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

Name	Student ID
Fariha Tarannum Zaman Upoma	190051206
Md. Tahmid Ahshan	190051225
Abu Safwan	190051244

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PROJECT APPROVAL

This is to certify that the thesis entitled “INFLUENCE OF USING LADLE FURNACE SLAG AS A PARTIAL REPLACEMENT FOR SAND ON THE PROPERTIES OF UHPC” submitted by Fariha Tarannum Zaman Upoma, Md. Tahmid Ahshan and Abu Safwan has been approved as partial fulfillment of the requirement for the Degree, Bachelor of Science in Civil Engineering at Islamic University of Technology (IUT).

Supervisor

Dr. Tanvir Ahmed

Assistant Professor,

Department of Civil and Environmental Engineering,

Islamic University of Technology,

Board Bazar, Gazipur- 1704, Bangladesh.

DECLARATION

We hereby declare that the undergraduate research work presented in this thesis has been conducted by Fariha Tarannum Zaman Upoma, Md. Tahmid Ahshan and Abu Safwan 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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Fariha Tarannum Zaman Upoma
Student ID: 190051206

____

Md. Tahmid Ahshan
Student ID: 190051225

____

Abu Safwan
Student ID: 190051244

____

Dr. Tanvir Ahmed
Assistant Professor,
Department of Civil and Environmental Engineering,
Islamic University of Technology,
Board Bazar, Gazipur- 1704, Bangladesh.

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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Our gratitude is to Almighty Allah for blessing us with a chance to complete this thesis and for enabling us in resolving issues that emerged throughout our project work. We would like to express our sincere appreciation to our supervisor, Dr. Tanvir Ahmed, Assistant Professor, Department of Civil and Environmental Engineering, Islamic University of Technology, for his kind supervision, helpful advice, and continuous support. His creative and technical guidance was essential to the success of this research project. The paper would never have been completed without his help and direction.

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ABSTRACT

The proliferation of industrial by-products as sustainable construction materials has given rise to the utilization of ladle furnace slag as a potential replacement for natural sand in ultra-high performance concrete (UHPC). This study investigates the influence of ladle furnace slag as a partial replacement for sand on the mechanical and durability properties of UHPC. A systematic approach has been adopted wherein natural sand in UHPC has been replaced with ladle furnace slag (LFS) at varying percentages of 0%, 10%, 15%, 20% and 30% by volume. Mechanical properties have been assessed through the evaluation of compressive strength at 7 and 28 days. Durability aspects have been examined through sorptivity, water absorption, and shrinkage tests. The experimental results indicate an initial decrease in workability with the incorporation of LFS, attributed to its finer size and rougher texture compared to sand. The inclusion of LFS up to 20% leads to a significant enhancement in the early age compressive strength which can be credited to the filler effect and the pozzolanic reactivity of the LFS. Durability assessments reveal an improved densification of the microstructure with lower permeability coefficients and water absorption in mixes containing LFS. A reduction in sorptivity with an increased substitution of natural sand with Ladle Furnace Slag has also been observed, indicating enhanced resistance to the ingress of detrimental substances and improved durability properties of the concrete matrix. However, beyond 20% replacement level, the benefits diminished and negative effects on the mechanical strengths and durability became prominent. This decline at higher substitution rates can possibly be attributed to the interference of the voluminous LFS particles with the matrix's packing density and their weaker bond with the cementitious binder. The study confirms that LFS can be used as a partial replacement for sand in UHPC that can foster sustainable construction practices by recycling industrial waste and reducing sand mining impacts to some extent.

Moreover, the optimal utilization of LFS not only conserves natural resources but also improves certain properties of UHPC, making it a promising material for advanced civil engineering applications. Further research is however encouraged to understand the long-term effects and to explore the pre-treatment of LFS to overcome workability and bonding issues for higher replacement percentages.

Keywords: Ladle Furnace Slag (LFS), Packing Density, Pozzolanic Reactivity, Sorptivity, Ultra-High Performance Concrete.

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CHAPTER 1: INTRODUCTION

1.1 General

Ultra-high-performance concrete (UHPC) is a marvel of civil engineering, boasting exceptional strength, durability, and workability, making it a suitable choice for various infrastructure applications. The development and utilization of ultra-high-performance concrete (UHPC) in bridge engineering have been extensively studied, with researchers exploring different methods to enhance its performance further. One potential approach to improve the properties of ultra- high-performance concrete is the incorporation of industrial byproducts, such as ladle furnace slag, as a partial replacement for sand. Ladle furnace slag is a waste material generated during the steel-making process and has been successfully used in the production of normal concrete and high-performance concrete (Reiterman et al., 2014), (Tu et al., 2006). However, its reliance on large amounts of conventional fine sand raises concerns about resource depletion and environmental impact. The importance of this natural resource is given by the fact that, nowadays, after fresh water, sand is considered to be the second most consumed natural resource on Earth (Jakob Villioth, 2014). Sand mining, a major global industry, has significant environmental consequences (The environmental impacts of river sand mining, 2022). The extraction of sand from rivers and coastal areas can lead to habitat destruction and changes in sediment flow (Koehnken et al., 2020). These alterations can negatively impact aquatic species, affecting their abundance, movement, and community structures (Koehnken et al., 2020). Moreover, sand mining can exacerbate coastal erosion by disrupting the natural sediment balance (Yuhi, 2008). The increasing demand for sand necessitates sustainable mining practices and regulations to mitigate its environmental toll (Environmental Impacts of Sand Exploitation. Analysis of Sand Market, 2017).

1.2 Background of the study

The construction industry is a major consumer of natural resources, with sand being the second most extracted material worldwide after water. This high demand for sand, primarily used in concrete production, has led to unsustainable sand mining practices with detrimental environmental consequences (Global sand and gravel extraction conflicts with half of UN Sustainable Development Goals, 2021). These include habitat destruction, riverbed erosion, and increased coastal vulnerability (Koehnken et al., 2020). To mitigate these issues, there's a growing need to find alternative materials to replace sand in concrete. Simultaneously, the production of industrial byproducts, such as ladle furnace slag from the steel industry, poses a significant environmental challenge (Kaish et al., 2021). Traditionally, ladle furnace slag is landfilled or stockpiled, posing a storage challenge. However, when ground into a fine powder, ladle furnace slag exhibits cementitious properties, making it a promising candidate for replacing a portion of sand in concrete mixes. Ultra- high-performance concrete is a material that exhibits exceptional mechanical properties, including high compressive strength, flexural strength, and tensile strength, exceeding those of traditional concrete (Richard & Cheyrezy, 2008). Its unique composition, featuring fine aggregates, high-volume cement paste, and mineral admixtures, results in a dense, near-zero porosity matrix that contributes to its superior performance. This fine particle size further densifies the mix and promotes better interaction between the binder and aggregates. Utilizing an industrial byproduct like ladle furnace slag as a partial replacement for sand in ultra-high-performance concrete offers a two-fold solution: reducing reliance on natural sand and finding a useful application for an industrial waste material. This approach aligns with the principles of sustainable construction by conserving natural resources and promoting a circular economy.

1.3 Objectives of the study

In this study, we tried to explore the possibility of using ladle furnace slag as a partial replacement of sand. The objectives of this study will be:

- To explore the influence of different percentages of ladle furnace slag as a replacement of sand on the compressive strength.
- Study the effects of ladle furnace slag on the mechanical (compressive strength) and durability (absorption and sorptivity) properties of UHPC with different percentages replacement of sand.
- To lower the usage of sand as a filler material.

1.4 Research Flow Diagram

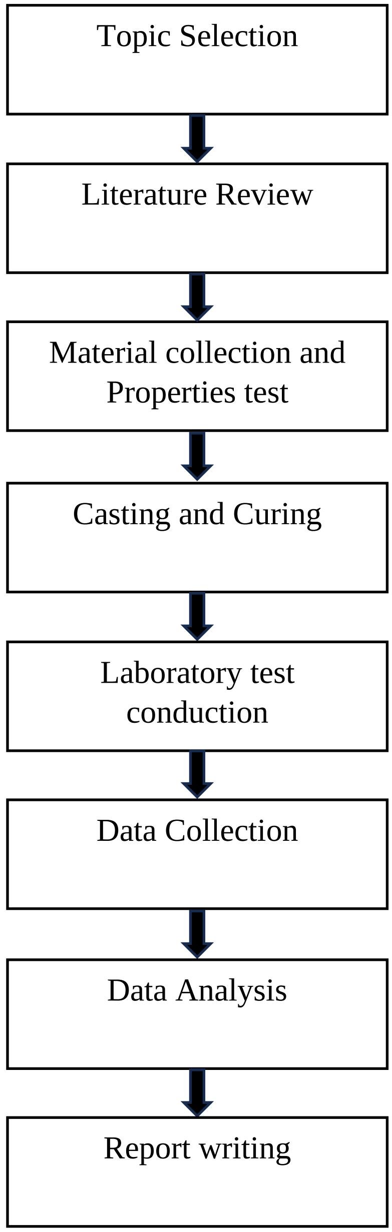

Figure 1.1 Research flow diagram

1.5 Layout of the thesis

The thesis consists of the following layout:

Chapter 1:

Introduction - The current chapter, that discusses about the theory, background, objectives, scope of the study and research flow diagram.

