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Sustainable use of seashells as binder in concrete production: Prospect and challenges

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ABSTRACT

Cement production has a lot of adverse effects on the environment and the globe at large. With all these negativities, it becomes imperative to find alternative materials that are sustainable and environmentally friendly to reduce some of these adverse effects. Seashells are one of the numerous wastes that are quickly accumulating onshore coasts. Using seashells in cement aids in ridding seashells from seashores and landfills, and transforming these wastes to viable cementitious materials. This review paper summarizes past studies on using seashell ash powder as a partial replacement for cement in several proportions. The workability of concrete reduces with the addition of seashell ash. It also indicates a reduction in compressive strength of concrete whose cement content is partially replaced with seashells as compared to those of ordinary Portland cement (OPC). Also, at low percentages of 5%–15% ranges, the concrete absorption and porosity are less compared to standard. Though, with greater replacement levels of up to 25%–50%, these values are enhanced. The workability of concrete is reduced with the addition of higher percentage of seashell ash. After long curing periods, concrete permeability is also reduced, and the mechanical performance is enhanced.

1. Introduction

In construction materials, none is more widely used than concrete [1]. Due to its vast plethora of applications in construction compared with other materials, to its availability and global impact, concrete simply, in the long run, is preferred globally (Andrew, 2018). Concrete is primarily a conglomeration of water, cement, aggregates, and sometimes admixture [2]. Cement is the conventional binder in concrete; regrettably, it is also the most expensive, and its consumption globally is second only to water (Peow et al., 2004). Studies have shown that more than 4 billion metric tons of cement are produced annually, 0.56 ton for a single person since 2017, and with the demand, and world population increasing, cement demand and productions are expected to increase as well [3–5].

Also, substantial volumes of the greenhouse gas, such as CO_2 is released during cement production. One of the most vital issues globally currently is reducing the greenhouse effect caused by greenhouse gases (Felipe-Sese et al., 2011). An essential source of CO_2 emissions is from the manufacture of ordinary Portland cements (OPC) [6]. In OPC production, clinker is the primary ingredient, and the breakdown of limestone and fossil fuels is employed. The fossil fuels are burnt to heat the limestone at temperatures between 1450 °C-1500 °C. Fossil fuels and limestones are mostly carbonates. Heating these carbonates release CO_2 emission. 40–50% of the emissions are a result of fossil fuel burning, while the remaining 50–60% is due to the heating of limestone [4,6]. According to the reports, for every ton of OPC produced, 0.73–0.85 tons of CO_2 is emitted into the earth's atmosphere [6,7]. According to Refs. [8,9]; quarrying of limestone contributes seven percent of all greenhouse emissions caused by quarrying activities in Europe.

Planet earth is already bearing the brunt of these incessant activities, such as biodiversity loss, soil contamination, and surface and groundwater contamination from chemical reactions during quarrying processes. Increased quarrying will further push an irreparable environment [7]. Hence, the need to introduce sustainable and eco-friendly alternatives to cement production is imperative if we are ever to lessen significantly, emission of carbon and other greenhouse gases. Studies [6,10] have shown that it is possible to do this. Three potential ways of achieving this have been widely reported. Greenhouse

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emissions can be reduced by refining the production process, which includes reducing the decomposition energy of limestone, or the utilization of carbon storage and capture technologies. Secondly, partial replacement or total replacement of (OPC) with an alternative binder, which could be a geopolymer or non-carbonate material. Lastly, total replacement in the use of concrete in building infrastructure altogether with other eco-friendly materials that are viable for construction. This review shall focus on the second method, which involves the partial replacement of (OPC) with an alternative binder, in this case, being seashell ash and ground seashells. Reports show that 30% of CO_2 emissions could be lessened significantly if equivalent proportions of OPC are replaced with concrete demolitions waste, though strength was reportedly reduced [6]. Supplementary cementitious materials (SCM), also referred to sometimes as mineral admixtures, are materials that replace some parts of Portland cement or Portland cement itself as a component of concrete [6,11].

Attempts in looking for viable replacements among waste materials as substitutes for cement are ongoing in the research world. The production of these waste materials increases annually and cannot be gotten rid of by orthodox (conventional) means; thus, it would be safe to say that eliminating these waste materials by using them as alternative materials in construction would help in addressing the problems of increasing wastes and finding sustainable supplementary cementitious materials. Seashells, assembled from various molluscs, contribute to rapidly increasing wastes [12]. Reported that seashell processing is increasing without adequate means of getting rid of the shells. Coastal countries are known to be victims of this. Determining the exact quantity of seashell wastes globally is hard. Sixteen million tons representing nearly 22% of worldwide aquaculture production are reported to be produced [13]. Another study reported the range of 10–20 million tons of shell waste being disposed of annually from seashells processing [14]. Seashell disposal causes environmental harm and pollution because of both water leakage and landfill maintenance difficulties. Also, the awful smells and eyesores it produces offers detrimental impacts on the environment [15].

Seashell waste is reported by many studies to have a comparable chemical composition as limestone, which is used in the production of Portland limestone cement (PLC) [7]. It contains greater than 90% of $CaCO_3$ and is known as a calcium oxide source when burnt to grind to powdery form. Hence, seashells can be used as potential replacements for limestone in cement production [7,14,16]. Seashell exists in various kinds, viz: cockle, mussel, scallop, and periwinkle shells [17]. Core seashells used in cement partial replacement are those of bivalves and gastropods [14]. Very popular among marine shellfish species are bivalve molluscs. About 87% of aquaculture (molluscan) are bivalve molluscs - 33.0% consists of clamshells, oysters contribute 31.3%, mussels take 12.1%. At the same time pectens and scallops have 10.9%, constituting the least percentage are abalones, winkles, and conchs at 2.8% of molluscan aquaculture production [13]. Some of the seashell types are shown in Fig. 1.

To appraise the efficacy of integrating shells in concrete, properties such as the fresh and hardened concrete should be taken into consideration for construction purposes. This paper attempts to summarize the earlier works on the utilization of seashells as a binder in concrete and to establish gaps in their findings.

2. Properties of seashells

2.1. Chemical composition

Seashells usually contain over 90% calcium carbonate. The collection locations and shell types determine the chemical composition of seashells [13,20]. In general, the chemical composition of seashell waste is well documented in the existing literature [21]. found that cockle shells possess up to 99% by weight of $CaCO_3$, which is useful in concrete production as filler. A threshold of 15% and above by weight of cement could significantly decrease the porosity, permeability, and strength of concrete. The results of chemical spectroscopy by Refs. [22,23] are presented in Fig. 2 with samples of oyster shells collected from river and sea sources; Fig. 3 shows the chemical composition of burnt seashells. It was observed that there are small differences between the raw and burnt seashell chemical compositions. The significant difference is that $CaCO_3$ is abundant in raw seashells, whereas burnt seashells are abundant in CaO. The CaO amounts rely on shell type, treatment methods, and burning temperatures, which ranges from 500 °C–1000 °C [18,24,25]. [13] conducted a study on seashells composition in Nigeria and found that oyster, periwinkle, and snail shells have large amounts of CaO and SiO_2. It was concluded that washing of seashell diminishes the impurities, salt content, and organic matters, especially the chloride ions. The quantity of Sulphur trioxide (SO_3) available in each of the shell ash ranges in the maximum acceptable limit of less than 3%. The large amount of silica in the oyster, periwinkle, and snail shells implies their inclination to be used as possible cementitious material. They are potential precursors for alkaline activated binder synthesis and geopolymer when doped with alumina, mainly amorphous silica. Contamination level or geographical location could also influence the chemical composition of the seashells [26]. Evidence is shown through disparities in the chemical makeup of Cockle CaO composition amounts as described by Ref. [18,27].

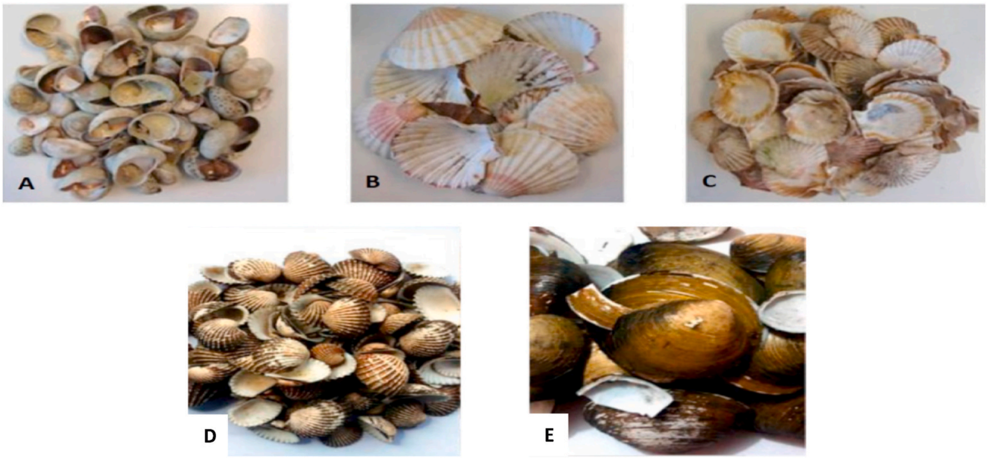


Fig. 1. Seashell types: [a] Crepidula [b] Scallops [c] Queen scallops [d] Blood clam/cockle [e] Marsh clam [13,18,19].

