
STRUCTURAL RELIABILITY ASSESSMENT OF REINFORCED CONCRETE BEAM INCORPORATING GROUNDNUT SHELL ASH FOR TILAPIA CONCRETE INCUBATOR.

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ABSTRACT

Structural reliability is the probability of the structure performing its required function adequately for a specific period of time under stated conditions. Reliability analysis on reinforced concrete beam containing Groundnut shell ash as a partial replacement for cement was conducted in this research. The properties of concrete constituents were determined, COREN concrete mix design guidelines were used and the fresh concrete density was 2130Kg/m³. Twenty (20) samples of concrete cubes of 150mm x 150mm x 150mm size were tested each for 7, 14, 21 and 28 days after casting at 0, 5, 10, 15 and 20% of groundnut shell ash replacement, making a total of 400 cubes. The samples were cured for ages of 7, 14, 21 and 28 days and the compressive strengths were determined. The average compressive strength of 21.38N/mm² at 5% replacement for 28 days curing was determined and used for structural design of the beam. The designed beam was subjected to reliability analysis using First Order Reliability Method (FORM). It was observed that the beam designed was safe in bending under Ultimate Limit State of loading, at the span of 2.7m, 300mm depth, 402mm² area of steel and 7.454kN/m live load with safety index of 3.90091. Sensitivity analysis revealed that safety index is directly proportional to the depth/area of steel but inversely proportional to the span/ live load of the reinforced concrete beam.

Keywords: Structural reliability; Compressive strength; RC Beam; Groundnut shell ash

1. INTRODUCTION

1. INTRODUCTION

Beams are structural elements made to withstand loads that can cause bending and they are always identified using parameters like its length, material and cross-sectional shape. Concrete is one of the most commonly used construction materials in the world. Reinforced concrete is a widely used material in structural engineering practices due to its strength and durability. Due to its unique feature combination of workability, mechanical properties, durability, fire resistance and the wide availability of raw materials sources, concrete has become highly attractive for many applications in the civil engineering industry (Rosa, *et al.*, 2023). Several studies have been conducted to investigate the behavior of reinforced concrete structures under different loading and environmental conditions (Szép *et al.* 2023). Concrete is obtained by mixing cement, fine aggregate, coarse aggregate and water in required proportions. The mixture when placed in forms and allowed to cure becomes hard like stone. The hardening is caused by chemical action between water and the cement due to which concrete grows stronger with age. The strength, durability and other characteristics of concrete depend upon the properties of its ingredients, proportion of the mix, the method of compaction and other controls during placing and curing. Concrete possess a high compressive strength and is usually more economical than steel and is non-corrosive which can be made with locally available materials.

Structural reliability is the probability of the structure performing its required function adequately for a specific period of time under stated conditions (Aguwa, 2010; Aguwa, 2013). Structural assessment is a procedure utilized to check the adequacy, integrity and soundness of structures and their components, made to evaluate a structures current and future use and conformance to codes. A reliability evaluation of a structure in engineering is well-defined as the assurance on its

capacity to achieve its design determination within a specified time. Reliability evaluation is founded on the probability philosophies which provide the platform for its measurement. The reliability of a system can be regarded as the likelihood of its acceptable performance based on certain given performance functions. This function is for a definite purpose and it is laid open to extreme settings within a given time (Dey and Kudmetha, 2013; Ishola *et al*, 2021).

All structures have two basic requirements in common; safety from collapse and satisfactory performance of the structure for its intended use. The limit states define the various ways in which a structure fails to satisfy these basic requirements. Ultimate limit states relate to satisfactory performance and correspond to excessive deflection, vibration and local deformation. Limit state design thus refers to the calculations made by the designer to ensure that these failures do not occur.

Due to increasing industrial and agricultural activities, tons of waste materials are deposited in the environment with little effective method of waste managing/recycling. Some of these deposits are not easily decomposed and the accumulation is a threat to the environment and people at large. Some of these waste materials are groundnut shell, rice husks, maize combs, snail shells, palm-kennel shell, coconut shell and saw dust. Groundnut shell is an agro-waste generated from milling of groundnut (Usman, *et al*, (2019). The rising cost of housing and construction materials especially cement in developing countries in the world including Nigeria is a major concern. Therefore, Groundnut shell being a total waste in agriculture for decade has resulted for a decade research to ascertain the use of the ash as soil stabilizer in clay brick production, as a fertilizer on soil and in partial replacement of cement Samuel, (2020).