Chapter 2:

Literature Review - The chapter describes the related research in the field of our study by former authors and their findings.

Chapter 3:

Methodology - This chapter describes the procedures and steps that were followed to conduct our study.

Chapter 4:

Results and Discussion - Collected data and processing of the data, results were included in the chapter.

Chapter 5:

Conclusion and Recommendations - General discussion, limitations, recommendations and future scopes of work were discussed here.

CHAPTER 2: LITERATURE REVIEW

This chapter summarizes key studies and their important findings conducted by prominent researchers in the areas of UHPC, sand replacement and ladle furnace slag.

Kosmas K. Sideris , Ch. Tassos, A. Chatzopoulos, P. Manita (2018) stated that ladle furnace slag (LFS) can be used as a filler for self-compacting concretes (SCC), improving their fresh properties and viscosity. When LFS replaced sand, the compressive strength of SCC increased significantly after 28 days, especially in mixtures with higher LFS content. A mixture with 25% LFS showed high compressive strength, classifying it in a higher strength category. However, using LFS as a cement replacement reduced compressive strength at 28 days but did not compromise the strength class. The durability of SCC improved with LFS as sand replacement, with notable enhancements in mixtures with 25% LFS. Conversely, using LFS as a cement replacement had a smaller impact on durability. Overall, higher LFS dosages led to more durable SCC mixtures when used as a sand replacement. The effects of manufactured sand (MS) as a partial replacement in Ultra-High Performance Concrete (UHPC) was experimented by Rui Yang et al. (2019). They studied the flowability, mechanical properties, volume stability, hydration kinetics, and microstructure of UHPC with manufactured sand. The fine particles in manufactured sand reduced UHPC flowability and increased shrinkage but also improved compressive strength due to better paste-aggregate bonding and reduced water-binder ratio. Manufactured sands physical characteristics enhanced UHPC's mechanical properties. It is a suitable alternative in areas with limited river sand, though attention must be given to the fine powders in manufactured sand. Ahmed S. Ouda, Hamdy A. Abdel-Gawwad (2019) experimented with a view to evaluating the effect of replacing sand by iron slag on physical, mechanical and radiological properties of cement mortar. They discovered that incorporating basic-oxygen furnace slag (BOFS) at 40%, 80%, and 100% replacement levels improved the physio-mechanical properties of the mixes compared to normal sand mortar. The mix with full sand replacement showed the highest compressive strength, outperforming the control mix by 32%, 31%, 39%, 40%, and 38%. Additionally, mortar made entirely with slag as the fine aggregate demonstrated significant shielding efficiency in thin mortar shields (up to 8 cm) against gamma rays from 137Cs and 60Co radiation sources, compared to normal mortar. The study concluded that iron slag can completely replace sand in cement mortar.

Using glass sand as an alternative for quartz sand in UHPC was investigated by Nancy A. Soliman, Arezki Tagnit-Hamou (2017). Nancy A. Soliman et al. (2017) came to conclusion that the compressible packing model (CPM) is adaptable to various glass sands to achieve an ideal particle-size distribution and optimal packing density. This study obtained glass sand (GS-275) with a mean particle diameter of 275 µm, enhances workability but slightly reduces compressive strength compared to traditional UHPC. Suboptimal packing density in UHPC due to high air content can weaken mechanical strength. A UHPC mix replacing 50% quartz sand with glass sand can maintain flowability and compressive strength akin to standard concrete, offering a dense microstructure without alkali-silica reaction. Utilizing glass sand in UHPC production can replace quartz sand economically. Tanvir Ahmed et al. (2021) investigated the Development of ECO-UHPC utilizing gold mine tailings as quartz sand alternative. Their research revealed that UHPC made with WAGT1(Western Australian Gold mine Tailings sourced from Mine1) aggregate achieves a 28-day compressive strength exceeding 120 MPa, superior water tightness compared to quartz sand UHPC, and similar carbonation resistance to traditional UHPC. Utilizing WAGT1 instead of quartz sand can reduce costs and CO2 emissions for projects near Mine 1. UHPC incorporating up to 80% tailings displayed similar or superior compressive strength compared to UHPC containing 100% sand. They also found that substituting sand with tailings could decrease material and transportation expenses by as much as 33.1% and reduce CO2 emissions by up to 12.1%.

Carbonated ladle slag fines for carbon uptake and sand substitute was studied by Sean Monkman, Yixin Shao and Caijun Shi (2009). This process efficiently reduces calcium hydroxide and CaO in the slag, converting CO2 to calcium carbonate. Carbonation for 56 days at atmospheric pressure yielded results comparable to 2 hours at 500-kPa pressure, offering an effective, low-pressure method for sequestering CO2. Mortars with slag sand exhibit strengths akin to those with river sand after conventional moist curing, with carbonated mortars showing significant strength gains post-2-hour carbonation and further moist curing. Carbonated ladle slag is viable as fine aggregate, offering substantial carbon sequestration benefits without compromising mortar strength. Tarek U. Mohammed, Md. Mahafizul Hassan , Md Nafiur Rahman and Shibly Mostafiz Apurbo (2019) undertook a comprehensive investigation to analyze Brick fine aggregate (BFA) and ladle furnace slag (LFS) as alternative to natural river sand. They came to conclusion that substituting river sand with BFA lowers concrete workability regardless of the BFA source. Replacing river sand with LFS boosts concrete workability up to 20%, declining with higher replacements. Concrete's compressive strength, splitting tensile strength, and modulus of elasticity rise with up to 30% BFA replacement and 20% LFS replacement before declining.

The partial replacement of sand with LFS in UHPC presents a promising avenue for enhancing material properties. The findings from various studies underscore the potential benefits and pave the way for future research and practical applications in the construction industry. As the demand for high-performance grows, the integration of Ladle furnace slag in UHPC as sand replacement is likely to become increasingly significant and this is the core focus of our research.

CHAPTER 3: METHODOLOGY

3.1 General

In this chapter, the experimental method of the study is described. Mixture proportions of concrete, cases investigated in this study, collection and preparation of materials, methods and standards of testing constituent materials, testing sample preparation, curing method and different testing procedures to study the mechanical and durability properties of UFPC is summarized in this chapter.

3.2 Collection of Materials

To make concrete mixtures, natural river sand was used that was collected from Durgapur. CEM Type 1 (OPC) and CEM Type II A-M as per BDS EN 197 [80%-94% clinker plus 6%-2-% mineral admixture and 5% gypsum] and silica fume were used as binding materials which were sourced from local manufacturer. The ladle furnace slag used in this study was collected from a cement manufacturing plant situated in Chattagram. As admixture, two admixtures were tried out to find the appropriate one. The admixtures were sourced from local manufacturer company.

3.3 Material Properties

The material properties were examined in the laboratory before casting according to proper specifications. The aggregates that were used in this study were tested for specific gravity, absorption capacity, gradation and unit weight. The specifications followed are stated in **Table 3.1**.

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) ASTM C 188 (for cement, silica fume and ladle furnace slag)
Absorption Capacity	ASTM C 128
Unit Weight	ASTM C 29
Gradation	ASTM C 136

3.3.1 Fine Aggregates

In this study, 4 types of natural river sands were used as fine aggregates. The natural sands were passed through 450 micro meter and 600 micro meter sieve for getting the finest sand for concrete casting. Basing on the results of the compressive strength test, the natural river sand that was collected from Durgapur and passed through 600 micro meter sieve was fixed for main concrete mixes. The comparison of gradation of sands in shown in **Figure 3.1**. The material properties of the sands used for this study is shown in **Table 3.2**.

