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Research Article

Probabilistic Flexural Reliability of Reinforced Concrete Beams with Palm Kernel Shell as a Partial Coarse Aggregate Replacement

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About Article

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ABSTRACT

This study uses the probabilistic approach to analyze concrete beams made by replacing the coarse aggregate present in the concrete matrix with palm kernel shell at different percentages (0%, 5%, 10%, 15%, 20%, and 25%). A total of 78 concrete cubes were cast. A mix ratio of 1:2:4 was used to obtain the compressive strengths at 7, 14, 21, and 28 days of curing, respectively. At 28 days of curing, the control (0%) had the highest compressive strength of 11.21 N/mm^2. The compressive strength obtained for the control was not up to standard due to the silt content of the fine aggregate (8.7%) exceeding the recommended limit (8%). Reliability analysis was conducted on the concrete beam using the First-order reliability method on CalREL. The compressive strength results were utilized. The analysis revealed that an increase in the input parameters, such as span, dead load, and live load, led to a decrease in the reliability indices of the beam. However, an increase in the depth of the beam led to an increase in the reliability indices. Although the 5% PKS beam demonstrated comparatively higher reliability than the mixes with greater replacement levels under the study's conditions, its performance is evaluated relative to a low-quality control mix. The results have therefore shown that low-level replacement of PKS (5%) could provide acceptable reliability in terms of lightweight construction within the limitations of the tested materials, but further validation with the standard-quality control concrete is required.

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1. INTRODUCTION

Nigeria is a developing country, and like every developed country, continuous development is required for growth, and at the forefront of such development is infrastructure. Construction typically involves the use of large amounts of concrete. Kolo *et al.* (2020) identified a few factors, such as reduced cost, durability, availability, and ability to withstand extreme weather conditions as the reasons for the famous and common use of concrete in the world for construction purposes. The concrete itself is a mixture of a few other materials like cement, fine aggregate, coarse aggregate, water, and other materials (admixtures) (Ogunwemimo *et al.*, 2019). According to Danso and Appiah-Agyei (2021), concrete production has become a major source of concern as a result of the relentless depletion of the raw materials needed for its production. Odeyemi *et al.* (2019) identified how important concrete is in the construction industry. Significant growth in infrastructure usually hallmarks development in an environment. The increased production of infrastructure globally causes a corresponding increase in natural aggregate utilization, as aggregate makes up about 75% of the total concrete volume.

The overall cost of concrete production is greatly affected by its constituents. Therefore, the key to managing the rising costs of construction and combating environmental stresses for sustainable construction is in the use of alternative construction materials. This has necessitated research into replacement materials, especially the locally available ones, to determine their ability to replace the conventional, standard materials used in the production of concrete (Ogunwemimo *et al.*, 2019). The subject of partial replacement in the construction industry has been revisited multiple times as research develops due to the need to reduce the overall weight of a structure, reduce the total cost implications, reduce the carbon content being released into the environment (carbon footprint), minimize the rate of depletion of natural resources, etc.

This study evaluates the viability of utilizing Palm Kernel Shell (PKS) as a substitute for aggregates in lightweight concrete. The introduction of PKS for use in a structural member needs to be well assessed in order to properly identify the risks of adopting it as a suitable replacement material. A lot of previous PKS research has been based on deterministic strength-based comparisons, which do not fully capture the variability and uncertainty of material properties, loading conditions, and structural behavior. Also, very limited work has been done in assessing PKS concrete using probabilistic methods, and, so far, no study has used a First-Order Reliability Method (FORM) to evaluate the safety performance of PKS concrete structural elements such as beams. This gap is significant because incorporating probability concepts provides a more realistic framework for assessing structural safety (Alabi *et al.*, 2020), especially when introducing unconventional aggregates into critical load-bearing members.

This research addresses this gap by uniquely using a FORM reliability model to PKS concrete beams, going beyond deterministic strength evaluation to quantify how changes in the material strength, span, loads, beam width, and beam depth affect structural reliability. In this way the research would give a more serious evaluation of the risk of using PKS in place of coarse aggregate in lightweight structural applications to a certain degree.

