JOURNAL OF MATERIALS & CONSTRUCTION
Journal of Materials and Construction
ISSN 2734-9438
Website: www. jomc.vn

Partial replacement of natural sand with recycled waste oyster shells in concrete production of grade 30 MPA

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KEYWORDS

Concrete
Construction
Natural sand
Waste oyster shells
Environment

ABSTRACT

In the construction industry, concrete is a vital material, and natural sand is an essential aggregate component. However, natural sand resources are currently becoming increasingly scarce due to excessive exploitation. Furthermore, oyster shells, a waste product from aquaculture and seafood processing, are difficult to decompose and contribute to environmental pollution. Consequently, investigating the utilization of finely crushed waste oyster shells to partially substitute natural sand in concrete production represents a promising and necessary approach, simultaneously mitigating pollution and effectively utilizing available waste streams. In the present study, oyster shells were finely ground and used to replace natural sand at substitution ratios ranging from 5% to 20%. The results, based on measurements of slump, compressive strength, and water absorption of the concrete, conducted in accordance with Vietnamese standards, indicate that the crushed shell is capable of replacing up to 15% of the natural sand while maintaining the requisite properties and technical specifications of the concrete.

1. Introduction

The rapid growth of global construction activities in recent decades has placed an unsustainable burden on natural resources, most notably on natural sand. As the primary fine aggregate, sand constitutes a substantial 30 to 40 % of the volume of conventional concrete mixes [1], [2]. This immense demand has led to the overexploitation of natural sand. The extensive overexploitation of a non-renewable resource precipitates a cascade of severe environmental and socio-economic consequences. The removal of vast quantities of sand from natural ecosystems, particularly rivers and coastal areas, results in profound ecological and geographical disturbances [3]. These include accelerated riverbank and coastal erosion, critical alterations to natural river flow regimes, destabilization and imbalance of riverbed ecosystems, and a demonstrably increased risk of flooding in surrounding communities.

The situation is particularly acute in developing nations with rapid urbanization. In Vietnam, for instance, illegal and excessive mining of river sand has reached alarming levels, especially within the vital Mekong Delta [4] and the Red River Delta regions. The long-term environmental degradation in these areas threatens the livelihoods of millions and demands immediate, comprehensive intervention.

Consequently, there is an urgent and non-negotiable requirement within the building materials sector to identify, develop, and implement sustainable, environmentally friendly alternative sources of aggregates. Initial efforts have explored alternatives such as the use of crushed stone to replace natural sand [5], [6], [7] and the incorporation of industrial waste products like waste glass as a partial sand substitute [8], [9], [10]. However, the scale of the challenge necessitates the continuous exploration of novel, locally available, and high-volume waste streams.

Against this backdrop of resource depletion and environmental concern, the burgeoning aquaculture sector presents a unique opportunity for a circular economy solution. Vietnam's flourishing oyster farming and processing industry, concentrated in coastal provinces such as Tien Giang, Ben Tre, Tra Vinh, Bac Lieu, and Da Nang, generates tens of thousands of tons of waste oyster shells annually [11].

The current disposal practices for this massive volume of shell waste are overwhelmingly inadequate. The majority of oyster shells are often discharged directly into the environment without sufficient pretreatment. This practice contributes significantly to environmental pollution, degrades the aesthetic quality of coastal landscapes, and adversely impacts the health and living environment of surrounding populations.

Crucially, from a materials science perspective, waste oyster shells are not merely refuse but a valuable resource. Chemical analysis reveals a composition of over 95 % calcium carbonate ($CaCO_3$), with trace amounts of organic matter and other elements [12]. Furthermore, the shells possess a stable mechanical structure, notable hardness, and an intrinsic ability to be crushed into fine particles that exhibit physical characteristics comparable to those of natural sand. These inherent properties strongly suggest that processed waste oyster shells represent a highly viable and potent source of material capable of partially replacing natural fine aggregate in concrete production.

