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Effective Economic Combination of Waste Seashell and River Sand as Fine Aggregate in Green Concrete

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Abstract: This research elucidates the idea of eco-friendly concrete and highlights the benefits attainable from its effective practice towards sustainable construction materials. The design mix employed a water/cement ratio of 0.5, a concrete mix ratio of 1:2:4, varying percentages of 2.5 mm seashells, 4.75 mm river sand as fine aggregates, and granite 20 mm as coarse aggregates. Laboratory tests showed that the true slump was achieved for all mixes as a decrease in workability was observed with seashell additions. Compressive strength declined with increasing percentages of seashells at all curing ages (7, 14, and 28 days). No seashell-modified mix achieved the target strength for concrete grade 25. Nevertheless, the 10 and 20% seashell blends obtained strength requirements for concrete grade 20. The splitting tensile strength results indicated that 10–50% seashell-concrete blends yield acceptable splitting tensile strength after 28 days of curing. Correlation and regression analysis showed that compressive strength has a high negative correlation with seashell percentage and a significant correlation with splitting tensile strength. However, no significant correlation was seen between seashell percentage and splitting tensile strength. Models were further developed for predicting workability, splitting tensile strength, and compressive strength, with seashell percentage data. Green concrete production, which reutilizes waste seashells should be promoted, bearing in mind its environmental sustainability and economic prospects.

Keywords: sustainable materials; green concrete; compressive strength; solid waste; waste management

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1. Introduction

The trend of material diversification in the construction industry has received so much emphasis in the last few decades due to natural resource conservation and sustainable development. Concrete remains the most extensively produced construction material and the second most utilized material worldwide) [1–3]. Gagg [4] reported that the annual per capita consumption of concrete is 3 tons. It is a composite that principally constitutes cement and aggregates (fine and coarse) [5–7]. Cement is produced from the industrial processing of natural limestones and clays and serves as the binder material. However, both cement and aggregates are obtained from the exploration of rapidly-depleting natural resources [8,9]. It is assessed that the annual global consumption of aggregates surpasses 40 billion tons, of which concrete production utilizes between 64 and 75 percent [10,11]. Some of the effects of these explorations on the environment are illustrated in Figure 1.

A variety of solid wastes are currently being adopted as alternative materials in the production of concrete, especially in countries with high rates of generation [10]. Some of the wastes used in previous studies include rubber for making a clean green base and subbase [12], construction and demolition wastes as aggregates in pervious concrete [13], use of plastics fiber in high-strength reinforced concrete beams [14], use of agricultural wastes as additional material in green concrete [15,16], and several industrial and aquaculture wastes to list a few. These materials are generated in high volumes in certain countries and have the potential for usage in the mass production of green concrete.

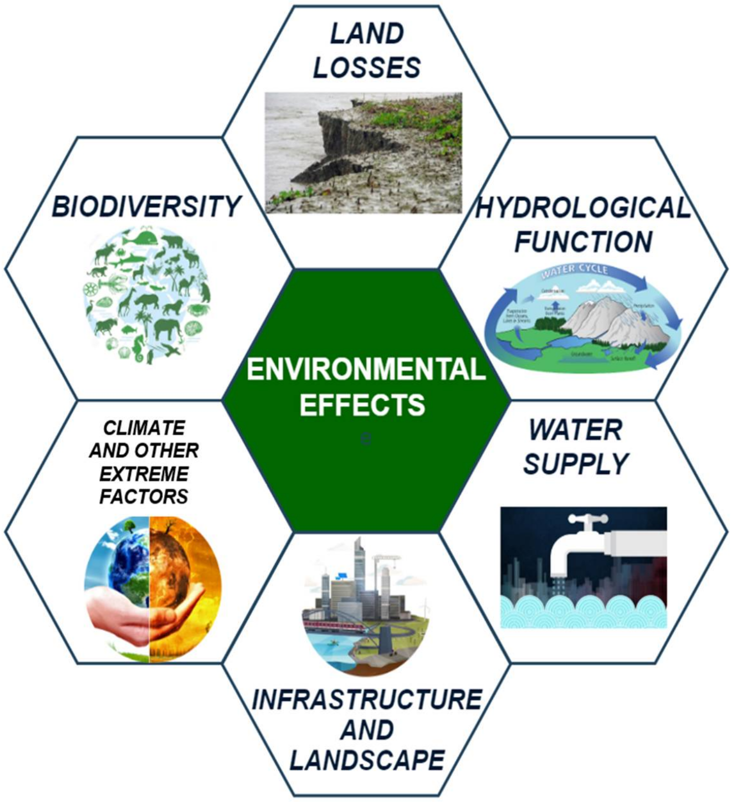

Figure 1. Summary of major environmental factors affected by aggregate exploration [10].

A significant by-product of the aquaculture industry is seashells [10]. Seashells are the natural defensive shields of shellfishes. They are inedible and, hence, discarded as waste in open dumpsites. They are known to have zero to very minimal salvage value, thereby constituting a physical nuisance to the environment. There are various kinds of seashells obtainable. However, bivalve shells and mollusc shellfish gastropods are the major seashells used to substitute for aggregate in concrete. Mollusc production accounts for about 16 million tons and represents about 22 percent of the aquaculture industry's global production [17]. Bivalve molluscs are one of the most common shellfish species and account for about 87 percent of all molluscs. They include mussel shells, oyster shells, pectens, scallop abalones, winkle shells, clams, and cockle shells. *Senilia senilis* is an edible genus of bivalve mollusc and saltwater clam of the Arcidae family, also known as ark shells [18]. They are often found buried underneath the silty sands of water channels and coastal lagoons between the tropical lands of Western Sahara and Angola [19]. Some of these seashells have been locally sourced and used in the mixture of composites for buildings and local roadway maintenance works in some remote communities in the Southern coastal states of Nigeria [10].

