ecological degradation, the production of regular Portland cement is a significant contributor to global carbon dioxide emissions. Innovative, environmentally friendly substitutes that can lessen the industry's environmental impact without sacrificing structural performance are desperately needed as a result (Dwivedi et al. 2024). The circular economy concept, in particular the recycling of construction and industrial waste, offers a viable remedy. It has been determined that Construction Waste (CW) are a practical substitute for cement and sand. According to studies, adding CW can decrease water absorption, increase durability, and strengthen mortar. Utilizing CW reduces carbon emissions, helps with efficient waste recycling, and reduces the need for virgin sand by partially replacing cement (Gholampour et al. 2020). The long-term durability of concrete may also be enhanced by Recycled Waste Water (RW), a frequently discarded by-product of construction processes that has a higher pH and alkalinity than regular water (Ranaweera et al.2023). Using RW supports a circular economy and encourages sustainable waste management.

Table 2.1 Studies on Fine Aggregate Replacement

Author	Title	Major Findings
Dwivedi et al. (2024)	Use of waste brick fines in high-strength mortar	30 % sand replacement increased compressive strength by ~49 % and lowered shrinkage.
Wong et al. (2025)	CO_2-cured masonry fines as sand	Up to 75 % replacement improved strength ~30 % and reduced drying shrinkage.
Yosri et al.	Valorization of engineered biochar to develop	10–20 % replacement gave

(2024)	ultra-high-performance fiber-reinforced concrete with low carbon emission	~14 % higher strength and reduced porosity.

Table 2.2 Studies on Cement Replacement

Author	Title	Major Findings
Gholampour et al. (2020)	Development of a Waste‑Based Eco‑Friendly Structural Mortar Without Portland Cement and Natural Sand	≤15 % replacement slightly reduced shrinkage; higher levels lowered strength by 10–25 %
Beniddar et al. (2024)	Sustainable utilization of phosphate mine waste rocks as sand substitutes in cement mortar production	Low dosages densified matrix; higher dosages increased porosity and reduced flexural strength.

Table 2.3 Studies on High Strength Concrete with Waste Fines and Waste Water Replacement

Waste Material & Replacement Level	Mechanical Properties (Compressive, Flexural, Tensile Strength)	Durability Properties (Water Absorption, Chloride Resistance, Microstructure)	Optimal/Noted Effects	Author

Copper slag (CS) as fine aggregate, 0–100% (best at 50%)	Highest compressive and splitting tensile strength at 50% CS; improved workability with CS	Best sulfate, chloride, and water absorption resistance at 50% CS; 25% CS yields densest microstructure	50% CS: optimal strength and durability; 25% CS: best microstructure	Singh et al.(2024)
Wastewater (ready-mix plant), 0–100% (best at 75%)	Compressive strength peaks at 75% wastewater; trend: decrease, then increase, then decrease	75%: densest microstructure, lowest porosity; 25–75%: negative for carbonation	75% wastewater: optimal strength, microstructure, and frost resistance	Yao et al.(2022)
C&D waste (clay brick powder 0–25%, fine clay brick 0–50%, FA 0–25%)	Compressive: 38–70.3 MPa; Tensile: 4.1–8.2 MPa; Flexural: 5.2–10 MPa; best at 5% CBP, 5% FA, 40% FCB	17.7% increase when anti-carbonation, 14.6% increase when freeze resistance, 8.4% decrease for porosity; thick amorphous gel	5% CBP, 5% FA, 40% FCB: optimal for strength and durability	Elemam et al. (2023)
E-waste plastic as coarse aggregate, 0–20% (best at 15%)	13–25% ↓ compressive, 11–19% ↓ tensile at 10–20%; 15%: best balance	Water permeability improved at 15%; electrical resistivity ↑ 239–478%	15% e-waste: best durability, sustainable material	Islam et al. (2025)
Ceramic waste powder (HCCP) as cement, 0–20% (best at 5–20%)	5% HCCP: increase for compressive (26.5%), tensile (22%), flexural (22.4%) at 90 days	20% HCCP: decrease for water absorption (47%), chloride depth (62.3%), improved microstructure	5%: best strength; 20%: best durability	Hashim et al. (2025)
Industrial wastewater (varied concentration)	Up to 10% decrease for compressive strength at high concentration; main properties unchanged at low/moderate	Durability decreases nonlinearly with concentration; high concentration disrupts pore	Low/moderate: minimal effect; high: negative durability	Nasseralshariati et al. (2021)

		structure.		
Textile factory wastewater (100% replacement)	19% increase for compressive, 16% increase for tensile	Highest water absorption with domestic sewage;highest chloride penetration	Textile wastewater: best mechanical; others: variable durability	Raza et al.(2020)
Fine recycled aggregate (FRA) from C&D waste, 0–100% (best at 25%)	25% FRA: optimal strength; higher levels decrease strength	Two-stage mixing: ↓ water absorption (7.45%), chloride penetration (18.18%), improved ITZ	25% FRA, two-stage mixing: best performance	Sivamani et al. (2021)

2.1 Research Gap

Even though different waste fines have been studied separately, there is still a significant research gap about how they can be used. No literature exists where both Construction Waste (CW) and Recycled Waste Water(RW) are used simultaneously in high-strength mortar. This fact is even though previous literature has focused on the utilization of CW to substitute either sand or cement. There is no information on the exact effects of this dual substitution on key engineering properties. Therefore, through a systematic evaluation of the mechanical performance and durability characteristics of high-strength mortars under a combination of CW as well as RW, this paper addresses this gap in knowledge. This investigation is the key to the development of useful and sustainable building materials and the approval of the correctness of this mixed method.

Chapter 3: Methodology

3.1 General

This chapter provides an exhaustive description of the experimental methods that will be used to explore the mechanical and durability properties of high-strength mortar (HSM) with the addition of Construction Waste (CW) and Recycled wastewater (RW). It begins with an in-depth explanation of the ratios of the mixture of concrete, which indicates the specific cases that are under investigation in this study. The chapter continues to elaborate on the procedure to be followed in the process of gathering and preparing the materials and much more the procedures and criteria employed in testing the constituent materials. This section ensures that the materials under consideration during the experiments will be of the necessary specifications and ready to be utilized all through.

Moreover, the methods of making testing samples are also well described, as it guarantees that the experiment is accurate and repeatable. In the chapter, the curing methods used are also discussed as the various techniques used to maximize the nature of the HSM. The different testing processes used to ascertain the mechanical and durability properties of HSM are also presented and the essence of testing to test the performance of the concrete brought to light.

Further, this chapter presents a critical argument of the appropriateness of these means to the general study objectives in ensuring that the entire experimental framework is fully congruent with the study objectives. The importance of every methodological step and its importance is highlighted in this discussion.
made to the attainment of the objectives of the study. In addition, the proportions of mixing of both the control mix and the replacement mix are given. The molding process, compressive strength test standards, sorptivity and shrinkage tests standards are also carefully outlined. The overall and critical approach to the experimental methodology will ensure that this chapter will ensure the research framework is well understood in accordance with the research objectives of determining the performance and sustainability of HSM integrated with CW and RW.

3.2 Collection of Materials

In order to come up with the concrete mixtures, natural river sand that was acquired in Durgapur was used. The binder materials were CEM Type I (Ordinary Portland Cement, OPC) and CEM Type II A-M that meets the standards of BDS EN 197 [comprising of 80-94% clinker, 6-20% mineral admixture, and 5% gypsum]. Silica fume as well was supplied by a local manufacturer. The two types of Construction Waste (CW) and Recycled Wastewater (RW) used in this research were collected at Crown Cement which is a cement manufacturing plant in Dhaka. The superplasticizer in the study was gathered in Best Con.

3.3 Material Properties

The use of waste fines, which is a by-product of the activities of ready mix concrete plants has come under the limelight in recent years, mainly due to the dual mission of improving the performance of materials and limiting the environmental effects. High Strength Mortar (HSM) is one such advancement in technology with its advanced level of mechanical performance and longevity which makes it to be suitable in the high demand projects of structure such as bridges, buildings and other significant infrastructure.

The current research will evaluate the feasibility of replacing traditional elements with a large variety of sustainable ones in HSM, specifically, the inclusion of ready-mix concrete plant by-products into the process, including CW and washed RW. An integrated experimental programme was made to determine the performance of these materials when used in HSM mixtures.

The constituent materials entailed in the study are treated in a comprehensive manner and this entails the collection and characterisation of fine aggregates, cementitious materials and water. Special emphasis is placed on the characteristics of these materials that are in place before the concrete mix to be incorporated to comply with the performance standards that are required in the application of HSM. This approach not only aims to enhance the understanding of the potential of HSM but also seeks to contribute to the development of more sustainable construction practices.

Table 3.1 Specification followed for testing material properties

Name of the Property Evaluated	Specification/Guideline Followed
Specific Gravity	ASTM C 128 (for fine aggregates and CW)
	ASTM C 188 (for cement and silica fume)
Absorption Capacity	ASTM C 128
Unit Weight	ASTM C 29
Gradation	ASTM C 136

3.3.1 Fine Aggregates

In this study, high strength natural river sand collected from durgapur were used as fine aggregates. The sands were sieved through 600 micrometer meshes and retained in 75 micrometer mesh to obtain the finest particles for concrete casting. To maintain the consistency and accuracy of the water-binder ratio calculations the sand was used in a Saturated Surface Dry (SSD) condition. The high strength sand used in the mixes partially increased the compressive strength of the HSM, so based on the compressive strength test results of the trial mixes the high strength sand was selected for the main concrete mixes.

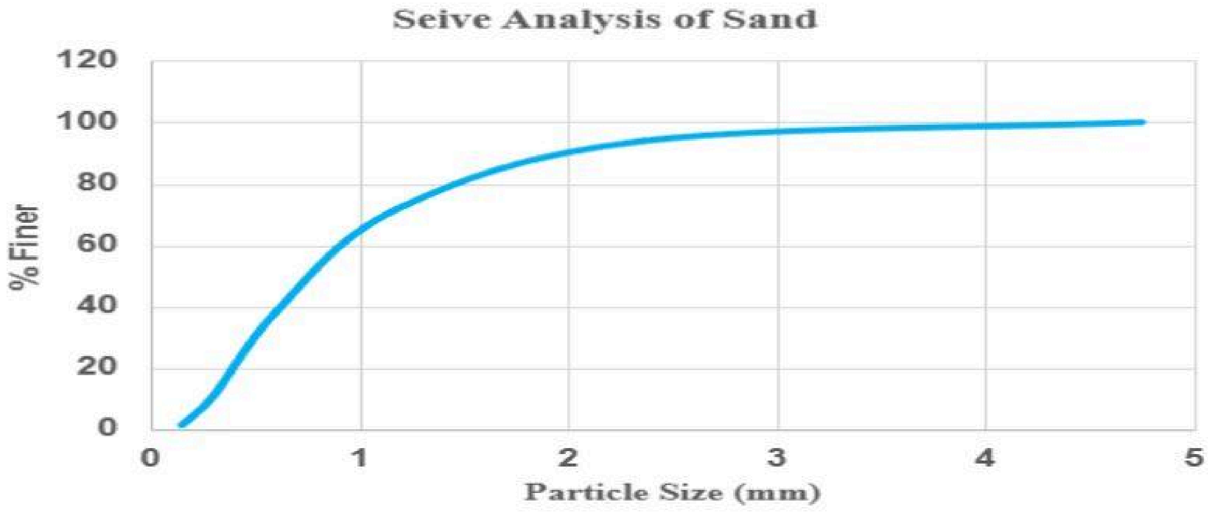

Figure 3.1 :- Gradation Curve of High Strength Sand

Figure 3.1 provides a visual representation of the gradation of sand utilized in this research. The figure effectively illustrates the particle size distribution and showcases it's gradation. The gradation curve shown in Figure 3.1 shows that the sand has a well graded particle size distribution, which is needed to provide dense packing of particles to minimize the void content in the high strength mortar (HSM) matrix. This optimal gradation directly contributes to the improved mechanical strength and durability of the mortar. The material characteristics of the sand used in the current study are exhaustively listed in Table 3.2. It measures the relevant physical parameters such as specific gravity and absorption capacity thus providing a detailed description of the characteristics of the sand. As a result, these visual and tabulated data represent a solid framework to evaluate the behavior and the appropriateness of the sand in the framework of the experimental research.