Many studies have already established the potential of oyster shells in construction materials. Studies have successfully demonstrated their use as an ingredient in artificial stone production [13], as a partial cement replacement (up to 30 % while maintaining technical performance) [14], and as a fine aggregate in mortar mixes, often

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Received 29/01/2026, revised 04/04/2026, accepted 06/04/2026
Link DOI: https://doi.org/10.54772/jomc.v16i01.1240

combined with materials like fly ash (FA) and ground granulated blast furnace slag (GGS) [15]. These applications have highlighted significant benefits, including potential cost reductions and enhanced resistance to chloride ion intrusion. The latter is particularly vital for coastal infrastructure, as the calcium carbonate within the shells can facilitate the sequestration of chloride ions through the formation of Friedel's salt. Nevertheless, the literature also indicates a threshold effect, where excessive shell content may compromise the matrix density and increase water absorption, potentially offsetting the chemical benefits.[16] Furthermore, research on the effects of seashell powder on the properties of cement-based materials has yielded positive outcomes.

Despite this promising foundational research, the specific application of ground oyster shells as a full or partial replacement for natural sand in structural concrete production has not yet received the broad and dedicated attention it warrants.

Therefore, this current research effort is strategically focused on exploiting the demonstrated potential of waste oyster shells to partly replace natural sand in the concrete production. To this end, the study addresses a dual environmental challenge: it significantly reduces the mounting problem of solid waste generated by the aquaculture industry while simultaneously limiting the destructive exploitation of finite natural sand resources. Ultimately, this study is intended to serve as a substantive contribution to the development and adoption of green building materials and to actively promote the principles of a circular economy within the construction sector.

2. Materials and Methods

2.1. Cement

In this study, we used Hoang Thach PCB40 cement with specifications according to Vietnamese standards TCVN 6260:2020 as shown in Table 1.

Table 1. The specifications of Hoang Thach cement PCB40.

Specification Parameters	Unit	Specification TCVN 6260:2020
Compressive strength - 3 days ± 45 minutes - 28 days ± 8 hours	MPa	≥ 18 ≥ 40
Setting time - Initial setting time - Final setting time	Min	≥ 45 ≤ 420
Fineness - 0.09 mm residue - Blaine	% cm^2/g	≤ 10 ≥ 2800
Soundness - Le chaterlier	mm	≤ 10
SO_2 content	%	≤ 3.5

2.2. Coarse aggregates

The coarse aggregate we used in this study is Da Son crushed stone. The physical and mechanical indicators of Da Son crushed stone include density, volumetric weight shown in Table 2 and granular distribution composition shown in Figure 1.

Figure 1. Da Son crushed stone.

Table 2. Experimental results of quality indicators of Da Son crushed stone according to Vietnamese standard TCVN 7572:2006.

No	Specification Parameters	Unit	Results
1	Density	g/cm^3	2.70
2	Volumetric weight	g/cm^3	1.44

2.3. Fine aggregate

In this study, the fine aggregate used was Dai Loc sand (Figure 2). The experimental results showed that the sand had a density of 2.67 g/cm^3 and a fineness modulus of 2.53 (Table 3) with a particle size distribution shown in Figure 3.

Figure 2. Dai Loc sand.

Table 3. Experimental results of Dai Loc sand according to Vietnamese standard TCVN 7572:2006.

No	Specification Parameters	Unit	Results
1	Density	g/cm^3	2.67
2	fineness modulus		2.53

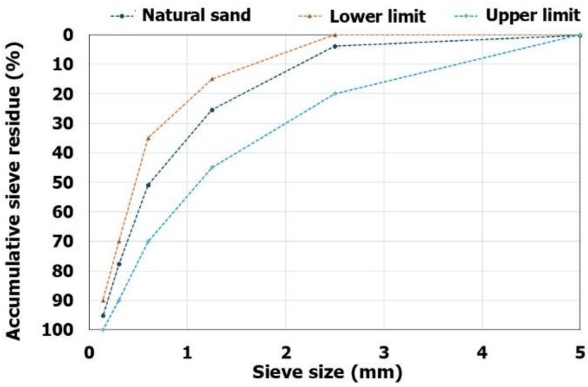

Figure 3. The particle size distribution of Dai Loc sand.