2. LITERATURE REVIEW

Palm oil has, over the years, proven to be a significant agricultural commodity in Nigeria. It has made a notable contribution to the country's economy while serving as a crucial source of income for many rural communities. Nigeria ranks among the world's largest producers of palm oil, boasting a long history of both cultivation and processing. Biodun *et al.* (2021) revealed an estimation of 1.34×10^6 metric tonnes of palm oil was consumed in the year 2018. He stated that before the discovery of crude oil, Nigeria was one of the major exporters of palm oil. This statistic shows us just how invested Nigerians are in Palm Oil. According to Samuel (2020), Nigeria produces approximately 1.5 million tons of Palm Kernel Shell (PKS) annually. He pointed out that most of the PKS are disposed of as waste products of the extraction process. He also described the shells as flaky, parabolic, and angular, amongst other properties. The sizes of PKS may differ from one another depending on how the palm nut is cracked and handled. The sizes of the shells are generally in the range of 2 – 15 mm thick, and the PKS varies from 1.5 to 3 mm. The applicability of PKS and palm fibers in the development of lightweight and environmentally friendly concrete mixes that have enhanced sustainability performance is further supported by experimental results (Seng *et al.*, 2024).

Structural reliability is the capability of a structural system to support a given load level without failing. It is a measure of the probability of survival of the system under the specified loading conditions. When a system lacks reliability, it means that there is a certain probability that it may fail under the specified loading conditions. This indicates that there is a possibility that the system will not be able to perform its intended function, and may cause collapse and cause damage, and harm. Therefore, ensuring structural reliability is essential for safety and efficiency in construction (Adewumi *et al.*, 2017). According to Kolo *et al.* (2020), the reliability of a structural element can be assessed using the First-Order Reliability Method (FORM). FORM has been described as a simplified model that gives the reliability index as the result. It utilizes the mean and standard deviation values for load and resistance in a specific limit state. For assessing the reliability of a reinforced concrete beam subjected to bending forces, essential input parameters, including effective beam depth and beam width, are utilized. Various methods, such as the First Order Reliability Method (FORM), Second Order Reliability Method (SORM), and Monte Carlo Simulation (MCS). Akingbonmire (2022), can be used in assessing structural reliability. Parameters such as length, depth, dead load, and live load of the beam can be altered based on requirements to give a safe value. Similar probabilistic analyses have been conducted using BS 8110 provisions to confirm the safety of reinforced concrete beam bending and shear (Bamidele *et al.*, 2025).

CalREL is a software program designed for structural reliability analysis and was used in this study. The evaluation is done using FORM, and a connection between MATLAB and CalREL is established using a custom program written by the author. The analysis is performed for various values of the coefficient of variation, determining the required mean concrete strength for each specified value. The author's written program changes the input file for CalREL and runs the program. The results of the reliability analysis are displayed in the output file in each iteration of the MATLAB root-solving process (Nader, 2017).

2.1. Previous studies on PKS in structural and non-structural concrete applications

Several researchers have examined the application of Palm Kernel Shell (PKS) in concrete and have in many reported a lower compressive strength than conventional aggregate concrete.

Olusola and Babafemi (2021) examined the impact of coarse aggregate size and PKS replacement level on compressive and splitting tensile strengths. They discovered that these two strengths decline as the natural aggregate is further replaced by PKS. They recorded a maximum PKS replacement of 25%, at which the compressive strength was approximately 22.97 N/mm². However, at 50% PKS, the strength decreased to 18.13 N/mm².

Ogunjiofor *et al.* (2021) tested the structural behavior (compressive strength and slump) of concrete containing 0%, 10%, 20%, and 30% PKS. Their findings indicated that 10% PKS replacement did not substantially decrease strength, which points out that it can be used in some structural applications.

Sahputra *et al.* (2023) tested concrete containing 0%, 25%, and 60% of PKS replacement and showed a definite decline in compressive strength with increasing levels of PKS content.

Boateng *et al.* (2023) examined the use of concrete with both PKS and waste tyre chips. They discovered that workability, density, and strength all decrease with an increase in PKS and tyre content. Nevertheless, a total aggregate replacement (aggregate of tyre and PKS) of up to 50% provided structurally adequate strength.