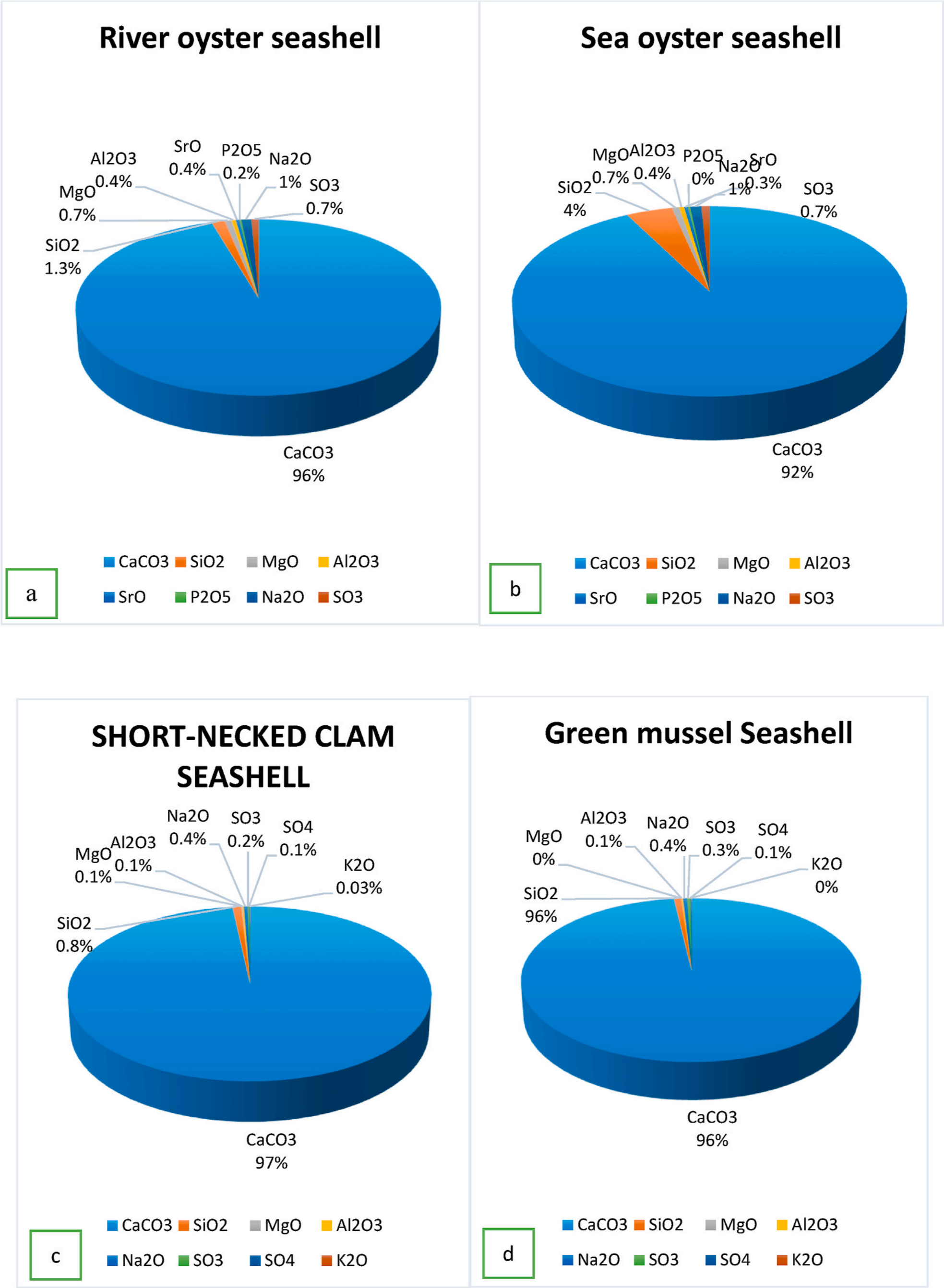


Fig. 2. Raw seashells chemical composition [a] River oyster seashell [b] Sea oyster Seashell [c] Short-necked clam seashell [d] Green mussel seashell [e] Oyster seashell [f] Cockle seashell. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2. *Physical properties of seashells*

The physical properties that are of significant importance in evaluating the seashell applications as mineral admixture because of their influence on the mechanical strength and durability of concrete include; specific gravity, surface area and mean particle size. Previous studies have established that the physical properties of seashells varied from one type to the other (Felipe-Sese et al., 2011). These differences arise as a result of location; and the formation of the inherent traits of the mollusc, climate, and food. This segment summarizes the physical properties of shells and the seashell ash powder utilized in past studies. The specific gravity of seashell ash is less than that of OPC, and the sizes of the seashells rely on the calcination temperature and grinding process [13]. [28] attained different average sizes, D50 of 1.61 and 58.53 μm in methods (wet and dry) of Oyster shell grinding, whereas [23] attained 13.93 μm. Ez-Zaki et al. (2016) obtained 6.27 μm and 10.22 μm for oyster shells, while [29] documented 23.97 μm in their study for the cockleshell samples. The mean size of the clam, cockle, and mussel shells were 20.20 μm, 13.56 μm and 29.87 μm, respectively. Seashell ashes have finer particle sizes than ordinary Portland cement. Therefore, the fineness of blended cement increases with the level of OPC replacement. The finer the cementitious material, the larger the surface area, which consequently increasing the rate of reaction with other substances forming an appreciable strength binder and surface area [13]. The

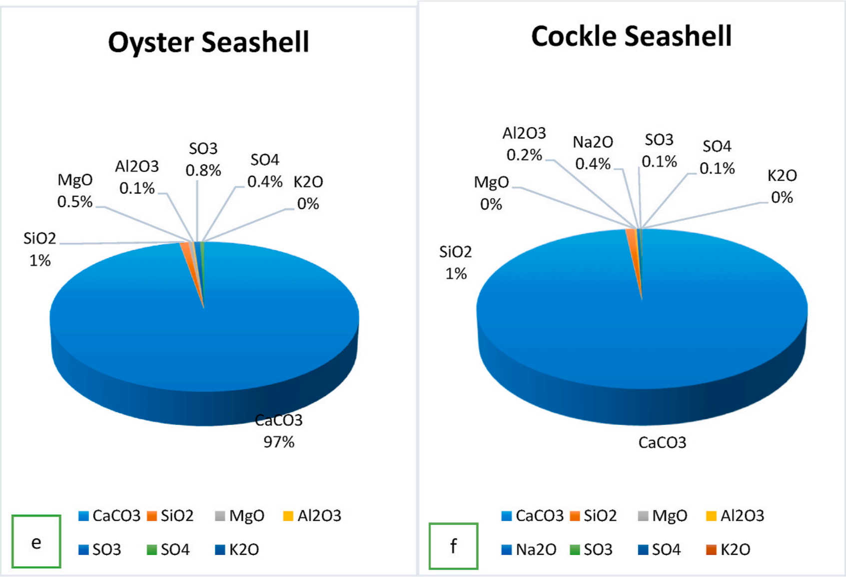
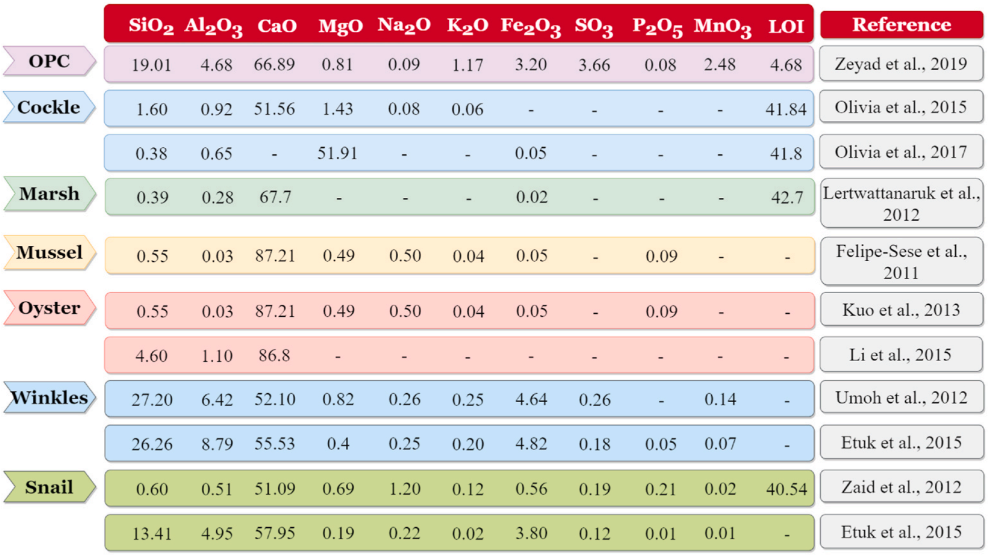


Fig. 2. (*continued*).



	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	SO_3	P_2O_5	MnO_3	LOI	Reference
OPC	19.01	4.68	66.89	0.81	0.09	1.17	3.20	3.66	0.08	2.48	4.68	Zeyad et al., 2019
Cockle	1.60	0.92	51.56	1.43	0.08	0.06	-	-	-	-	41.84	Olivia et al., 2015
	0.38	0.65	-	51.91	-	-	0.05	-	-	-	41.8	Olivia et al., 2017
Marsh	0.39	0.28	67.7	-	-	-	0.02	-	-	-	42.7	Lertwattanaruk et al., 2012
Mussel	0.55	0.03	87.21	0.49	0.50	0.04	0.05	-	0.09	-	-	Felipe-Sese et al., 2011
Oyster	0.55	0.03	87.21	0.49	0.50	0.04	0.05	-	0.09	-	-	Kuo et al., 2013
	4.60	1.10	86.8	-	-	-	-	-	-	-	-	Li et al., 2015
Winkles	27.20	6.42	52.10	0.82	0.26	0.25	4.64	0.26	-	0.14	-	Umoh et al., 2012
	26.26	8.79	55.53	0.4	0.25	0.20	4.82	0.18	0.05	0.07	-	Etuk et al., 2015
Snail	0.60	0.51	51.09	0.69	1.20	0.12	0.56	0.19	0.21	0.02	40.54	Zaid et al., 2012
	13.41	4.95	57.95	0.19	0.22	0.02	3.80	0.12	0.01	0.01	-	Etuk et al., 2015

Fig. 3. Summary of the chemical composition of seashell ash.

specific surface areas are within the range of 6186 cm^2/g 1420 cm^2/g [23]. documented Clamshell surface area to be 8279 cm^2/g, while Cockle shell to be 8299 cm^2 per gram and Mussel shell 6186 cm^2/g, for specific gravity, the cockles were observed to be the least heavy with a specific gravity reported as 2.07 by Ref. [29]. Table 1 gives a summary of physical properties of seashells ash.

2.2.1. *Microstructure of selected seashells*

Microscopic analysis on Oyster shells reported by Ref. [34] indicates that just like all bivalve seashells, mussel structure can be categorized into three distinct strata. The outer stratum called the periostracum, the middle (or prismatic) stratum, and the inner stratum called the nacre [34]. The $CaCO_3$ rich prismatic layer was similarly observed in other past studies [26,35].

Furthermore, the morphology of ground Clam, Oyster, Cockle, and Mussel seashell powder showed irregularities in particle shape with multi-angular shapes and flakiness. Averagely, the particle sizes in μm for clam, oyster, cockle, and mussel shells were reported to be 20.8,

Table 1
Summary of physical properties of seashell ash.

