Structural Performance and Mechanical Evaluation of Two-Layer Reinforced Concrete Beams Incorporating Clam Shell Aggregates

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Abstract
*Concrete remains a primary building material in civil engineering, but its overall cost is heavily dictated by its constituent materials. In region-specific contexts like the Niger Delta and coastal Nigeria, traditional coarse aggregates such as crushed granite incur substantial costs due to heavy transport logistics and inflation, while discarded clam shells create severe waste disposal and environmental challenges. This study investigates the structural performance, cost-benefit feasibility and failure modes of two-layer reinforced concrete (RC) beams utilizing recycled clam shells as a partial alternative aggregate. By strategically allocating premium, high-strength aggregates to high-stress compressive zones and lower-performing, environmentally friendly recycled clam shell aggregates to lower-stress zones, this study investigates the structural performance, failure modes of a two-layered composite beam under flexural loading and can it be maintained alongside cost reduction? Laboratory testing was conducted on a scaled beam specimen composed of an upper compressive layer and a lower tensile layer joined at a defined shear interface. Load-deflection curves, interfacial shear slip, and ultimate failure mechanisms were systematically monitored up to structural collapse. Various mix configurations on rectangular beam measuring (1200X100X150) of Types MC (control), M1, M2, M3 and concrete cube specimens MP were subjected to comprehensive laboratory testing, including sieve analysis, compressive strength testing, tensile stress analysis, shear strength measurement, and flexural load-deflection evaluation. The beam specimens (M1 and M2) clam shell concrete was formed with 1:2:3 mix with depth of 75mm at the compression layer and the crushed stone aggregate concrete was formed with 1:2:4 mix with a depth of 75mm and beam specimens (M3) clam shell concrete was formed with 1:2:3 mix with depth of 50mm at the tension layer and the crushed stone aggregate concrete was formed with 1:2:4 mix with a depth of 100mm at the compression layer . Experimental findings indicate that while 28-day cube compressive strength decreases with clam shell integration (*28.60 *Mpa for control down to* 12.30 -17.33 *Mpa for modified mixes) the two-layered beam exhibits a maximum load-bearing capacity of [35.06Kn] with an ultimate mid-span deflection of [5.96mm]. Initial linear-elastic behavior was observed up to [60.0% - 80.0% depending on the sample] of the ultimate load, after which composite action began to degrade due to progressive interface shear failure. Full-depth flexural cracking originated in the lower tension layer and propagated upward into the compression zone, triggering complete delamination at the layer interface prior to ultimate failure, the two-layer beam structural configurations demonstrate comparable or superior ultimate load capacities. Specifically, Beam Type-M3 (*50 *mm clam shell concrete tension layer /* 100 *mm conventional concrete compression layer) achieved an ultimate*

load capacity of 35.06 *Kn, outperforming the control beam Type-MC (*34.82 *Kn). Modified beams exhibited enhanced ductility and deflection capacity prior to failure.*

1. INTRODUCTION

Sustainable construction practices necessitate the exploration of agricultural and marine waste materials as alternative aggregates in structural concrete. Clam shells present a potential substitute for natural coarse aggregates. However, lower compressive strengths in full-depth clam shell concrete often limit structural applications. This paper examines a layered approach combining conventional crushed stone concrete in primary compression zones with clam shell aggregate concrete in tension zones to optimize structural performance while promoting material sustainability.

2. MATERIALS AND SIEVE ANALYSIS

2.1 Aggregate Grading

Particle size distribution analyses were conducted on fine aggregates, standard coarse aggregates, and clam shell aggregates to ensure compliance with structural mix requirements.

- **Fine Aggregate:** Passing 4.76 mm (100%) down to 0.076 mm (2.07%).
- **Standard Coarse Aggregate:** Nominal maximum size 25.4 mm (100% passing).
- **Clam Shell Aggregate:** Nominal maximum size 25.4 mm (100% passing), with 72% passing 12.7 mm and 3% passing 4.76 mm.

Table 1: Particle Size Distribution Summary

Sieve Size (mm)	Fine Aggregate (% Passing)	Coarse Aggregate (% Passing)	Clam Shell Aggregate (% Passing)
25.4	100.00	100.00	100.00
19.0 / 19.1	100.00	48.00	96.00
12.7	100.00	1.00	72.00
9.52	100.00	0.94	28.00
6.35	100.00	0.64	14.00
4.75 / 4.76	100.00	0.00	3.00
2.36	99.97	—	—
1.10 / 1.18	98.87	—	—
0.60	69.87	—	—
0.30	26.87	—	—

Sieve Size (mm)	Fine Aggregate (% Passing)	Coarse Aggregate (% Passing)	Clam Shell Aggregate (% Passing)
0.15	17.64	—	—
0.076	2.07	—	—

3. EXPERIMENTAL PROGRAM AND SPECIMEN CONFIGURATIONS

Five distinct mix/layer configurations were evaluated:

- **Type-MC (Control):** Full-depth standard crushed stone aggregate concrete (1: 2: 4 mix).
- **Type-M1:** 75 mm compression layer (1: 2: 4 crushed stone) / 75 mm tension layer (1: 2: 3 clam shell).
- **Type-M2:** 75 mm compression layer (1: 2: 3 clam shell) / 75 mm tension layer (1: 2: 4 crushed stone).
- **Type-M3:** 100 mm compression layer (1: 2: 4 crushed stone) / 50 mm tension layer (1: 2: 3 clam shell).
- **Type-MP:** Alternative mix reference cube series.

