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Original Article

Experimental Study on Acid Effect on Compressive Strength of M40 Concrete with Blast Furnace Slag as a Partial Replacement of Course Aggregate

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Abstract **-** *This study evaluates the viability of incorporating Blast Furnace Slag (BFS) as a partial replacement for natural aggregates in M40 grade concrete, with a focus on its performance under acidic exposure conditions. The research investigates compressive strength and durability by preparing concrete specimens with BFS replacement levels of 15%, 30%, 45%, 60%, and 75%. Specimens were subjected to curing in 1% HCl and 1% HNO_3 solutions for durations of 7 and 28 days. The results revealed that replacing 15% to 30% of natural aggregates with BFS achieved optimal performance, balancing mechanical strength and durability, even under aggressive acidic environments. However, BFS replacement levels exceeding 45% led to substantial reductions in compressive strength, with the most pronounced degradation observed at 75% replacement. This study highlights the potential of BFS as a sustainable alternative to natural aggregates, reducing environmental impact and promoting the use of industrial by-products in construction. The findings underscore the importance of optimizing BFS content to ensure structural integrity while supporting sustainable development in the construction sector.*

Keywords **-** *M40 concrete, BFS, Aggregate replacement, Compressive strength, Acidic curing, Durability, Sustainability, HCl, HNO_3.*

1. Introduction

Concrete is among the most extensively used construction materials globally, valued for its adaptability, durability, and resistance to fire. It is primarily composed of cement, aggregates, water, and various admixtures. Aggregates, accounting for 60% to 75% of the total concrete volume, play a vital role in its composition, as noted by Sawant et al., The accelerated growth of urbanization and infrastructure development has led to a sharp rise in concrete demand, with India consuming nearly 3 million tons annually. Zhao et al., (2022) explored how key factors influence the properties of alkali-activated concrete (AAC) made with Blast Furnace Slag (BFS) and Fly Ash (FA). Their study introduced a streamlined mix design method that combines experimental validation with empirical analysis, offering accurate predictions of compressive strength while improving fresh and hardened concrete properties. This innovative approach simplifies the complexity of designing BFS/FA-AAC mixtures, ensuring consistent quality and performance. By advancing the use of sustainable materials in construction, the research provides a practical framework for integrating AAC into mainstream applications, supporting environmentally friendly building practices. Alkali-Activated Concrete (AAC) manufactured from fly ash and Ground Granulated Blast Furnace Slag (GGBFS) is developed and analysed in the study "Mix Design and Mechanical Properties of Fly Ash and GGBFS-Synthesized Alkali-Activated Concrete (AAC)" by Ramamohana Reddy Bellum and Ruben Nerella. The research offers valuable perspectives on mixed design techniques, with a particular focus on optimising mechanical attributes, including compressive, tensile, and flexural strengths. Their research highlights the potential of AAC as a sustainable alternative to traditional concrete, contributing to the advancement of green construction practices while ensuring consistent performance under various curing conditions. [4]. Sarıdemir and Çelikten examined the durability of alkali-activated lightweight aggregate concretes (AALWACs), demonstrating that these concretes exhibit better performance than conventional concrete under acid and sulfate exposure. Incorporating Blast Furnace Slag (BFS) and other industrial by-products in construction not only mitigates waste management issues but also supports sustainable development goals. This study evaluates the compressive strength of concrete when coarse aggregates are partially replaced with

BFS, specifically under acid test conditions. Understanding the effects of BFS on compressive strength during acid exposure is critical for assessing its feasibility as a substitute for traditional aggregates, promoting sustainable and environmentally friendly construction practices. Wei Fan &Yan Zhuge study on Durability of Fibre-Reinforced Calcium Aluminate Cement (CAC)-Ground Granulated Blast Furnace Slag (GGBFS) Blended Mortar after Sulfuric Acid Attack. The durability of fibre-reinforced calcium aluminate cement (CAC)–ground granulated blast furnace slag (GGBFS) blended mortar is a critical consideration.[7] This study investigates the performance of polyethylene (PE) fibre-reinforced CAC-GGBFS blended mortar under aggressive sulfuric acid exposure. The research focuses on the effects of acid attack on the physical properties, compressive strength, and tensile strain-hardening behavior of the material. Additionally, a microstructural analysis is conducted to understand the mechanisms influencing the durability of the mortar. The use of Blast Furnace Slag (BFS) and other industrial by-products in construction presents a sustainable solution to waste management challenges while contributing to environmental conservation goals. BFS is emerging as a viable substitute for natural aggregates (NA) in concrete production. This research investigates the compressive strength of M40 grade concrete when coarse aggregates are partially replaced with BFS.

