UTILIZATION OF SURFACE TREATED INDUCTION FURNACE SLAG (IFS) AS REPLACEMENT OF COARSE AGGREGATE IN CONCRETE

FINAL YEAR PROJECT UG-2020

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2024

This is to certify that the Final Year Design Project Titled

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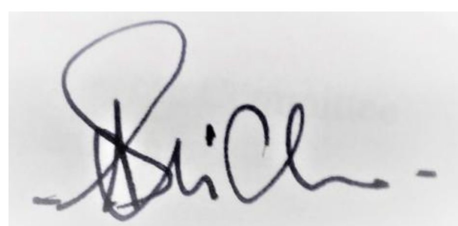

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ABSTRACT

This study aims to mitigate the environmental and economic impacts of steel and concrete production by exploring the utilization of Induction Furnace Slag (IFS) Aggregates in Concrete. The potential benefits include reduced reliance on natural aggregates and mitigation of steel slag dumping, alongside cost reductions in the construction sector. Literature review highlighted the heterogeneous properties of IFS, necessitating innovative mechanical and chemical treatments to enhance its bonding with cement matrix. Mechanical abrasion, particularly with a 10-minute treatment, demonstrated a significant improvement in compressive, split tensile, and flexural strengths compared to natural aggregate. Chemical treatments, notably 4M NaOH solution, also exhibited notable enhancements in strength parameters. Moreover, IFS showed comparable water absorption and soundness test results to natural aggregate, affirming its suitability as a replacement. These findings suggest the viability of IFS in concrete applications, with potential extensions to rigid pavements due to its robust mechanical properties. In conclusion, the study underscores the significance of treatment methods in optimizing IFS performance and highlights its potential as a sustainable alternative in concrete production.

DEDICATION

We owe a huge debt of gratitude to our families who have always been there for us and our teachers who ignited our passion for learning.

ACKNOWLEDGEMENTS

Deepest thanks to Allah for guiding us through our incredible NUST journey and making achievements seem effortless. Completing this FYP thesis is a major accomplishment. We owe immense gratitude to Dr. Shaukat Ali Khan for his guidance, encouragement, and belief in us. His mentorship has shaped the project and equipped us with valuable research skills. We also thank the lab staff for their expertise and assistance. Our deepest thanks extend to our families, especially parents, for their unwavering support; this journey wouldn't have been possible without them. Finally, we thank our friends for their support and camaraderie.

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CHAPTER 1

1. INTRODUCTION

1.1. Background

The construction industry is a major pillar of global progress, fueling urbanization, driving infrastructural advancements, and shaping the built environment that underpins our society. This sector is experiencing tremendous growth, driven by several factors:

- **Urbanization:** The world is rapidly urbanizing, with the United Nations predicting that the global urban population will reach 68% by 2050. This surging urbanization necessitates the construction of new housing units, commercial spaces, and infrastructure to accommodate growing urban populations.
- **Developing Economies:** The rapid economic development of countries like China and India is driving a significant demand for new construction projects. These countries are investing heavily in infrastructure development, including transportation networks, power plants, and industrial facilities. According to a report by the Global Construction Perspectives, GCP Global, the global construction industry is expected to reach $17.5 trillion by 2030, with developing economies playing an increasingly prominent role in this growth.
- **Infrastructure Renewal:** Aging infrastructure in developed countries requires significant investment in repairs and upgrades. Bridges, roads, and buildings deteriorate over time, necessitating ongoing maintenance and reconstruction projects to maintain safety and functionality.

1.1.1. Pakistan's Construction Industry: A Context for Sustainable Practices

Pakistan's construction sector holds immense strategic importance for the nation's economic development and progress. As the 5th most populous country globally, Pakistan boasts a young and rapidly growing population exceeding 220 million, with a strong labor force of approximately 60 million. This demographic boom translates into a constant demand for new housing units to accommodate the growing population and address the existing housing shortage. Additionally, Pakistan's urban-rural population distribution, with 63.62% of citizens residing in rural areas, necessitates the expansion of residential and infrastructural facilities in these regions [1].

The Pakistani government recognizes the pivotal role of the construction industry in driving economic growth and job creation. Consequently, significant investments have been directed towards infrastructure projects, with the China-Pakistan Economic Corridor (CPEC) being a prime example. This multi-billion-dollar initiative aims to connect China's Xinjiang province to Gwadar Port in Pakistan through the construction of roads, railways, power plants, and special economic zones, significantly boosting construction activity across the country.

Beyond housing, the government is actively pursuing the development of large-scale infrastructure projects to enhance connectivity and support economic growth. These mega civil projects encompass the construction of new dams (e.g., Diamer-Bhasha Dam, Dasu Dam), motorways (e.g., Sukkur-Multan Motorway, Karachi-Lahore Motorway), and railway upgrades (e.g., Main Line 1 under CPEC). The execution of these projects necessitates substantial investment in construction materials, labor, and machinery, thereby propelling the construction industry forward.

Notably, the gross fixed capital formation (GFCF) in Pakistan's private sector witnessed a substantial 20.6% increase between the fiscal years 2019 and 2020, with the private sector GFCF accounting for over 95% of the total. This surge in private investment, coupled with government initiatives and demographic factors, collectively accentuates the immense potential of Pakistan's burgeoning construction industry, and underscores the imperative for sustained investment and development [1].

While the construction boom presents exciting opportunities, it is crucial to address the environmental impact of the industry's reliance on conventional materials and practices, which can lead to increased resource depletion, greenhouse gas emissions, and pollution. Embracing sustainable construction practices is essential to mitigate these concerns and ensure the long-term viability of the sector.

1.1.2. Concrete: The Workhorse of Construction

Concrete is the cornerstone of modern construction, a ubiquitous material shaping our built environment. It's a composite material comprised of coarse aggregate (gravel, crushed rock), fine aggregate (sand), Portland cement as the binder, and water. Here's a closer look at concrete's composition:

- Coarse Aggregate: These larger particles, typically ranging from 63mm to 4.75mm in size, occupy a substantial portion of the concrete mixture, ranging from 60% to 75% by volume. Sourced from crushed rock quarries or recycled construction debris, they play a critical role in providing strength and stability to the concrete matrix.
- Fine Aggregate: Sand (particles less than 4.75mm) fills the voids between the coarse aggregate and contributes to the workability of the concrete mix. Sand is primarily obtained from riverbeds or sand mines.
- Portland Cement: The binding agent that holds the entire mixture together. It's produced by heating a blend of limestone, clay, and other materials to high temperatures in a rotary kiln in a process known as clink erization.
- Water: Essential for the chemical reaction (hydration) between cement and water that creates the binding paste, giving concrete strength and setting properties.

1.1.2.1. Coarse aggregate: properties and selection

Coarse aggregate plays a critical role in determining the overall performance and properties of concrete. Here, we delve into the key properties of coarse aggregate essential for successful concrete production:

- Size and Gradation: The size and size distribution (gradation) of course aggregate significantly impact the workability, strength, and porosity of concrete. Well-graded aggregate with a variety of particle sizes creates a denser packing, minimizing voids and leading to stronger concrete. Conversely, poorly graded aggregate with limited size variation can lead to segregation (separation of different sized particles) and reduced workability, impacting the overall quality of the concrete.

- Shape: The shape of coarse aggregate particles also influences concrete properties. Angular aggregates with rough surfaces interlock better, enhancing the strength and stability of the concrete matrix. Rounded particles, while offering good workability, can lead to a slightly weaker concrete mix.
- Strength and Durability: Coarse aggregate itself needs to be strong and durable to withstand the loads placed upon the concrete structure. Weak or friable aggregates can lead to cracking and premature failure of the concrete.
- Cleanliness: Adherent dirt, dust, or organic coatings on coarse aggregate can impair the bond between the aggregate and the cement paste, compromising the strength and durability of concrete. Therefore, ensuring clean aggregates free from impurities is crucial for optimal concrete performance.
- Soundness: Coarse aggregate should be sound, meaning it should be free from cracks, flaws, or internal weaknesses that might deteriorate over time and lead to concrete failure.
- Specific Gravity and Absorption: The specific gravity and absorption characteristics of coarse aggregate influence the overall unit weight and water demand of the concrete mix. These properties need to be considered during mixed design to ensure proper proportions and workability.

Selecting the proper coarse aggregate for a specific concrete application requires careful consideration of the desired properties and performance requirements. Factors such as the type of structure, anticipated loads, and environmental exposure conditions all play a role in the selection process. International standards like ASTM C33 (Standard Specification for Concrete Aggregates) provide guidelines for selecting suitable coarse aggregate based on previously stated properties.

By understanding the properties of coarse aggregate and implementing proper selection methods, we can ensure the production of high-performance, durable concrete structures.

1.1.3. The Reinforcement Backbone: Steel Rebars in Concrete

Concrete, while renowned for its compressive strength, exhibits limited tensile strength. To compensate for this limitation and ensure structural integrity under tension, steel rebars (reinforcing bars) are incorporated into concrete elements. These rebars act as a skeletal reinforcement system, absorbing tensile forces and preventing concrete from cracking or failing prematurely. Some of the key properties of steel are:

- High Tensile Strength: Steel rebars are specifically designed to possess high tensile strength, enabling them to effectively resist pulling forces that would otherwise cause concrete to crack. The specific strength requirements for rebars are defined by standards like ASTM A615 (Standard Specification for Deformed and Plain Bar Steel for Concrete Reinforcement).
- Ductility: Ductility, the ability of the steel to deform plastically before fracture, is another vital property for rebars. Ductile rebars allow for some yielding before failure, providing a warning sign of structural stress and enhancing the overall safety of the concrete structure.
- Bond with Concrete: The effectiveness of steel rebars relies on a strong bond with the surrounding concrete. Deformations (ribs or lugs) are typically rolled onto the surface of rebars to enhance this mechanical bond between the steel and concrete.
- Corrosion Resistance: Exposure to moisture and chloride ions can lead to corrosion of steel rebars, compromising their structural integrity. Depending on the application and environmental conditions, different types of steel rebars with enhanced corrosion resistance may be employed. For example, epoxy-coated rebars offer improved corrosion protection for use in harsh environments.

1.1.3.1. Production of Steel Rebars

Traditionally, steel rebars were primarily produced using the blast furnace process. This process involves heating iron ore, coke (a high-carbon fuel), and limestone in a blast furnace to a very high temperature. The resulting molten iron contains impurities that are removed through a further process called steelmaking. However, the blast furnace process has a significant environmental impact, these concerns include high energy consumption leading to CO_2 emissions and air pollution from coke production.

1.1.3.2. Shifting Towards Sustainable Alternative

Due to the environmental concerns associated with blast furnaces, the steel industry is increasingly turning towards alternative production methods for rebars:

- **Electric Arc Furnace (EAF):** EAFs utilize electric energy to melt scrap steel, offering a more environmentally friendly approach compared to blast furnaces. This process reduces reliance on virgin iron ore and coke, minimizes air pollution emissions, and has a lower overall carbon footprint. Studies suggest that EAF steel production can result in a reduction of CO_2 emissions by up to 80% compared to blast furnaces.
- **Induction Furnace (IF):** Induction furnaces employ electromagnetic induction to heat and melt steel scrap. This method boasts even greater energy efficiency compared to EAFs and offers precise control over the melting process. While the global production of steel rebars through IFs is still developing, it represents a promising approach for minimizing environmental impact.

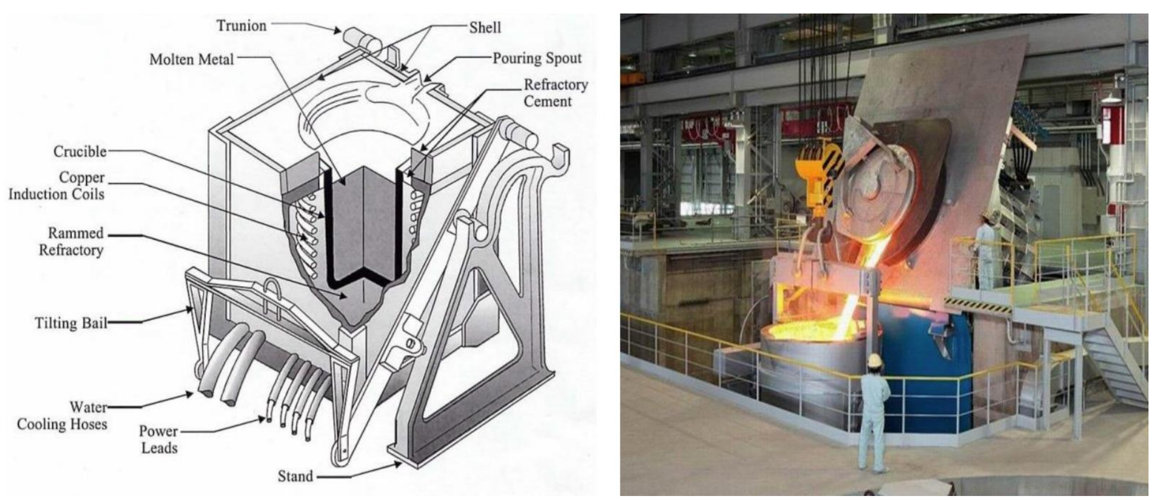

Figure 1 Induction furnace

The growing adoption of EAFs and IFs for steel rebar production signifies a crucial step towards a more sustainable construction industry. By utilizing recycled scrap steel and minimizing reliance on virgin resources and fossil fuels, these alternative methods can pave the way for a greener future.

1.1.4. The Environmental Cost of Conventional Construction Materials

1.1.4.1. Environmental Impact of Concrete

The tremendous growth of Pakistan's construction industry, while promising, comes with an environmental cost. Traditional construction materials, particularly concrete, have a significant impact on the environment. Let's delve deeper into the specific environmental concerns associated with concrete:

- High CO2 Emissions: The production of Portland cement, a key component in concrete, is a major source of global CO2 emissions, accounting for an estimated 4-8%. This energy-intensive process, particularly the clink erization stage, releases significant amounts of carbon dioxide. For example, one ton of Portland cement production emits approximately 662 kg of CO2. This underscores the environmental impact of concrete production and the need for sustainable industry practices [2].
- Resource Depletion: Concrete relies heavily on natural aggregates, such as sand, gravel, and crushed rock, for its strength and structure. The extraction of these aggregates can lead to environmental degradation, including deforestation, habitat destruction, and disruption of natural ecosystems. A report by the United Nations Environment Programmed estimates that the construction sector consumes approximately 50% of all extracted resources globally [3].

1.1.4.2. Environmental Impact of Steel

Steel, another crucial construction material, also presents environmental challenges. According to World Steel, Pakistan produced approximately 6 million tons of crude steel in 2022, up from 5.4 million tons in the proceeding annum [4]. This significant increase in steel production produces the following environmental issues:

- Energy Consumption: Steel production is an energy-intensive process, requiring vast amounts of fossil fuels like coal. This high energy demand contributes to greenhouse gas emissions and air pollution. Studies suggest that steel production accounts for around 8% of global CO2 emissions. [5]
- Pollution Concerns: The steel production process can also generate significant air and water pollution. The release of pollutants such as sulfur oxides, nitrogen oxides, and particulate matter can have detrimental effects on human health and the environment.
- Waste Production: The steel industry generates a significant amount of waste, particularly in the form of slag. Slag is a byproduct of the steelmaking process, produced when impurities in the iron ore, flux, and other materials are separated from the molten iron. The slag ends up in landfills not only contributing to the growing problem of waste management but also represents a loss of potentially useful materials. Therefore, finding effective ways to reduce, reuse, and recycle slag is a major challenge for the steel industry.

