

**EVALUATION OF CONCRETE STRENGTH BY PARTIALLY REPLACING THE
COARSE AGGREGATE WITH BLAST FURNACE SLAG**

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**THE DEPARTMENT OF STRUCTURAL ENGINEERING,
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UNIVERSITY OF BENIN,
BENIN CITY, NIGERIA**

SEPTEMBER, 2025.

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**A PROJECT SUBMITTED IN
PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF
BACHELOR OF ENGINEERING (B.ENG).**

IN

**THE DEPARTMENT OF STRUCTURAL ENGINEERING,
FACULTY OF ENGINEERING,
UNIVERSITY OF BENIN,
BENIN CITY, NIGERIA**

SEPTEMBER, 2025.

PLAGIARISM

This work “Evaluation of Strength of Concrete Partially Replacing the Coarse Aggregate by Blast Furnace Slag” by Orhionkpanwan Andrew with Mat Number ENG2002187 of the Department of Structural Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria, has PASSED the PLAGIARISM TEST.

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CERTIFICATION

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Signature

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Date

DEDICATION

This project is dedicated to God Almighty, whose grace and guidance have brought me this far.

ACKNOWLEDGEMENT

My deep gratitude goes to my project supervisor Engr. N. K. Oghoyafedo for his support despite his busy schedule and his guidance during moments I felt overwhelmed, and for taking the time to correct and direct me through this Project. I also sincerely appreciate the Head of Department of Civil Engineering Prof. Ngozi. I. Ihimekpen for her leadership, encouragement and steady support.

I am sincerely grateful for the tremendous leadership and continuous support of Engr. Prof. N. I. Ihimekpen, Head of Civil Engineering Department at University of Benin, whose excellent and profound dedication to academic excellence has been a continuous source of strength, hope and inspiration. I would also like to acknowledge my esteemed and dedicated lecturers: Engr. Prof. O.C. Izinyon, Engr. Prof. O.U. Orie, Engr. Prof. S.O. Osuji, Prof. A.N. Aniekwu, Engr. Prof. H.A.P. Audu, Engr. Prof. J.O. Okovido, Engr. Prof. E. Nwankwo, Engr. Prof. N. Kayode Ojo, Engr. Prof. R.O. Ogirigbo, Engr. Dr. A.I. Agbonaye, Engr. Dr. Iziengbe Inerhunwa, Engr. Dr. A. Rawlings, Engr. Dr. R. Ilaboya, Engr. Dr. L.O. Bobor, Engr. Dr. S.E. Okunofua, Engr. Dr. U. Ukeme, Engr. Dr. S.A. Adegbemileke, Engr. E. Oria Usifo, Engr. E. Musa, Engr. Mrs Ambrose Agabi, Engr. B. Omosefe, Mr. O. Osasu, Mr. C. Okolie, Engr. (Mrs.) E. Gloria Evbaru-Ohuathesuyi, Engr J.O. Odemerho and Engr. A.A. Musa, and all lab coordinators, technologist and all administrative staff for their dedication to establishing professionalism within the department.

I extend my deepest gratitude to my parents and my siblings, for their unwavering support, encouragement, and sacrifices, which have shaped me into the person I am today. And also, my sincere appreciation to my friends, and my course mates, thank you for being part of my journey.

ABSTRACT

This project aims to evaluate the strength of concrete by partially replacing the coarse aggregate by Blast Furnace Slag (BFS). The primary objective is to determine the effect of replacing natural granite with BFS in varying percentages (2.5%, 5%, 7.5%, and 10%) on the strength and durability of concrete. The research is motivated by the need to find sustainable alternatives to natural aggregates, reduce construction costs, and promote the reuse of industrial by-products in the construction industry.

The methodology involved preparing concrete mixes with BFS replacing granite at 0%, 2.5%, 5%, 7.5%, and 10% by weight. The materials to be used include Ordinary Portland Cement, fine aggregates (sharp sand), coarse aggregates (granite and BFS), and potable water. Standard laboratory tests were conducted, including sieve analysis for particle size distribution, slump test for workability, compressive strength and flexural strength tests at curing ages of 7, 14, and 28 days, and Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests to assess aggregate quality. A constant mix proportion was maintained for all specimens, with curing performed under controlled conditions to ensure comparability of results.

The results revealed that the control mix (0% BFS) achieved the highest compressive strength of 21.08 N/mm² and flexural strength of 9.60 N/mm² at 28 days, while 2.5% BFS replacement yielded comparable strengths of 19.29 N/mm² and 8.56 N/mm², respectively. Workability decreased with increasing BFS content, with slump values reducing from 30 mm (control) to 16 mm (10% BFS). The AIV and ACV values confirmed that both aggregates were mechanically durable, though granite performed slightly better. It was concluded that BFS can be used as a partial replacement for granite up to 2.5% in structural concrete without significant loss of performance, while higher percentages are more suitable for non-structural applications.

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ACRONYMS

BFS - Blast Furnace Slag

OPC - Ordinary Portland Cement

ASTM - American Society for Testing and Materials

w/c - Water-to-Cement Ratio

M15- Mix design grade of concrete (15 MPa compressive strength)

NCA - Natural Coarse Aggregate

RCA- Recycled Coarse Aggregate

SEM - Scanning Electron Microscope

SCM - Supplementary Cementitious Material

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

The accelerating growth of the construction industry has led to an unprecedented demand for natural resources, particularly coarse aggregates, which are vital constituents in the production of concrete for infrastructure development worldwide, (Mr. A. B. Sewant, Ms. V. H. Lavangare, 2019). Traditional sources of coarse aggregate, such as crushed stone and gravel, are depleting at alarming rates due to ongoing urbanization and large-scale infrastructural projects. This increased consumption has contributed to the exhaustion of natural resources, landscape disruption, and the environmental burden associated with quarrying activities. Consequently, researchers and industry practitioners are compelled to explore sustainable alternatives to conventional aggregates.

One promising approach is the use of blast furnace slag (BFS), an industrial by-product generated during iron and steel manufacturing, as a partial replacement for natural coarse aggregates in concrete. It is produced during the separation of molten iron from impurities in blast furnaces. (R. Krishnasami, R. Malathy, 2013). When cooled and processed appropriately, blast furnace slag possesses physical and mechanical properties suitable for use in concrete applications. Its rough texture, angular shape, and durability make it comparable to or, in some cases, superior to natural aggregates. This waste material, if not repurposed, accumulates in large stockpiles, leading to disposal challenges and environmental concerns. Its valorization in concrete represents a circular economy solution by recycling industrial waste, reducing environmental impact, and addressing raw material scarcity.

In terms of physical and mechanical characteristics, BFS is regarded as a potential aggregate due to its satisfactory strength, stiffness, porosity, and wear resistance. In the present

investigation BFS from local industries has been utilized to find its suitability as a coarse aggregate in concrete making. Various properties of such concrete have been compared with those of the conventional concrete with granite stone chips as coarse aggregate. The results indicate that the unit weight of BFS aggregate concrete is lower than that of the conventional concrete with stone chips. The compressive strength of BFS aggregate concrete is found to be higher than that of conventional concrete at the age of 90 days, but such strength is comparable at 28 days aging. Further, BFS aggregate concrete has higher split tensile strength, more or less same flexural strength, and higher modulus of elasticity at the age of 28 days. It has also reduced water absorption and porosity beyond 28 days in comparison to that of conventional concrete with stone chips used as coarse aggregate. (D. K. S. Roy, 2007).

Concrete incorporating BFS as coarse aggregate has demonstrated favorable results regarding mechanical performance, including compressive strength, tensile strength, and flexural strength, often comparable to or sometimes exceeding those of conventional concrete. (R. Krishnasami, R. Malathy, 2013). For instance, research has shown that up to 30–40% partial replacement of natural coarse aggregate with BFS enhances these properties, with optimal performance typically around 30% substitution. Notably, BFS aggregate concrete has also shown improved long-term mechanical strength, such as higher compressive strength at 90 days compared to conventional mix. (D. K. S. Roy, 2007).

While the technical feasibility of BFS aggregate has been validated, it is also crucial to consider its effects on workability and fresh concrete behavior. Results indicate that BFS maintains or improves workability at optimal replacement percentages, contributing positively to the constructability of complex or densely reinforced structures. (R. Krishnasami, R. Malathy, 2013). Furthermore, utilizing BFS in this manner supports environmental initiatives by diverting significant volumes of industrial waste from landfills and conserving natural stone resources. Economic analysis accentuates reduced production

costs due to lower raw material expenses, underpinning BFS's role in affordable and sustainable construction practices. Blast furnace slag has a great potential as it can be used as an artificial aggregate. Keeping this in view, the present study encourages the utilization of waste material such as air-cooled blast furnace slag in concrete. The combined effect of Blast Furnace Slag as replacement for coarse aggregates on the workability test, split tensile strength test, compressive and flexural strength of concrete has to be investigated. (P. Dewangan et al., 2019).

Despite these advantages, the application of BFS aggregate faces challenges that must be addressed, such as potential variability in material quality, potential increases in porosity and water absorption, and the need for meticulous mix design to ensure consistent mechanical and durability performance. (R. Krishnasami, R. Malathy, 2013). The exploration of BFS as a partial or full substitute for natural coarse aggregates is thus not just a technical pursuit but a strategic response to sustainability imperatives in construction. (Mr. A. B. Sewant, Ms. V. H. Lavangare, 2019).

The study will provide valuable insights into optimizing slag usage in concrete design and contribute to the development of sustainable construction materials. It will highlight key performance indicators, safety considerations, and practical recommendations for the application of blast furnace slag in construction projects, particularly in regions facing aggregate scarcity or waste disposal challenges.

In summary, the study of blast furnace slag as a replacement for coarse aggregate is set within the broader context of sustainable resource management, environmental stewardship, and the development of cost-effective, durable concrete materials. By leveraging industrial by-products, the construction sector can advance toward eco-efficient and circular production systems, bolstering both technological progress and environmental responsibility.

1.2 Statement of The Problem

The excessive extraction of natural coarse aggregates for construction purposes has led to significant environmental degradation, including habitat destruction, landscape alteration, and depletion of natural resources. As construction demand increases, the availability of quality aggregates diminishes, leading to higher material costs and increased project expenses.

Despite the growing interest and documented benefits of utilizing blast furnace slag as a replacement for coarse aggregate, several disadvantages and limitations have come to light in both field and laboratory observations. One predominant concern is the variability in the physical and chemical properties of BFS, depending on its source and processing method, which can lead to inconsistencies in concrete quality and performance. Increased porosity and water absorption are often cited as critical drawbacks, potentially compromising durability and long-term service life, especially in environments subject to freeze-thaw cycles or chemical attack. (D. K. S. Roy, 2007). At higher replacement levels, BFS aggregate can adversely affect the workability of fresh concrete, necessitating careful adjustments in mix proportions to ensure suitable fluidity and compaction characteristics. (D. Morian, et al., 2012).

There are also concerns about the reduced early-age strength in some BFS concrete mixes, with compressive strength sometimes only matching that of conventional concrete at later curing ages (e.g., 28 or 90 days), which can pose challenges for projects with tight construction schedules. Field performance data suggest that under certain service conditions, BFS aggregate concrete may display material-related distresses, and its long-term durability needs further validation across diverse climatic zones and load conditions. (D. Morian, et al., 2012). The limited popularity and reluctance of widespread adoption are further attributed to lack of norms, standard acceptance in some regions, and conservatism within the construction industry. Therefore, although BFS offers potential as an aggregate replacement, these

negative observations form the basis for comprehensive scientific inquiry to optimize its use and reliably address associated risks.

1.3 Aim and Objective of The Study

To evaluate the concrete strength by partially replacing the coarse aggregate with blast furnace slag.

The Objectives are to:

- i. Establish a baseline data on slag characteristics relevant to concrete applications.
- ii. Determine the optimal slag replacement percentage for the desired concrete performance.

1.4 Scope of Study

The scope of this study encompasses a systematic investigation into the employment of blast furnace slag as a partial replacement for coarse aggregate in concrete. The work includes the collection and characterization of BFS samples, preparation of concrete mixes at various BFS replacement levels (i.e. 2.5%, 5%, 7.5%, and 10%), and detailed testing of both fresh and hardened concrete properties. Activities will focus on experimental laboratory work, including slump, and workability tests for fresh mixes, as well as compressive, and flexural strength tests on cured specimens at standard ages (7, 14, and 28 days). A comparative analysis between BFS concrete and conventional aggregate concrete will be performed. The work specifically addresses coarse aggregate substitution, excluding BFS use as a fine aggregate or cement replacement unless referenced for comparison. Long-term field performance evaluations and industrial scale trials are beyond the present study's laboratory scope; however, findings will inform recommendations for future scale-up and potential standardization.

1.5 Justification of Study

The significance of this study is rooted in its alignment with sustainable construction objectives and resource conservation. By recycling blast furnace slag as a replacement for natural coarse aggregate, significant reductions in raw material extraction and environmental degradation can be realized. BFS concrete offers favorable mechanical properties such as high strength and durability that meet or exceed those of conventional concrete, thus promising reliable, long-lasting infrastructure. The diversion of industrial waste from landfills through its utilization in concrete not only addresses pressing waste management challenges but also embodies circular economy principles and green construction standards. Additionally, economic advantages gotten through lowered aggregate purchase costs and potential reductions in project outlays. This study hence provides essential technical evidence, to promote the broader adoption of BFS aggregate, contributing to enhanced sustainability, performance, and cost-efficiency in the construction sector

CHAPTER TWO

LITERATURE REVIEW

2.1 Concrete

This is a mixture of water, cement or binder, and aggregates. Chemical admixtures are also incorporated in most modern concrete constituents. Here, the binder phase for concrete is assumed to be based on Portland cement, the aggregates phase is the coarse and fine aggregates (Akinkurolere et al 2007; Neville and Brook, 2008; Matthias, 2010).

Concrete remains one of the most extensively utilized construction materials worldwide due to its strength, durability, and versatility in structural applications. However, the rising demand for natural aggregates has led to severe depletion of quarry resources and environmental degradation. In response, researchers and engineers have explored industrial by-products such as blast furnace slag (BFS), fly ash, rice husk ash (RHA), and silica fume as sustainable substitutes for cement and aggregates. The use of BFS, in particular, aligns with the principles of circular economy and sustainable construction by converting waste from iron and steel industries into valuable construction material (McGinnis et al., 2017; Gao et al., 2020).

Several studies have established that incorporating BFS in concrete, either as a fine or coarse aggregate replacement, can improve mechanical performance, durability, and long-term sustainability (Rafat Siddique and Kaur, 2012; K.G. Hiraskar and Patil, 2013). The literature review presented in this chapter examines experimental studies, methodologies, and findings from various researchers to understand how partial replacement of coarse aggregate with BFS affects the strength characteristics, workability, and overall performance of concrete. The review also highlights the influence of curing conditions, replacement ratios, and particle characteristics of BFS on compressive, flexural, and tensile strength.

2.1.1 Properties of Concrete and Role of Aggregates

Aggregates constitute approximately 70–80% of concrete volume and significantly influence its mechanical properties and long-term behavior. According to Mehta and Monteiro (2014), the bond between the cement pastes and aggregates governs the stress transfer mechanism within hardened concrete. Coarse aggregates primarily enhance compressive strength and dimensional stability, while fine aggregates improve cohesiveness and workability. Traditional aggregates such as crushed granite, limestone, and river gravel have been widely used, but their extraction contributes to environmental degradation, loss of biodiversity, and high energy consumption (Behera et al., 2014).