The study focuses on evaluating the performance of concrete under exposure to acidic environments, specifically hydrochloric acid (HCl) and sodium hydroxide (NaOH). The comparative analysis aims to determine how BFS influences the compressive strength of concrete when subjected to these aggressive conditions. Understanding the effects of BFS on concrete's durability and mechanical properties is essential for assessing its potential as an alternative to traditional aggregates. By incorporating BFS, this research not only promotes the utilization of industrial by-products but also advances sustainable construction practices. The findings will provide valuable insights into the feasibility of using BFS in concrete, supporting the development of eco-friendly materials that meet performance requirements while minimizing environmental impact.

2. Literature Review

As per the study of Raghuvanshi et al., Ground Granulated Blast Furnace Slag (GGBFS), a steel industry by-product, effectively replaces up to 50% of Portland cement in concrete, reducing CO_2 emissions and improving durability, workability, and strength. It offers a sustainable alternative with lower energy use and waste management benefits for greener construction practices [9]. According to the investigation of Zhou et al., this research studies the impact of integrating anhydrite and Ground Granulated Blast-Furnace Slag (GGBFS) on the workability, setting time, and compressive strength of concrete, along with the influence of steam curing on early strength development. The workability of cement paste is noticeably altered by the addition of GGBS and anhydrite [10]. Goyal et al., say that Tartaric acid-Treated Steel Slag (TTSS) has demonstrated positive outcomes when added to concrete in terms of enhancing compressive strength, resistance to water absorption, and other durability concerns. When compared to traditional mixes, concrete mixes with up to 50% TTSS replacement have shown greater compressive strengths, suggesting that TTSS can be utilised successfully in structural applications [11]. Because Air-Cooled Blast Furnace Slag (ACBFS) is less expensive than natural stone aggregates, it has garnered attention as a possible aggregate for pavement sub-base as per Kunaev et al., [12]. The study by Lee et al., set out to investigate how the mechanical characteristics, resistance to chloride ions, and crack recovery of self-healing cement mortars were affected by the combination of BFSA and CMC. The study examined the effects of various CMC and BFSA combinations on mortar performance over time. The results showed that adding CMC to BFSA greatly increased compressive strength, especially after 28 days of curing [13].

Studies of Bai et al., have shown that BFS has a major impact on the mechanical characteristics of both RAC and NAC. According to studies, using BFS at a 35% substitution rate produces different results depending on the curing age. Techniques such as Nuclear Magnetic Resonance (NMR), Scanning Electron Microscopy (SEM), and Acoustic Emission (AE) have made it easier to investigate microscopic damage mechanisms. BFS incorporation reduces internal porosity and promotes the formation of hydration products over time, according to NMR and SEM analyses [14]. The Arjomandi et al., research demonstrates that using recycled nylon granules and steel fibres can enhance concrete's durability in acidic conditions. A 20% nylon content was found to provide the best strength, supporting sustainable construction and effective reuse of plastic and industrial waste [15]. The strength and durability of coal gangue-based geopolymer concrete with Granulated Blast Furnace Slag (GBFS) are investigated in this study by Zhang et al., According to the study, freeze-thaw resistance can be increased by more than two times with the right GBFS concentration and alkali activator modulus.