Odeyemi *et al.* (2017) (in self-compacting concrete) have examined flexural and bond strength in concrete in which a 50% ratio of coarse aggregate had been substituted with PKS. They established lower bond strength and satisfactory flexural behavior, which indicated some possibility of being used in lightly loaded structural elements or non-critical members.

Purwanti *et al.* (2018) examined high-performance lightweight concrete with PKS and fly ash and with superplasticizer; they obtained densities of about 1,700-1,800 kg/m³. They achieved 17-22 Mpa compressive strength with optimum mix (e.g., 10% fly ash, 1 per cent SP).

3. METHODOLOGY

This research work involved casting concrete samples and conducting various tests on them to accurately ascertain their compressive strengths. The concrete constituents were also adequately tested. The compressive strength obtained was used as a parameter for the reliability analysis of the beam.

3.1. Cement

The cement utilized in this research was Dangote Portland Limestone Cement specified with grade 42.5R, and it was obtained from a local depot around the school environment at The Federal University of Technology, Akure. To mitigate the effect of negative external factors on the cement, the bags were stored on a raised platform.

3.2. Fine aggregate

The fine aggregate was sourced locally. The sand was free of dirt. It was obtained within the university environment. The code BS 882 (1992) was followed.

3.3. Coarse aggregate

It was also sourced locally from Zibo quarry, along Ijare road, Akure, Ondo State. BS 882 (1992) was followed.

3.4. Water

Water, when added, forms a mixture that binds all of the particles together. It is that component that initiates the entire chemical reaction. Both the mixing and curing water were obtained from the well near the Geotechnical Laboratory at the Federal University of Technology, Akure.

3.5. Palm kernel shell

The shell acted as a substitute for the coarse aggregate and was added at percentage intervals to get the relative percentage for replacement. The shells were obtained from local vendors within Akure township.

3.6. Tests

The mix ratio adopted for the project was 1:2:4 with a water-cement ratio of 0.6. The concrete cube mold dimensions were 150 mm × 150 mm × 150 mm. A total of 78 concrete cubes were cast for the experiment. For each specified percentage of the coarse aggregate replaced with palm kernel shell (0%, 5%, 10%, 15%, 20%, 25%), three concrete cubes were tested for their compressive strength at 7 days, 14 days, 21 days, and 28 days post-casting. In addition, one separate concrete cube was used to test for water absorption for each percentage, bringing the total number of cubes cast to 13. The 0% percentage replacement represents the control specimen.

All materials (sand, granite, palm kernel shell, cement) involved were tested on the needed parameters to guarantee their correlations with the standards. Some of the tests conducted on the materials included bulk density, specific gravity, particle size distribution, aggregate impact value, aggregate crushing value test, etc., while the tests conducted on concrete included compressive strength test, compacting factor, and slump test.

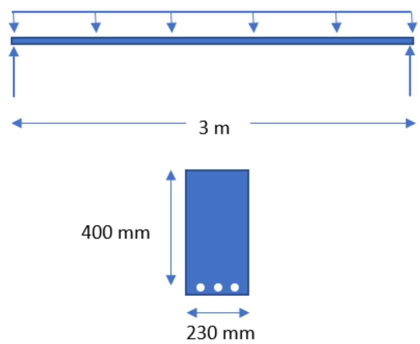

Figure 1. Model beam and its dimensions

3.7. Limit state function

Equation 1 represents the beam limit state function (G).

$$G = R - S \quad ....(1)$$

Where,

R symbolizes Resistance and S symbolizes the Load Effect.

