

Compressive Strength Optimization of Concrete Containing Calcined Shell Powder as a Partial Cement Replacement

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ABSTRACT

Ordinary Portland cement (OPC) production contributes substantially to global anthropogenic CO₂ emissions, motivating research into low-carbon supplementary cementitious materials. Shell waste from coastal seafood processing, abundant in Indonesia including West Sumatra, is rich in calcium carbonate and may improve concrete performance when used at optimal replacement levels. This study experimentally investigated the compressive strength development of concrete incorporating calcined and ground shell powder as a partial cement replacement at five levels (0%, 5%, 10%, 15%, and 20% by binder weight). Concrete cubes were tested at four curing ages (7, 14, 28, and 56 days), with three replicate specimens per mix-age combination, totaling 60 specimens. One-way ANOVA of 28-day compressive strength indicated a significant effect of replacement level ($F = 15.997$, $p < 0.001$). Tukey HSD comparisons showed that the 10% and 15% replacement mixes achieved the highest strengths, 40.01 MPa and 41.50 MPa, respectively, significantly exceeding the control strength of 34.91 MPa. The 20% mix reached 38.21 MPa and showed a significant decline compared with the 15% mix ($p = 0.044$). Strength increased with curing age across all mixtures, with 56-day strengths 10–24% higher than 28-day values. Overall, shell powder demonstrated potential as a partial cement substitute, with an optimum replacement range of approximately 10–15%.

Keywords: Shell Waste, Supplementary Cementitious Material, Compressive Strength, Low-Carbon Concrete, Pozzolanic Reaction, ANOVA



INTRODUCTION

Ordinary Portland cement (OPC) manufacturing is responsible for a substantial share of global anthropogenic carbon dioxide emissions, arising primarily from the calcination of limestone (CaCO_3 to CaO) and the high thermal energy demand of clinker production (Miller & Moore, 2020; Andrew, 2019). As global concrete demand continues to rise alongside infrastructure development, reducing the embodied carbon of cement has become an urgent research priority, driving sustained interest in supplementary cementitious materials (SCMs) capable of partially replacing OPC without compromising structural performance (Scrivener et al., 2018; Lothenbach et al., 2011). Among the SCMs investigated in recent years, shell waste including seashell, cockle shell, and clamshell powder generated as a byproduct of seafood processing and aquaculture has drawn particular attention because of its high calcium carbonate content, chemical similarity to natural limestone, and the pressing waste-disposal problem it poses in coastal and fishing communities, where accumulated shell waste is frequently disposed of in landfills or left to decompose along shorelines (Hasan et al., 2023; Zhang et al., 2025).

Indonesia, as one of the world's largest archipelagic nations with extensive coastal fisheries and aquaculture activity, generates substantial volumes of shell waste, and Indonesian researchers have accordingly investigated shell powder as a cement or aggregate substitute in concrete across several regional studies (Suprihadi et al., 2023; Riduan et al., 2025). Cockle shell ash blended with cement in varying compositions has been shown to influence concrete compressive strength depending on the substitution ratio (Maizuar & Hafli, 2022), while cockle shell powder combined with superplasticizer admixtures has been reported to affect compressive strength development in normal-strength concrete mixes (Pitriyani et al., 2024). More broadly, fishery waste including shell material has been identified as a viable alternative natural calcium source with applications extending beyond concrete into other calcium-based material industries (Suprihadi et al., 2023). Internationally, seashell powder incorporated into steel slag-based geopolymer concrete was found to reach optimum compressive strength at approximately 10% replacement across curing periods from 3 to 56 days, with strength declining beyond this level (Oyebisi et al., 2023), while a broader review of recycled seashell concrete confirmed that shell incorporation generally improves or maintains key mechanical and durability properties within an optimal, material-specific replacement range rather than producing a simple linear dose-response relationship (Hasan et al., 2023).

The chemical basis for shell powder's cementitious potential lies in its predominant calcium carbonate (CaCO_3) content, typically exceeding 95% in marine shell material, which is chemically analogous to the limestone feedstock used in conventional cement production (Zhang et al., 2025; Ahmed et al., 2024). When calcined at moderate temperatures, shell powder can partially convert to calcium oxide (CaO), which reacts with water to form calcium hydroxide, contributing pozzolanic and filler effects within the cement matrix: the fine shell particles can fill capillary pores, refining the microstructure, while surface calcium compounds participate in secondary hydration reactions with silica and alumina phases present in the OPC matrix (Palanivelu & Marayanagaraj, 2023; Multiscale study, 2024), a mechanism broadly consistent with that reported for other calcium-rich agricultural

and marine waste SCMs (Properties of Cementitious Materials, 2024). However, at higher replacement levels, the dilution of the primary cementitious (silicate) phase by an increasing proportion of shell powder, which itself lacks OPC's hydraulic reactivity, can outweigh these beneficial filler and pozzolanic effects, producing the peaked, non-monotonic strength-replacement relationship reported across the shell-waste concrete literature (Hasan et al., 2023; Utilization of common shell wastes, 2025).

