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Assessing the Compressive and Flexural Performance of Eco Friendly Concrete Incorporating Ground Granulated Blast Furnace Slag and Jute Fibers

Joshua Ozioko [1], Benjamin Anyaehie [2], John Eso [3], Boluwade Segun [4]

[1] *Department of Civil Engineering, Faculty of Engineering, University of Nigeria, Nsukka, Nigeria.*
[2] *Department of Civil Engineering, Federal University of Technology, Owerri, Nigeria.*
[3] *Department of Civil, Construction, and Environmental Engineering, North Carolina State University.*
[4] *Department of Project Management Technology, Federal University of Technology, Akure.*

Abstract

The industrial production of traditional Portland cement is a primary contributor to global greenhouse gas emissions. To mitigate this environmental impact and address the inherent brittleness of conventional concrete, the integration of industrial byproducts and natural fibers has emerged as a vital area of sustainable construction research. This experimental investigation evaluates the mechanical characteristics of eco-friendly concrete by utilizing Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash as partial cement replacements. Specifically, 30% of ordinary Portland cement was substituted with either GGBS or Fly Ash in separate mix designs. To counteract micro-cracking and improve ductility, 0.5% natural jute fiber (by weight of cement) was incorporated into the matrix. The structural performance of these modified Jute Fiber Reinforced Cement Concrete (JFRCC) mixes was rigorously assessed through 7-day and 28-day cube compression tests and two-point beam bending tests. Experimental findings demonstrated that the integration of 30% GGBS yielded superior structural outcomes compared to both the conventional concrete baseline and the Fly Ash mixtures. The GGBS-modified composite achieved a peak compressive strength of 24.85 N/mm² at 7 days and 46.32 N/mm² at 28 days, representing an 8.86% increase over standard concrete. Furthermore, under flexural evaluation, the GGBS-enhanced beams exhibited significantly improved toughness, recording a maximum deflection of 20.46 mm under a 2.475 kNm bending moment. Conversely, the incorporation of 30% Fly Ash resulted in a notable reduction in overall load-bearing capacity and compressive strength. Ultimately, combining 30% GGBS with 0.5% natural jute fibers provides an optimal, sustainable solution for developing highly durable and ductile structural concrete.

Keywords: Ground Granulated Blast Furnace Slag, natural fibers, brittle cement matrix, toughness, Jute Fiber Reinforced Cement Concrete mix (JFRCC).

INTRODUCTION

Concrete is the most abundant man-made material in the world. The industrial production of cement, the primary binder in concrete, is a major source of greenhouse gas emissions [Ige et al., 2024]. Specifically, the manufacture of one ton of cement results in the emission of approximately one ton of carbon dioxide, primarily due to the calcination of limestone and the combustion of fossil fuels during clinker production [Ige et al., 2024]. Consequently, this energy-intensive process is responsible for an estimated 65% of global warming [Bharathi & Kumar, 2019]. To mitigate these severe environmental impacts and optimize construction costs, ongoing research focuses on modifying standard concrete properties through the integration of various supplementary cementitious materials [Liu et al., 2021]. Recent advancements in material technology have driven the development of specialized concretes tailored for specific performance requirements. These innovations include polymer concrete for high durability, high- and ultra-high-strength concrete for applications in tall buildings and bridges, and lightweight concrete for reducing foundation loads. Prominent among these solutions is the use of industrial byproducts [Liu et al., 2021]. Fly ash, one of the most abundant materials on Earth, is a primary byproduct created from the combustion of coal in coal-fired power plants [Hossain et al., 2023]. Similarly, Ground Granulated Blast Furnace Slag (GGBS) comprises mainly calcium oxide, silicon di-oxide, aluminum oxide, and magnesium oxide. It shares the main chemical constituents of Ordinary Portland Cement (OPC) but in different proportions, and is used to construct highly durable concrete structures when combined with OPC [Liu et al., 2021]. The simultaneous incorporation of GGBS and natural fibers has proven highly effective in developing eco-friendly concrete with significantly enhanced ductile characteristics. Despite these material advancements, a prevailing technological challenge remains the design of durable, low-cost fiber-reinforced cement concrete [Mohammed et al., 2024]. Traditional concrete possesses high compressive strength but is inherently brittle, exhibiting poor resistance to crack propagation [Hossain et al., 2023]. To address this, Fiber Reinforced Concrete (FRC) can be utilized in structural members such as beams, columns, staircase slabs, and pre-stressed concrete structures. The introduction of natural fibers into this relatively brittle cement matrix fundamentally alters its failure mechanism, attaining significant toughness and strength for the composite material by bridging micro-cracks and resisting tensile stresses [Mohammed et al., 2024]. Among natural fibers, jute presents a highly sustainable and effective alternative to conventional steel or synthetic reinforcement [Hossain et al., 2023].