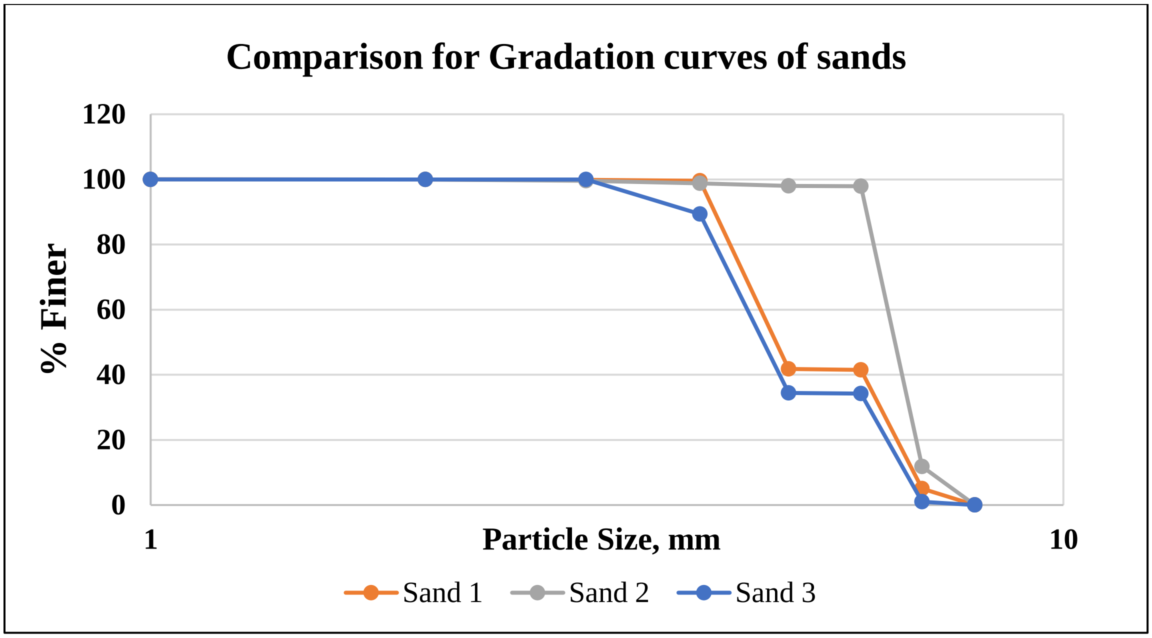

Figure 3.1 Comparison for Gradation curves of Sands

Table 3.2 Properties of Fine aggregate

Aggregate Type	Bulk (SSD) Specific Gravity	Absorption Capacity (%)	SSD Unit Weight (kg/m^3)
Natural River Sand 1	2.54	1.98	
Natural River Sand 2	2.58	1.98	
Natural River Sand 3	2.63	1.98	

3.3.2 Binder Material

In this study, as binding materials, CEM Type I (Ordinary Portland Cement) and CEM Type II A-M and silica fume were used. The composition of the mineral properties of cements and the specific gravity of the cementitious materials are given in **Table 3.3** and **Table 3.4** respectively.

Table 3.3 Mineral Composition of CEM Type I and CEM Type II A-M

Binder Type	Clinker	Mineral Admixture	Gypsum
CEM Type I	95-100%	0%	0-5%
CEM Type II A-M	80-94%	6-20%	0-5%

Table 3.4 Specific Gravity of Cementitious Materials

	CEM Type I	CEM Type II A-M	Silica Fume	Ladle Furnace Slag
Specific Gravity	3.15	2.90	2.25	2.20

3.3.3 Ladle Furnace Slag

For this study, ladle furnace slag or LFS was used as a replacement for sand in the mixes of UHPC. The ladle furnace slag used in this study was collected from a cement factory from Chittagong and before replacing with sand the specific gravity was measured which is specified in Table 3.4. The gradation curve of the ladle furnace slag is shown in **Figure 3.2**. The comparison of gradation curves of Sand 3 and the ladle furnace is also shown in **Figure 3.3**.

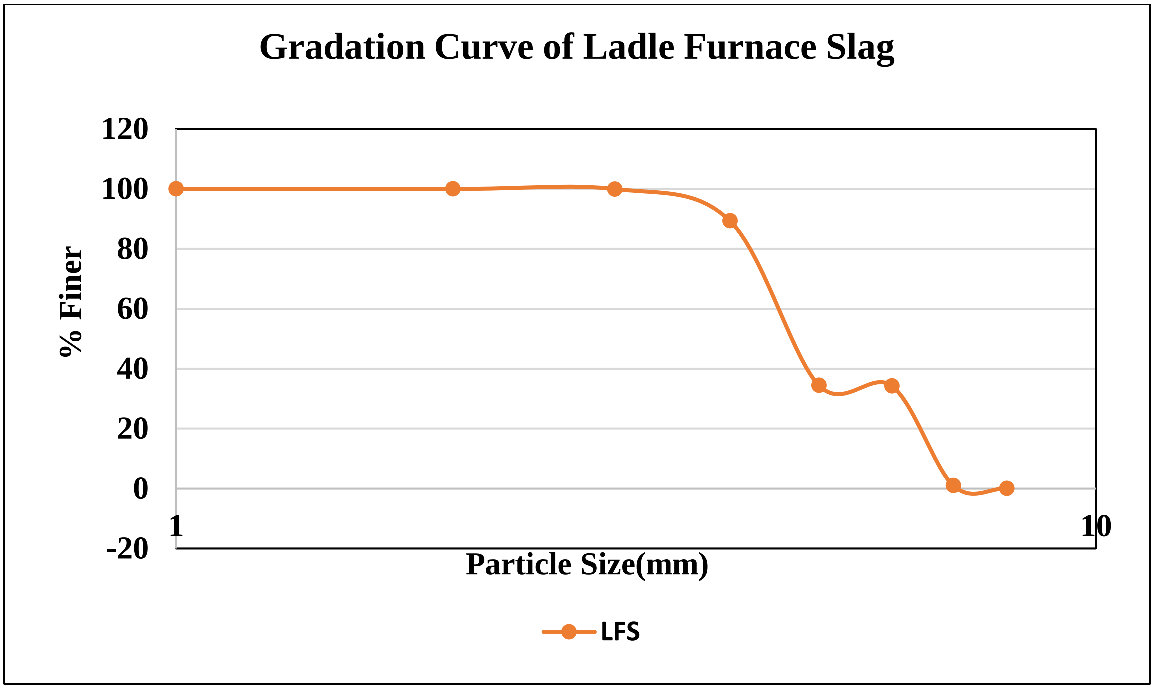

Figure 3.2 Gradation curve of Ladle Furnace Slag

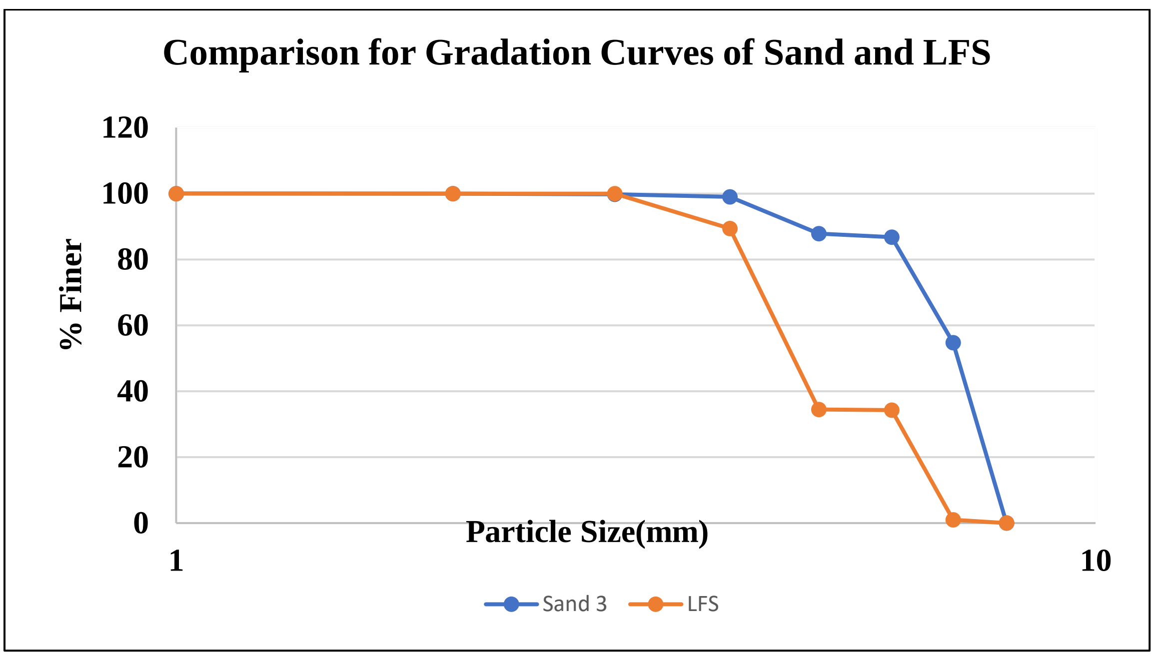

Figure 3.3 Comparison for Gradation Curve of Sand and LFS

3.3.4 Water

For mixing of concrete and curing of the concrete specimens, water was used in this study that had a unit weight of 1000 kg/m^3. The water was not polluted and free from any kinds of detrimental contaminants.

3.3.5 Admixture

In this study, two admixtures were tried in the trial mixes to find the suitable one for the control mix of UHPC. AURAMIX 500 and ARMIX Emmecrete PC 10 are the two admixtures that were used for this study. The properties of the admixtures are stated in **Table 3.5** and **Table3.6**.