Many past studies have focused on understanding the effects that various types of seashells pose on concrete behavior. Olivia et al. [20] and Tayeh et al. [21] used blood clam cockle shells in a partial replacement of cement, whereas Safi et al. [22] used seashells as a fine aggregate in self-compacting mortars. Panda et al. [8] studied the effect of rice husk ash (RHA) on the mechanical properties of concrete containing crushed seashells as fine aggregates and findings showed that the partial replacement of cement with RHA increases the strength in all concrete mixes. Wang et al. [23] worked on frost resistance and vegetation performance of seashell waste in pervious concrete in cold areas and discovered that the addition of silica fume improved the seashell pervious concrete compressive strength. It was further observed that pervious concrete made from scallop waste seashells is far better than that of oyster shells. Zhang et al. [24] focused on the engineering properties of foam concrete containing waste seashells and discovered that the workability of concrete decreased with an increase in the foam-filled shell (FFS) but in terms of engineering properties and environmental perspectives the FFS provided a way to recycle seashell waste continuously.

Previous studies showed that 5% of protein glue could be found in shells, which are responsible for their toughness [25]. The measure of tensile strength in the innermost stratum of shells is well-balanced by the compressive strength acting on the outermost stratum. Molluscs are predominantly $CaCO_3$ and other elements like potassium, sodium, silicon, iron, etc. are present in minimal amounts. A typical crude sea shell structure comprises over 90% calcium carbonate ($CaCO_3$) by weight and little amount of organic materials [26]. This amount of $CaCO_3$ is considered very high and is similar to limestone powder from grinding limestone. This high amount is highly significant when converted to calcium oxide (CaO) to increase concrete strength and density. The seashells are heated at very high temperatures to change the $CaCO_3$ to CaO and carbon. The amount of CaO can differ in seashells due to the difference in the calcining temperature, prior to the chemical composition test. For example, for the case study of mussel shells, a high CaO of 87.2% was achieved at a temperature of 1100 °C, whereas other studies achieved a CaO level of 53.0% at lower temperatures [27,28].

However, no study has been conducted using *Senilia senilis* shells as fine aggregates in plain concrete from the available literature. This study aims to examine the effect of using *Senilia senilis* as a partial substitute for fine aggregates on the early-age and strength properties of ordinary Portland cement concrete. It is expected that the results obtained hereon provide a useful alternative material for green concrete production, support conservation, reduce environmental pollution, and promote environmental sustainability at reduced monetary costs.

2. Experimental Program

Standard procedures in line with ASTM C33/C33M-18 [29], ASTM C125-20 [30] and ASTM C136/C136M-19 [31] were adopted to prepare all concrete samples. Several tests were conducted to assess both seashell-modified and unmodified control mix concrete's workability and strength properties based on relevant standards such as ASTM C143, ASTM C39 [32], and ASTM C496/C496M [33]. Results were also analyzed and compared with conventional practices.

2.1. Materials

This study was conducted using the following listed materials:

1. Crushed *Senilia senilis* seashells shown in Figure 2a,b were selected from the Seme coastal borders of southwestern Nigeria as a substitute for fine aggregates. The seashells were washed, dried, and crushed.
2. Dangote brand, 42.5 N grade, Nigerian-made ordinary Portland cement as a binding agent.
3. Fine aggregates used included river sand obtained from the shores of the Ogun River, Nigeria.
4. Coarse aggregates used included granite obtained from the Igbo-Ora quarry in Ogun State, Nigeria. The granites were angular-shaped crushed rock, free from organic matters, clay, loose particles, and dust. Table 1 shows the different aggregate sizes used in the study.
5. Potable water sourced within the Covenant University Campus, Ota, Ogun State, Nigeria, was used to ensure mix consistency and workability.

Table 1. Aggregate sizes used in the experiment.

Material	Aggregate Class	Maximum Size
Senilia senilis seashells	Fine	2.5 mm
River sand	Fine	4.75 mm
Granite	Coarse	20 mm

(**a**) (**b**)

Figure 2. *Senilia senilis* seashells. (**a**) Before crushing; (**b**) after crushing.

2.2. Chemical Composition

According to Mo et al. [34], Bivalvia mollusc seashells can have similar chemical properties, as long as the same calcining temperature is used for all of them. Table 2 shows the typical chemical composition of the *Senilia senilis* seashell. Limestone-type aggregates have a similar chemical composition to seashell aggregate; as a result, the use of seashell aggregate to certain extents in concrete production has the potential to improve the compressive strength, tensile, and density of concrete [10].

Table 2. Characteristic chemical configuration of *Senilia senilis* shells [1].

Compound	Formula	Composition
Calcium Carbonate	$CaCO_3$	97.13%
Silicon dioxide	SiO_2	0.98%
Magnesium oxide	MgO	0.02%
Aluminium oxide	Al_2O_3	0.17%
Sodium oxide	Na_2O	0.37%
Sulphur trioxide	SO_3	0.13%
Sulphate	SO_4	0.07%
Potassium oxide	K_2O	0.03%

2.3. Methodology

All mixing, sampling, and laboratory experiments were conducted in the Concrete Laboratory of the Department of Civil Engineering, Covenant University, Ogun State, Nigeria. The experimental scope is shown in Figure 3.

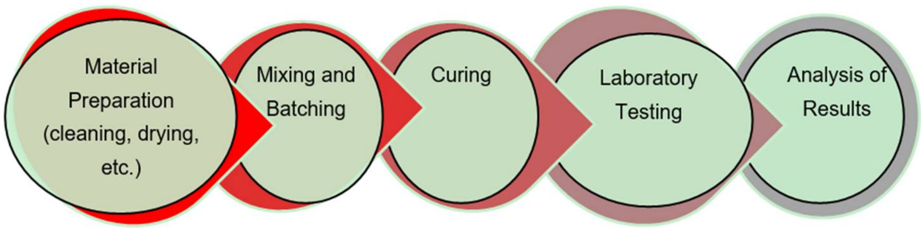

Figure 3. Experimental process flowchart.

2.3.1. Batching and Mix Design

The seashells used in this study were first selected, appropriately cleaned to remove impurities, and dried in the open air. The shells were then crushed using a Los Angeles (LA) abrasion machine before sieving to obtain a maximum size of 2.5 mm. The drinkable water flowing in Covenant University Civil Engineering laboratory was used for the study. The river sand and granite collected were also sieved, washed separately, and allowed to dry properly before mixing.