Substitution of natural aggregates with industrial by-products is therefore seen as an environmentally responsible innovation. Studies by Patel and Pitroda (2013) and Ghorpade (2013) emphasized that concrete containing recycled or waste aggregates can achieve comparable strength performance if properly proportioned and treated. Similarly, Xiao et al. (2005) demonstrated that the mechanical behavior of concrete depends not only on the aggregate type but also on the interfacial transition zone (ITZ), which can be modified by supplementary materials such as BFS or RHA.

Recent findings by Verma and Dubey (2022) confirmed that using waste-based aggregates significantly reduces embodied energy and carbon emissions associated with concrete production. Their results showed that replacement ratios of up to 40% BFS can maintain desirable compressive strength while lowering environmental impact. Hence, understanding the microstructural and chemical properties of BFS is crucial for optimizing its performance in concrete mixtures.

2.1.2 Types and Innovative Forms of Concrete

Concrete technology has evolved to encompass a wide variety of specialized types, each designed to meet specific structural, environmental, or architectural requirements. Ordinary

concrete serves general construction purposes, while high-performance concrete (HPC) and ultra-high-performance concrete (UHPC) feature optimized mix designs, low water-binder ratios, and advanced admixtures or fibers, leading to superior strength, durability, and workability for demanding structures such as bridges, high-rise buildings, and marine installations (Jayesh, 2016; Awari, 2018; Alireza Rashno, et. al., 2023).

Fiber-reinforced concrete (FRC) integrates fibers made of steel, polypropylene, glass, or hybrids, significantly improving tensile strength, ductility, crack control, and post-cracking behavior, making it suitable for industrial floors, pavements, seismic-resistant structures, and precast segments. Polymer concretes, which utilize synthetic resins (e.g., epoxy or vinyl ester) instead of cement, offer rapid curing, high chemical resistance, and elevated compressive and tensile strengths, meeting the needs of specialized repairs and infrastructure applications. (Abdelaziz, et. Al., 2024; Aravinthan, 2013).

Lightweight concretes, including foamed concretes and aggregate-modified concretes, reduce density and improve thermal insulation, often employed in geotechnical fills, nonstructural elements, and secondary applications, while maintaining adequate strength and durability. (Roderick Jones, 2005; Jagdeo, 2024).

Recent innovations include green concretes utilizing recycled materials and industrial by-products, transparent concrete for aesthetic applications, and concretes with photocatalytic or carbon-sequestering properties for enhanced sustainability and environmental performance. (Tran Stanley, 2010).

2.1.3 Applications of Concrete in Construction and Infrastructure

Concrete's versatility is reflected in its ubiquitous use in construction and infrastructure. It forms the backbone of buildings, bridges, highways, tunnels, water reservoirs, dams, and foundations. In roadway and airport infrastructure, precast and cast-in-place concrete

elements provide long-lasting, high-capacity surfaces. Precast and prefabricated concrete is widely deployed to expedite construction schedules and improve quality control in commercial and residential buildings, while innovative products like self-compacting concrete (SCC) and fiber-reinforced precast elements increase labor efficiency and structural performance. (Wang Hu, 2009; Albert, 2014).

In geotechnical and environmental engineering, lightweight and foamed concretes are used for ground stabilization, backfilling, and even as radiation shielding in specialized facilities. Advanced forms like ultra-high-performance concrete are increasingly adopted in infrastructure requiring high durability, reduced maintenance, and slender, aesthetically unique forms such as pedestrian bridges and sculptural facades. (Ponomarev, 1956).

2.1.4 Production Methods, Mixing Techniques, and Quality Control

Concrete production involves precise proportioning, thorough mixing, and stringent quality control to ensure uniformity and performance. There are two principal mixer categories: batch mixers most commonly used in the industry which process one batch at a time, and continuous mixers, which deliver constant output suitable for specific applications. Batch mixers include drum types (tilting, non-tilting, or reversing) for general mixing, and pan mixers, which can offer more intensive blending for high-performance concretes. (Chiara, 2001).

Critical mixing procedures determine the homogeneity, workability, and final mechanical properties of concrete. Optimum mixing time and speed, order of addition of ingredients, and mixer design are key factors; too little mixing leads to uneven distribution of materials, while excessive mixing may reduce workability or entrain unwanted air. Recent automation and the use of advanced control systems, such as IoT-based production controls, enhance real-time monitoring and regulation of batching, mixing, and delivery, optimizing quality and process efficiency. (Chiara, 2001; Dils, 2012).

Quality criteria commonly evaluated include the workability as measured by slump or flow tests, air content, compressive strength, density, and segregation resistance. Non-destructive testing methods and robust quality assurance/quality control (QA/QC) processes support early detection of inconsistencies and enable predictive strength assessments during production, reducing the risk of structural failures or delays in construction.

Concrete remains the cornerstone of modern construction due to its mechanical robustness, workability, and adaptability to diverse structural requirements and environmental conditions. However, its large-scale use generates notable environmental impacts, particularly attributed to cement production and aggregate sourcing, necessitating the adoption of innovative materials, sustainable mix designs, recycling, and process optimizations for future resilience. Advances in fiber reinforcement, admixtures, smart production controls, and eco-friendly substitutes are shaping the next generation of concrete, supporting sustainable growth and high-performance construction worldwide.

Aggregates, the other mineral constituent which makes up 70% of the concrete volume, are one of the main constituent materials in concrete production. Aggregates provide the concrete its necessary property of volume stability and practice a significant effect on solid quality and solidness giving inflexibility to the material that is fundamental for designing use. In numerous nations, there is a shortage of characteristic totals, while in different nations; there is an expansion in the utilization of total, because of the more prominent interest by the development business. Hence, the fast development in the development business is imperiled by the absence of common assets accessible. A significant test for the total and the development enterprises is to locate an elective total source to beat the deficiency. In the event that optional materials are related to appropriate characteristics, the amount of regular total required by the development business would be decreased.

Due to the significance of sparing energy and protection of assets, proficient reusing of all strong squanders is currently a worldwide need, requiring broad exploration pursue investigating fresher applications and boosting the utilization of existing advances for reasonable and ecologically stable administration. To diminish reliance on regular totals as the fundamental wellspring of totals in concrete, the counterfeit total created from mechanical squanders give an option in contrast to the development business. Additionally, such use will generally address the ecological concerns raised already.

2.2 Aggregates in the Construction Industry

In construction, aggregates are indispensable materials that serve as the backbone of various composite building materials. Typical examples include sand, gravel, crushed stone, industrial byproducts like slag, and recycled construction materials such as crushed concrete. Natural aggregates originate directly from mineral deposits, while artificial or recycled aggregates are manufactured from industrial residues or by reprocessing demolition waste. Their physical characteristics such as size, texture, grading, and mechanical strength bear a critical influence on the workability, durability, and strength of end products like concrete and asphalt. (Anmol 2017; Kumar, 2017; Christie, et. al., 2007).

Table 2.1: Common Types of Construction Aggregates

Type	Natural or Artificial	Typical Source	Common Applications
Sand	Natural	Riverbeds, pits	Concrete, mortar, bedding
Gravel	Natural	Riverbeds, quarries	Concrete, road base, drainage
Crushed Stone	Natural	Quarries (limestone, granite)	Concrete, road aggregate, ballast
Slag	Artificial	Industrial byproduct (steelworks)	Concrete, fill material
Recycled Concrete	Artificial	Demolition waste	Road base, engineered fill
Geosynthetic	Artificial	Manufactured polymer products	Lightweight fill, cellular concrete

Source: (A. Dinku, 2005)

2.2.1 Technical Properties and Testing of Construction Aggregates

The quality and utility of aggregates in construction are determined by their physical and mechanical properties, as well as their chemical stability. Properties such as grain size distribution, shape, surface texture, bulk density, moisture content, compressive strength, abrasion resistance, and chemical inertness are routinely tested to ensure suitability for specific engineering requirements. Experimental methods for assessing aggregate durability include crushing resistance, impact testing, etc. (Dinku, 2005).



Figure 2.1: Natural Coarse Aggregate

Source: <https://m.indinmart.com/proddetail/coarse-aggregate>

Description: The image below shows conventional crushed granite used in concrete as a coarse aggregate. It is typically hard, angular, and obtained from natural rock quarries.

Standards Used:

BS 812-103.1:1985 – Testing aggregates – Part 103: Method for determination of particle size distribution – Section 103.1 Sieve tests

BS EN 933-1:2012 – Tests for geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method

2.2.2 Particle Size Distribution (Sieve Analysis)

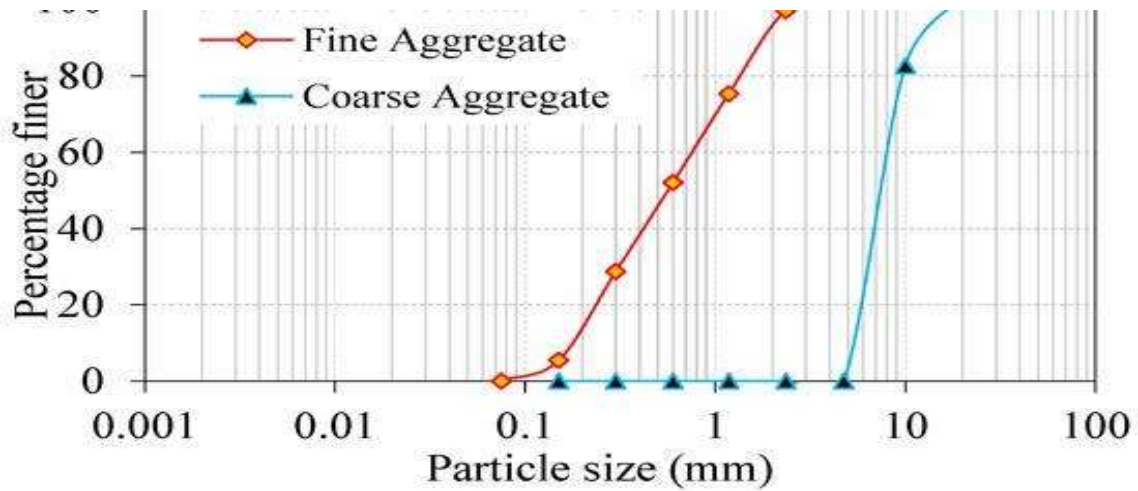


Figure 2.2: Particle Size Distribution Chart (Gunasekaran, 2012)

Description: The particle size distribution curve is a critical factor in determining the grading and packing efficiency of aggregates in concrete. The chart below compares the particle size distribution of fine aggregates and coarse aggregates

To determine the **gradation** of aggregates and verify compliance with required standards for proper:

Workability, Strength, Durability, Gradation matching for concrete mix design

2.2.2.1 Apparatus Required

- i. Set of standard sieves (dry and clean)
- ii. Weighing balance
- iii. Brush, scoop, trays, pan

2.2.2.2 Procedure for Both Fine and Coarse Aggregates

1. Sample Preparation

- i. Fine Aggregate (Sand): 500g – 1000g
- ii. Coarse Aggregate (Granite/BFS): 2000g – 5000g

Dry the samples in an oven at 105–110°C for 24 hours and cool.

2. Sieving – Fine Aggregate

Standard sieve sizes (BS): 4.75 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm, 150 µm, pan

Procedure:

- i. Place the sand in the top sieve (4.75 mm)
- ii. Stack the sieves in descending order
- iii. Sieve for 10 minutes using a sieve shaker or by hand
- iv. Weigh the material retained on each sieve
- v. Express results as percentage retained and cumulative passing

3. Sieving – Coarse Aggregate (Granite and BFS)

Standard sieve sizes (BS): 37.5 mm, 20 mm, 14 mm, 10 mm, 5 mm, pan (adjust based on aggregate size)

Procedure:

- i. Place the dry sample on the top sieve
- ii. Stack sieves from largest to smallest
- iii. Shake for 10 minutes
- iv. Weigh and record the mass retained on each sieve
- v. Calculate % **passing** and % **retained**

2.3 Typical Grading Limits (BS EN)

Table 2.2: Fine Aggregate (Zone II Sand – BS 882)

Sieve Size (mm)	% Passing (Zone II)
4.75	90–100
2.36	75–100
1.18	55–90
0.60	35–59
0.30	8–30
0.15	0–10

Source: (A. Dinku, 2005)

Table 2.3: Coarse Aggregate (10–20 mm Nominal Size)

Sieve Size (mm)	% Passing (Typical)
37.5	100
20	85–100
14	10–30
10	0–5
5	0–1

Source: (A. Dinku, 2005)

Table 2.4: Coarse Aggregate (10–20 mm Nominal Size)

Sieve Size (mm)	Weight Retained (g)	% Retained	Cumulative % Retained	% Passing
20.0	250	12.5%	12.5%	87.5%
14.0	1000	50%	62.5%	37.5%
10.0	600	30%	92.5%	7.5%
Pan	150	7.5%	100%	0%
Total	2000	100%		

Source: (A. Dinku, 2005)

2.4 Overview of Concrete Testing

Concrete testing is an indispensable aspect of quality control in the construction industry, ensuring that the material complies with project specifications and achieves its intended performance. Various degrees of processing are required for concrete between its arrival on site and its final placement, compaction, finishing, and curing, necessitating comprehensive sampling and testing. The primary purposes of concrete quality control tests include detecting variations in the quality of supplied concrete, confirming that the concrete has attained sufficient strength for activities like stripping or opening to traffic, and establishing whether it has gained adequate strength for its intended purpose. It is important to note that conducting all available tests may not be feasible due to cost and time constraints. (Behnam, 2017).

Table 2.5: Concrete Grade Table

Group	Concrete Grade	Mix Ratio	Characteristic Compressive Strength (N/mm²)
Ordinary Concrete	M5	1:5:10	5 N/mm²
	M7.5	1:4:8	7.5 N/mm²
	M10	1:3:6	10 N/mm²
	M15	1:2:4	15 N/mm²
	M20	1:1.5:3	20 N/mm²
Standard Concrete	M25	1:1:2	25 N/mm²
	M30	Design Mix	30 N/mm²
	M35	Design Mix	35 N/mm²
	M40	Design Mix	40 N/mm²
	M45	Design Mix	45 N/mm²
	M50	Design Mix	50 N/mm²
High Strength Concrete	M55	Design Mix	55 N/mm²
	M60	Design Mix	60 N/mm²
	M65	Design Mix	65 N/mm²
	M70	Design Mix	70 N/mm²

Source: (A. Dinku, 2005)

2.4.1 Tests for Fresh Concrete Properties

Testing the properties of fresh concrete is crucial for assessing its workability and consistency before it hardens.

1. Slump Test for Workability

The slump test is a widely recognized and simple method used globally to measure the consistency of fresh Portland cement concrete. Invented by Chapman in 1913, this test assesses the concrete's plasticity, or its ability to fill a given form properly with desired vibration and without reducing quality. The procedure involves filling an Abrams cone with a fresh concrete sample in three layers of equal volume, with each layer being tamped with a

steel rod to consolidate it. After the cone is carefully lifted, the amount the enclosed material slumps due to gravity are measured. High slump values, historically associated with high water content, can now be achieved with low water/cement ratios due to high-range water-reducing admixtures. (Shilstone, 1991; Xuhao et. al., 2017; Stanley, 2011).