This study was conducted to address the Limited information available on the structural behavior and load-carrying capacity of reinforced concrete beams incorporating Groundnut Shell Ash (GSA) for tilapia concrete incubator support systems. The uncertainties associated with GSA concrete properties, applied loads, material strength, and structural dimensions are not adequately addressed by conventional deterministic design methods, making the actual safety and probability of failure of the beam uncertain and also to address the inadequate reliability-based assessment for determining the optimum GSA replacement level that can achieve sufficient structural strength, acceptable reliability, and sustainable performance in reinforced concrete beams for tilapia concrete incubators.

The aim of this research is to carry out structural reliability assessment of reinforced concrete beams incorporating groundnut shell ash for tilapia concrete incubators. The objectives are; to determine the physical properties of concrete constituent materials and chemical oxide composition of groundnut shell ash, to determine the compressive strength of concrete, to carry out structural design of the reinforced concrete beam using data from objective one and two and to carry out reliability analysis of the reinforced concrete beam.

2. METHODOLOGY

The materials that were used in this study are Limestone cement, River sharp sand, River gravel, Groundnut Shell Ash and water.

2.1 Limestone Cement

Limestone cement of 42.5 grade was used in this study. It was sourced from a nearby building material shop in Minna. The Limestone cement conformed to requirement for cement to be used for concrete production in accordance with BS 8615-1&2 (2019).

2.2 Fine Aggregates (River Sharp Sand)

The sharp sand used in this study was locally sourced from New Bussa, Niger State which passed through 4.75mm BS sieve. The fine aggregate conformed to requirement for fine aggregate to be used for concrete production in accordance with BS EN 1008: part 1: (2002).

2.3 Coarse Aggregates (River Gravel)

The natural stone used in this research was locally sourced from New Bussa, Niger State. New Bussa natural stone is characterized with rough surface, reddish-brown in color and consist of maximum size of 19mm. The coarse aggregate conformed to requirement for coarse aggregate to be used for concrete production in accordance with BS EN 1008: part 1: (2002).

2.4 Groundnut Shell Ash

The groundnut shell ash used in this study was sourced locally, from New Bussa, Niger State. The groundnut shell was dry and burnt ensuring control burning to produce ash which passed through BS sieve 0.075mm size. The chemical composition of the groundnut shell ash was conducted using x-ray fluorescence (XRF). XRF is an analytical technique that uses the interaction of x-rays with materials like groundnut shell ash to determine its elemental composition; The oxide composition of groundnut shell ash was conducted in conformity to requirement for natural pozzolana used with Portland cement in concrete production in accordance with ASTM C143/C143M (2020).

2.5 Water

Clean potable water devoid of acid and organic substances from Civil engineering laboratory tap of Federal University of Technology, Minna was used during the study. In accordance with BS EN 1008 (2002).

2.6 Mix Design and Casting of Concrete

The mix design that was used for all concrete cubes cast in this work was COREN Standard for Concrete Mix Design Manuel (2017). Table 1 shows the quantity of materials for each mix batch.

Table 1: Quantity of Materials for each Mix Batch

Mix batch	GSA Content(%)	Water (kg)	Cement (kg)	Sand (kg)	Gravels (kg)	GSA (Kg)
M1	0	13.41	21.28	45.48	90.68	0.00
M2	5	13.41	20.22	45.48	90.68	1.06
M3	10	13.41	19.15	45.48	90.68	2.13
M4	15	13.41	18.09	45.48	90.68	3.19
M5	20	13.41	17.02	45.48	90.68	4.26
Total Sum		67.03	95.76	227.42	453.40	10.64

2.7 Compressive Strength Test

The compressive Strengths of the concrete cubes were determined in accordance with the standard procedure given in ASTM C143/C143M (2020). In accordance with small sample theory in statistical analysis, which deals with small samples sizes, typically less than 30 samples, twenty (20) samples of concrete cubes were tested each for 7, 14, 21 and 28 days after casting at 0, 5, 10,15 and 20% of groundnut shell ash replacement. The average compressive strength for 28days curing at 5% replacement was used for structural designs.