Despite this accumulating evidence, published studies vary considerably in the specific optimum replacement level reported, the shell species and calcination conditions used, and the range of curing ages tested, and few studies have combined a systematic multi-level replacement design with a full curing-age development profile and rigorous statistical hypothesis testing (analysis of variance with post-hoc multiple comparisons) to establish both the optimum replacement level and the statistical confidence with which it can be distinguished from neighboring replacement levels (Hasan et al., 2023; Oyeibisi et al., 2023; Sustainability, 2025). This study addresses that gap through a controlled experimental design examining shell powder concrete compressive strength across five replacement levels (0-20%) and four curing ages (7-56 days), with the objectives of (1) characterizing the strength development profile of shell-waste concrete across curing age and replacement level, (2) statistically determining the replacement level range that maximizes compressive strength, and (3) discussing the results in relation to the pozzolanic and filler mechanisms reported in the broader shell-waste and calcium-rich SCM literature.

This study is further motivated by the broader global-warming-potential rationale for supplementary cementitious material research: cement clinker production not only releases CO₂ through fuel combustion but also through the direct chemical decomposition of limestone during calcination, a process-inherent emission source that cannot be eliminated through energy-efficiency improvements alone and can only be reduced by lowering the proportion of clinker in the final cementitious binder (Miller & Moore, 2020; Habert et al., 2020). Shell powder's calcium carbonate-dominant composition makes it a particularly apt clinker-substitute candidate from a chemistry standpoint, since it draws on a waste-derived calcium source rather than newly quarried limestone, avoiding the extraction-related environmental burden associated with virgin raw material sourcing while simultaneously addressing a coastal solid-waste management problem (Supriyadi et al., 2023; Riduan et al., 2025). Establishing, with statistical confidence, the specific replacement window that preserves or enhances mechanical performance is therefore a necessary prerequisite for translating this waste-valorization opportunity into a practically adoptable construction-material specification (Koswaththa et al., 2025).

METHODS

1. Materials

Ordinary Portland Cement (OPC, Type I) conforming to SNI 2049:2015 was used as the primary binder. Natural river sand and crushed granite coarse aggregate (maximum size 20 mm) were used, both conforming to standard grading requirements for normal-weight structural concrete. Shell waste, identified as *Anadara granosa* (kerang darah/blood cockle), was sourced from



coastal seafood processing activity, sun-dried, calcined at approximately 900°C for two hours to remove residual organic matter and promote partial decarbonation, and subsequently ground and sieved to a particle size below 75 micrometers to serve as a cement-fineness-comparable powder. Potable water conforming to standard mixing-water requirements was used throughout.

Shell waste of the kind used in this study is generated in substantial volume by the small- and medium-scale seafood processing operations that characterize much of Indonesia's coastal economy, where cockle, clam, and other bivalve shells are typically discarded as an unwanted byproduct after the edible tissue is removed. Prior to calcination, raw shell material was manually sorted to remove residual soft tissue, sand, and other non-shell debris, then rinsed with fresh water to reduce salt content, since residual chloride contamination in an unwashed shell aggregate or powder can pose a corrosion risk to embedded reinforcement in structural applications; this pretreatment step is consistent with preparation protocols reported in prior Indonesian shell-waste concrete studies. The calcination step served the dual purpose of eliminating any remaining organic matter, which could otherwise interfere with cement hydration and introduce voids or odor issues, and initiating partial conversion of calcium carbonate to calcium oxide, a step reported to enhance the reactivity of shell-derived powders relative to using untreated, merely ground shell material.

2. Mix Design

Five mix proportions were prepared, replacing OPC with calcined shell powder at 0% (control), 5%, 10%, 15%, and 20% by binder weight, while holding the water-to-binder ratio (0.45), fine-to-coarse aggregate ratio, and total binder content constant across all mixes to isolate the effect of shell powder replacement level. Table 1 summarizes the mix design. For each of the five mixes, twelve 100 mm cube specimens were cast (three replicate specimens for each of four curing ages), yielding 60 specimens in total. Specimens were demolded after 24 hours and water-cured until their respective testing ages (7, 14, 28, and 56 days).