2.4.2 Tests for Hardened Concrete Properties

Tests on hardened concrete assess various properties crucial for structural integrity and long-term performance, ranging from strength to durability.

a. Compressive Strength Tests

Compressive strength is a fundamental property of concrete, and its determination is a sequential process often involving cube testing, core testing, rebound hammer, and ultrasonic pulse velocity. The compressive strength of cylindrical concrete specimens is regulated by BS EN 12390 and ASTM C 39, and is a necessary step for acceptance testing of specified concrete strength in construction. This process includes making cylinders or beams on-site and transporting them to a laboratory for strength testing, following procedures outlined in standards like ASTM C31/C31M. The ASTM C31/C31M standard specifies test procedures for both standard-cured and field-cured cylinders or beams. When testing the strength of structural concrete, the rebound method is often prioritized, with the core-drill method used for verification when results are doubtful to enhance accuracy. Factors such as in-place concrete strength and cubes cast at project sites can affect the results, necessitating careful selection of sampling locations consistent with investigation objectives. (Irving, 1999; Jin-Jian, 2024; Diwan, 2016).

Nondestructive methods such as rebound testing and ultrasonic testing are also employed, though their interpretation can be influenced by the surrounding environment. In practical engineering, it is recommended to use more than two nondestructive methods to verify each other and enhance reliability. (Pandey et al., 2019; Dong, 2005).

b. Flexural Strength Tests

Flexural strength, also known as modulus of rupture, evaluates concrete's resistance to bending loads. The ASTM Test Method for Flexural Strength of Concrete (C 293) uses a simple beam with center-point loading, while other methods, such as ASTM C 78, employ third-point loading. This test is particularly important for concrete used in surfacing and pavements. Beams for flexural strength tests are typically molded to standard sizes, and the load is applied gradually at specified rates until the beam fails. Studies have explored reducing the specimen size for flexural strength tests to improve safety and ease of handling.

2.4.3 Importance of Standards and Equipment

Adherence to specific standards, such as those from ASTM, BS, or IS, is crucial for ensuring the reliability and comparability of test results. For example, the ASTM standards include test methods for compressive strength, flexural strength, unit weight, slump, air content, and making and curing concrete test specimens. Specialized equipment, such as compression testing machines, flexural test machines, slump cones, tamping rods, and permeability testers, are essential for conducting these tests accurately. The appropriate use of equipment, along with proper specimen preparation and curing conditions, is vital for obtaining consistent and reliable results.

2.5 Blast Furnace Slag: Origin, Classification, and Properties

Iron blast furnace slag results from the fusion of iron ore, fluxing materials, and coke; the reduction reactions; and the separation of iron from the ore. The term blast furnace slag is used often to refer to iron blast furnace slag to distinguish it from other types of blast furnace slag such as copper, lead, and zinc blast furnace slag. Because the blast furnace operation is a continuous process with carefully controlled raw materials being fed in and furnace conditions, among the various slags, iron blast furnace slag is the easiest to deal with technically to use in construction-related applications. Like other slags, although blast

furnace slag varies in chemical and mineral composition, its physical structures depend on the method of cooling of the slag and the processing method used. The nature of the minerals formed when slag cools slowly is of concern in the use of the materials as a dense aggregate. It is of less direct interest for slag in the glassy, or granulated form used as an aggregate, but its hydraulic activity is essential in its use as a cementitious material (Murphy et al., 1997; Rendón-Angeles et al., 2004).

Blast furnace slag cannot be used for the manufacturing of cement concrete pavements since typically it is not able to meet the relevant high requirements. The by-product can be generally utilized for the production of cement concrete base courses.



Figure 2.3: Blast Furnace Slag Aggregate

Source: (Hwang-Heekim, 2016)

Blast furnace slag (BFS) is a non-metallic by-product formed when iron ore, coke, and limestone are melted in a blast furnace at temperatures exceeding 1500°C. The molten slag, primarily composed of silicates and aluminosilicates of calcium and magnesium, is rapidly cooled with water or air to form a glassy, granular material. According to Habel and Gauvreau (2008), the cooling rate determines the type of slag formed granulated, air-cooled, or expanded slag each with distinct physical and chemical characteristics.

Air-cooled BFS, which resembles crushed stone, is particularly suitable as a replacement for coarse aggregate. Studies by Hiraskar and Patil (2013) revealed that the angular and rough texture of BFS particles enhances the mechanical interlock between aggregate and paste, leading to higher compressive strength compared to conventional granite aggregates. Similarly, Bhat (2021) reported that BFS exhibits lower density but superior abrasion resistance, making it suitable for structural concrete applications where weight reduction is advantageous.

Chemical composition plays a pivotal role in determining the reactivity and compatibility of BFS in concrete. The major oxides CaO, SiO₂, Al₂O₃, and MgO contribute to pozzolanic and cementitious reactions, especially when used in finely ground form. Corinaldesi et al. (2016) noted that BFS aggregates improve the alkalinity and reduce porosity, thereby enhancing the durability of concrete against chloride and sulphate attack. Additionally, studies by Gao et al. (2020) and Mohammadinia et al. (2019) demonstrated that BFS-modified concrete exhibits reduced thermal conductivity and improved microstructure, making it suitable for pavements and marine structures.

Overall, BFS has gained attention not only as a sustainable alternative to natural aggregates but also as a performance-enhancing additive. Its favourable mechanical properties, low water absorption, and environmental benefits make it a viable component for producing eco-efficient concrete.

2.6 Blast Furnace Slag as Coarse Aggregate in Nigeria

Blast furnace slag (BFS) is a significant industrial byproduct generated by Nigeria's iron and steel sector, particularly during the production of iron in blast furnaces and through electric arc furnace (EAF) steelmaking processes in facilities such as Prism Steel Mill, Ikirun, and Nigerian Federated Steel Ltd, Ota, among others. The use of BFS as a replacement for coarse aggregate in concrete is gaining widespread research and practical traction in Nigeria,

propelled by the dual motives of sustainable construction and the effective management of industrial waste. Given the depletion of naturally occurring aggregate resources and mounting concerns over environmental pollution from industrial byproducts, BFS presents a promising alternative that aligns with the global push for sustainable and environmentally responsible construction practices.

Air-cooled slag is solidified under ambient conditions. Immediately after being discharged from the blast furnace, the molten blast furnace slag is dumped into cooling pits for air-cooling before further processing for slag products. (Chandra, 1997). When the slag undergoes air-cooling in the pit, stratification of the layers resulting from pouring hot molten slag over partially cooled slag, causes cracking so that upon further cooling it can be readily picked up with power shovels. (GOI, 2013-2014). Water is used in air-cooling to aid fragmentation and to hydrate possibly incomplete fused pieces of fluxing materials that might produce spalls or popouts when slag is used as a concrete aggregate. After cooling to 93°C (200°F) or lower, the slag is transported to a plant for crushing and screening to a size appropriate for concrete use (Dobrowolski, 1998). Air-cooled blast furnace slag has been extensively used as a construction aggregate.

In 2002, granulated slag accounted for approximately 70% of the total blast furnace slag production in the world; the proportion of cement containing GGBFS is as high as 80% in some countries (Geiseler and Vaattinen, 2002).

Multiple studies have identified an optimal BFS replacement level of around 30–40% for coarse aggregate, balancing improvements in strength and durability with mix workability and cost considerations. Exceeding this range may lead to marginal decreases in mechanical performance, necessitating careful monitoring of aggregate proportions and mix adjustments.

The compressive strength of Blast Furnace Slag aggregate concrete is found to be higher than that of conventional concrete at the age of 90 days and it has also reduced water absorption and porosity beyond 28 days in comparison to that of conventional concrete with stone chips used as coarse aggregate (Hiraskar and Patil, 2013).

2.6.1 Types and Sources of Blast Furnace Slag in Nigeria

The primary types of blast furnace slag available and utilized in Nigeria for coarse aggregate replacement are Air-Cooled Blast Furnace Slag (ACBFS) and Granulated Blast Furnace Slag (GBFS). ACBFS is produced by slowly cooling molten slag in air, resulting in dense, angular, and hard particles ideal for aggregate applications. GBFS, by contrast, is made by rapidly quenching molten slag with water, producing a glassy material more commonly employed as a fine aggregate or as a supplementary cementitious material in concrete. Steel slags, including those from EAF, also enter the construction material stream, expanding the spectrum of available slags for aggregate substitution. Major sources for these byproducts in Nigeria remain steel mills and foundries primarily located in states like Osun and Delta, where annual slag generation is measured in several million tonnes.

2.6.2 Properties of Blast Furnace Slag as Coarse Aggregate

Blast furnace slag is a non-biodegradable industrial by-product formed during steel production, typically comprising silicates and aluminosilicates of calcium and other metal oxides. Air-cooled BFS is widely studied and applied as a coarse aggregate due to its stable chemistry, rough surface texture, and favorable mechanical properties. BFS aggregate concrete generally exhibits lower density, improved strength development at later ages, and enhanced resistance to environmental stressors such as freeze-thaw cycles and chemical attacks.

Physical and mechanical properties of the steel slag aggregate are similar to those of natural aggregate. Hence the former can be utilized as an alternative to natural aggregate in concrete

production. The aging process of steel slag affects the properties of concrete made with steel slag as coarse aggregate.

The abrasion loss of concrete decreased with an increase in compressive strength. This shows that the 'abrasion resistance of concrete" also increases significantly with the aging period of SSA. In general, the comparison of all strength results for control mix and HPC mixes shows that the HPC mix results are lower at an early age. Thereafter, at later ages, due to delayed action of fly ash and steel slag, all test results are comparable or higher than those relating to the control mix.

It can be concluded that, after sufficient aging, the steel slag can be used as concrete aggregate along with chemical and mineral admixtures, to produce a higher quality concrete.

2.6.3 Physical and Chemical Properties of Nigerian Blast Furnace Slag

Blast furnace slag produced in Nigeria exhibits physical and chemical properties conducive to its use as a coarse aggregate substitute. Physically, BFS is characterized by its rough, angular texture and moderately porous structure, attributes that promote favorable mechanical interlock and bond strength in the concrete matrix. It typically has a lower specific gravity than natural aggregates, leading to reduced unit weight in concrete, which can confer structural and handling advantages. Chemical analysis of Nigerian slags indicates a preponderance of stable silicate compounds, predominantly comprising oxides of calcium, magnesium, manganese, and aluminum, which impart chemical inertness and resistance to deleterious reactions. These factors combined with high compressive and tensile strength potential, support BFS's technical suitability as a coarse aggregate replacement.

2.6.4 Mechanical Performance of BFS Aggregate Concrete in Nigeria

Research in Nigeria consistently demonstrates that the mechanical properties of concrete incorporating BFS, either as partial or total replacement for coarse aggregates, are at least

comparable if not superior to those of conventional concrete at optimal replacement levels. Laboratory data show compressive strengths of BFS aggregate concrete meeting or exceeding the required 25 MPa for structural use at 28 days when replaced at 20–40% intervals, with some studies reporting even higher strength at elevated replacement ratios, notably when EAF steel slag is employed. The split tensile and flexural strengths of such concretes similarly reveal improvements or equivalency due to the angular and rough surface of slag enhancing the mechanical bond within the matrix.

Notably, beyond a certain replacement threshold (generally above 40–60%), a reduction in both compressive and tensile strength begins to manifest, attributed predominantly to excessive porosity and reduced matrix density. Thus, careful optimization in mix design is essential to ensure both workability and strength targets are met.

The use of slag aggregates by replacing coarse aggregates decreases compressive strength, flexural strength and tensile strength of concrete, but these blocks can be used as non-structural members in construction papers. The weight of block can be reduced further by increasing the percentage of BFSA within specific range of compressive strength.

2.6.5 Studies on Partial Replacement of Coarse Aggregate with Blast Furnace Slag

A wide range of experimental investigations have been conducted to assess the effect of partially replacing coarse aggregate with blast furnace slag on the strength, durability, and workability of concrete. Researchers have approached this issue through controlled laboratory mix designs, typically substituting 10–60% of natural aggregate with air-cooled or granulated slag and measuring compressive, flexural, and split tensile strength after 7, 14, and 28 days of curing. The following review summarizes key methodologies and findings from relevant studies.

S. Andavan (2018) investigated the mechanical properties of concrete with partial cement replacement using rice husk ash (RHA) and compared it to BFS-modified concrete to

establish performance benchmarks. The study adopted a mix ratio of 1:1.5:3 and replaced cement at 10%, 15%, and 20%. The methodology included slump tests for workability and compressive strength tests at 7, 14, and 28 days. Results indicated that a 15% replacement achieved optimum compressive strength of 38.5 N/mm², outperforming the control. The author concluded that industrial by-products such as BFS could yield similar strength improvements if properly graded and cured under standard conditions.

Er. Ravi Bhushan (2017) conducted a similar investigation focusing specifically on the use of RHA as a pozzolanic additive and BFS as a coarse aggregate substitute. Using M25-grade concrete, Bhushan replaced natural aggregate with BFS at varying levels (10–50%) and measured slump and compressive strength at 28 days. The results revealed that 30% replacement gave maximum compressive strength of 40.2 N/mm², slightly higher than the control (38.8 N/mm²). Beyond 40%, strength began to decline due to increased porosity and poor aggregate interlock. The study concluded that BFS offers structural benefits up to an optimum limit and significantly enhances sustainability by reducing natural stone consumption.

Gupta Priyanka (2017) explored the effect of substituting both fine and coarse aggregates with BFS on concrete's mechanical performance. The methodology involved casting cubes and beams with BFS replacement levels from 0–60%. The experimental design followed IS:10262-2009 standards, and results were evaluated using compressive, split tensile, and flexural tests. The findings showed a 15–20% increase in compressive strength at 30% replacement compared to the control, while tensile strength improved by 8–10%. Gupta concluded that BFS could act as a high-performance aggregate when combined with proper water-cement ratios and curing conditions.

Chandraul Kirti (2015) emphasized microstructural development in BFS concrete. Using scanning electron microscopy (SEM), the study examined hydration products and ITZ

bonding in concrete with 40% BFS aggregate replacement. The experimental program revealed a denser ITZ with fewer microcracks and voids, which explained the higher compressive strength (45.1 N/mm²) compared to the conventional mix (42.3 N/mm²). Kirti concluded that BFS not only serves as a filler but also chemically participates in pozzolanic reactions that enhance long-term strength and durability.

Manjit Kaur (2012) examined BFS as a substitute for both fine and coarse aggregates in high-strength concrete. The methodology involved M40-grade concrete with BFS replacing 25%, 50%, and 75% of the total aggregate content. Compressive strength tests at 7, 28, and 56 days showed that 25% replacement provided the highest strength, while 75% resulted in reduced workability and segregation. The author concluded that BFS at moderate levels can produce high-performance concrete suitable for structural applications such as pavements and bridge decks.

George Washington (2017) assessed the combined effect of BFS and fly ash on concrete performance. The study employed a factorial design where BFS replaced coarse aggregates at 30% and fly ash replaced cement at 20%. The results showed a synergistic improvement in strength and resistance to sulphate attack, with 28-day compressive strength increasing by 12% compared to conventional concrete. The author concluded that hybrid use of BFS with supplementary cementitious materials (SCMs) promotes strength and durability while reducing embodied CO₂.

Harshit Varshney (2015) studied the impact of granulated BFS as a coarse aggregate replacement in M30 concrete. The methodology involved replacement levels from 0% to 50% and testing for compressive, split tensile, and flexural strengths at 7, 14, and 28 days. Results indicated that optimum performance occurred at 30% replacement with 42.8 N/mm² compressive strength. At higher replacements ($\geq 40\%$), marginal decreases were observed due to increased void content. Varshney concluded that BFS aggregate enhances bonding and

compressive strength within controlled replacement ranges.

Rafat Siddique and Deepinder Kaur (2012) provided one of the foundational studies on BFS in concrete. They replaced natural coarse aggregate with air-cooled BFS at 0%, 25%, 50%, 75%, and 100% and measured mechanical and durability parameters. Results demonstrated that up to 50% replacement improved compressive strength and reduced permeability, while higher levels increased water absorption. The authors concluded that BFS can substitute up to 50% of coarse aggregate without adverse structural effects, provided adequate curing is maintained.