Table 3.5 Properties of AURAMIX 500

Admixture Name	Chemical Type	Polycarboxylic Ether Polymer
AURAMIX 500	pH	Minimum 6.0
	Appearance	Light yellow colored liquid
	Volumetric mass at 20^0 C	1.1 ± 0.02 kg/litre
	Alkali Content	Typically less than 1.5 g Na_2O equivalent/ litre of admixture

Table 3.6 Properties of ARMIX Emmecrete PC 10

Admixture Name	Chemical Type	Polycarboxylic Ether Polymer
ARMIX Emmecrete PC 10	pH	Minimum 6.0
	Appearance	Clear to light brown liquid
	Chloride Content	Nil

3.4 Trial Mixes

The definition of Ultra-High Performance Concrete (UHPC) may be broadly defined as a cementitious, composite material that has enhanced strength, durability and tensile ductility compared to High Performance Concretes (HPC). UHPC frequently uses fibers for post-cracking ductility, have specified compressive strength of at least 120 MPa at 28 days, and are formulated with a modified multi-scale particle packing of inorganic materials of less than 0.6 mm diameter (larger sizes can be used). [Canadian Standards Association CSA A23.1/2 Annex S on Ultra-High Performance Concrete, Rexdale, ON, Canada 2018 (Draft)]. So, to achieve strength of more than 120 MPa, a total of 8 trial mixes were conducted to find the control mix. The test specimens were cubic in shape (25 mm x 25 mm x 25mm). Potable water was used for mixing the concrete mixes. CEM Type I and CEM Type II A-M were used to find the suitable one for the control mix. In the second trial, CEM Type I showed better results due to being finer than CEM Type II A-M. So later on, the trial mixes were conducted with CEM Type I. A total of 4 sands were tried to find the control mix. The Sand 1 is natural river sand passed through 450 µm sieve. Sand 2 is natural sand passed through 600 µm sieve. Sand 3 is natural river sand collected from Durgapur and passed through 2.3 mm sieve and Sand 4 is the same sand but passed through 600 µm sieve. Two superplasticizers were used in these cases and AURAMIX 500 showed better results. The compressive strength test was conducted at 7 and 28 days to find the control mix. A mixture of water curing and Increased temperature curing was conducted. Specimens were dissolved in water for 72 hours at room temperature and then shifted to oven at 70^0 C and kept for 96 hours for Increased temperature curing. The compressive strength enhanced when the specimens were cured through this mixed curing process. The mix design of the trial mixes is shown in **Table 3.7** and **Table 3.8**.

Table 3.7 Mixture proportions of Trials Mixes (1-4)

	Type of Content	$C_2WB_{20}SP_1$ NC	$C_1WB_{29}SP_1$ NC	$C_1WB_{21}SP_2$ NC	$C_1WB_{21}SP_2$ NC
Unit contents (kg/m^3)	CEM Type I		823	881	897
	CEM Type II A-M	923			
	Silica Fume	231	206	220	224
	Sand 1	969	905		
	Sand 2			964	941
	Sand 3				
	Sand 4				
	Water	221	291	211	206
	SP 1 (ARMIX E.PC 10)	15	12		
	SP 2 (AURAMIX 500)			34	43

Table 3.8 Mixture proportions of Trial Mixes (5-8)

	Type of Content	$C_1WB_{23}SP_2$ NC	$C_1WB_{18}SP_2$ IC	$C_1WB_{17}SP_2$ IC	$C_1WB_{17}SP_2$ IC
Unit contents (kg/m^3)	CEM Type I	877	930	932	932
	CEM Type II A-M				
	Silica Fume	220	232	233	233
	Sand 1				
	Sand 2	920			
	Sand 3			978	
	Sand 4		976		978
	Water	232	184	173	173
	SP 1 (ARMIX E.PC 10)				
	SP 2 (AURAMIX 500)	34	46	47	47

3.5 LFS Replacement Mixes

After investigating 8 trial mixes, the maximum compressive strength was found for the mix ratio of $C_1WB_{17}SP_2$. In this case, the water to binder ratio was 0.17 and the cement used was CEM Type I. AURAMIX 500 superplasticizer was used in this mix. For this case, the mixture of water curing and Increased temperature curing was used where the cubic specimens were first cured in water for 72 hours and then shifted to oven for Increased temperature curing under 70^0 C for 96 hours. Considering higher strength compared to all other trial mixes, $C_1WB_{17}SP_2$ was recognized as the "control mix" for the study. Subsequently, replacement mixes were introduced. In this study, different percentages of sand replacement were tried to examine the effect of LFS on the mechanical and durability properties of UHPC. In this experimental study, sand was replaced by ladle furnace slag in proportions of 10%, 15%, 20%, and 30% by volume of the sand in the control mix. The proportions of the replacement mixes are shown in **Table 3.9**.

Table 3.9 Mixture proportions of LFS replacement mixes

	Type of Content	LFS_0	LFS_{10}	LFS_{15}	LFS_{20}	LFS_{30}
Unit contents (kg/m^3)	CEM Type I	932	932	932	932	932
	Silica Fume	233	233	233	233	233
	Sand 4	1006	921	870	819	717
	LFS	0	86	128	171	257
	Water	173	173	173	173	173
	SP 2 (AURAMIX 500)	47	47	47	47	47

3.6 Specimen Mold Preparation

Two types of specimens were casted for this study. 50 mm x 50 mm x 50 mm cube shaped concrete specimen and 25 mm x 25 mm x 285 mm prism shaped concrete specimen. These molds are available at CEE Concrete Laboratory of Islamic University of Technology. Before casting, the molds were ensured to be air tight by adjusting the available screws and the inner surfaces were lubricated using grease according to ASTM C 31-03. The pictures of the molds are shown in **Figure 3.4** and **Figure 3.5.**

Figure 3.4 Cubic Mold for UHPC Casting

Figure 3.5 Mold for Sorptivity testing specimens

3.7 Casting Procedure of UHPC

For the casting of UHPC specimens, an electrically driven mechanical mixer machine was used that was available in the Concrete lab of Islamic University of Technology. The casting begins with positioning the paddle and the mixing bowl of the mixer machine in the fixed positions. Then at first, cement and silica fume were added in the mixing bowl and mixed in slow pace (140 ± 5 r/min) for 90 seconds. Then sand in SSD condition was added in the mixing bowl and mixed in slow pace for 90 seconds. Afterwards, water and superplasticizer were added and mixed in medium pace (285 ± 10 r/min) for 5 minutes. Then, the machine was set to high pace (revo/min) and let the mixture mix till it reaches a standard workability. The mixing procedure usually took 18 to 20 minutes in total. After mixing, the concrete was then shifted to a non-absorbent sheet for proceeding the casing operation concurrently.

3.7.1 Molding of Concrete Cube Specimens

The cubic specimens were prepared following ASTM C 109/109 M standard. Firstly, a 25 mm thick layer of concrete was placed in each cube section. Next, the concrete layer was tamped 16 times over approximately 10 seconds in four rounds using a non-absorbent wooden tamper. Each round was performed at right angles to the previous one, with 8 adjacent strokes covering the surface of the specimen. The tamping pressure applied was sufficient to ensure uniform filling of the mold. After finishing the tamping of the first layer, the remaining space in the cubes were filled with concrete mixture and the previously described tamping method was repeated. The top surface of the cubes was then smoothened using trawl’s flat side. A steel scale was used to level the surface. Order of tamping of the molds is shown in **Figure 3.6**.

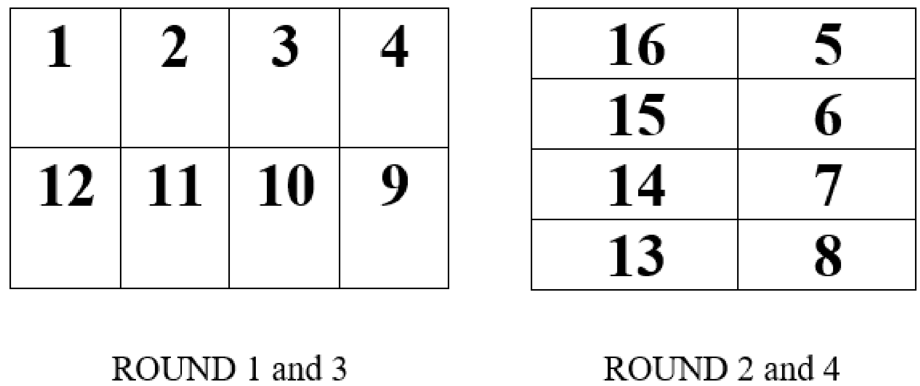

Figure 3.6 Order of tamping of molds

3.7.2 Molding of Concrete Shrinkage Specimen

To measure the drying shrinkage of UHPC, shrinkage specimens were casted. The control mix and the replacement mixes with proportions of 10%, 15%, 20% and 30% of sand with LFS were tested for drying shrinkage. For total 5 cases, 3 prism specimens of size 25 mm x 25 mm x 285 mm were casted. A total of 15 prisms were casted in this study. ASTM C 490 specification was followed in case of casting of the shrinkage specimens. Before molding the specimens, the outside joints of the molds, the contact line and the base plate were sealed to avoid loss of mixing waster from the molded specimens. Afterwards, gauge studs were fixed at the ends of the molds. For tamping, firstly a layer of approximately 12.5 mm was casted and tamping was done using a non-absorbent tamper. To ensure homogeneous distribution over the whole specimen, scale was used near the gauge stud areas. After tamping the first layer, the remaining compartments was filled with concrete and the tamping method described above was repeated. The top layer was finally smoothened using trawl's flat side removing the extra mixture from the top. Finally, a steel scale was used for levelling the top surface.