The value of the maximum bending moment (Mmax) of a simply supported beam at the mid-span can be obtained using equation 2.

$$M_{max} = wl^2/8 \quad ....(2)$$

Where w is the load intensity and L is the span of the beam. The design of the beam must ensure that the maximum bending moment caused by the applied loads does not surpass the ultimate moment of resistance, i.e. $M_{max} \leq MR$, where M_R represents the ultimate moment of resistance. The formula is given in equations 3 and 4.

$$k = \frac{M_R}{f_{cu}\, bd^2} \quad ....(3)$$

Therefore,

$$M_R = kf_{cu}bd^2 \quad ....(4)$$

The limit state function is obtained by bringing together the load and the resistance equations into equation 5, where k = 0.156.

$$g_1(x) = 0.156f_{cu}bd^2 - \frac{WL^2}{8} \quad ....(5)$$

Where,

b is the width of the beam, d is the effective depth, w is the beam load intensity, and L is the beam span. fcu is the concrete characteristic strength, and L is the beam span.

But,

$$w = 1.4g_k + 1.6q_k \quad ....(6)$$

Where g_k is the dead load of the beam, and q_k is the imposed load on the beam. Inserting equation (6) into equation (5), the limit state function is as given in equation (7).

$$g_1(x) = 0.156f_{cu}bd^2 - (0.175g_k + 0.2q_k)L^2 \quad ....(7)$$

The linearized version gives equation 8, where fcu is X(1), b is X(2), d is X(3), gk is X(4), qk is X(5), and L is X(6).

$$g_1(x) = (0.156X_1X_2X_3^2) - (0.175X_4 + 0.2X_5)X_6^2 \quad ....(8)$$

Table 1 shows the input parameters, their notation, distribution type, and values of the mean and standard deviation. These parameters are utilized to perform the reliability analysis for the model beam using CalRel.

Table 1. Input parameters for reliability analysis

Input Parameters	Notation	Mean	Standard Variation	Distribution Type	COV
Compressive Strength, fcu in (N/mm^2)	X_1	12	3.6	Log-Normal	0.3
Beam Width, b in (mm)	X_2	230	23	Normal	0.1
Effective Beam Depth, d in (mm)	X_3	400	40	Normal	0.1
Dead Load, gk in (kN/m^2)	X_4	15	4.5	Log-Normal	0.3
Live Load, qk in (kN/m^2)	X_5	3	0.9	Log-Normal	0.3
Span of Beam, L in (m)	X_6	3000	300	Normal	0.1

3.8. Justification for the choice of input parameters and coefficient of variation (COV)

Compressive Strength:

- Compressive strength is very important to concrete performance. Variability in strength (due to PKS substitution, mixing, curing, and compaction) affects structural reliability, making it essential for probabilistic analysis.
- COV: Concrete strength is always positive and can vary due to material quality, mixing, and curing. This variability is captured in the Log-Normal. Hence, the COV used is 0.3.

Beam Width:

- The width determines the cross-sectional area resisting bending.
- COV: Beam width can vary slightly due to formwork and finishing tolerances. These deviations are symmetric around the mean (as likely to be slightly smaller or even larger). COV = 0.10 is that of normal construction variability.

Beam Depth:

- Depth affects the lever arm of the internal stresses, affecting the bending moment capacity.
- COV: Formwork, finishing, and placing of concrete result in minor deviations. The variations are symmetrical, and so, the Normal distribution is appropriate. COV = 0.10 shows small, practical construction tolerances.

Dead Load:

- Dead load refers to the permanent weight of the structure, including slabs, beams, and finishes.
- COV: Variability is due to a difference in the density of materials, finish, and slight variations in the construction. The Log-Normal distribution takes into consideration skewness in variability, which permits sometimes heavy-than-normal situations. COV = 0.30 represents moderate variability.

Live Load:

- Live load represents occupancy or service loads, which vary by use.
- COV: Certain areas can be overloaded and some underloaded (skewed distribution). This positive skewness is captured by the Log-Normal distribution. COV = 0.30 is realistic for moderate uncertainty in occupancy load.

Span of Beam:

- Span has a direct effect on the bending moments and shear forces in the beam.
- COV: Beam span can be slightly changed because of as-built variations in construction. The variations around the design span are symmetric; thus, Normal distribution is suitable. COV = 0.10 represents a small, practical construction tolerance.

4. RESULTS AND DISCUSSION

A series of tests was conducted to evaluate the properties of the materials utilized in the production of concrete. Further tests were performed on the hardened concrete, including the compressive strength test. The result of the reliability analysis was obtained as the reliability index using CalRELiability.

