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Ultimate Load and Workability Optimisation of Coconut-Shell Plain-Concrete Beams Incorporating Sikament-NN

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ABSTRACT

Agricultural coconut-shell waste offers a renewable alternative to mineral aggregate, but its porous surface may reduce concrete workability and mechanical performance. This study evaluates whether Sikament-NN can compensate for these effects in plain-concrete beams. Twenty-one specimens measuring 600 x 150 x 150 mm were produced in seven mixtures: a normal-concrete control, three mixtures containing 1.5%, 1.7% and 1.9% coconut-shell fragments as partial coarse-aggregate replacement, and three corresponding mixtures incorporating 2.3% Sikament-NN by cement mass. Slump, 28-day compressive strength and ultimate beam load under central loading were assessed. Increasing coconut-shell content without admixture reduced slump from 100 to 75 mm and decreased mean ultimate beam load from 37.00 to 35.37 kN. Sikament-NN restored slump to 100-110 mm and maintained mean ultimate beam load between 36.50 and 36.87 kN. The mixture containing 1.9% coconut shell and Sikament-NN achieved 29.73 MPa compressive strength and a 36.80 kN ultimate beam load, retaining 98.78% and 99.46% of the control values, respectively. Because the archived test record did not preserve sufficient crack-pattern evidence to distinguish diagonal-shear failure from mid-span flexural-tensile failure, the response is reported as ultimate beam load rather than shear capacity. The findings indicate that Sikament-NN effectively offsets the workability loss and most of the mechanical-performance reduction associated with low-volume coconut-shell incorporation.

1. Introduction

Concrete remains the principal material for buildings and infrastructure because it can be cast into complex forms, is widely available and provides high compressive resistance. Its large material demand, however, creates continuous pressure on natural aggregate resources and increases the amount of agricultural and industrial waste requiring disposal. Recent research therefore focuses on replacing a limited proportion of conventional constituents with renewable or recycled materials while retaining the performance needed for structural applications [1]-[4], [9], [12], [16], [21]. Coconut shell is particularly relevant in tropical countries because it is hard, lightweight and available as a by-product of food and agricultural processing.



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Coconut-shell particles differ substantially from crushed stone. Their lower density and more porous surface can reduce concrete density, but they can also increase water demand, reduce slump and weaken the interfacial transition zone when the replacement level is excessive. Experimental and review studies published from 2021 to 2025 generally report that low or moderate coconut-shell contents can be used successfully, whereas high replacement levels tend to reduce compressive strength and stiffness [1], [2], [5], [6], [23], [24]. Performance is strongly influenced by particle grading, pre-soaking, surface treatment, water-cement ratio and the use of mineral or chemical admixtures [2], [7], [13], [14], [18].

The structural behaviour of concrete containing plant-based aggregates cannot be assessed solely through cube or cylinder compression because tensile, flexural and post-cracking responses may be affected differently. Studies of coconut-shell lightweight concrete, beam specimens and coconut-fibre systems report changes in mechanical response, cracking and post-cracking behaviour [6], [8], [10], [11], [15], [17], [19]. For plain unreinforced beams, the measured peak load under a particular loading geometry reflects matrix tensile capacity, aggregate interlock, paste-aggregate bond quality and the combined moment-shear distribution. The observed crack pattern therefore needs to be identified before the response is described as shear-controlled.

Chemical admixtures provide one route for maintaining performance. Superplasticisers disperse cement particles and permit the required consistency at a lower effective water demand. This function is valuable in mixtures containing porous bio-aggregates, which otherwise absorb part of the mixing water and reduce workability. Recent investigations show that particle treatment, mixture optimisation and suitable admixture strategies can improve fresh-state behaviour and support strength development in coconut-shell and other waste-modified concretes [7], [13], [18], [23], [24]. The Civilla literature also shows that the timing of chemical-additive application can materially affect concrete setting and compressive strength [22]. This material-level mechanism is also reflected in Zulkarnain et al. [27], who tested the same 1.5-1.9% coconut-shell range with 2.3% Sikament-NN and reported that the admixture recovered compressive strength whilst improving fresh-concrete workability. This evidence supports evaluating the shell-admixture combination as an integrated system rather than treating shell replacement in isolation.