Table 3.2 Material Properties of Sand

	Test	**Result**
Sand	Specific Gravity	2.53
	Absorption Capacity (%)	1.98

3.3.2 Binder Material

In this investigation, the binding materials that were used included CEM Type I (Ordinary Portland Cement), CEM Type II A-M, and silica fume. The message to be heard is silica fume, also known as micro silica, which is an ultrafine product of silicon and ferrosilicon alloy manufacture and mainly comprises amorphous silicon dioxide (SiO2). Silica fume cannot be omitted in High Strength Mortar (HSM) in an effort to enhance strength, durability, and density. It has a good surface area and pozzolanic reactivity that helps to occupy any gaps that exist between cement particles, hence create more calcium silicate hydrate (C-S-H) gel. The mineralogical structure of the cements is clarified in Table 3.3, but the mineral characteristics of the silica fume are outlined in Table 3.4.

Table 3.3 Material Properties of Cement

Binder Type	Specific Gravity	Clinker	Mineral Admixture	Gypsum
CEM Type I	3.15	95-100%	0%	0-5%
CEM Type II	2.90	80-94%	6-20%	0-5%

Table 3.4 Material Properties of Silica Fume

Silica Fume	**Test**	**Result**
	Specific Gravity	2.53

3.3.3 Construction Waste (CW) as Cement and Sand Replacement

Construction Waste (CW) in this study which is a by-product of industrial and construction based processes were used as an alternative material with sustainable use as a partial replacement of both cement and natural sand in the High-Strength Mortar (HSM) mixes. The application of CW is in line with the main goal of creating a more environmentally-friendly construction material. The basic property of the CW was considered in order to make it integrated into the mix designs. The laboratory measurement of the specific gravity of the CW was established and the finding is indicated in Table 3.4 beneath.

Table 3.4 Material Properties of Construction Waste (CA)

Material	Test	Result
Construction Waste (CW)	Specific Gravity	2.06

The gradation curve of CW is depicted in Figure 3.2.

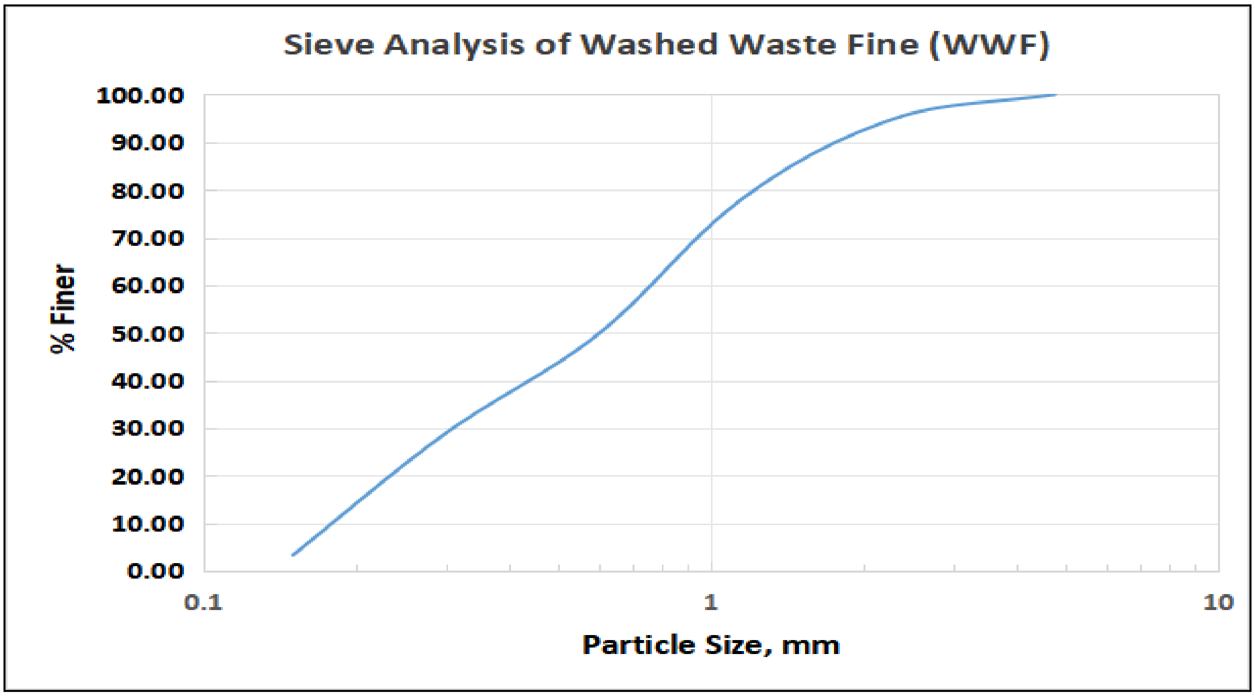

Figure 3.2 :- Gradation Curve of Construction Waste (CW)

Additionally, Figure 3.3 presents a comparison of the gradation curves between Sand and washed waste fine

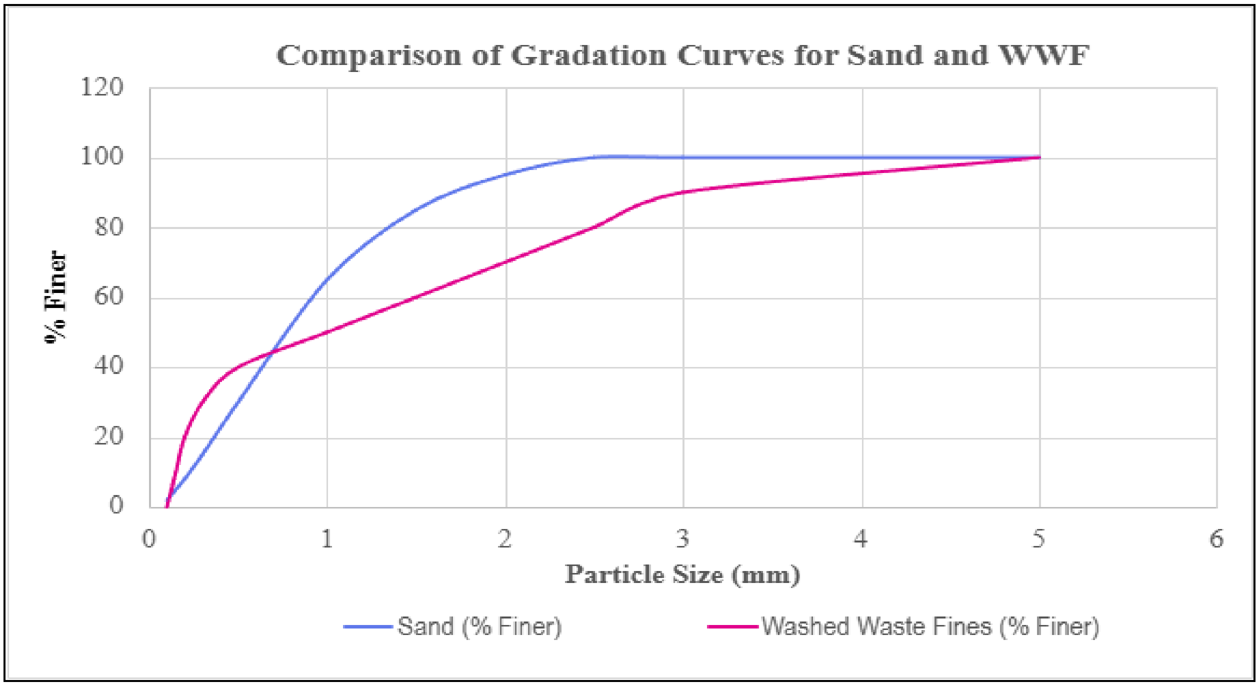

Figure 3.3 :- Gradation Curve Comparison between sand and Construction Waste (CW)

The gradation analysis shows that there is significant difference in the physical properties of the two materials. Distribution of the natural sand is well graded with the size of the particles having a wide range between about 0.5mm to 5mm. Comparatively, the gradation curve of Construction Waste (CW) is much steeper, and has shifted to the left, indicating that the material is mostly fine. The vast majority of the particles in Construction Waste (CW) are less than 1 mm in diameter, a significant fraction of them are less than 0.3 mm.

This characteristic particle-size distribution is also a key parameter and determinants of the behaviour of high-strength mortar (HSM). When used as a replacement sand, the smaller Construction Waste (CW) particles play the role of a micro-filler, which can fill the interstitial void space between the larger sand particles and cement grains. This leads to a more compact particle arrangement that could reduce porosity and increase the mechanical strength and impermeability of mortar matrix. On the other hand, the fineness of the Construction Waste

(CW) used as a cement replacement shows that it could be pozzolanic. These fine particles have a high surface area, which helps in a reaction with calcium hydroxide liberated during cement hydration, to form more secondary cementitious compounds (C -S -H gel), thus, contributes to long-term strength and durability. The unique gradation and low specific gravity of Construction Waste (CW) compared to natural sand were some of the basic factors in the design of the replacement mixes to be used in this study.

3.3.4 Recycled Wastewater (RW) as Fresh Water Replacement

In this study, Recycled Wastewater (RW) was used, which was derived as the waste-washing product of ready-mix concrete in Crown Cement, as a total replacement of potable mixing water. The key chemical parameter measured was the pH of the RW that may typically be more alkaline than standard mix water because of the dissolution of the cementitious residues. The high pH of RW is disposed to cement hydration and does not have a negative effect on the growth of the cementitious matrix. Its use corresponds to the principles of the circular-economy by offering a twofold environmental benefit consisting of saving freshwater resources and reusing an industrial effluent, which will decrease the environmental impact related to the wastewater disposal. The use of RW in the current study completely replaced potable water in the given mortar mixtures and allowed evaluation of the effect of RW on material characteristics.

Table 3.5 Material Properties of Recycled Water (RW)

Material	Test	Result
Recycled Wastewater (RW)	pH	10.95

Figure 3.4 :- Recycled Wastewater

3.3.5 Admixture

To achieve the desired workability in low water-to-binder ratio compositions a polycarboxylate ether (PCE)-based superplasticizer, that is, Bestcon A71, was used. Such high-range water-reducing admixture would provide adequate dispersal of cementitious constituents and optimum compaction and therefore it is essential in the formation of dense microstructure in high-strength mortar (HSM).

Table 3.6 Chemical Properties of Admixture

	Chemical Properties	
Bestcon A71	Chemical Type	Polycarboxylic Ether
	pH	Minimum 6.0
	Appearance	Pale Yellow Liquid
	Volumetric Mass@ 200 C	1.05 ± 0.05 kg/l

	Chloride Ion Content	3%

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 m3 of mortar. This approach ensures accurate scaling and can be expressed by the following equation:

$$\frac{S}{G_s\gamma_w} + \frac{C}{G_c\gamma_w} + \frac{W}{G_w\gamma_w} + Air(\%) = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Where,

C = Unit content of cement (kg/m3 of mortar)

S = Unit content of fine aggregate (kg/m3 of mortar)

W = Unit content of water (kg/m3 of mortar)

γ_w = Unit weight of water (kg/m3)

G_c = Specific gravity of cement 27

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)

3.4.1 Mix Cases with Washed Waste Fine and Washed Wastewater

Seven different mix cases were developed to conduct a systematic study of the impacts of the sustainable materials. The case scenarios were aimed at testing the personal and combined effects of Construction Waste (CW) as a partial substitute to either cement or sand, and Recycled Wastewater (RW) as a full substitute to potable mixing water.

The experimental matrix comprised the following cases:

1) Recycled Wastewater Control (RWC) (0% CW, 100% RW): A mix with 100% natural sand and cement, but using 100% Washed Wastewater to isolate the effect of the alternative water source.