The environmental impact of conventional construction materials is not just a theoretical concern. Consider the example of the China-Pakistan Economic Corridor (CPEC) - a massive infrastructure project vital for Pakistan's economic development. While CPEC offers significant opportunities, concerns have been raised about its potential environmental footprint. The large-scale construction involved in this project necessitates vast quantities of concrete and steel, which could translate to increased greenhouse gas emissions and resource depletion if sustainable practices are not prioritized.

Pakistan's booming construction industry demands a concerted effort to mitigate the environmental impact of conventional materials like concrete and steel. We must actively seek ways to reduce their environmental footprint and embrace sustainable construction practices for a greener future.

1.1.5. The Production and Environmental Impact of Slag

Slag is a byproduct generated during the steelmaking process. It forms when impurities in the raw materials (such as iron ore, fluxes like limestone, and other additives) separate from the molten iron. This material, once cooled and solidified, possesses various properties making it useful in several industrial applications. Slag is commonly categorized into two types based on the production process: blast furnace slag and steel furnace slag.

Blast Furnace Slag (BFS): Produced during the extraction of iron from iron ore in a blast furnace.

Induction Furnace Slag (SFS): Produced from steelmaking processes in an Induction furnace.

Figure 2 Induction furnace slag

1.1.5.1. Production of Slag in Detail

The production of slag involves several stages, primarily during the separation of metal from impurities in the molten state. Here's a detailed overview of the process:

Melting and Separation: In both blast and induction furnaces, raw materials including iron ore, coke, and limestone are heated to high temperatures. As these materials melt, the impurities separate from the molten iron and float to the top, forming a layer of slag.

Tapping: The molten slag is tapped off from the top of the molten iron at intervals. This slag is then processed further.

Cooling: The molten slag is cooled using different methods to produce either granulated or solid slag. Granulated slag is formed by rapid water cooling, resulting in a glassy, sand-like material, while solid slag is produced by slow air cooling, leading to a crystalline, rock-like material.

1.1.5.2. Constituents of Slag

The chemical composition of slag varies depending on the type and the raw materials used, but it generally includes:

- Silicon Dioxide (SiO_2)
- Calcium Oxide (CaO)
- Aluminum Oxide (Al_2O_3)
- Magnesium Oxide (MgO)
- Iron Oxide (FeO)

These constituents contribute to the slag's properties, making it suitable for applications such as cement production, road construction, and as a soil amendment.

1.1.5.3. Current Wasting Practices

Despite its potential uses, a significant portion of slag is wasted. In Pakistan, approximately 250,000 tons of slag is produced annually, much of which is disposed of in landfills or left in waste dumps. These practices not only squander valuable materials but also pose environmental challenges.

Figure 3 Dumping of induction furnace slag

1.1.5.4. Environmental Impacts of Slag Disposal

The improper disposal of slag can lead to several environmental issues:

- Heavy Metal Leaching: Slag often contains heavy metals like lead, cadmium, and chromium. When exposed to rain, these metals can leach into the ground and contaminate soil and groundwater. This leaching process poses significant risks to ecosystems and human health, as these heavy metals can enter the food chain through contaminated water sources.
- Land Degradation: Disposing of slag in landfills or open dumps can lead to land degradation. The slag can alter the physical and chemical properties of the soil, reducing its fertility and making it unsuitable for agriculture or natural vegetation.
- Air Pollution: The fine particles from slag dumps can become airborne, contributing to air pollution. Inhalation of these particles can cause respiratory issues and other health problems in nearby communities.

- Water Contamination: Besides heavy metal leaching, slag dumps can also contribute to the contamination of surface water bodies through runoff, especially during heavy rains. This can harm aquatic life and disrupt local ecosystems.

1.1.6. Environmental Impact of Coarse Aggregate Production

Concrete, a cornerstone of construction, relies heavily on coarse aggregate for strength and stability. However, the production of coarse aggregate can have significant environmental consequences. Let's delve into the process and its environmental impact:

Production of Coarse Aggregate:

Coarse aggregate is typically obtained from two primary sources: crushed rock quarries and recycled construction and demolition debris.

1.1.6.1. Quarrying

Quarrying for natural aggregates involves the following processes:

- Site Selection and Exploration: Identifying suitable geological formations and conducting feasibility studies to assess resource availability and potential environmental impacts.
- Land Acquisition and Clearing: Acquiring land for the quarry operation and removing any existing vegetation or structures.
- Blasting and Excavation: Using explosives or mechanical means to break up the rock formations and extract the raw material.
- Crushing and Screening: Processing the extracted rock through crushers to achieve the desired size gradations for coarse aggregate.
- Transportation: Hauling the crushed aggregate by trucks to concrete production plants or construction sites.

Figure 4 Quarrying of natural aggregates

1.1.6.2. Recycled Aggregates

Recycled Aggregates: An alternative approach involves using crushed concrete and demolition debris as a source of coarse aggregate. This process includes:

Collection and Segregation: Collecting construction waste materials and separating them from other debris like wood or metal.

Crushing and Screening: Similar to quarried aggregate, the concrete debris is crushed and screened to meet size requirements.

1.1.6.3. Environmental Impact of Coarse Aggregate Production:

Both quarrying and recycled aggregate production methods have environmental drawbacks:

Quarrying:

- Habitat Destruction and Biodiversity Loss: Establishment of quarries can disrupt ecosystems, destroy natural habitats, and displace wildlife. This is particularly concerning in Pakistan, which is home to a diverse range of flora and fauna, including endangered species like the Himalayan brown bear, the houbara bustard, and the Indus dolphin. The destruction of natural habitats due to quarrying can disrupt these species' breeding grounds and food sources, threatening their populations.
- Air and Noise Pollution: Blasting, crushing, and transportation activities generate dust, noise, and vibrations, impacting air quality and disturbing surrounding communities. In Pakistan, air pollution is already a major concern, particularly in urban areas like Lahore and Karachi. Emissions from quarrying can further exacerbate air quality issues and respiratory problems among residents.
- Land Degradation: Quarrying activities can leave behind scars on the landscape and alter soil properties, hindering future land use options. Pakistan faces challenges with desertification and land degradation, and irresponsible quarrying practices can worsen these problems.
- Water Resource Depletion and Pollution: Quarrying operations can disrupt water tables and potentially contaminate water resources with dust and sediment runoff. Water scarcity is a growing concern in Pakistan, and quarrying can strain already limited water resources. Contamination of water sources can also have severe consequences for human health and aquatic ecosystems.

Recycled Aggregates:

- Energy Consumption: While preferable to quarrying, crushing recycled concrete still requires energy consumption. Pakistan's energy sector relies heavily on fossil fuels like coal, and this can contribute to greenhouse gas emissions and air pollution. However, the overall energy consumption compared to virgin aggregate production is still significantly lower. Exploring alternative energy sources for crushing facilities, such as solar or wind power, could further reduce the environmental impact.

- Air and Noise Pollution: Similar to quarrying, crushing recycled materials can generate dust and noise, albeit potentially to a lesser extent.
- Contamination Risks: Recycled aggregates might contain residual contaminants like asbestos or heavy metals from the original construction materials, requiring careful screening and monitoring.

1.1.7. Problem Statement

The construction industry in Pakistan is experiencing tremendous growth, driven by urbanization, infrastructure development, and a growing population. This surge in construction relies heavily on concrete, a material with significant environmental drawbacks. Traditional concrete production utilizes coarse aggregate, primarily sourced from crushed rock quarries. While this method fulfills the construction needs, it contributes to several environmental concerns:

Habitat Destruction and Biodiversity Loss: Quarrying disrupts ecosystems, destroys natural habitats, and displaces wildlife, threatening Pakistan's diverse flora and fauna.

Air and Noise Pollution: Blasting, crushing, and transportation activities associated with quarrying generate dust, noise, and vibrations, impacting air quality and disturbing communities.

Land Degradation: Quarrying activities scar landscapes, alter soil properties, and hinder future land use options, potentially worsening desertification issues faced by Pakistan.

Water Resource Depletion and Pollution: Quarrying operations can disrupt water tables and potentially contaminate water resources with dust and sediment runoff, straining already limited water resources and harming aquatic ecosystems.

As mentioned previously, quarrying for coarse aggregate harms the environment through habitat destruction, air and noise pollution, land degradation, and water resource depletion.

Furthermore, the steel industry, a vital sector for construction, generates a substantial amount of byproduct known as slag. Landfilling of this slag is a common practice, leading to:

- Landfill Consumption: Slag disposal occupies valuable landfill space, a growing concern in Pakistan.
- Loss of Resources: Slag potentially contains valuable materials that could be reused in various applications. Landfilling represents a loss of these resources.
- Environmental Issues: Landfilled slag can pose environmental threats if not managed properly. Rainwater can leach out heavy metals and disrupt the natural pH balance of soil and water bodies.

Therefore, there is a critical need for innovative and sustainable solutions in the construction industry of Pakistan. This research aims to address this challenge by investigating the potential of utilizing surface treated Induction Furnace Slag (IFS) as a replacement for coarse aggregate in concrete. By exploring this alternative, the research seeks to achieve the following objectives:

- Reduce reliance on virgin coarse aggregate sourced from environmentally damaging quarrying practices.
- Promote the beneficial reuse of slag, a byproduct of the steel industry, minimizing landfill waste and promoting resource efficiency.
- Evaluate the engineering properties and performance of concrete incorporating surface treated IFS as a replacement for coarse aggregate, ensuring the structural integrity and durability of concrete structures.

By successfully replacing coarse aggregate with surface treated IFS, this research has the potential to significantly reduce the environmental impact of the construction industry in Pakistan, while simultaneously contributing to a more sustainable and resource-efficient future.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Induction Furnace Slag

2.1.1. An overview

Ansu John and Elson John conducted a study that explored the feasibility of using IFS as an alternative to conventional fine aggregate. In their experimental investigation, they prepared concrete mixes with varying percentages of IFS as a replacement for fine aggregate. The percentages ranged from 20% to 60%. The results of their study indicated that a 30% replacement of fine aggregate with IFS resulted in a concrete mix that performed better than the control mix. This suggests that IFS can be effectively used as a partial replacement for fine aggregate in concrete, potentially leading to cost savings and environmental benefits. [6]

In another study, researchers assessed the possibility of using IFS as a full replacement for fine aggregate and a partial replacement for coarse aggregate. They found that the properties of the hardened concrete improved progressively with an increase in the percentage of IFS used as a replacement for coarse aggregate, up to a replacement level of 15%. This suggests that IFS can also be used as a partial replacement for coarse aggregate, further expanding its potential applications in concrete production. [7]

The potential of IFS as a replacement for coarse aggregate was also explored in a study that focused on its performance against chloride and sulphate damage. The researchers found that concrete mixes containing IFS as a partial substitute for Ordinary Portland Cement (OPC) exhibited good resistance to chloride and sulphate damage. This indicates that IFS can enhance the durability of concrete, making it a promising material for use in harsh environments. [8]

A study suggested the utilization of steel slag, including IFS, as a partial replacement for aggregate in concrete. The researchers concluded that steel slag could potentially be used as an alternative material to replace natural aggregate in concrete, resulting in a concrete mix that is environmentally friendly, cheap, and sustainable. [9]

In conclusion, the literature suggests that IFS has significant potential as a replacement for both fine and coarse aggregates in concrete. The use of IFS in concrete can lead to cost savings, environmental benefits, and improvements in the properties and durability of the concrete. However, the optimal replacement percentages may vary depending on the specific properties of the IFS and the requirements of the concrete mix. Further research is needed to fully understand the implications of using IFS in various concrete applications. This literature review provides a comprehensive overview of the current state of knowledge on the subject, and it can serve as a foundation for future research in this area.

"ASSESSING DURABILITY PROPERTIES OF INDUCTION FURNACE SLAG BLENDED NATURAL AGGREGATE CONCRETE" (2022)

This paper studied the long-term performance and durability characteristics of concrete containing a blend of natural aggregate and IFS aggregate as coarse aggregate. The performance characteristics of concrete samples with varying percentages of NA replaced by IFS, specifically 0%, 20%, 60%, and 80% by weight, were also studied.

The tests conducted in this study are as follows:

- Compressive Strength (ASTM C39)
- Water absorption of concrete (ASTM C642)
- Rapid Chlorine Penetration test (ASTM C1202)
- Drying Shrinkage Test (ASTM C157)

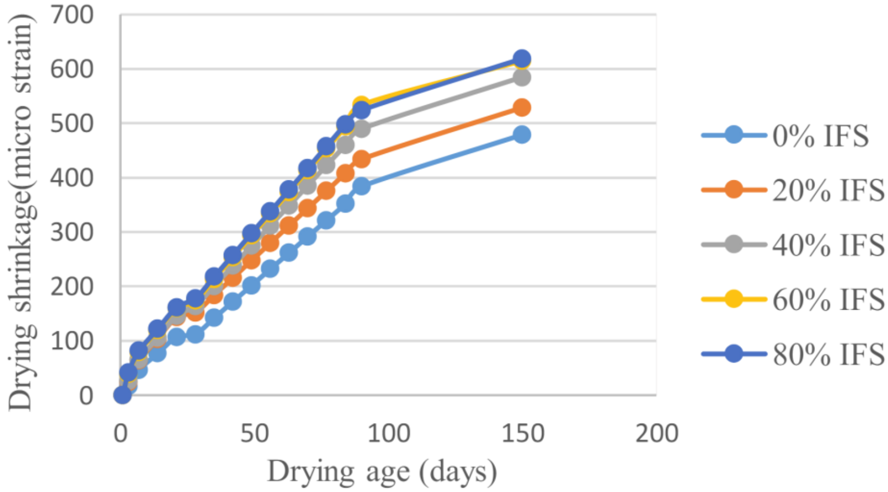

Figure 5 Drying shrinkage of concrete with varying composition of IFS

The study concluded that higher replacement percentages of Natural aggregate with IF-slag aggregate generally caused a decrease in the concrete performance. More specifically, the samples made with a higher percentage of IFS as coarse aggregate had poorer compressive strength, the RCPT (ASTM C1202) values were larger, and the drying shrinkage was more severe.

The authors recommended a 20% replacement of natural aggregate with IFS-aggregate as being viable for use in concrete.

"EXPERIMENTAL INVESTIGATIONS ON PARTIAL REPLACEMENT OF STEEL SLAG AS COARSE AGGREGATES AND ECO SAND AS FINE AGGREGATE" (2016)

This paper studied the replacement of coarse aggregate with IF-slag aggregate and fine aggregate with eco-sand, to make environmentally friendly concrete. Replacement of Natural Aggregate with IFS was studied up to 90%, while fine aggregate was replaced at a maximum percentage of 30%. The tests conducted in this study were:

- Compressive strength on concrete cubes at 7,14, and 28 days
- Split Tensile Strength on concrete cylinders at 28 days

The study concluded that the combination of 60% IFS and 30% eco-sand is the most optimal for use in concrete. Higher use percentages of IFS resulted in a reduction in strength.