Properties	Portland cement [23,30,31]	Cockle [23,29]	Mussel [23,31]	Oyster [23,28,31–33]	Periwinkle [32]	Mollusk [31]	Clam [23]	Snail shell [32]
Specific gravity	3.11–3.15	2.82	2.86–3.01	2.33–3.09	2.50	3.01	2.71	2.44–2.47
Surface area (wet and dry) (μm)		13.56–23.97	29.87	1.61–58.53			20.20	
Bulk density (g/cm^3)	1.30						1.32	1.26

13.6, 13.9, and 29.9, respectively. Particles with needle-like form were also noticed in the Scanning Electron Microscope (SEM) micrographs for ground oyster shells [33]. Fig. 4 shows describe ground seashell microstructure using SEM micrographs.

2.2.2. *Thermal characteristics of seashells*

Thermogravimetric analysis (TGA) showed that under ambient temperatures up to 200 °C, mussel shells endure weight loss of about 0.4% as a result of the expulsion of absorbed water molecules; at the 200 °C–356 °C temperature range, weight loss increased to about 1.7% due to the oxidation and deletion of volatile substances in the samples. Further temperature increases up to 600 °C led to a further weight loss of 2.3%, and beyond 850 °C, weight loss up surged radically to about 43.3%, which was as a result of the mussel shell decomposition [37]. This TGA results were in line with the observations of [34] in which for a 670–800 °C, a weight loss of over 40% was recorded for mussel shell as shown in Fig. 5. Likewise, other studies found that oyster shells decompose almost completely at temperatures exceeding 760 °C [38], while cockle shells endure substantial weight loss at the 700 °C–900 °C temperature range as a result of carbonate decomposition [39,40]. Differential thermal analysis (DTA) verified that seashells decarbonate at an endothermic peak of about 842.5 °C; a comparable peak was also observed for natural limestone. The TGA outcomes generally imply that the calcination of seashell wastes at temperatures beyond 600 °C potentially leads to higher CaO contents in ground seashell wastes [36].

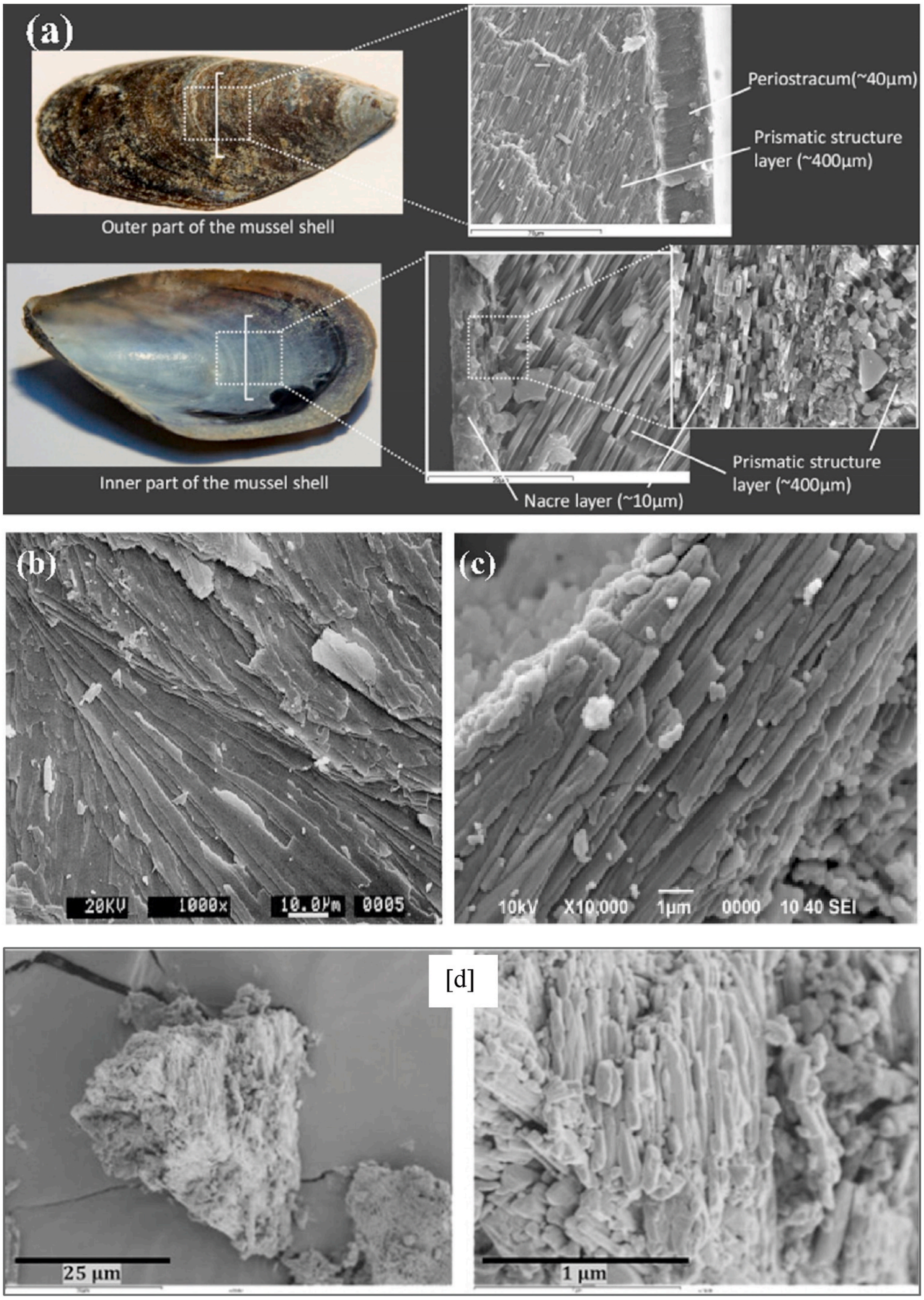


Fig. 4. Micrographs on seashells [a] mussel [b] oyster [c] cockle [d] clam showing morphology at various magnifications [23,34,35,36].

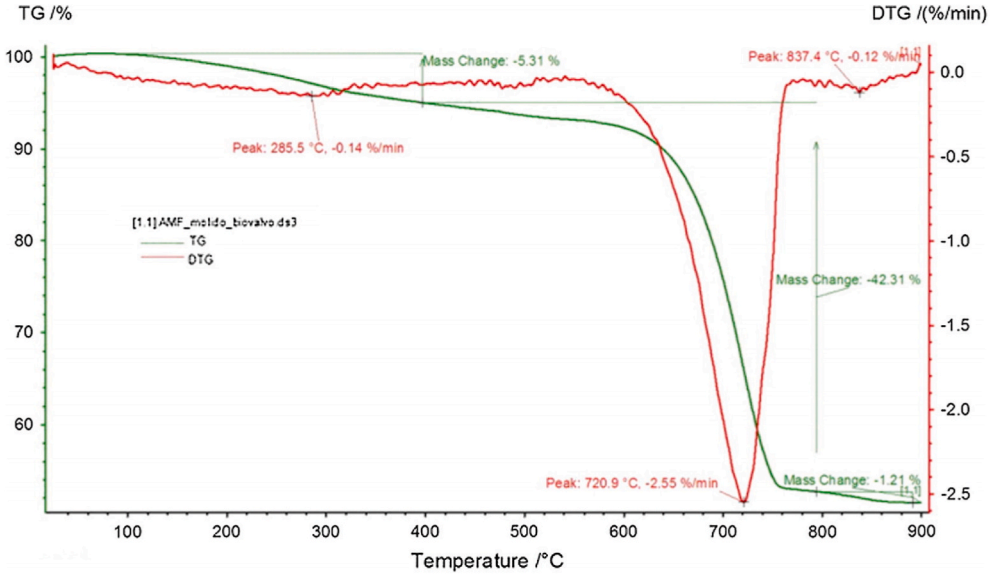


Fig. 5. Mussel TGA curves [34,36].

2.3. *Constituent impurities of seashells*

Waste seashells, being a form of solid wastes, are generally considered to possess pertinent levels of impurities. On a broad note, it has been recorded that the organic matter and chloride ion content in seashells exceed permissible limits for use as aggregates in concrete [36]. However, no study reported any potential adverse effects when used as cement. The small quantities of impurities found in oyster shells were regarded as non-toxic when the oyster shells were utilized in concrete [41,42]. It was further noticed that non-calcined oyster shells indicated chloride ion content of up to 3.7%, whereas after calcination at 650 °C, a chloride ion content less than 1.34% could be attained, depending on calcination duration [38].

Regarding the heavy metal leaching, it was observed that concentrations of heavy metal leachates in oyster shells fell well below the permissible limits; hence, they are regarded as a safe material [38]. Based on further leaching tests, uncrushed mussel shells were classified and reported to be inert wastes; also, crushed mussel shells were categorized as non-hazardous materials per EU specified regulations [36].

3. Seashell ash powder preparation

In several previous studies, the processing of seashells to powder follows the same procedure of cleaning, drying, and calcining [13,20]. The most commonly employed cleaning process involves seashell washing with water and then drying to remove dirt, salt, and the remaining flesh. Seashell ash is obtained by burning of seashell either by open field burning or under the incineration conditions with the regulation of burning temperature and duration. Seashells are, in most cases, subjected to high temperatures and later ground to enable it to pass the sieve number 200. The burning temperature and duration employed in previous studies are shown in Table 2. It is apparent that the grinding of seashells before burning effectively reduces the temperature required, which ranges between 500 °C and 1000 °C according to several studies [7,13,18,29]. Also, due to high calcination temperatures, the $CaCO_3$ undergoes transformation to become CaO and CO_2 [13]. [23] reported that the values of CaO percentages of burnt seashells exceeding the ranges of 52%–57%, which are the ranges usually reported. Different temperatures employed prior to the chemical composition test have been confirmed by researchers to be responsible for the CaO content difference [24]. presented shells burning at range temperatures of 850 °C–950 °C. Therefore, it was confirmed that higher burning

Table 2
Temperatures and burning periods of selected seashells from previous studies [13]].