Jute fiber is 100% bio-degradable, recyclable, and environmentally friendly. As the second most important vegetable fiber after cotton, it offers substantial agricultural availability and functional versatility for various uses. To address these combined environmental and structural challenges, this experimental investigation seeks to minimize cement consumption while simultaneously enhancing composite toughness. By substituting 30% of ordinary Portland cement with either Fly Ash or Ground Granulated Blast Furnace Slag (GGBS) within a natural jute fiber-reinforced matrix, this study aims to engineer a construction material that is cost-effective, durable, and sustainable. To rigorously evaluate the efficacy of these modifications, the structural performance of the distinct mix designs is assessed through comprehensive compressive and flexural strength testing.

MATERIALS & METHODOLOGY

MATERIALS

A. Cement

Ordinary Portland Cement of 53 Grade is used throughout this investigation. To verify binder quality, the cement samples were tested. The important properties of the cement from the test results are given in TABLE 1.

Table 1: Properties of Cement

Grade	OPC 53
Specific Gravity	3.15
Fineness	3%
Initial setting time	28 min
Final setting time	310 min

B. Fine Aggregate

Locally available river sand conforming to Grading zone II of IS: 383 –1970. Weight of sample is 200g. The properties of fine aggregates were tested as per IS: 383-1970 as shown in Fig 2. The test results are given in TABLE 2.

Table 2: Properties of Fine Aggregate

Fineness modulus	2.25
Specific gravity	2.60
Water absorption	1%

The particle size distribution of Fine Aggregate is shown in Fig 1.

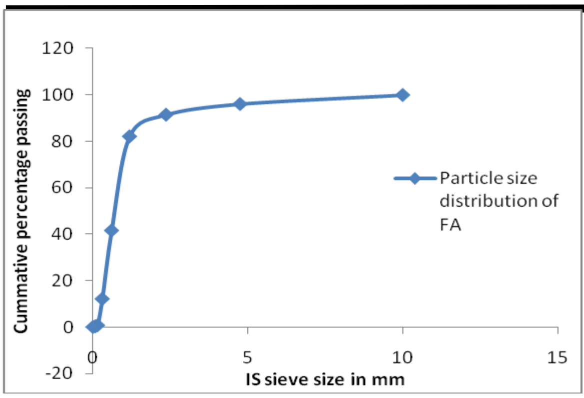

Fig 1. Particle size distribution curve of fine aggregate

C. Coarse Aggregate

Crushed granite aggregate with a maximum nominal size of 20mm have been used. The test sample of 200 g was taken the tests were carried out as per the code IS: 2386 and 383-1970. The summaries of properties of coarse aggregate are given in the TABLE 3.

Table 3: Properties of Coarse Aggregate

Fineness modulus	6.05
Specific gravity	2.60
Water absorption	1%
Size Aggregate	20mm

D. Fly Ash

Fly ash is one of the most abundant materials on the Earth. Fly ash is the main byproduct created from the combustion of coal in coal-fired power plants. The properties of Fly ash and GGBS are compared in the TABLE 4.

E. GGBS

Ground granulated blast furnace slag comprises mainly of calcium oxide, silicon di-oxide, aluminum oxide, magnesium oxide. It has the same main chemical constituents as OPC (Ordinary Portland Cement) but in different proportions. GGBS is used to make durable concrete structures in combination with OPC (Ordinary Portland Cement) or PPC (Portland Pozzolana Cement).