Table 1 Determination of flexural strength

MIX ID	% OF STEEL SLAG	% OF ECO SAND	ULTIMATE LOAD (kN)	FLEXURAL STRENGTH AT 28 DAYS IN N/mm^2
MC	0	0	28	11.2
M1	0	30	35	13.6
M2	15	30	37	14.0
M3	30	30	43	14.8
M4	45	30	48	17.2
M5	60	30	31	19.2
M6	75	30	27	12.4
M7	90	30	24	10.8

"UTILIZATION OF INDUCTION FURNACE SLAG IN CONCRETE AS COARSE AGGREGATE." (2017)

This study was conducted in Bangladesh. It compared the use of IFS as coarse aggregate in concrete, to burnt clay aggregate- which is the most widely used aggregate in the country. The main properties that were compared were workability, compressive strength, and tensile strength of concrete. Concrete having different design strengths and w/c ratios was also studied.

The study concluded that IF-Slag aggregate is a better coarse aggregate than burnt clay aggregate. Aggregate testing showed that IFS aggregates had a lower water absorption than burnt clay aggregates, which directly translated into better workability of the concrete mix and a higher ultimate strength.

The largest strength increase was observed with a 50% replacement of burnt-clay aggregates with IFS. A further increase in percentage use of IFS aggregate led to a reduction in strength from the 50% maximum. However, it was noted that the strength of the concrete did not reduce below the strength level for the case of no replacement (100%BC+0%IFS) even with 100% IFS usage.

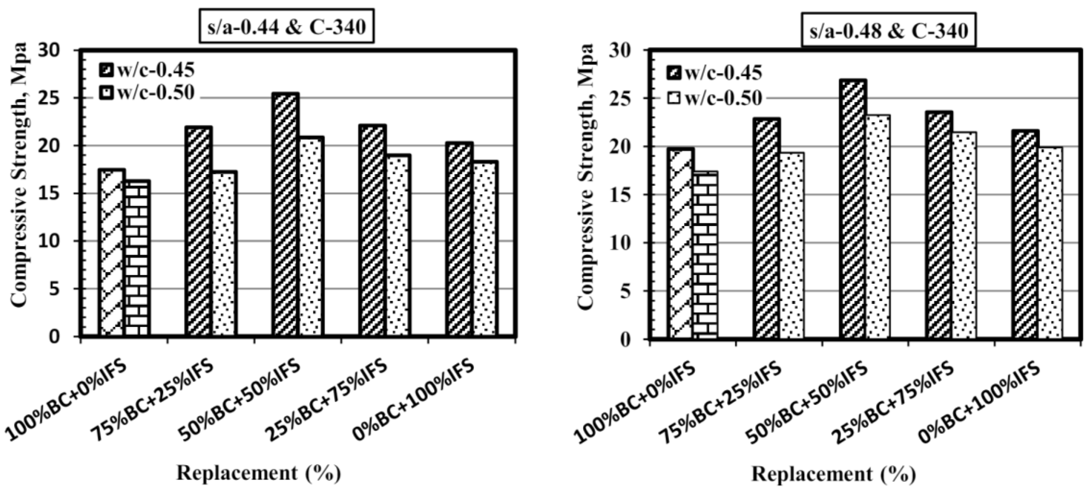

Figure 6 Compressive strength of concrete

This study did not compare the performance characteristics of IFSA concrete with concrete made from natural aggregates. Natural limestone aggregate has significantly different properties from burnt clay aggregate. As such, the findings of this study cannot directly be extrapolated to a comparative analysis of IFS concrete and NA concrete.

"MECHANICAL AND DURABILITY CHARACTERISTICS OF CONCRETE CONTAINING INDUCTION FURNACE STEEL SLAG AS AN ALTERNATIVE TO COARSE AGGREGATES." (2023)

This study compares the properties of IFS aggregate with Natural limestone aggregate. It also studied the feasibility of using IFS aggregate in concrete as a method to safely 'dispose' this industrial waste product. The following tests were conducted in this:

Aggregate tests:

- Unit weight and Specific gravity
- LA Abrasion test

Concrete Tests:

- Compressive tests of concrete cubes

- XRD of IFS concrete
- SEM of IFS concrete

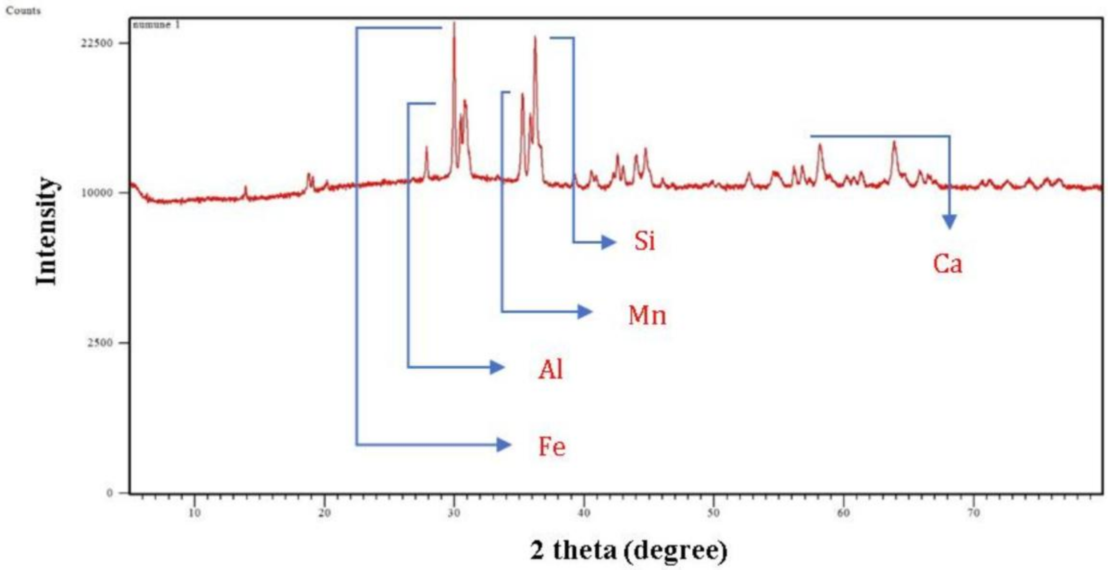

Figure 7 XRD analysis of induction furnace steel slag

This paper highlighted the use of micro-analyses to study the small-scale structure of IFS concrete and how it compares to natural aggregate concrete. It was observed that the IFS had a slightly porous micro-structure. However, this morphology was not seen on all samples, in some locations the slag had very few pores. It was concluded that slag had a heterogenous composition at the micro-level. Furthermore, the rough surface of the slag seen in SEM images likely contributed to having a better bond with the cement matrix.

Additionally, the composition of slag was also studied using X-ray diffraction. It was found out that slag mostly consists of metals and metal alloys like Fe, Si, Mn, and Al. Since these metals are present in the form of alloys, they do not react with water, nor do they get corroded. It was also found that the composition of the slag varied with the raw material entering the induction furnace, as well as the performance characteristics of the furnace itself.

Lastly, the compressive tests conducted on concrete cubes showed that IFS concrete had a higher ultimate strength at both 28 and 90 days, as compared to NA concrete. IFS50 concrete (50% replacement of natural aggregate with IFS aggregate) showed a 12%

increase in strength over the control sample. Similarly, IFS100 Concrete showed a 16.1% increase in strength over the control sample.

"IMPACT OF INDUCTION FURNACE STEEL SLAG AS REPLACEMENT FOR FIRED CLAY BRICK AGGREGATE ON FLEXURAL AND DURABILITY PERFORMANCES OF RC BEAMS" (2021)

This study aims to fill the gap in the literature by investigating the flexural and durability properties of RC beams made with various replacement levels of FCBA by IFSSA. The research includes a comprehensive experimental program to assess the workability, compressive strength, flexural performance, and durability properties (such as porosity, chloride ion penetration resistance, and water absorption) of the resulting concrete.

Table 2 Physical and chemical properties of aggregates.

	FCBA	IFSSA	Sand
Specific gravity	2.0	3.24	2.62
Unit weight (kg/m^3)	1140	1810	1565
Abrasion resistance (%)	41.87	18.89	-
Absorption capacity (%)	20.56	1.2	5.86
CaO (%)	4.18	4.94	-
SiO_2 (%)	60.43	26.18	-
Fe_2O_3 (%)	14.27	44.39	-
Al_2O_3 (%)	9.96	4.93	-
MgO (%)	1.69	0.46	-
K_2O (%)	5.23	0.56	-
TiO_2 (%)	1.81	1.73	-
MnO (%)	0.30	12.9	-
Na_2O (%)	0.90	0.45	-
ZnO (%)	0.10	2.33	-
SO_3 (%)	0.57	0.43	-
P_2O_5 (%)	0.24	0.08	-
SrO (%)	0.05	0.09	-
ZrO_2 (%)	0.05	0.11	-

The experimental program involved casting 27 RC beams with nine different replacement levels of FCBA by IFSSA (0%, 10%, 20%, 30%, 40%, 50%, 60%, 80%, and 100%). Flexural tests were conducted using a four-point loading test setup, and durability properties were evaluated based on compressive strength tests, porosity measurements, chloride ion penetration resistance, and capillary water absorption tests.

The results indicated that the flexural load capacity of RC beams increased significantly with higher IFSSA content, with the beam containing 80% IFSSA showing a 27% higher load capacity than the control beam. Compressive strength also improved markedly, with increases of 56% and 61% for concrete with 80% and 100% IFSSA, respectively. Durability properties showed a corresponding improvement, with reductions in porosity, chloride penetration, and water absorption by 43%, 54%, and 68%, respectively, for the 100% IFSSA replacement.

Previous studies have shown that incorporating industrial by-products like steel slag in concrete can enhance mechanical properties and durability**.** Research has indicated that the flexural load of concrete beams can be improved by replacing traditional aggregates with steel slag, leading to increased strength and reduced porosity**.**

The literature suggests that the relationship between the content of steel slag aggregate in concrete mixes and the mechanical and durability properties of reinforced concrete elements is a crucial aspect to consider for sustainable construction practices**.**

This study contributes to the growing body of evidence supporting the use of industrial by-products in concrete production. The findings suggest that IFSSA can effectively replace FCBA in RC beams, enhancing both mechanical and durability properties. This research provides a basis for future studies and practical applications in regions where natural aggregates are scarce and brick aggregate concrete is commonly used.

"APPLICABILITY OF INDUCTION FURNACE STEEL SLAG IN RC COLUMNS SUBJECTED TO AXIAL AND UNIAXIAL LOADING" (2023)

Researchers investigated the possibility of using Induction Furnace Steel Slag (IFS) partially instead of fine aggregate and as an additive in concrete for reinforced concrete (RC) columns. They focused on the amount of slag used and how the load was applied (cantered or off-centre). Ten small concrete columns were tested under different loading conditions.

Oxides	Cement	IF slag
Loss on ignition	2.25	7.71
CaO	60.74	15.94
SiO_2	18.14	36.1
Al_2O_3	2.9	26.4
Fe_2O_3	6.71	8.35
MgO	1.28	4.43
SO_3	2.09	1.11

Figure 8 Chemical properties of cement and IFS.

The researchers used regular concrete ingredients and processed IFS to a specific size. They created four concrete mixes with the same water-to-cement ratio:

- Regular concrete (no slag)
- Concrete with a small amount of IFS replacing cement
- Concrete with IFS replacing some of the fine aggregate (sand) in two amounts (10% and 30%)
- A mix combining regular concrete on the ends and concrete with 30% slag replacement in the middle

Half the columns were loaded directly in the centre, and the other half were loaded slightly off-centre. The researchers measured how much weight each column could hold before breaking, how much it bent, its initial stiffness, and how much energy it absorbed before failing.

The results showed that using slag generally reduced bending but allowed the columns to hold more weight. The mix with the most slag replacement (30%) held the most weight in both loading scenarios. However, this mix also bent less and absorbed less energy, indicating it was more brittle. Cracking typically started in the middle of the columns.

Overall, the study suggests that IFS can be a viable substitute for up to 30% of the fine aggregate in concrete for RC columns. It can improve the load-carrying capacity, but the concrete may be more brittle. Further research is needed to improve the flexibility of concrete containing slag.

2.2. Slag Surface Treatment

2.2.1. Effect of Aggregate Surface on the Properties of Concrete

The surface texture of aggregate, which can be either smooth or rough, plays a significant role in the properties of concrete. A smooth surface can improve workability, yet a rougher surface generates a stronger bond between the paste and the aggregate, creating a higher strength.

*2.2.1.1. **Effect on Strength and Permeation Characteristics***

A study by Hilal examined the effect of surface roughness of lightweight aggregate particles on the strength and permeation characteristics of lightweight aggregate concrete (LWAC). The study found that using treated lightweight aggregate with a rough surface helped in enhancing the compressive strength by about 13.5% and improving the permeation properties. This indicates that the surface roughness of the aggregate can significantly influence the strength and permeation characteristics of the concrete. [10]

*2.2.1.2. **Influence on Interfacial Bond Strength***

Research by Caliskan found that the surface roughness plays a significant role in determining the interfacial bond strength, particularly of smaller size aggregates. However, the effect diminishes as the aggregate size increases. This suggests that the surface roughness of the aggregate can influence the bond strength at the interface between the aggregate and the cement paste, which is a critical factor in the overall strength of the concrete. [11]

*2.2.1.3. **Aggregate Properties on Concrete Mix Design and Behaviour***

The characteristics of the aggregates significantly affect the performance properties of fresh and hardened concrete. It is found that shape, texture, and gradation have the most important role on the properties of fresh concrete, particularly workability. This suggests that the surface roughness of the aggregate can influence the mix design and behavior of the concrete. [12]

2.2.1.4. ***Conclusion***

In conclusion, the surface roughness of aggregate plays a significant role in the properties of concrete. It affects the workability, strength, permeation characteristics, and fracture surface roughness of concrete. Further research is needed to fully understand the complex interactions between aggregate surface roughness and concrete properties, and to develop guidelines for the selection and treatment of aggregates to optimize concrete performance.