2) 10CRW (10% Cement replacement, 100% RW): A mix where 10% of the cement by volume was replaced with CW and 100% RWr was used.

3) 20CRW (20% Cement replacement, 100% RW): A mix with a 20% volumetric replacement of cement by CW and 100% RW.

4) 25CRW (25% Cement replacement, 100% RW): A mix with a 25% volumetric replacement of cement by CW and 100% RW.

5) 20SRW (20% Sand replacement, 100% RW): A mix where 20% of the natural sand by volume was replaced with CW and 100% RW was used.

6) 40SRW (40% Sand replacement, 100% RW): A mix with a 40% volumetric replacement of sand by CW and 100% RW.

7) 10CNW (10% Cement replacement, 0% RW): A mix with 10% of cement replaced by CW but using 100% potable water. This case was crucial for isolating the effect of CW from the effect of RW.

3.4.2 Details of Specimens

Based on the preliminary studies and identification of an optimal control mixture, the actual experimental program was developed to investigate the results of Construction Waste (CW) and Recycled Wastewater (RW). The base composition of any mix was based on a high-density cementitious mix. The binding system consisted of CEM Type I cement and silica fume and a constant cement to silica fume (C/SF) ratio of 0.2, which also guaranteed a thick micro-filler effect and high pozzolanic activity. The water to binder (w/b) ratio was maintained at 0.167 in all combinations to allow the directly comparison of the effect of the replacement materials as the water content did not affect the comparison.The absolute volume method was used in calculating the mixture proportions. The target workability was achieved by adding a polycarboxylate -ether -based superplasticizer (Bestcon A71) in different percentages of the binder content. The unit content of each constituent material of control and replacement mixtures is shown in detail in Table 3.6. The table contains seven different cases among which are the control mixture with potable water, the wastewater control mixture, and different mixtures of cement and sand replacement with CW along with the RW.

Table 3.7 Mix Proportions with CW and RW

Mix		RWC	10CNW	10CRW	20CRW	25CRW	20SRW	40SRW
Contents	CEM I	932	830	830	738	692	932	932
	CEM II							
	Silica Fume	233	233	233	233	233	233	233
	Sand	980	970	970	970	970	784	588
	CW		158	158	185	231	159	319
	RW	164		164	164	164	164	164
	Water		164					
	Superplasticizer	52	52	52	52	52	52	52

	WB	0.167	0.167	0.167	0.167	0.167	0.167	0.167

[Notes on Nomenclature: Here, WB = Water-binder ratio, 10C/20C/25C = Cement replacement with CW percentage, 20S/40S = Sand Replacement with CW percentage, NW = Fresh Water]

3.5 Specimen Mould Preparation

For this study, two types of specimens were cast: 50 mm x 50 mm x 50 mm cube-shaped concrete specimens and 25 mm x 25 mm x 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 3.5. 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 3.5 :- Prepared Moulds for HSM mix

3.6 Casting Procedure of HSM

The casting process started by setting up the mixer machine. A sequence of systematic mixing of High-Strength Mortar (HSM) specimens was carried out using an electrically driven mechanical mixer in order to achieve compositional homogeneity. It was initiated by the introduction of the CEM Type I cement and silica fume into a dry batch mixture at low speed (140 ± 5 rpm) during 90 seconds. It was then mixed with saturated surface dry (SSD) sand and mixed an additional 90 seconds. Washed Wastewater or Potable water, as well as the superplasticizer was added, and The mixture was agitated at a medium speed (285 ± 10 rpm) in 2 minutes. The last process was high-speed mixing until the mixture was homogenous and workable, which was usually the sum of 10 to 15 minutes of total mixing time after which the fresh mortar was then moulded without delay.

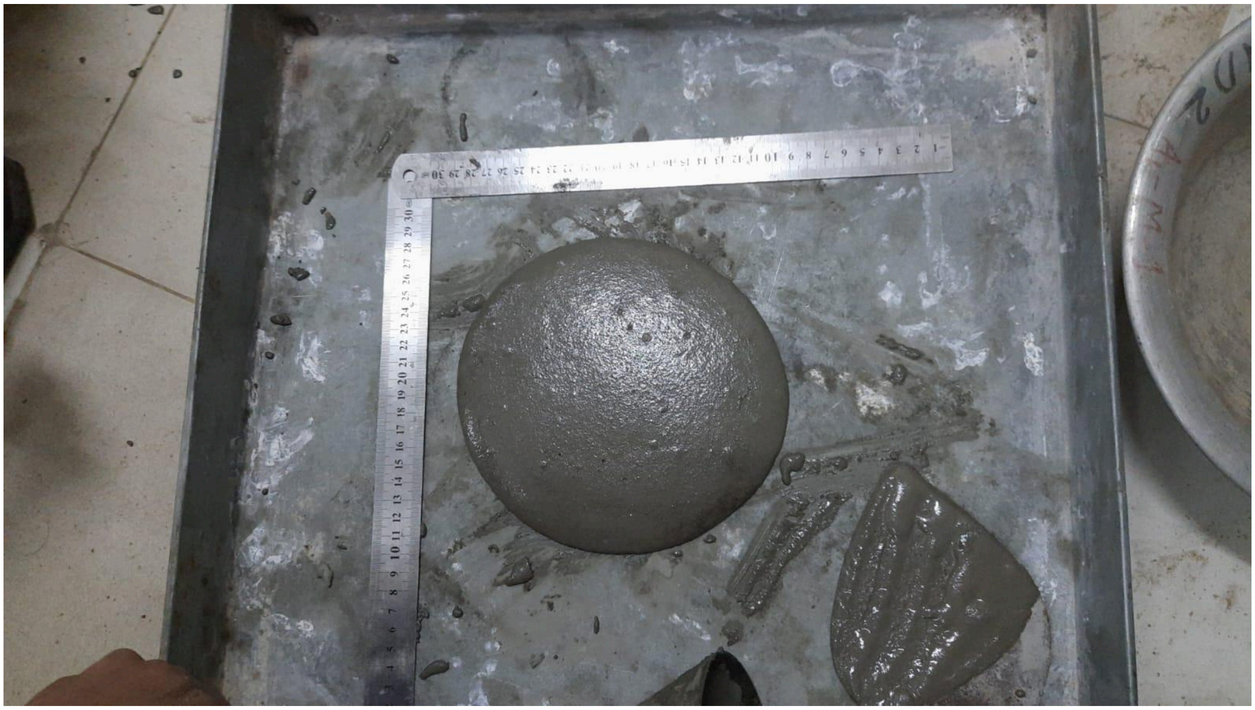

Figure 3.6 :- Casting of HSM Mix

3.6.1 Moulding of Concrete Cube Specimen

The cubic specimens were prepared according to ASTM C 109/109M standard. Firstly, one layer of concrete of 25mm thickness was placed in each cube section. Then the concrete layer was tamped 16 times in about 10 seconds for four rounds with a non-absorbent, wooden tamper. Each round was completed at right angles to the one before and 8 adjacent strokes covered the surface of the specimen. The pressure applied (i.e. tamping) was sufficient to ensure the mold was filled uniformly. After completing the tamping of the first layer the remaining space in the cubes were filled with concrete mixture and the method of tamping already described above was repeated. The top surface of the cubes was then smooth with trawl's flat side. Leveling of the surface was done with a steel scale.

Figure 3.7 :- Moulding of HSM Mix

3.6.2 Moulding of Concrete Shrinkage Specimen

Drying shrinkage behavior was tested with prismatic specimens having nominal size of 25 x 25 x 285 mm according to the specifications of ASTM C490. The experimental program consisted of seven different mix formulations with three replicate specimens being cast for each formula for a total of twenty-one shrinkage specimens to ensure statistical significance. Prior to casting, gauge studs were carefully placed at both ends of the molds, and all external joints were covered to cover any premature moisture loss. The fresh mortar was deposited in two roughly uniform layers, which were systematically compacted by means of a non-absorbent tamping rod, in order to provide a homogeneous density and remove possible voids, especially in critical areas adjacent to the gauge studs. 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. (Chen, 2021)

Figure 3.8 :- Moulding of HSM Mix for shrinkage

3.7 Curing of Specimens

The curing technique that was used in this research was in conjunction with water curing, and increased temperature curing (Chen, 2021). The cube specimens and shrinkage bar were initially put in water at room temperature to allow preliminary hydration and the development of strength after the demoulding process, the length change readings of the shrinkage bar were recorded respectively in between the curing process. The specimens were then placed in an oven to undergo further curing under higher temperatures of 70 o C and take 96 hours duration to undergo further hydration and strengthen the mechanical characteristics of the concrete. The objective of this curing regime was to maximize HSM specimen strength and durability. Upon the completion of the increased temperature curing process, the specimens were then carefully removed out of the oven and then put through a series of mechanical tests to test their performance.

Figure 3.9 :- Curing of Specimens

Figure 3.10 :- Increased temperature Curing of Specimens

3.8 Conducted Tests

The experimental program incorporated a comprehensive series of standardized tests to evaluate the mechanical and durability properties of the developed High-Strength Mortar (HSM) mixtures. These tests have been designed to quantify the effect of Construction Waste Fines (CW) and Recycled Wastewater (RW) on the performance characteristics of the material. The testing regime comprised compressive strength testing, sorptivity evaluation, and drying shrinkage evaluation with all procedures following strict compliance of established standards by the ASTM International in order to ensure reproducibility and reliability of the results

3.8.1 Compressive Strength Test

Compressive strength, which is defined here as the maximum value of the axial stress a material resists before failure, is a basic mechanical property relevant for cementitious composites. This parameter has prime importance since the structural constituents mainly counteract the compressive forces during service. In the current investigation compressive strength was determined according to the 50 mm cubic specimens in strict accordance to the specifications of the standard ASTM C 109. The testing protocol provided critical performance data under uniaxial compression, thus making it possible to achieve a quantitative evaluation of mechanical appropriateness of the developed high-strength mortar in structural applications. The Universal Testing Machine (UTM) was used to conduct the Compressive Strength test in the lab of Islamic University of Technology (IUT).

Figure 3.11:- Setup for Compressive Strength testing

3.8.2 Sorptivity Measurement

The sorptivity method was used to evaluate the transport properties of the HSM mixtures, which measures the rate of capillary rise by water uptake. This test is a key parameter to indicate the pore structure of the material as well as its susceptibilities to penetration by harmful substances [1]. The experimental protocol was performed according to ASTM C1585-20.

3.8.2.1 Sample Conditioning

Prior to testing, the cubic specimens of 50 mm were conditioned to a uniform initial moisture condition. After de-moulding, the specimens were submitted to a combined curing process, i.e., water curing for 72 h to achieve sufficient hydration and thermal curing in an oven at 70°C for 96 h. The thermal treatment that was produced eliminated all evaporable water and thus provided a dry baseline condition necessary for accurate absorption measurements.

Figure 3.12:- Specimen Setup for Sorptivity Coefficient Measurement as per ASTM 1585- 13

3.8.2.2 Test Procedure and Analysis

After conditioning and cooling to ambient temperature, the lateral surfaces of the specimens were covered with impermeable tape such that only the bottom surface was exposed to ingress of water. The top was covered with a plastic film in order to prevent evaporation. The mass of each prepared specimen was measured prior to its placement in a shallow tray, having its exposed surface in contact with a 1-3mm deep water film and mass changes were recorded at pre-defined time intervals. The experimental setup is illustrated in Figure 3.12.

The sorptivity coefficient which is the rate of water absorption was calculated from the slope of a straight line between cumulative absorption of water and square root of time. The governing equations for this analysis are the following [2]:

The cumulative absorption per unit area of the inflow surface, I (mm), was calculated as:

$$I = S_i + B \tag{3.2}$$

$$S_i = I / \sqrt{t} \tag{3.3}$$

$$I = m / (d \times A) \tag{3.4}$$

Here,

I = water absorption (mm), S_i = Sorptivity coefficient (mm/$\sqrt{sec}$), t = time (sec), m = change in specimen mass in grams as per specific time, 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.