Recent studies by independent research groups have expanded the evidence base for coconut-shell concrete through surface treatment, particle substitution, self-compacting mixtures, hybrid coconut-fibre/coir systems and broader biological-shell aggregates [7], [18]-[24]. Collectively, these studies show that workability and mechanical response depend on replacement level, particle condition, grading and matrix modification, and that structural behaviour cannot be inferred from compressive strength alone [6], [8], [10]. A related study by Zulkarnain et al. [26] examined the split-tensile response of coconut-shell concrete incorporating Sikament-NN, but it did not address the peak-load response of plain beams under central loading. This leaves a specific gap concerning whether low-volume shell replacement and Sikament-NN can preserve both fresh-state properties and the ultimate load of small plain-concrete beams. More recently, Zulkarnain et al. [28] showed that combining Mount Sinabung volcanic ash with silica fume improved compressive performance relative to volcanic-ash-only mixtures, further illustrating how a compensating modifier can offset part of the mechanical penalty associated with waste substitution. However, neither that binder-level study nor the coconut-shell strength studies resolved the specimen-level peak-load behaviour addressed here.

The experimental data considered in this study were obtained from plain-concrete beams incorporating small quantities of coconut-shell fragments, with and without Sikament-NN. The laboratory dataset recorded slump, compressive strength and peak beam load, but it did not include a systematic crack-classification record. Accordingly, this paper analyses mixture-level averages, variability measures and performance-retention indices. The objectives are to determine the influence of 1.5-1.9% coconut-shell replacement on workability and ultimate beam load, quantify the recovery provided by 2.3% Sikament-NN, and identify a technically balanced mixture for further verification. Because the beams were centrally loaded and the archived failure-pattern evidence is incomplete, the measured peak load is not interpreted as a pure shear capacity.

2. Research Methods

2.1 Experimental design

An experimental comparative design was used. The reference concrete was proportioned for a nominal compressive strength of approximately 30 MPa. The materials comprised Portland cement, natural fine aggregate, natural coarse aggregate, clean mixing water, crushed coconut-shell fragments

and Sikament-NN. The base batch quantities were kept constant, while coconut shell replaced a small fraction of the coarse aggregate by mass. Sikament-NN was incorporated at 2.3% of the cement mass in the admixture series.

Seven mixtures were prepared. BN was the normal-concrete control. BTK mixtures contained 1.5%, 1.7% or 1.9% coconut-shell fragments without chemical admixture. BTKN mixtures used the same coconut-shell contents and included Sikament-NN. Three nominally identical beams were cast for each mixture, producing 21 specimens in total. This replication level represents the statistical minimum for a descriptive comparison and limits the precision of the estimated variability. With $n = 3$ per mixture, an individual observation can materially influence the mean and sample standard deviation; therefore, the analysis is restricted to descriptive comparisons, effect magnitudes and consistency checks. No inferential hypothesis testing, population-level generalisation or structural design value is derived from this sample. The small replacement interval was selected to identify a threshold at which waste utilisation could be increased without a pronounced reduction in measured performance.

