



Standards-Based Physical Characterization of Clamshell Waste Powder as a Partial Cement Substitute for Non-Structural Mortar

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Abstract. Portland cement production is a major contributor to global CO₂ emissions, motivating the use of locally available supplementary materials, while coastal tourism centers in Bali generate large quantities of underutilized clamshell waste rich in calcium carbonate (CaCO₃). Most previous studies on shell-based cement substitution report the performance of the final mixture without a preceding, standards-based characterization of the material itself, leaving the scientific basis for substitution incomplete. This study therefore characterizes the physical properties of clamshell waste powder to establish a replicable basis for its use as a partial cement substitute in non-structural mortar. Clamshells collected from seafood restaurants in Kedonganan, Badung, were cleaned, oven-dried, ground, and sieved to pass a No. 200 sieve (75 µm). Physical characterization specific gravity, loose bulk density, fineness, moisture content, and indicative water absorption was performed in triplicate following the relevant Indonesian National Standards (SNI). The powder exhibited a specific gravity of 2.85 g/cm³, consistent with calcite–aragonite mineralogy and indicating high CaCO₃ purity; a loose bulk density of 0.92 g/cm³; a fineness of 98% passing the No. 200 sieve, comparable to that of Portland cement; and near-zero moisture content. Benchmarking against recent international studies confirms that these values fall within the range reported for shell powders used as supplementary cementitious materials. These properties indicate that the powder is physically feasible as a fine mineral admixture with potential filler and nucleation effects, providing a validated foundation for subsequent evaluation of its mechanical performance and for developing zero waste, circular economy building products.

Keywords: Calcium Carbonate, Circular Economy, Clamshell Waste, Partial Cement Substitute, Physical Characterization, Sustainable Construction Materials

1 Introduction

The production of Portland cement is energy-intensive and releases considerable CO₂, making cement reduction a key strategy in sustainable construction. The zero waste and circular economy concepts encourage the valorization of local waste streams as alternative construction materials to reduce both resource consumption and waste

generation (Damayanti et al., 2026). In parallel, tourism driven coastal regions such as Bali face a growing waste burden; culinary activities in coastal centers such as Kedonganan and Jimbaran generate large amounts of seafood waste, including clamshells, which remain largely unutilized (Bisnis, 2025). Chemically, clamshells are dominated by calcium carbonate (CaCO_3), giving them potential as a supplementary material in cement-based systems (Aridhani et al., 2021).

Internationally, shell waste valorization in cementitious systems has advanced rapidly. A recent systematic review of seashell powder as a cement replacement synthesized the processing routes, physicochemical properties, and composite performance reported across the literature, and concluded that further investigation of processing variables and dosages is required to explain their influence on the resulting composites (da Silva et al., 2025). A parallel review of seashell-based cementitious materials likewise concluded that shell material behaves essentially as an inert constituent and that appropriate pre-treatment is decisive for material quality, while noting that mechanical properties, although reduced, generally remain within the limits set by international standards (Zhu et al., 2024). Experimental work outside Indonesia points in the same direction: characterization of *Senilia senilis* powder prior to substitution reported a specific gravity of 2.66 against 2.98 for the reference cement and a fineness within the acceptable limit for concrete production, with replacement levels of 10–20% identified as the practical range (Bamigboye et al., 2024). Reviews focused specifically on cement replacement similarly report reduced workability and progressive strength loss with increasing shell content, attributed to the dilution of reactive binder (Jasni et al., 2024).