2.8 Cylindrical tilapia concrete incubator

Five cylindrical tilapia concrete incubators were idealized as five concentrated point loads acting at their respective positions on the supporting beam, which forms a major component of the incubator stand as shown in figure 1. Each point load represents the combined weight of the reinforced concrete cylindrical incubator, water, and tilapia eggs. Considering the maximum moment of the beam, the incubator loads were further considered as uniformly distributed load. During the deterministic design, the load was used to calculate the beam's support reactions, bending moments, and required structural capacity. In structural reliability analysis, the same load effects were treated as uncertain variables together with material and geometric properties, allowing the relationship between the beam's structural resistance (R) and applied load effect (S) to be evaluated through a limit-state function, $g(X)=R-S$, using reliability methods such as FORM. Thus, the five incubators provide the discrete loading system, while the beam provides the load-carrying and load-distribution mechanism for assessing both structural safety and reliability.

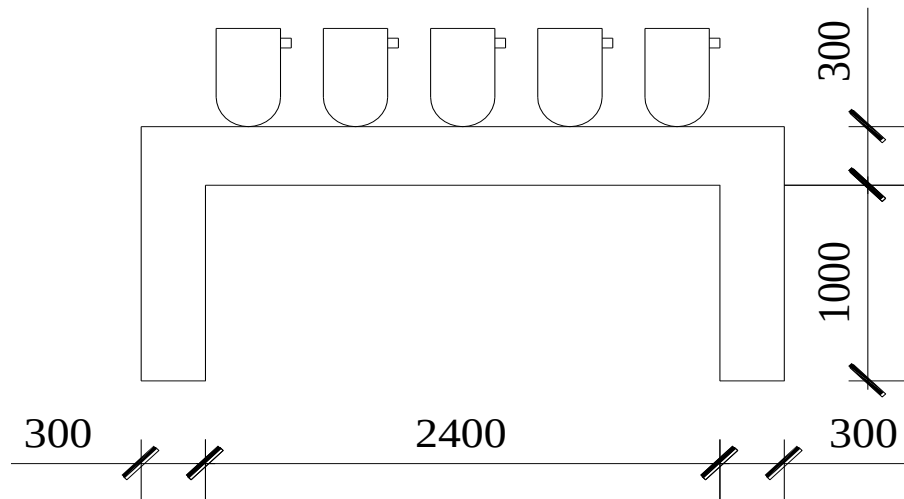


Figure 1: Structural frame (column and beam) carrying five tilapia concrete incubator

2.9 Deterministic Design

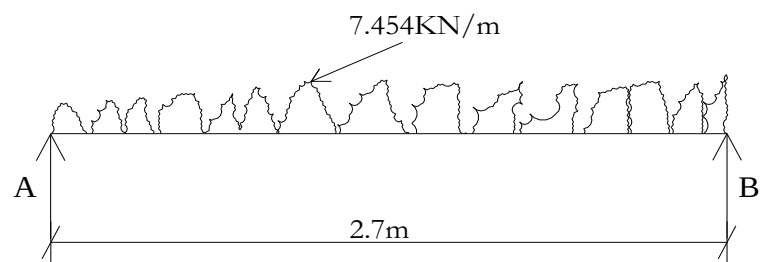


Figure 2: The Cross section of loaded beam to be designed structurally

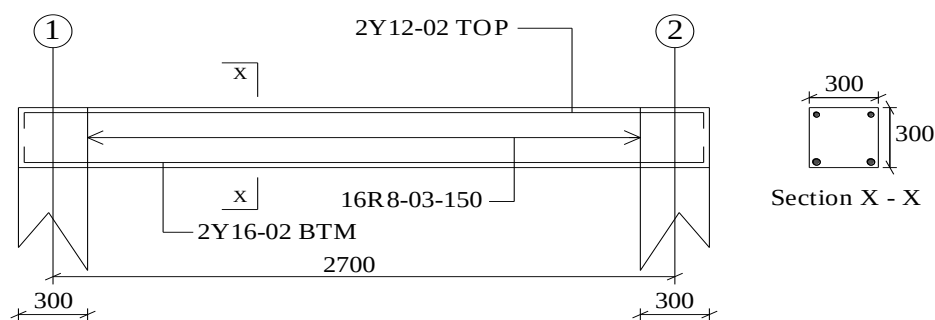


Figure 3: The section of designed beam detail.