Table 1. Experimental mixture matrix and specimen allocation

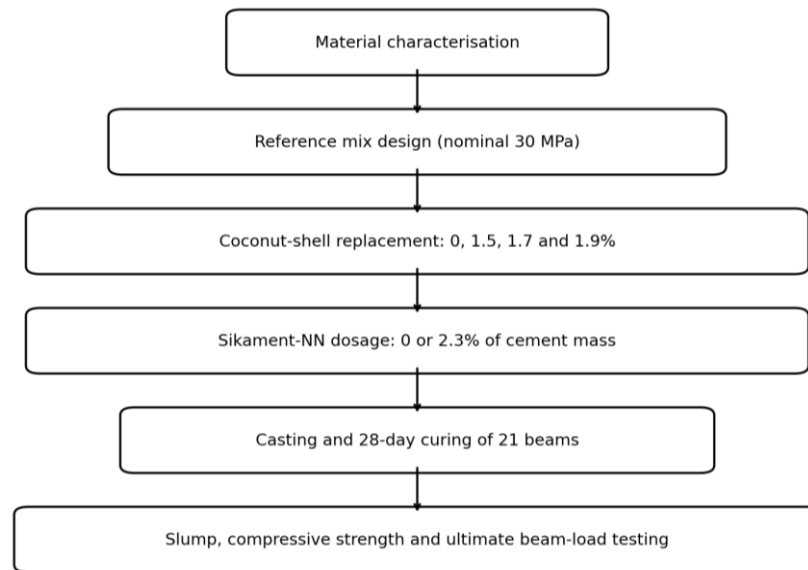
Mixture	Natural coarse aggregate (%)	Coconut shell (%)	Fine aggregate (%)	Sikament-NN (% cement)	Beams
BN	100.0	0.0	100	0.0	3
BTK 1.5%	98.5	1.5	100	0.0	3
BTK 1.7%	98.3	1.7	100	0.0	3
BTK 1.9%	98.1	1.9	100	0.0	3
BTKN 1.5%	98.5	1.5	100	2.3	3
BTKN 1.7%	98.3	1.7	100	2.3	3
BTKN 1.9%	98.1	1.9	100	2.3	3

Source: Authors' experimental programme (2025).

2.2 Specimen preparation and testing

The concrete constituents were mixed until a visually uniform mixture was obtained. Coconut-shell fragments were introduced with the coarse aggregate, while Sikament-NN was added through the mixing water in the relevant batches. Fresh consistency was evaluated using the slump test. The beam specimens measured 600 x 150 x 150 mm and were cast without longitudinal or transverse reinforcement. After demoulding, the specimens were cured until 28 days.

At the testing age, each beam was placed on a rigid loading frame and loaded hydraulically with a single load applied at the beam centre. Loading was increased progressively until failure, and the peak machine load was recorded as the ultimate beam load. Centre-point loading of a simply supported plain-concrete beam has historically been used as a flexural-strength configuration; the former ASTM C293/C293M-16 specifically described flexural testing using simple-beam centre-point loading [25]. The archived laboratory record available for the present analysis does not document the effective support spacing or shear-span-to-depth ratio and does not contain systematic crack maps or post-failure photographs sufficient to classify the dominant failure as diagonal/shear cracking or mid-span flexural-tensile cracking. Consequently, no claim of pure shear failure is made, and the term “ultimate beam load under central loading” is used throughout. Companion compressive-strength values were used to interpret the influence of matrix strength on the measured beam response. Figure 1 summarises the experimental programme, while Figure 2 shows the laboratory loading arrangement.



Source: Authors' analysis (2025)

Figure 1. Experimental Programme and Assessment Sequence



Source: Authors' laboratory documentation (2025)

Figure 2. Hydraulic Centre-point Loading Arrangement for The Plain-concrete Beam Test

2.3 Data analysis

For each mixture, the mean and sample standard deviation of compressive strength and ultimate beam load were calculated from three specimens. Performance retention was expressed as the ratio of the mixture mean to the control mean, and the benefit of Sikament-NN at each coconut-shell level was evaluated by comparing the corresponding BTKN and BTK mixtures. Because only three specimens were available per mixture, the analysis emphasises descriptive effect sizes and within-group consistency rather than inferential claims; the reported standard deviations should therefore be interpreted as preliminary estimates of variability.