Observing the experimental particle size distribution of Dai Loc sand in Figure 3, it shows that Dai Loc sand has a particle size distribution within the permissible range according to TCVN 7572-2:2006, suitable for making fine aggregates for concrete.

2.4. Oyster shells

Figure 4. Oyster shells are crushed and sieved with a grain size range of 0.14 – 5 mm.

The oyster shells used in this study were collected from oyster processing facilities in Da Nang. They were subsequently washed to remove organic impurities, dried, and ground. After treatment, the shells were fed into a crusher to produce granules with a size range of 0.14–5 mm (Figure 4), equivalent to the particle size distribution of natural sand used in concrete (Figure 5).

Experimental results indicated that the oyster shells had a density of 2.22 g/cm^3 and a fineness modulus of 2.48 (Table 4). The particle size distribution of the crushed oyster shells is shown in Figure 5. This distribution falls within the permissible range for fine aggregates in concrete according to the Vietnamese standard TCVN 7572-2:2006.

Table 4. Experimental results of crushed oyster shells according to Vietnamese standard TCVN 7572:2006.

No	Specification Parameters	Unit	Results
1	Density	g/cm^3	2.22
2	Fineness modulus		2.48

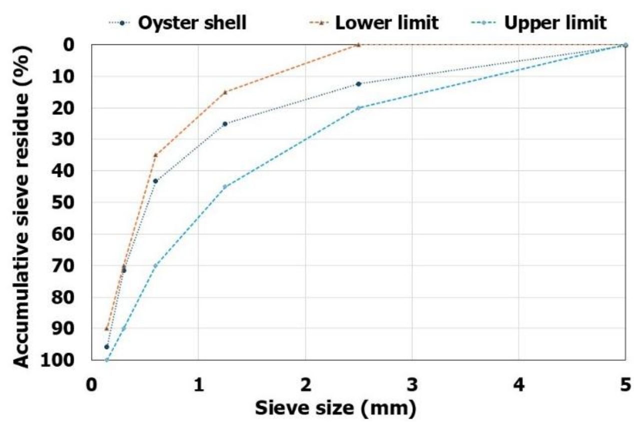

Figure 5. Particle size distribution of waste oyster shells after processing through a crusher.

2.5. Mix proportion

The composition of the concrete mixture for 1 m^3 is designed according to the grade of 30 MPa and a slump of 8 cm. In this study, natural sand was replaced with crushed oyster shell at ratios of 5 %, 10 %, 15 % and 20 % by mass. The corresponding distribution parameters are presented in Table 5 (where: Oy – oyster shells; S – sand; St – Stone; C– cement; W – water).

Table 5. Mixing proportion for 1m^3 of concrete.

Samples	% Oy	Oy (kg)	S (kg)	St (kg)	C (kg)	W (kg)
M0	0%	0.000	0.613	1.162	0.408	0.206
M1	5%	0.031	0.582	1.162	0.408	0.206
M2	10%	0.061	0.552	1.162	0.408	0.206
M3	15%	0.092	0.521	1.162	0.408	0.206
M4	20%	0.123	0.490	1.162	0.408	0.206

2.6. Slump

The slump is used as an indicator reflecting the workability of the concrete mixture. The process of measuring the slump of the concrete mixture is carried out using the N1 standard cone according to TCVN 3106:2022. The cone is laid on a flat foundation and the concrete mixture is poured into the cone in 3 equal layers; each layer is compacted 25 times with steel bars. After compacting the last layer, flatten the mouth of the cone and lift the cone upright for 5–10 seconds. The slump is determined by the height difference between the cone mouth and the top of the concrete block after the cone is lifted. The instrumentation and procedure for slump measurement experiments are illustrated in Figure 6.