2.10 Reliability of the Designed Beam

2.10.1 Estimation of Parameters for Reliability of Beam

The load component of the beam considered was dead load and live load. The live load is the total load of five (5) cylindrical concrete incubators of 15 litres capacity. Load components are treated as random variables, their variation is described by a mean value and a coefficient of variation.

2.10.2 Applied Dead and imposed Load on the beam

Mode of failure by bending.

A beam is subjected to the following failure modes; Bending, Shear, Deflection and Compression failure. For the purpose of this research, Beam failure by bending occurs when the moment capacity is exceeded, causing excessive bending.

From the deterministic design carried out, total live load from the five cylindrical concrete incubators to the beam = 7.454 kN/m

Self-wt of beam = 2.67 kN/m

Hence, Dead load G_K on the beam = 2.67 kN/m

Live load Q_K on the beam = 7.454 kN/m

Design load, $w = 1.4G_K + 1.6Q_K$

Applied moment, $M_S = \frac{wl^2}{8}$; (2.1)

where w = design load and L = span length

$$M_S = \frac{(1.4G_K + 1.6Q_K)L^2}{8}; \quad (2.2)$$

$$\therefore M_S = 0.125l^2(1.4G_K + 1.6Q_K)$$

$$\text{Hence, Applied Moment; } M_S = 0.175l^2G_K + 0.2l^2Q_K \quad (2.3)$$

2.10.3 Structural Resistance Models and equation

Applying force Equilibrium in simply supported reinforced concrete beam above,

According to (Aguwa *et al*, 2015), The Moment resistance of the beam.

$$M_R = \phi A_s F_y \left(d - \frac{\phi A_s F_y}{0.85 F_{cu} 2b} \right); \text{ Where: } \phi = 0.87,$$

$$M_R = 0.87 A_s F_y \left(d - \frac{0.87 A_s F_y}{1.7 F_{cu} b} \right) \quad (2.4)$$

Where; $g(x)$ = Performance function, R = Resistance (material strength) and S = Demand (Applied stress).

Therefore, the limit state equation is

In reliability, the limit state function ($G(X)$) is used to ensure the moment of resistance (M_R) exceeds the applied moment (M_S)

$$G(X) = M_R - M_S \quad (2.5)$$

$$G(X) = 0.87 A_s F_y \left(d - \frac{0.87 A_s F_y}{1.7 F_{cu} b} \right) - 0.175 G_K L^2 - 0.2 Q_K L^2 \quad (2.6)$$

Let, $X_1 = F_y$, $X_2 = F_{cu}$, $X_3 = L$, $X_4 = G_K$, $X_5 = Q_K$, $X_6 = d$, $X_7 = A_s$, $X_8 = b$,

Initial values; $X_1(f_y) = 460 \text{ N/mm}^2$, $X_2(f_{cu}) = 21.38 \text{ N/mm}^2$, $X_3(L) = 2700 \text{ mm}$,
 $X_4(G_K) = 2.67 \text{ kN/m}$, $X_5(Q_K) = 7.454 \text{ kN/m}$, $X_6(d) = 260 \text{ mm}$, $X_7(A_s) = 402 \text{ mm}$, $X_8(b) = 300 \text{ mm}$,

Table 2: Input Variables

Variables	Property	Mean (μ)	C.O.V (%)	STD (σ)	PDF(Distribution)
X1	$f_y(N/mm^2)$	460	0.15	69	Normal
X2	$F_{CU}(N/mm^2)$	21.38	0.0347	0.7428	Normal
X3	L (mm)	2700	0.1	270	Normal
X4	$G_K(KN/m)$	2.67	0.09	0.2403	Normal
X5	$Q_K(KN/m)$	7.454	0.3	2.24	Normal
X6	d (mm)	260	0.05	13	Normal
X7	$A_S(mm^2)$	402	0.07	28.14	Normal
X8	b (mm)	300	0.05	15	Normal
X9	h_b (mm)	300	0.05	15	Normal
X10	$\gamma_c(N/mm^2)$	21.30	0.04	0.852	Normal
X11	$\oslash$ bar (mm)	16	0.04	0.64	Normal

2.10.4 Performance function linearization

$$G_{(X)} = 0.87X_7X_1 \left(X_6 - \frac{0.87X_7X_1}{1.7X_2X_8} \right) - 0.175X_4X_3^2 - 0.2X_5X_3^2 \quad (2.7)$$

Using the equation 2.7, substitute the variables as indicated in Table 2.