References	Seashell	Temp. (^{o}C)	Duration	Remarks
[23]	Clam, Mussel, Cockle, Oyster	105–115	24 h	The coarse grinding machine was used to ground seashells for 3–4 h.
[43]	Periwinkle, Oyster, Snail	800	4 h	Shells were washed thoroughly and then sun-dried for three days followed by burning at 800 °C. Samples were then crushed to go through 63 μm sieve.
[39]	Cockle shell	850°c	30 min	The samples were cooled down to room temperature after been burnt for 30 min at 850 °C to ensure the completion of the process.
[29]	Cockle	1000	1 h	After washing the seashell, it was oven dried for 24 h at about 110 °C. The shells were crushed to pass through the 5 mm sieve.
[44]	Snail shell	–	–	After the shells have been washed to remove impurities, it was crushed to fine powder to enable it to pass through a 90 mm sieve.
[45]	Periwinkle	600	20–30 min	The shell was subjected to fire, leaving the shell ash powder, and it was cooled for 24 h in the furnace. The ash powder obtained was sieved to size below 75 μm.
[46]	Cockle & Marsh clam	500–600	72 h	Cleaning, drying and burning of shells at 500 °C and crushing to pass sieve #200.

temperatures lead to higher amounts of CaO content [13].

4. Properties of fresh concrete containing seashells

4.1. Concrete setting time

In OPC blended concrete, the addition of seashell powder as an additive has been documented to have an adverse effect on its workability [18]. Though, the initial and final setting times of cement containing various types of seashells according to the results are lower compared to those of the standard cement and further increase as the percentage replacement of the shell ash increase. Due to the effect of dilution of the seashell ash in the cement matrix, the CaO content could hamper the initial and final setting times. Slow hydration process, caused by decreasing the surface area of the blended cement, was also reported as having being responsible for retardation or increase of initial setting time [16,23]. It was also noted in a study that the delay in the setting time could be caused by an addition in the water of the mix required, and initial hydration triggered by higher fines available in the mix than employing only cement [43]. [18] discovered that the combination of marsh clam *(Polymesoda expansa)* and cockle/blood clam *(Anadra granosa)* powder as partial replacement in cement to produce eco-friendly concrete increases the setting time of concrete leading to high density, tensile, and compressive strength of concrete at early age when compared with OPC concrete which served as a control. At the late ages (91 days), the strength of concrete produced with waste cockle and clam seashells were lower than that of OPC concrete. The results of the findings show that the durability of concrete produced with clam cockle seashells needs to be worked on [30]. attributed the higher setting times of cement containing snail shell compared to that of reference cement and those with clam shell only and the combination of snail and clam shells to the presence of bivalent nature and the large amount of calcium carbonate [47]. stated that the delayed in setting times due to the addition of oyster shell powder could lead to a reduction in stiffening potentials which is advantageous when concreting in hot weather. Setting times documented in previous research are summarized in Table 3 and Fig. 6. It was highly apparent that the delay in the setting times for several shell ash mixes was proportionately linked to the increased content of shell ash.

Table 3
Comparison of setting times between seashell cement and standard cement.

References	Shell ash type	Percentage of cement replaced with shell ash	Time of setting (min.)	
			Initial	Final
[18]	Marsh and Clam shell ash	Control	80	138
		4% by Blood Cockle	80	106
		4% by Marsh Clam	78	106
[27]	Cockle shell ash	Control	90	210
		5%	150	250
		10%	180	270
		15%	180	290
		25%	190	310
		50%	200	340
[30]	Snail	Control	100	160
		10%	110	200
		15%	120	215
		20%	130	225
		25%	145	238
		30%	160	245
	Calm	10%	108	180
		15%	112	200
		20%	125	210
		25%	135	225
		30%	153	230
[16]	Seashell ash	Control	60	90
		4%	75	110
		5%	75	90
		6%	75	90
		7%	75	110
		8%	90	110
		9%	110	140
		10%	110	120
		15%	110	140
		20%	120	140
		30%	120	140

4.2. Workability and consistency of the seashell cement

Fig. 7 shows the increase in the water consistency of cement pastes with additions in the replacement percentages of cement in the following pattern: Periwinkle shell ash (PSA) > Oyster shell ash (OSA) > Snail shell ash (SSA) [13]. This pattern occurred due to the lesser silica contents in OSA and SSA when compared to PSA. For SSA the low water consistency could also be as a result of the high lime content. It is generally believed that concrete workability diminishes with increasing seashell ash percentages due to the irregularities in the shapes of seashell particles. However, the reverse occurs. Workability increases with increased seashell percentages. This was attributed to the hydration period of the seashell cement while maintaining the same water/cement ratio as OPC cement. The advantage of this is that it is possible to lessen the water/cement ratio when using seashell cement to attain identical workability as the standard mix [44]. Reported a decrease in workability from compacting factor test carried out on concrete with the addition of seashell ash. Similar results were observed by Refs. [48,49] with periwinkle and oyster shell ash, respectively. However, the slump of concrete containing oyster shell ash increases with increase in water/cement ratio [49]. In addition [50], also reported the decreasing trend of slump values for concrete containing 5–30% periwinkle shell ash as replacement for cement and fixed Sisal fiber of 1% as reinforcement. The compacting factor results as illustrated in Table 4 show that the compactive energy rises as the composition of seashell ash rises. To measure workability, the vee-bee test is used. Ubachukwu and Okafor, (2017) found an increase in slump indicating higher workability with an increase in the content of oyster shell powder in the concrete mix, as shown in Fig. 8. According to the authors, the higher workability can result to reduction in water demand in order to maintain constant slump and has influence in lowering concrete bleeding and segregation. It was further stated that the improved workability of concrete containing oyster shell powder offered the advantage of easier placing and concrete compaction [51]. investigated the use of calcined mussel shell powder as a partial replacement for OPC. It was observed that the concrete containing mussel shell powder exhibited rapid initial strength development compared to control. However, the strength of the control increased with an increase in curing age up to 28 days, while those containing mussel shells showed no significant improvement in strength. According to the authors, an increase in mussel shell powder content increases the effective surface area could lead to an insufficient proportion of cement, which leads to poor bonding properties of cement matrix with aggregate resulting in lower strength of concrete. It was concluded that the influence of mussel shell powder's inclusion is only effective at lower replacement level and excess amount of the material causes inbalance in the proportion of binder leading to poor bonding properties of concrete matrix.

4.3. Density of concrete with seashells

The standard density and replacement mixes rise with age. It was reported that concrete produced with marsh clam has a higher density than the standard mix, while cockle has a lower density than the standard mix across all concrete ages [18]; Norhazurina et al., 2013). The variation of density of concrete with varying clam shell ash and reference concrete was presented in Fig. 9. It was also reported that clamshell at 6% replacement had the highest density of the partial cement replacements [7]. The high content of CaO in seashells that causes densification of the hydration products of marsh clam is probably the

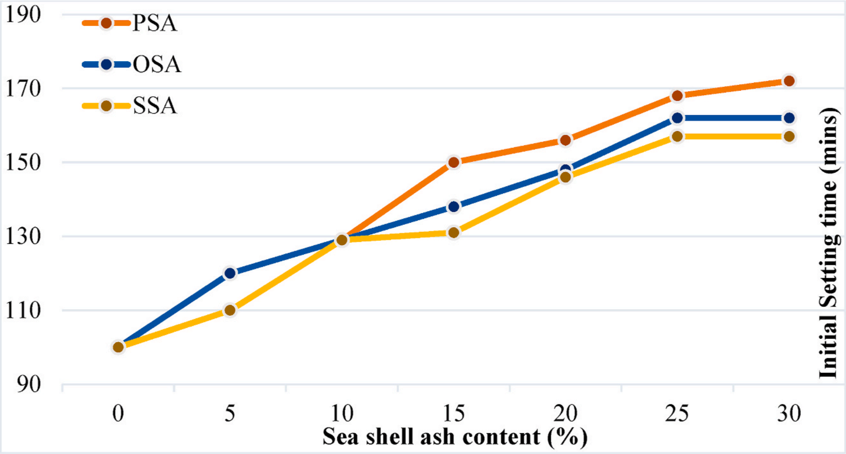


Fig. 6. Percentage replacement of cement with seashell ash powder Initial setting time [18].

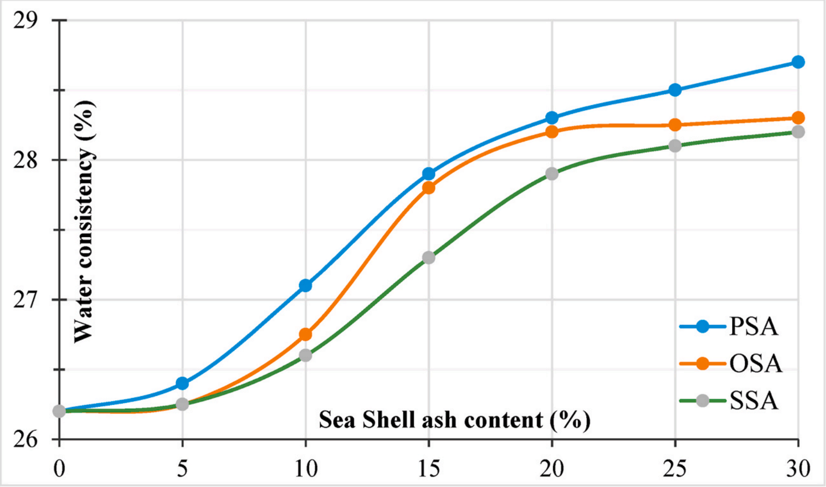


Fig. 7. Water consistency with percentage replacement with seashell ash [43].

Table 4
The fresh properties of seashell replacement with cement results [44]].

Percentage of Cement Replacement	Compaction factor results	Vee - Bee time (sec)	Slump (mm)
0%	0.901	3	90
5%	0.865	5	60
10%	0.824	6.5	30
15%	0.801	7	10
20%	0.734	10.5	–
25%	–	–	5
50%	–	–	0

cause of density variations [13,18]; Hazurina et al., 2012). Fig. 10 shows the density of OPC, which serves as a control, marsh clam, and blood cockle concretes at 7 days, 28 days and 91 days is [18].