The samples were batched into eight groups by weight. A control batch with traditional natural aggregates was designed with a cement: fine: coarse ratio of 1:2:4 and a water/cement (w/c) ratio of 0.5. Seven other concrete batches were composed of a combination of river sand and crushed seashells in varying percentages (10%, 20%, 30%, 40%, 50%, 60%, and 100%) as fine aggregate, as shown in Table 3. The W/C ratio was constant for all mixes. Each batch was composed of four concrete cubes of L100 mm × B100 mm × H100 mm for compressive strength testing, and three concrete cylinders (with a diameter of 100 mm and length of 200 mm) for splitting tensile strength testing in line with ASTM C39/C39M [32] and ASTM C496/C496M-[33] standards, respectively. The mix design adopted is shown in Table 4. A total number of 72 cubes and 72 concrete cylinders were produced.

Table 3. Mix batches and description.

Batch ID	Description
MC-00 (Control)	100% river sand + 0% crushed seashells as fine aggregate
MC-10	90% river sand + 10% crushed seashells as fine aggregate
MC-20	80% river sand + 20% crushed seashells as fine aggregate
MC-30	70% river sand + 30% crushed seashells as fine aggregate
MC-40	60% river sand + 40% crushed seashells as fine aggregate
MC-50	50% river sand + 50% crushed seashells as fine aggregate
MC-60	40% river sand + 60% crushed seashells as fine aggregate
MC-100	0% river sand + 100% crushed seashells as fine aggregate

Table 4. Mix design adopted.

Mixed Batch		Material Content in Kilograms				
ID	Seashell: River Sand	Water	Cement	Crushed Seashell	River Sand	Granite
MC-00	0:100	1.94	3.80	0.00	7.60	15.20
MC-10	10:90	1.94	3.80	0.76	6.84	15.20
MC-20	20:80	1.94	3.80	1.52	6.08	15.20
MC-30	30:70	1.94	3.80	2.28	5.32	15.20
MC-40	40:60	1.94	3.80	3.04	4.56	15.20
MC-50	50:50	1.94	3.80	3.80	3.80	15.20
MC-60	60:40	1.94	3.80	4.56	3.04	15.20

2.3.2. Tests Performed

Several tests were performed at three distinct stages during this study: the pre-batching stage (to assess the physical and mechanical properties of each material set), during concrete mixing (to assess the ease of handling and consistency of the fresh mix), and the concrete post-setting stage (to assess the strength properties of the produced composites).

Preliminary Aggregate Tests

Particle size distribution: Sieve analysis was performed to evaluate the distribution of the particle sizes of the fine (crushed seashells and river sand) and coarse (granite) aggregates separately. This analysis was done as per ASTM C136/C136M [31] in which 1 kg of the aggregate was emptied into a well-graded set of sieves placed on an electro-mechanical sieve shaker and allowed to vibrate. The mass of retained aggregate on individual sieves was computed in determining the particle size gradation of the three materials.

Aggregate impact value: Aggregate impact value (AIV) of the coarse aggregates used in the study was also assessed. This was done as per BS 812-Part 112 [35]. The aggregate was subjected to a predefined quantity of blows from a rammer suspended at a specified drop distance. AIV was then computed as the fraction of fines resulting from the process and indicated the aggregate's capacity to withstand direct impacts. The standard requirements for fine and coarse aggregates in concrete are presented Table 5.

Specific gravity and water absorption: The specific gravity (S_g) of individual sets of fine aggregate was evaluated using a pycnometer as per ASTM 1429 [36]. The bulk density was calculated as the weight of measured aggregate filling the top-leveled mold divided by the mold's volume. At the same time, the test for water absorption was performed on the coarse aggregates and was expressed in percentage [36].

Table 5. Criteria for aggregates in concrete [37–39].

Property	Criteria	Reference Statute
	Fine Aggregate	
Fineness modulus	2.0–3.3	ASTM C33/C33M [29]
Absorption (%)	<5	ASTM C127 [40]
Bulk specific gravity (kg/m^3)	2.3–2.9	ASTM C127 [40]
Soundness (%)	<15	ASTM C88/C88M [41]
	Coarse Aggregate	
Aggregate impact value (%)	<30	BS 812-110 [35]
Nominal maximum size (mm)	9.5–90	ASTM C33/C33M [29]
Abrasion resistance (%)	<30	ASTM C131/C131M [42]
Elongation index (%)	<20	BS 812-105.2 [35]
Flakiness index (%)	<20	BS EN 933-3 [43]
Absorption (%)	<2	ASTM C128-15 [44]
Bulk specific gravity (kg/m^3)	2.6–2.9	ASTM C128-15 [44]
Dry rodded bulk density (kg/m^3)	1280–1920	ASTM C125-20 [30]

Concrete Fresh-Mix Tests

- Workability

The slump cone test was used to estimate the consistency and workability of the fresh mixes. This test was carried out as per ASTM C143 [45]. During the mixing of each batch, the slump was measured by filling the leveled slump cone and tamping the concrete appropriately. Then, the cone was raised and the height difference between the cone and the top of the sample was recorded as the slump.

Concrete Post-Setting Tests

- Compressive Strength Test

A compressive strength test was conducted on all produced concrete batches after 7, 14, and 28 days of curing. The test was conducted as per ASTM C39 [32] on the cube specimens with the aid of a compression testing machine (CTM), as shown in Figure 4. Each sample was placed in the CTM and loaded gradually at a rate of 140 kg/cm^2/minute till failure. The compressive strength was recorded as the load at failure and computed equations as per [32].

Figure 4. Compression testing machine for compressive and splitting tensile strength tests.

- Splitting Tensile Strength Test

A splitting tensile strength test was also conducted on all produced concrete batches after 7, 14, and 28 days of curing. The test was carried out as per ASTM C496/C496M [33] on the cylindrical specimens with a CTM aid. Each sample was placed in the CTM with the aid of two steel strips above and beneath the specimen's axis-of-split and loaded gradually at a rate of 140 kg/cm^2/minute until split failure. The splitting tensile strength was recorded as the load at failure and computed using the relevant equation in ASTM C496/C496M [33]. Table 6 presents the standard requirements of proper concrete.