$$G_{(X)} = 90932.4X_1 - 239.87X_1^2X_2^{-1} - 1275750X_4 - 1458000X_5 \quad (2.8)$$

The calculation for the reliability analyses was carried out using excel spreadsheet.

$$\mu_G = 90932.4X_1 - 239.87X_1^2X_2^{-1} - 1275750X_4 - 1458000X_5$$

$$\therefore \mu_G = 25181005.46$$

Partial derivatives of equation 2.8

$$\sigma_G^2 = \sigma_{X_4}^2 \left(\frac{\partial G}{\partial X_4} \right)^2 + \sigma_{X_2}^2 \left(\frac{\partial G}{\partial X_2} \right)^2 + \sigma_{X_6}^2 \left(\frac{\partial G}{\partial X_6} \right)^2 + \sigma_{X_7}^2 \left(\frac{\partial G}{\partial X_7} \right)^2 \quad (2.9)$$

$$\sigma_G = 6455164.586$$

$$\beta = \frac{\mu_G}{\sigma_G} = \frac{25181005.46}{6455164.586} = 3.90091$$

$$\therefore \beta = 3.90091$$

2.10.5 Sensitivity Analysis.

The sensitivity analyses carried out were done using Excel spreadsheet. The research considered span of the beam, area of steel, effective depth of beam and live load. Iterations were carried out and they converged after three iterations.

3. RESULTS AND DISCUSSION

3.1 Material Characterization.

The physical characteristics and chemical oxide composition were tested and the results were adequately utilized during testing of the concrete strengths and the deterministic design carried out.

3.1.1 Average Specific Gravity for the Materials used or this Study

The average specific gravity reported in Table 3 are suitable and fall within expected ranges based on established literature and technical standards: Fine aggregate (2.63), coarse aggregate (2.55), and cement (3.15) conform to BS EN 1097-6:(2013) specifications. Groundnut shell ash (2.39), falls within the expected range for many agricultural waste ashes and pozzolans, suggesting it is a lightweight, porous material compared to OPC.

Table 3: Average Specific Gravity of the materials after 3 trials

Material	Bulk Density
Fine Aggregate	2.63
Coarse aggregate	2.55
Groundnut Shell Ash	2.39
Cement	3.15

3.1.2 Average Bulk Density of the materials for Uncompacted and Compacted

The average bulk densities reported in Table 4 are suitable and fall within expected ranges based on established literature and technical standards: Fine aggregate (1503.26 kg/m³) and coarse aggregate (1459.86 kg/m³) conform to BS EN 1097-3 and ASTM C29 specifications. Groundnut shell ash (230.90 kg/m³), though much lower than conventional materials, is consistent with published data on agricultural biomass ashes.

Table 4: Average Bulk Density of the materials for Uncompacted and Compacted

Material	Bulk Density		
	Uncompacted	Compacted	Avg. Density
Fine Aggregate	1445.55	1560.96	1503.26
Coarse aggregate	1376.95	1542.77	1459.86
Groundnut Shell Ash	194.33	267.47	230.90

3.2 Chemical Composition of Groundnut Shell Ash

Table 4 shows the results obtained from Inorganic Geochemical Analysis using X- Ray Fluorescence Spectrophotometry. However, the total of 68.6% for its main oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) is classified as Class C pozzolan according to ASTM C618 which is suitable for partial replacement of cement in structural work.

Table 5: Chemical Composition of Groundnut Shell Ash

Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	P_2O_5	K_2O	MnO	MgO	Na_2O	SO_3	CO_2	LOI
GSA	57.5	9.8	1.3	0.6	4	0.4	1.1	0.15	1.8	0.75	0.4	1.8	4.1

3.3 Compressive Strength

The replacement percentages of GSA used for this study were 0, 5, 10, 15 and 20% by weight of cement. The strength of the five replacement percentage samples was tested. The average compressive strength (21.38N/mm^2) for 28days and 5% replacement was used throughout the design.

3.4 Reliability Analysis.

The results of deterministic design carried out were subjected to reliability tests using First order reliability method (FORM). The Reliability index was obtained using Equation (2.8-2.16), at 2.7m span of the beam; the result was 3.90091 which is an indication of safe for such concrete mixture.