4.4. Reactivity and hydration of seashell-cement mixtures

Hydration of cement is the chemical reaction whereby the key compounds present in cement blends bond chemically with molecules of water to form hydrates. As such, the reactivity of cement blends plays a key role in the performance of produced cementitious composites. Several literature have reported that seashells offer less reactivity compared to ordinary Portland cement [15,52,53]. However, there are insufficient literature available addressing the reactivity and hydration properties of seashell cement blends. Some studies observed that seashells offer improved hydration and reactivity compared to limestone powder [14] and palm oil fuel ash [54] in normal and pervious concrete, respectively. During a cement hydration test on seashell and natural limestone powder, more seashell powder was consumed, and was concluded to offer higher reactivity (Fig. 11). The setting time of mortars was seen to increase significantly with increasing proportions of seashells in mortars as a result of the reduced reactivity and hydration properties of seashells [36]. On the other hand, the reduced degree of hydration considerably improved the workability of mortars [23]. The degree of reactivity further influences the compressive strength of composites. Reductions in compressive strength with increasing percentages of various seashells have been observed in many studies and attributed to the low reactivity and hydration property of seashell cement blends [15,23,52,53]. The improvement of the reactivity of seashell powder was further studied by Ref. [24]; it was seen that waste seashells, when treated by heating at high temperatures and decomposing in raw lime (Calcium oxide) resulted in a rapid reaction with water thereby forming hydrated lime in cementitious mixtures [24].

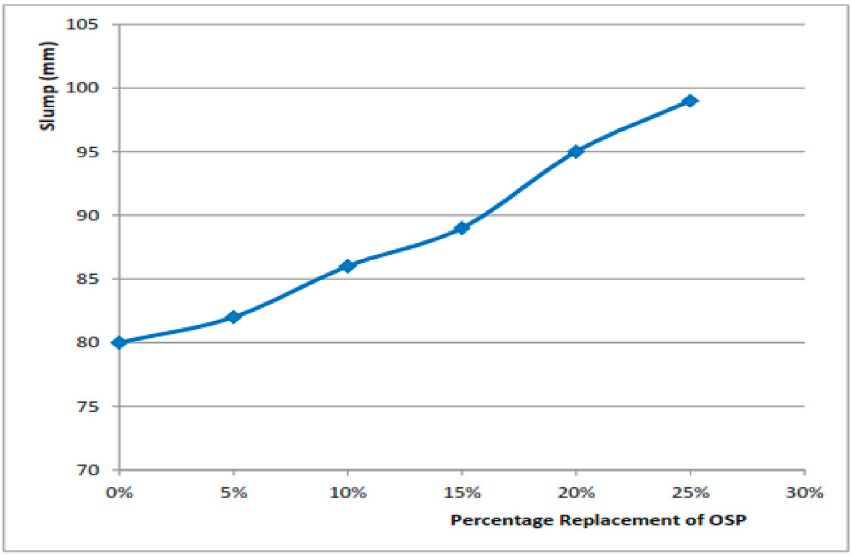


Fig. 8. Variation of slump of concrete with several percentages oyster shell powder (Ubachukwu and Okafor, 2017).

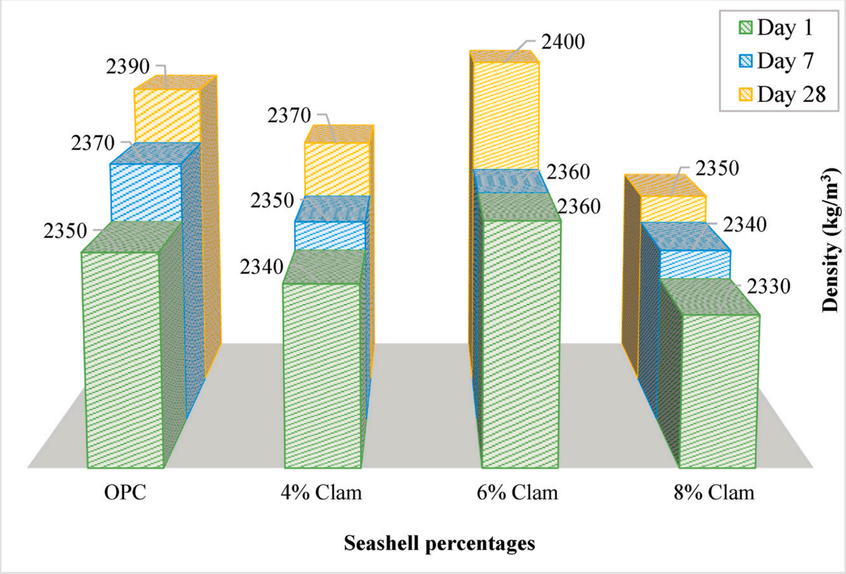


Fig. 9. Density of varying clam shell ash concrete with reference with control [43].

5. Hardened seashell concrete properties

5.1. Compressive strength of concrete with seashells

Compressive strength data reported in previous works are tabulated in Table 5. The results of the previous studies shown in Table 5 revealed that seashell ash powder causes reduced early-age strength in concrete according to most of the previous studies. This reduction is attributed to the presence of CaO in the ground seashell ash that could form reactions with gypsum and Al_2O_3, this is responsible for elite early hydration [13]. Due to the lethargic pozzolanic activity as a result of the addition of shell ash powder to concrete, it was observed that there is a rise in concrete compressive strength compared to that of control concrete when cement percentage replacement rose by weight up to 10% in periwinkle seashell ash, 15% in oyster seashell ash, and finally 20% in snail shell ash [40]). Compressive strength declined as the replacement of the seashell ash surpassed these percentages [43] as shown in Fig. 12. By increasing the period of curing, compressive strength was also increased. Though compressive strength of the seashell concrete is less than that of the control samples, for seashell concrete, compressive strength increase was noted to have occurred after 28 days curing time [23]. It was further noted that the OPC-clam concrete compared to OPC and OPC-cockle concrete displayed higher compressive strength. With ground clamshell replacing OPC, improvement of the later-age concrete compressive strength occurred. Limestone formation due to CO_2 infiltration into higher levels of CaO-containing clamshell-concrete could be solely accountable for strength development [18], the density of concrete produced with percentages of clamshells as cement replacement as shown in Fig. 13 For example, the 5%- and 15%-concrete mixes of cockle shell ash have compressive strength of 35 MPa at a curing time of 28 days. CaO content in excesses could improve the $CaCO_3$ formation because of the penetration of CO_2 which leads to gain in strength for a considerable while. Mixes of concrete with 5% and 10% cockle shell ash have a 47% strength augmentation within 7 and 90 days in comparison with normal concrete with a 26% augmentation [29]. Olivia et al. (2016) examined the mechanical properties of the blood clam or cockle

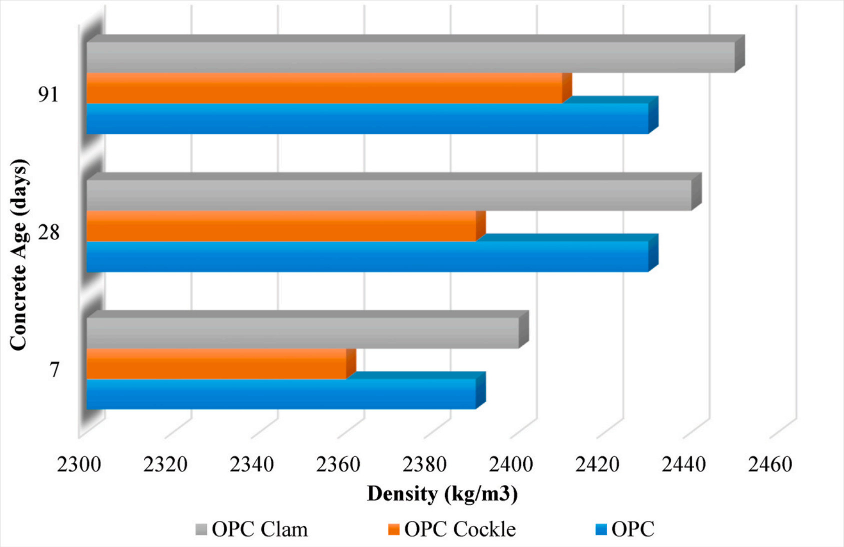


Fig. 10. Density of seashells/cement-concrete compared to a control mix [18].

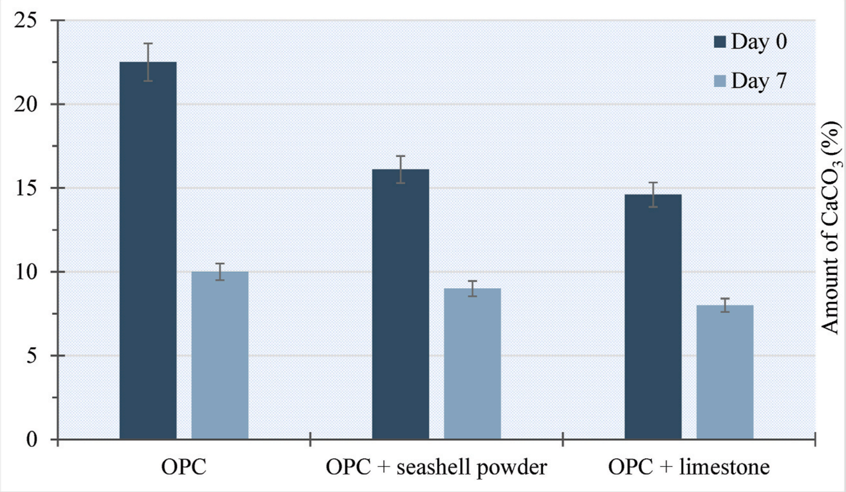


Fig. 11. Reactivity of OPC, OPC-seashell, and OPC-limestone blended cement pastes; comparing the amount of $CaCO_3$ consumed after a 7-day hydration test [14].