Table 6. Strength criteria for normal concrete.

Property	Criteria	Reference Statute
Density (kg/m^3)	2240–2400	ASTM C138/C138M [46]
Compressive strength (N/mm^2)	20–40	ASTM C39/C39M [32]
Flexural strength (N/mm^2)	3–5	ASTM C293/C293M [47]
Tensile strength (N/mm^2)	2–5	ASTM C496/C496M [33]
Shear strength (N/mm^2)	6–17	ASTM D6916 [48]
Elastic Modulus (kN/mm^2)	14–41	ASTM C469/C469M [33]

3. Results and Discussions

3.1. Particle Size Distribution

Sieve analysis results classified the river sand and crushed *Senilia senilis* seashells as poorly-graded sand and well-graded sand, respectively, based on the unified soil classification system (USCS) as over half of both fine aggregate materials was seen to pass the No. 200 sieve. The addition of the seashells to the river sand would improve the fine aggregate grading, thereby improving the workability and reducing the voids. The granite used was classified based on USCS as poorly-graded coarse-grained gravel. Based on the ASTM C136/C136M [31] and IS 2386 (part I):1963 [49], these materials are suitable for plain concrete use as they offer better aggregate interlocking and improved strength. The fineness modulus was also computed as 2.78, 2.50, and 7.50 for the river sand, crushed *Senilia senilis*, and granite, respectively. This met the requirements of ASTM C 33 [29], as shown in Table 4. The plotted sieve analysis graphs for all aggregate materials used are presented in Figure 5.

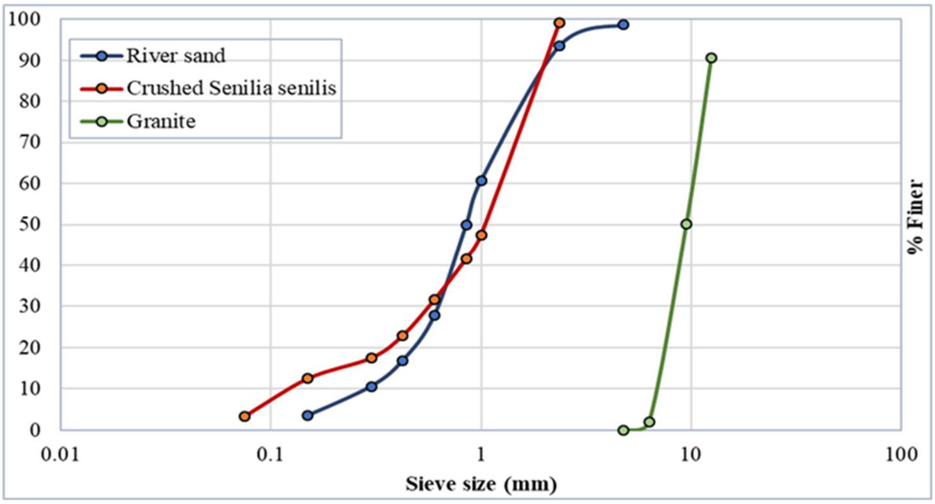

Figure 5. Gradation curves from sieve analysis on aggregate used.

3.2. Specific Gravity Test (S_g)

The S_g of the aggregate is considered an indication of its mechanical strength. The S_g of the river sand and crushed *Senilia senilis* seashells was 2.6 and 2.3, respectively, with a 2.5 fineness modulus for *Senilia senilis*. Both values fall within the standard range, as indicated in Table 7, according to ASTM C 127 [40]. Table 7 illustrates the S_g test results for both fine aggregate materials.

Table 7. Results of specific gravity, water absorption, and impact tests on aggregate materials.

Parameter	Fine Aggregate		Coarse Aggregate
	River Sand	Crushed *Senilia senilis*	Granite
Specific gravity	2.6	2.3	-
Water absorption	-	-	0.50%
Aggregate impact	-	-	26.64%

3.3. Water Absorption Test

A water absorption test was conducted on the coarse aggregates (granite) used in this study. It was used to evaluate the porosity and the freeze-thaw resistance of the aggregates. The water absorption obtained was 0.5%, which meets the requirements of ASTM C 128 [44] as depicted in Table 7. Higher water absorption exceeding 2% means more pores; hence the aggregate will be considered weak.

3.4. Aggregate Impact Test

An aggregate impact test was performed on the granite (coarse aggregates) used in this study. It evaluated the resistance of the aggregates to abrupt direct loading. The aggregate impact value (AIV) obtained was 26.64%, which is <30, as such, meeting the requirements of BS 812-110 [35], as depicted in Table 6.

3.5. Slump Test

Slump tests showed a workability and consistency decrease with rising *Senilia senilis* seashell percentage. The true slump was achieved for all mixes; hence, seashell addition did not lead to early-stage collapse or shear. The slump values of all seashell-modified batches fell below that of the control mix (MC-00). All the MC-00, MC-10, MC-20, MC-30, MC-40, MC-50, MC-60, and MC-100 mixes met the acceptable slump range of 20–100 mm as per ASTM C143 [45], with slump values of 75 mm, 60 mm, 56 mm, 45 mm, 42 mm, 34 mm, 25 mm, and 20 mm, respectively, as shown in Figure 6. The reduction in workability may be associated with the high presence of fines in the crushed seashells used, which causes increased stiffness and reduced voids.