The sorptivity coefficient, S (mm/$\sqrt{s}$), was then determined from the linear portion of the plot of I versus the square root of time $\sqrt{t}$ ($\sqrt{s}$) where *B* is the y-intercept of the best-fit line (mm).

This methodology provides a reliable measure of the capillary porosity and microstructural refinement of the HSM, critical for evaluating its long-term durability.

3.9 Drying Shrinkage of HSM

Drying shrinkage behaviour of High-Strength Mortar (HSM) mixtures was measured quantitatively in order to assess their dimensional stability in drying conditions. The test method was in strict conformity with ASTM C596 - 07, "Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement." Prismatic specimens measuring 25 mm 25 mm 285 mm were made in accordance with ASTM C490-07, "Standard Specification for Apparatus for Use in Measurement of Length Change of Hardened Cement Paste, Mortar, and Concrete." Demountable stainless steel gage studs were cast into the center of each face of the ends as fixed reference locations for accurate length-change measurements. After curing the specimens in the molds for 24 h, the specimens were demolded and the initial reference length (Li) was immediately measured with a calibrated length comparator to an accuracy of 0.001 mm. Subsequently, the samples were kept in a controlled environment chamber at a temperature of (23 ± 2) °C and relative humidity of (50 ± 4%). Length change measurements were taken at 1, 2, 3, 4, 5, 6 and 7 days post-demolding. Length change measurements were taken at 1, 2, 3, 4, 5, 6 and 7 days post-demolding.

The drying shrinkage strain, ϵ_{sh} (µm/m), for each measurement interval was calculated using the following relationship:

$$\epsilon_{sh} = (L_i - L_t) / L_g * 10^6 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..3.5)$$

Where,

L_i = initial reference length of the specimen (mm)

L_t = length of the specimen at time t (mm)

L_g = nominal gauge length (285mm)

The shrinkage behaviour of a High Strength Mortar (HSM) mixtures was thoroughly measured to determine the dimensional stability of the HSM mixtures under desiccation. The experimental procedure was in perfect accordance with ASTM C596-07, "Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement."For statistical robustness and to better define the contribution of compositional variables on HSM shrinkage behaviour, a total of twenty-one samples, three replicates for each of the seven different mix designs were evaluated. The systematic approach provided a rich dataset which was used to analyse the impact of washed waste fines and washed wastewater on long term volumetric stability of the material.

Figure 3.13: Setup for measuring Shrinkage

Chapter 4: Results and Discussion

4.1 General

This chapter presents a detailed discussion of the experimental data presented from a systematic study of the mechanical and durability properties of High-Strength Mortar (HSM) with Construction Waste (CW) and Recycled Wastewater (RW). The presented data form the empirical foundations for the evaluation of the potential of these green materials as partial replacements of the conventional constituents in the production of high performance cementitious composites.

The results are presented in a sequential manner which first determines a performance baseline from the analysis of the trial mixes before arriving at an optimum control mix. In this connection, the effect of CW as a partial substitute for both cement and sand, separately and in combinations with RW, is investigated rigorously thereafter. In addition to this, the key performance indicators such as slump, compressive strength, sorptivity and drying shrinkage are addressed in detail. A critical evaluation of the results obtained with reference to the current literature is presented, focusing especially on the understanding of the mechanisms (e.g. filler effects, pozzolanic reaction, microstructural modification) that can explain the phenomena observed.

In this combined synthesis of the results and discussion an attempt is made to provide a clear understanding of the structure-property relationships that control the performance of the sustainable HSM formulations developed in this study.

4.2 Compressive Strength Test

The compressive strength development of High-Strength Mortar (HSM) mixtures incorporating Construction Waste (CW) and Recycled Wastewater (RW) is systematically evaluated. The results demonstrate distinct behavioral patterns based on replacement strategy and percentage, as detailed in Table 4.1 and illustrated in Figures 4.1 and 4.2.

Table 4.1 Compressive strength results of HSM mixtures

Mixture	Compressive Strength (MPa)	Normalized with RW Control	Normalized with ACI 363R
RW Control	91.3	1	1.66
10CRW	90	0.98	1.64
20CRW	70.6	0.77	1.28
25CRW	60.3	0.66	1.09
20SRW	91.6	1	1.67
40SRW	91.7	1	1.67
10CNW	72.9	0.79	1.33

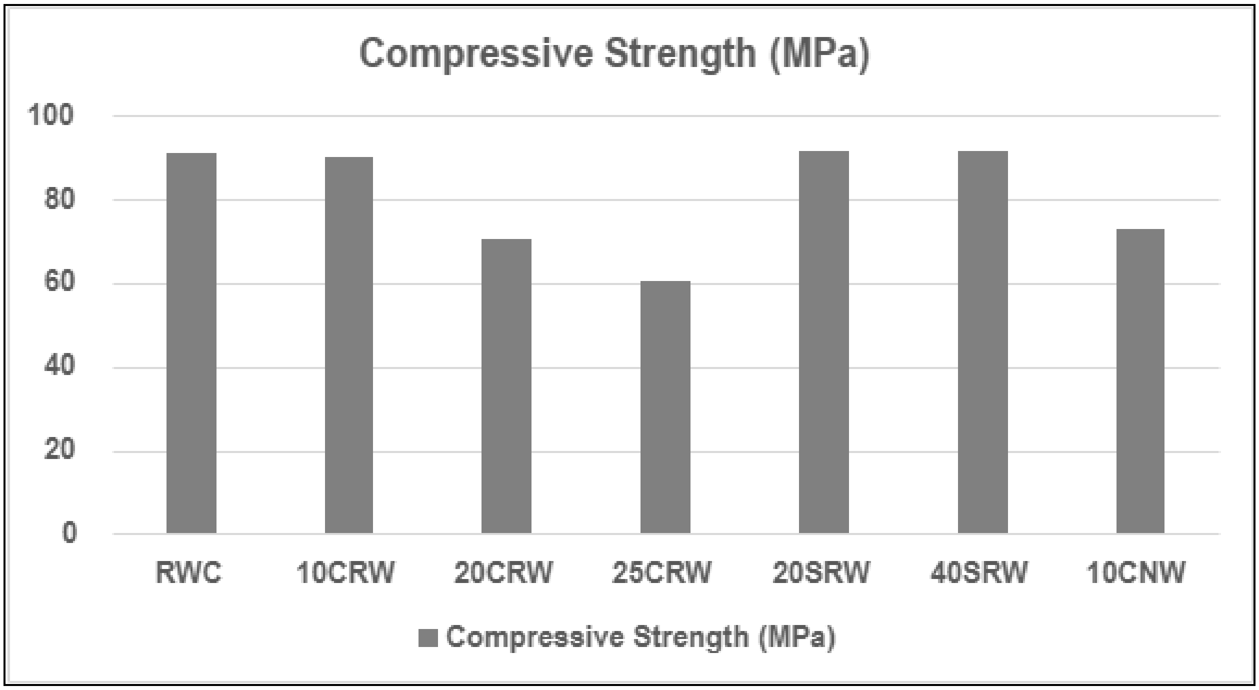

Figure 4.1 :- Average 7 days Compressive Strength test Results

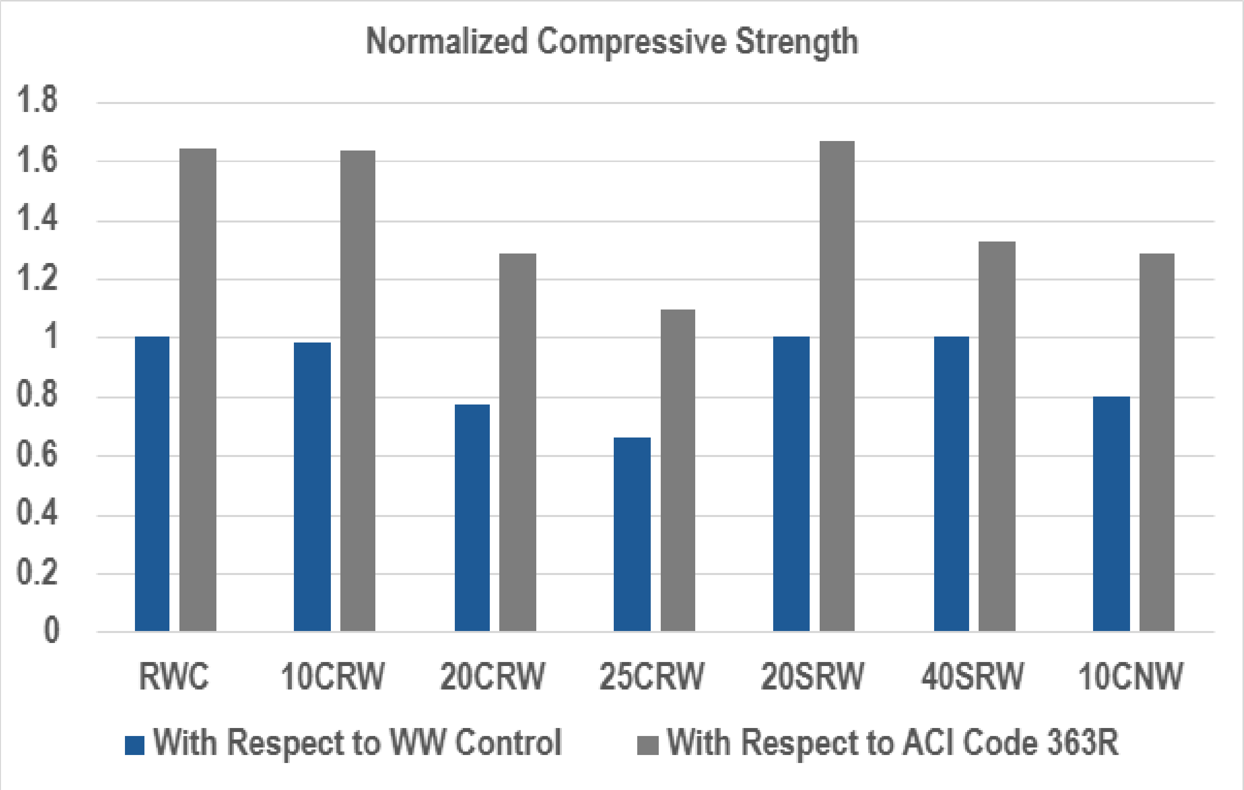

Figure 4.2 :- Normalized Compressive Strength Results

4.2.1 Absolute Compressive Strength Performance

The compressive strength results, illustrated in Figure 4.1, demonstrate significant variations based on replacement type and percentage. The RW Control mixture established the baseline performance at 91.3 MPa, confirming that washed wastewater alone does not compromise the mechanical properties of HSM. The cement replacement series showed a progressive strength reduction with increasing CW content, from 90.0 MPa (10CRW) to 60.3 MPa (25CRW), indicating a clear dependency on cement content. In contrast, sand replacement mixtures maintained exceptional strength levels, with both 20SRW (91.6 MPa) and 40SRW (91.7 MPa) performing comparably to the control mixture, demonstrating the effectiveness of CW as a fine aggregate replacement.

4.2.2 Normalized Performance Relative to Control Mix

Figure 4.2 presents the normalized compressive strength relative to the RW Control mix, providing a clear comparison of the relative performance of each mixture. The sand replacement mixtures (20SRW and 40SRW) maintained 100% of the control strength, indicating no adverse effects on mechanical performance even at 40% replacement level. The cement replacement mixtures showed a progressive decrease in normalized strength, with 10CRW maintaining 98% of control strength, while 20CRW and 25CRW dropped to 77% and 66% respectively. The 10CNW mixture, incorporating CW with normal water, showed 79% of control strength, highlighting the beneficial interaction between CW and washed wastewater.