3.8 Curing of Specimens

The curing method followed in this study was a combination of water curing and increased temperature curing. After removing the cubes from the molds, the cube specimens were firstly placed in water for 72 hours in room temperature. After that, the specimens were then shifted to oven, where the cubic specimens undergo Increased temperature curing in 70^0 C temperature for 96 hours. Then the specimens were finally removed from the oven and tested.

3.9 Conducted tests

3.9.1 Compressive Strength

Compressive strength is defined as the maximum stress a concrete or mortar specimen can withstand when loaded axially. This parameter is crucial because both concrete and mortar predominantly experience compressive stresses in most structural applications. In this study, the compressive strength of the cubic concrete blocks having dimensions 50 mm x 50 mm x 50 mm were tested according to the ASTM C 109 specification.

3.9.2 Sorptivity measurement of UHPC

3.9.2.1 Sample Conditioning

Absorption of UHPC specimens was measured in terms of sorptivity coefficient following ASTM c 1585-20 specification. For sample conditioning in case of finding the absorption of specimens, a well-defined method is used. In this study, the specimens were cured using a combination of water curing and Increased temperature curing. In Increased temperature curing, the test specimens were kept in oven at 70^0 C temperature for 96 hours, which allowed to remove free water present in the cubic specimens. The test specimens were then cooled and prepared for the next stage of the test.

3.9.2.2 Sample Preparation and Test Conduction

After completion of conditioning of the test samples, the 4 faces of the specimens were sealed using a duct tape keeping two sides exposed. Then, the top surface of the specimen was covered using plastic sheet and rubber band to ensure that no evaporation of water took place. Sample weight was measured in an air tight weight machine at specified time intervals described in ASTM C 1585-20 specification. The sorptivity coefficient was then determined using the following equations. The experimental setup is shown in **Figure 3.7**.

$$I = S_i + B \tag{3.1}$$

$$S_i = \frac{I}{\sqrt{t}} \tag{3.2}$$

$$I = \frac{m}{d \times A} \tag{3.3}$$

Here,

I = water absorption, mm

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

t = time, sec

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

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.

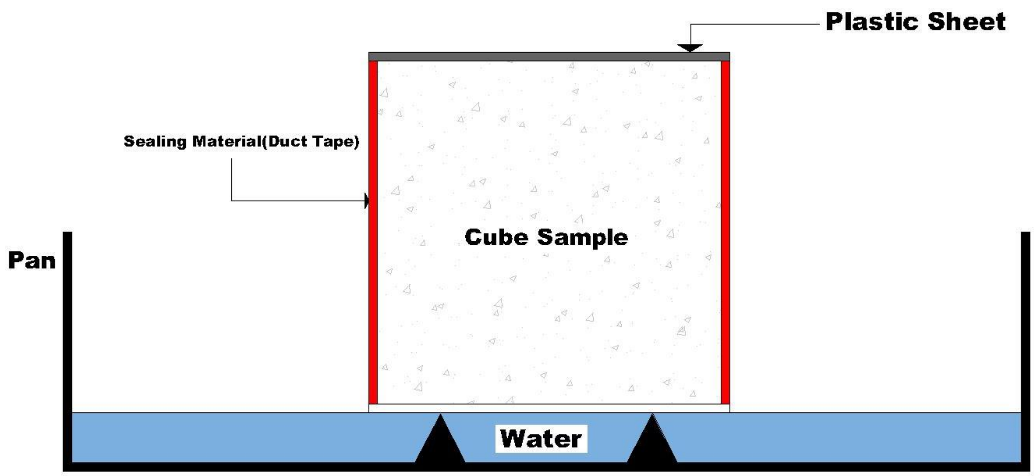

Figure 3.7 Setup for Soprtivity Coefficient Measurement as per ASTM 1585- 13

3.9.3 Drying Shrinkage of UHPC

The drying shrinkage for UHPC specimens were measured maintaining ASTM C 596-07 specification. For this test, prism shaped specimens were prepared with dimensions 25 mm x 25 mm x 285 mm as per ASTM C 490-07. At the end points of each prism bar, two gauge studs were fixed to measure the change in length of the specimens at pre-specified ages. The combination of water curing and Increased temperature curing was used for the test specimens of drying shrinkage test. For each replacement cases, 3 prism specimens were prepared. The procedure of taking compactor reading of the specimens in shown in **Figure 3.8**.

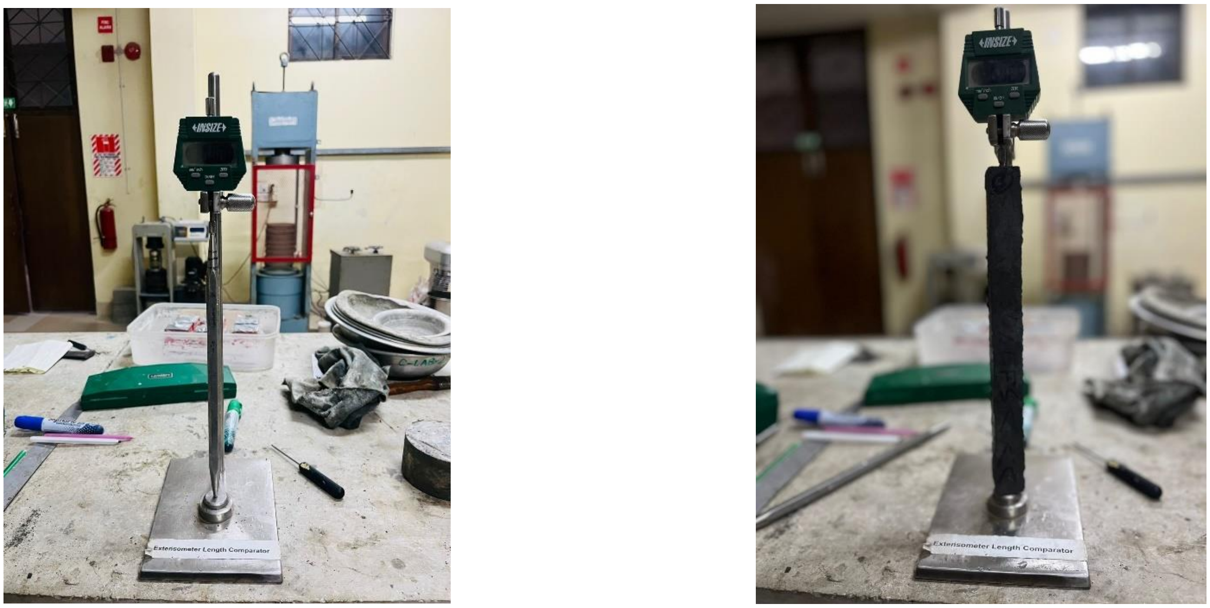

Figure 3.8 Calibration of Compactor and taking the reading of change in length

CHAPTER 4: RESULT AND ANALYSIS

4.1 General

In this chapter, the results of the conducted tests are presented. Furthermore, the analysis of the findings of this study has also been mentioned. The analysis of the compressive strength of the trial mixes was carried out to find the control mix of the study. Afterwards, the test results and the analysis of the sand replacement mixes were also shown.

4.2 Compressive Strength Test

4.2.1 Trial Mix results and analysis

The objective of these trial mixes was to identify a control mix for Ultra-High-Performance Concrete (UHPC) that could be used as a baseline for further experiments involving the partial replacement of sand with ladle furnace slag. This section presents an analysis of the trial mixes based on cement type, water to binder ratio, and sand type, aiming to determine the mixture with the highest overall performance. The compressive strength test results of 7 days and 28 days have been shown in **Figure 4.1**.

4.2.1.1 Analysis of Cement Types

CEM Type II-AM was tried in two mixtures ($C_2WB_{20}SP_1$ and $C1WB_{29}SP_1$). Both these mixtures showed comparatively lower compressive strength. The cement's composition, designed for moderate sulfate resistance, may contribute to its relatively lower performance in UHPC applications where higher early and long-term strengths are critical. CEM Type I was utilized in the majority of the mixtures and exhibited superior performance characteristics. Mixtures with CEM Type I generally showed higher strength and better overall properties. The higher early strength and durability of CEM Type I make it more suitable for UHPC, contributing to its better performance in the trial mixes.