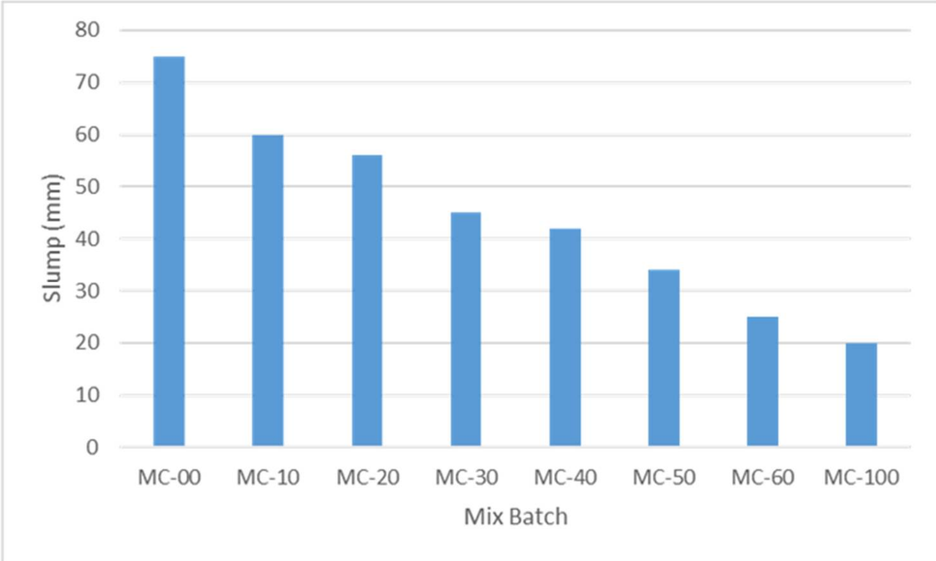

Figure 6. Results of the slump tests on all mix batches.

3.6. Compressive Strength Test

Compressive strength indicates the load-bearing capacity of the produced composite to resist crushing. Since a major characteristic of concrete is its compression ability, the need to assess the used seashell effects on concrete strength is apparent. Tests carried out on concrete cube samples as per ASTM C39/C39M [32] indicated a continuous strength decrease with the addition of the *Senilia senilis* seashells as shown in Figure 7.

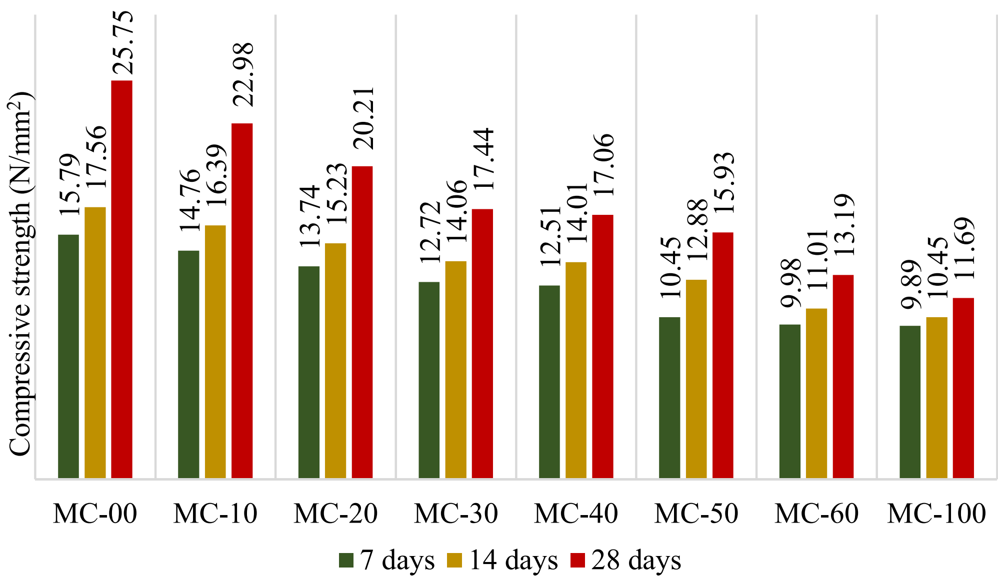

Figure 7. Compressive strength test after 7, 14, and 28 days of curing.

On the 7th day of curing, concrete is expected to reach 65% of its characteristic strength [50]. Only the MC-00 control mix achieved 63.1% (less than 2% shy of 65%) of the characteristic strength on the 7th day, whereas the MC-10 and MC-50 batches only came as close as 59.04% and 57.8%, respectively, the MC-100 samples yielded 9.89 N/mm^2 at 7 days, achieving only 39.56% of the characteristic strength. By the 14th day of curing, further strength decrease compared to the control mix was noticed. As the percentage of seashell increased, the strength decreased, but at 50% (MC-50), the strength increased slightly, after which further decrease was noticed in MC-60 and MC-100.

The design target strength at 28 days of 25 N/mm^2 was adopted following the 1:2:4 mix ratio for grade 25 concrete. Only the MC-00 mix yielded 25.75 N/mm^2, exceeding the target strength value. The MC-10 and MC-20 mixes on the 28th day yielded compressive strength values of 22.98 N/mm^2 and 20.21 N/mm^2, respectively, which are less than the target strength by about 8% and 19%, respectively, only meeting the strength requirement for concrete grade 20. The MC-30, MC-40, and MC-50 yielded compressive strength values of 17.44 N/mm^2, 17.06 N/mm^2, and 18.93 N/mm^2, respectively, meeting the requirements for grade 15 concrete. Whereas the MC-60 and MC-100 mixes achieved the lowest strength values with 13.19 N/mm^2 and 11.69 N/mm^2, and hence are not recommended in mass concrete production.

3.7. Splitting Tensile Strength Test

A splitting tensile strength test on the cylindrical samples was conducted after 7, 14, and 28 days of curing. The tests were performed and computed as per ASTM C496/C496M [33]. The results illustrated in Figure 8 indicate that at 7 days, the addition of *Senilia senilis* seashells improved the concrete's resistance to tensile stresses. The tensile strength increased gradually with the increasing seashell percentage up to 50% (MC-50), after which a decrease was noticed. The MC-50 mix achieved 2.1 N/mm^2, which was the highest tensile strength value of all mixes on the 7th day. On the 14th day, the MC-50 and MC-20 mixes achieved 2.0 N/mm^2 and 1.95 N/mm^2, respectively, which were the highest tensile strength values out of all seashell-modified mixes. However, the MC-00 control mix yielded 2.15 N/mm^{2,} surpassing all other mixes.