Table 4: Properties of Fly Ash and GGBS

S/No	Property	Fly ash	GGBS
1	Specific Gravity	2.44	2.58
2	Fineness	227.8 g/m2	202.7 g/m2
3	Fineness Modulus	5	7
4	Density	1029.7 Kg/m3	2067.06 Kg/m3

F. Jute Fiber (Natural Fiber)
Jute Fiber is 100% bio-degradable and recyclable and environmentally friendly. Jute is the second most important vegetable fiber after cotton not only for cultivation, but also for various uses. The properties of Jute fiber are shown in TABLE 5.

Table 5: Properties of Jute Fiber

Parameter	Value
Diameter	0.6 mm
Fiber Length	20mm
Density	1460 kg/m3
Tensile Strength	400-800 MPa
Stiffness	10-20 kN / mm2

G. Super Plasticizers
To manage the reduction in workability associated with the inclusion of micro-fine SCMs and water-absorbing natural fibers (Ahmad et al., 2022), a chemical admixture was required. The commercially available CONPLAST SP 430 superplasticizer was used for this investigation. By dispersing cement particles efficiently, it allows for water reduction while maintaining flow. The rate of addition is generally maintained in the range of 0.5 to 2 kg per 100 kg of cement to achieve the necessary slump.

TESTING OF SPECIMENS

As per IS10262-2009, the obtained design mix for M40 grade concrete is 1:2.35:3.2 for the water cement ratio 0.4. The super plasticizer CONPLAST SP 430 is added as 1 % by weight of cement in order to increase the workability. And to increase the toughness of the cement matrix the addition of Jute fiber is limited to 0.5% by weight of cement.

In the first combination the specimen has casted with 30 % of Fly ash as a cement replacing material and in the second combination 30 % GGBS by weight of cement has been used as a cement replacing material. The behavior of both the combination has been compared under compression and bending test.

A. Cube Compression test on concrete
The load shall be applied without shock and increased continuously at a rate of approximately 140 kg/sq cm/min until the resistance of the specimen to the increasing load breaks down and no greater load can be sustained as shown in the Fig 2. From the test results, it was observed that the maximum compressive strength was obtained for mix Combination JFRCC with 30% GGBS as shown in the Table 6.

Fig 2. Cube compression test

Table 6: Compressive Strength Test Results

MIX	JUTE FIBER (%)	Compressive strength N/mm2 (7th Day)	Compressive strength N/mm2 (28th Day)
Normal	-	19.50	42.55
JFRCC (30 % Fly Ash)	0.5	17.09	38.97
JFRCC (30 % GGBS)	0.5	24.85	46.32

B. Bending Test on Beams

Singly reinforced beam with 10 mm diameter bar as main reinforcement and 8 mm 2-legged stirrups at 300 mm c/c as shear reinforcement is used as a test specimen in flexural or bending (two-point bending) test. The test specimen shall be placed in the machine correctly centered with the longitudinal axis of the specimen at right angles to the rollers. The load shall be applied at a rate of loading of 180 kg/min. The results of flexural strength of concrete at the age of 28 days are presented in TABLE 7.

Table 7: Bending Test Results of Beam Specimens

Beam	Maximum Deflection in mm (Right L/3)	Maximum Deflection in mm (Middle L/2)	Maximum Deflection in mm (Left L/3)	Maximum Moment in kNm
Normal Beam	16.2	17.1	16.1	2.25
JFRCC with 30% Fly ash	12.9	13.7	12.87	2.025
JFRCC with 30% GGBS	19.3	20.46	19.1	2.475

C. Results and Discussions

As From the compressive strength test of cube specimens, it is noted that the JFRCC with 30% GGBS has the maximum cube compressive strength of 24.85 N/mm2 (in 7 days) which is 21.5% higher than normal beam and 31.22 % higher than JFRCC with 30 % Fly ash. When comparing the 28th day test results it is noticed that the JFRCC with 30% GGBS has maximum compressive strength of 46.32 N/mm2 which is 8.86% higher than normal concrete and 15.8% higher than JFRCC with 30 % Fly ash. The JFRCC with 30% FA has the compressive strength of 17.09 N/mm2 and 38.97 N/mm2 in 7 days and 28 days respectively. The comparison of strength in cube compression test is shown in Fig 3.