However, strength and resistance to chloride penetration are diminished when pores deteriorate as a result of freeze-thaw damage [16]. With an emphasis on concrete, steel, and GGBS characteristics, the study by Pasla investigated the corrosion performance of RAC concretes. According to the data, concretes containing GGBS had a lower strength at an early age than control concretes, but their strength grew as the curing period extended [17]. As the slag aggregates are frequently lighter than traditional natural aggregates, their usage in concrete can assist in making lighter structures, which is advantageous for reducing the weight of massive constructions like roads, bridges, and high-rise buildings, as said by Ballari et al., [18]. Choudhary et al., say that using coarse slag aggregate (CSA) as a partial replacement in concrete presents a promising approach to reducing environmental impact and conserving natural resources. However, its effectiveness depends on mix proportions and material properties, necessitating further research into its long-term durability and economic feasibility [19]. The performance of concrete with different amounts of GBS as a substitute for natural sand was investigated in the study of Preethi et al., The replacement percentages ranged from 0% to 30% in 5% increments.

The water-to-cement ratio was kept at 0.5, and the concrete utilised in this investigation was grade M20. Workability, compressive strength, split tensile strength, and flexural strength were among the important characteristics of the concrete that were evaluated [20]. The results from the investigation of Sarıdemir et al., showed that concrete mixtures with up to 20% GBS replacement had better mechanical qualities, but their workability decreased as the quantity of GBS grew. Results show that when compared to traditional LWACs, AALWACs-especially those with a larger percentage of FA-have better fire resistance and higher temperatures [21].

According to the study of Cao et al., concrete made with ACBFSA has poorer mechanical and workability qualities than concrete made with natural aggregates (NAs). Nonetheless, UHPFRCs with 30% SAR% show characteristics that are comparable to those of natural aggregate. The parameters of UHPFRCs with 50% and 100% SAR% decrease: the UR100 mix decreases by 4.5% and the UB100 mix decreases by 14.4%; the modulus of elasticity decreases by 2%; and the UR100 mix decreases by 9.44% and the UB100 mix decreases by 30.25%. UHPFRC is an eco-friendly and cost-effective alternative to natural aggregates because it may be made using single or dual fiber up to 30% slag aggregates [22].

The study by Liu et al., indicated that replacing sand with fly ash or GGBS greatly boosted the compressive strength of concrete. Concrete that included 30% fly ash instead of sand had a 45% greater compressive strength, and concrete that used 30% GGBS instead of sand had a 112% higher strength. This implies that high-performance concrete can be made with fly ash [23].

2.1. Gaps in Literature

Despite the extensive research exploring the integration of industrial by-products such as GGBFS, BFS, and steel slag in concrete production, several gaps remain unaddressed. While numerous studies affirm the benefits of substituting cement and aggregates with these materials in terms of enhanced compressive strength, durability, and sustainability, there is limited research focusing on their behavior under aggressive environmental conditions, especially acidic exposure. Although isolated studies have examined resistance to sulfuric, hydrochloric, or nitric acid, a comparative analysis across different acids or mixed exposure scenarios remains lacking. Additionally, much of the research prioritizes mechanical performance—mainly compressive strength—without giving adequate attention to other essential parameters like flexural strength, split tensile strength, or long-term durability indicators such as permeability and resistance to micro-cracking.

Moreover, most investigations utilize GGBFS or BFS either as a binder or coarse aggregate replacement, with very few exploring their potential as a partial substitute for fine aggregates like natural sand. Studies such as those by Preethi et al., and Liu et al., have begun to highlight this application, but a broader understanding of how GBS replacement influences workability, setting time, and long-term strength under diverse curing and environmental conditions is still needed. Furthermore, microstructural analysis tools like SEM, NMR, and XRD are underutilized in connecting observed mechanical changes with underlying physical and chemical transformations within the concrete matrix. There is also a scarcity of data regarding large-scale structural behavior or field-level validation of slag-incorporated concretes, which is crucial for real-world application. Lastly, while environmental benefits are widely acknowledged, economic viability, lifecycle cost analysis, and carbon footprint assessments are rarely incorporated in a holistic manner. Addressing these research gaps could significantly advance the development of sustainable, durable, and performance-optimized concretes using slag-based materials.

3. Composition of Concrete and Its Characteristics

The following Table 1 contains the ingredients of concrete and their properties as shown below.