Alaa Bashandy (2019) expanded on thermal performance by testing BFS concrete under elevated temperatures (200–800°C). Using 20% and 40% replacement levels, the study found that BFS concrete retained 82% of its original compressive strength at 400°C compared to 70% in control samples. SEM analysis showed reduced microcracking in BFS concrete, confirming its superior thermal stability. Bashandy concluded that BFS aggregates improve thermal resilience and microstructural integrity.

B. G. Buddhdev and H. R. Varia (2014) examined the combined replacement of BFS and recycled aggregates in M25 concrete. The study's methodology included partial replacement of natural coarse aggregates with 25% BFS and 25% recycled concrete aggregate (RCA). Tests showed a 10% increase in compressive strength and a 15% improvement in split tensile strength compared to RCA-only concrete. The authors concluded that BFS helps counteract the weaknesses of RCA by filling voids and enhancing interfacial bonding.

P. Jyotsna Devi and K. Srinivasa Rao (2014) investigated the influence of BFS as coarse aggregate on M30 concrete's mechanical behavior. Concrete specimens were prepared with BFS replacing 0%, 20%, 40%, and 60% of natural aggregates. The study followed IS:516 (1959) standards for strength testing. The maximum compressive strength of 43.9 N/mm² was

observed at 40% replacement, beyond which workability reduced and bleeding increased. The study concluded that 40% BFS is the optimum level for structural applications.

Khaled Mohammed Nassar and Prof. Samir (2011) evaluated BFS concrete's resistance to chloride penetration. Using rapid chloride permeability tests (RCPT), they demonstrated that BFS aggregates significantly lowered ion permeability, enhancing durability in marine and coastal environments. Their findings recommended BFS use in reinforced concrete exposed to aggressive chemical conditions.

Rahul Subhash Patil (2014) compared BFS and steel slag aggregates in M20 concrete. The study's experimental results indicated that BFS-modified concrete achieved higher compressive strength (32.5 N/mm²) than steel slag (30.8 N/mm²) and conventional mixes (31.2 N/mm²). The conclusion emphasized BFS as a superior eco-friendly aggregate with minimal adverse effects on workability.

Rajesh Kumar et al. (2014) explored BFS and copper slag as combined replacements for coarse aggregates. Their results showed that a 25% BFS + 10% copper slag blend yielded the highest compressive strength (41.6 N/mm²) and reduced density. The authors recommended this mixture for lightweight structural elements.

K.G. Hiraskar and Chetan Patil (2013) conducted one of the earliest studies in India evaluating BFS as coarse aggregate. They observed that air-cooled BFS exhibited angular particle shapes enhancing paste-aggregate adhesion. Concrete specimens with 30% BFS replacement exhibited 12% higher compressive strength than the control mix. Their findings reinforced BFS's potential as a sustainable replacement for crushed granite.

2.7 Influence of Environmental Exposure on BFS Concrete

Temperature and curing conditions play a crucial role in determining the mechanical and durability properties of BFS-based concrete. Numerous studies have demonstrated that the

inclusion of BFS not only enhances compressive strength at ambient conditions but also significantly improves resistance under elevated temperatures and aggressive environmental exposure.

Alaa A. Bashandy (2019) examined the influence of elevated temperatures on reactive powder concrete incorporating BFS aggregates. The experimental program exposed concrete specimens to temperatures ranging from 200°C to 800°C. Bashandy reported that BFS-modified concrete retained approximately 82% of its original compressive strength at 400°C, compared to 70% in conventional concrete, and exhibited fewer surface cracks. The methodology included compressive, split tensile, and ultrasonic pulse velocity (UPV) tests after thermal exposure, providing a comprehensive assessment of microstructural integrity. The author concluded that the improved thermal performance was due to the lower thermal expansion coefficient of BFS and its ability to refine pore structure, reducing internal vapor pressure during heating.

Similarly, Khaled Mohammed Nassar and Prof. Samir (2011) explored the fire resistance of reinforced concrete columns incorporating BFS aggregates. Their study used full-scale column specimens exposed to fire loads in accordance with *IS:1641–1988* (Fire Safety of Building Code). They observed that BFS-concrete columns experienced slower temperature rise, smaller crack propagation, and higher residual load capacity than normal concrete columns. The authors concluded that BFS aggregates enhance thermal inertia and structural integrity under prolonged fire exposure, recommending their application in high-temperature industrial and structural environments.

In another study, Rahul Subhash Patil (2014) analysed the effect of cooling regimes on M20-grade BFS concrete after heating to 600°C. The methodology compared air-cooled, water-cooled, and naturally cooled specimens. Patil found that air-cooled BFS concrete retained 75% of its 28-day compressive strength, while water-cooled specimens showed only 60%

retention, due to thermal shock-induced microcracking. This result demonstrated BFS's advantage in maintaining structural performance under thermal cycles.

P. Jyotsna Devi and K. Srinivasa Rao (2014) focused on the flexural and split tensile strengths of steel fibre reinforced BFS concrete exposed to elevated temperatures. The specimens were subjected to 200°C, 400°C, and 600°C, with strength testing per *IS:516-1959*. Their results revealed that BFS combined with steel fibres improved post-heating residual strength by 10–15% compared to control mixes, indicating synergistic performance under thermal stress.

Rajesh Kumar et al. (2014) and K.G. Hiraskar and Chetan Patil (2013) both confirmed that BFS aggregates reduce permeability and resist sulphate and chloride ingress during long-term curing in marine exposure conditions. Using the Rapid Chloride Penetration Test (RCPT) and Sorptivity tests, they found a 35% reduction in chloride ion diffusion for 40% BFS replacement, correlating to extended service life in coastal structures. Similarly, Rafat Siddique and Deepinder Kaur (2012) observed that BFS concrete subjected to 60-day curing exhibited higher durability indices and lower water absorption, further confirming the material's ability to resist degradation in harsh environments.

The combined outcomes of these studies establish that BFS aggregates not only improve ambient mechanical performance but also significantly enhance high-temperature resilience, reduce permeability, and extend service life under aggressive environmental conditions.

2.8 Environmental and Economic Impacts

The environmental appeal of BFS utilization in Nigeria is underscored by its considerable contribution to waste minimization and conservation of natural aggregates. Using BFS effectively diverts large industrial byproduct streams from landfills, mitigating pollution and reducing natural resource extraction rates. Life cycle assessments reveal that BFS-replaced

concrete in Nigeria presents significantly reduced footprints in terms of fossil fuel use, greenhouse gas emissions, resources depletion, and pollution indices relative to traditional concrete.

The application of blast furnace slag in concrete aligns closely with global sustainability goals, particularly in promoting waste valorisation and reducing dependence on natural aggregates. Rajesh Kumar et al. (2014) highlighted the dual environmental and economic benefits of using BFS and other industrial by-products in eco-friendly concrete production. The study demonstrated that utilizing BFS reduced overall project costs by up to 20% due to lower material and disposal expenses, while also minimizing greenhouse gas emissions associated with quarrying and cement production.

Behera et al. (2014) provided an extensive review on recycled aggregates and BFS utilization, emphasizing that slag use in concrete mitigates the environmental burden of steel production by diverting large quantities of waste from landfills. Their findings showed that concrete containing BFS exhibited higher density and reduced water absorption, thus contributing to sustainability through durability and resource efficiency.

McGinnis et al. (2017) and Gao et al. (2020) expanded this perspective by demonstrating that BFS-modified concrete improves lifecycle performance and reduces maintenance needs. McGinnis et al. quantified a 15–25% increase in service life expectancy for BFS-based structures compared to conventional concrete. Gao et al. employed nano-scale characterization to reveal that BFS aggregates promote microstructural refinement, reducing long-term shrinkage and carbonation effects. These results suggest that the sustainability advantages of BFS are not limited to material substitution but extend to structural performance optimization.

Coppola et al. (2016) and Corinaldesi et al. (2016) evaluated lightweight mortars and foamed concrete using BFS and other recycled aggregates, demonstrating significant reductions in embodied energy. Coppola's work showed that substituting natural aggregates with BFS decreased energy consumption by 12% per cubic meter of concrete, while Corinaldesi reported improved thermal insulation properties. Both authors concluded that BFS use contributes to sustainable building design by enhancing energy efficiency and reducing construction costs.

Patel and Pitroda (2013), Hashim and Agarwal (2014), and Naresh et al. (2015) further reinforced BFS's environmental benefits by showing reduced quarry waste, lower CO₂ emissions, and improved reusability of by-products. BFS-based mixes not only enhance mechanical strength but also address waste management challenges associated with steel and metal industries.

Binici et al. (2008), in their experimental evaluation of granite and marble waste aggregates, found BFS to be more durable and less reactive under sulphate and acid exposure. Their study underscored the potential for BFS to replace natural aggregates in structural and pavement applications without compromising quality, while simultaneously promoting environmental stewardship.

2.9 Past Review of Studies on SCMs and Aggregate Replacement

The incorporation of industrial and agricultural by-products as supplementary cementitious materials (SCMs) has gained global attention as a sustainable approach to concrete production. Among these materials, rice husk ash (RHA), metakaolin, granite powder, and marble dust have been extensively investigated for their ability to partially replace cement or natural aggregates, thereby reducing environmental impact and improving concrete performance.

2.9.1 Rice Husk Ash (RHA) as Cement Replacement

Andavan (2018) and Bhushan (2017) both carried out experimental studies on the partial replacement of cement with rice husk ash (RHA) in concrete. Their methodologies involved preparing several concrete mixes with varying RHA content typically 5%, 10%, 15%, and 20% by weight of cement while maintaining a constant water-to-cement ratio. The concrete samples were subjected to compressive strength, split tensile strength, and flexural strength tests after curing periods of 7, 14, and 28 days. Andavan (2018) reported that the optimum RHA content was around 10%, at which compressive strength improved by approximately 12% compared to the control mix. This improvement was attributed to the pozzolanic reaction of amorphous silica in RHA, which refined the pore structure and increased density. Similarly, Bhushan (2017) concluded that while RHA enhances strength and durability at moderate replacement levels, higher proportions beyond 15% reduce workability and compressive strength due to reduced calcium hydroxide availability for hydration. Both studies recommend RHA as an effective SCM for sustainable concrete when used judiciously within 10–15% replacement levels.

Complementing these findings, Gupta (2017) and Varshney (2015) conducted similar investigations focusing on optimum RHA replacement percentages. Gupta (2017) employed a systematic design of concrete mixes following IS 10262:2009 standards, testing mechanical properties at different curing ages. The study found that 10% RHA replacement yielded compressive strengths nearly equivalent to conventional OPC concrete, while 15% showed a minor reduction but significant improvement in resistance to sulphate attack. Varshney (2015) extended this by including durability and permeability tests, observing that RHA-replaced concrete exhibited reduced water absorption and enhanced chemical resistance. The researchers attributed this to the high specific surface area of RHA, which promotes better micro filling and silica reaction with calcium hydroxide to form additional C-S-H gel. These

cumulative results underscore RHA's efficiency as a green alternative binder that also minimizes waste disposal issues associated with rice milling industries (Andavan, 2018; Bhushan, 2017; Gupta, 2017; Varshney, 2015).

2.9.2 Metakaolin and Marble Dust as Supplementary Materials

In another important study, Kaur and Bansal (2015) explored the combined effects of metakaolin and marble dust as partial cement replacements in concrete. Their experimental methodology involved replacing cement with 10%, 15%, and 20% combinations of metakaolin and marble dust. The researchers evaluated compressive, split tensile, and flexural strengths at 7, 14, and 28 days, and also tested for water absorption and rapid chloride permeability. Results indicated that the 15% combined replacement mix achieved a 20% increase in compressive strength and a 25% reduction in permeability relative to the control concrete. The study concluded that the synergistic effect of metakaolin's pozzolanic activity and marble dust's filler property significantly enhanced microstructural densification, resulting in improved durability performance. Kaur and Bansal (2015) thus advocated for using such dual mineral admixtures to improve both strength and sustainability of concrete.

Similarly, Hashim and Agarwal (2014) examined granite and marble powder as mineral admixtures in concrete. Their research methodology included replacing fine aggregate with up to 30% of marble and granite waste powder and testing mechanical strength parameters according to IS 516 (1959). The compressive strength improved by 8–10% at 15% replacement but declined beyond 25% due to particle agglomeration and excess fines. Their microstructural analysis revealed enhanced bonding between cement paste and aggregate due to the fine filler effect, contributing to denser interfacial transition zones (ITZ). The study concluded that moderate incorporation of these stone powders not only enhances strength but also provides a sustainable means of recycling quarry waste, reducing environmental burden.

2.10 Past Review of Studies on BFS and Industrial By-Products in Concrete

2.10.1 Ground Granulated Blast Furnace Slag (GGBFS) as a Partial Replacement Material

Manjit Kaur (2012) conducted one of the earliest notable studies on the performance of GGBFS concrete with partial replacement of sand by sawdust. Her experimental methodology involved preparing M30-grade concrete mixes where fine aggregate was partially replaced with sawdust in increments of 5%, 10%, 15%, and 20%. Additionally, cement was partially replaced with 20% GGBFS to investigate combined pozzolanic and lightweight effects. The tests conducted included compressive strength, density, and water absorption following IS 516 (1959) and IS 10262 (2009). Results showed that the optimum replacement level occurred at 10% sawdust and 20% GGBFS, yielding compressive strength only 7% lower than control concrete but with improved durability and reduced unit weight, making it suitable for non-load-bearing applications. The study concluded that the incorporation of GGBFS reduces cement consumption, enhances workability, and contributes to sustainable concrete production (Kaur, 2012).

In a related investigation, Rafat Siddique and Deepinder Kaur (2012) examined the properties of concrete containing GGBFS at elevated temperatures. Their methodology involved replacing OPC with 20%, 40%, and 60% GGBFS by weight and then exposing cured specimens to temperatures of 200°C, 400°C, 600°C, and 800°C. Tests included compressive strength, weight loss, ultrasonic pulse velocity (UPV), and microstructural analysis. Results demonstrated that up to 400°C, GGBFS concrete retained higher residual strength compared to OPC concrete, due to its denser pore structure and lower calcium hydroxide content. However, beyond 600°C, all mixes experienced degradation, with GGBFS mixes exhibiting slower strength loss rates. Scanning electron microscopy (SEM) confirmed that slag-blended concrete formed a more stable and compact microstructure, enhancing thermal stability. The

study concluded that GGBFS incorporation enhances both fire resistance and long-term strength of concrete, particularly under thermal stress conditions (Siddique and Kaur, 2012).

Similarly, Bashandy (2013) analyzed the influence of elevated temperatures on the behavior of economical reactive powder concrete (RPC) containing mineral admixtures such as slag and silica fume. The research followed a factorial experimental design where RPC specimens were subjected to temperatures ranging from 100°C to 800°C. The compressive strength and microcracking patterns were observed. Findings indicated that while compressive strength declined with temperature increase, the presence of GGBFS and silica fume significantly minimized structural deterioration and delayed thermal cracking. Bashandy (2013) concluded that the combination of finely ground slag and reactive powders can produce highly durable concretes suitable for fire-resistant applications.

Furthermore, Buddhdev and Varia (2014) performed a feasibility study on the application of blast furnace slag in pavement concrete. Their methodology followed IS 383 (1970) and IS 10262 (2009) for concrete design, replacing coarse aggregate with BFS in proportions of 0%, 20%, 40%, and 60%. Laboratory tests included compressive strength, flexural strength, and abrasion resistance after 28 days of curing. Results revealed that up to 40% BFS replacement yielded strength values comparable to conventional concrete, while surface hardness and abrasion resistance improved. Beyond 50% replacement, mechanical properties declined due to increased porosity. The researchers observed that BFS aggregate improved bonding due to its angular texture and high silica content, suggesting its effective utilization in rigid pavements and industrial flooring (Buddhdev and Varia, 2014).