3. Technical Assessment Framework

The technical assessment considered three linked responses. First, workability indicates whether the mixture can be placed and compacted consistently. Coconut-shell particles are more absorptive and irregular than conventional stone aggregate; therefore, higher shell content is expected to reduce free

water and slump. Second, compressive strength represents the quality of the hardened cementitious matrix and its bond with the aggregate. Third, ultimate beam load under central loading is an integrated specimen-level response governed by geometry, matrix tensile resistance, aggregate interlock, bond integrity and crack development. For the present plain beams, this response cannot be assigned to shear alone because the archived failure mode was not documented. A mixture is therefore considered technically promising when it maintains adequate workability and retains a high proportion of both compressive strength and measured ultimate beam load.

For the present data, the control values were 100 mm slump, 30.10 MPa mean compressive strength and 37.00 kN mean ultimate beam load. A practical performance-retention criterion of approximately 95% of the control ultimate beam load was used as a comparative benchmark, while the highest feasible coconut-shell content was favoured where workability remained within the control range. This criterion is not a design-code substitute and does not define shear or flexural resistance; it is an experimental screening tool for selecting mixtures for larger-scale verification.

4. Results and Discussion

4.1 Workability response

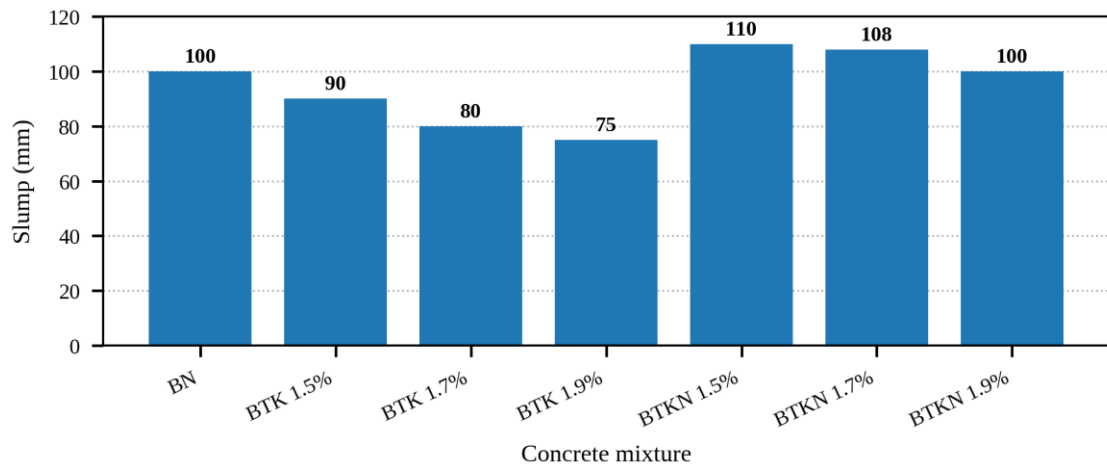
Table 2 and Figure 3 show a systematic reduction in slump as coconut-shell content increased without Sikament-NN. Relative to the 100 mm control, the slump fell to 90, 80 and 75 mm for 1.5%, 1.7% and 1.9% shell content, respectively. The trend is consistent with studies reporting that porous coconut-shell aggregate can increase water demand and internal friction, particularly when particles are untreated [1], [2], [7], [13], [14], [23], [24]. A similar fresh-state sensitivity has been reported in self-compacting coconut-shell concrete, where aggregate and matrix modifications strongly influence flowability [18]. The decrease was progressive rather than abrupt, indicating that even a small increase in shell fraction influenced fresh-state behaviour.

Sikament-NN reversed this workability loss. At 1.5%, 1.7% and 1.9% shell content, the admixture increased slump by 20, 28 and 25 mm, respectively, compared with the corresponding mixtures without admixture. The 1.5% and 1.7% BTKN mixtures exceeded the control slump, while BTKN 1.9% returned exactly to 100 mm. This improvement is attributable to cement-particle dispersion and reduced flocculation, which increased paste mobility despite the water demand of the shell particles. Comparable workability improvements have been reported when particle treatment or mixture modification is used with coconut-shell and other bio-based aggregates [2], [7], [18], [23], [24]. An analogous fresh-state trade-off was reported by Tanash et al. [29], where palm-oil-fuel-ash incorporation reduced the workability of polypropylene-fibre concrete even though an optimum replacement level improved mechanical performance. The comparison supports the present emphasis on assessing workability and hardened performance together when agricultural by-products are introduced.