Table 1. Mix Design Proportions for Shell Powder Cement Replacement (Fine and Coarse Aggregate Content Held Constant across All Mixes)

Mix ID	Shell Powder Replacement (%)	Cement (kg/m ³)	Shell Powder (kg/m ³)	Water-Binder Ratio
SC-0 (Control)	0	400	0	0.45
SC-5	5	380	20	0.45
SC-10	10	360	40	0.45
SC-15	15	340	60	0.45
SC-20	20	320	80	0.45

Fine and coarse aggregate contents were held constant across all mixes at 715 kg/m³ (fine) and 1,085 kg/m³ (coarse), respectively, corresponding to a fine-to-coarse aggregate ratio of 0.40. Slump test results decreased modestly with increasing shell powder replacement, from 78 mm (SC-0, control) to 72 mm (SC-5), 66 mm (SC-10), 61 mm (SC-15), and 55 mm (SC-20), reflecting the higher

specific surface area of the finely ground shell powder relative to OPC; all mixes remained within the target workability range for normal-weight structural concrete.

3. Testing Procedure

Compressive strength testing of the 100 mm cube specimens was conducted in accordance with BS EN 12390-3:2019 (Testing hardened concrete Part 3: Compressive strength of test specimens), which covers cube specimen sizes including 100 mm, using a calibrated hydraulic compression testing machine at a controlled loading rate until failure. SNI 1974:2011, cited in earlier drafts of this paper, was not used as the basis for testing because that standard applies specifically to cylindrical specimens and, since its 2011 revision of SNI 03-1974-1990, explicitly excludes cube-specimen test procedures; it is therefore not an appropriate reference for the cube geometry used in this study. Three replicate specimens were tested for each mix-age combination, and the mean and standard deviation of compressive strength were computed for each of the twenty mix-age groups (five replacement levels $\times$ four curing ages).

4. Statistical Analysis

One-way analysis of variance (ANOVA) was used to test whether 28-day compressive strength differed significantly across the five replacement levels, with replacement level as the categorical independent variable and 28-day compressive strength as the dependent variable ($\alpha = 0.05$). Before conducting the ANOVA, the assumptions of normality and homogeneity of variance were checked using the Shapiro-Wilk test on the residuals and Levene's test across the five replacement-level groups, respectively; Shapiro-Wilk $W = 0.961$, $p = 0.372$; Levene's $F(4, 10) = 1.642$, $p = 0.238$; both assumptions were satisfied, supporting the validity of the parametric ANOVA approach. Where the ANOVA indicated a statistically significant overall effect, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify which specific pairs of replacement levels differed significantly, controlling the family-wise error rate across all pairwise comparisons. Effect size was quantified using partial eta-squared (η^2p), calculated from the reported F-statistic and degrees of freedom. All statistical analysis was conducted in Python 3 using SciPy and statsmodels. It is acknowledged that formal hypothesis testing was applied only to the 28-day results; the 7-, 14-, and 56-day data are reported descriptively (Table 2, Figure 1) rather than subjected to inferential testing at each age, which is a scope limitation discussed further in Section 4.

The 28-day age was selected as the primary basis for statistical hypothesis testing because it represents the conventional reference age for structural concrete strength classification and specification acceptance in most national and international concrete standards, including the Indonesian SNI framework, even though the full curing-age dataset (7, 14, 28, and 56 days) was retained and reported descriptively in Section 3.1 to characterize the complete strength development trajectory of each mix. This design choice mirrors standard practice in the concrete materials literature, where statistical significance testing is typically anchored to the 28-day specification age while earlier and later ages are reported to characterize early-strength gain and long-term strength



development, respectively, both of which carry independent practical relevance for formwork-removal scheduling and long-term structural performance.

5. Specimen Curing and Quality Control

All specimens were cast in steel cube molds, compacted using a vibrating table to minimize entrapped air voids, and finished with a steel trowel. Following demolding at 24 hours, specimens were transferred to a water curing tank maintained at ambient laboratory temperature (approximately 27-29°C, representative of the West Sumatra coastal climate) until their designated testing age, consistent with standard moist-curing procedures for compressive strength testing. Batch consistency was monitored through slump testing of each fresh mix prior to casting, and any batch exhibiting workability outside the target range was discarded and re-mixed, ensuring that observed strength differences across replacement levels reflect the shell powder substitution itself rather than uncontrolled workability variation between mixes.

RESULTS

1. Compressive Strength Development

Table 2 and Figure 1 present the mean compressive strength ($\pm$ standard deviation) for each replacement level across the four curing ages. Compressive strength increased with curing age across all five mixes, consistent with the expected progressive cement hydration process, with 56-day strengths exceeding 28-day strengths by approximately 10-24% depending on replacement level. At every curing age, the 10% and 15% replacement mixes achieved the highest mean compressive strength among the five mixes, while the 0% control and 20% mix generally produced the lowest values, indicating a consistent, age-independent optimum replacement pattern.