2.2.2. Mechanical Abrasion of Slag Surface

2.2.2.1. Abrasion Resistance of Concrete with Coarse Aggregate

A study published in Springer developed lower-cement ultra-high-performance concrete (UHPC) incorporating basalt and calcined bauxite coarse aggregate. The UHPC with calcined bauxite aggregate showed 28% higher compressive strength than UHPC with basalt aggregate due to the rough surface texture and super high stiffness of the calcined bauxite. The evaluated UHPCs with coarse aggregate show good mechanical strength as well as excellent abrasion resistance than normal concrete. [13]

2.2.2.2. Influence of Coarse Aggregate Parameters on Abrasion Resistance

An experimental investigation used the ASTM C1138 (underwater) test method to investigate the influence of the quantity and type of coarse aggregates on the hydrodynamic abrasion resistance of concrete. [14]

2.2.2.3. Recycled Concrete Aggregates

A review on Recycled Concrete Aggregates (RCA) discussed the properties of RCA, the effects of RCA use on concrete material properties, and the large-scale impact of RCA on structural members. The review study found that replacing natural aggregate (NA) in concrete with RCA decreases the compressive strength but yields comparable splitting tensile strength. [15]

Figure 9 Los Angeles Abrasion Machine

2.2.2.4. Comprehensive Review on Abrasion Resistance of Concrete

A comprehensive review on abrasion resistance of concrete has been published in Gigvvy Science. The review covers various aspects of abrasion resistance of concrete, including the influence of aggregate properties and mechanical properties on the abrasion resistance of concrete. [16]

2.2.2.5. Mechanical Abrasion Using the Los Angeles Machine

The LA abrasion machine is often used to mechanically abrade coarse aggregate. The machine consists of a rotating drum with steel spheres, which abrade the aggregate as the drum rotates. The aggregate, along with the abrasive charge, are placed in the Los Angeles machine, which rotates at a specified speed for a predetermined number of revolutions.

2.2.2.6. Abrasion Process and Aggregate Degradation

During the rotation of the LA machine, the aggregate is subjected to abrasion, impact, and grinding. This process results in the degradation of the aggregate, with smaller particles passing through a sieve and larger particles remaining. The degree of abrasion can be controlled by adjusting the number of steel spheres in the drum and the number of revolutions.

2.2.2.7. Influence of Aggregate Properties on Abrasion

The properties of the aggregate, such as its hardness and toughness, can influence the degree of abrasion in the LA machine. Harder and tougher aggregates are more resistant to abrasion, while softer and weaker aggregates are more easily abraded.

2.2.2.8. Applications of Mechanical Abrasion

Mechanical abrasion using the LA machine can be used to prepare aggregate for further testing or for specific applications. For example, abraded aggregate can be used in concrete mixtures to improve the bond between the aggregate and the cement paste. Additionally, the abrasion process can be used to remove weak or undesirable material from the aggregate surface.

In conclusion, the Los Angeles machine provides a versatile tool for mechanically abrading coarse aggregate. The degree of abrasion can be controlled to suit specific requirements, and the abraded aggregate can be used in a variety of applications. However, further research is needed to optimize the abrasion process and to fully understand the effects of mechanical abrasion on the properties and performance of coarse aggregate.

2.2.3. Use of HCL Treatment for Coarse Aggregate in Concrete

The use of recycled concrete aggregates (RCAs) in construction has been gaining attention due to its potential benefits in sustainability. However, the performance of RCAs in concrete is often inferior to that of natural aggregates due to the presence of residual cementitious mortar, which has higher porosity and lower strength. This results in decreased mechanical and durability strength parameters of the hardened recycled aggregate concrete (RAC). Therefore, various treatment methods have been explored to improve the quality of RCAs.

2.2.3.1. Acid Etching Process

Acid etching is a chemical process where a strong acid, known as an etchant, is applied to the surface of a piece of metal to remove a portion of the metal's surface to create an image, design, or component. Unlike other processes, acid etching does not change the properties of a metal. The grain structure and strength of a metal remain intact after the etching process. Acid etching can be used on every type of metal and is ideal for thin materials that could be damaged by other processes. Various types of acids can be utilized in the etching of steel and stainless steel, including nitric acid, hydrochloric acid, or sulfuric acid.

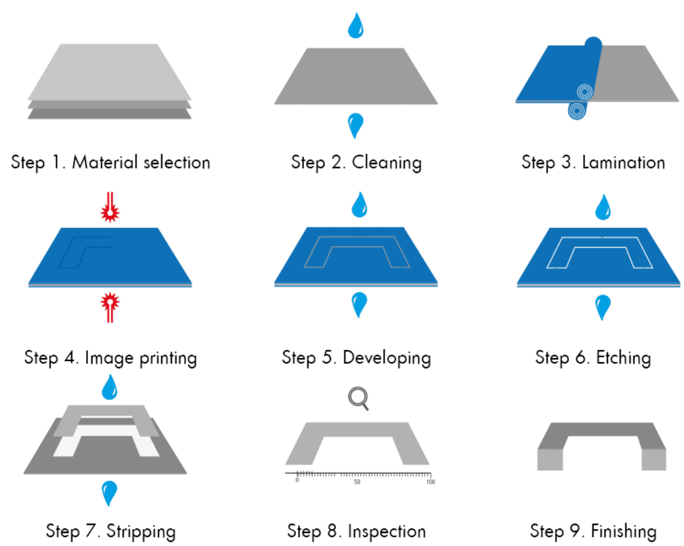

Figure 10 Acid Etching Process

Hydrochloric acid (HCl) is one of the acids used in acid etching. It is mixed with other chemicals, such as hydrogen peroxide, to etch the metal. The rate at which the metal will be etched is generally determined by the acid's strength. The stronger the acid, the faster the etching process. [17]

Silicon dioxide (SiO_2) does not appreciably etch with HCl. However, in the presence of chlorine, SiO_2 can be etched. Chlorine atoms diffuse and/or Cl^+ ions are implanted through the thin oxide, leading to the formation of a $SiCl_x$ interface layer between the two layers of Si and SiO_2. [18]

The reaction of calcium oxide (CaO) with hydrochloric acid (HCl) results in the formation of calcium chloride ($CaCl_2$) and water (H_2O). The balanced chemical equation for this reaction is:

$$CaO + 2HCl \rightarrow CaCl2 + H2O$$

2.2.3.2. HCL Treatment for Coarse Aggregate

One such method involves the use of acid treatment, specifically with hydrochloric acid (HCL). While specific literature on HCL treatment for coarse aggregate in concrete is limited, it is known that acid treatment can help in removing the adhered mortar, thus improving the quality of RCAs. [19]

2.2.3.3. Performance Enhancement

A study by Rampit-Greaves & Smith developed an innovative technique to treat coarse RCAs using a waterproofing agent. The water absorption was reduced by 50% while the bulk density and specific gravity had almost a 1% increase after treatment. The treated coarse RCAs were used to create new concrete at various replacement ratios to natural concrete aggregates (NCAs) to investigate the fresh and hardened concrete parameters. The treated RAC showed improvement in workability, hardened density, and compressive strength when compared to the untreated RAC. [20]

While the use of HCL treatment for coarse aggregate in concrete shows promise, more research is needed to fully understand its effects and potential benefits. It is also important to consider the environmental impact of using such treatments, as well as their feasibility on a commercial scale.

2.2.4. Alkali Etching

Alkali etching is a chemical process used to modify the surface of a material, often imparting an aesthetic effect or finish. It is commonly applied on aluminium which is to be anodized. The process is performed in caustic soda (NaOH) solutions, sometimes with additives. Alkali etching can also be used in the fabrication of microstructures for microelectromechanical systems (MEMS), where it is used to chemically remove undesired copper layers in the circuit pattern under alkaline conditions. [21]

2.2.4.1. NaOH Etching

Sodium hydroxide (NaOH) is often used in etching processes. For instance, etching aluminium in sodium hydroxide is a common pretreatment for aluminium that is to be anodized. It imparts a matte finish to the end product. In the context of silicon, NaOH has been used in a non-conventional etchant in the form of hydroxylamine (NH2OH) added sodium hydroxide (NaOH) solution, which has shown to improve etching characteristics such as etch rate, undercutting at convex corners, and etched surface morphology. [22]

When silicon dioxide (SiO2) reacts with concentrated sodium hydroxide (NaOH), the formation of sodium silicate (Na2SiO3) and water takes place. This reaction is as follows:

$$SiO2(s) + 2NaOH(aq) \rightarrow Na2SiO3(aq) + H2O$$

2.2.4.2. NaOH HCL Treatment for Coarse Aggregate

The use of NaOH to treat coarse aggregate, particularly waste tire rubber aggregates, has been explored in several studies. The treatment process involves immersing the aggregates in a NaOH solution for a certain duration.

A study by Younis and Nazari investigated the impact of NaOH solution pretreatment on the compressive strength of Tire-Derived Aggregate Concrete (TDAC). The results showed that NaOH-treated tire-derived aggregate (TDA) improved workability but did not significantly enhance compressive strength, causing a 34% reduction. However, when NaOH pretreatment was combined with a Sikalatex bonding agent, it enhanced workability by 28% and boosted compressive strength by 21% at the same water-cement ratio. [23]

Another study by Khern et al. examined the effect of surface treatment of waste tire rubber as coarse aggregates with different oxidizing solutions, including a 20% NaOH solution, on the mechanical, durability, and thermal properties of concrete. The study found that the improvement of concrete strength was only significant when the treatment with NaOH was prolonged to 72 hours. [24]

A similar study found that the split tensile strength was maximum for 15% replacement of rubber and for treatment with NaOH. However, as the percentage of rubber increased, the value of split tensile decreased, although an improvement was seen when treated rubber was used to replace coarse aggregate. [25]

In conclusion, the treatment of coarse aggregate with NaOH has shown mixed results in terms of mechanical properties of concrete. While some studies have reported improvements in workability and strength, others have found a decrease in strength. The duration of treatment and the percentage of aggregate replacement appear to be significant factors influencing these outcomes.

2.2.5. Summary

2.2.5.1. Mechanical and Durability Characteristics

Studies have shown that IFS concrete has higher compressive strength compared to traditional concrete. Research in 2021 on RC beams indicated that higher IFS content significantly improved flexural load capacity and durability properties.

2.2.5.2. Surface Treatment of Aggregates

The surface texture of aggregates plays a crucial role in concrete properties. Rough surfaces generally create stronger bonds with cement paste, enhancing strength and permeation resistance. Studies confirmed that rougher aggregates improve compressive strength and interfacial bond strength.

2.2.5.3. HCL and NaOH Treatment for Aggregates

Hydrochloric acid (HCL) and sodium hydroxide (NaOH) treatments can improve the quality of recycled concrete aggregates (RCA) by removing adhered mortar. While HCL treatment shows promise, more research is needed to understand its full impact. NaOH treatment has shown mixed results, with some studies reporting improved workability and strength, depending on treatment duration and aggregate replacement percentage.

2.2.5.4. Conclusion

IFS has significant potential as a sustainable replacement for both fine and coarse aggregates in concrete, offering environmental benefits, cost savings, and enhanced durability and mechanical properties. Surface treatments like HCL and NaOH can further enhance aggregate performance, though optimal methods and replacement levels vary. Further research is necessary to optimize IFS use in concrete applications.

CHAPTER 3

3. METHODOLOGY

3.1. Materials & Testing

3.1.1. Materials

The materials used in this study are generally pertaining to those used in the construction industry, with the inclusion of Induction Furnace slag (IFS), which was used as a 100% replacement for the coarse aggregate.

The following are brief overviews of the materials used:

3.1.1.1. Cement:

The Cement used was ordinary Portland cement (Type 01) that is widely used in the construction industry. Bestway Cement was used, which is a brand that is widely available for use in Pakistan.

Table 3 OPC properties

Specification	**Details**
Product Name	Bestway Cement Limited Ordinary Portland Cement
Components	Clinker 95%, Gypsum 5%, No Other Additives
Grade	53
Compressive Strength	Up to 10,000 PSI (LBF/IN2) at 28 Days
Initial Setting Time	30 minutes
Final Setting Time	600 minutes
Fineness	225 m^2/kg
Specific Gravity	3.0
Sulphate Content	2.5% max
Chloride Content	0.1% max
Bulk Density	1,450 kg/m^3

3.1.1.2. Superplasticizer

To improve workability and reduce water content in the concrete mix, ultimately enhancing strength, a high-range water reducer (HRWR) was employed. Sika® ViscoCrete®-20 HE, a commercially available superplasticizer compatible with Ordinary Portland Cement (OPC) was selected.

Dosage Optimization:

A series of trial mixes were conducted with varying Sika® ViscoCrete®-20 HE concentrations within the recommended range to determine the optimal dosage for the specific mix design. Workability was assessed using slump tests according to ASTM C143, targeting a slump of 75 to 100 mm. The final dosage selected minimized the impact on setting time, which was monitored using the Vicat apparatus according to ASTM C191, while achieving the target workability.

Superplasticizer Use in Concrete Mixing:

The predetermined dosage of Sika® ViscoCrete®-20 HE was added to the mixing water

Table 4 Superplasticizer properties

Specification	Details
Product Name	Sika® ViscoCrete®-20 HE
Product Type	High-Range Water-Reducing and Superplasticizing Admixture
Appearance / Color	Light brown liquid
Density	Approximately 1.08 kg/L at 20°C (68°F)
pH	4.0 - 6.0
Main Component	Modified polycarboxylate ether
Chloride Content	< 0.1%
Alkali Content	< 1.0%
Dosage	0.2% - 2.0% by weight of cementitious material
Standards / Approvals	ASTM C494/C494M Type F and G, EN 934-2: T3.1/3.2

- Natural Aggregate: Natural Limestone Aggregate (Margalla Crush) was used to make a baseline concrete mix, against which the properties of IFS concrete were evaluated.
- Induction Furnace Slag (IFS) Aggregate: Evaluating the properties of IFS aggregate and its use as a feasible replacement of coarse aggregate in concrete was one of the primary objectives of this study. The IFS was obtained from Fazal Steel Mills, I-9, Islamabad. It was then crushed into a size that was suitable for use in concrete.

3.1.1.5. Slag Procurement

One of the first steps of our research was the procurement of slag. We reached out to several steel mills located in I-9 sector of Islamabad and finally Fazal Steel Mill cooperated with us and provided us with induction furnace slag throughout our research.

3.1.1.6. Selection of Gradation

Different applications have varying requirements for strength, workability, permeability, and other properties. For example, concrete for pavements needs a different gradation than concrete for slabs. Dense gradations, with a balanced mix of coarse, medium, and fine particles, are preferred for high-strength concrete as they allow efficient packing and minimize voids that could weaken the structure. In contrast, applications requiring good flow and pumpability, such as cast-in-place walls, might need a higher content of fine aggregate. Driveways or slabs might benefit from a slightly coarser gradation for better stability during placement.

Densely graded concrete generally offers better freeze-thaw resistance by minimizing water absorption and potential cracking. It also provides lower permeability, which is desirable for structures exposed to water or moisture. However, extremely low permeability can sometimes trap air bubbles, affecting strength. Factors like freeze-thaw resistance and sulfate resistance might influence gradation selection.

The size distribution and surface texture of treated slag will influence how well it packs together and interacts with the cement paste. Standards like the Fuller Curve or Fuller-

Thompson Curve provide a good starting point for densely graded concrete, depicting the ideal relationship between particle size and the percentage of material passing a specific sieve size.

Selecting the best gradation often requires trial mixes. In this study, several trials were conducted, and the crushed slag passing through a 1-inch sieve and retained on a #16 sieve was used in the concrete mix.

3.1.2. Treatment of Slag

Mechanical and Chemical Methods were chosen to treat the Slag aggregate. Slag treatment was deemed required because of two of the properties of Untreated Slag:

- Heterogenous composition of Slag: Some of the slag lumps were extremely hard, impermeable, and resistant to being crushed. On the other hand, some lumps were porous, extremely fragile, and would have likely reduced the ultimate compressive strength of our concrete mix.
- Glassy Surface: Even the stronger slag lumps possessed a glassy surface that would likely have inhibited the formation of a strong ITZ. This hypothesis was also corroborated by our initial testing.