Table 2. Slump and workability change of the concrete mixtures

Mixture	Slump (mm)	Change from control (%)	Sikament-NN gain over paired BTK (mm)
BN	100	0.0	-
BTK 1.5%	90	-10.0	-
BTK 1.7%	80	-20.0	-
BTK 1.9%	75	-25.0	-
BTKN 1.5%	110	10.0	20
BTKN 1.7%	108	8.0	28
BTKN 1.9%	100	0.0	25

Source: Authors' analysis of experimental data (2025).



Source: Authors' analysis (2025)

Figure 3. Slump Response of Concrete with Coconut-shell Fragments and Sikament-NN

4.2 Compressive strength and ultimate beam load

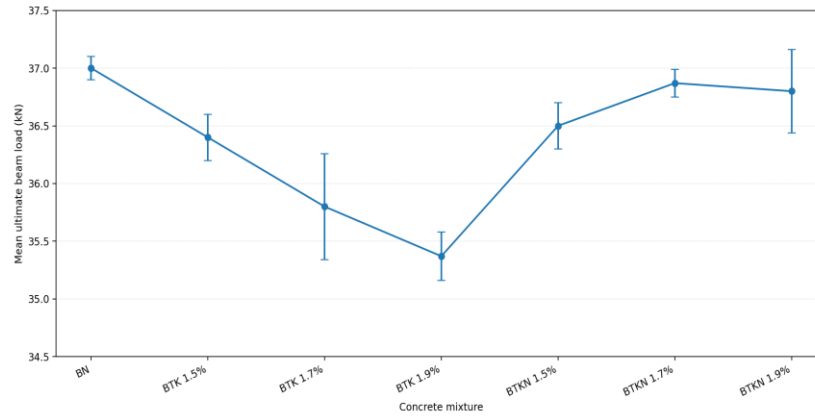
The control mixture achieved a mean compressive strength of 30.10 MPa and a mean ultimate beam load of 37.00 kN. Without Sikament-NN, increasing coconut-shell content reduced both properties. Mean compressive strength declined by 3.43%, 6.53% and 8.86% for BTK 1.5%, BTK 1.7% and BTK 1.9%, respectively. The corresponding reductions in ultimate beam load were smaller, at 1.62%, 3.24% and 4.41%. This difference indicates that the measured peak-load response was relatively less sensitive than compressive strength over the narrow replacement range; it does not, however, establish that shear resistance was preserved because the physical failure mode was not documented.

The reduction is technically plausible because coconut shell has a lower stiffness and a more heterogeneous surface than crushed mineral aggregate. Increasing shell content can create a weaker interfacial zone and reduce continuity of the load-transfer path. Contemporary studies report comparable mechanical reductions when coconut-shell aggregate is used beyond its optimum level, while also showing that low replacement levels can remain technically useful [4]-[7], [13], [14], [18], [23], [24]. The low standard deviations in most mixtures indicate reasonably consistent specimen production within the limited sample; the greatest variability occurred in the BTK 1.7% group. Given $n = 3$, these variability estimates remain preliminary and should not be treated as robust population parameters. A comparable dosage-sensitive mechanical response was observed by Zulkarnain et al. [30] in fly-ash geopolymers concrete: the lowest replacement level produced the highest elastic modulus, whereas further substitution reduced the response. Although the binder system and test method differ, this pattern reinforces the need to identify an experimentally supported replacement range rather than assume that greater waste content will preserve structural performance.