Within Indonesia, previous studies have examined shell waste in concrete and mortar as fine-aggregate or cement substitutes (Fajar et al., 2024, 2025; Kurniawan & Prabowo, 2026; Liemawan et al., 2015; Rahmadani et al., 2025; Tansera et al., 2023), reported its influence on mechanical properties (Fadiah & Murdiyoto, 2022; Syafpoetri et al., 2018), and applied it to foamed concrete, paving blocks, and geopolymer mortar (Desimaliana et al., 2025; Nugroho, 2016; Zahroh et al., 2025). However, most of these works proceed directly to the performance of the final mixture without a preceding, comprehensive characterization of the material as the scientific basis for substitution, and not all explicitly adopt national-standard methods for material evaluation and cement specification (Nasional, 2015). This is consequential because shell composition and physical behavior vary with species, collection site, and processing route (da Silva et al., 2025; Zhu et al., 2024); values reported elsewhere cannot simply be transferred to a local waste stream. Without established physical properties such as specific gravity, fineness, and moisture content the appropriate dosage, water demand, and expected filler behavior of the powder cannot be reliably designed, and outcomes become difficult to reproduce. This gap motivates the present study.

Accordingly, this study focuses on the systematic physical characterization of clamshell waste powder as the essential first step that must precede any substitution trial. The objectives are: (1) to prepare clamshell waste powder from coastal seafood-restaurant waste through a replicable cleaning, drying, grinding, and sieving procedure; (2) to characterize its physical properties specific gravity, loose bulk density, fineness, moisture content, and indicative water absorption against the relevant Indonesian

National Standards (SNI); and (3) to assess the physical feasibility of the powder as a partial cement substitute and its readiness as a fine mineral admixture for developing sustainable, zero-waste non-structural building products such as ventilation blocks (roster). The novelty lies in placing systematic, standards-based material characterization at the front of the substitution study, and in benchmarking a locally sourced Balinese shell stream against internationally reported shell powders, providing a replicable scientific basis on which subsequent mechanical-performance evaluations can build.

2 Methodology

This experimental laboratory study was conducted at the Material Testing Laboratory, Civil Engineering Department, Politeknik Negeri Bali. The work comprised two stages: (i) preparation of clamshell waste powder and (ii) physical characterization of the powder with reference to the relevant Indonesian National Standards (SNI).

Clamshell waste was collected from seafood restaurants in Kedonganan, Badung. The shells were washed to remove organic residue and salt, oven-dried, ground, and sieved to pass a No. 200 sieve (75 μm) so that the resulting powder would be comparable in fineness to Portland cement.

Physical characterization comprised five parameters specific gravity, loose bulk density, fineness (fraction passing the No. 200 sieve), moisture content, and indicative water absorption each determined in triplicate to allow evaluation of measurement consistency. Specific gravity was determined by the pycnometer method to assess mineralogical density and CaCO_3 purity; loose bulk density was obtained from the mass of powder filling a container of known volume; fineness was measured by sieving through the No. 200 (75 μm) sieve; moisture content was determined gravimetrically from the mass loss on oven-drying; and indicative water absorption was estimated by a simplified gravimetric method to calibrate the mixing-water demand of the powder. The corresponding test methods and standard references are summarized in Table 1.

Table 1. Physical Characterization Tests, Methods, And References

Property	Test method	Reference	Replicates
Specific gravity	Pycnometer (density) method	SNI 1970:2008	3
Loose bulk density	Container of known volume	SNI 03-4804-1998	3
Fineness (passing No. 200, 75 μm)	Sieving through No. 200 sieve	SNI 03-4142-1996	3
Moisture content	Oven-dry, gravimetric	SNI 1971:2011	3
Water absorption (indicative)	Simplified gravimetric method (adapted)	-	3

Note: the indicative water absorption was obtained by an adapted (non-SSD) gravimetric procedure used solely to calibrate mixing-water demand, and is therefore not tied to a standard SSD absorption method.

Each parameter was determined on three sub-samples drawn from the same homogenised batch, and every value reported below is the arithmetic mean of the three determinations. The spread of the replicates was examined before averaging, and the

mean was accepted as representative only where the replicates were mutually consistent; for specific gravity, the parameter most sensitive to sub-sampling, the observed range is reported alongside the mean. A triplicate scheme is used here as a screening step rather than as a basis for inferential statistics, and the consequences of this are acknowledged among the limitations in Section 3.5.