4.2.1.2 Relation of W/B ratio with compressive strength of UHPC

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

4.2.1.3 Evaluation of Sand types

Mixtures utilizing sand passed through 425 µm sieve showed the lowest performance. The finer particles can lead to higher water demand and potentially more shrinkage, negatively impacting the concrete's overall strength and durability. Mixtures conducted with sand passed through 600 µm was associated with better performance. The particle size distribution of 600 µm sand helps achieve a denser packing and a more optimal particle arrangement, improving the mechanical properties of the UHPC. The balance between particle size and surface area in 600 µm sand appears to provide the best conditions for achieving high strength and durability. Some mixtures were tried with sand passed through 2.3 mm sieve to check the performance of coarser sand on UHPC. The use of this coarser sand in one of the mixtures showed average strength, albeit slightly lower than the 600 µm sand. The larger particle size can contribute to better internal bonding and reduced shrinkage, enhancing the overall strength of the UHPC. However, the optimal performance still favored the 600 µm sand, likely due to better particle packing and reduced voids.

4.2.1.4 Assessment of admixtures and curing methods

In normal water curing, the UHPC specimens were kept in water for 72 hours. Normal water curing method was used in combinations with both ARMIX and AURAMIX admixtures. While effective, normal water curing did not achieve the highest performance levels observed in the trial mixes. The method provides adequate moisture for hydration but may not be sufficient for the rapid strength gain required in UHPC. Afterwards, increased temperature curing method was introduced where the UHPC specimens were cured in water for 72 hours, followed by curing in the oven for 96 hours in 70^0 C temperature. Increased temperature curing significantly enhanced the performance of the mixtures. The application of heat accelerates the hydration process, leading to quicker strength gain and improved overall properties. Increased temperature curing was particularly effective in combinations with AURAMIX 500 admixture, which are designed to optimize performance under such conditions.

4.2.1.5 Conclusion

Based on the analysis, $C_1WB_{17}SP_2IC$ was selected as the control mix for replacing sand with ladle furnace slag in UHPC. This mix, with CEM Type I, a water to binder ratio of 0.17, sand passed through a 600 µm sieve, and cured with increased temperature with AURAMIX 505, achieved the highest compressive strength. This mix demonstrates the optimal balance of material properties and curing methods, making it the ideal candidate for further research involving the partial replacement of sand with ladle furnace slag. Future work will focus on the performance of this control mix with varying proportions of ladle furnace slag, aiming to enhance sustainability without compromising the exceptional properties of UHPC.

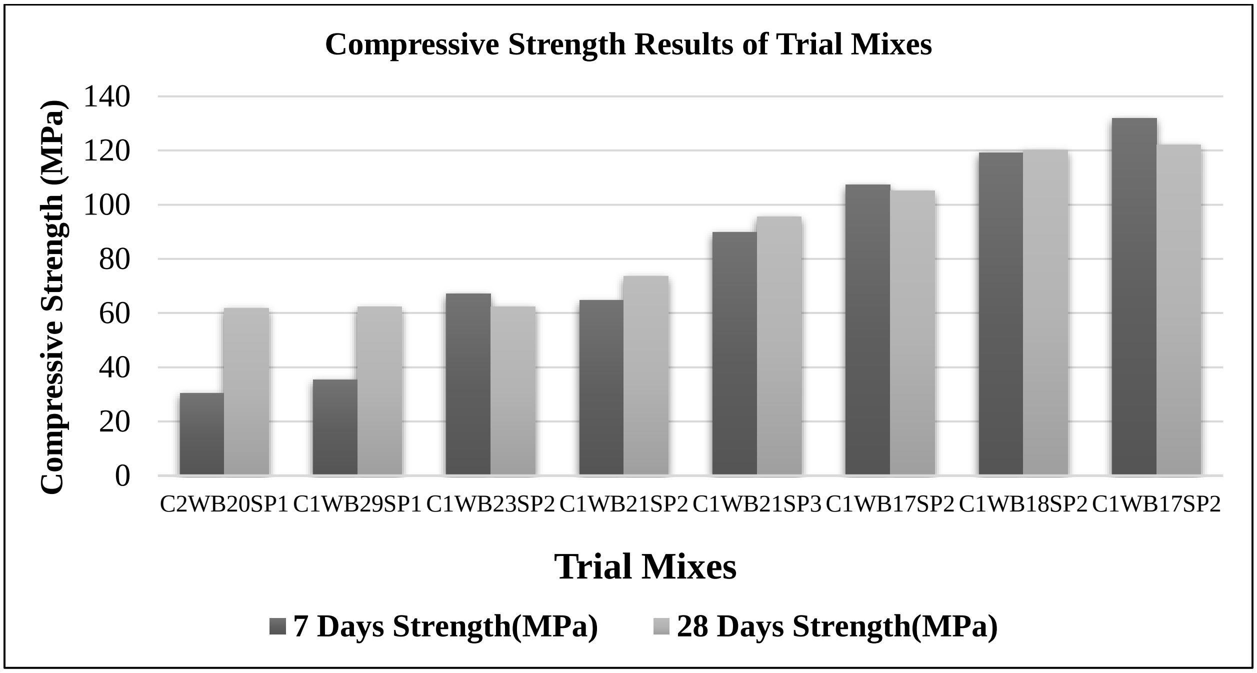

Figure 4.1 Compressive Strength Results of Trial Mixes

4.2.2 Analysis of Sand Replacement Percentages

Four different mixtures were tested with varying percentages of sand replaced by LFS: 10%, 15%, 20%, and 30%. The analysis focuses on how these varying replacement levels influenced the performance characteristics of UHPC, specifically the compressive strength at early (7 days) and later (28 days) stages. The compressive strength test results of replacement mixtures have been graphically demonstrated in **Figure 4.2**.

4.2.2.1 10% Sand Replacement

Replacing 10% of sand with LFS resulted in a noticeable decline in performance compared to the control mix. This decrease suggests that at lower replacement levels, the presence of LFS may interfere with the optimal particle packing density and microstructure. The reduction in compressive strength at both early and later stages indicates that even a small amount of LFS can disrupt the cohesion and compactness of the concrete matrix, potentially due to differences in particle shape, size distribution, or chemical composition between sand and LFS. (Compare with High Strength).

4.2.2.2 15% Sand Replacement

At a 15% replacement level, the performance shows some improvement over the 10% replacement but still does not match the control mix. The slight improvement could be attributed to a better integration of LFS particles within the concrete matrix, suggesting a potential threshold where LFS starts contributing beneficially to the mix without excessively compromising the properties. However, the overall performance remains suboptimal, indicating that while LFS can be partially integrated, its effects are still significantly pronounced.

4.2.2.3 20% Sand Replacement

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

4.2.2.4 30% Sand Replacement

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

4.2.2.5 Implications of Sand replacement with LFS in UHPC

LFS particles, having different shapes and sizes compared to natural sand, affect the packing density and microstructure of UHPC. Optimal particle packing is crucial for high-performance concrete, and any disruption can lead to increased porosity and reduced strength. The chemical composition of LFS can alter the hydration process of the cementitious matrix. LFS may contain compounds that either react differently or inhibit the formation of the dense hydration products necessary for UHPC. The use of LFS in concrete is driven by sustainability considerations.

While the incorporation of industrial by-products like LFS can reduce environmental impact, it is essential to balance this with the performance requirements of UHPC. The findings suggest that a lower percentage of LFS can be integrated without severely compromising the mechanical properties, but higher percentages lead to significant decrease in compressive strength. In comparison with the compressive strength of normal concrete and high strength concrete, the replacement mixtures showed higher strength. (López-Ausín et al., 2024)