Additionally, Hiraskar and Patil (2013) explored the use of blast furnace slag aggregate as a replacement for natural coarse aggregate in concrete. The study involved replacing 25%, 50%, 75%, and 100% of natural aggregate with BFS and conducting mechanical tests per IS

516 (1959). Results indicated that BFS aggregate mixes achieved higher compressive and flexural strengths at 28 days, especially at 50% replacement, due to the rough surface and improved interfacial transition zone (ITZ). The study concluded that BFS aggregate not only reduces dependence on natural resources but also enhances the durability and chemical resistance of concrete in aggressive environments.

2.10.2 Recycled Aggregate Concrete and Industrial Waste Utilization

Behera et al. (2014) presented a comprehensive review on recycled aggregates (RA) from construction and demolition (CandD) waste and their potential use in sustainable concrete. The methodology of this meta-analysis involved collating experimental data from over 100 studies to assess the mechanical and durability properties of recycled aggregate concrete (RAC). The authors reported that RAC generally exhibited 10–25% lower compressive strength than conventional concrete, depending on the quality of the recycled aggregates. However, incorporating mineral admixtures such as fly ash, GGBFS, and silica fume could restore or even enhance strength through microstructural refinement. The review concluded that, with proper mix proportioning and pre-treatment of aggregates, RAC can achieve comparable performance to conventional concrete while significantly reducing environmental impact (Behera et al., 2014).

McGinnis et al. (2017) advanced this discussion through a detailed experimental investigation on the strength and stiffness of concrete with recycled aggregates. They cast concrete mixes containing 0%, 25%, 50%, and 100% recycled coarse aggregates and measured compressive strength, modulus of elasticity, and stress-strain behavior. Their results revealed a linear reduction in modulus of elasticity with increasing recycled content but found that mixes with up to 50% RA still met design requirements for structural applications. The study concluded that recycled concrete aggregates (RCA) can safely replace up to half of natural aggregates in

structural concrete when combined with SCMs such as slag and fly ash (McGinnis et al., 2017).

Expanding on sustainable aggregate alternatives, Gao et al. (2020) explored the mechanical properties of recycled aggregate concrete modified with nanoparticles such as nano-silica and nano-alumina. Their methodology involved producing concrete with 50% recycled coarse aggregate and 2–3% nanoparticle addition by weight of cement. Tests conducted included compressive strength, splitting tensile strength, and microstructural examination using SEM. Findings revealed that nano-modified RAC exhibited up to 18% higher compressive strength and 12% reduced water absorption compared to unmodified RAC, owing to improved hydration kinetics and densified microstructure. The authors concluded that the integration of nanoparticles and industrial waste materials such as BFS or RHA can effectively enhance the structural performance and sustainability of recycled aggregate concrete (Gao et al., 2020).

2.11 Challenges and Limitations in the Nigerian Context

Despite the clear benefits, several challenges restrict the widespread adoption of BFS as coarse aggregate in Nigerian construction. Variability in slag properties, arising from differences in steelmaking processes, source materials, and cooling regimens, necessitates rigorous quality control and standardization in construction applications. The lack of nationally harmonized technical standards specific to BFS aggregate use in Nigeria further limits quality assurance and industry confidence.

Workability concerns, especially at higher replacement levels, are reported due to slag's angularity and higher absorption characteristics; this makes mix proportioning and water management critical. The presence of potentially hydratable oxides such as lime and magnesia in unprocessed Nigerian slag introduces risk for long-term expansion and durability issues, unless adequately processed or aged.

(i) Literature review of BFS recycling methods shows, that the main problem preventing the full replacement of natural stone aggregate with Blast Furnace slag aggregate (BFSA) based on ACBFS in base pavement layers is different porosity of this material grains. Studies have shown that ACBFS contains both high-porosity and low-porosity grains. It was also experimentally proved that high-porosity grains have significantly higher water absorption, low bulk density, low frost resistance and a higher aggregate crushing value (ACV) compared with low-porosity grains. The purpose of this study is to evaluate the effectiveness of this complex technology and determine the optimal parameters of its implementation, allowing to achieve a reduction in SA water absorption sufficient for its use as a material of the subbase pavement layer.

Some of SA grains are characterized by high porosity and, accordingly, high water absorption, while others have low porosity and, accordingly, low water absorption. In this regard, an urgent task is to separate the low-porosity grains (for subsequent use as aggregate of the pavement structural layers) from the high- porosity ones and further additional treatment the selected low-porosity grains to further reduce water absorption. Vyacheslav suggested to reduce water absorption of materials, methods such as the use of nano-TiO₂-modified recycled coarse aggregate, using the air entraining agent (for mortars), slurry coating modified methods (for recycled coarse aggregate), silane emulsion impregnation, cement-silica fume slurry coating method, compression casting method (to reduce water absorption) (Vyacheslav Kunarz et. al., 2024).

(ii) This paper investigated the effect of selective crushing and surface hydrophobization of slag aggregate (based on ACBFS) on its water absorption. The key results of the research are listed as follows; Selective crushing of slag aggregate (SA) helps eliminate weak, high-porosity grains while preserving stronger, low-porosity ones, which reduces water

absorption. The optimal crushing time is 35–40 minutes beyond that, the yield drops significantly, making the process less economical.

Their method can reduce water absorption from 4.54% to 2.53% in about 35% of the original material. Further treatment with waste engine oil a hydrophobic agent lowers water absorption even more, down to 1.05%, due to its moisture-resistant properties.

The results obtained from the characterization of blast furnace slag treated at different temperatures show that the samples have high content of calcium. The samples treated at 960 and 1060 °C exhibited mainly calcium aluminum silicate and gehlenite mineral, which favors the application of slag as heavy metal adsorbent and vitrocement production. (Gill B, et. al., 2020).

2.11.1 Eco-Friendly Concretes, Alternative Aggregates Studies

The contemporary drive toward sustainable construction and circular economy practices has encouraged widespread research into replacing conventional concrete constituents with waste-derived materials. In this context, the use of blast furnace slag (BFS) and similar industrial by-products has become central to the development of eco-friendly concretes. This section reviews selected studies that have examined various waste materials, including BFS, marble and granite waste, recycled plastics, fibres, and other supplementary components. It discusses each study's methodology, key findings, and conclusions, providing a foundation for understanding the structural and environmental implications of using BFS as a partial coarse aggregate replacement.

Rajesh Kumar and Singha Roy (2014) conducted a seminal synthesis on the development of eco-friendly concretes using industrial wastes such as fly ash, ground granulated blast furnace slag (GGBFS), copper slag, rice husk ash (RHA), and marble dust. Their work was largely a meta-analysis of experimental evidence across multiple studies, aiming to determine performance trends and common methodological standards. The authors reported that partial

substitution of cement with SCMs typically improves long-term strength and durability due to pozzolanic reactions, though early-age strength may be compromised when reactivity or curing conditions are insufficient. Similarly, replacing natural aggregates with industrial by-product aggregates such as BFS or copper slag resulted in compressive strengths comparable to, or even greater than, those of conventional concrete, particularly at 30–50% replacement levels. Beyond this range, workability issues and higher porosity became evident.

In a related study, Patel and Pitroda (2013) examined the valorisation of stone waste in concrete production, particularly within the Indian construction industry, where quarry by-products are abundant but underutilized. Their methodology combined field surveys on waste generation with laboratory testing of concrete mixes incorporating stone waste powder and crushed fragments as partial replacements for fine and coarse aggregates. Tests such as particle size distribution, specific gravity, water absorption, and compressive strength at 7 and 28 days were conducted according to Indian Standard (IS) specifications. Their findings demonstrated that incorporating properly graded stone waste up to 30% substitution produced compressive strengths comparable to the control mix, whereas poorly graded waste or excessive fines led to workability challenges.

Further research into sustainable concrete systems was undertaken by Ghorpade (2013), who evaluated the behavior of fibre-reinforced high-strength concrete containing recycled coarse aggregates (RA). The experimental design substituted natural coarse aggregate with 25%, 50%, and 100% recycled aggregate and incorporated short steel and polypropylene fibres at 0.5–1.0% volume fractions. The study measured workability, compressive and tensile strengths, and shear performance. Results indicated that fiber inclusion mitigated the adverse effects of recycled aggregates on workability and enhanced both post-crack ductility and shear strength. The hybrid mixes of recycled aggregates and fibres showed a substantial recovery of lost mechanical properties compared to mixes without fibres. Ghorpade

concluded that fiber addition, coupled with supplementary materials such as slag or fly ash, can be a practical solution for improving the mechanical integrity of recycled or waste-based concrete systems.

Xiao et al. (2005) provided fundamental insights into the mechanical response of recycled aggregate concrete (RAC) under uniaxial compression. Their study employed cylindrical specimens with recycled aggregate contents ranging from 0% to 100% and measured stress–strain behavior, elastic modulus, and failure modes. The authors found that increasing recycled aggregate content led to a reduction in peak compressive strength and stiffness, while ductility slightly improved due to microcracking and aggregate fracture. Although this study did not specifically involve BFS, its experimental rigor establishes a benchmark for evaluating the mechanical response of concretes where traditional aggregates are replaced by industrial by-products such as BFS. The authors emphasized that comprehensive stress–strain characterization is crucial for developing accurate design models for such concretes.

Recent innovations in nanotechnology have also influenced concrete modification approaches. Gao et al. (2020) investigated the use of nano-silica to enhance the performance of recycled aggregate concrete. In their methodology, concrete mixes containing 50% recycled aggregates were modified with 1–3% nano-silica by cement weight. Tests on compressive strength, water absorption, and microstructure were conducted using scanning electron microscopy (SEM). The addition of nano-silica improved packing density and increased the rate of pozzolanic reaction, leading to a 10–20% improvement in compressive strength at 28 days compared to unmodified mixes. SEM images revealed a significantly densified interfacial transition zone (ITZ) between aggregate and matrix. The authors concluded that nano-modification effectively compensates for the lower reactivity or higher porosity typical of recycled aggregates and similar waste materials such as BF.

Beyond mineral and nanomaterial additions, research into plastic and glass waste utilization

also offers valuable parallels. Mohammadinia et al. (2019) explored the performance of concrete incorporating 10–30% recycled plastic and crushed glass as fine aggregate replacements, particularly for non-structural applications such as footpaths. Their tests covered compressive strength, abrasion resistance, and freeze–thaw durability. Findings revealed that up to moderate replacement levels, compressive strength remained acceptable for pedestrian service loads, while glass waste enhanced abrasion resistance and recycled plastics reduced density. However, plastics also reduced bonding and required adjustment of admixture content. The study concluded that the application of waste materials in concrete should be purpose-specific, with stricter quality and durability requirements applied for structural use cases such as BFS aggregate concretes.

Complementary studies by Binici et al. (2008), Hashim and Agarwal (2014), and Verma and Dubey (2022) focused on marble, granite, and stone waste as partial aggregate replacements. These researchers conducted laboratory experiments involving 10–25% replacement levels and evaluated mechanical strength, permeability, and chemical durability through rapid chloride permeability tests and sulfate exposure. Their collective findings indicated that moderate replacement levels maintained or marginally improved compressive strength, enhanced durability, and reduced costs, though the risk of alkali–silica reactivity and compositional variability necessitated thorough material screening. These studies reinforced the view that with adequate pretreatment and characterization, waste stone aggregates can substitute for natural aggregates in concrete, paralleling the behavior observed with BFS.

The potential of fiber reinforcement in improving the ductility of high-performance concretes has also been well documented. Habel and Gauvreau (2008) examined ultra-high-performance fiber-reinforced concrete (UHPRFC) under both static and impact loads, finding that the inclusion of steel fibres significantly improved post-cracking capacity, energy absorption, and overall toughness. Similarly, Wong (2004) demonstrated that short fiber

addition enhances tensile strength and crack control in structural concrete. These findings imply that incorporating fibres in BFS aggregate concretes may counteract brittleness and improve residual capacity under severe loading conditions, making them suitable for structural applications.

Taken together, these diverse studies illustrate a consistent trend toward integrating industrial by-products and waste materials into high-performance, sustainable concrete systems. The research demonstrates that the success of such concretes depends heavily on material characterization, optimization of replacement levels, and the synergistic use of supplementary additives such as SCMs, fibres, and nanomaterials. For BFS-based concrete, these findings provide clear methodological guidance: replacement ratios should generally remain within the 20–50% range to balance strength and workability; supplementary binders or nano-modifiers can mitigate early-age strength deficits; and durability testing under environmental stressors should be prioritized to ensure long-term performance. Ultimately, the reviewed literature supports BFS as a technically viable and environmentally responsible coarse aggregate alternative that aligns with sustainable engineering practices and global circular economy objectives.

CHAPTER THREE

METHODOLOGY

3.1 Study Area

The research was conducted in University of Benin, in Benin City, the capital of Edo State in southern Nigeria. The city lies between latitude 6.338°N and longitude 5.625°E. Benin City is an urban center with a mix of residential, commercial, and industrial activities. Its infrastructure and proximity to cement plants and steel industries make it an ideal location for sourcing industrial by-products such as blast furnace slag.

The selection of University of Benin, Benin City was also influenced by its accessibility to laboratory facilities at the University of Benin, Department of Civil and Structural Engineering Laboratory, faculty of Engineering and proximity to building materials suppliers and construction sites where coarse aggregates and slag samples could be obtained and tested.

3.2 Sample Collection

3.2.1 Blast Furnace Slag (BFS)

Blast furnace slag (Fig. 2.4) will be sourced from a blacksmith at Igun Street along Akpakpava, Edo State, who produces and supplies slag as a by-product of his brass/steel production. The slag will be collected in its granulated form and transported in sealed polyethylene bags to prevent contamination. Upon arrival, the slag will be sun-dried for 72 hours, then crushed and sieved through a 20 mm sieve to obtain a size range suitable for coarse aggregate use in concrete.

3.2.2 Conventional Coarse Aggregate

For control experiments, crushed granite (Fig. 2.1) stone will be sourced from a local quarry in Benin City. It was sieved and categorized similarly to ensure size uniformity with the prepared blast furnace slag.

3.2.3 Water and Cement

Portable water conforming the required standards will be used throughout the experiment. Ordinary Portland cement will be sourced from a local supplier, and its batch will be conformed to the relevant Nigerian Industrial Standard.

3.3 Calculating Materials

Calculate Volume of one Cube

Calculate the total volume for 75 cubes with addition of a 25% allowance for wastage

Concrete Mix Ratio 1:2:4, Calculate Material Quantities in kg

Percentage replacement of Coarse aggregate by BFS (2.5%,5%,7.5%,10%)

This procedure will be repeated and followed through in batches (per cube) and multiplied by 3 (3 cubes) for 7, 14, 28 days curing period.

3.4 Physio-Chemical Analysis of Materials

3.4.1 Physical Properties

The following physical properties of both BFS and granite aggregate will be analyzed:

1. Bulk Density

Determined in both loose and compacted states using the standard cylinder method (ASTM C29/C29M).

3.4.2 Mix Design and Concrete Preparation

Concrete mix designs followed the standard method for grade 15 (Table 2.2) concrete. Five different mixes were prepared:

1. Mix 1 (Control): 0% BFS, 100% granite
2. Mix 2: 2.5% BFS, 97.5% granite
3. Mix 3: 5.0% BFS, 95% granite
4. Mix 4: 7.5% BFS, 92.5% granite
5. Mix 5: 10% BFS, 90% granite

Particle size distribution will be done for the Fine aggregate and Coarse aggregate (Granite and BFS) affects the Paste requirements and finishing quality of fine aggregates and also affects the strength and aggregates interlock for coarse aggregates (Fig 2.2).