Figure 6. Measuring the slump of concrete mixtures.

2.7. Sample casting and curing

The concrete mixture after mixing is homogeneous and has the required slump is molded in a mold with a size of 100 × 100 × 100 mm. Cover the surface of the sample with a wet cloth for 24 hours, then proceed to remove the mold and soak the samples in an immersion bath containing water. (Figure 7).

Figure 7. The curing of concrete samples.

2.8. Compressive strength

After 3-day, 7-day and 28-day curing, the samples were compressed on the 3000KN capacity compression machine (Figure 8) according to the Vietnamese standard TCVN 3118:2022. Each sample group (M) consists of 3 samples, in order to determine the average compressive strength of each sample so that the error obtained is minimized. Before compressing the sample, it is necessary to measure accurately to 1 mm the parallel edge pairs of the 2 compression sides.

The compressive strength (R in MPa) of a concrete sample (100 × 100 × 100 mm) is determined according to the following formula:

$$R = \alpha \times P/F$$

Where P is the destructive load (N); α is the conversion factor, $\alpha = 0.95$ and F is the compressive area of the sample (mm^2).

Figure 8. Compression machine.

2.9. Water absorption

The water absorption of concrete is determined according to the process in the Vietnamese standard TCVN 3113:2022, using three concrete samples made according to TCVN 3105:2022.

The samples were placed in the soaking tank and the water level was increased in three stages: (i) submerged 1/3 of the sample height for 1 hour; (ii) immersion of 2/3 of the sample height for 1 hour; and (iii) add water until the sample is completely submerged, while maintaining the water level approximately 5 cm above the surface of the sample. The sample is kept in this condition until it reaches water saturation.

To check the level of saturation, after every 24 hours of immersion, the sample is removed, the surface is dried with a damp cloth and weighing is carried out with an accuracy of 0.5 %. The sample is considered saturated when the mass difference between two consecutive weighings does not exceed 0.2 %. After reaching the saturation state, the sample is dried in a drying oven at 105–110 °C until the mass remains constant (the difference between two consecutive weighings is not greater than 0.2 %). The water absorption of concrete is calculated based on the difference between the saturated mass and the absolute dry mass.

Water absorption H (%) is calculated according to the formula:

$$H = (m_1 - m_0)/m_0 \times 100$$

Where m_1 is the mass of the sample in the state of water saturation (g), m_0 is the mass of the sample in the dry state with a constant mass (g).

The water absorption results were taken as the average of the three test samples, with the measurement accuracy reaching 0.1 %.

3. Results and Discussion

3.1. *Slump*

The experimental results of the slump measurement show that the workability of concrete gradually decreases when the proportion of replacing natural sand with oyster shells is increased (Figure 9). The reference sample, using 100 % natural sand has a value of 8.1 cm; samples replacing sand with oyster shells from 5 %, 10 %, 15 % and 20 % have a value of 7.6 cm, 7.2 cm; 6.8 cm and 6.4 cm, respectively.

The decrease in slump is mainly due to the angular oyster shell grain shape, layer, and porous structure of oyster shells. Therefore, the oyster shell has a higher water absorption than sand. This causes the amount of free water to decrease sharply when the content of oyster shells increases, leading to a decrease in the workability of concrete. This result is consistent with previous studies using seashell aggregates as fine aggregates [16], [17].

The results showed that when the proportion of oyster shells replacing sand was greater than 10 %, the slump of the concrete mixture decreased significantly, which could affect the construction characteristics. Therefore, for replacement level greater than 10 %, it is necessary to add superplasticizing additives or adjust the water/cement ratio to maintain workability without reducing the long-term strength.