In conclusion, the treatment was to reduce the number of weak, porous slag lumps, as well as to roughen the surface of the slag. Two main methods were used:

3.1.2.1. Mechanical:

A Los Angeles (LA) Abrasion Machine was employed for the mechanical treatment of the induction furnace slag (IFS). This standardized test apparatus, commonly used in construction, evaluates the resistance of aggregate to degradation through crushing and abrasion. The mechanical treatment process involved the following steps:

1. Crushing Time Variation (5, 10, 15 minutes): The IFS was crushed in the LA Abrasion Machine for varying durations (5, 10, and 15 minutes) to investigate the impact of crushing intensity on several aspects:

- Particle Size Distribution: Generally, longer crushing times result in finer slag particles with a wider range of sizes. This can be beneficial for achieving denser packing within the concrete mix.
- Surface Texture: The crushing process roughens the surface of the slag particles, potentially improving the mechanical bond with the cement paste. However, excessive crushing might create excessively angular and flaky particles, potentially hindering workability.
- Sieving (Removing Fines): After crushing, the slag was sieved using a #16 sieve (1.18 mm opening) to remove any very fine particles or dust. These fines can negatively impact workability and hinder the formation of a strong bond between the aggregate and cement paste.

2. Washing: Following sieving, the crushed slag was washed with clean water to remove any remaining dust or debris that could affect the bond with the cement paste during concrete production.

The methodology adopted for mechanical treatment employed a LA Abrasion Machine with varied crushing durations (5, 10, and 15 minutes) to investigate the influence of crushing intensity on particle size distribution, surface texture, and the removal of fines. This approach aimed to optimize the mechanical treatment for achieving a balance between generating a finer particle size for denser packing, enhancing surface texture for improved bonding, and avoiding excessively crushing that could lead to workability issues. The subsequent sieving and washing steps ensured a clean, well-graded aggregate suitable for concrete production.

3.1.2.2. Chemical:

The induction furnace slag (IFS) underwent chemical treatment with sodium hydroxide (NaOH) solution to investigate its influence on surface characteristics and subsequent performance in concrete. The process involved the following steps:

1. Dissolution of Weak Components and Surface Etching: The IFS was submerged in NaOH solutions of varying concentrations (1M, 4M, and 8M) for a 24-hour period. This aimed to achieve a dual effect:
    - Dissolution of weaker, more porous components within the slag matrix, leading to a denser structure.
    - Slight etching of the slag particle surfaces, creating a rougher texture for enhanced mechanical bonding with the cement paste in the concrete mix.
2. Washing and Drying: Following the soaking period, the chemically treated IFS was thoroughly washed with clean water to remove any residual NaOH solution that could potentially react with the cement paste in an uncontrolled manner. The washed slag was then dried to achieve a consistent moisture content suitable for concrete production.

The selection of NaOH concentrations and soaking time were used to explore the impact of solution strength and treatment duration on the chemical treatment's effectiveness. The washing and drying procedures ensured consistency and minimized potential negative interactions between the treated slag and the cement paste within the concrete mix.

3.1.3. Preparing Mix Design

The American Concrete Institute (ACI) standard provides a methodology for selecting proportions for normal, heavyweight, and mass concrete. It outlines a process for calculating water-cement ratio, cementitious content, and aggregate proportions based on desired strength, workability, and other factors. Initially, two cubes were cast to assess the viability of the project. These cubes used a concrete mix made in accordance with ACI 211.1-91 for a baseline strength of 15 MPa.

Afterwards the mix design was further refined in accordance with a baseline of 20 MPa. Most of the specimens in our study used this mix design, with the only difference being how we prepared the IF-Slag aggregate.

3.1.3.1. Mix Design of Concrete

The Concrete mix was prepared according to ACI code 211.1-91. Because no data is available on coarse aggregates made from Induction-furnace slag, the following mix is designed by assuming the coarse aggregates as normal. The data is then extrapolated to fit the differing properties of IFS aggregate, namely its higher density and lower water absorption.

Problem Statement: A Concrete mix is to be designed having a compressive strength of 20 MPa at 28 days. The concrete is assumed not to be exposed to freeze-thaw cycles. Maximum aggregate size of 25 mm is required. Statistical data is not available. The materials available are as follows:

Cement: Type I with relative density of 3.0.

Coarse aggregate: Well graded, 25-mm nominal maximum-size IFS aggregate relative density of 2.72, absorption of 0.5% and oven-dry rodded bulk density of 1600Kg/m^3 (assumed).

Fine aggregate: Natural sand with oven-dry relative density of 2.64 and absorption of 0.7%. The laboratory sample moisture content is 3%. The fineness modulus is 2.80.

The required compressive strength for proportioning f'_{cr} is given by:

$$f'c + 7.0$$

$$i.e. f'cr = 20 + 7.0 = \mathbf{27\ MPa.}$$

Table 5 Relationship Between Water to Cementitious Material Ratio and Compressive Strength of Concrete

Compressive Strength at 28 days, Mpa	**Water-cementitious materials ratio by mass**	
	Non-air-entrained concrete	**Air-entrained concrete**
45	0.38	0.30
40	0.42	0.34
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

For 27 MPa, the w/c ratio is 0.57 (non-air-entrained concrete)

Table 6 Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate

Slump, mm	Water, Kilograms per cubic meter of concrete, for indicated sizes of aggregate							
	9.5 mm	12.5 mm	19 mm	25 mm	37.5 mm	50 mm	75 mm	150 mm
	Non-air-entrained concrete							
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
Appropriate amount of entrapped air in non-air-entrained concrete, percent	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2
	Air-entrained concrete							
25 to 50	181	175	168	160	150	142	122	107
75 to 100	202	193	184	175	165	157	133	119
150 to 175	216	205	197	184	174	166	154	-
Recommended average total air content, percent, for level of exposure:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

The required slump is taken as 50 mm, for non-air-entrained concrete, the % entrained air is 1.5%.

***Water content*:** In accordance with Table 9-5 or Fig 9-5, the required water content for a 50-mm slump, air-entrained concrete with 25-mm aggregate size is about 180 Kg/m^3.

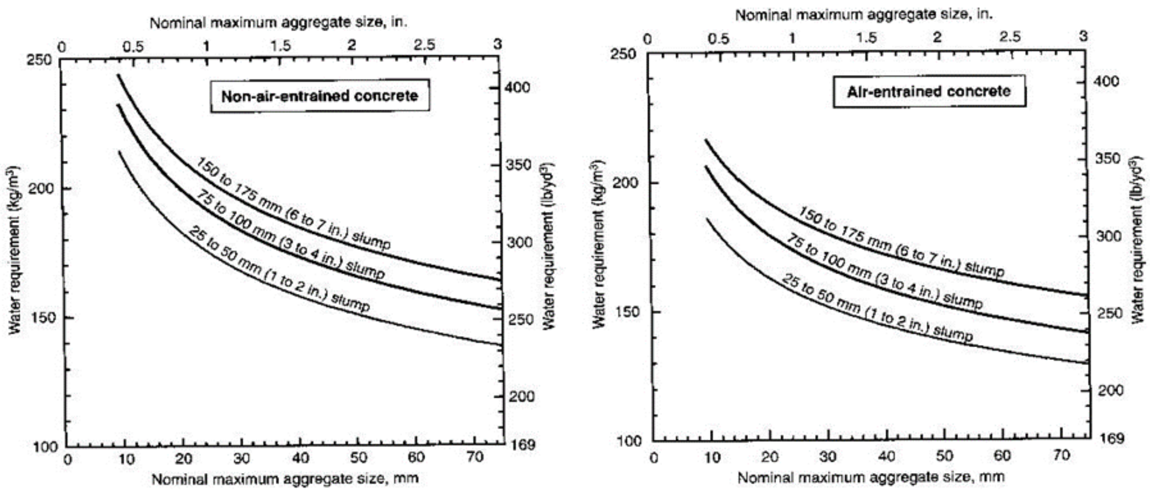

Fig. 9-5. Approximate water requirement for various slumps and crushed aggregate sizes for (left) non-air-entrained concrete and (right) air-entrained concrete. Adapted from Table 9-5, ACI 211.1 and Hover (1995 and 1998).

Figure 11 Water requirement for various slumps and aggregate sizes

***Cement content*:** The water content of 180 kg/m^3, and the w/c ratio of 0.57 dictates a cement content of 316 kg/m^3.

Coarse aggregate content: The bulk volume of CA (of 25-mm size) recommended when using sand with fineness 2.90 is 0.66. (Table 9-4 or Fig 9-3).

Therefore, the oven-dry mass of CA for a cubic meter of concrete will be density times the volume.

$$i.e. 1600 * 0.67 = 1056\,Kg.$$

Table 7 Bulk Volume of Coarse Aggregate Per Unit Volume of Concrete

Nominal maximum size of aggregate, mm (in.)	**Bulk volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate**			
	2.40	**2.60**	**2.80**	**3.00**
9.5 (3/8)	0.5	0.48	0.46	0.44
12.5 (1/2)	0.59	0.57	0.55	0.53
19 (3/4)	0.66	0.64	0.62	0.6
25 (1)	0.71	0.69	0.67	0.65
37.5 (11/2)	0.75	0.73	0.71	0.69
50 (2)	0.78	0.76	0.74	0.72
75 (3)	0.82	0.8	0.78	0.76
150 (6)	0.87	0.85	0.83	0.81

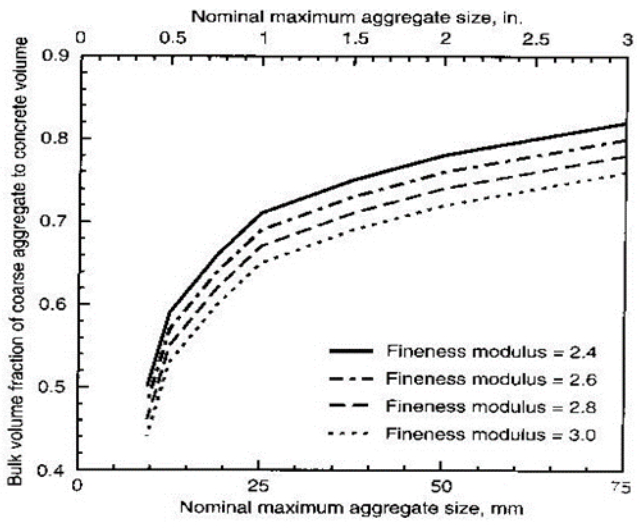

Fig. 9-3. Bulk volume of coarse aggregate per unit volume of concrete. Bulk volumes are based on aggregates in a dry-rodded condition as described in ASTM C 29 (AASHTO T 19). For more workable concrete, such as may be required when placement is by pump, they may be reduced up to 10%. Adapted from Table 9-4, ACI 211.1 and Hover (1995 and 1998).

Figure 12 Bulk volume of coarse aggregate per unit volume of concrete

Fine Aggregate content:

At this point, we have calculated the amount required of all the ingredients except fine aggregate.

By the Absolute volume method, FA content can be obtained by subtracting the absolute volumes of the known ingredients from 1 cubic meter.

Absolute volume is calculated by dividing the mass of ingredient by the product of its relative density and the density of water:

Total Volume of known ingredients = 0.673 m^3.

Hence, absolute volume of FA is: 1 – 0.673 = 0.327m^3.

The mass of dry FA is: 0.327*2.64*1000 = 863 Kg.

Thus, the proportions before trial mixing per cubic meter of concrete are:

Table 8 Fina mix proportion

Constituent	Weight
Water	180 kg
Cement	316 kg
Fine Aggregate (dry)	863 kg
Coarse Aggregate (dry)	1056 kg
Total	2415 kg

3.1.4. Samples Preparation

Following is a complete breakdown concrete mixing, casting, curing, and testing procedures used in the project:

3.1.4.1. Mixing:

Following ACI 211.1-91; As mentioned earlier, this standard provides a framework for proportioning concrete mixes. It guided us in determining the quantities of the following components for each mix variation:

- Cement
- Treated slag aggregate.
- Water
- Super Plasticizer Admixtures

Mixing Sequence: The mixing sequence involved first mixing the dry ingredients (cement, slag, and normal aggregate) for a set time. Then, water and any admixtures were added and mixed thoroughly to achieve a homogeneous concrete mix with the desired workability.

3.1.4.2. Casting:

4" x 8" Cylindrical Molds were used for the casting of samples for compressive strength test and split tensile strength test. These are standard mold dimensions for testing concrete compressive strength. The use of multiple molds allowed for replicate specimens for each mix variation (treated slag vs. normal aggregate) and testing time point (3, 7, and 14 days).

Proper Consolidation: After filling the molds with fresh concrete, consolidation is crucial to remove air voids and ensure uniform density throughout the specimen. This was achieved through various techniques like rodding, tapping the sides of the mold, or vibration.

3.1.4.3. Curing:

Demolding after 48 hours: After 48 hours, the concrete specimens gained some initial strength and could be safely removed from the molds.

Curing Conditions: Specimens underwent a controlled curing regime to promote proper hydration of the cement and achieve optimal strength development. This involved storing the specimens in a curing tank with lime-saturated water, at a specific temperature (room temperature).

3.1.5. Testing

3.1.5.1. Raw material testing:

Since the only major variable that was changed was the type of coarse aggregate, most of the material testing focused on comparing the properties of natural aggregate with IFS aggregate. Both mechanical properties and chemical properties of IFS were tested and compared with natural aggregate. Following are the results obtained from material testing:

1. **Gradation of Coarse Aggregate (ASTM C33):** This test determines the particle size distribution of the coarse aggregate. Ensuring well-graded coarse aggregate is crucial for achieving good workability and ultimate compression strength in a concrete mix. The gradation curves for both natural aggregate and IFS aggregate were analyzed to verify compliance with ASTM specifications.
2. **Specific Gravity of Coarse Aggregate (ASTM C127):** This test measures the specific gravity of the aggregates. Specific gravity is an essential property that influences the concrete mix's proportions and its overall performance.
3. **Absorption Capacity (ASTM C127):** This test determines the amount of water the aggregate can absorb. The absorption capacity of both IFS and natural aggregate was measured to assess how it might affect the water content and workability of the concrete mix.

4. **Los Angeles Abrasion Test (ASTM C535 Grade 3):** This test evaluates the resistance of aggregates to abrasion and wear. It is used to determine the suitability of the aggregate for use in concrete subjected to high wear.
5. **The Aggregate Soundness Test (ASTM C88):** This test evaluates the durability and weathering resistance of aggregates by subjecting them to cycles of wetting and drying in a sodium sulfate solution. The procedure begins with preparing and drying the aggregate sample to a constant weight. The sample is then immersed in a saturated sodium sulfate solution, which penetrates the aggregate's pores. Upon drying, the sodium sulfate forms crystals, creating internal stresses that simulate natural weathering processes. This cycle of immersion and drying is repeated several times to assess the aggregate's durability. After completing the cycles, the sample is washed to remove residual sodium sulfate, dried, and weighed to determine the weight loss. The loss, expressed as a percentage of the original weight, indicates the aggregate's resistance to weathering, with minimal loss suggesting higher durability.