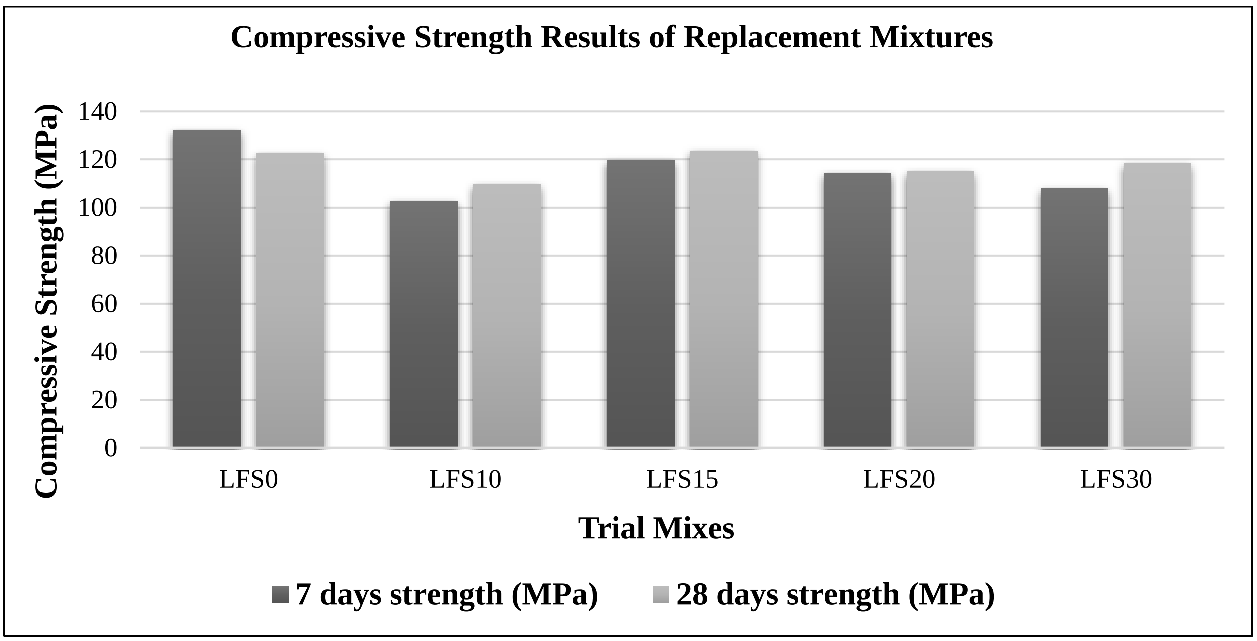

Figure 4.2 Compressive Strength Results of Replacement Mixtures

4.3 Sorptivity Test

Sorptivity measures the capacity of a material to absorb and transmit water through capillary action, which is a critical property for assessing the durability of concrete. In this study, the effect of partially replacing sand with ladle furnace slag (LFS) in Ultra-High-Performance Concrete (UHPC) on sorptivity was investigated. The sorptivity coefficients for different percentages of sand replacement with LFS were compared to evaluate the impact on UHPC's capillary absorption. Four different replacement levels and the control mixture were tested: 0%, 10%, 15%, 20%, and 30%. The related curves for initial sorptivity and secondary sorptivity are shown in **Figure 4.3** and **Figure 4.4**.

4.3.1 Overview of the Sorptivity Co-efficient

For the control mix with 0% LFS, the initial and secondary sorptivity coefficients provide a baseline for comparison. As LFS content increases, there are notable variations in these coefficients. At 10% replacement, there is a slight increase in both initial and secondary sorptivity, indicating an initial disruption in the capillary network due to the introduction of LFS particles. At 15% replacement, a significant reduction in both coefficients is observed, suggesting an optimal level where the benefits of LFS in reducing porosity outweigh the initial disruption caused.

At 20% replacement, the initial sorptivity coefficient shows an increase, but the secondary sorptivity remains lower than the control. This indicates that while the initial absorption rate is affected, the long-term capillary action is still reduced compared to the control. At the highest replacement level of 30%, both initial and secondary sorptivity coefficients increase, surpassing the control mix. This suggests that excessive LFS content leads to a higher porosity and less effective pore structure, thus increasing the capillary water absorption.

4.3.2 Analysis of Sorptivity Co-efficient Results

The variations in sorptivity coefficients can be attributed to several factors related to the inclusion of LFS in the UHPC matrix. Initially, the introduction of LFS particles at lower replacement levels (10%) may increase porosity due to inadequate packing density and disruption of the existing pore structure. This explains the initial increase in sorptivity coefficients. However, as the replacement level reaches 15%, the LFS particles seem to optimize the microstructure, reducing the overall porosity and thereby lowering the sorptivity coefficients. This indicates that there is an optimal replacement level where the benefits of LFS in refining the pore structure and reducing capillary pathways are maximized.

At higher replacement levels (20% and 30%), the sorptivity coefficients increase again. This can be attributed to the excessive presence of LFS, which may lead to a higher volume of unreacted particles and a less dense microstructure. The increased porosity at these levels facilitates greater capillary action, hence higher sorptivity. The increase in both initial and secondary sorptivity at 30% replacement level highlights the threshold beyond which the inclusion of LFS becomes detrimental to the capillary absorption properties of UHPC.

The secondary sorptivity, which reflects the longer-term water absorption capacity, shows similar trends. The optimal reduction at 15% replacement indicates that LFS can positively impact the long-term durability of UHPC by reducing the rate at which water is absorbed over time. However, beyond this optimal point, the benefits diminish, and the sorptivity coefficients increase, suggesting compromised durability. In conclusion, the partial replacement of sand with ladle furnace slag in UHPC can enhance the material’s performance by reducing sorptivity, but only up to an optimal level. Beyond this level, the benefits diminish, and the risk of increased capillary absorption and reduced durability rises. These findings underscore the importance of precise mix design and optimization in the development of high-performance concretes incorporating industrial by-products like ladle furnace slag. Further research is recommended to explore the long-term implications and to fine-tune the mix proportions for various practical applications.

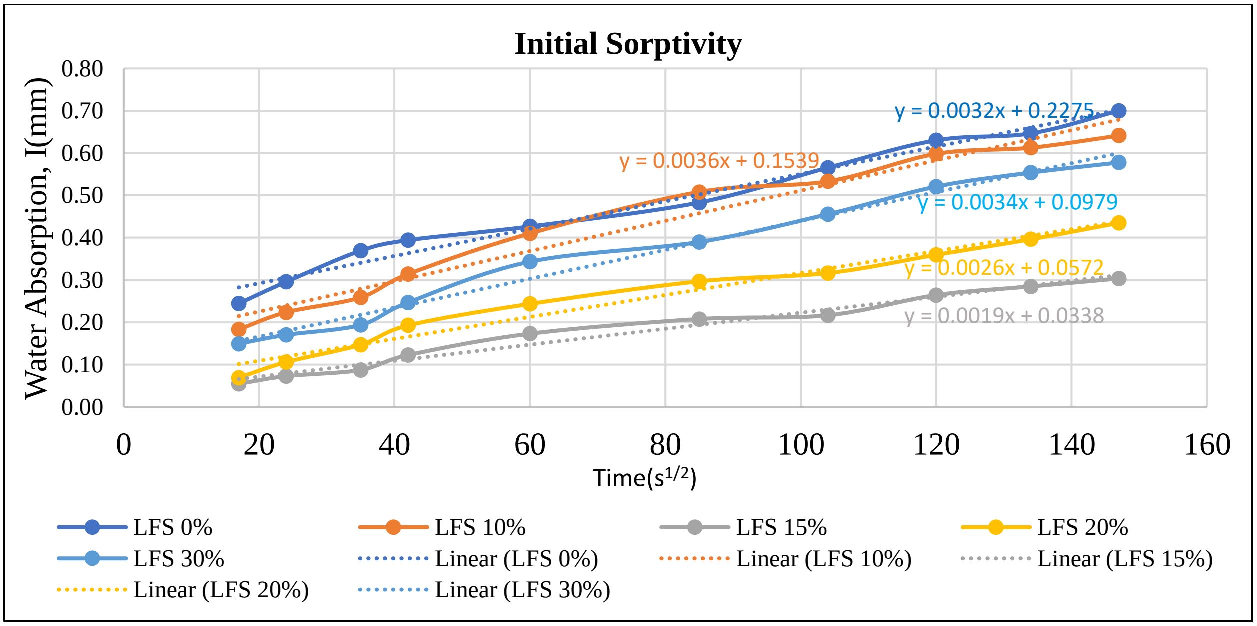

Figure 4.3 Initial Sorptivity

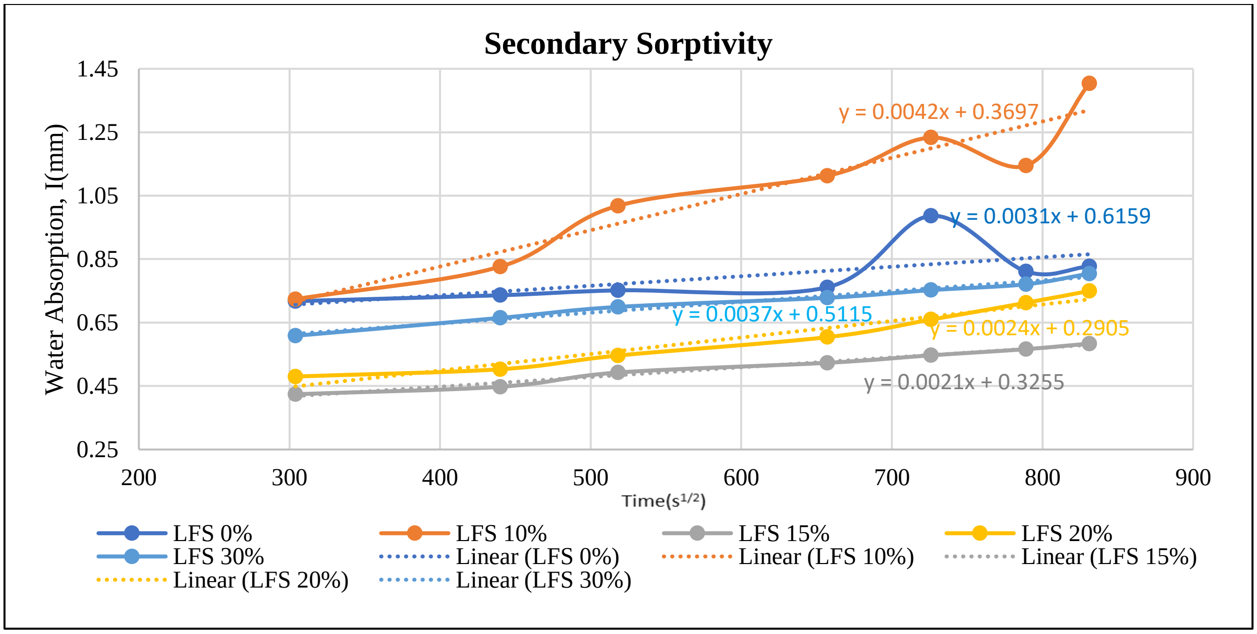

Figure 4.4 Secondary Sorptiviy

4.4 Drying Shrinkage

4.4.1 Overview of drying shrinkage for sand replaced UHPC specimens

The drying shrinkage of ultra-high-performance concrete (UHPC) with varying percentages of ladle furnace slag (LFS) as a partial replacement for sand in **Figure 4.5** indicates a noticeable trend. As the proportion of LFS increases, there is a corresponding increase in drying shrinkage. This behavior suggests that the inclusion of LFS affects the internal microstructure and moisture movement within the UHPC matrix.