3.4.1 Sensitivity Analysis

Figure 3 presents the result of sensitivity analysis conducted in bending for beam varying the span (L) of the beam. As seen from Figure 3, increasing the span of the beam reduce the safety index with reliability index lower than the 3.0 target reliability (β_T), whereas decrease in the span increases the safety level for the concrete under consideration. The beam is reliable at span of 2.7m with reliability index of 3.90091. Kolo, *et al*, (2021) reported that safety index is very sensitive to the span and depth of the beam, hence they are the critical factors to be put into consideration when designing reinforced concrete beam utilizing the natural stone (gravel) as coarse aggregate.

Increasing the span of beam increases the bending moment experienced which contributes to the bending of beam. The span is indirectly proportional to safety index.

Table 6: Reliability index values against the varying beam span

Beam Span, L (mm)	2.700	3.000	3.300	3.600	3.900	4.200
Reliability Index, β	3.90091	3.11644	2.41611	1.73309	1.09189	0.50662

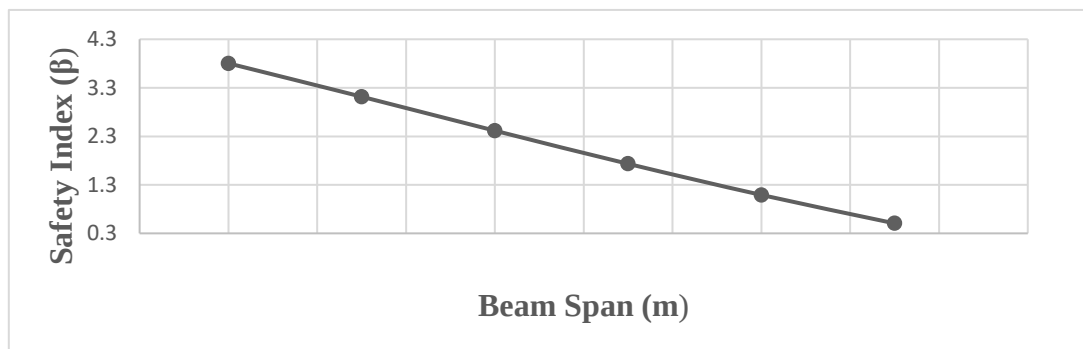


Figure 3: Safety Index-Span Relation for Reinforced Concrete Beam in Bending.

Figure 4 shows the result of sensitivity analysis conducted in bending for beam varying the effective depth of the beam. The Figure indicated an increase in safety index (β) as the effective depth (d) increased from 180mm to 340mm. Safety index was found to be directly proportional to the effective depth for the beam.

Table 7: Reliability index values against the varying effective depth of beam

Effective Depth d (mm)	180.000	220.000	260.000	300.000	340.000	380.000
Reliability Index, β	2.46198	3.24172	3.90123	4.21976	4.53701	4.78533

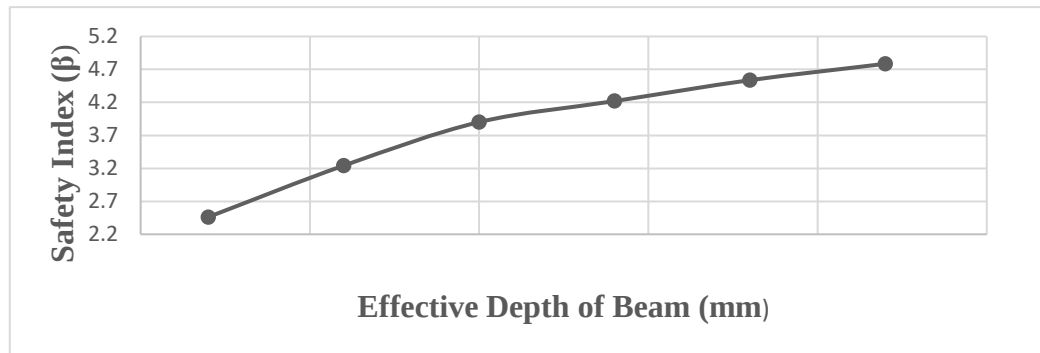


Figure 4: Safety Index-Depth Relation for Reinforced Concrete Beam in Bending

Figure 5 shows the result of sensitivity analysis conducted in bending for beam varying the live load (Q_K) of the beam. The Figure indicated a decrease in safety index (β) as the live load increased from 7.454kN/m to 14.954kN/m. Safety index was found to be indirectly proportional to the live load of the beam.