(*Anadara gronosa*) seashells as partial replacement of cement in concrete production. After subjecting the seashell concrete samples produced to various mechanical tests such as compressive strength, split tensile, flexural strength, and modulus of elasticity with results from concrete produced with 100% OPC which served as a control mix. It was reported that a 4% substitution level of grounded seashell serves as the threshold for compressive strength while flexural and split tensile strength results generated were higher than those of the OPC concrete. In their study, [55]; recommended a 5% seashell (Oyster shell) addition in the partial replacement of sand in concrete production. It was observed that the use of Oyster shells reduced water absorption rate, filled the available pores, and at the same time, produced a compressive strength similar to that of the control concrete produced from OPC. Senthil (2019) discovered that at 20% partial replacement of seashell with cement, the maximum strengths (Flexural and Compressive Strength) were achieved. Bharathi et al. (2016) conducted an experimental study on the use of seashells as cement and coarse aggregate in concrete and concluded that the use of seashell ash in concrete is feasible and economical [30]. carried out a comparative study on the compressive strength of mortar containing snail and clamshell ash and their mixtures as partial replacement of cement. It was observed that the mortar containing the mixture of snail and clamshell ash exhibited highest compressive strength of 38 N/mm^2 at 25% replacement level which represents the reduction of 21% compared to the reference mortar while those containing snail and clam shell ash had their maximum strength values at 20% and 25% replacement level with 58% and 38% reductions, respectively with respect to the reference mortar. It was concluded that the snail and clam and their combinations are useful as cementitious material in construction [47]. attributed the decrease in compressive strength with increase in the content of oyster shell powder compared to the reference concrete as shown in Fig. 14 to the lesser reactivity of oyster shell powder when mixed with OPC which consequently result in higher water demand and later reduced the compressive strength of concrete. Furthermore, the poor binding effect of oyster shell ash compared to OPC is responsible for a decrease in the strength of concrete [49]. [50] reported the maximum compressive strength of 28.8 N/mm^2 at 28 days curing age for concrete containing 5% periwinkle shell ash as a replacement for cement and 1% Sisal fiber as reinforcement which represent an increase of 15% compared to the reference concrete (Fig. 15).

In self-compacting concrete (SCC), which is another type of concrete requiring no additional mechanical effort for compaction, the maximum compressive strength was obtained at 10% oyster shell partial cement

Table 5
Compressive strength of concrete with varying seashells percentages compared to control mixes [13]].

References	Materials of Binding	Percentage of Cement Replacement	Mix Proportion	Compressive Strength (MPa)		
				7 days	28 days	90 days
[46]	OPC type 1	Control	1:0.355:1.27:1.92	32.00	36.20	37.90
		2%		–	30.84	–
		4%		31.50	35.80	36.50
		6%		–	28.86	–
		8%		–	30.56	–
[18]	OPC type 1	Control	1:0.36:1.62:1.41	33.8	38	41
		4% (Blood cockle)		33.5	36	38.2
		4% (marsh clam)		34	40	42
[45]	OPC type 1	(0% PSA, 0% $NaNO_3$)	1:0.6:2:4	16.67	21.12	24.86
		(30% PSA, 0% $NaNO_3$)		14.60	17.22	20.86
		(30% PSA, 1% $NaNO_3$)		17.07	20.16	23.30
		(30% PSA, 2% $NaNO_3$)		19.83	22.50	25.10
		(30% PSA, 3% $NaNO_3$)		17.90	20.24	23.83
[22]	OPC type 1	0	–	21	38	–
		2.5		22	40	–
		5		23	42	–
		7.5		21.5	40	–
		10		21.5	39.5	–
[27]	OPC type 1	Control	1:0.54:2.5:1.35	38	45	48
		5%		29.80	36	40.80
		10%		25	31	36
		15%		30	36	39.90
		25%		24	27.50	32
		50%		10	13	15
[44]	ACC 53 e Grade OPC	Control	1:0.44:1.45:2.79	20.51	27.748	
		5%		21.42	31.52	
		10%		15.616	24.4	
		15%		14.546	22.04	
		20%		13.855	20.68	
	OPC type 1	Control	1:0.54:2.5:1.35	37.5	45	47
		5%		29.5	36	42
		10%		25	33	36
		15%		30	36	40
		25%		24	27	32
		50%		10	13	15

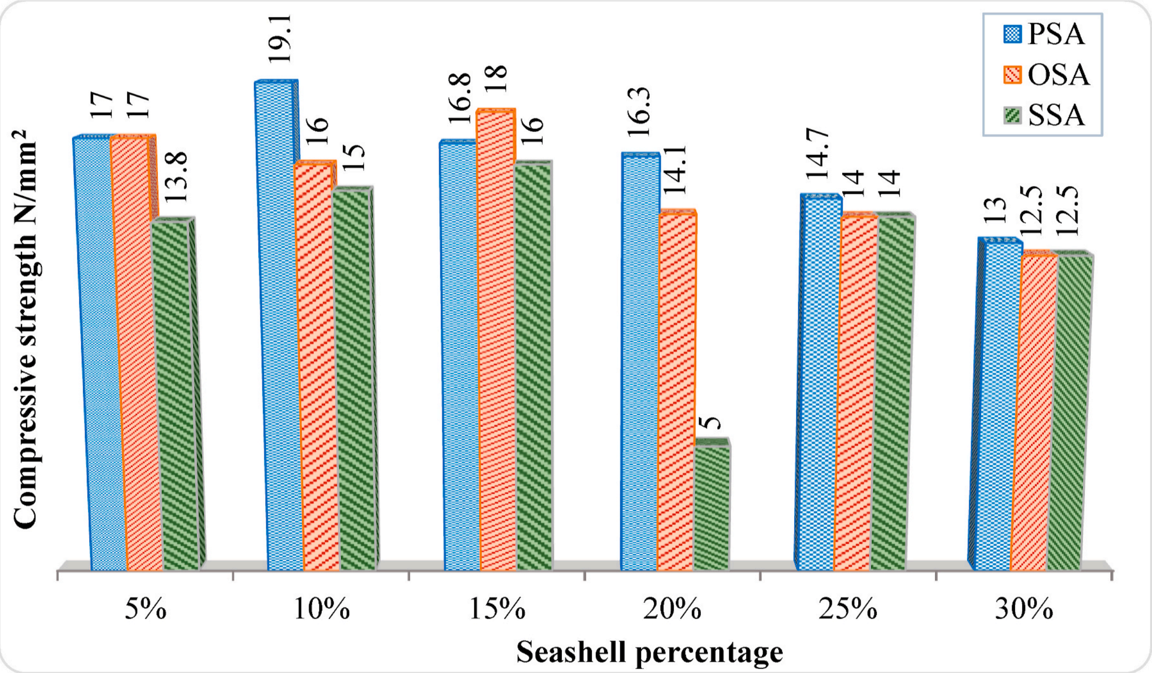


Fig. 12. Compressive strength of mortar with several percentages and kinds of seashells at 7 days [43].

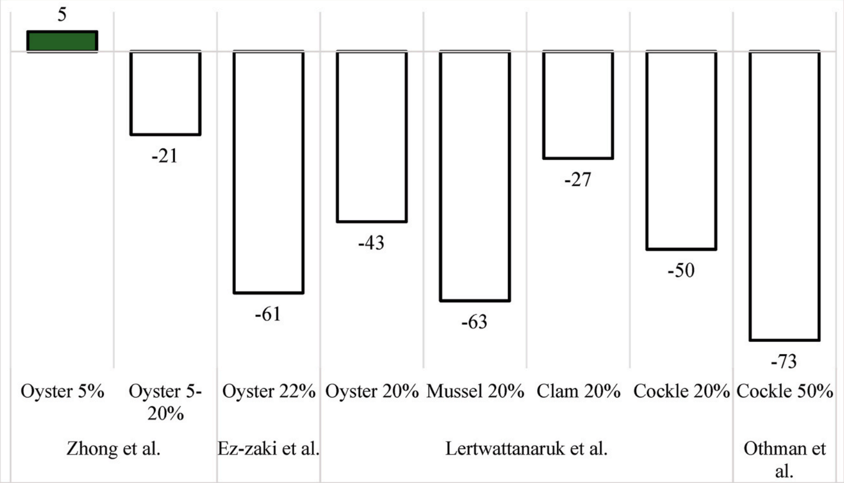


Fig. 13. % Increase [+]/decrease [−] in the 28-day compressive strength compared to control mixes for different seashell-cement mixes (Source [36].

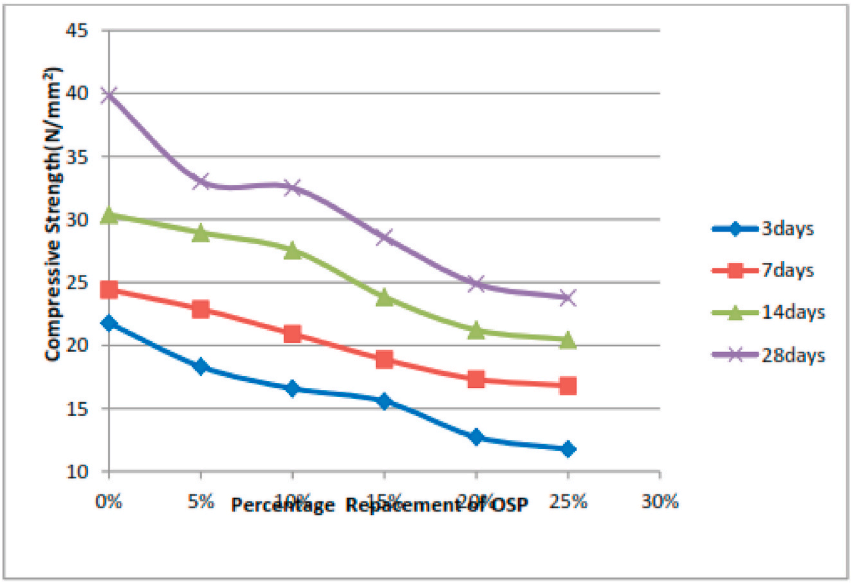


Fig. 14. Variation of concrete compressive strength with different content of oyster shell powder (Ubachukwu and Okafor, 2017).

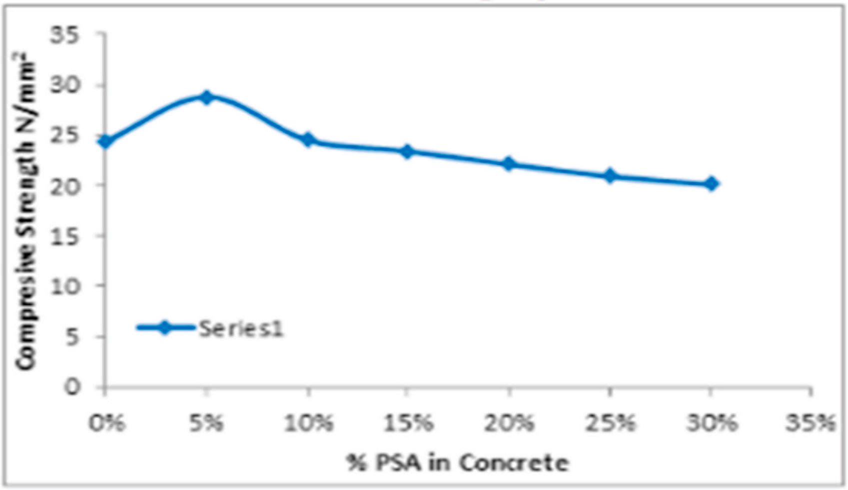


Fig. 15. Variation of 28-day concrete compressive strength with different content of periwinkle shell [50].