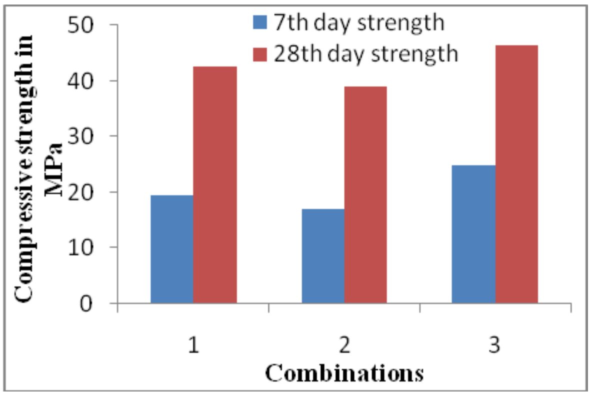

Fig 3. Interpretation of results from cube compressive strength

When comparing the results of bending test the JFRCC with 30 % Fly ash has the maximum deflection of 13.7 mm under the maximum bending moment of 2.025 kNm which is 11.1 % lower than normal beam. In case of JFRCC with 30 % GGBS has the maximum deflection of 20.46 mm under the moment of 2.475 kNm which is 9.09% higher than the normal RCC beam. The load Vs deflection behavior of JFRCC with normal RC beam under bending has been shown in the Fig 4.

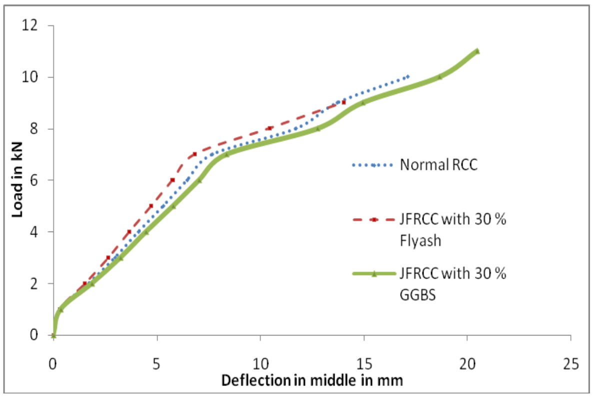

Fig 4. Interpretation of results from bending test

CONCLUSION

This experimental investigation evaluated the efficacy of utilizing supplementary cementitious materials, specifically Fly Ash and Ground Granulated Blast-furnace Slag (GGBS), as partial cement replacements within Natural Jute Fibre Reinforced cement concrete. The primary objective was to reduce overall cement consumption while simultaneously enhancing the strength and structural toughness of the concrete matrix. The performance of these modified mixes was rigorously tested under compression and bending conditions and directly compared against standard Reinforced Cement Concrete (RCC) control beams.

Analysis of the cube compression tests demonstrated that replacing 30% of the cement with GGBS yielded the most favorable structural outcomes. The JFRCC mix containing 30% GGBS achieved a maximum compressive strength of 24.85 N/mm² at 7 days and 46.32 N/mm² at 28 days. These results represent strength increases of 21.5% and 8.86%, respectively, over the normal concrete baseline. Conversely, the incorporation of 30% Fly Ash resulted in a substantial decrease in load-bearing capacity. The compressive strength for the Fly Ash combination exhibited reductions ranging from 9.18% to 14.1% between the 7-day and 28-day curing periods when compared to the standard mix.

The bending test results further corroborated the superior performance of the GGBS mixture. The JFRCC specimen containing 30% GGBS recorded a maximum deflection of 20.46 mm under a bending moment of 2.475 kNm. This deflection capacity is 16.4% higher than the normal RCC beam and 33% greater than the mix containing 30% Fly Ash, indicating significantly enhanced ductility and flexural strength. Ultimately, the experimental data confirms that increasing the proportion of GGBS directly correlates with improvements in both compressive and flexural strength. In stark contrast, increasing the percentage of Fly Ash compromises the structural integrity of the concrete, leading to a consistent decrease in overall strength. Therefore, the combination of 30% GGBS with 0.5% natural jute fiber reinforcement presents an optimal, eco-friendly solution for producing high-strength, durable concrete.

Conflicts of Interest: All authors declare that they have no conflict of interest associated with this research work.
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