Table 3. Mean mechanical properties and performance retention at 28 days

Mixture	Compressive strength (MPa)	SD (MPa)	Retention (%)	Ultimate beam load (kN)	SD (kN)	Retention (%)
BN	30.10	0.20	100.00	37.00	0.10	100.00
BTK 1.5%	29.07	0.35	96.57	36.40	0.20	98.38
BTK 1.7%	28.13	0.76	93.47	35.80	0.46	96.76
BTK 1.9%	27.43	0.32	91.14	35.37	0.21	95.59
BTKN 1.5%	29.20	0.30	97.01	36.50	0.20	98.65
BTKN 1.7%	29.83	0.15	99.11	36.87	0.12	99.64
BTKN 1.9%	29.73	0.51	98.78	36.80	0.36	99.46

Source: Authors' analysis of experimental data (2025).



Source: Authors' analysis (2025)

Figure 4. Mean Ultimate Beam Load and Specimen Variability

4.3 Performance recovery provided by Sikament-NN

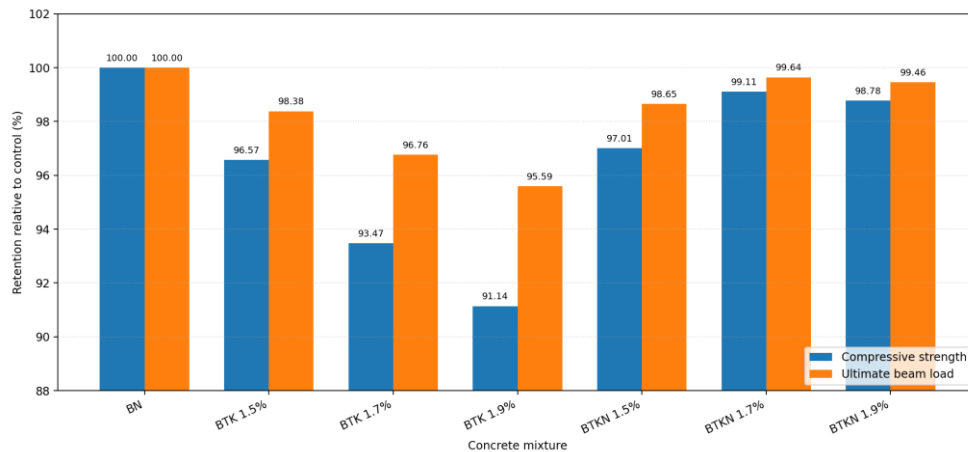
The admixture series clearly recovered mechanical performance relative to the shell-only mixtures. At 1.5% shell content, Sikament-NN increased mean compressive strength by 0.13 MPa and ultimate beam load by 0.10 kN. The recovery was much more pronounced at 1.7% and 1.9% shell content. BTKN 1.7% gained 1.70 MPa in compressive strength and 1.07 kN in ultimate beam load compared with BTK 1.7%, while BTKN 1.9% gained 2.30 MPa and 1.43 kN. The increasing benefit at higher shell content supports the interpretation that the admixture primarily compensated for workability and compaction limitations caused by the absorptive shell particles. This interpretation is consistent with literature showing that surface treatment and matrix modification can improve the interfacial quality and mechanical performance of coconut-shell concrete [2], [7], [18], [23], [24].

The BTKN mixtures retained between 98.65% and 99.64% of the control ultimate beam load. The maximum difference from the control was only 0.50 kN. The 1.7% mixture produced the highest mean ultimate beam load in the admixture series (36.87 kN), whereas the 1.9% mixture achieved 36.80 kN while using the greatest amount of coconut-shell waste. These small differences should be interpreted descriptively because each mean is based on only three specimens. Recent coconut-shell studies likewise show that particle treatment, supplementary materials and mixture modification can recover part of the mechanical performance lost through aggregate substitution [7], [18], [20], [23], [24].

Table 4. Mechanical recovery due to 2.3% Sikament-NN

Coconut shell (%)	Compressive strength gain (MPa)	Ultimate-beam-load gain (kN)	Slump gain (mm)	BTKN beam-load retention (%)
1.5	0.13	0.10	20	98.65
1.7	1.70	1.07	28	99.64
1.9	2.30	1.43	25	99.46

Source: Authors' analysis of experimental data (2025).