4.2.3 Compliance with ACI 363R Standards for High-Strength Concrete

ACI 363R-92 "State-of-the-Art Report on High-Strength Concrete" establishes guidelines and requirements for concrete mixtures achieving compressive strengths above 41.4 MPa (6000 psi). The code provides comprehensive specifications for materials selection, mix proportioning, and testing procedures for high-strength concrete applications. According to ACI 363R, high-strength concrete typically ranges from 41.4 MPa to 138 MPa (6000 to 20,000 psi), with specific attention to mixture design, material quality, and curing conditions.

All mixtures developed in this study comfortably exceeded the minimum threshold for high-strength concrete as per ACI 363R, with normalized values ranging from 1.09 to 1.67 times the code requirements (Figure 4.3). The RW Control mixture achieved 166% of the minimum requirement, demonstrating excellent compliance with high-strength concrete specifications. The sand replacement mixtures (20SRW and 40SRW) showed the highest compliance levels at 167% of the ACI 363R requirement, indicating that these sustainable mixtures not only maintain mechanical performance but actually enhance compliance with industry standards.

4.2.4 Control and Reference Mixes:

RW Control (0% CW, 100% RW): The control mixture with 100 percent of the washed wastewater had a compressive strength of 91.3 MPa, which established the baseline performance of all the comparative analyses. This finding proves the practicability of washed wastewater as a total substitute of potable water in the production of HSM.

10CNW (10% Cement replacement, 0% RW): In this mix, 10% cement was substituted by CW, however, with potable water, the mix produced a strength of 72.9 Mpa. This is a 20% decrease of the RW control and it isolates the impact of the cement dilution by CW without the influence of washed wastewater.

4.2.5 Cement Replacement with CW and RW

10CRW (10% Cement replacement, 100% RW): A slight decrease in the strength to 90.0 Mpa was measured, which was 98.6% of the control strength. This implies that at low replacement volumes, there is virtually no compensation of the cement dilution by the filler effect and possible latent hydraulicity of CW.

20CRW (replacement of cement 20 percent, 100 percent RW): There was a serious reduction in strength to 70.6 Mpa, which is equivalent to 77.3 percent of the control. This suggests that at a certain critical level (10-20 percent) the decrease in the clinker content has a more pronounced effect to weaken the cementitious matrix.

25CRW (25% Cement replacement, 100% RW): The maximum cement replacement produced the lowest cement strength of 60.3 Mpa (66.0% of control), which indicates that the negative trend was maintained. The mechanism that appears to govern volumetric movement of cementitious material by less-reactive CW particles is the volumetric movement of the cementitious material.

4.2.6 Sand Replacement with CW and RW

20SRW (20% Sand replacement, 100% RW): This blend gave a strength of 91.6 Mpa which was almost the same as the control (100.3%). It proves that a part of fine aggregate may be replaced by CW without interfering with the structural integrity of the mortar.

40SRW (40% Sand replacement, 100% RW): The mixture had a strength of 91.7 Mpa (100.4% of control) even at a high replacement level. This implies that the smaller CW particles increase the skeleton aggregate particle packing which could result in a denser microstructure that compensates for a minor loss of strength.

4.2.7 **Critical Analysis of Replacement Strategies**

The normalized analysis reveals a fundamental finding regarding replacement strategies. Sand replacement retains superior mechanical performance even at 40% replacement level, whereas cement replacement above 10% dramatically lowers compressive strength. This behaviour is explained by the micro-filling effect of CW particles, which improves the interfacial transition zone and increases particle packing density when used in place of sand. On the other hand, replacing cement directly lowers the matrix's binding capacity, which results in a strength decrease proportionate to the replacement percentage.

With its high waste material utilisation (40% CW + 100% RW), maintained mechanical performance, and exceptional compliance with ACI 363R standards, the 40SRW mixture is the most sustainable formulation. This combination represents a major breakthrough in green construction technology and shows that sustainable construction methods can be used without sacrificing structural performance.

Every tested mixture remained in compliance with ACI 363R specifications, confirming that they are appropriate for structural applications requiring high-strength concrete. The potential for broad use of these sustainable mixtures in the construction sector is highlighted by the successful integration of industrial byproducts while upholding code compliance.

4.3 Sorptivity Test Results and Analysis

4.3.1 General

The sorptivity test measures the rate of water absorption in concrete through capillary suction, a key indicator of potential durability. For each mixture, the average water penetration depth (I avg in mm) from multiple samples was plotted against the square root of time (√s). The slope of the best-fit line through the initial, linear portion of this data represents the Sorptivity or Absorption Coefficient (S). The following sections provide a detailed, mix-by-mix analysis of these scatter plots.

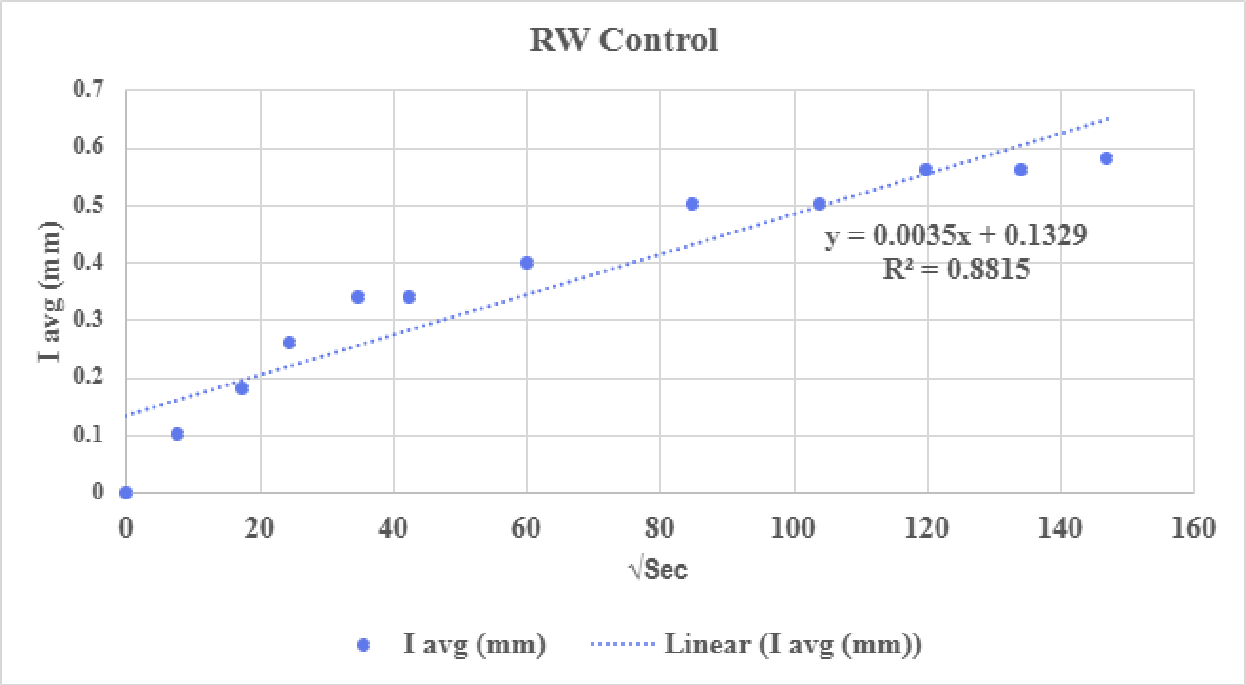

Figure 4.3 :- Water Absorption(I) vs √Sec for RW Control mix

4.3.2 RW Control Mix

Data Range & Linearity: From Figure 4.3 the data for the RW Control mix shows a strong and consistent linear relationship from the first measurement at √t = 7.75 √s up to approximately √t = 60 √s.As anticipated, the rate of absorption starts to drop after this because the capillary suction drive is diminished. The linear phase is clearly defined.

Scatter and Consistency: There is very little scatter in the data points, which suggests that the two tested samples are very consistent. There is a clear trajectory and a smooth transition from I=0.1 mm to I=0.4 mm.

Slope Determination: The data points from the first linear phase (t = 0 to 60 s) would be used to compute the best-fit line. The reported sorptivity coefficient of S = 0.0035 mm/√s is the consequence of a precise and dependable slope calculation, as indicated by the high consistency between samples. All other mixtures are compared to this plot as the standard.

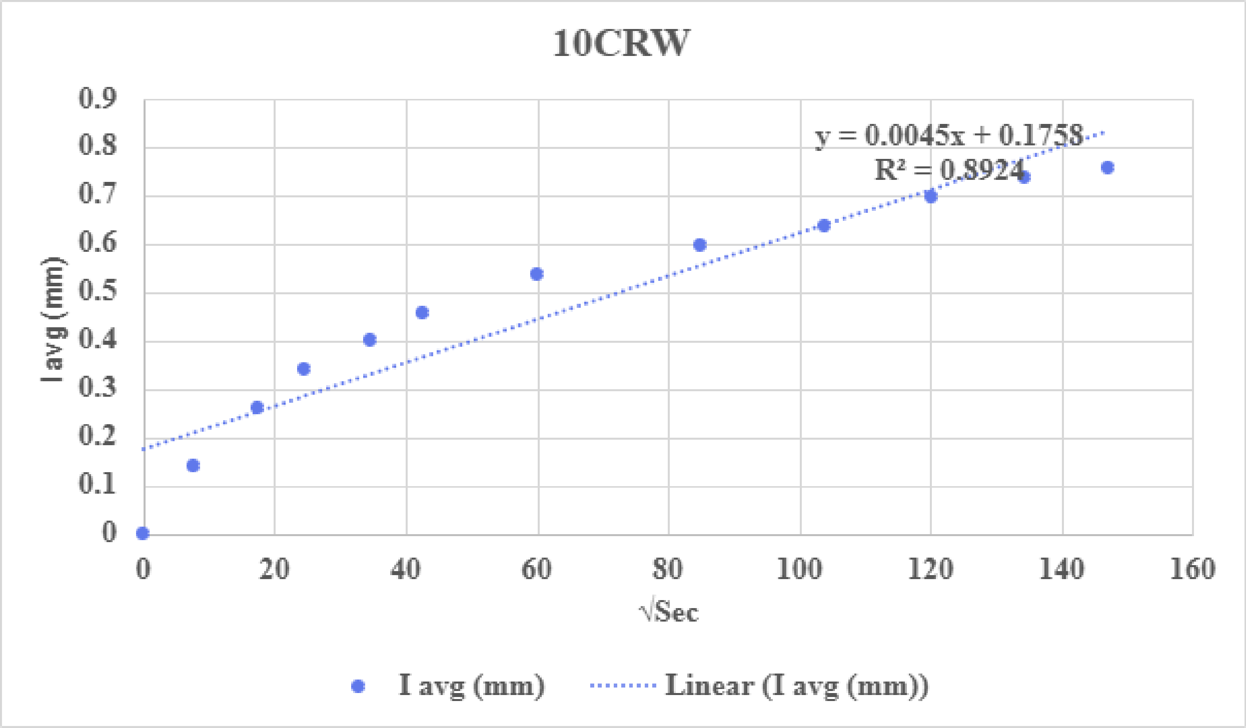

Figure 4.4 :- Water Absorption(I) vs √Sec for 10CRW mix

4.3.3 10CRW Mix (10% Cement Replacement with CW and Washed Wastewater)

Data Range & Linearity: Looking at the Figure 4.4 the 10CRW mix also displays a clear linear trend in the initial stage. However, the absorption values (I avg) are consistently higher than the control at nearly every time interval. For example, at √t = 60 √s, I avg is 0.54 mm compared to 0.4 mm for the control

Scatter and Consistency: The data shows slightly more scatter than the control mix, particularly in the mid-range (e.g., between √t = 34.64 √s and √t = 60 √s), but the overall trend remains clear. This suggests minor variability between samples but does not obscure the linear relationship.

Slope Determination: The best-fit line for this dataset would have a steeper slope than the control. The linear regression of the initial data points confirms a higher rate of water absorption, yielding a sorptivity coefficient of S = 0.0045 mm/√s. This indicates that 10% cement replacement with CW increases capillary porosity.