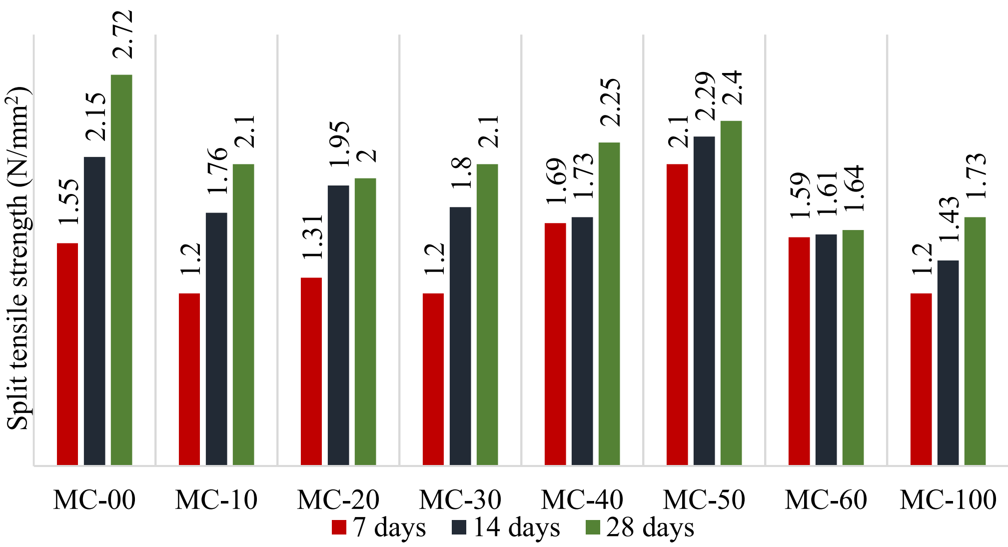

Figure 8. Splitting tensile strength test results (N/mm^2) after 7, 14, and 28 days of curing.

The 28th-day test results showed that the MC-10, MC-20, MC-30, MC-40, and MC-50 batches yielding 2.1 N/mm^2, 2.0 N/mm^2, 2.1 N/mm^2, 2.25 N/mm^2, and 2.4 N/mm^2, respectively, all achieved the recommended tensile strength values as indicated in Table 5. However, these values were lower than the 2.72 N/mm^2 obtained by the MC-00 control mix. The reduced tensile strength values may be attributed to the crushed seashell's lower specific gravity being used as fine aggregate replacement. The MC-60 and MC-100 mixes produced unacceptable tensile strength values and are not recommended.

3.8. Correlation and Regression between Compressive Strength, Splitting Tensile Strength, and Percentage of Seashells

Correlation analysis was used to understand the relationship between the compressive and splitting tensile strength parameters and the percentage of seashells used. The correlation coefficients presented in Table 8 based on the Pearson r method show a positive and significant correlation between compressive strength and splitting tensile strength with an R-value of 0.585. This indicates that with a higher sample size (N) value, compressive strength can be a good predictor of splitting tensile strength. A very strong negative correlation was also seen between the seashell percentage and the compressive strength, whereas a weak negative correlation was noticed between the percentage of seashell and the splitting tensile strength. The descriptive statistics used in the correlation analysis are presented in Table 9.

Table 8. Correlation coefficients for seashell percentage, splitting tensile strength, and compressive strength. **. Correlation is significant at the 0.01 level (2-tailed).

Variables		Compressive Strength	Split Tensile Strength	Seashell Percentage
Compressive strength	Pearson Correlation	1	0.585	−0.920 **
	Sig. (2-tailed)	-	0.128	0.001
	N	8	8	8
Split tensile strength	Pearson Correlation	0.585	1	−0.311
	Sig. (2-tailed)	0.128	-	0.454
	N	8	8	8
Seashell percentage	Pearson Correlation	−0.920 **	−0.311	1
	Sig. (2-tailed)	0.001	0.454	-
	N	8	8	8

Table 9. Descriptive statistics for correlation analysis. N = sample size.

Variables	Mean	Std. Deviation	N
Compressive strength	18.4063	4.68190	8
Splitting tensile strength	2.1775	0.31226	8
Seashell percentage	38.7500	31.81981	8

The dependence of compressive strength, split tensile strength, and slump test results on the seashell percentage are further regressed in Figure 9. The slump and compressive strength functions are seen to give steep downward-trending linear functions with increasing percentages of the *Senilia senilis* seashells. The coefficients of determination (R^2) for compressive strength and slump against seashell percentages are R^2 = 0.8464 and R^2 = 0.8394. This indicates high degrees of dependence in both scenarios, and as such, the model is suitable for the prediction of compressive strength and slump values, provided all other variables remain constant. On the other hand, the split tensile strength regression gives a polynomial trend function with an insignificant R^2 value of 0.3036. The regression models developed with the slump, compressive, and splitting tensile strengths as criterion variables and the percentage of seashells as the predictor variable are shown in Table 10.

Table 10. Summary of regression analysis.

Dependent Variable	Independent Variable	Model	Std. Error	R	R^2
Slump (W_s)	Seashell %	$Ws = -0.2349s + 25.603$	3.53217	−9.16	0.8394
Compressive Strength (C_{st})	Seashell %	$C_{st} = -0.1354s + 23.652$	1.98165	−0.920	0.8464
Split tensile strength (S_{ts})	Seashell %	$S_{ts} = 0.001s^2 - 0.0163s + 2.4896$	0.32056	−0.311	0.3036