Table 8: Reliability index values against the varying live load

Live Load, Q_K (KN/m)	7.454	8.954	10.454	11.954	13.454	14.954
Reliability Index, β	3.90123	3.31016	2.84248	2.40799	2.00889	1.64593

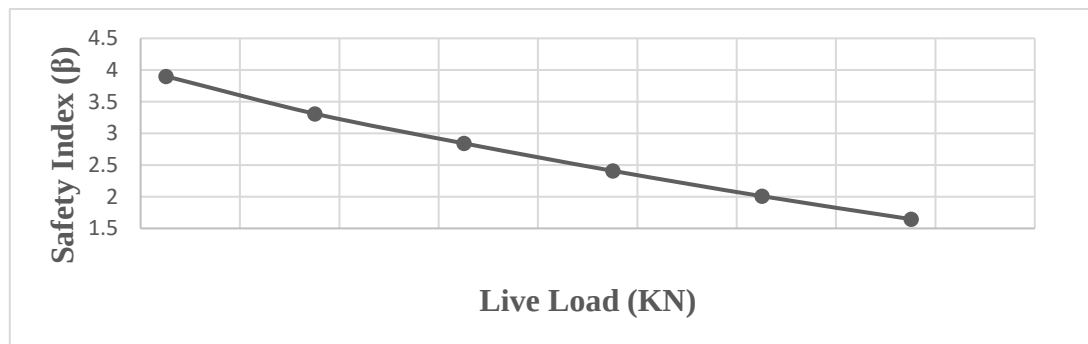


Figure 5: Safety Index-Live Load Relation for Reinforced Concrete Beam in Bending

Figure 6 shows the result of sensitivity analysis conducted in bending for beam varying the area of steel (A_s) for beam. The Figure indicated an increase in safety margin (β) as the area of steel increased from 302mm² to 552mm². Safety index was found to be directly proportional to the area of steel for the beam.

Table 9: Reliability index values against the varying Area of steel

Area of Steel, A_s (mm ²)	302.000	352.000	402.000	452.000	502.000	552.000
Reliability Index, β	2.88573	3.39813	3.90123	4.12919	4.39435	4.6133

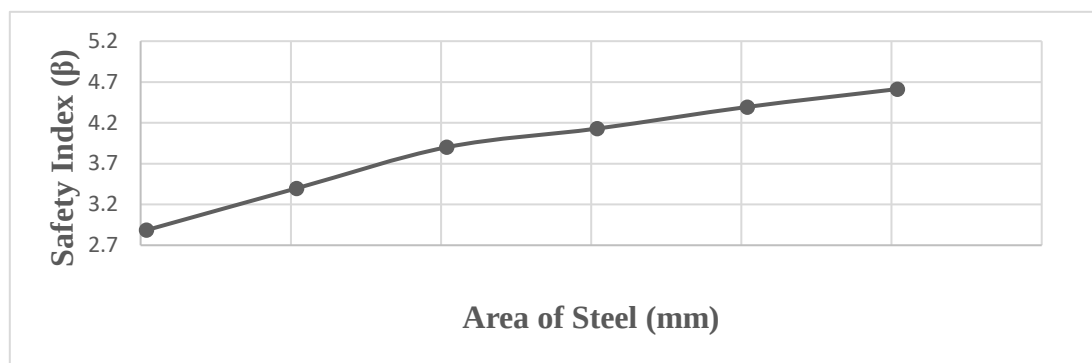


Figure 6: Safety Index-Area of Steel Relation for Reinforced Concrete Beam in Bending

4. CONCLUSION AND RECOMMENDATION

The comprehensive analysis of the Data revealed the following key conclusions, which provide insight into the feasibility of using groundnut shell ash as a partial replacement for cement in structural concrete applications:

- (i) The specific gravities of river natural stones, river sand and groundnut shell ash were found to be within the required range. The results obtained from oxide composition shows that the percentage of various chemical oxide compositions of GSA was within the ranges obtainable for the cement.
- (ii) The optimum result obtained at 5% replacement GSA was used throughout the structural design.
- (iii) From the structural design carried out on tilapia incubator support beam using the average result of compressive strength at 5% replacement showed very impressive results with little increase in reinforcement.
- (iv) Safety index was found to be directly proportional to the effective depth and area of steel but inversely proportional to the span and live load of the reinforced concrete beam during Sensitivity Analysis.

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