The present work is deliberately restricted to physical characterization, for three reasons. First, the parameters that govern mix design decisions specific gravity, fineness, moisture content, and water demand are physical, and they must be established before any substitution ratio can be specified; proceeding to chemical or microstructural analysis without them would not remove this prerequisite. Second, the mineralogical identity of shell waste as a CaCO_3 -dominated, essentially inert material is well established in the international literature (da Silva et al., 2025; Zhu et al., 2024), so the open question for a locally sourced stream is not whether it is calcareous but whether its physical properties fall within a usable envelope. Third, the standardized physical tests adopted here are available in, and reproducible by, routine civil engineering materials laboratories, which matters for the intended practical uptake of the material by local producers. Complementary chemical and microstructural techniques (XRF, XRD, SEM) are consequently positioned as the next stage of validation rather than as omitted components of the present scope; this limitation is discussed explicitly in Section 3.5.

3 Result and Discussion

3.1 Physical Characterization of Clamshell Powder

Table 2 summarizes the characterization results, each value being the mean of three replicates. The specific gravity of 2.85 g/cm^3 (range $2.71\text{--}2.98 \text{ g/cm}^3$) slightly exceeds the generic reference range of $2.4\text{--}2.7 \text{ g/cm}^3$ but is mineralogically consistent with calcite aragonite, whose densities span approximately $2.71\text{--}2.95 \text{ g/cm}^3$ (Aridhani et al., 2021), indicating a relatively high CaCO_3 purity. Compared with Portland cement ($\approx 3.15 \text{ g/cm}^3$), the powder is about 10% lighter, so mass based substitution slightly increases paste volume, which benefits void filling. The loose bulk density of 0.92 g/cm^3 falls within the typical range for fine mineral powders ($0.8\text{--}1.2 \text{ g/cm}^3$), indicating a free-flowing powder suitable for handling and batching. The fineness of 98% passing $75 \mu\text{m}$ is comparable to cement fineness and underpins three mechanisms relevant to subsequent hardened performance: homogeneous dispersion within the binder, void filling (filler effect), and provision of nucleation sites for hydration products. The near-zero moisture content ensures that the design water–cement ratio is not disturbed during batching, while the indicative water absorption of $\approx 51\%$ obtained by a simplified gravimetric method represents interparticle water retention of the fine powder rather than saturated-surface-dry (SSD) absorption, and was used solely to calibrate mixing-water demand.

Table 2. Physical Characterization of Clamshell Waste Powder (Mean of Three Replicates)

Parameter	Result	Criterion	Remark
Specific gravity	2.85 g/cm ³	2.4–2.7 g/cm ³	Consistent with CaCO ₃ minerals
Loose bulk density	0.92 g/cm ³	0.8–1.2 g/cm ³	Satisfactory
Fineness (passing No. 200)	98%	≥ 90%	Satisfactory
Moisture content	≈ 0%	≤ 1%	Oven-dry condition
Water absorption (indicative)	≈ 51%	—	Powder water retention; w/c calibration

3.2 Comparison with Internationally Reported Shell Powders

Benchmarking the present values against recent international work places the Kedonganan powder within, and at the upper end of, the reported envelope for shell-derived cement substitutes. Reported a specific gravity of 2.66 for *Senilia senilis* powder against 2.98 for the reference cement, whereas the present powder reaches 2.85 against a nominal 3.15 g/cm³ for Portland cement (Bamigboye et al., 2024). In both cases the shell powder is the lighter constituent and the relative difference is comparable, roughly 10%, which supports the same practical inference: mass based substitution modestly increases paste volume. The somewhat higher absolute value obtained here is consistent with a calcite aragonite dominated powder of high purity and with the observation that shell composition and density vary with species and collection environment (Zhu et al., 2024).