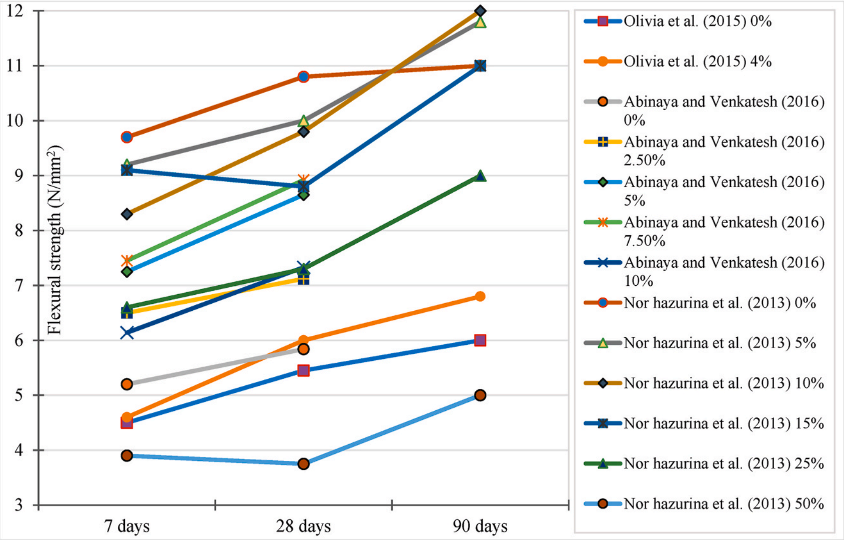


Fig. 16. Summary of flexural strength results in comparison with control mixes.

replacement as a result of its microstructural reinforcement [22]. A study documented that snail ash cement replacement of 5% gave a stronger compressive strength in 7 days compared with the control mix [44]. Hence, it can be said that seashell could add to the increase in microstructural density and blended concrete strength.

5.2. *Flexural and split tensile strength of concrete containing seashells*

Several previous studies have reported improved flexural and tensile characteristics of concrete with the inclusion of seashells in the concrete mix. The gain in tensile and flexural characteristics is majorly attributed to the high calcium content of seashell, which improved the bonding at the interface of cement paste and aggregates [21,46]. Past research shows a 5% addition of cockle ash to the concrete mix, which significantly improved the tensile strength [29]. According to research, it was discovered that the tensile strength of Cockle-OPC combination and Clam-OPC combination in comparison with OPC concrete (control) was significantly lower [18]. Also, it was reported in another research that the replacement of 5% with snail ash shell rose by 3.54% the split tensile strength when compared with the control sample [44]. [22] reported that at 10% oyster shell ash-cement replacement for conventional concrete, the maximum split tensile strength was obtained while for SCC, the maximum flexural strength was obtained at a 15% replacement level. A study carried out by Umoh (2015) employed $NaNO_3$ as an additive alongside shell ash (periwinkle) to replace cement at 0–30% range. It was noticed that at a 30% periwinkle shell replacement and a 2% $NaNO_{3,}$ the highest tensile strength was obtained. This shows the potential for $NaNO_3$ to be used in improving the tensile strength performance of large amounts of periwinkle shell ash blended cement concrete. The flexural strength after 28 days for oyster shell concrete recorded by Ref. [22] ranged between 5.84 and 8.92 N/mm^2 for replacements of 0–10%. The minimum flexural/compressive strength ratio for control concrete was 15.37%, while the maximum flexural/compressive ratio for 7.50% replacement was 22.30% [56]. Fig. 16 showing the summary of studies on flexural strength results in comparison with control mixes.

5.3. *Modulus of elasticity*

[13] found that the modulus of elasticity (MoE) of shell concrete was less than the MoE of OPC, though, the increase rate in MoE for seashell concrete is more compared to the standard. At early curing ages, the lower MoE value of seashell shows early strength development. This can be ascribed to the high CaO content in seashells [46]. It was also

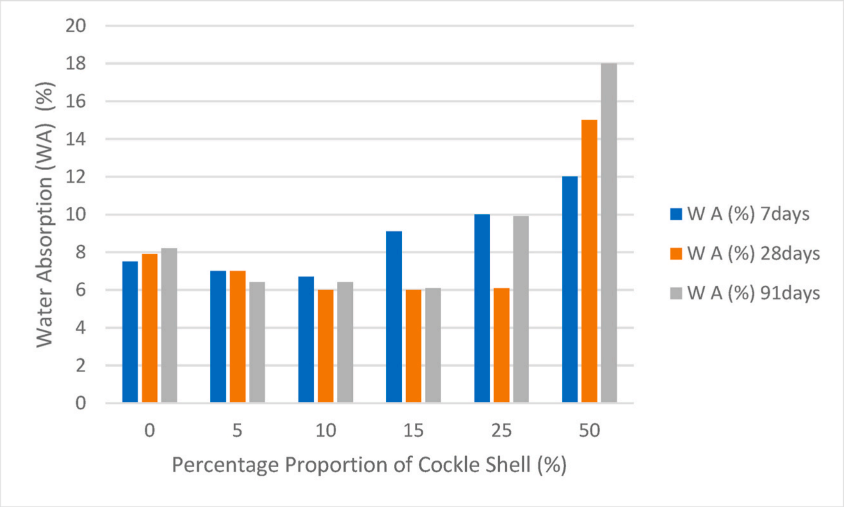


Fig. 17. Absorption test results [27].

discovered that the MoE of seashell concrete produced lower strength when compared with OPC concrete strength, and it increases with the age of concrete; this is because the MoE depends on aggregate-cement paste interfacial transition zone [42]. studied the elastic modulus of oyster shells and found that, its elastic modulus is less than that of limestone. Therefore, for concrete containing the 20% oyster shell its elastic modulus reduced by 10–15% compared with conventional concrete.

5.4. Absorption and porosity of seashell ashes

Past research as shown that the water absorption of concrete increases as the content of seashell increases due to the porous nature of seashell (Hazurina et al., 2013). However, seashell exhibited the potential for better durability performance. The absorption and porosity of concrete formed with burnt shell ashes as partial cement replacement are rarely considered and documented [13]. The results of the absorption and porosity tests on concrete made with several cockle shell ash/cement replacements were compared with standard mixes, and are shown in Fig. 17.

It is visibly shown that seashell ash of cockle minimizes the concrete absorption at low replacement percentages of 5%, 10%, and 15%. It was observed that the absorption is increased with an increase in seashell powder content. The results of porosity and absorption can be associated with the amorphous aragonite inclination of seashell ash powder. The particles of the ash join with each other and enclose the concrete matrix spaces. Due to this, the absorption and porosity are minimized. It is noted that higher absorption and porosity are attained at higher replacement levels due to the formation of voids as a result of the aragonite shape of shell ashes [40]. Cuadrado-Rica et al. (2015) reported the deficiency of queen scallop shells as a partial replacement for coarse aggregates, which could lead to a decrease in compressive strength, flexural strength, split tensile strength, and porosity of the concrete.

5.5. Permeability of concrete containing seashell

Concrete ought to be impenetrable by liquids like water (Norhazurina et al., 2013). The permeability of seashell concrete needs to be investigated more as it is scarcely reported in past studies. The Illustration in Fig. 18 compares the permeability of concrete at curing ages up to 120 days for various percentages of cement replacement with cockleshell ash to that of standard concrete. It indicates that after 120 days of curing, water permeability of the concrete mix containing cockleshell ash diminished in levels except for the 50% replacement mix [13]. The decline in seashell-concrete permeability possibly shows that the seashell ash powder is lower compared to OPC. After curing of long periods, the CaO hydrates expands, and improves the concrete matrix. Not all seashell ash readily reacts with water, especially at high percentages. It is reported that these unrestrained particles could absorb water molecules with ease (Felipe-Sese et al., 2011).

5.6. Effect on concrete porosity

A study combining oyster shells and marine sediments as replacements for cement at 8, 16, and 33% recorded an increase in the apparent porosity of mortars. The control mortar achieved an apparent porosity of 17.4%, while the 33% cement replacement achieved an increased apparent porosity of 19.4% [33]. On the other hand, another study reported the potency of concrete porosity being reduced with the use of ground cockle shells as substitutes for cement up to 15% [21]. Also, a study comparing fly ash- and lime-based mortars modified with oyster shells observed that the combination of ground oyster shells alongside lime reduced the porosity of mortar. The percentage of pores smaller than 50 nm was increased, the presence of ground oyster shells promoted the fly ash pozzolanic reaction in the mortar [24].

In the study by Ref. [33]; cement replacement with ground oyster shell was seen to improve mortar's resistance to chloride penetration. This was ascribed to the filler effect offered by the seashell powder in refining the pores. Nevertheless, concrete produced with scallop shells were recorded to give higher coefficients of chloride diffusion. Therefore, they were classified as highly porous to chloride ions [57]. Furthermore, increased percentages of ground oyster shells (>33%) in cement replacement was found to lead to the increased penetration of CO_2 into cement mortars, hence, increased risk of carbonation [33]. Fig. 19 shows the water absorption and porosity of concrete mixtures of varying seashell.

5.7. Effect on concrete shrinkage and thermal insulation

Shrinkage tests conducted after 90 days showed that mortars with ground seashells finer than cement exhibited less shrinkage when compared with control mortars. This was due to the large pore segmentation, which further resulted in a refined structure of pores [23]. As for mortars composed of fly ash and ground oyster shells, a higher shrinkage was recorded at early-age compared to the later-age shrinkage values. This was ascribed to fly ash's pozzolanic reactivity in the presence of ground oyster shells whereby lower shrinkage resulted from later-age pore refinement [24].