4.1. Fine aggregate

The results of the moisture content, bulk density, and specific gravity were obtained and were all within the standard required of them, as seen in Table 2. The silt content, however, was higher than the 8% regulation. Figure 2 reveals a very high silt/clay content present in the fine aggregate. This had a negative impact on the overall strength of the concrete.

Table 2. Fine aggregate test

Moisture Content	3.91%
Bulk Density	1.54 g/cm^3
Specific Gravity	2.65
Silt Content	8.70%

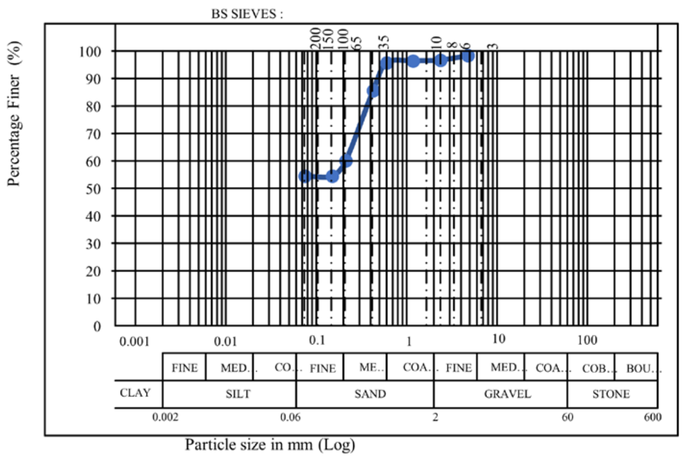

Figure 2. Particle size distribution for fine aggregate

4.2. Coarse aggregate

The values obtained for the bulk density, specific gravity, water absorption, aggregate impact value, and aggregate crushing value were all okay according to their respective standards. Table 3 is a summary of all the values obtained.

Table 3. Coarse aggregate test

Bulk Density	1.47 g/cm^3
Specific Gravity	2.55
Water Absorption	0.45%
Aggregate Impact Value	11.05%
Aggregate Crushing Value	25.29%

4.3. Palm kernel shell (PKS)

Since the PKS was intended as a substitute for coarse aggregate, its properties as obtained by the test in Table 4 were compared with the coarse aggregate. The notable differences include a lower value for the bulk density and specific gravity. PKS absorbs more water, although it records very good strength for the Impact and Crushing Value tests.

Table 4. Palm kernel shell test

Bulk Density	0.51 g/cm^3
Specific Gravity	1.22
Water Absorption	11.68%
Aggregate Impact Value	6.35%
Aggregate Crushing Value	4.33%

4.4. Water

Water, when added, forms a mixture that binds all of the particles together. It is that component that initiates the entire chemical reaction. Both the mixing and curing water were obtained from the well near the Geotechnical Laboratory at the Federal University of Technology, Akure. BS EN 1008: 2002 was used as the standard.

4.5. Compacting factor and slump test

Table 5 outlines the results of the slump test and compaction factor. The average value of the compacting factor falls within the range of 0.9 to 0.96, which gives a medium to high workability rating.

Table 5. Compacting factor and slump

% Replaced	Slump in (mm)	Compaction Factor
0%	60	0.9545
5%	70	0.9294
10%	40	0.9551
15%	50	0.9205
20%	70	0.9318
25%	40	0.9080

4.6. Compressive strength and density

Figure 3 displays the plot of the compressive strength against the percentage replacement of coarse aggregate (0%, 5%, 10%, 20%, and 25%) with the curing days (7, 14, 21, and 28 days). The compressive strength reduces as the curing days and the percentage replacement increases. The control, which is at 0% replacement of PKS, gave the highest value of the compressive strength. The silt/clay content of the sand obtained within the institution greatly affected the strength of the concrete.

A progressive reduction in the strength of the concrete (Figure 4) as the percentage replacement was increased was observed.