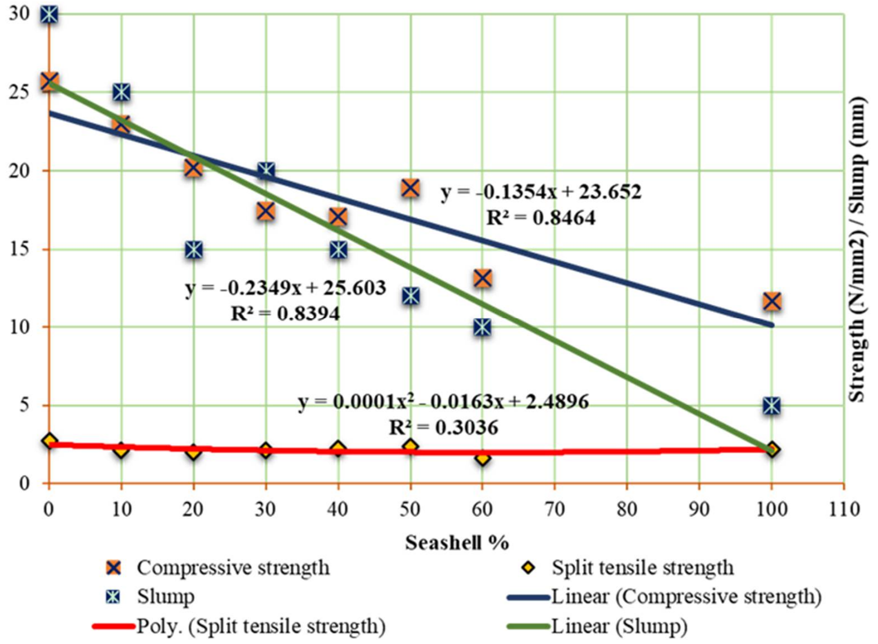

Figure 9. Regression of workability and strength parameters against seashell percentage.

3.8.1. Model Testing

Validity tests were further performed on the established models and the model testing operation results are shown in Table 11. The results from the split tensile strength tests were not included due to the low dependency shown in its R and R^2 values. The standard error data presented in Table 8 further explains this fit. On the other hand, despite high R and R^2 values obtained from the slump/% seashell regression, a high margin of error is noticed from the model tests. This shows a lack of fit between the measured data and the linear function [51]. The compressive strength prediction model test gave a relatively low margin of error; since significant R and R^2 values were also obtained, the model is suitable for prediction. However, the mean error must be factored in.

Table 11. Results for model validity tests.

Compressive Strength Prediction Model (C_{st} = −0.1354s + 23.652)			
Predictor Value (%)	**Measured Value (y_m)**	**Predicted Value (y_p)**	**Error ($y_m - y_p$)**
0	25.750	25.652	0.098
10	22.980	24.298	−1.318
20	20.210	22.944	−2.734
30	17.440	21.59	−4.150
40	17.060	20.236	−3.176
50	15.930	18.882	−2.952
60	13.190	17.528	−4.338
100	11.690	12.112	−0.422
Slump Determination Model for Workability (W_s = −0.2349s + 25.603)			
Predictor Value (%)	**Measured Value (y_m)**	**Predicted Value (y_p)**	**Error ($y_m - y_p$)**
0	30.000	25.603	4.397
10	25.000	23.254	1.746
20	15.000	20.905	−5.905
30	20.000	18.556	1.444
40	15.000	16.207	−1.207
50	12.000	13.858	−1.858
60	10.000	11.509	−1.509
100	5.000	2.113	2.887

3.8.2. Economic and Cost Analysis

The study examined the effective economic blending of *Senilia senilis* and river sand as fine aggregates in green concrete. The acquisition costs of river sand and seashells with their respective weights are portrayed in Table 10. The table indicates an increasing proportion of crushed Senilis Senilia to river sand, accompanied by a decreasing proportion mix of fine aggregate. Their corresponding prices and weights in kilograms are equally presented in Table 12. The evidence from the comprehensive strength analysis suggests a significant relation with the cost of seashells for the 7-, 14-, and 28-day tests whereas the split tensile strength shows no significant outcome. Specifically, a unit increase in the cost and proportion of fine aggregates remarkably enhanced concrete strength by 0.759, 0.888, and 0.916 N/mm^2. Most importantly, it could be observed that there is an increasing direct influence of expenditure on green concrete compressive strength in relation to an increase in the number of days for the test periods. However, the split tensile strength suggests no significant relations with *Senilia senilis* and natural fine aggregate substitution effect as indicated in the Table 13 results.

Table 12. Fine aggregates weight and cost acquisition.

Mix Proportion	Natural Sand: Seashell Weights (kg)	Natural Fine Aggregates Price (#)	Seashell Price (#)
MC00	24:0	10,008	0
MC10	21.6:2.4	907.2	74.4
MC20	19.2:4.8	823.2	148.8
MC30	16.8:7.2	705.6	223.2
MC40	14.4:9.6	604.8	297.6
MC50	12:12	504	372
MC60	9.6:14.4	403.2	446.4

Table 13. Economic and cost analysis. Note: ***, * represents significance at 1% and 10% level.

	Comprehensive Strength Analysis			Split Tensile Strength		
Predictors Mix Proportions (%): Sea Shell/River Sand Costs	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
Constant	8.994 *	8.763 ***	7.137 *	2.094 ***	1.114 *	1.575 *
Coefficients	0.759 *	0.888 ***	0.916 ***	−0.552	0.662	0.548
R-squared	0.575	0.789	0.839	0.304	0.438	0.300
Adjusted R	0.491	0.747	0.807	0.165	0.326	0.160
F-Statistics	6.776 *	18.719 ***	26.138 ***	2.187	3.90	2.144

Hence, evidence from the study supports the usage of seashells as a more cost-effective and economically plausible substitute for fine aggregates (natural fine) in green concrete construction approaches for enhanced compressive strength of the concrete. At the same time, a higher proportion of *Senilia senilis* revealed a retarded strength.

The explanatory power of the model also revealed an increasing power of estimation with respect to higher testing days at 57.5, 78.9, and 83.9 percent change in concrete strength owing to the variations in the cost of fine aggregates. This was further supported by the adjusted R-squared evidence. The model validity (F-statistic = 6.776, p-value < 0.05; 18.747, p-value < 0.01 and 0.807, p-value < 0.01) shows satisfactory result at 5 percent, and 1 percent significance level for 7-, 14-, and 28-day testing periods. Table 14 shows the cost-effectiveness of seashells and river sand.

Table 14. Economic and cost analysis. Note: ***, **, * represents significance at 1%, 5%, and 10% level.