Table 1. Composition of concrete

Component	Details	Properties
Cement	53-grade Ordinary Portland Cement (OPC)Complies with IS 8112:2013	Specific Gravity: 3.15 [10] Physical Tests: IS 4031:1988
Fine Aggregate	Material: Manufactured crushed sand Sieve Analysis: Passes through 4.75 mm sieve Standards: IS:383 Zone I	Specific Gravity: 2.95 Bulk Density: 1510.96 kg/m³
Coarse Aggregate	Natural Aggregate: Locally sourced crushed stone Blast Furnace Slag (BFS): Green Age Agro Engineers,	Natural Aggregate**:** Specific Gravity: 3.15

	Kolhapur, Maharashtra BFS processed by hand-crushing to 20 mm	Loose Density: 1503.97 kg/m³ Compacted Density: 1677.90 kg/m³ [10] BFS: Specific Gravity: 2.42 Loose Density: 937.83 kg/m³ Compacted Density: 1071.54 kg/m³ [10]
Water	Type: Potable water used for mixing and curing	
Chemical Admixture	Product: Armix Plast 111 (High-performance concrete admixture)	Specific Gravity: ~1.20 pH Value: Below 7.0 [13]

4. Mix Design M40

The concrete mix was developed in line with the guidelines outlined in ACI 211.1-1991 standards, aiming for a target compressive strength of 40 N/mm². This mix incorporates 410 kg/m³ of cement and utilizes a water-to-cement ratio of 0.45. Additionally, a high-performance concrete admixture was included to enhance the workability and strength of the mix. The design process considered factors such as aggregate size, specific gravity, and durability requirements to achieve the desired performance. The mix proportions were carefully calculated to ensure a balance between workability, durability, and strength. Aggregates, both fine and coarse, were selected based on their compliance with relevant standards and their compatibility with the mix. The mix design includes 410 kg/m³ of cement, a critical binder that provides the necessary strength. The water-to-cement ratio of 0.45 was chosen to optimize hydration while maintaining adequate workability.

To further enhance performance, a chemical admixture specifically formulated for high-performance concrete was incorporated. Fine aggregates, such as manufactured crushed sand, were used to meet the gradation requirements and ensure proper packing density. Coarse aggregates, including natural crushed stones and partially replaced blast furnace slag (BFS), were added for their durability and strength-contributing properties.

1.	Grade Designation	: M 40
2.	Cement Used	: OPC 53 grade (IS 8112 compliant)
3.	Maximum Nominal Size of Aggregate	: 20mm
4.	Minimum Cement Content	: 380/m^3
5.	Maximum Water-Cement Ratio	: 0.45
6.	Workability	: 75mm (slump)
7.	Exposure Condition	: Severe exposure
8.	Degree Of Supervision	: Good
9.	Type Of Aggregate	: Crushed rough aggregate
10	Maximum Cement Content	: 450/m^3
11.	Chemical Admixture Type	: Superplasticizer

4.1. Target Strength for Mix Proportion

	$= F_{ck} + 1.65$ X S
1.Target Strength	= 40 + 1.65 X 6
	= 49.9
2. Water Cement Ratio	= 0.45
3. Cement Content	= 410 kg/m^3

4.2. Mix Proportion

Table 2 shows the mix proportion of ingredients of concrete in mix design M40.

Table 2. Mix proportion

Cement	Sand	Aggregate (10 mm)	Aggregate (20 mm)	Water
1.000	1.881	1.005	1.832	0.45

5. Improvement of BFS Aggregate in Conventional Concrete

This research involved replacing coarse aggregates with BFS coarse aggregates at varying levels of 15%, 30%, 45%, 60%, and 75% to analyse the resulting compressive strength and compare it to that of natural aggregates (NAs). The mix design parameters developed for this analysis are detailed as follows in Table 3.