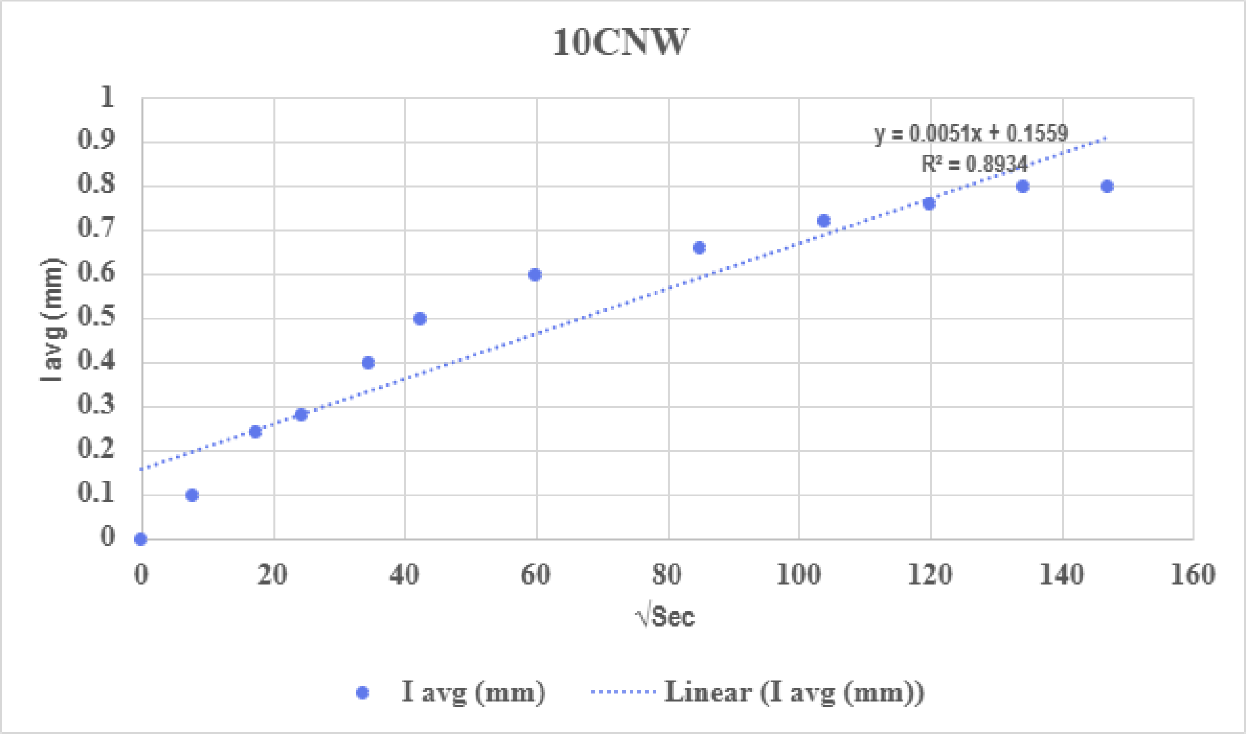

Figure 4.5 :- Water Absorption(I) vs √Sec for 10CNW mix

4.3.4 10CNW Mix (10% Cement Replacement with CW and Normal Water)

Data Range & Linearity: Deriving from the Frigure 4.5 this mix exhibits the highest absorption values of all the cement replacement series. The linear trend is pronounced and persists through the measured time range. The I avg values are significantly higher; at √t = 60 √s, absorption reaches 0.6 mm.

Scatter and Consistency: There is some observable scatter, especially at later time intervals (e.g., between √t = 84.85 √s and √t = 146.97 √s), where the data points do not form a perfectly smooth line. This could indicate higher variability in the pore structure of these samples.

Slope Determination: Despite the minor scatter, the strong linear trend allows for a reliable slope calculation. The best-fit line through this data has the steepest slope among the cement replacement mixes, resulting in the highest recorded sorptivity coefficient of S = 0.0051 mm/√s. This highlights the significant impact of both cement replacement and the type of curing water on porosity.

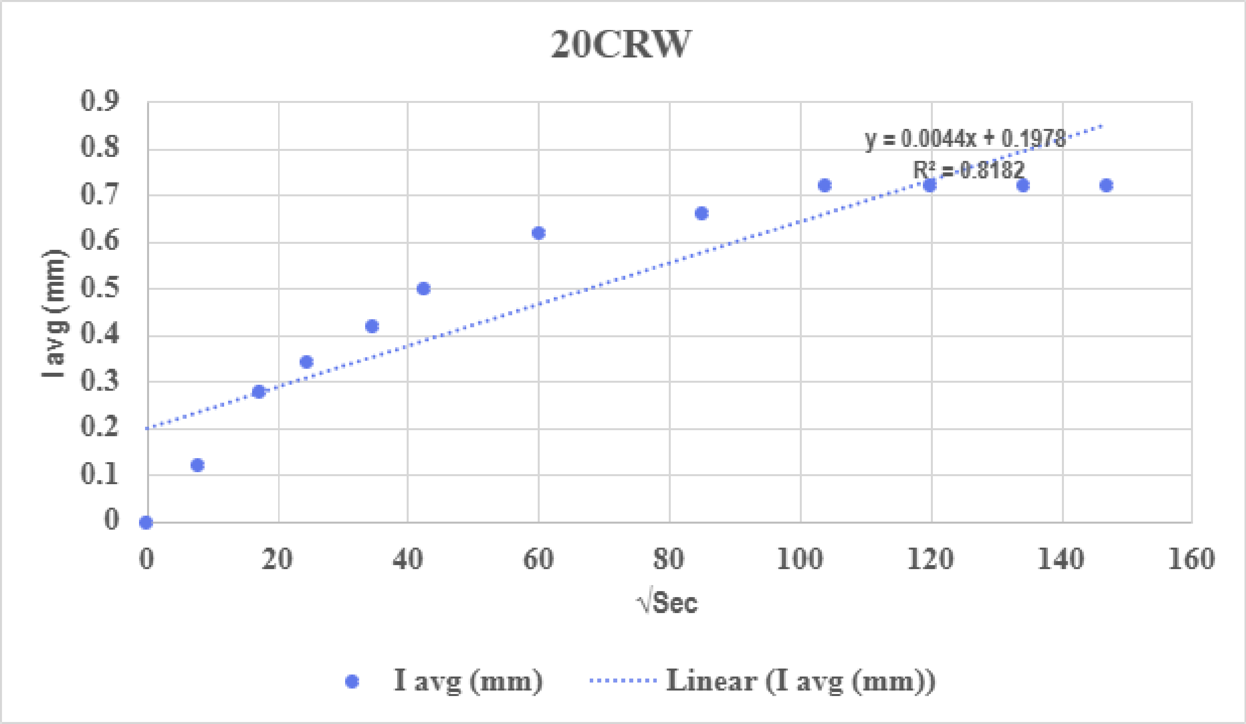

Figure 4.6 :- Water Absorption(I) vs √Sec for 20CRW mix

4.3.5 20CRW Mix (20% Cement Replacement with CW, Waste Water)

Data Range & Linearity: Originating from the Figure 4.6 mix 20CRW show a linear trend but with more pronounced scatter in the data compared to the 10CRW mix. The absorption values lie between those of the 10CRW and the control mix.

Scatter and Consistency: This mix displays the most significant scatter among all mixtures. For instance, at √t = 24.49 √s, I avg is 0.28 mm, but the progression to adjacent points is not perfectly smooth. This higher variability might suggest less uniformity in the capillary pore network caused by the higher cement replacement level.

Slope Determination: The best-fit line would be influenced by this scattered data. The calculated slope is less steep than that of 10CRW, leading to a sorptivity coefficient of S = 0.0044 mm/√s. The non-linear trend (higher replacement leading to lower sorptivity than 10% replacement) is intriguing and may point to pore refinement at 20% replacement, albeit with greater sample variability.

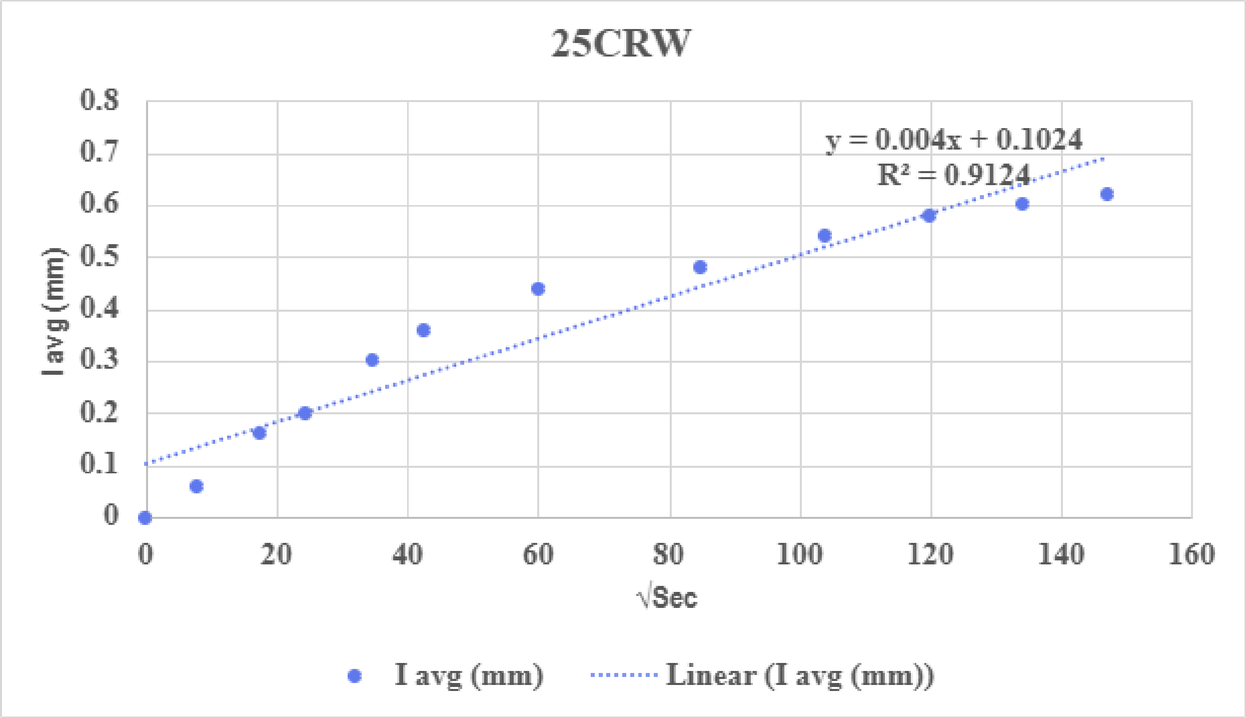

Figure 4.7 :- Water Absorption(I) vs √Sec for 25CRW mix

4.3.6 25CRW Mix (25% Cement Replacement with CW and Washed Wastewater)

Data Range & Linearity: Observing the data from the Figure 4.7 the 25CRW mix returns to a tighter, more linear progression after the scatter seen in the 20CRW mix. The absorption values are lower than both 10CRW and 20CRW, indicating a further reduction in capillary suction.

Scatter and Consistency: The data points show good consistency and low scatter, forming a clear and well-defined linear path. This suggests a more homogeneous microstructure at this replacement level compared to 20CRW.

Slope Determination: The best-fit line for this dataset has a gentler slope than the 10CRW and 20CRW mixes. The linear regression confirms this, resulting in a sorptivity coefficient of S = 0.0040 mm/√s. This supports the hypothesis of increased pore refinement at higher cement replacement levels, which reduces capillary flow.