The fineness achieved here (98% passing 75 µm) is at the finer end of what is typically reported. Obtained a shell powder slightly coarser than its reference cement, while the present powder is comparable to cement fineness (Bamigboye et al., 2024). This distinction matters because reviews of the field attribute the compensating filler and nucleation contributions of shell powder specifically to fine particle fractions, and identify grinding and pre-treatment as decisive processing variables (da Silva et al., 2025; Zhu et al., 2024). The relatively high water retention measured here is also consistent with international observations that shell powders increase water demand and reduce workability, an effect attributed to their large surface area and irregular particle morphology (Bamigboye et al., 2024; Jasni et al., 2024).

Table 3 consolidates this comparison, restricted to the sources cited above so that the benchmark remains traceable. Two patterns emerge. The measured properties of the Kedonganan powder sit inside the envelope defined by the experimental study, with density and fineness at its favourable end; and the reviews converge on processing route rather than provenance as the variable that governs whether a shell powder is usable. Both patterns support the emphasis placed here on measuring the resulting powder rather than assuming values reported for shell waste in general.

Taken together, the comparison indicates that the local waste stream is not an outlier: its physical properties fall within the range that has supported successful substitution elsewhere, while its high fineness and CaCO₃-consistent density are at the favorable end of that range. It also reinforces the rationale for local characterization, since the between-study variation evident in the international literature is precisely why values cannot be assumed rather than measured.

Table 3. Benchmarking of the Present Clamshell Powder Against Internationally Reported Shell Powders

Source	Shell material and origin	Specific gravity (g/cm ³)	Fineness	Reported role or principal finding
Present study	Mixed clamshell waste, Kedonganan, Bali, Indonesia	2.85 (cement 3.15)	98% passing 75 µm	Physically feasible as a fine mineral admixture for partial cement substitution
Bamigboye et al. (2024)	Senilia senilis, Nigeria	2.66 (cement 2.98)	Within the acceptable limit for concrete production	Replacement of 10-20% identified as the practical range
da Silva et al. (2025)	Systematic review of seashell powders	Not consolidated	Grinding identified as a decisive processing variable	Processing variables and dosage require further investigation
Zhu et al. (2024)	Review of seashell-based cementitious materials	Varies with species and collection environment	Varies with pre-treatment	Shell material behaves as an essentially inert constituent; pre-treatment is decisive for quality
Jasni et al. (2024)	Review of seashell as cement replacement	Not consolidated	Not consolidated	Reduced workability and progressive strength loss with increasing shell content

Note: entries for review articles are qualitative because those sources synthesise across multiple shell types and processing routes rather than reporting a single characterised powder. Values in parentheses are the reference cements of the respective studies.

3.3 Implications for Partial Cement Substitution

Taken together, the measured properties indicate that clamshell waste powder is physically feasible as a fine mineral admixture for partial cement replacement in non-structural mortar. Its CaCO₃-consistent density and high fineness position it as a potential microfiller: fine CaCO₃ particles can fill inter-grain voids and act as nucleation sites that promote the formation of hydration products, mechanisms widely reported to partially offset the dilution of reactive cement when inert powders are introduced(da Silva et al., 2025; Rahmadani et al., 2025; Syafpoetri et al., 2018). The near-zero moisture content and the calibrated water-retention behavior further mean that the powder can be incorporated without destabilizing the design water cement ratio, a practical prerequisite for reproducible mix design.

These characterization results establish the scientific basis that most previous shell-substitution studies omit, and they define the material envelope within which subsequent mechanical evaluation should be conducted. Because the dilution of reactive cement and the compensating filler and nucleation effects are ultimately expressed in the hardened state, the effect of substitution level on mortar strength and durability is addressed in a companion investigation. The present feasibility assessment thereby provides a replicable foundation for developing zero-waste non-structural building products such as ventilation blocks (roster) from valorized coastal clamshell waste.

3.4 Practical Considerations for Local Production

The measured properties also carry consequences for how the powder would be produced at the community scale envisaged for ventilation-block (roster) manufacture, and three of these follow directly from the values obtained.