Table 3. Mix design for M40 concretewith BFS aggregate replacement

C	Improvement of BFS Aggregate in Conventional Concrete M40
C1	0 % Replacement of NA
C2	15 % Replacement of NA
C3	30 % Replacement of NA
C4	45 % Replacement of NA
C5	60 % Replacement of NA
C6	75 % Replacement of NA

5.1. Concrete Sample Preparation

Concrete was prepared following IS 516-1959, with the quantities of cement, fine aggregates, and coarse aggregates measured by weight. The mixing process was carried out manually using a shovel on a non-porous surface. The workability of the mix was evaluated using a slump cone test. For the compressive strength tests, concrete specimens were molded into 150 x 150 x 150 mm steel molds and compacted using a table vibrator. The specimens were covered with wet burlap for the first 24 hours to retain moisture.

5.2. Testing of Concrete Cubes

For specimens cured in 1% HCl and 1% NaOH solutions, the process involved immersing them in these solutions after an initial 28-day water curing period. The specimens were kept in the solutions for 7 and 28 days. After the respective curing periods in the solutions, the specimens were carefully cleaned to remove any surface residues.

Their weight and dimensions were recorded before testing. Mechanical properties, including compressive strength, were determined using a Compression Testing Machine (CTM) to evaluate the impact of chemical exposure over time on the strength and durability of the concrete.

6. Test Outcomes

6.1. Compressive Strength Testing of Concrete Cubes

A compression test is performed to evaluate the behavior of materials under compressive loads, measuring their resistance to crushing forces and deformation under pressure. The compressive strength of concrete was tested on cube specimens measuring 150 x 150 x 150 mm after curing in 1% HCl and 1% NaOH solutions. The specimens were initially water-cured for 28 days, followed by immersion in the chemical solutions for 7 and 28 days.

The table and graph below present the compressive strength results, comparing concrete made with 100% natural aggregates (NAs) to concrete with partial replacement of NAs by BFS coarse aggregates. Tables 4 to 7 show the compressive strength of concrete cured in 1% HCl solution and 1% solution of HNO_3 solution for 7 days and 28 days, and Figures 1 to 4 show the graphical presentation of data given in Tables 4 to 7, respectively.

Table 4. 7 Days compressive strength (M-40) concrete cured 1% HCl solution

Cube ID Mark	Average Compressive Strength in N/mm^2
C1	33.846
C2	33.342
C3	32.523
C4	31.036
C5	30.736
C6	28.722

Table 5. 28 Days compressive strength (M-40) concrete cured 1% HCl solution

Cube ID Mark	Average Compressive Strength in N/mm^2
C1	52.683
C2	51.592
C3	51.712
C4	50.592
C5	48.610
C6	45.327

Table 6. 7 Days compressive strength (M-40) concrete cured 1% HNO3 solution

Cube ID Mark	Average Compressive Strength in N/mm^2
C1	33.556
C2	32.553
C3	31.935
C4	30.626
C5	30.228
C6	28.280

Table 7. 28 Days compressive strength (M-40) concrete cured 1% HNO3 solution

Cube ID Mark	Average Compressive Strength in N/mm^2
C1	52.467
C2	50.905
C3	50.728
C4	49.754
C5	48.439
C6	44.756