3.5 Testing Procedures

3.5.1 Compressive Strength Test

3.5.1.1 Curing of Concrete Cubes

Curing ensures that concrete maintains sufficient moisture, temperature, and time to allow proper hydration of cement and development of strength.

Method (Standard Curing – BS 1881)

Materials:

Water curing tank (or curing room)

Procedure:

1. Demold cubes after 24 hours of casting.
2. Mark each cube with an ID or date.
3. Immerse cubes in clean water at $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$.
4. Leave the cubes in water until the day of testing:
 - 7 days (early strength)
 - 14 days (intermediate)
 - 28 days (standard strength).

3.5.1.2 Compressive Strength Test of Concrete Cubes BS EN 12390-3:2019

Testing hardened concrete – Part 3: Compressive strength of test specimens

Test Specimen:

Cube Size: 100 mm × 100 mm × 100 mm

Minimum specimens per age: 3 cubes

Equipment Required:

Compression testing machine

Test Procedure:

1. Remove cube from water, wipe off surface moisture.
2. Place cube in machine with cast face against platens.
3. Apply load gradually until failure.
4. Record the maximum load applied at failure.

Compressive Strength Formula:

$$\text{Compressive Strength (MPa)} = \frac{\text{Maximum Load (kN)}}{\text{Cross-Sectional Area (mm}^2\text{)}} \quad \text{Equation (3.1a)}$$

Or

$$f_c = \frac{P}{A} \quad \text{Equation (3.1b)}$$

Where;

f_c = compressive strength (MPa)

P = maximum load (N)

A = loaded area (mm²) = 100 × 100

3.5.2 Slump Test for Workability - BS EN 12350-2:2019 - Testing fresh concrete – Part**2: Slump test**

The slump test measures the consistency and workability of fresh concrete, how easily it flows and how cohesive the mix is. It's especially useful for on-site quality control.

3.5.2.1 Equipment Required

- i. Slump cone:
 - a. Top diameter: 100 mm
 - b. Bottom diameter: 200 mm

- c. Height: 300 mm
- ii. Tamping rod: 16 mm diameter, 600 mm long, bullet-shaped tip
- iii. Base plate: Flat, non-absorbent
- iv. Trowel and measuring scale
- v. Scoop or shovel
- vi. Fresh concrete sample

3.5.2.2 Test Procedure

- i. Place the cone on a clean, flat, and moist base plate.
- ii. Fill the cone in 3 layers, each approximately 1/3 of the cone's height: Each layer is tamped 25 times using the tamping rod.
- iii. Strike off the top surface level using the tamping rod or trowel.
- iv. Carefully lift the cone vertically within 5–10 seconds without twisting or shaking.
- v. Allow the concrete to slump.

3.5.2.3 Measurement of Slump

Measure the vertical difference between the top of the cone and the highest point of the slumped concrete using a ruler.

Table 3.1: Types of Slumps

Type	Description	Indicates
True slump	Concrete subsides evenly and maintains shape	Good, cohesive mix
Shear slump	Concrete slips sideways like a wedge	Lack of cohesion
Collapse slump	Concrete collapses completely	Overly wet or high water/cement ratio

Source: S. Nishibayashi et al. 1987

3.5.3 Flexural Strength Test of Concrete Beams

BS EN 12390-5:2019 – *Testing hardened concrete – Part 5: Flexural strength of test*

specimens. To measure the **tensile strength** of concrete indirectly by applying a **bending load**. Flexural strength is critical for elements like: Pavements, Slabs, Beams, Precast products

Details

- i. Length: 500 mm
- ii. Width and Height: 100 mm × 100 mm
- iii. Type: Prismatic beam
- iv. Curing: Standard water curing at for 7 and 28 days

Testing Method (as per BS EN 12390-5)

- i. **3-point loading** (most common for beams ≤ 600 mm)
- ii. **Load applied** at mid-span until failure

FORMULA FOR FLEXURAL STRENGTH (F_r)

For **3-point loading**:

$$f_r = \frac{P.L}{b.d^2} \quad (3.2)$$

Where;

f_r = Flexural Strength (MPa or N/mm²)

P = Maximum applied load (N)

L = Span length (mm)

b = width of specimen (mm)

d = depth of specimen (mm)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Particle Size Distribution

4.1.1 Sieve Analysis on Aggregates

Proper sieve analysis was carried out on the Blast Furnace Slag (BFS) as per BS 812-103.1:1985 to determine the particle size distribution in a sample of the aggregates. The sieve analysis results in Tables 4.1-4.2 show that BFS is largely dominated by coarse particles, with 54.51% retained on the 19 mm sieve and 37.42% on the 13.26 mm sieve, with little material below 10 mm. Granite, however, has a better gradation, with 18% retained on the 19 mm sieve, 54% on the 13.26 mm sieve, and 15% and 11% on the 10 mm and 8 mm sieves respectively, ensuring finer fractions for improved workability and compaction. This indicates that while BFS has strength-bearing sizes, its poor grading and lack of fines make it unsuitable as a full replacement for granite, though it can be used as partial replacement for granite in concrete.

Table 4.1: Sieve analysis of Materials Used

S/N	Sample Used	% Passing Sieve						
		19.00mm	10mm	5mm	4.75mm	1.18mm	0.425mm	0.075mm
1	Blast Furnace Slag	45.49	0.5	0	0	0	0	0
2	Granite	82.00	13.00	0.2	0	0	0	0
3	Fine aggregate (Sand)	0	0	0	95.74	96.04	68.03	3.23

The sieve analysis in Table 4.1 shows that most of the sand particles are fine, with the highest % passing (96.04%) on the 1.18 mm sieve, followed by 95.74% on 4.75 mm and 68.03% on 0.425 mm. Over 95% passed the 4.75 mm sieve, confirming it as fine aggregate. The grading is well distributed, indicating suitability for concrete production.

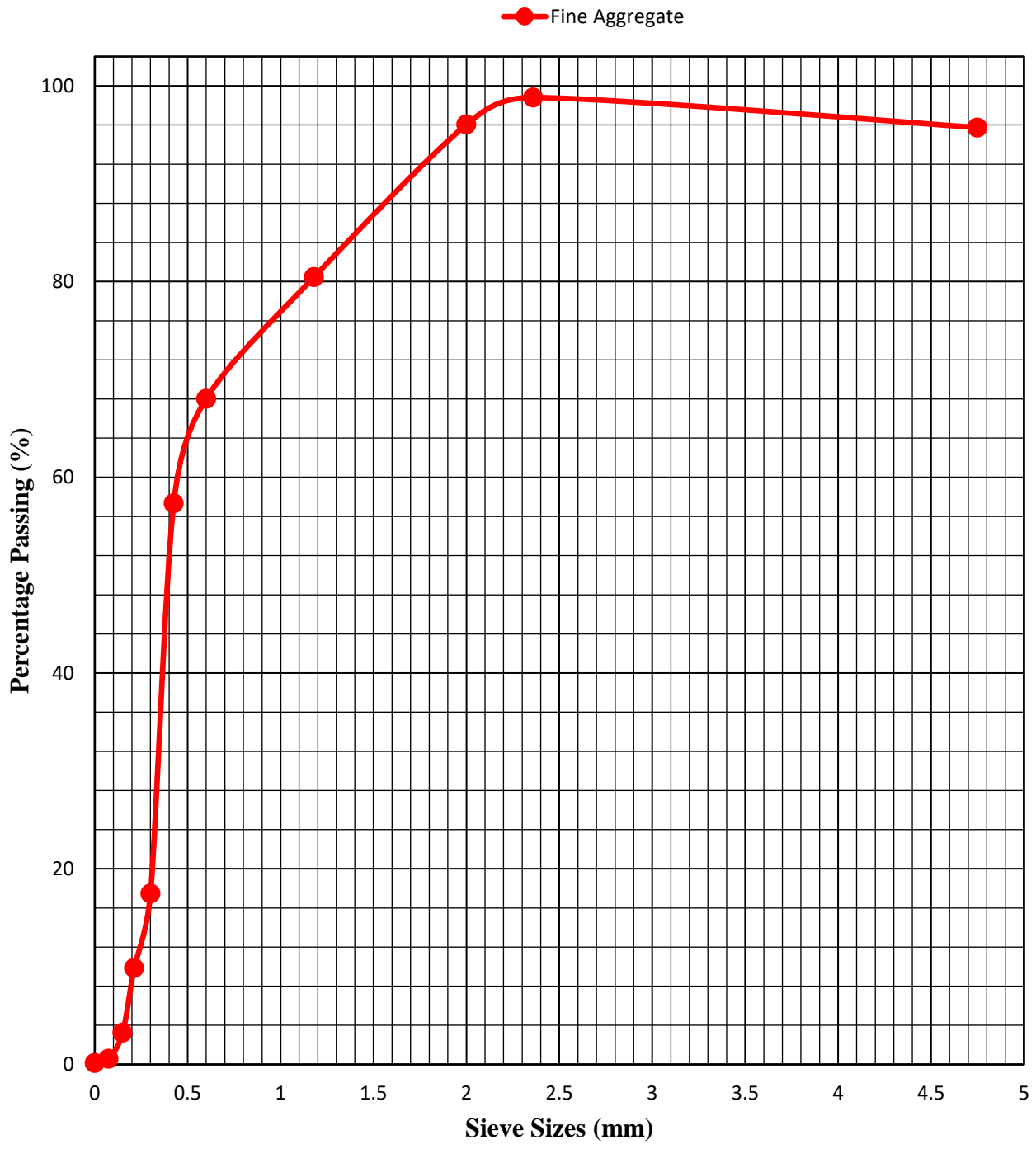


Figure 4.1: Particle size distribution of fine aggregate (sand)

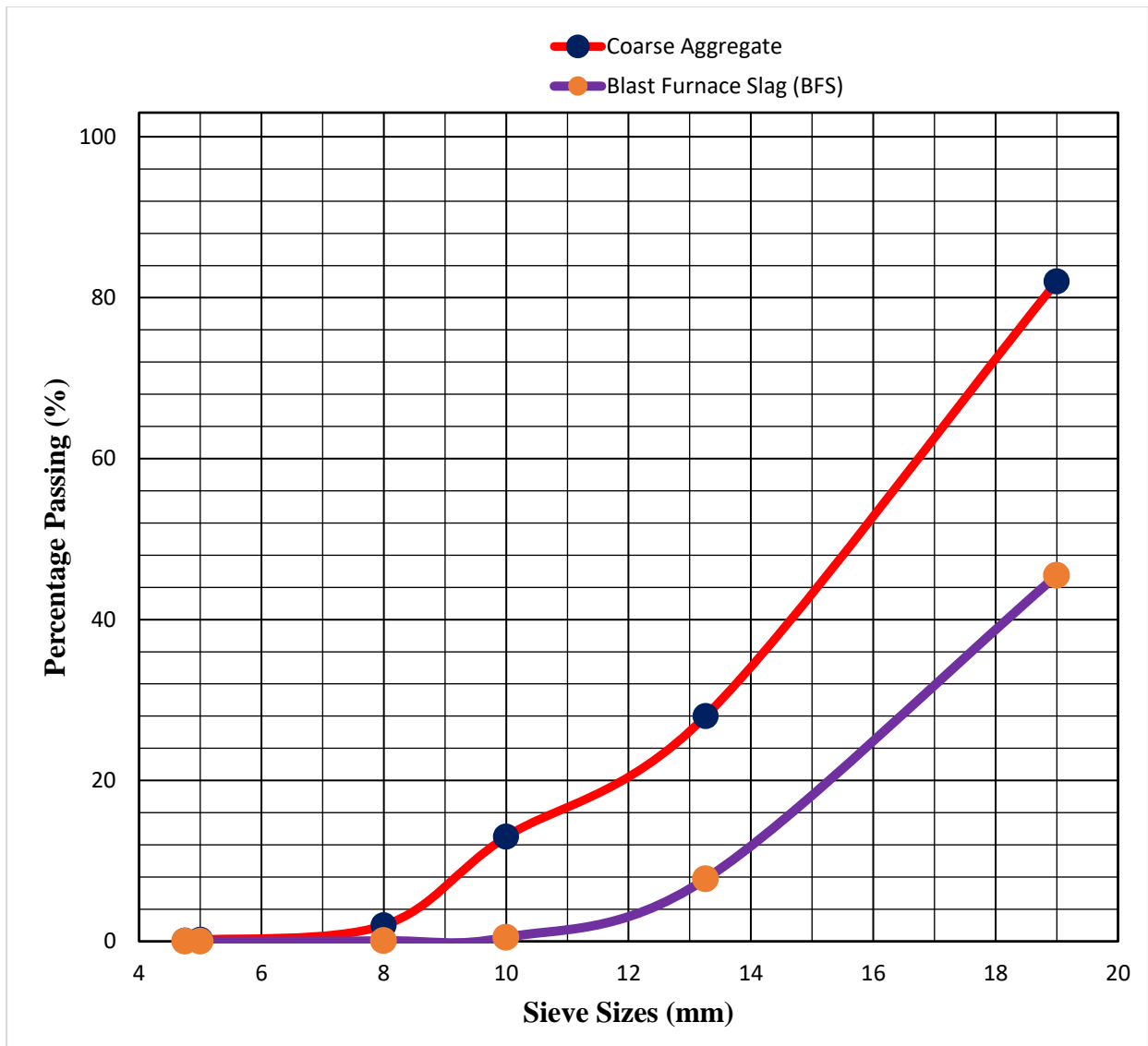


Figure 4.2: Particle size distribution of BFS and Granite

Figure 4.2 show the size distribution of the coarse aggregates used in this study (BFS and Granite). From the graph it is clearly seen that BFS can be used as partial replacement for coarse aggregate as it has similar characteristics as the coarse aggregate.

4.2 Compressive Strength Test on Concrete

Compressive strength of concrete progressively increases, and at day 28, the mixture containing 2.5% Blast Furnace Slag (BFS) aggregates replacement was observed as the optimum replacement percentage. The compressive strength test was carried out as per BS 1881-116:1983 and it is obtained using the mathematical expression in equation 3.1.