These tests were conducted to ensure that the IFS aggregate met the required standards and to compare its performance with that of natural aggregate.

3.1.5.2. Concrete Testing

Tests were performed to create an extensive comparative analysis on four different concrete batches. These batches are outlined below:

1. M20 Concrete using Natural aggregate: This batch was used as a benchmark.
2. M20 Concrete using 100% untreated IFS aggregate: Concrete was prepared using the exact same mix design as above, with the only difference being that natural aggregate was completely replaced with IFS Aggregate (that had the proper size and gradation according to #456 stone.)
3. M20 Concrete using Mechanically abraded IFS aggregate: Untreated Slag had a very glassy surface. Mechanical abrasion was used to solve this issue. Batch 3 concrete was prepared using IFS that had been treated using an LA Abrasion Machine. Batch 03 was further sub-divided into three types, based on the amount

of time the IFS spent being abraded. Three different time demarcations were used of 5, 10, and 15 minutes respectively. This slag was then used to make three different types of concrete specimens, which were labelled ‘5 min LA’, ‘10 min LA’, and ‘15 min LA’ respectively.

4. M20 Concrete using Chemically treated IFS Aggregate: The 2nd method used to treat (roughen) the surface of the IFS Aggregate was by dipping it in different concentrations of NaOH for 24 hrs. Like in batch 3, three different sub-batches were prepared based on the NaOH concentration the slag was dipped in. The concrete samples were labelled ‘2M NaOH’, ‘4M NaOH’, and ‘8M NaOH’ respectively.

Slump Test was performed on all the batches and a standard slump of 3-4 inches was ensured. The samples prepared were tested after 7, 14, and 28 days to compare both the ultimate strength achieved, as well as the rate of strength gain.

The following tests were performed on the concrete samples:

1. **Compression Test (ASTM C39/C39M)**: The Compression Test, as per ASTM C39/C39M, was conducted to evaluate the compressive strength of cylindrical concrete specimens at various curing ages (7, 14, and 28 days). Concrete cylinders, typically 150 mm in diameter and 300 mm in height, were cast and cured under controlled conditions. Specimens were maintained in a moist environment at 23 ± 2°C until the designated test age. At each testing age, the specimen was placed in a compression testing machine where a continuous load was applied at a rate of 0.25 ± 0.05 MPa/s until failure. The maximum load at failure was recorded, and the compressive strength was calculated by dividing this load by the cross-sectional area of the specimen.
2. **Split-Tensile Test (ASTM C496/C496M):** The Split-Tensile Test, in accordance with ASTM C496/C496M, was performed to measure the tensile strength of cylindrical concrete specimens at 7, 14, and 28 days. Concrete cylinders, typically 150 mm in diameter and 300 mm in height, were prepared and cured in a moist environment at 23 ± 2°C until testing. At each designated age, the specimen was

placed horizontally in the testing machine, and a diametral compressive load was applied at a constant rate until failure. The maximum load at failure was recorded, and the tensile strength was calculated using the formula

3. **Flexure Test (ASTM C293/C293M):** The Flexure Test, following ASTM C293/C293M, was conducted to determine the flexural strength of concrete specimens, typically at 14 days. Concrete beams, usually 150 mm x 150 mm x 500 mm, were cast and cured in a moist environment at 23 ± 2°C until the testing age. The beam specimen was placed in the testing machine, supported at both ends, and a load was applied at the mid-span at a constant rate until failure. The maximum load at failure was recorded, and the flexural strength was calculated using the formula

These ASTM standards ensure that concrete is tested consistently and accurately to evaluate its mechanical properties over time. The Compression Test (ASTM C39/C39M), Split-Tensile Test (ASTM C496/C496M), and Flexure Test (ASTM C293/C293M) provide critical data on the compressive, tensile, and flexural strengths of concrete, respectively. By performing these tests at various ages (7, 14, and 28 days), we can assess the concrete's development and predict its long-term performance.

3.1.5.3. Statistical Significance.

To ensure that the results obtained in the previous sections were statistically significant, many concrete samples were cast for each batch. Unequal Variance t-test was performed on the sample results between Batch 01 (Natural Aggregate) and Batch 02 (Untreated IFS Aggregate). This was done to ensure that any changes in the results (i.e. an increase in compressive strength) were caused by the change in aggregates, and not by random error. A t-value of above the threshold for a α-value of 0.05, indicates that the change in strength cannot be attributed to random error and is a statistically significant result.

3.1.6. Performance Testing:

- **Compression Testing**: At designated ages (7, 14, and 28 days), the concrete cylinders were subjected to compression testing. This test measures the maximum compressive load a specimen can withstand before failure. The compressive strength is calculated by dividing the maximum load by the cross-sectional area of the cylinder.

- **Split-Tensile Testing**: Split-tensile testing is another common test for concrete. It provides an indirect measure of the concrete's tensile strength, which is important for understanding its resistance to cracking. In this test, a cylindrical specimen is loaded diametrically until it splits along its vertical axis. The split-tensile strength is calculated based on the applied load and the dimensions of the specimen. Specimens were tested at 7, 14, and 28 days.
- **Flexure Strength Testing**: Separate prismatic molds were used to cast concrete specimens specifically for flexural testing. The dimensions for these molds were 4" x 4" x 21". The testing machine records the applied load throughout the test until the specimen fails in flexure (bending and cracking). The load-deflection curve is a valuable output that can reveal information about the flexural behavior of the concrete. After the test, the flexural strength (modulus of rupture) is calculated based on the maximum applied load, the dimensions of the specimen, and the span between the supports. The same curing procedures used for the compression test specimens would apply to the flexural test specimens. These specimens were also tested at 7, 14, and 28 days.
- **Number of Specimens per Mix:** It's important to test multiple specimens for each mix variation and testing age to account for inherent variability in concrete. For this reason, 3 specimens were tested.
- **Data Analysis:** The collected compressive, split-tensile strength and flexure strength data was statistically analyzed to assess the average strength and standard deviation for each mix variation at different ages.
- **Comparison with Control Mix:** The performance of the concrete mixes containing treated slag aggregate was compared to the control mix prepared with normal aggregate. This comparison helped evaluate the effectiveness of the slag treatment methods in terms of achieving the desired strength properties.

By following these procedures, we were able to prepare concrete specimens with different slag aggregate variations and assess their mechanical performance through compression and split-tensile testing. The data obtained can provide valuable insights into the feasibility of using treated IF-Slag as a replacement for conventional aggregate in concrete.

CHAPTER 4

4. TESTING RESULTS

4.1. Aggregate testing

A comprehensive set of tests was performed to evaluate the properties of the aggregates used in this study, including natural aggregates (NA), untreated Induction Furnace Slag (IFS), NaOH treated IFS, and mechanically abraded IFS. The results from these tests provide a detailed understanding of the physical and mechanical characteristics of these materials and their suitability for use in concrete

4.1.1.1. Gradation of Coarse Aggregate (ASTM C33)

The gradation test, conforming to ASTM C33, was performed on natural aggregate and untreated induction furnace slag to ensure that the aggregates met the required particle size distribution. The results showed that both types of aggregates fell within the acceptable limits for coarse aggregate gradation.

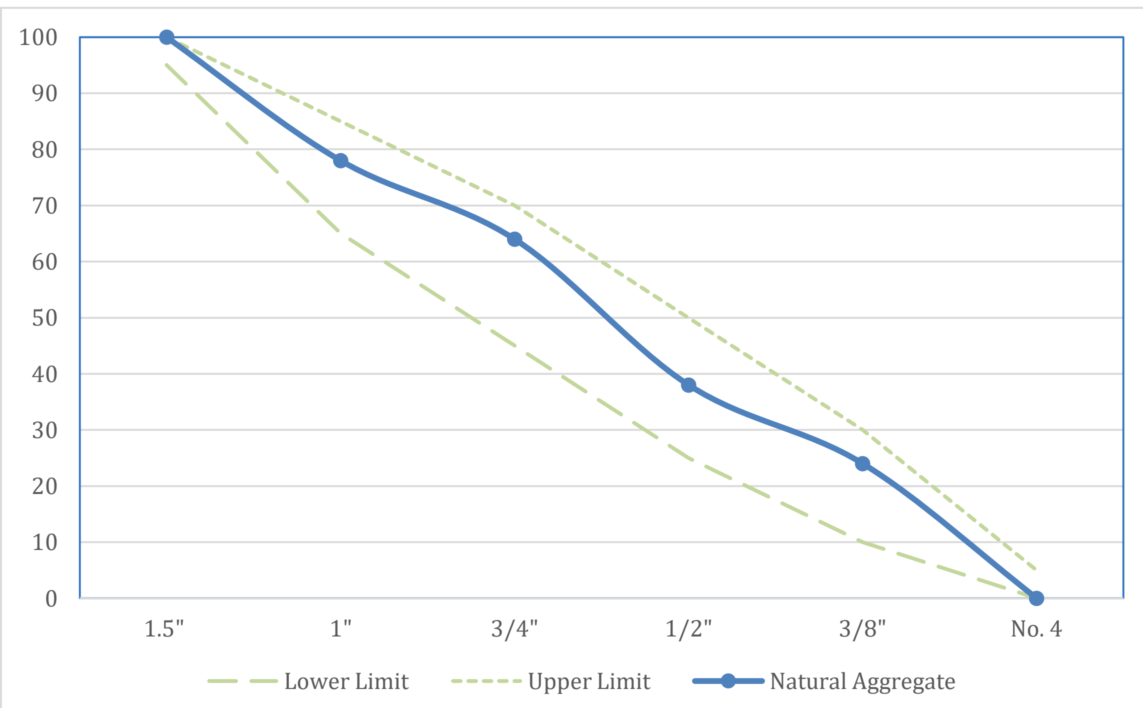

Figure 13 Sieve Analysis of Natural Aggregate

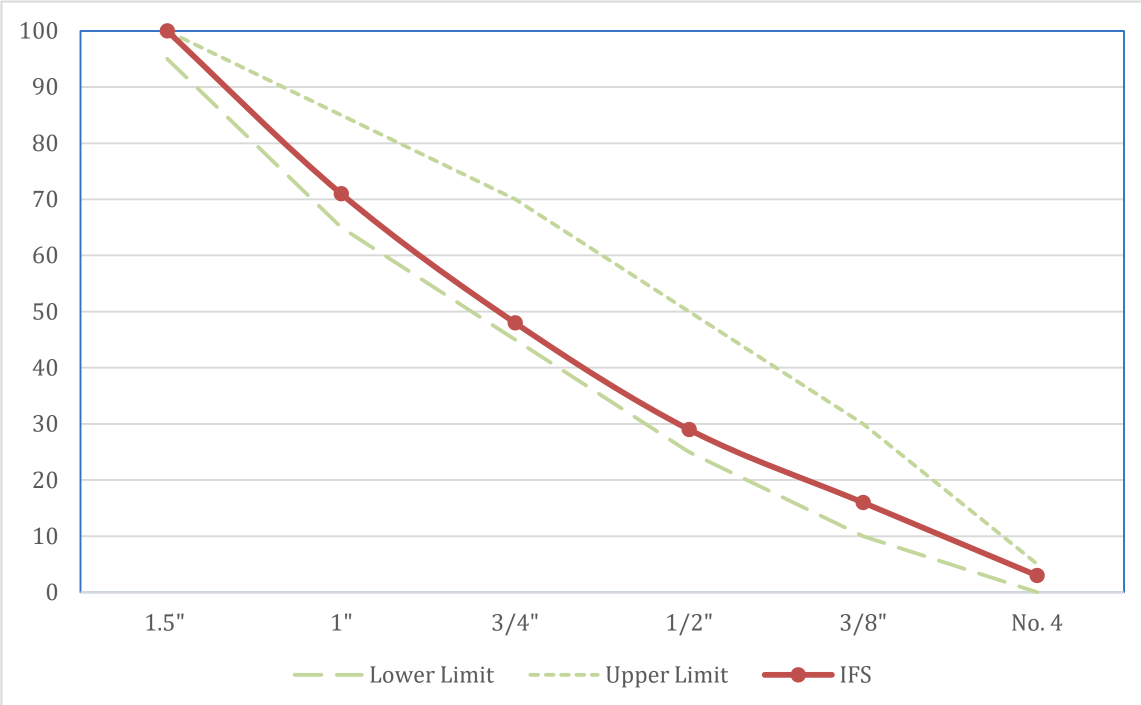

Figure 14 Sieve Analysis of IFS

4.1.1.2. Specific Gravity and Absorption (ASTM C127)

Specific gravity and water absorption tests were conducted to determine the density and porosity of the aggregates. The results are summarized in the table below:

Table 9 Specific gravity and absorption of NA and IFS

Aggregate Type	Specific Gravity (kg/m³)	Water Absorption (%)
Natural Aggregate	2.411	1.9
Untreated IFS	2.567	2.3
NaOH Treated IFS	2.555	2.2
Mechanically Abraded IFS	2.560	2.1

The results indicate that IFS aggregates generally have a higher specific gravity and water absorption compared to natural aggregates. The NaOH treatment slightly reduced the water absorption, suggesting an improvement in surface characteristics.

3. Soundness Test (ASTM C88)

The soundness test, using sodium sulfate, assessed the resistance of aggregates to weathering and chemical attack. The results are as follows:

Table 10 Soundness test of NA and IFS

Aggregate Type	Soundness (%)
Natural Aggregate	4.05
Untreated IFS	3.78
NaOH Treated IFS	4.78
Mechanically Abraded IFS	3.95

The untreated IFS showed a lower soundness value compared to natural aggregates, indicating better resistance to weathering. However, NaOH treated IFS exhibited a slightly higher soundness value, which may be attributed to changes in the slag surface properties due to the chemical treatment.

4.1.1.3. Aggregate Resistance to Degradation (ASTM C535)

The Los Angeles abrasion test (ASTM C535) was performed to evaluate the resistance of aggregates to wear and degradation. The results are as follows:

Table 11 Aggregate Resistance to Degradation of NA and IFS

Aggregate Type	Abrasion Value (%)
Natural Aggregate	27
Untreated IFS	30
NaOH Treated IFS	28
Mechanically Abraded IFS	21

The mechanically abraded IFS showed the lowest abrasion value of 21%, indicating the highest resistance to degradation. This demonstrates that mechanical abrasion effectively enhances the durability of IFS, making it more suitable for use in concrete.

4.1.1.4. Summary of Aggregate Testing Results

The testing of natural aggregates and various types of IFS aggregates revealed several important findings:

- Gradation: All aggregates met the required particle size distribution, ensuring their suitability for use in concrete.
- Specific Gravity and Absorption: IFS aggregates had higher specific gravity and water absorption compared to natural aggregates. Surface treatments slightly reduced water absorption.
- Soundness: Untreated IFS showed better resistance to weathering compared to natural aggregates. NaOH treatment improved soundness slightly, while mechanically abraded IFS maintained a comparable soundness to natural aggregates.
- Abrasion Resistance: Mechanically abraded IFS exhibited superior resistance to degradation, with the lowest abrasion value among the tested aggregates.

These results indicate that surface-treated IFS aggregates, particularly those subjected to mechanical abrasion, can serve as a viable replacement for natural aggregates in concrete, offering comparable or enhanced performance characteristics.