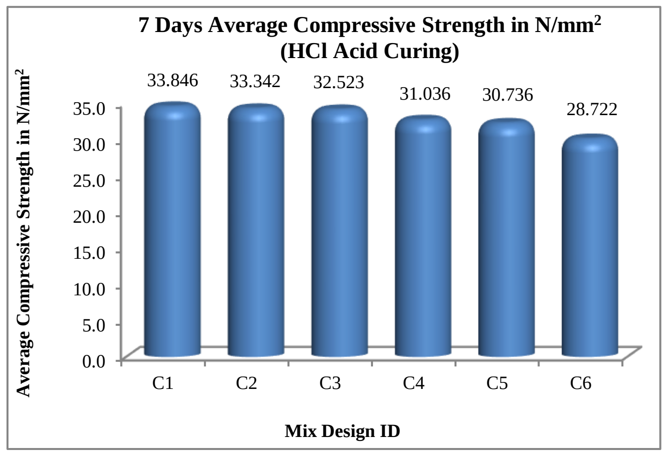

Fig. 1 7 Days compressive strength (M-40) concrete cured 1% HCl solution

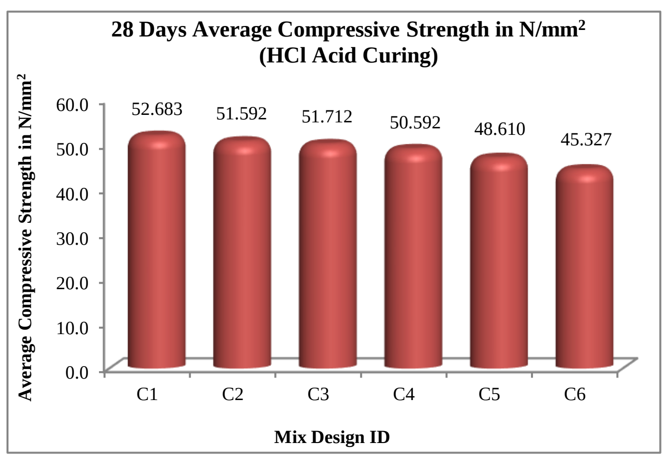

Fig. 2 28 Days compressive strength (M-40) concrete cured 1% HCl solution

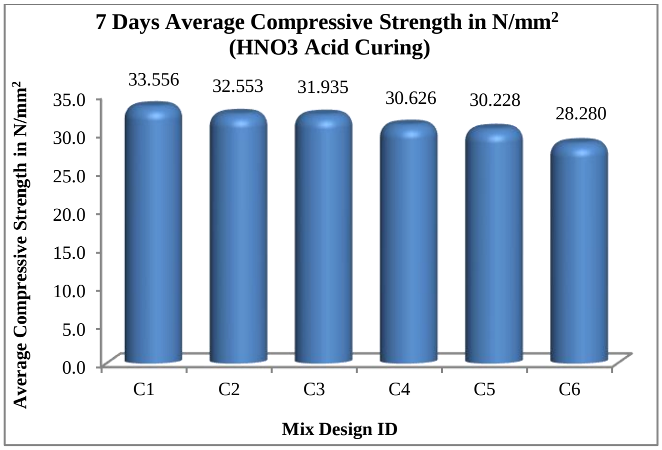

Fig. 3 7 Days compressive strength (M-40) concrete cured 1% HNO_3 solution

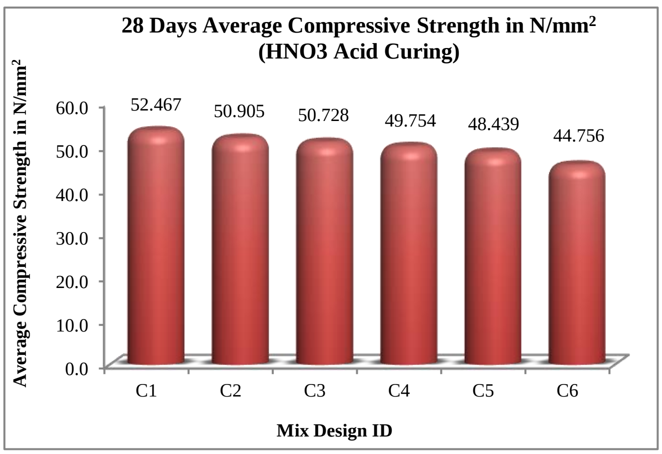

Fig. 4 28 Days compressive strength (M-40) concrete cured 1% HNO_3 solution

6.2. Effect of Replacement of Aggregate with BFS Aggregate on the Compression Strength of Concrete

The influence of substituting a portion of natural aggregate with Blast Furnace Slag (BFS) aggregate on the compressive strength of M40 grade concrete was investigated. This evaluation was carried out by subjecting cube specimens to compression tests after curing them in hydrochloric acid (HCl) and nitric acid (HNO_3) solutions for 7 and 28 days.

- The effects of BFS aggregate on the strength of the concrete were analyzed under these acidic curing conditions, which simulated aggressive environmental exposure. The compressive strength was compared at different replacement levels of natural aggregate with BFS and at varying curing durations to assess the impact of this substitution on the concrete's durability and performance.