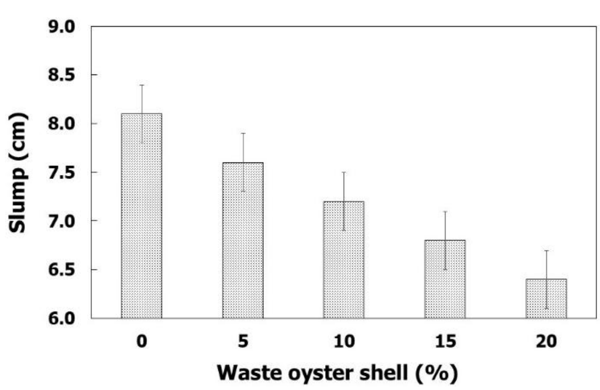

Figure 9. Concrete mixture slump.

3.2. *Compressive strength*

The compressive strength results of concrete samples after 3, 7 and 28 days of curing are shown in Figure 10.

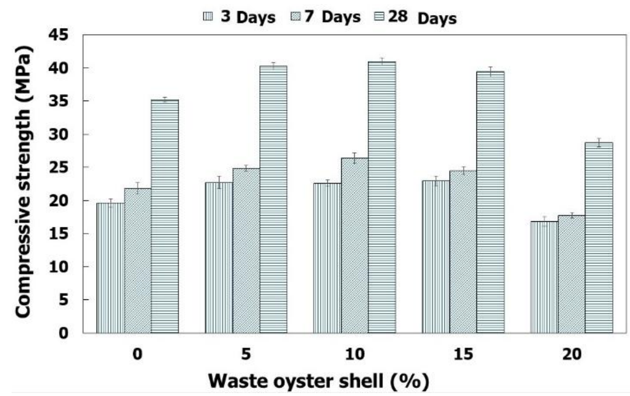

Figure 10. Compressive strength at 3,7 and 28 days of curing of concrete samples.

The data in Figure 10 shows that compressive strength increased with curing age for all samples. Notably, the strength peaked at a 10 % replacement level across all three curing periods. Specifically, compared to the reference sample (M0), the strength at 10 % replacement increased to 22.61 MPa (up 15.6 %) at 3 days, 26.35 MPa (up 20.9 %) at 7 days, and 40.95 MPa (up 16.3 %) at 28 days. Samples with substitution levels of 5 % and 15 % also exhibited 28-day strengths higher than the reference sample (40.22 MPa and 39.39 MPa, respectively). However, at a 20 % replacement level, the compressive strength dropped significantly to 28.72 MPa, a decrease of 18.4 % compared to the control sample.

Although the oyster shells were crushed to a similar particle size distribution and fineness modulus as natural sand, a noticeable increase in strength was observed at 5–15 % replacement levels. The primary reason is the surface texture of oyster shells; their layered aragonite structure and higher roughness compared to natural sand enhance the mechanical interlocking with the cement paste. Furthermore, finely ground oyster shell particles can fill capillary pores and improve the interfacial transition zone, thereby densifying the concrete microstructure and enhancing overall compressive strength. The calcium carbonate in the shells may also act as nucleation sites, promoting the formation of C-S-H gel and reacting with aluminates to form stable carboaluminates. However, when the substitution level exceeds 15 %, negative factors become dominant. The excessive water absorption of the porous shells reduces the free water available for cement hydration. Additionally, the porous and fragile nature of the shells can introduce weak points within the aggregate-paste transition zone, leading to a marked decrease in strength. These findings are consistent with previous studies using crushed seashells as fine aggregates [18], [19].

In summary, Under the same mixing conditions as natural sand, the optimal replacement rate is 10 %, which increased the 28-day compressive strength by 16.3 %. Substitution levels of 5–15 % yielded results superior or equivalent to the control sample. A replacement rate of 20 % should only be considered if combined with superplasticizers or mineral admixtures to compensate for the reduced workability and strength.

3.3. Water absorption

The water absorption of the concrete samples is measured for the sample cured 28 days. The water absorption measurement values are shown in Figure 11.