4.2. Concrete testing

4.2.1. Chemical Treatment of IFS with HCl

To enhance the surface properties of Induction Furnace Slag (IFS) and improve its bonding with the cement matrix, we initially explored chemical treatment using hydrochloric acid (HCl). We prepared three samples of HCl-treated IFS with different concentrations of HCl: 5%, 10%, and 15%. These treated samples were then subjected to a 7-day compressive strength test. The results are summarized in the table below:

Table 12 Compressive strength of HCl treated IFS incorporated concrete

Sample Type	7-day Compressive Strength (MPa)
5% HCl Treated IFS	8.05
10% HCl Treated IFS	7.23
15% HCl Treated IFS	6.17
Natural Aggregate (NA)	12.75

4.2.1.1. Analysis of HCl Treatment Results

The 7-day compressive strength test results indicated that the compressive strength of HCl-treated IFS was significantly lower compared to natural aggregate. The highest compressive strength among the HCl-treated samples was achieved with 5% HCl treatment, which was only 8.05 MPa. This value is considerably lower than the compressive strength of natural aggregate, which was 12.75 MPa. Furthermore, increasing the concentration of HCl to 10% and 15% resulted in even lower compressive strengths of 7.23 MPa and 6.17 MPa, respectively.

These results demonstrate that HCl treatment of IFS is not a viable method for enhancing the performance of IFS as a replacement for coarse aggregate in concrete. The acid treatment not only failed to improve the compressive strength of the concrete but also seemed to degrade the structural integrity of the IFS.

4.2.1.2. Transition to NaOH Treatment

Given the unsatisfactory results of HCl treatment, we shifted our focus to using sodium hydroxide (NaOH) for the chemical treatment of IFS. NaOH is known to enhance the surface properties of aggregates by creating a rougher surface texture, which can improve the bonding with the cement matrix.

We prepared NaOH-treated IFS samples using different molar concentrations: 1 Molar, 2 Molar, 4 Molar, and 8 Molar solutions. The NaOH-treated samples showed promising results, with the 4 Molar NaOH treatment providing the best performance. The results of the compressive strength tests for the NaOH-treated IFS indicated a significant improvement over the HCl-treated samples.

4.2.2. Performance testing and comparison with NA concrete

To thoroughly assess the performance of Induction Furnace Slag (IFS) as a replacement for coarse aggregate in concrete, a comprehensive series of tests were conducted. These tests compared the performance of Natural Aggregate (NA) concrete with various treated and untreated IFS concrete samples. The specific tests performed included the Centre Point Loading Flexural Test of beams (ASTM C293), Compressive Strength of concrete cylinders (ASTM C39), and Splitting Tensile Strength (ASTM C496). The detailed results of these tests are discussed below.

4.2.2.1. Compressive Strength of Concrete Cylinders (ASTM C39)

Compressive strength is a critical property of concrete, indicating its ability to withstand axial loads. The compressive strength tests were conducted at 7, 14, and 28 days for concrete made with different aggregate types. The results are summarized in the graphs below:

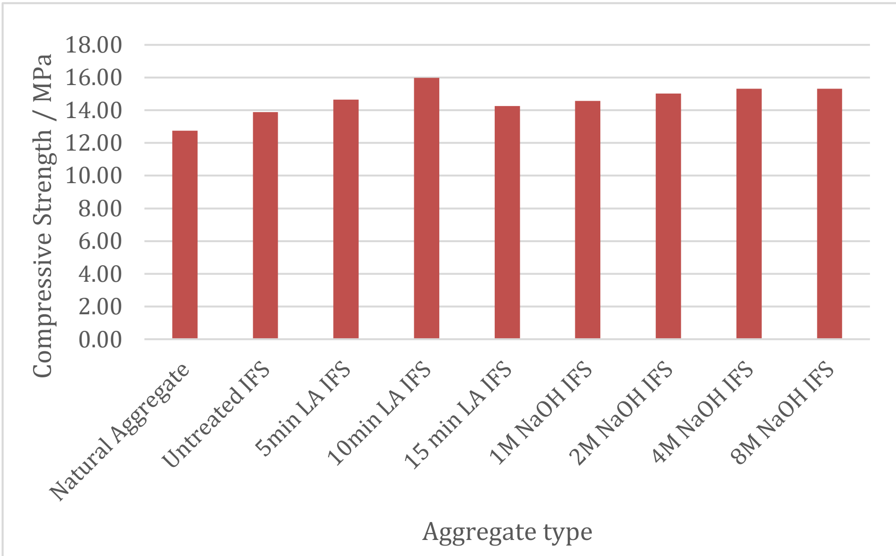

Figure 15 7-day compressive strength of NA and IFS incorporated concrete

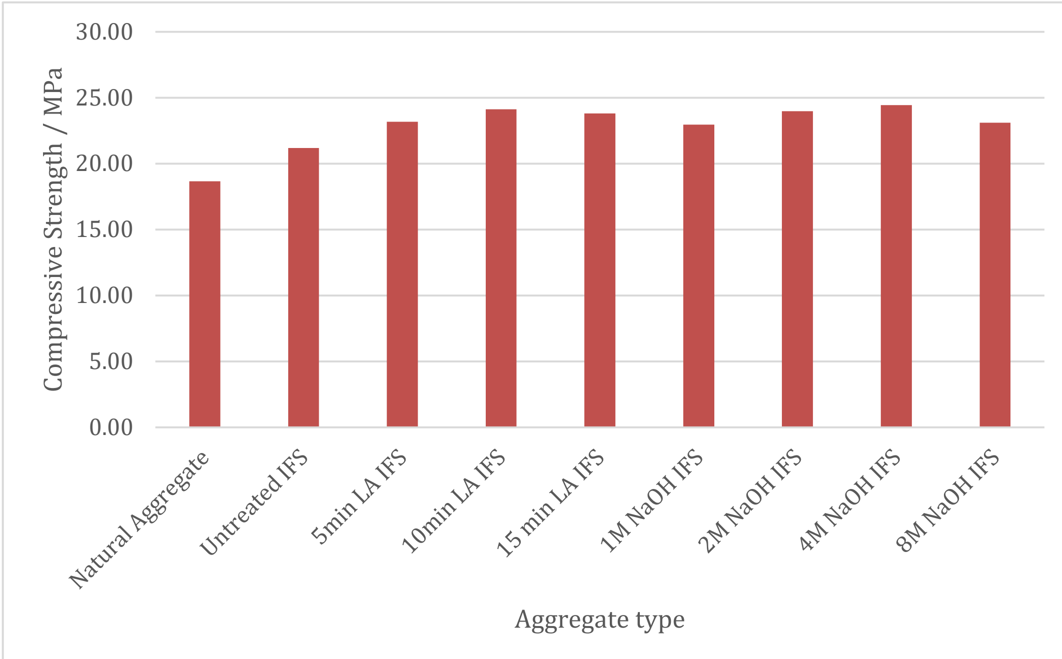

Figure 17 14-day compressive strength of NA and IFS incorporated concrete

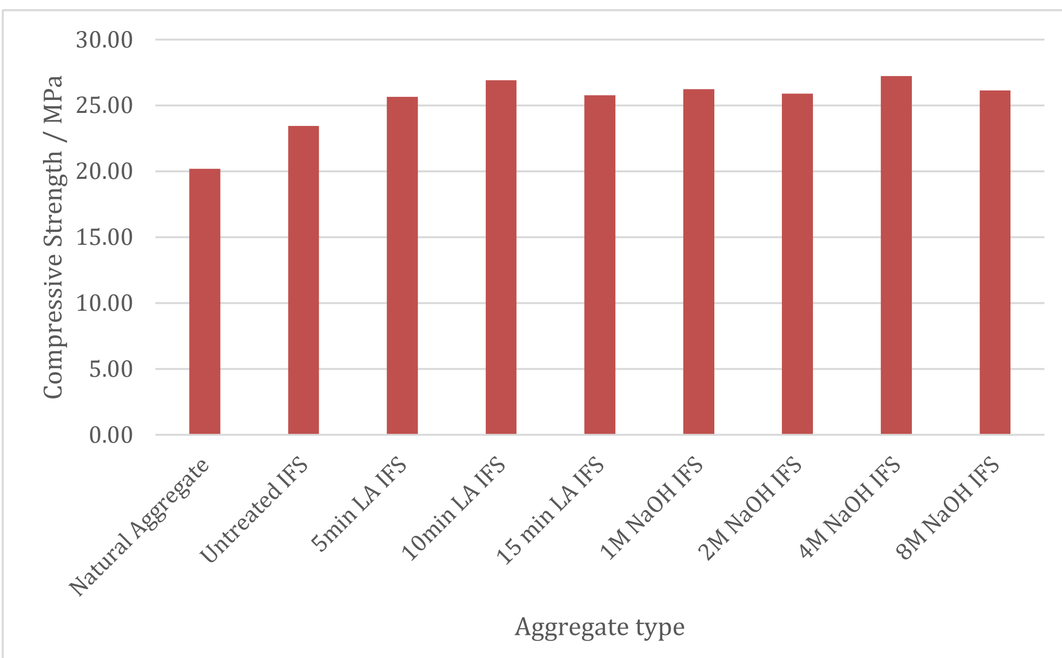

Figure 16 28-day compressive strength of NA and IFS incorporated concrete

The results indicate that all types of IFS-treated aggregates generally exhibited higher compressive strengths compared to the natural aggregate. Notably, the 10-minute LA abrasion treated IFS showed the highest 28-day compressive strength of 26.91 MPa, significantly outperforming the natural aggregate, which had a 28-day compressive strength of 20.18 MPa. This enhancement in strength can be attributed to the improved surface texture and better bonding of the treated IFS with the cement matrix.

4.2.2.2. Splitting Tensile Strength (ASTM C496)

The splitting tensile strength test measures the tensile strength of concrete, which is critical for assessing its resistance to cracking and failure under tensile loads. The results for the splitting tensile strength tests at 7, 14, and 28 days are presented below:

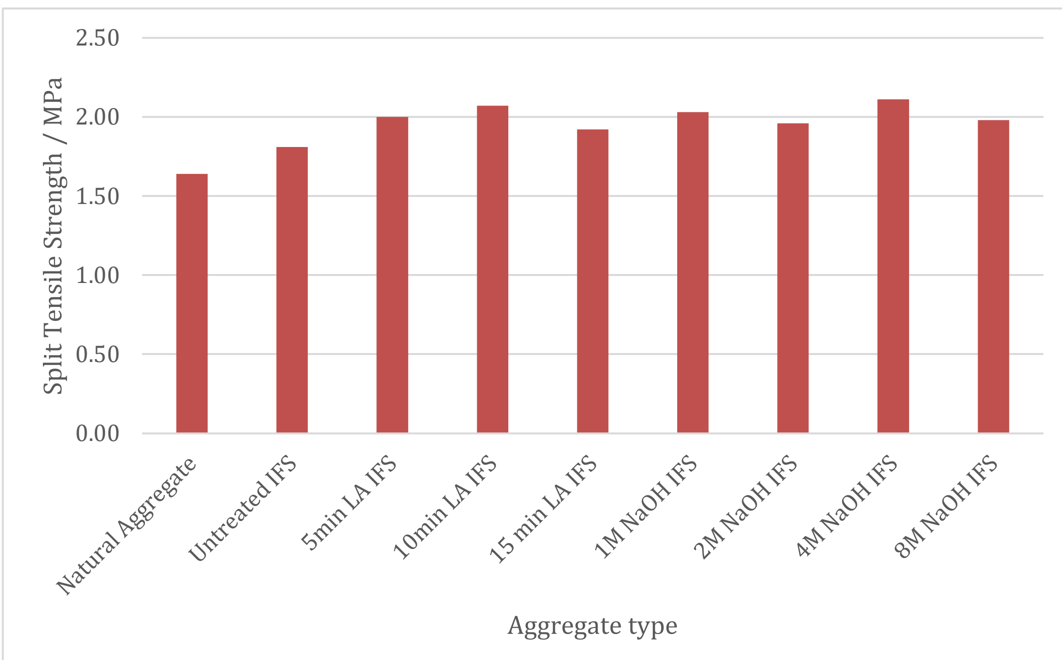

Figure 18 7-day split tensile strength of NA and IFS incorporated concrete

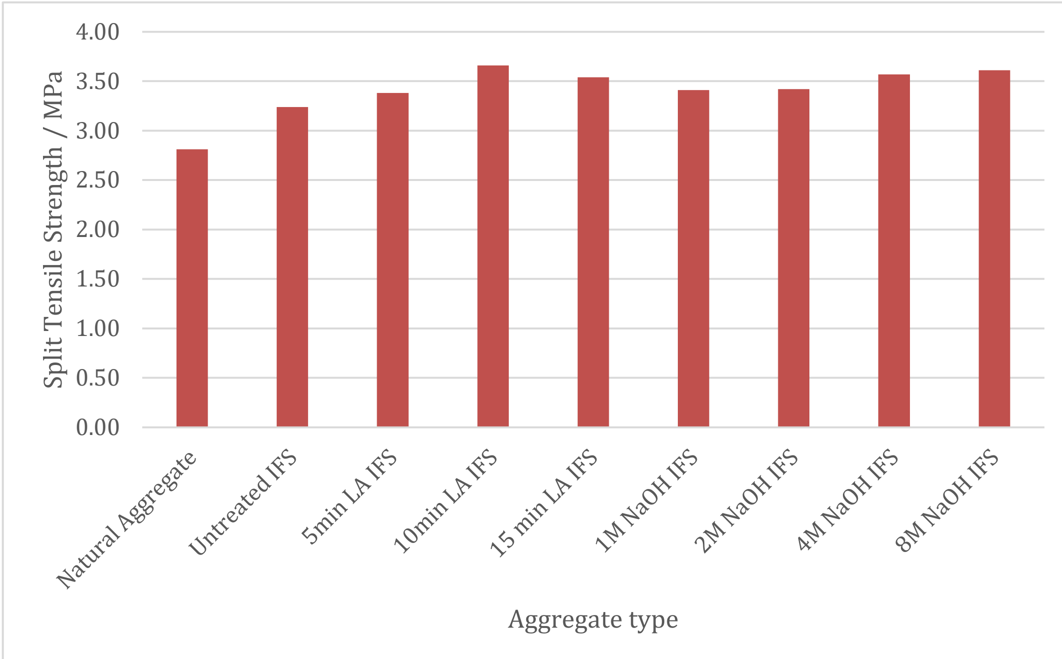

Figure 19 14-day split tensile strength of NA and IFS incorporated concrete

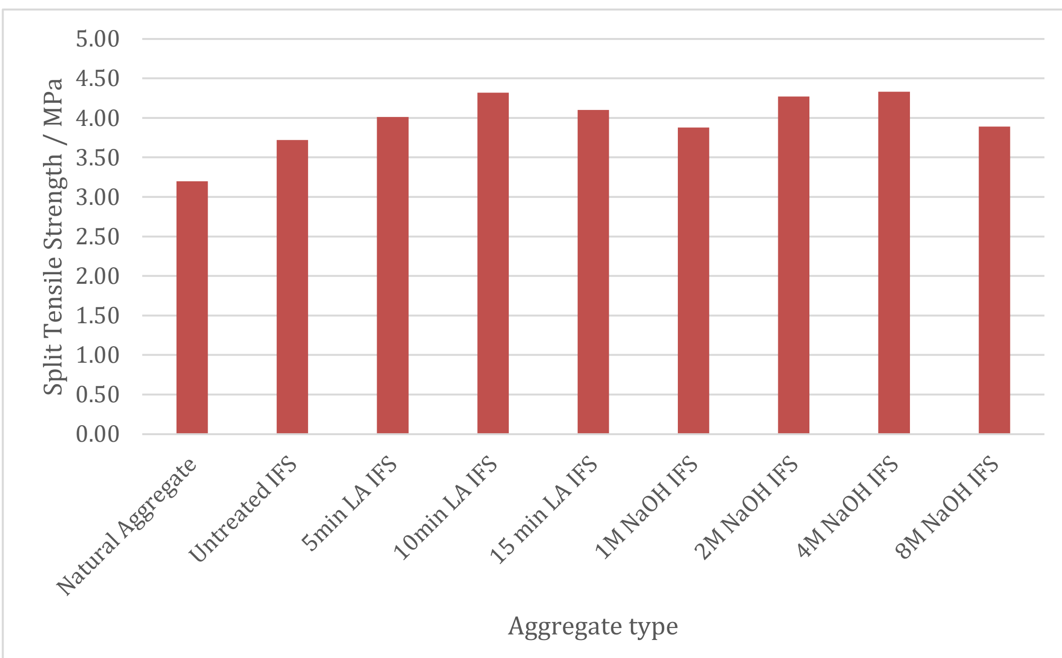

Figure 20 28-day split tensile strength of NA and IFS incorporated concrete

The data shows that treated IFS aggregates provided higher splitting tensile strengths compared to natural aggregate. The highest 28-day splitting tensile strength was observed in the 4M NaOH treated IFS at 4.33 MPa, which is significantly higher than the natural aggregate's 3.20 MPa. This improvement is likely due to the enhanced roughness and reactivity of the treated IFS surfaces, promoting better adhesion within the cement matrix.