Table 4.2: Average Compressive Strength Obtained after Curing, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

AVERAGE COMPRESSIVE STRENGTH TEST RESULTS			
Replacement %	7 DAYS	14 DAYS	28 DAYS
0%	13.45	17.58	21.08
2.5%	12.84	16.92	19.29
5%	12.36	16.26	18.01
7.5%	11.92	15.72	16.52
10%	11.46	15.17	15.48

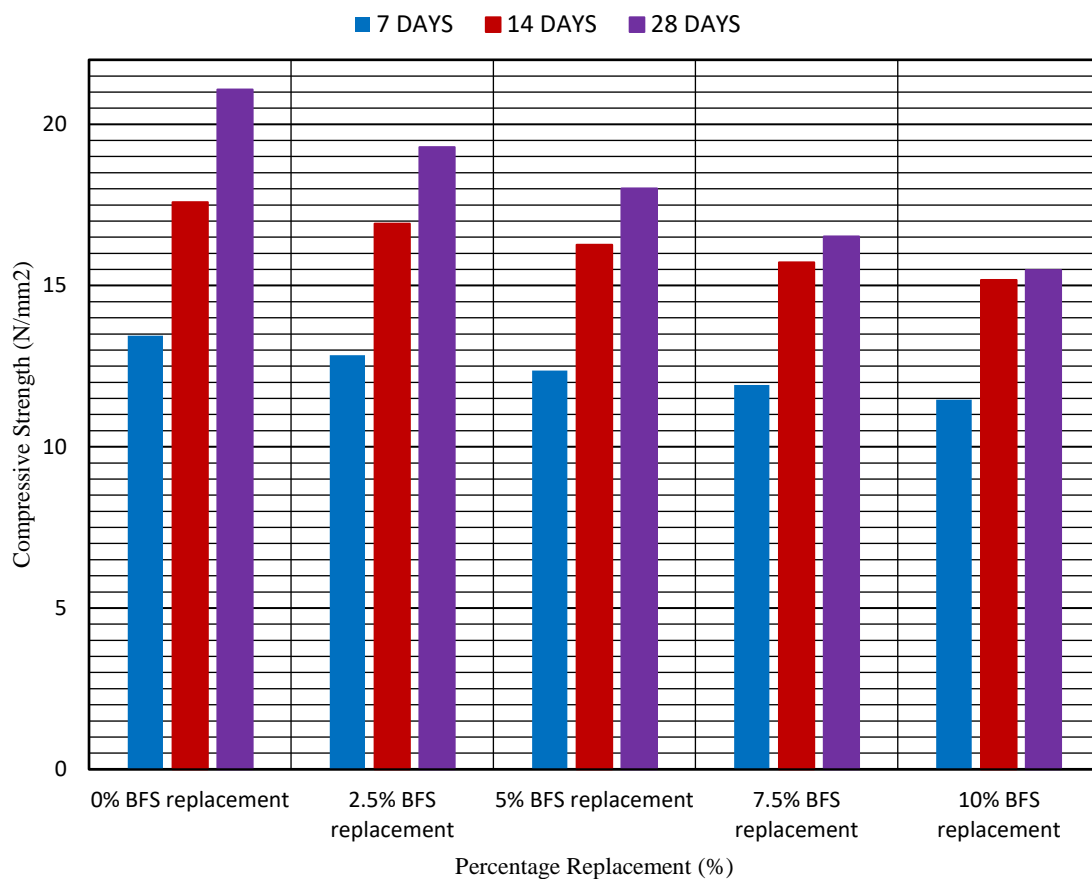


Figure 4.3: Comparative Chart Variation of Compressive Strength

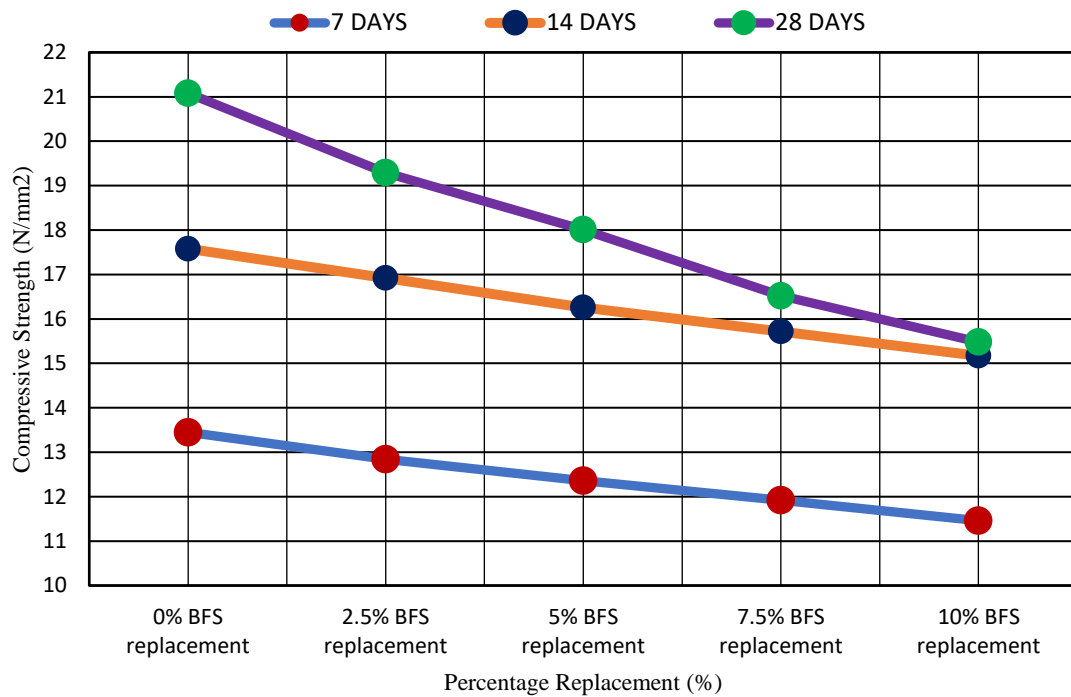


Figure 4.4: Comparative Graph of Compressive Strength

The control mix (0% BFS) achieved the highest compressive strength of 21.08 N/mm² at 28 days. The mix with the highest replacement (10% BFS) yielded the lowest strength of 15.48 N/mm² at 28 days. The introduction of 2.5% BFS caused a slight drop to 19.29 N/mm², while increasing the replacement to 10% resulted in a significant strength reduction of approximately 26.5% compared to the control mix. This indicates that the inclusion of Blast Furnace Slag reduces the compressive strength of the concrete. While the BFS concrete does gain strength overtime, it does not match the early-age strength of the pure control mix.

4.3 Flexural Strength Test on Concrete

The flexural strength is determined according to BS 1881-118:1983 “Testing concrete- Method for determination of flexural strength (F_{cf}) using the mathematical expression in equation 3.2.

Table 4.3: Average Flexural Strength Obtained after Curing, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

AVERAGE FLEXURAL STRENGTH TEST RESULTS			
Replacement %	7 DAYS	14 DAYS	28 DAYS
0%	4.50	7.50	9.60
2.5%	3.90	6.05	8.56
5%	3.60	5.00	5.70
7.5%	2.90	4.35	5.10
10%	2.60	3.35	3.4

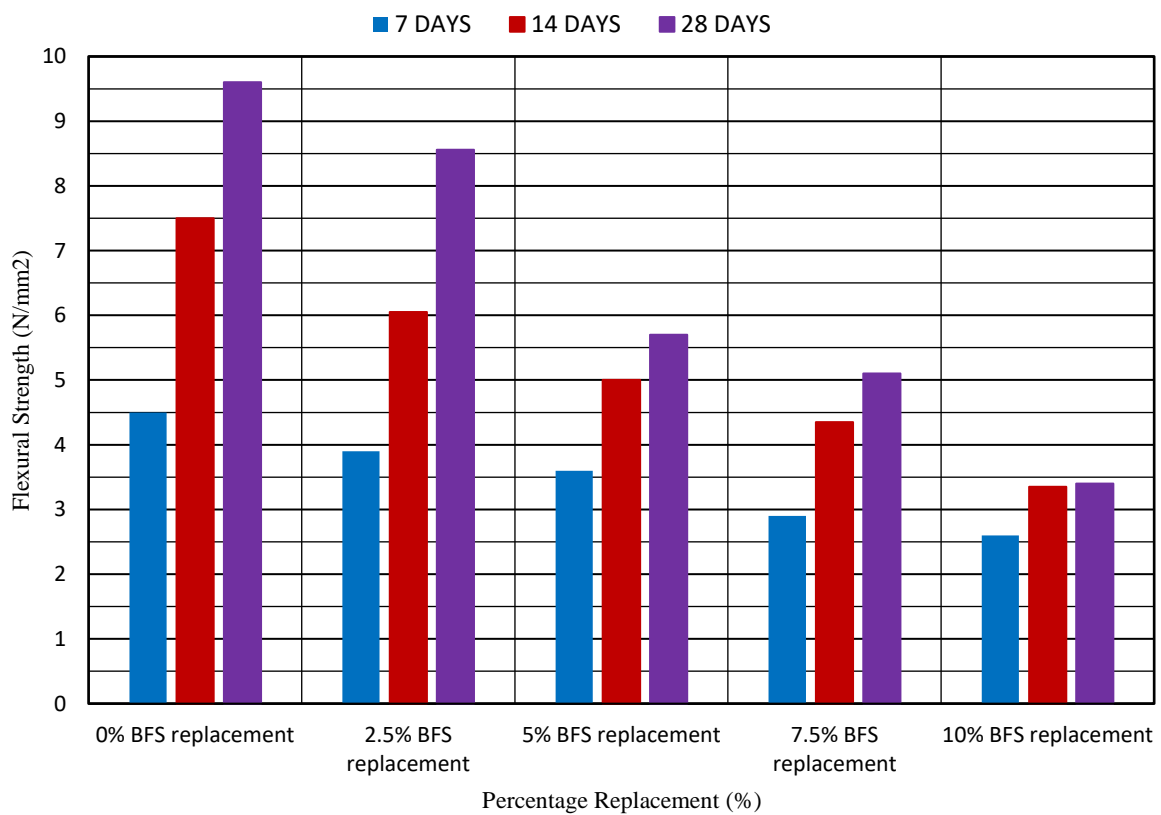


Figure 4.5: Comparative Chart Variation of Flexural Strength

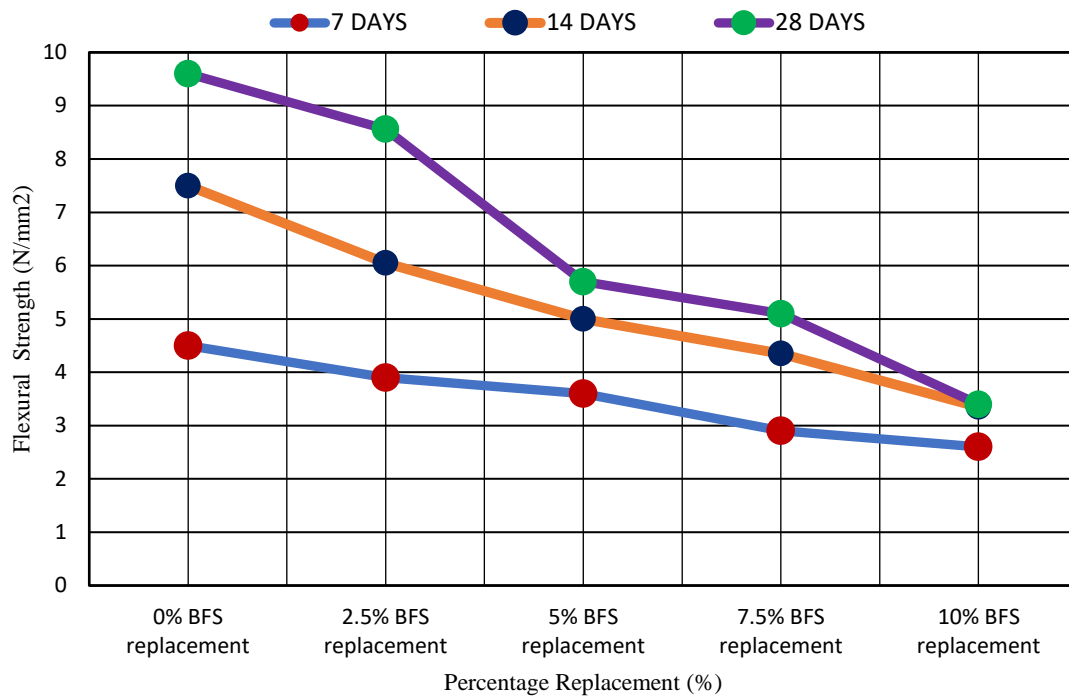


Figure 4.6: Comparative Graph of Flexural Strength

The Slope in Figure 4.6 Line Graph indicates a sharp decrease in flexural capacity as the granite is replaced by slag. The drop in flexural strength is proportionally larger than the drop seen in compressive strength. Peak performance was at 0% BFS control of 9.60 N/mm² after 28 days and at 10% the strength was recorded at roughly 3.35 N/mm², indicating the lowest resistance to bending among all tested samples. The experimental data confirms that partial replacement of granite with BFS has a significant negative impact on the flexural strength of concrete at 28 days.

4.4 Workability of Concrete

4.4.1 Slump Test on Concrete

The slump test was carried out to determine the workability of fresh concrete at varying replacement levels of the aggregate proportions. This test provided an indication of the consistency and ease of placement of the mixes. The procedure followed was in accordance with BS EN 12350-2 (2009) standards. The test was repeated for each replacement level (0%,

2.5%, 5%, 7.5%, and 10%), and the recorded values indicated the influence of aggregate proportioning on the workability of concrete. The results obtained from the slump test were subsequently tabulated in Table 4.10 below and used to evaluate the fresh properties of the concrete mixes, enabling comparison between the control mix and the modified mixes.

Table 4.4: Slump Obtained during casting, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

Slump Values at 2.5%, 5%, 7.5%, and 10% Replacement with Blast Furnace Slag (BFS)					
S/N	W/C Ratio	Percentage of Blast Furnace Slag (BFS) replaced (%)	Height of Mould H1 (mm)	Height of subsided concrete H2 (mm)	Slump H1-H2 (mm)
1	0.53	0	300	270	30
2	0.53	2.5	300	273	27
3	0.53	5	300	279	21
4	0.53	7.5	300	283	17
5	0.53	10	300	284	16

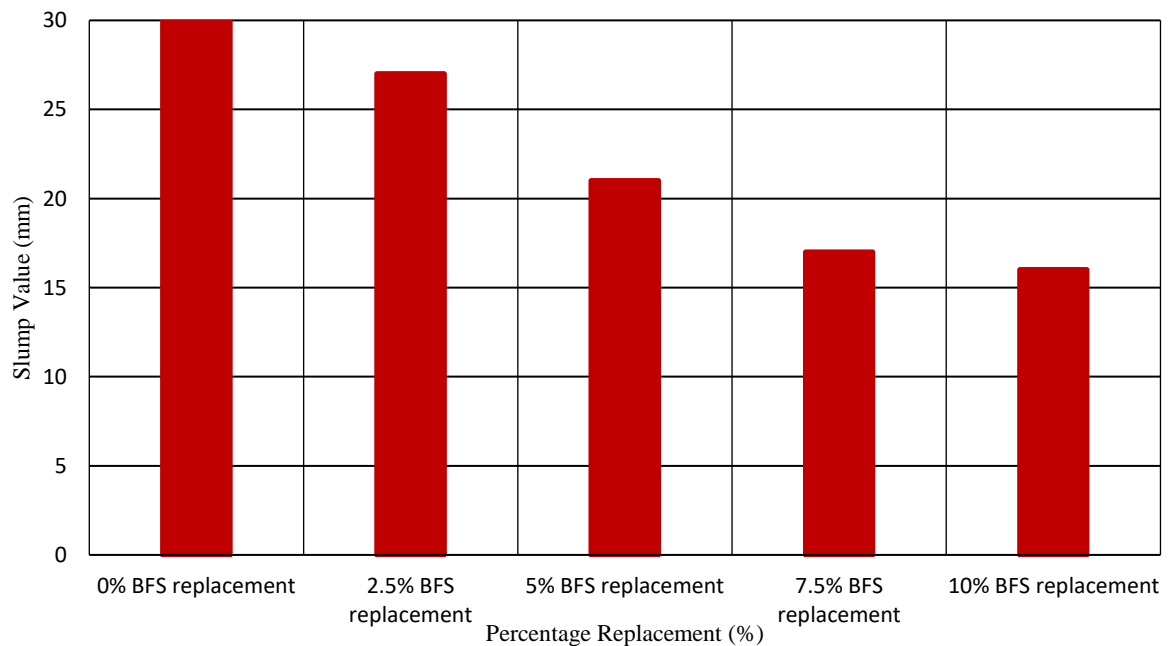


Figure 4.7: Comparative Chart variation of slump of concrete with Blast Furnace Slag (BFS) replacement