Cost Analysis	Comprehensive Strength			Split Tensile Strength		
River Sand Acquisition Costs	**7 Days**	**14 Days**	**28 Days**	**7 Days**	**14 Days**	**28 Days**
Constant	9.029 ***	8.796 ***	7.211 **	2.098 ***	1.114 **	1.588 **
Price	0.755 **	0.886 ***	0.913 ***	0.557	0.664 *	0.537
R-squared	0.569	0.784	0.833	0.310	0.441	0.289
Adjusted R	0.483	0.741	0.800	0.172	0.329	0.146
F-Statistics	6.612 **	18.171 ***	25.013 ***	2.248	3.941 *	2.028
Seashell Acquisition Costs						
Constant	15.523 ***	17.294 ***	24.608 ***	1.274 ***	2.086 ***	2.429 ***
Price	−0.758 **	−0.888 ***	−0.916 ***	0.552	−0.661	−0.547
R-squared	0.575	0.789	0.839	0.305	0.437	0.299
Adjusted R	0.490	0.746	0.807	0.166	0.325	0.159
F-Statistics	6.760 **	18.668 ***	26.094 ***	2.191	3.889	2.137

The analysis of the acquisition cost of river sand and seashell as fine aggregates was examined in a bid to ascertain their cost effectiveness, as presented in Table 12. The price estimates of fine aggregates (river sand and crushed *Senilia Senilis*) were analyzed in relation to the extent of their correlation with comprehensive and split tensile strength for 7-day, 14-day, and 28-day solidification periods. The result of the estimated price coefficient of river sand for 7 days (0.755; p-value < 0.01); 14 days (0.886; p-value < 0.01) and 28 days (0.913; p-value < 0.01) shows that there is a significant positive impact of river sand on the comprehensive strength of concrete whereas there exists an insignificant but positive relationship between the cost of river sand acquisition and the split tensile strength of concrete. At a 1 percent significance level, a unit increase in natural fine acquisition cost is directly linked with a rise in comprehensive strength by 0.755, 0.886, and 0.913 N/mm^2 for 7 days, 14 days, and 28 days, respectively.

A deeper insight from Table 12 indicates that the specific impact of seashell price in relation to the cost of river sand exhibits a greater significant impact (in absolute value and magnitude) on the comprehensive strength of the concrete. This is observed for the 7-day (−0.758; p-value < 0.01), 14-day (−0.888; p-value < 0.01), and 28-day (−0.916; p-value < 0.01) periods of solidification. However, there exists an inverse relationship between seashell price and the comprehensive strength of concrete and an insignificant inverse relationship with split tensile strength. This implies that increases in the acquisition cost for crushed seashell has a declining effect on the comprehensive strength of green concrete with respect to the duration of concrete solidification. The economic analysis of the cost estimates (Table 12) shows that seashell with a relatively lower cost of procurement indicates a higher magnitude effect on the comprehensive strength of green concretes compared to river sand. This result thus implies that the application of seashells as a substitute for fine aggregate is more cost-effective, though it is associated with a retarded period of concretization in relation to the proportion of river sand.

3.8.3. Economic and Sustainability Implications

From a sustainability–economic perspective, the costs of disposal of waste seashells keep rising in both developed and developing countries. These costs include all internal and external monetary and environmental costs incurred by the producers of these wastes and by third parties [52]. Effective reuse of these wastes would help save these costs, provide a sustainable environment, and recover bio-degraded environments caused by indiscriminate dumping and landfilling. Converting these seashells into bio-calcium carbonates for concrete use will reduce the exploration of natural limestones, thus reducing both construction and environmental costs [53]. Seashells have been proven to offer suitable and sustainable engineering properties when combined with certain natural minerals such as cement and as aggregates for construction, enhancing its value economically.

The use of crushed *Senilia senilis* seashells obtained from waste seashell dumps is becoming an auspicious material for modifying Portland cement concrete. It presents a brilliant simulation of the combination of biological wastes and innovation in cement-based composites [54]. Seashell reuse can also pave the way for the incorporation of other comparable bio-based wastes such as bio-silica. Hence, promoting the reuse of biological wastes in construction material. An extensive Life cycle and Life cycle costs analysis is encouraged to assess the energy efficiency of these practices on environmental and economic sustainability.

4. Conclusions and Recommendations

This study highlighted the prospects obtainable from effectively implementing eco-friendly concrete production practices. Based on the laboratory test results, the following conclusions are drawn:

1. The crushed Senilia senilis seashells used in this study are classified as well-graded sand as per USCS.
2. The addition of crushed Senilia senilis seashell within the range of 10–100% reduced the workability of the concrete; however, all seashell mixes achieved allowable values for ease of handling and consistency of freshly mixed concrete.
3. With increasing proportions of crushed Senilia senilis seashells beyond 20%, the compressive strength of the concrete reduced at 7, 14, and 28 days of curing. No seashell-based mix attained the target strength for concrete grade 25. However, the 10% and 20% seashell blends attained strength requirements for concrete grade 20, which could be used in the construction of slabs, beams, columns, and footings for mild exposure
4. For 30%, 40%, and 50%, they can be applied in construction where M15 grade concrete is required, such as pavement curbs and floor blinding, whereas the 60% and 100% can be used for low-bearing concrete structures.
5. The initial split tensile strength of the concrete after 7 days of curing showed an increase in split tensile strength with increasing proportions of crushed Senilia senilis seashells. Results after 28 days of curing showed that 10–50% seashell mixes met standard split tensile strength requirements.
6. A high negative correlation was seen between seashell percentage and compressive strength with $R = -0.920$, and slump values also showed a high correlation with $R = -0.916$. However, no significant correlation was seen between seashell percentage and split tensile strength with $R = -0.311$.
7. Regression models show high-dependent linear relationships between seashell percentage and compressive strength with $R^2 = 0.8464$, and between workability (slump) and seashell percentage with $R^2 = 0.8394$. However, a statistically insignificant relationship was observed between seashell percentage and split tensile strength with $R^2 = 0.3036$.
8. The economic analysis of cost estimates shows that the application of seashell as a substitute for fine aggregate is more cost-effective.

Finally, to promote a sustained and effective utilization of *Senilia senilis* seashells in concreting, effective systems for waste collection should be put in place. Additionally, active monitoring, regulations, and support policies are highly recommended in developed and developing countries.

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