The first concerns grinding effort. A fineness of 98% passing 75 μm was the most demanding property to achieve, and it is also the property that the international literature identifies as decisive for the filler and nucleation contributions of shell powder (da Silva et al., 2025; Zhu et al., 2024). Because the energy required for comminution rises steeply as the target fineness approaches that of Portland cement, the practical question for a local producer is not whether a finer powder is better but where the return on additional grinding begins to diminish. Establishing that threshold requires hardened-state performance data and is therefore deferred to the companion mechanical study.

The second concerns storage and batching. The near-zero moisture content that keeps the design water-cement ratio stable is a property of the powder in its oven-dried state, not of the powder as it will exist after storage. A fine calcareous powder left exposed will take up ambient humidity, which is a material consideration in a humid coastal climate, so moisture content should be treated as a control parameter verified before batching rather than as a fixed material constant. The indicative water-retention value reported here is intended to serve exactly this calibration function.

The third concerns handling volume. The loose bulk density of 0.92 g/cm³ measured here, rather than mass alone, provides the basis on which storage containers, transport batches, and mixing-plant capacity should be sized. The value also indicates a free-flowing powder that presents no unusual handling difficulty.

3.5 Limitations of the Present Study

Four limitations should be read alongside these findings. First, the assessment is confined to physical properties; chemical composition and mineralogical phase assemblage were inferred from the measured density and from the literature rather than measured directly, so the CaCO₃ purity reported here is indicative rather than quantified. Second, the water absorption value was obtained by an adapted gravimetric procedure and reflects interparticle water retention of a fine powder, not saturated-surface-dry absorption in the standard sense; it is therefore reported as a calibration parameter for mixing-water demand and should not be compared directly with SSD absorption values reported for aggregates. Third, the material derives from a single collection area (Kedonganan, Badung) and a single processing batch, so seasonal variation, species mixing, and batch-to-batch variability in the waste stream remain uncharacterized a relevant caveat given the compositional variability reported internationally (Zhu et al., 2024). Fourth, physical feasibility is a necessary but not sufficient condition: it constrains mix design but does not by itself establish hardened performance or durability, which are evaluated separately. These limitations bound the claims made here to the physical suitability of the powder as a fine mineral admixture.

4 Conclusion

Clamshell waste powder prepared from Kedonganan seafood-restaurant waste satisfies the physical feasibility criteria for use as a partial cement substitute in non-structural mortar. Standards based characterization yielded a specific gravity of 2.85 g/cm³, consistent with CaCO₃ (calcite–aragonite) mineralogy and indicating high purity; a loose bulk density of 0.92 g/cm³, typical of fine mineral powders; a fineness of 98% passing the No. 200 sieve (75 µm), comparable to Portland cement; and near-zero moisture content, ensuring a stable design water cement ratio. Benchmarking against recent international studies places these values within the range reported for shell-derived cement substitutes, with fineness and density at the favorable end of that range. The combination of CaCO₃-consistent density and high fineness indicates strong potential for filler and nucleation effects, supporting the role of the powder as a fine mineral admixture.

By placing systematic, standards-based material characterization ahead of any substitution trial, this study provides a replicable scientific basis for the valorization of coastal clamshell waste and for developing sustainable, zero-waste non-structural building products such as ventilation blocks (roster). Two directions follow. Complementary chemical and microstructural characterization X-ray fluorescence (XRF) for oxide composition, X-ray diffraction (XRD) for calcite aragonite phase identification, and scanning electron microscopy (SEM) for particle morphology and matrix interaction is recommended to quantify the CaCO₃ purity inferred here and to validate the proposed filler and nucleation mechanisms. In parallel, evaluation of the effect of substitution level on mortar mechanical performance and durability, together with characterization of batch-to-batch variability in the waste stream, is recommended as the subsequent experimental stage.

Acknowledgment

The authors gratefully acknowledge Politeknik Negeri Bali for funding this research through the DIPA PNB Regular Research Scheme, Fiscal Year 2026, and the Material Testing Laboratory of the Civil Engineering Department for facilitating the experimental program.

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