Source: Authors' analysis (2025)

Figure 5. Mechanical-property Retention Relative to Normal Concrete

4.4 Optimum mixture and practical implications

Selection of an optimum mixture depends on whether the priority is maximum mean strength or maximum waste utilisation. BTKN 1.7% gave the highest mean ultimate beam load among the modified mixtures and a slump of 108 mm. BTKN 1.9%, however, retained 98.78% of the control compressive strength and 99.46% of the control ultimate beam load while returning the slump to the 100 mm control level. On a performance-retention basis, BTKN 1.9% is therefore the preferred mixture within the tested range because it incorporates the greatest shell content without a practically important reduction in the measured peak beam load.

The result should be interpreted as a laboratory optimisation within a narrow substitution range. It does not establish a universal structural design value or a shear-capacity parameter. Before field application, the mixture should be verified using full mix proportions, larger sample numbers, explicitly documented support spacing and shear-span-to-depth ratio, reinforced and plain beams, systematic crack mapping, load-deflection monitoring and durability tests. Nevertheless, the data demonstrate a useful mixture-design principle: low-volume coconut-shell replacement can be combined with a high-range water-reducing admixture to preserve placement quality and measured load-bearing response. This principle is consistent with current developments in sustainable shell-aggregate concrete and the broader objective of reducing dependence on virgin aggregate [18]-[24].

4.5 Study limitations

The principal limitations are the use of only three specimens per mixture, the absence of a reinforced-beam comparison, the restricted coconut-shell range and incomplete structural-test documentation. Three replicates provide only a minimum descriptive basis; consequently, the mean and standard deviation for each mixture have limited precision and are sensitive to individual observations. In addition, the archived experimental record did not include the effective support spacing or shear-span-to-depth ratio, systematic crack maps, sufficiently documented post-failure photographs, load-deflection curves, density, absorption or long-term durability. The physical failure mechanism therefore cannot be classified with confidence as diagonal-shear or mid-span flexural-tensile failure, and the recorded peak load should not be used as a shear design resistance or as a modulus of rupture. The findings apply only to the tested materials, dimensions and curing conditions. Future work should use larger replicate numbers and explicitly document span geometry, crack initiation and propagation, load-deflection response and code-based comparisons.

5. Conclusions and Recommendations

5.1 Conclusions

Increasing coconut-shell replacement from 1.5% to 1.9% without admixture progressively reduced workability, compressive strength and ultimate beam load under central loading. The largest shell-only mixture produced a 75 mm slump, 27.43 MPa mean compressive strength and 35.37 kN mean ultimate beam load.

Adding 2.3% Sikament-NN restored slump to 100-110 mm and substantially recovered the measured mechanical performance of all coconut-shell mixtures. The recovery was most pronounced at the higher shell contents, supporting the interpretation that the admixture compensated for the increased water demand and compaction difficulty associated with the shell fragments.

BTKN 1.7% achieved the highest mean ultimate beam load among the modified mixtures, at 36.87 kN. BTKN 1.9% provided the best balance between waste utilisation and measured performance, retaining 98.78% of control compressive strength and 99.46% of control ultimate beam load while matching the control slump. Within the tested range, 1.9% coconut-shell replacement with Sikament-NN is therefore recommended for further structural and durability verification. These conclusions concern peak load under the tested central-loading arrangement only; because crack observations and shear-span information were unavailable, they should not be interpreted as direct evidence of shear capacity.

5.2 Recommendations

Further research should use at least five specimens per mixture and include both plain and reinforced beams with explicitly controlled and reported shear-span-to-depth ratios. Measurements should include load-deflection response, crack initiation and propagation, failure-mode classification, toughness, density, water absorption, chloride resistance and life-cycle impact. Investigating pre-soaked

or surface-treated coconut shell together with lower Sikament-NN dosages may identify a more economical mixture while preserving workability and load-bearing performance.

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