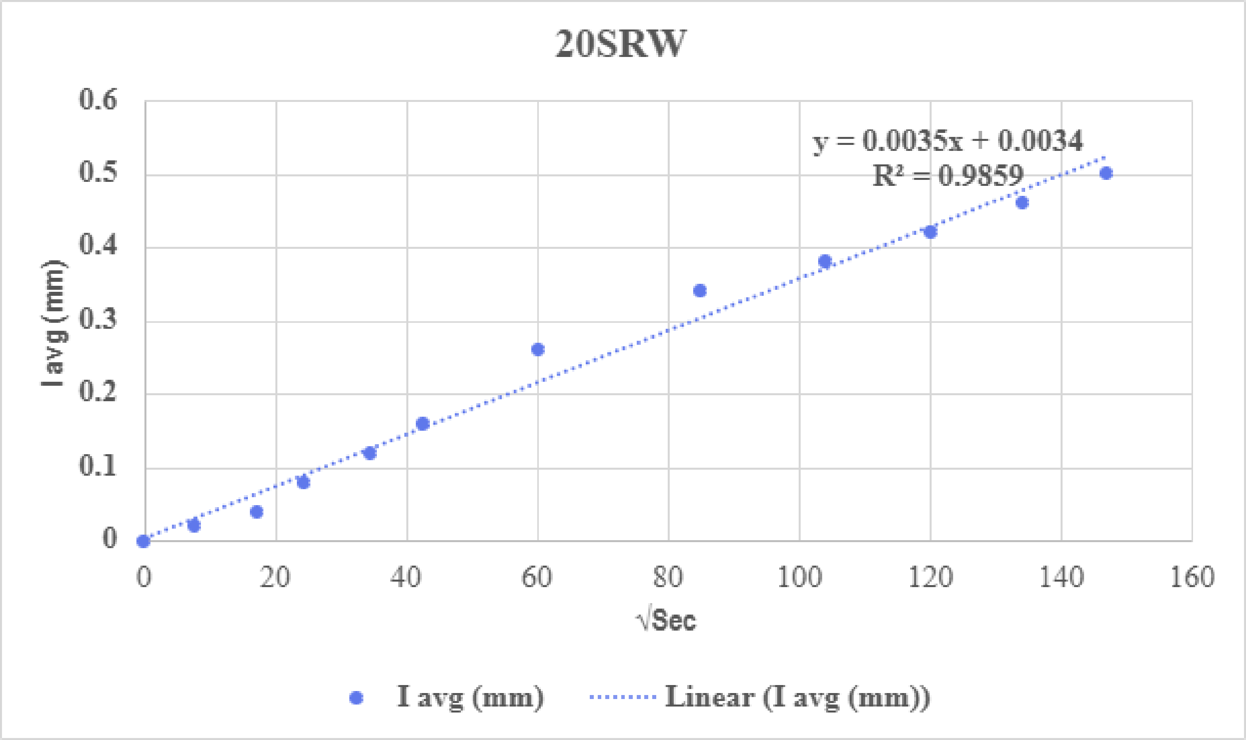

Figure 4.8 :- Water Absorption(I) vs √Sec for 20SRW mix

4.3.7 20SRW Mix (20% Sand Replacement with CW and Washed Wastewater)

Data Range & Linearity: The scatter plot in Figure 4.8 mix 20SRW is remarkable for its very low absorption values and extremely tight data grouping. The I avg values are minimal, reaching only 0.5 mm even at √t = 146.97 √s.

Scatter and Consistency: The data exhibits exceptionally low scatter, with data points forming a near-perfect straight line. This indicates a very consistent and impermeable pore structure between samples.

Slope Determination: The best-fit line for this data is very shallow. The slope is calculated to be S = 0.0035 mm/√s, which is identical to the RW Control mix. This graphically demonstrates that replacing 20% of sand with CW has a negligible effect on the capillary water absorption of the concrete.

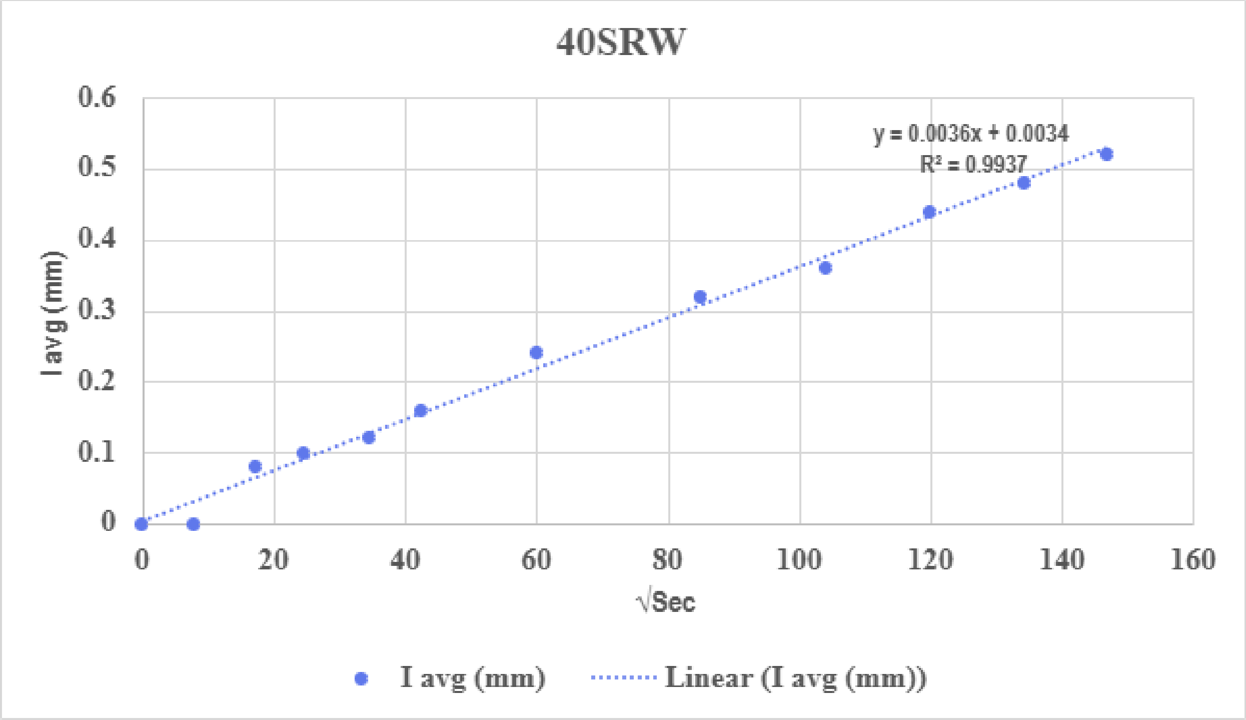

Figure 4.9 :- Water Absorption(I) vs √Sec for 40SRW mix

4.3.8 40SRW Mix (40% Sand Replacement with CW and Washed Wastewater)

Data Range & Linearity: Similar to the 20SRW mix from the Figure 4.9, the 40SRW data shows low absorption and a strong linear trend. The values are marginally higher than the 20SRW mix but still very close to the control.

Scatter and Consistency: The data is consistent with very little scatter, indicating a homogeneous material. The progression of I avg over time is smooth and predictable.

Slope Determination: The best-fit line is almost as shallow as that of the control and the 20SRW mix. The calculated sorptivity coefficient is S = 0.0036 mm/√s, confirming the trend that sand replacement with CW, even at 40%, does not adversely affect the sorptivity property of the concrete.

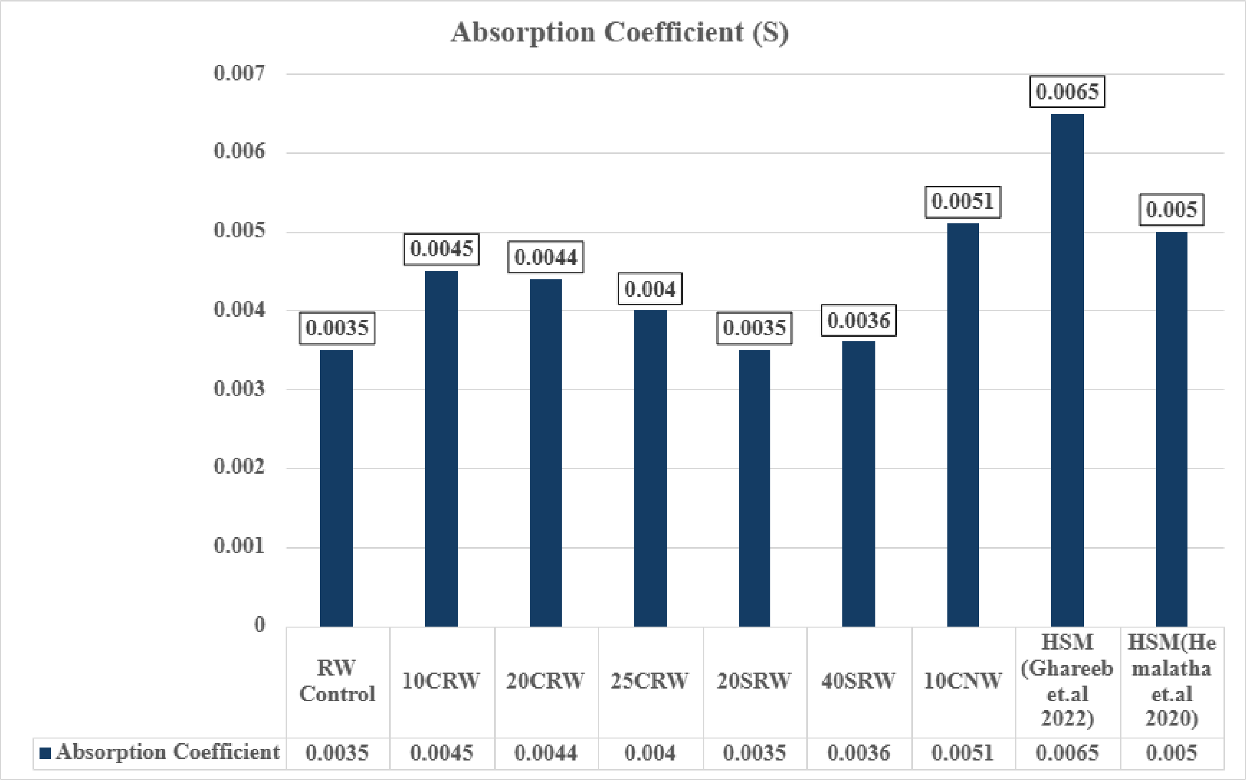

Figure 4.10 :- Absorption Coefficient (S) vs mix cases and comparison from previous study

4.3.9 Comparative Assessment of Sorptivity Performance of the Mixes

The sorptivity performance of the various concrete mixes gives important information about the impacts of different replacement methods on a critical durability parameter, the capillary water absorption. To make the findings more understandable, the results are compared with the established literature values for high-strength concrete.

4.3.9.1 Performance of Control and Cement-Replacement Mixes

The RW Control mix, produced with waste water, set a strong standard with a sorptivity coefficient of 0.0035 mm/√s. This number is within the limits for high-performance concrete which means that there is a very dense microstructure with almost no capillary porosity.

Mixed cement replacement with Construction Waste (CW) usually resulted in a higher sorptivity. The 10CRW mix (10% cement replacement with waste water) indicated a 29% increase in sorptivity (0.0045 mm/√s), on the other hand, the 20CRW mix (20% replacement) showed a 26% increase (0.0044 mm/√s). This pattern is consistent with literature, where partial cement replacement by different supplementary cementitious materials tends to increase porosity first because of a dilution effect and only later significant pozzolanic reactions happen

The performance of the 10CNW mix (10% cement replacement with normal water) was the most important discovery in this category, and it had a sorptivity coefficient of 0.0051 mm/√s. This was a 46% increase from the control. This might indicate that the chemical composition of the waste water used in other mixes has helped the formation of capillary pores to some extent. If the high strengths mixes (HSM) from Ghareeb et al. (2022) and Hemalatha et al. (2020), which have reported the coefficients of 0.0065 mm/√s and 0.005 mm/√s, are taken into account, the 10CNW mix is able to compete with conventional high-strength concrete in terms of performance but it still does not surpass the waste-water-based control mix developed in this study.