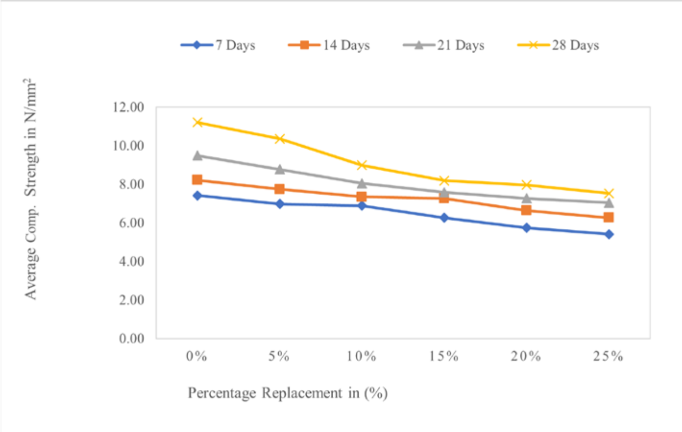

Figure 3. Compressive strength

This led to the production of lighter-weight concrete with palm kernel shells when compared with normal concrete with granite.

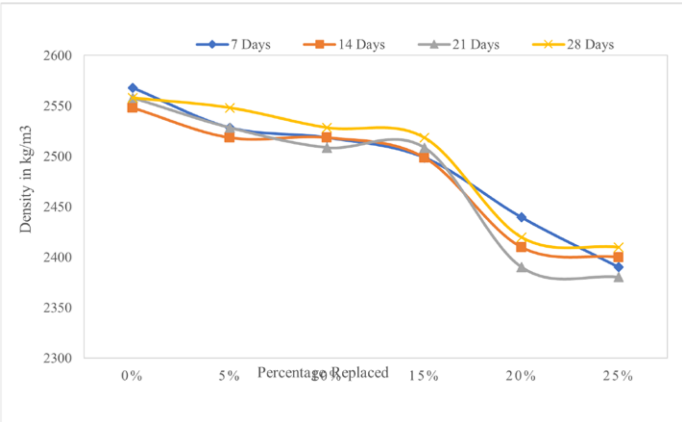

Figure 4. Density against the different percentages

4.7. Reliability analysis

The analysis was performed using the First Order Reliability Method encoded in CalREL. All the necessary input parameters were provided appropriately, and the results were obtained as the reliability indices. With a beam depth of 230 mm, dead and live loads at 15 kN/m² and 3 kN/m² respectively at a span of 3000 mm (Figure 5), the depth was varied at 450, 500, 550, and 600mm. The reliability indices increase as the depth of the beam increases, with 5% replacement performing better than other replacements apart from the control. However, if the dead load increases as shown in Figure 6, the reliability indices reduce drastically, with 25% replacement performing worse. This shows that structures should be designed with great care with respect to dead loads. Moreover, the live loading of the selected beam was varied while keeping other parameters constant; it was observed that there was a decrease in the reliability indices as the live load increased (Figure 7). This follows the same trend as in the case of a proportional increase in the dead load.

Finally, an increase in the beam span also caused a decrease in the reliability indices (Figure 8). With this value of live load and dead load, the beam will fail at 5 m.

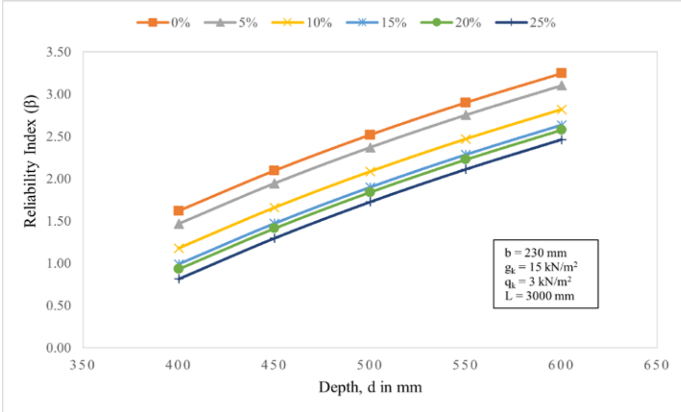

Figure 5. Reliability index against the depth for the different replacement percentages