- When the aggregate replacement rises from 0% to 15%, the concrete strength decreases by approximately 2.1%, even after 7 days of curing in 1% HCl. Between 15% and 30% replacement, the strength reduces further by about 3.4%. At 45% replacement, the reduction becomes more significant, reaching 6.2%, with acid curing amplifying this effect. From 45% to 60%, the decrease is smaller, around 1.2%, though 1% HCl curing slightly worsens it. At 75% replacement, the strength shows a notable drop of 4.2%, with the acidic environment further intensifying the loss.

- The compressive strength of conventional concrete is 33.566 MPa. After 7 days of curing in 1% HNO_3, the strength decreases as the aggregate replacement increases. At 15% replacement, strength drops by 3.0%, reaching 32.553 MPa. At 30%, it reduces by 4.9%, reaching 31.935 MPa. With 45%, strength drops by 8.8%, to 30.626 MPa. At 60%, the reduction is 10.0%, and at 75%, it decreases by 15.7%, reaching 28.280 MPa. These results show the effect of HNO_3 curing.

- The compressive strength of conventional concrete after 28 days of curing in a 1% HCl solution is 52.683 MPa. With 15% aggregate replacement, the strength decreases slightly to 51.592 MPa, showing a 2.1% reduction. At 30% replacement, the strength increases slightly to 51.712 MPa, a 0.1% increase. With 45% replacement, the strength drops to 50.592 MPa, reflecting a 4.0% reduction. At 60%, the strength further decreases to 48.610 MPa, indicating a 7.7% reduction. Finally, with 75% replacement, the strength decreases to 45.327 MPa, showing a 13.9% reduction.

- After 28 days of curing in 1% HNO_3, the compressive strength of conventional concrete is 52.467 MPa. With 15% aggregate replacement, the strength decreases by 3.0% to 50.905 MPa. At 30%, it drops by 3.3% to 50.728 MPa. With 45% replacement, the strength reduces by 5.2% to 49.754 MPa. At 60%, it decreases by 7.7% to 48.439 MPa. Finally, with 75% replacement, the strength drops by 14.8% to 44.756 MPa, showing the impact of aggregate replacement on concrete strength.

7. Conclusion

This study has examined the impact of replacing natural aggregates with Blast Furnace Slag (BFS) in M40 grade concrete, especially under acidic curing conditions using 1% HCl and 1% HNO_3 solutions. The findings provide key insights into the effects of BFS on compressive strength and durability.

7.1. Impact of BFS Replacement

Replacing 15% to 30% of the natural aggregate with BFS yielded the best performance, maintaining reasonable strength and durability even in acidic environments. Higher replacement percentages beyond 45% resulted in notable reductions in compressive strength, indicating that excessive BFS incorporation negatively affects the strength of the concrete.

7.2. Influence of Acidic Curing

The acidic curing environment significantly contributed to the reduction in strength, especially at higher levels of BFS replacement. Concrete exposed to 1% HCl and 1% HNO_3 solutions exhibited considerable strength loss, particularly with increased BFS content.

7.3. Strength Reduction Trends

The strength reduction was minimal with 15% BFS replacement, showing a reduction of around 3%. However, as the BFS content increased to 30%, 45%, 60%, and 75%, the compressive strength continued to decrease.

At 75% BFS replacement, the strength decreased by 15.7%, demonstrating that higher BFS content led to more pronounced performance degradation, particularly under acidic conditions.

7.4. Optimal BFS Replacement

Replacing up to 30% of natural aggregate with BFS provides a good balance between sustainability and maintaining concrete's strength and durability. Beyond this replacement level, strength reductions become more significant, making higher BFS percentages unsuitable for applications that require high compressive strength.

7.5. Sustainability and Performance Considerations

BFS serves as a sustainable alternative to natural aggregates, offering environmental benefits by reducing the carbon footprint of concrete production. However, the study emphasizes that BFS should be used in moderation to avoid compromising concrete strength, especially in structures exposed to harsh environmental conditions. Further research could focus on refining the use of BFS to enhance both sustainability and performance.

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