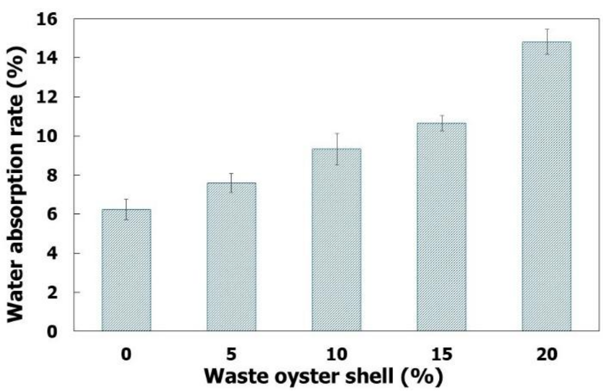

Figure 11. Water absorption of concrete samples.

The results in Figure 11 show that the water absorption of concrete gradually increased as the proportion of replacing natural sand with oyster shells increased from 0 % to 20 %. Particularly, the reference sample (0 %) had the lowest average water absorption, reaching 6.554 %. When replacing 5 % oyster shells, water absorption increases to 8.068 %; at 10 %, it is 9.877 %; and at 15 % reached 12.281 %. The sample contained 20 % of oyster shells with the highest value, at about 15.641 %, nearly 2.4 times higher than the reference sample.

This upward trend comes from the material properties of oyster shells. Compared with natural sand with a dense surface and low porosity, oyster shell particles have a porous hollow structure, many small capillary pores and a heterogeneous surface. These characteristics make oyster shell particles more capable of absorbing and retaining water. As the oyster shell content increases, the total porosity and surface area of water absorption in the concrete mixture increases, resulting in a significant increase in the water absorption of concrete.

In summary, replacing natural sand with crushed oyster shells at low levels (5–10 %) increases water absorption but remains within an acceptable range for typical uses. However, when the replacement proportion reaches 15–20 %, the increase in water absorption becomes pronounced and can adversely affect the long-term strength of the concrete, so a combination of additives or adjustment of the mix level should be considered accordingly.

4. Conclusions

Based on the experimental investigation into the partial replacement of natural sand with crushed oyster shells in concrete production, the following conclusions can be drawn:

Crushed oyster shells can be effectively utilized as a fine aggregate substitute in concrete production, meeting technical requirements at appropriate replacement levels.

The workability of the concrete mixture consistently decreased as the oyster shell content increased from 0 % to 20 %. This reduction is attributed to the angular particle shape and the higher water absorption capacity of the porous shell material compared to natural river sand. However, the 10 % mix maintained sufficient cohesive properties, allowing the formation of a stable, interlocked mineral skeleton under proper mechanical vibration.

The incorporation of crushed oyster shells significantly improved compressive strength at replacement levels between 5 % and 15 %. The optimal replacement ratio was identified at 10 %, which yielded the highest 28-day compressive strength (an increase of 16.3 % compared to the reference sample). This enhancement is primarily driven by the synergistic filler effect and $CaCO_3$ nucleation, which refines the cement matrix and strengthens the interfacial transition zone. Although the 15 % replacement level also showed positive results, the strength dropped sharply when the replacement rate reached 20 %, indicating a limit to the substitution ratio, where technical voids begin to outweigh the matrix densification.

The water absorption of the concrete increased proportionally with the replacement rate. This increase was particularly pronounced at replacement levels of 15–20 %, resulting from the porous microstructure and high specific surface area of the oyster shell particles. The data suggests that this increase reflects the intrinsic porosity of the shell particles themselves rather than a lack of density in the surrounding cement paste.

Overall, crushed oyster shells represent a promising, environmentally friendly fine aggregate. Their application offers a dual benefit: mitigating aquaculture waste pollution and reducing the overexploitation of natural sand resources, provided the replacement ratio is maintained within a reasonable range (ideally 10–15 %).

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