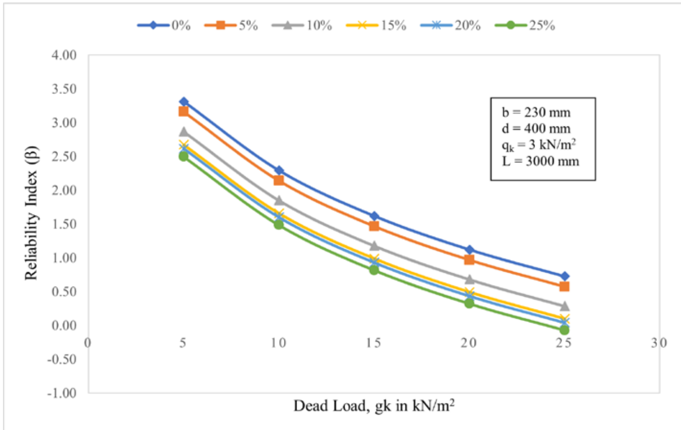

Figure 6. Reliability index against dead load for different replacement percentages

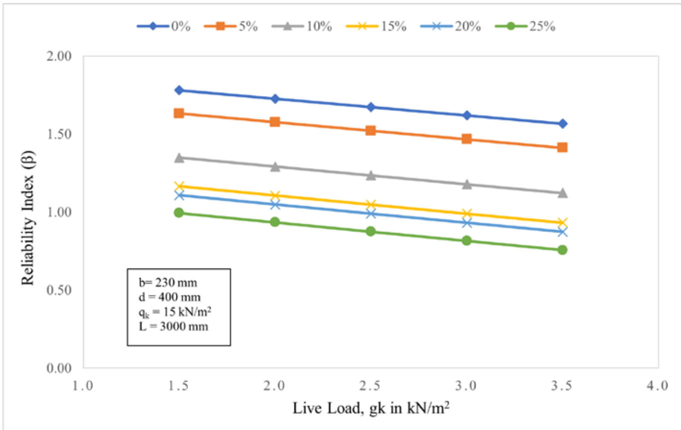

Figure 7. Reliability index against live load for different replacement percentages

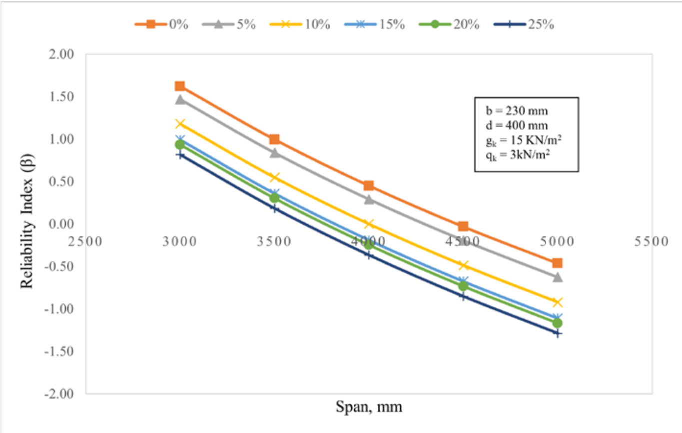

Figure 8. Reliability index against span for different replacement percentage

5. CONCLUSION

The reliability analysis of a concrete beam made by replacing the coarse aggregate present in the concrete matrix with palm kernel shell at different percentages (0%, 5%, 10%, 15%, 20%, and 25%) has been undertaken.

From the study, it can be deduced that concrete made with palm kernel shell has a lower density than conventional concrete made with conventional granite and therefore can fulfill the requirement as a lightweight aggregate in lightweight concrete. It was also observed that the control strength (at 0% replacement) was higher than the strength of all the percentages of the partially replaced concrete, showing that the conventional concrete is still stronger in comparison to concrete with PKS.

The reliability analysis showed that an increase in the value of input parameters, such as span, dead load, and live load, caused a continuous decrease in the reliability index of the concrete beam. Also, an increase in the value of the depth of the beam caused a continuous increase in the reliability index of the concrete beam as opposed to the other parameters.

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