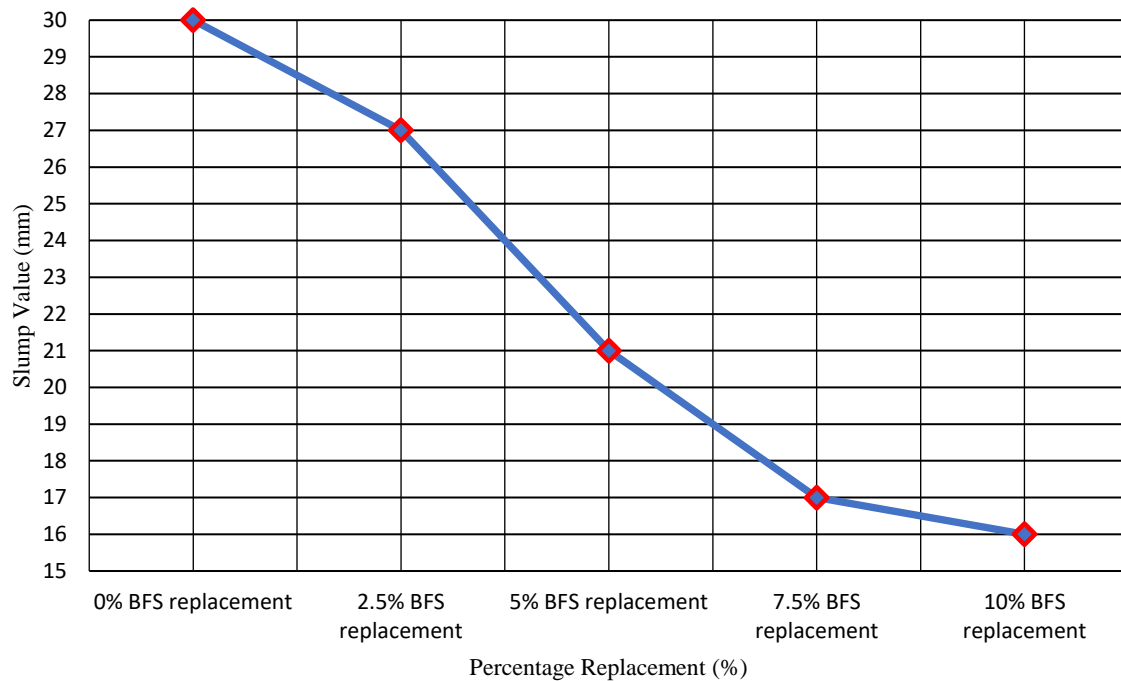


Figure 4.8: comparative graph variation of slump of concrete with Blast Furnace Slag (BFS) replacement

4.5 AIV and ACV Test

4.5.1 AIV Test Results Discussion

$$\text{AIV} = \frac{\text{Mass of aggregate passing 2.36mm sieve}}{\text{Mass of aggregate retained in 2.36mm sieve}} \times 100$$

For Blast Furnace Slag (BFS)

Average Mass of aggregate used = 332.1g

10% of 332.1 = 33.21

Since 33.21 > 30.34 (Average AIV value)

Hence AIV is <10% (EXCEPTIONALLY STRONG)

Table 4.5: AIV test results for Blast Furnace Slag (BFS)

Mass	TEST A	TEST B	TEST C
M1 (g)	330.3	334.8	331.2
M2 (g)	100.02	103.51	98.79
M3 (g)	242.17	239.64	223.52
M2 + M3 (g)	342.19	343.15	322.31
AIV	30.28	30.91	29.83

Average AIV = 30.34

For Granite

Average Mass of aggregate used = 334

10% of 334 = 33.4

Since 33.4 > 31.78 (Average AIV value)

Hence AIV is <10% (EXCEPTIONALLY STRONG)

Table 4.6: AIV test results for Granite

Mass	TEST A	TEST B	TEST C
M1 (g)	333.4	338.1	330.5
M2 (g)	109.83	105.34	103.23
M3 (g)	239.82	241.71	233.25
M2 + M3 (g)	349.65	347.05	336.48
AIV	32.94	31.16	31.23

Average AIV = 31.78

Table 4.7: AIV result interpretation

AIV	CLASSIFICATION
< 10%	Exceptionally Strong
10 – 20%	Strong
20- 30%	Satisfactory for road surfacing
>35%	Weak for road surfacing

4.5.2 ACV Test Result Discussion

$$\text{ACV} = \frac{\text{Mass of aggregate passing 2.36mm sieve}}{\text{Mass of aggregate retained in 2.36mm sieve}} \times 100$$

For Blast Furnace Slag (BFS)

Average ACV value = 20.59%

Since **20-25%** > 20.59% (Average AIV value)

Hence AIV is 20-25% (GOOD)

Table 4.8: ACV test results for Blast Furnace Slag (BFS)

Mass	Test
M1 (g)	2823.5
M2 (g)	581.3
M3 (g)	1942.2
ACV	20.59

For Granite

Average ACV value = 18.62%

Since **20.0** > 18.62 (Average AIV value)

Hence AIV is <20% (EXCELLENT)

Table 4.9: ACV test results for Granite

Mass	Test
M1 (g)	2802.7
M2 (g)	521.9
M3 (g)	2280.8
ACV	18.62

Table 4.10: ACV result interpretation

ACV Range (%)	Quality Assessment
< 20%	Excellent
20-25%	Good
25-30%	Satisfactory
30-35%	Fair
> 35%	Poor

The Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests revealed that both Blast Furnace Slag (BFS) and granite aggregates possess high mechanical strength and durability. BFS recorded an average AIV of 30.34% and an ACV of 20.59%, classifying it as satisfactory for road surfacing and good in crushing resistance, while granite showed better performance with an average AIV of 31.78% and ACV of 18.62%, rated excellent in crushing resistance. These results confirm that both aggregates are structurally reliable, with granite exhibiting marginally superior resistance to impact and compressive loads, making them suitable for concrete and pavement applications.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0 Conclusion

This study investigated the effect of partially replacing natural granite with Blast Furnace Slag (BFS) at varying percentages (2.5%, 5%, 7.5%, and 10%) on the properties of concrete, focusing on particle size distribution, compressive strength, flexural strength, workability, and aggregate quality (AIV and ACV).

From the sieve analysis, it was established that BFS is largely composed of coarse particles with poor grading and minimal fines, unlike granite which possesses a more balanced gradation that enhances workability and compaction. The fine aggregate (sand) exhibited suitable grading within BS standards, making it appropriate for concrete production.

Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests confirmed the structural reliability of both aggregates. BFS was rated satisfactory in impact resistance (AIV of 30.34%) and good in crushing resistance (ACV of 20.59%), while granite was rated exceptionally strong in impact (AIV of 31.78%) and excellent in crushing resistance (ACV of 18.62%). These results validate the mechanical durability of BFS but also show granite as the superior aggregate.

The compressive strength results showed that the control mix (0% BFS) consistently achieved the highest strength across curing ages. However, the 2.5% BFS replacement produced comparable strength values, with a 28-day compressive strength of 19.29 N/mm², only slightly lower than the control (21.08 N/mm²). Strength decreased progressively with higher BFS content, with 10% replacement giving the lowest performance (15.48 N/mm² at 28 days). This indicates that BFS can be incorporated at low levels (2.5% replacement advisable) without significant loss of strength, but higher replacement levels adversely affect structural performance.

Flexural strength tests results also showed decline in strength as the percentage of BFS replacement increases. The control specimens had the highest flexural strength (9.60 N/mm² at 28 days), while 2.5% BFS replacement provided an acceptable value (8.56 N/mm²). Higher replacement percentages led to substantial reductions in flexural performance, with the 10% BFS mix recording only 3.4 N/mm².

The slump test revealed that workability decreased as BFS content increased, due to the coarser and poorly graded nature of BFS. The slump reduced from 30 mm (control) to 16 mm (10% BFS replacement), highlighting reduced flowability and higher compaction effort at higher BFS levels.

Overall, the study concludes that BFS can be used as a partial replacement for granite in concrete up to 2.5% by weight without significant compromise on strength and durability. Beyond this percentage, strength and workability are adversely affected, limiting BFS's practical application in structural concrete.

5.1 Recommendations

Based on the experimental findings, the following recommendations are made:

1. BFS should be limited to 2.5% replacement of granite in structural concrete to maintain adequate compressive and flexural strength while also improving sustainability by reducing natural aggregate consumption.
2. To offset reduced workability at higher BFS levels, the use of superplasticizers or water-reducing admixtures is recommended if BFS content exceeds 2.5%. This will enhance consistency and ease of placement.
3. Higher BFS replacement levels (5–10%) may be considered for non-structural concrete works such as paving blocks, kerbs, or mass concrete where strength requirements are lower and sustainability considerations are more critical.

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APPENDIX

Sieve analysis for 5000g of BFS

Weight of Sample Taken = 5000g				
Sieve	Mass Retained (g)	% Retained	% Cumulative	% Passing
19.00 mm	2725.55	54.51	54.51	45.49
13.26 mm	1870.75	37.42	92.24	7.76
10 mm	378.50	7.57	99.50	0.5
8 mm	21.25	0.425	99.93	0.07
5 mm	3.85	0.077	100.00	0
Pan	0	0	100.00	0

Sieve analysis for 5000g of Granite

Weight of Sample Taken = 5000g				
Sieve	Mass Retained (g)	% Retained	% Cumulative	% Passing
19.00 mm	900.50	18.00	18.00	82.00
13.26 mm	2700.12	54.00	72.00	28.00
10 mm	749.50	15.00	87.00	13.00
8 mm	545.88	11.00	98.00	2.00
5 mm	94.00	1.8	99.80	0.2
Pan	5.03	0.1	99.90	0.1

Sieve analysis for 100g of Fine Aggregate (Sand)

Weight of Sample Taken = 100g				
Sieve Size (mm)	Mass Retained (g)	Cumulative Mass Retained (g)	Percentage Retained (%)	Percent Passing (%)
4.75	0.48	0.48	0.48	95.74
2.36	0.71	1.19	0.71	98.81
1.18	2.77	3.96	2.77	96.04
0.60	15.57	19.53	15.57	80.47
0.425	12.44	31.97	12.44	68.03
0.30	10.69	42.66	10.69	57.34
0.212	39.89	82.55	39.89	17.45
0.15	7.59	90.14	7.59	9.86
0.075	6.63	96.77	6.63	3.23
Pan	2.65	99.42	2.65	0.58

Average Compressive Strength Obtained after 14 days of Curing, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

COMPRESSIVE STRENGTH TEST RESULTS AFTER 14 DAYS						
Replacement %	Sample No	Weight (Kg)	Density (Kg/m³)	Failure load (KN)	Compressive Strength (N/mm²)	Average strength (N/mm²)
0%	1	2.546	2546	174.35	17.44	17.58
	2	2.463	2463	176.12	17.61	
	3	2.587	2587	176.19	17.62	
2.5%	1	2.512	2512	168.29	16.83	16.92
	2	2.473	2473	170.41	17.04	
	3	2.581	2581	168.47	16.85	
5%	1	2.431	2431	161.44	16.14	16.26
	2	2.493	2493	163.01	16.30	
	3	2.552	2552	162.14	16.21	
7.5%	1	2.541	2541	156.28	15.63	15.72
	2	2.462	2462	157.34	15.73	
	3	2.503	2503	157.91	15.79	
10%	1	2.451	2451	150.28	15.03	15.17
	2	2.482	2482	151.79	15.18	
	3	2.523	2523	151.83	15.18	

Average Compressive Strength Obtained after 28 days of Curing, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

COMPRESSIVE STRENGTH TEST RESULTS AFTER 28 DAYS						
Replacement %	Sample No	Weight (Kg)	Density (Kg/m³)	Failure load (KN)	Compressive Strength (N/mm²)	Average strength (N/mm²)
0%	1	2.568	2568	211.01	21.10	21.08
	2	2.589	2589	212.19	21.22	
	3	2.575	2575	209.20	20.92	
2.5%	1	2.559	2559	201.95	20.195	19.29
	2	2.532	2532	193.31	19.331	
	3	2.581	2581	183.42	18.342	
5%	1	2.572	2572	181.29	18.129	18.01
	2	2.493	2493	176.57	17.657	
	3	2.518	2518	184.53	18.453	
7.5%	1	2.491	2491	160.78	16.078	16.52
	2	2.506	2506	170.39	17.039	
	3	2.496	2496	164.34	164.34	
10%	1	2.584	2584	162.27	16.227	15.48
	2	2.452	2452	150.82	15.082	
	3	2.537	2537	151.39	15.139	

FLEXURAL STRENGTH TEST RESULTS AFTER 7 DAYS					
Replacement %	Sample No	Weight (Kg)	Density (Kg/m³)	Flexural Strength (N/mm²)	Average Flexural strength (N/mm²)
0%	1	13.027	2605.4	4.20	4.50
	2	13.249	2649.8	4.50	
	3	12.684	2536.8	4.80	
2.5%	1	12.815	2563	3.60	3.90
	2	12.689	2537.8	3.90	
	3	13.024	2604.8	4.20	
5%	1	13.313	2662.6	3.35	3.60
	2	12.601	2520.2	3.60	
	3	13.328	2665.6	3.85	
7.5%	1	12.879	2575.8	2.70	2.90
	2	12.984	2596.8	2.90	
	3	13.112	2622.4	3.10	
10%	1	12.939	2587.8	2.50	2.60
	2	13.423	2684.6	2.60	
	3	13.353	2670.6	2.60	

Average Flexural Strength Obtained after 14 days of Curing, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

FLEXURAL STRENGTH TEST RESULTS AFTER 14 DAYS					
Replacement %	Sample No	Weight (Kg)	Density (Kg/m³)	Flexural Strength (N/mm²)	Average Flexural strength (N/mm²)
0%	1	12.960	2592	7.45	7.50
	2	12.611	2522.2	7.50	
	3	13.444	2688.8	7.80	
2.5%	1	12.931	2586.2	5.65	6.05
	2	12.746	2549.2	6.00	
	3	12.978	2595.6	6.45	
5%	1	12.622	2524.4	4.65	5.00
	2	12.786	2557.2	5.00	
	3	13.108	2621.6	5.30	
7.5%	1	12.668	2533.6	4.00	4.35
	2	12.857	2571.4	4.40	
	3	12.746	2549.2	4.60	
10%	1	13.213	2642.6	3.30	3.35
	2	12.713	2542.6	3.40	
	3	12.695	2539	3.30	

Average Flexural Strength Obtained after 28 days of Curing, with Blast Furnace Slag (BFS) replacement of 2.5%, 5%, 7.5%, and 10%

FLEXURAL STRENGTH TEST RESULTS AFTER 28 DAYS					
Replacement %	Sample No	Weight (Kg)	Density (Kg/m³)	Flexural Strength (N/mm²)	Average Flexural strength (N/mm²)
0%	1	12.751	2550.2	9.00	9.60
	2	13.103	2620.6	10.50	
	3	13.021	2604.2	9.50	
2.5%	1	12.667	2533.4	8.00	8.56
	2	12.839	2567.8	8.20	
	3	13.191	2638.2	7.00	
5%	1	12.925	2585.0	6.10	5.70
	2	13.039	2607.8	6.00	
	3	12.716	2543.2	5.00	
7.5%	1	12.995	2599.0	4.80	5.10
	2	13.185	2637.0	5.50	
	3	13.359	2671.8	5.00	
10%	1	12.646	2529.2	4.00	3.4
	2	12.604	2520.8	2.50	
	3	13.119	2623.8	3.50	