4. EXPERIMENTAL RESULTS

4.1 Material Compressive Strength (28-Day Cube Test)

Standard 150 × 150 × 150 mm cube testing at 28 days yielded the results summarized in Table 2.

Table 2: 28-Day Cube Compressive Strength Results

Specimen Type	Weight (kg)	Applied Load (kN)	28-Day Compressive Strength (MPa)
Type-MC	8.0	643.30	28.60
Type-M1	8.5	302.50	13.44
Type-M2	7.8	390.00	17.33
Type-M3	8.0	387.50	17.22
Type-MP	8.8	276.67	12.30

4.2 Flexural Performance and Direct Beam Observation

Beam specimens were tested under flexural loading to record first crack load, failure load, maximum deflection, and failure modes.

Table 3: Direct Observation and Failure Metrics of Beam Specimens

Specimen Type	Sample No.	First Crack Load (kN)	Failure Load (kN)	Deflection at Failure (mm)	Failure Mode
Type-MC	1	29.31	36.64	4.69	Flexure / Crushing
	2	29.31	32.97	2.88	Flexure / Crushing
	3	27.48	36.64	4.05	Flexure / Crushing
Type-M1	1	21.98	36.64	5.92	Shear / Crushing
	2	25.65	32.97	4.29	Shear / Crushing
	3	23.65	34.79	5.12	Shear / Crushing
Type-M2	1	21.98	32.97	5.10	Flexure / Crushing
	2	25.65	32.97	4.22	Flexure / Crushing
	3	23.58	31.65	4.66	Flexure / Crushing
Type-M3	1	29.31	36.64	4.59	Shear / Crushing
	2	21.98	32.97	3.55	Shear / Flexure / Crushing
	3	24.85	35.56	4.21	Shear / Crushing

4.3 Computed Mechanical Properties

Calculated values for Cracking Capacity, Bending Capacity, Tensile Stress, and Shear Strength across samples are provided in Table 4.

Table 4: Computed Structural Parameters

Specimen Type	Sample	Cracking Capacity (kNm)	Bending Capacity (kNm)	Tensile Stress (MPa)	Shear Strength (kN)
Type-MC	1	5.37	6.72	14.33	18.32
	2	5.37	6.05	14.33	16.49
	3	5.04	6.72	13.43	18.32
Type-M1	1	4.03	6.72	10.75	18.32
	2	4.70	6.05	12.54	16.49
	3	4.33	6.38	11.56	17.40
Type-M2	1	4.03	6.05	10.75	16.49
	2	4.70	6.05	12.54	16.49
	3	4.32	5.80	11.53	15.83
Type-M3	1	5.37	6.72	14.33	18.32
	2	4.03	6.05	10.75	16.49
	3	4.56	6.52	12.15	17.78

5. DISCUSSION

5.1 Ultimate Load-Carrying Capacity

Control beam Type-MC exhibited an average ultimate failure load of 34.82 kN. Beam Type-M1 matched this capacity (34.82 kN) despite utilizing clam shell concrete in its tension zone. Beam Type-M3 recorded the highest load-carrying capacity at 35.06 kN. Beam Type-M2 (75 mm clam shell concrete in the compression zone) exhibited a reduced load capacity of 32.53 kN (6.6% lower than control). This indicates that placing higher-strength conventional concrete in the top compression zone effectively preserves beam capacity.

5.2 Load–Deflection Behavior and Ductility

Control beams (Type-MC) displayed greater initial stiffness. However, two-layer beams exhibited greater overall deflection at ultimate failure. Type-M1 reached deflections up to 26% higher than Type-MC prior to failure (5.92 mm vs. 4.69 mm). All layered beams failed in a ductile manner, accommodating inelastic deformation prior to ultimate failure.

5.3 Failure Modes

- **Type-MC & Type-M2:** Primarily flexural cracking leading to compression crushing.
- **Type-M1 & Type-M3:** Initial flexural cracking transitioning into combined shear-compression failure modes.

6. CONCLUSION

1. **Compressive Strength:** Clam shell concrete exhibits lower 28-day cube strength (13.44--17.33 MPa) compared to conventional concrete (28.60 MPa).
2. **Structural Integration:** Restricting clam shell concrete to the tension layer (Type-M1 and Type-M3) preserves full structural load capacity (34.82--35.06 kN) relative to pure standard concrete beams.
3. **Ductility:** Two-layer beams demonstrate enhanced deformation capability prior to failure, improving warning signs against sudden catastrophic collapses.
4. **Optimal Configuration:** Type-M3 (100 mm conventional compression layer / 50 mm clam shell tension layer) represents the most efficient structural configuration evaluated.