4.2.2.3. Flexural Strength (ASTM C293)

Flexural strength is crucial for applications where concrete is subjected to bending forces. The flexural strength of beams was tested at 14 days. The results are shown below:

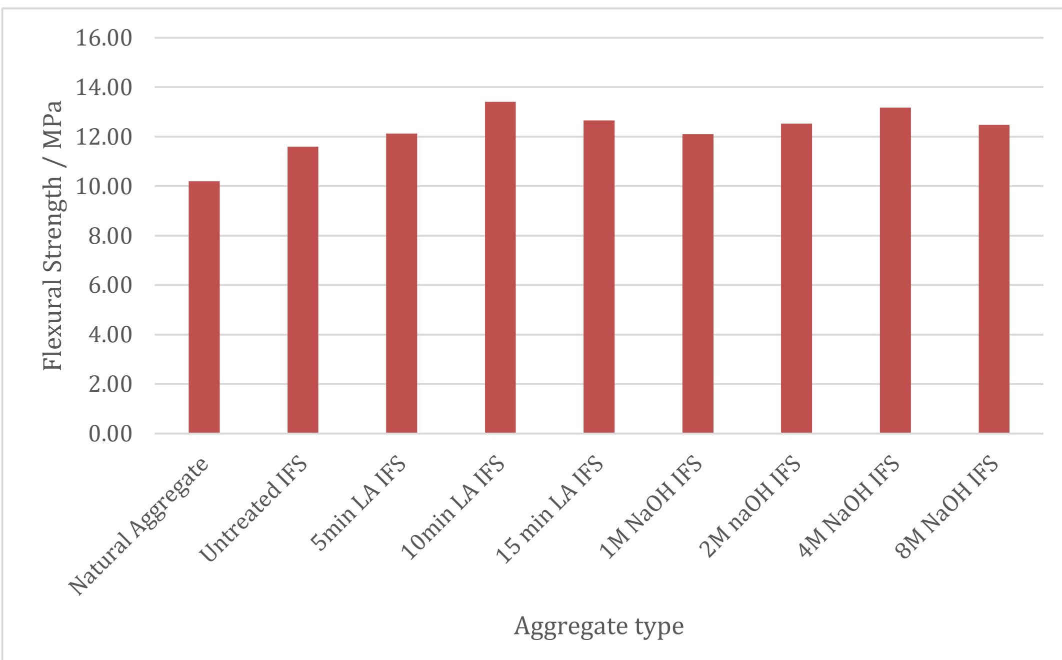

Figure 21 14-day flexure strength of NA and IFS incorporated concrete

The flexural strength results further support the superior performance of treated IFS aggregates. The highest flexural strength was recorded for the 10-minute LA abrasion treated IFS at 13.41 MPa, significantly higher than the 10.19 MPa observed for the natural aggregate. This enhanced flexural strength suggests that treated IFS aggregates can improve the bending resistance of concrete structures, making them suitable for applications requiring high flexural performance.

4.2.2.4. Analysis and Discussion

The comprehensive testing of compressive, tensile, and flexural strengths clearly demonstrates the benefits of using treated IFS as a replacement for natural aggregates in concrete. Treated IFS aggregates, particularly those subjected to LA abrasion for 10 minutes and 4M NaOH treatment, consistently outperformed natural aggregate in all measured strength categories.

The 10-minute LA abrasion treatment likely optimizes the surface texture and particle size distribution of the IFS, enhancing its bonding with the cement paste. Similarly, the 4M NaOH treatment improves the chemical reactivity and surface roughness of the IFS, resulting in better adhesion within the cement matrix. Both treatments lead to a significant increase in the mechanical properties of the concrete.

4.2.2.5. Statistical Significance

To ensure that the observed improvements in concrete performance were statistically significant and not due to random variation, an Unequal Variance t-test was performed on the compressive strength results at 14 days for samples made with Natural Aggregate (Batch 01) and Untreated IFS Aggregate (Batch 02).

The test results are as follows:

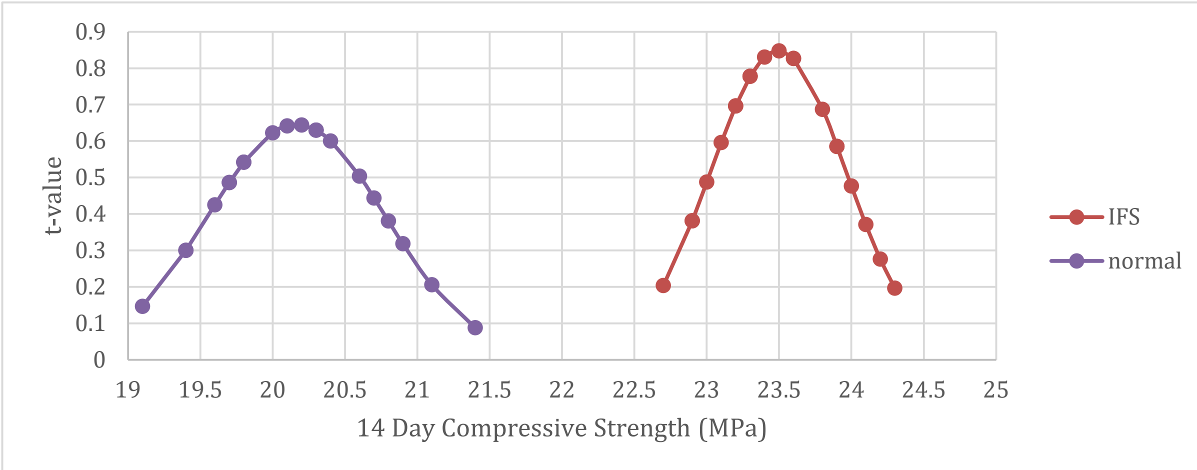

Figure 22 T-test of NA and IFS concrete

The mean compressive strength at 14 days for Natural Aggregate was 20.165 MPa, with a standard deviation of 0.618 MPa. For Untreated IFS, the mean compressive strength was 23.495 MPa, with a standard deviation of 0.471 MPa. The t-test yielded a t-value of – 8.23, which is well above the threshold for an α-value of 0.05. This indicates that the observed increase in compressive strength with Untreated IFS aggregates is statistically significant and not due to random error.

4.2.2.6. Conclusion

In conclusion, the results of our testing indicate significant improvements in concrete strength parameters with different treatments applied to the induction furnace slag (IFS). Untreated IFS demonstrated a commendable average enhancement of 13% across all strength parameters compared to natural aggregate, suggesting its potential as a viable substitute. However, more notable improvements were observed with specific treatments. The 4M NaOH treated IFS exhibited a remarkable average enhancement of 29% in all strength parameters, highlighting the effectiveness of chemical treatment in bolstering concrete strength. Similarly, the 10-minute mechanically treated IFS displayed an average improvement of 30% in all strength parameters, underscoring the importance of surface roughening for enhancing bonding with the cement matrix. These findings affirm the suitability of IFS as a coarse aggregate replacement and underscore the significance of treatment methods in optimizing its performance in concrete applications.

Chapter 5

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study's main objective was to reduce the environmental and economic costs of steel and concrete production. Using IF-Slag Aggregates in Concrete is an effective way to accomplish this goal, as it will reduce the usage of natural aggregates, as well as reducing the dumping associated with steel slag. Additionally, using IF-Slag aggregates is also cheaper than using Natural Aggregates, so it will lead to a reduction in costs in the construction industry.

From the literature it was apparent that the properties of IFS varied from area to area based on the performance characteristics of the Induction Furnace and the composition of the material being fed to it.

Additionally, the slag had heterogenous properties with glassy texture and porous surface which weakened its bonding with the cement matrix. Surface roughening was achieved through novel mechanical and chemical methods.

For mechanical treatment IFS was first hammered to make it in small pieces and further abraded in the LA Abrasion Machine for different time periods of 5,10, and15 minutes from which the 10 minutes abrasion showed the best results. The surface of IFS was adequately roughened, forming a stronger bond with the cement mix. A 33% increase in compressive strength was observed, 35% increase in split tensile strength was seen and in flexural strength 32% increase was seen in comparison with the natural aggregate. The obtained value of abrasion was 21%.

Chemical treatment was also studied to check if acid or alkali can roughen the surface of IFS and improve its bonding with the cement matrix. Acid was initially used as treating agent and different concentrations of acid were tested. The 3 different percentages of acid treatment were 5%, 10% and 15% respectively among which 10% showed the best results.

The cost of HCl was high so alkali was also tried for treating IFS as it also improves the surface of IFS. NaOH was used as a treating agent and similarly different concentrations of alkali were used. 1 Molar, 2 Molar, 4 Molar and 8 Molar solutions were prepared, and slag was kept in solution for 2 days which ultimately improved the slag surface resulting in better bonding. Among them 4 Molar showed the best results. An increase of 35%, 34% and 29% in compressive, split tensile and flexural strength respectively was observed.

Further testing was also carried out on the IFS; the water absorption value achieved was 2.3% compared to 1.9% for natural aggregate. IFS aggregate also had a slightly higher Specific gravity and bulk density than natural aggregate, at 2.56 versus 2.41 respectively.

Aggregate Soundness test was also conducted which showed comparable results between natural aggregate, untreated IFS, and 4M NaOH treated IFS.

All these tests and results showed that IFS can be used as a replacement of coarse aggregate in concrete. To expand this research, IFS can also be used to make rigid pavements as it has enough strength to carry high loads. It has a better LA Abrasion value and higher impact value than natural aggregate, which could mean it is a better substrate material for use in both rigid and flexible pavements.

5.2. Recommendations

To further the findings of this study on the utilization of surface-treated Induction Furnace Slag (IFS) as a replacement for coarse aggregate in concrete, several comprehensive recommendations are proposed. These recommendations aim to deepen the understanding of IFS concrete, optimize its performance, and broaden its applicability in the construction industry.

5.2.1.1. Durability Studies

Conduct extensive durability studies to evaluate the long-term performance of IFS concrete under various environmental conditions. The following tests are particularly recommended:

- **Rapid Chloride Permeability Test (ASTM C1202):** This test will help determine the ability of IFS concrete to resist chloride ion penetration, which is critical for structures exposed to de-icing salts or marine environments.
- **Sorptivity Test (ASTM C1585):** By measuring the rate of capillary water absorption, this test will provide insights into the potential for water ingress and related deterioration mechanisms in IFS concrete.
- **Freezing and Thawing Resistance Test (ASTM C666):** Assess the resistance of IFS concrete to freeze-thaw cycles, which is essential for applications in cold climates where freeze-thaw durability is a major concern.
- **Alkali-Silica Reaction Test (ASTM C1567):** Evaluate the susceptibility of IFS concrete to alkali-silica reactions, which can cause significant expansion and cracking over time.

5.2.1.2. Studies on IFS from Different Foundries

Since the properties of IFS can vary significantly based on the induction furnace's performance and the material composition, it is crucial to conduct studies on IFS sourced from different foundries. These studies should focus on:

- Characterizing the physical and chemical properties of IFS from various sources.
- Assessing the variability in performance characteristics of IFS concrete made with slag from different foundries.
- Identifying any regional or operational factors that may influence the suitability of IFS for concrete applications.

5.2.1.3. Optimization of Mix Design for Different Usages

Develop and optimize concrete mix designs incorporating IFS for a variety of specific applications. This should include:

- **Structural Concrete:** Tailor mix designs to achieve the required strength, durability, and workability for structural applications, such as beams, columns, and load-bearing walls.
- **Pavements:** Optimize the gradation and mix composition to enhance the performance of concrete in pavements, ensuring good load-bearing capacity and durability against traffic wear.
- **Precast Elements:** Adjust mix designs to suit the manufacturing processes and performance requirements of precast concrete elements, such as blocks, panels, and pavers.

5.2.1.4. High-Performance Concrete Applications

Investigate the feasibility of using IFS in high-performance concrete (HPC) with compressive strengths exceeding 50 MPa. This involves:

- Conducting experimental studies to assess the mechanical properties, such as compressive strength, tensile strength, and flexural strength, of HPC incorporating IFS.
- Evaluating the durability and long-term performance of HPC with IFS, particularly in aggressive environments.
- Comparing the performance of HPC with IFS to conventional HPC to identify any potential advantages or limitations.

5.2.1.5. Thermal Performance of IFS Concrete

Evaluate the thermal properties of concrete containing IFS, particularly its behavior under varying temperature conditions. This includes:

- **Thermal Conductivity and Insulation:** Measure the thermal conductivity of IFS concrete to determine its suitability for applications requiring thermal insulation or heat retention.

- **Thermal Expansion:** Assess the coefficient of thermal expansion to ensure that IFS concrete can withstand temperature-induced stresses without cracking or spalling.
- **Fire Resistance:** Conduct fire resistance tests to evaluate the performance of IFS concrete in high-temperature scenarios, such as in building facades or structural elements exposed to fire hazards.

By addressing these recommendations, the potential of IFS as a sustainable and cost-effective replacement for natural aggregates in concrete can be fully realized. This will contribute significantly to environmental conservation, reduce the economic costs associated with concrete production, and promote the use of industrial by-products in the construction industry.

CHAPTER 6

6. REFERENCES

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