Starting with the mixture containing no LFS replacement, we observe the lowest drying shrinkage. This baseline provides a reference point for comparing the effects of LFS inclusion. As LFS content increases to 10%, there is a marked increase in drying shrinkage. This initial increase can be attributed to the higher porosity introduced by the LFS particles, which likely leads to greater water movement and evaporation during the curing process.

Further increments in LFS content to 15% and 20% continue this trend of increasing drying shrinkage. The 15% replacement level shows a further rise, which can be linked to the cumulative effect of increased porosity and the changes in the hydration products formed due to the presence of slag. Slag particles may alter the pore structure, making the matrix more susceptible to drying shrinkage as it loses moisture over time.

At the highest replacement level of 30%, the drying shrinkage reaches its peak. This significant increase highlights the impact of excessive LFS content on the overall stability and dimensional integrity of UHPC. The high content of LFS could lead to more significant disruption in the cement matrix, thereby enhancing moisture movement pathways and contributing to higher shrinkage rates.

4.4.2 Analysis of drying shrinkage for sand replaced UHPC specimens

In conclusion, the inclusion of ladle furnace slag as a partial replacement for sand in UHPC influences the drying shrinkage characteristics significantly. While lower proportions of LFS result in moderate increases in shrinkage, higher proportions lead to a substantial rise. This trend underscores the importance of optimizing the LFS content to balance the benefits of slag inclusion with the potential drawbacks in terms of drying shrinkage. Comparative analysis with normal and high strength concrete reveals that UHPC with LFS generally shows higher shrinkage characteristics, highlighting its potential advantages for applications requiring high durability and dimensional stability. Further research is recommended to fine-tune the mix proportions and explore the long-term performance implications of LFS in UHPC.

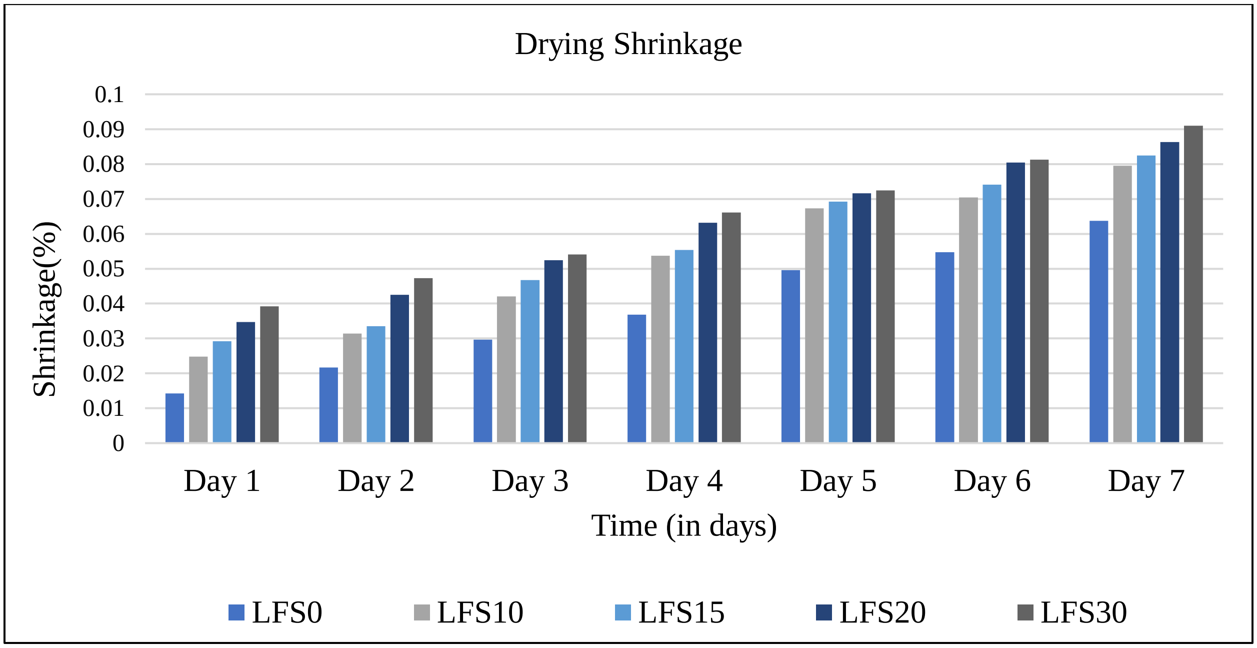

Figure 4.5 Drying Shrinkage of Sand Replaced Mixtures

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusive Remarks

The trial mixes reveal that compressive strength is influenced by cement type, water to binder ratio, and admixture. Mixes with CEM Type I cement generally show higher strengths than CEM Type II. Lower water to binder ratios increase strength, resulting in denser concrete. AURAMIX 500 admixture outperforms ARMIX Emmecrete PC 10, enhancing concrete properties significantly. For optimal compressive strengths, using CEM Type I cement, lower water to binder ratios, and AURAMIX 500 admixture, especially with increased temperature curing, is highly effective.

The UHPC mixtures with varying proportions of sand replacement by ladle furnace slag show a clear impact on compressive strength. As the percentage of sand replacement increases, there is a noticeable decrease in both 7-day and 28-day compressive strengths. The mixture with no sand replacement achieves the highest strength, while increasing slag content gradually reduces the strength. This indicates that while ladle furnace slag can be used as a sand replacement, higher replacement levels may compromise the structural integrity of UHPC, making lower replacement percentages more favorable for maintaining ultra-high compressive strengths.

The inclusion of ladle furnace slag as a partial replacement for sand in UHPC influences the drying shrinkage characteristics significantly. While lower proportions of LFS result in moderate increases in shrinkage, higher proportions lead to a substantial rise. This trend underscores the importance of optimizing the LFS content to balance the benefits of slag inclusion with the potential drawbacks in terms of drying shrinkage. Comparative analysis with normal and high-performance concrete reveals that UHPC with LFS generally performs better in shrinkage characteristics, highlighting its potential advantages for applications requiring high durability and dimensional stability. Further research is recommended to fine-tune the mix proportions and explore the long-term performance implications of LFS in UHPC.

5.2 Recommendations

The study suggests promising applications in real structural components such as mini beams and columns. To validate the practical viability of these replacement mixes, it is recommended that they be tested in actual structural applications. Conducting real-world tests on mini beams and columns will provide critical insights into their performance under various load and stress conditions. These tests will ensure that the material maintains its integrity and strength, which is crucial for structural safety and durability.

Further investigations should focus on the advancement of ductility, direct tensile strength, and resistance to carbonation of UHPC mixes with ladle furnace slag. Ductility is essential for the material's ability to absorb and dissipate energy, particularly in seismic zones. Testing the ductile performance of these mixes in structural elements will help understand their resilience during dynamic loading conditions. Additionally, direct tensile strength is a vital property for elements subjected to tensile stresses. Conducting direct tensile and split-cylinder tests on samples with different slag replacement levels will evaluate the tensile performance and identify potential enhancements.

Comprehensive durability testing, including freeze-thaw resistance, chloride penetration, and sulfate attack, should also be undertaken to provide a holistic view of the material's durability. These tests will confirm the suitability of UHPC with ladle furnace slag for various environmental conditions, contributing to the development of more robust and durable concrete structures and promoting sustainable construction practices by utilizing industrial by-products.

5.3 Limitations

Resistance to carbonation is another critical area for ensuring the long-term durability of UHPC structures. Due to absence of proper testing equipment, tests required to study the resistance to carbonation could not be conducted in this study. But it is expected that UHPC incorporated with ladle furnace slag will show higher resistance to carbonation.

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