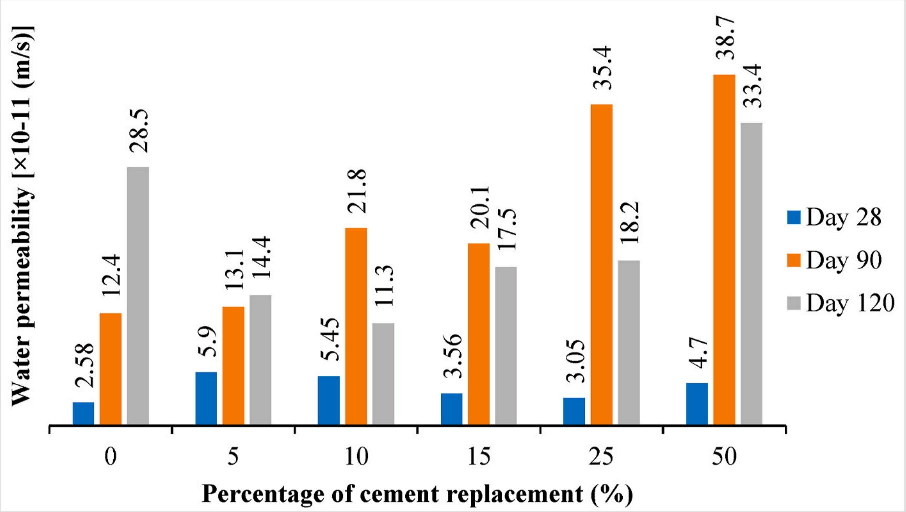


Fig. 18. Permeability of concrete mixtures of varying seashell [21].

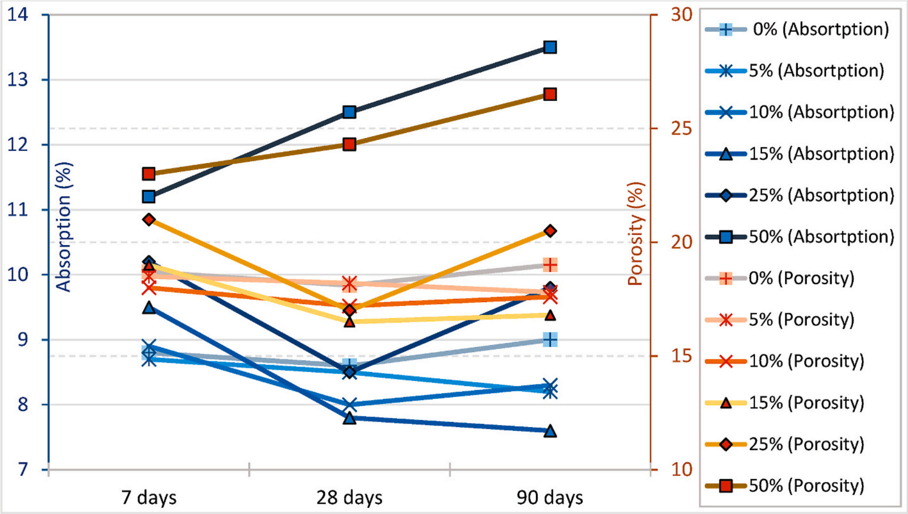


Fig. 19. Water absorption and porosity of concrete mixtures of varying seashell (Source: Norhazurina et al., 2013).

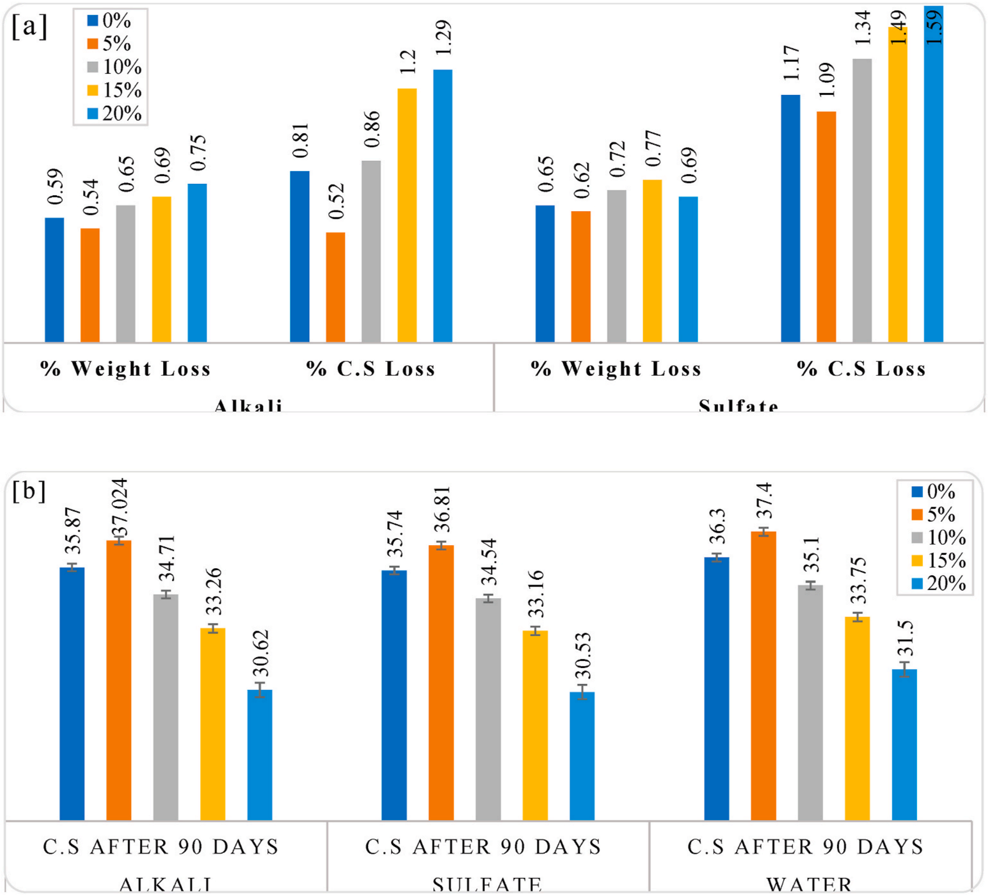


Fig. 20. Effect of Sulphate and Alkaline on [a] % weight and compressive strength (C.S) loss [b] 90 days compressive strength [58].

In the context of thermal insulation, the utilization of ground seashells as cement substitutes potentially reduces the thermal conductivity of mortars as a result of the increased permeability [23]. The rise in open porosity leads to the lower thermal conductivity of concrete, hence improved thermal insulation [37].

5.8. *Effects of sulphates and alkaline on seashell-cement concrete durability*

Since seashells are obtained from seawater or similar simulated environments, they have the potential for improved durability in salty water conditions, over conventional concrete. The resistance of concrete produced with seashells partially replacing cements to such attacks was studied using a 5% NaOH solution (alkali) and 5% $MgSO_4$ (sulphate) solutions. The results presented in Fig. 20 reveals that % loss in weight and compressive strength due to sulphate and alkaline attacks are least with the 0% and 5% seashell addition levels. It further indicated that alkaline sulphates led to a decline in compressive strength after 90 days for all mixed batches.

6. Discussion

Just like limestone, calcium carbonate is the dominant component in seashells, it can be classified in cement mortar or concrete as an inert material. Ground waste seashells, which may be utilized with or without calcination, dos not chemically react with ordinary Portland cement; it only works as a filler material. Notwithstanding, TGA results indicate that calcium oxides can be obtained from the conversion of calcium carbonates at high temperatures. As such, seashells rich in calcium oxide can be achieved by heat treatment [34,36–39]. This can improve reactivity if the concrete is composed of pozzolans.

Seashells are generally collected as waste matter, as such, before utilization in concrete production, adequate handling and treatment must be done to rid it of any form of impurity, as thoroughly as possible [19,59]. Furthermore, because of the natural plane surfaces of seashells, crushing and grinding are required to obtain particles fine enough for use as a cementitious material to aid in reducing internal voids usually present in organic materials [19,60].

There is currently insufficient literature from past studies regarding the utilization of ground seashell as substitutes for the cement to significantly conclude its impacts on concrete workability. The reduction in cement content with increasing seashell percentages could lead to improvements in workability due to reductions in hydration degree [23]. However, to use seashells as filler materials, it requires a higher fineness modulus compared to cement, which in turn leads to increased water demand [36].

Furthermore, considering the insufficient literature and conflicting outcomes reported, the effects of waste seashells on the mechanical performance of concrete are inconclusive. Strength decrease due to reduced cement content upon seashell addition could be the case. However, there could also be a positive effect on mechanical performance as a result of the filler effect [36]. In the context of durability, the higher fineness modulus of ground seashells compared to cement helps in reducing the voids in concrete, thereby contributing to reduced shrinkage when utilized as substitutes for cement [23]. Regardless of the variety of outcomes recorded in past studies, there are still conflicts concerning waste seashell's impacts on concrete durability, especially when utilized as substitutes for cement.

7. Conclusions

After examining the available literature reported by various researchers, it was noted that concrete produced with seashell ash has sufficient adequacy in lightweight structures due to its lower density compared to OPC concrete and for several structural applications pertaining to plastering. Also, Seashell usage in concrete helps in environmental sustainability and waste reduction. Seashells grinding and calcination have effects on the specific gravity, reactivity, and the resultant seashell ash surface area. Periwinkle and oyster seashells show to be top in quality types for producing seashell ash amongst various types of seashells. Also, the workability and setting time of the produced concrete are affected in general by the additions of seashell ash as cement replacement. The use of seashells increases the tensile strength properties of concrete.

Despite all the researches performed in the past on seashell usage as a cement replacement, many more questions still need to be answered in order to further develop the use of seashells for cement production and to widen its applications areas for usage as sulphate, chloride, acid, and alkali resistant cement thereby increasing durability than conventional cement. Also, further research will need to be conducted on the performance of seashells in alkali-activated cement and the combined effect of seashell ash with various admixtures.

CRediT authorship contribution statement

Gideon O. Bamigboye: Conceptualization, Writing - review & editing, critical reviewing and final approval of the version submitted. **Austin T. Nworgu:** Writing - original draft, drafting of the article, Methodology, design, Formal analysis, acquisition and analysis. **Abimbola O. Odetoyan:** Writing - review & editing, Critical reviewing and, Data curation. **Mutiu Kareem:** Writing - review & editing, Data curation, Investigation, Writing - review & editing, Critical reviewing, editing and, Data curation. **David O. Enabulele:** Data curation. **Daniel E. Bassey:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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