4.3.8.2 Performance of Sand-Replacement Mixes

On the other hand, replacing part of the sand with CW was a very efficient method. The 20SRW and 40SRW mixes both showed excellent performance with sorptivity coefficients of 0.0035 mm/√s and 0.0036 mm/√s, respectively. These figures are almost the same as the RW Control mix and are higher than the conventional high-strength concrete values from the literature.

The pozzolanic effect has been proposed as the reason for these performance levels as the CW particles not only make the concrete matrix denser but also do not chemically interfere with the cement hydration process. Therefore, the results indicate that CW can be safely adopted as a sand replacement material up to 40% without negatively impacting the impermeability of the concrete, which is a breakthrough in the context of eco-friendly concrete manufacturing..

4.4 Drying Shrinkage Test Results

4.4.1 General

The drying shrinkage performance of High-Strength Mortar (HSM) mixtures was experimentally studied for seven days in order to determine the dimensional stability implications of the addition of Construction Waste (CW) and Recycled Wastewater (RW). All results, presented in microstrain (µm/m), give important information on the long-term performance and possible cracking susceptibility of the sustainable mortar formulations. All values are the average of three replicate samples for each mix design.

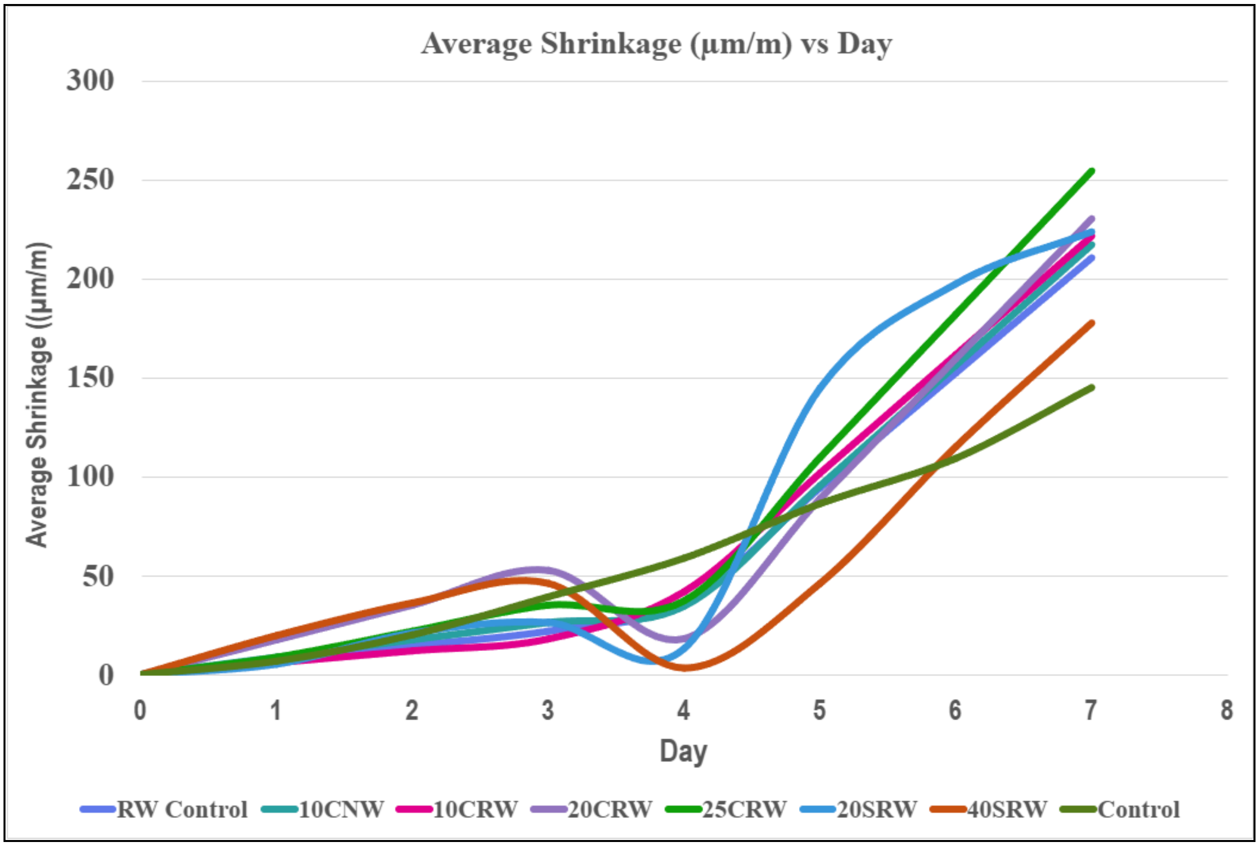

Figure 4.11 :- Average Shrinkage (µm/m) vs Day for different mix cases

4.4.2 Review of Drying Shrinkage of Cement Replacement Mixes.

From Figure 4.11 the shrinkage behavior of the cement replacement series has been found out to be complex, which fluctuated significantly with the replacement percentage. The final shrinkage value of 10CRW mixture (10% cement replacement) was 221.49 µm/m, which showed a moderate increment of 5.2% compared to RW Control. This would imply that low-volume cement replacement has very low impact on the shrinkage behavior.

However, drying shrinkage increased significantly with increasing replacement levels. The significant effect was obtained in the 25CRW mixture with 254.38 µm/m (20.8% increase) while the 230.26 µm/m (9.4% increase) effect was observed in the 20CRW. This increment is due to the reduction of cementitious content and its modification of the microstructure of the paste and the consequent increment of the capillary pore pressure during drying. As a result of cement dilution, the porosity would be higher, which in turn can make moisture migration easier, and hence the shrinkage strains would be higher.

4.4.3 Review of Drying Shrinkage of Sand Replacement Mixes.

The shrinkage properties of the sand replacement mixtures were different significantly from those of the cement replacement mixes. The shrinkage value of 20SRW mixture (20% sand replacement) was 233.68 µm/m, which is 11.0% larger than the control. This implies some rearrangement of the aggregate skeleton but the effect is within tolerable bounds.

From the statistical analysis of all the tested mixtures, it was found that the mixture containing 40% sand replacement (40SRW) had the best shrinkage performance with a final value of 177.69 µm/m. This is a substantial decrease of 15.6% over the RW Control. The improved performance is explained by the micro-fill effect of the components of CW particles, which increase particle packing density and lower capillary porosity. The finer aggregate has a finer pore structure which inhibits movement of moisture and reduces drying shrinkage.

4.4.4 Comparison Study with RW Control Mixture

The shrinkage behaviour of RW Control mixture was used as the baseline after seven days, which was 210.5 u e. Comparative analysis shows that there is a decisive difference between the two replacement strategies. Whereas, cement replacement typically increased percentage shrinkage with proportion of cement replacement, sand replacement especially at high replacement percentages exhibited better dimensional stability.

The final shrinkage of the 10CRW mixture (10% cement substitution with normal water) was 217.1 μm/m which is 3.1% greater than the RW Control but lower than its wastewater counterpart (10CRW). It was found that the shrinkage mechanism may be affected by the chemical composition of washed wastewater, however, the replacement strategy remains as the main factor.

The technical superiority of using CW as a sand replacement material is confirmed in the most effective performance of the mixture 40SRW. By having dimensional stability and using large quantities of waste materials, this mixture is a compromise between environmental concerns and long-term performance requirements to contribute to the sustainable mortar development.

The results show that choosing appropriate replacement method and percentage is an efficient way to control the drying shrinkage of sustainable HSM and the sand replacement at 40% level proves to be most promising method for the applications in which dimensional stability is very selective.

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

The main aim of the current study was to check the possibility of using Construction Waste (CW) and Recycled Wastewater (RW) as sustainable aggregates in high-strength mortar (HSM). In this chapter, the results of the experimental results and discussions described in Chapter 4 are summarized, providing definite conclusions and specific suggestions for future research.

Several important conclusions are drawn from the experimental results. First, the complete replacement of drinking water mixing with RW is completely viable. The compressive strength of RW-Control mix was 91.3 MPa indicating that the use of the alternative water source does not compromise the mechanical properties of HSM and that the use of alternative water can contribute to freshwater conservation in the concrete industry, and thus global sustainable water-management strategies (Miller 2020).

A systematic series of mix designs was developed to determine the effect of CW used in two different replacement schemes: a partial replacement of cement and a partial replacement of natural sand. Results showed that there was a large difference in performance depending on the strategy selected. Substitution of cement with CW led to the gradual decrease in compressive strength with the increase of substitution percentage, due to the dilution of the main cementitious binder which was confirmed by other research that investigated the incorporation of fine materials as cement replacements (Al Menhosh, 2018). On the other hand, the sand-replacement mixes presented good performance. The compressive strengths of both 20SRW and 40SRW mixtures were very close to that of the control mix, which confirmed CW to be an effective micro-filler that increased the packing density of aggregates without adversely affecting the binding matrix.

The conclusion is further supported by the durability test. Sorptivity coefficients for the sand-replacement mortars were found to be practically equal to the sorptivity of the RW- Control so as to show that replacement of up to 40% of sand with CW does not increase the capillary porosity or wetting of the mortar. The drying shrinkage, the dimensional stability of the parenchyma, gave significant information. Among all mixtures, the 40SRW mixture had the most desirable performance with final shrinkage value lower by 15.6% than the control. This high performance is explained by the fine pore structure due to the micro-porosity filling effect of the fine CW particles which reduces capillary pore pressure during drying (Neville, 2011).

The results of this research work are a major contribution to the field of sustainable construction materials. They underline the great significance of the application strategy for industrial by-products. The investigation finds that the 40SRW mixture that contains 40% CW as a sand substitute and 100% RW is the best sustainable mixture. This innovative circular strategy allows achieving a high mechanical performance and durability while optimum use of industrial waste, thus reducing the environmental footprint of natural sand extraction and wastewater disposal, and strengthening the concept of a circular economy (Ghisellini et al. 2016).

5.2 Recommendations

It can be concluded that the continuous research is needed in order to bring out the full potential of using RW and CW in high performance cementitious composites. Subsequent research should include an extensive long-term durability study including a thorough study of resistance to chloride-ion penetration, sulfate attack, and carbonation using standard test procedures such as ASTM C1556 and ASTM C1202. Such tests will provide a more detailed knowledge of the material's performance during long service life.

Another focus area involves the corrosion resistance of steel reinforcement which is present in the sustainable HSM. The development of corruption tests in microcells according to the methodology described by Andrade and Alonso (1996) is highly recommended, in prism specimens containing a steel reinforcing bar. The accelerated test will provide important initiation and propagation data on corrosion rate, directly testing the ability of the material to protect the steel reinforcement, the main concern for the structural use of any concrete mixture using alternative materials.

In order to demonstrate the applicability and validity of this sustainable HSM under realistic loading conditions, an attempt is made to validate its applicability and efficiency on small scale beams or columns. Further mechanical characterization such as flexural strength, modulus of elasticity, and bond strength with reinforcement should be conducted in order to assure the structural reliability of the material as well as its optimization for engineering practice.

In addition, microstructural features and hydration products should be analyzed in more detail by using advanced analytical techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD). These tests can provide insight into the mechanisms behind the observed performance, for instance the pozzolanic activity of CW and interaction with the cement matrix, and hence opportunity for material improvement.

Future work should also investigate variance of source materials. Available literature of CW and RW collected from various ready-mix concrete plants and cement manufacturing plants is needed to develop strong guidelines taking into consideration compositional variations of such industrial by-products. This way, the quality and performance will be consistent and will make it possible to apply it in expanded applications.

Environmental and economic benefits of HSM production with CW and CW should be quantitatively assessed in a detailed life-cycle assessment (LCA) in combination with a cost-benefit analysis. "Such analyses will form a strong basis for industry uptake by showing the overall sustainability and the possible economic advantage of the approach."

By considering these suggestions, the results presented in this study can be improved upon in future studies to further develop and apply sustainable high-strength mortar. In the end, this evolution will help the construction industry shift to practices that are more resource-efficient and environmentally friendly, which will also help this industry promote the model of circular economy by recycling industrial waste into resources for construction.

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