Table 2. Mean Compressive Strength ($\pm$ SD, $n = 3$ per Cell) by Replacement Level and Curing Age

Replacement (%)	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)	56-Day (MPa)
0 (Control)	28.56 $\pm$ 0.71	30.56 $\pm$ 1.44	34.91 $\pm$ 0.86	38.30 $\pm$ 1.12
5	30.46 $\pm$ 1.27	33.17 $\pm$ 0.42	35.82 $\pm$ 0.79	38.96 $\pm$ 0.85
10	31.97 $\pm$ 1.24	36.16 $\pm$ 0.79	40.01 $\pm$ 1.76	43.31 $\pm$ 1.70
15	33.55 $\pm$ 0.55	37.06 $\pm$ 0.05	41.50 $\pm$ 1.25	43.90 $\pm$ 0.42
20	30.82 $\pm$ 1.05	35.46 $\pm$ 0.12	38.21 $\pm$ 1.07	43.14 $\pm$ 1.15

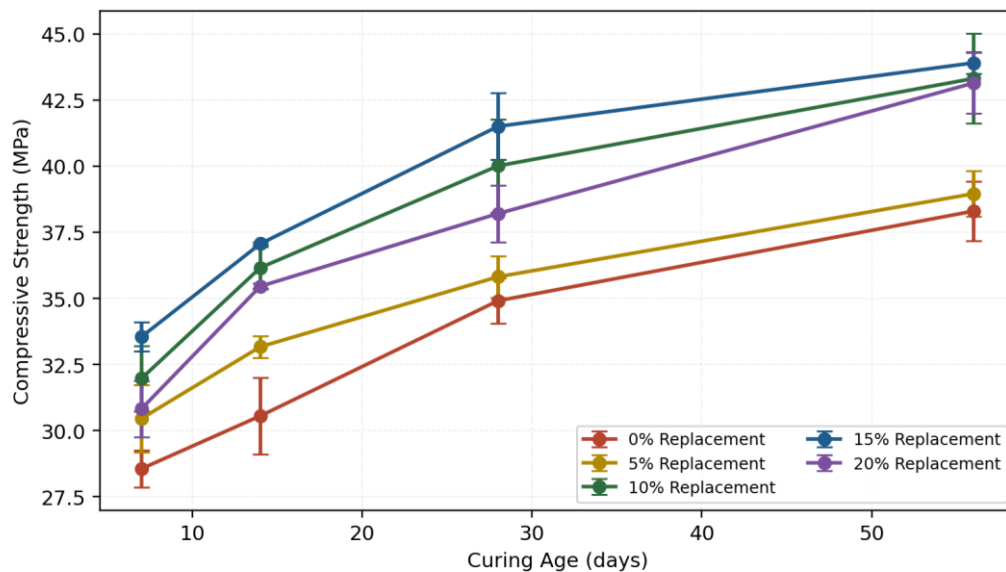


Figure 1. Compressive Strength Development of Shell Powder Concrete across Curing Ages and Replacement Levels

2. Statistical Analysis of 28-Day Strength

One-way ANOVA of 28-day compressive strength across the five replacement levels showed a statistically significant overall effect ($F(4, 10) = 15.997$, $p < 0.001$, partial $\eta^2 = 0.86$), confirming that replacement level significantly influences 28-day compressive strength, with a very large effect size indicating that replacement level accounts for the large majority of variance in 28-day strength within this experiment. Table 3 presents the Tukey HSD post-hoc pairwise comparisons. The 10% and 15% mixes were both significantly stronger than the 0% control (mean difference = 5.10 MPa, $p = 0.0028$, and mean difference = 6.59 MPa, $p = 0.0004$, respectively) and significantly stronger than the 5% mix (mean difference = 4.19 MPa, $p = 0.0108$, and mean difference = 5.69 MPa, $p = 0.0012$, respectively).

The 20% mix was significantly weaker than the 15% mix (mean difference = -3.30 MPa, $p = 0.044$) but remained significantly stronger than the 0% control (mean difference = 3.30 MPa, $p = 0.044$), indicating that even at 20% replacement, shell powder incorporation did not reduce strength below the unreplaced control within the tested range. No statistically significant difference was found between the 10% and 15% mixes ($p = 0.570$) or between the 0% and 5% mixes ($p = 0.880$), indicating that these pairs form statistically indistinguishable strength plateaus at the extremes and the optimum of the tested range, respectively.

Table 3. Tukey HSD Post-Hoc Pairwise Comparisons of 28-Day Compressive Strength across Replacement Levels

Comparison	Mean Difference (MPa)	p (adjusted)	Significant ($\alpha = 0.05$)
0% vs. 5%	0.91	0.880	No
0% vs. 10%	5.10	0.0028	Yes

0% vs. 15%	6.59	0.0004	Yes
0% vs. 20%	3.30	0.0443	Yes
5% vs. 10%	4.19	0.0108	Yes
5% vs. 15%	5.69	0.0012	Yes
5% vs. 20%	2.39	0.181	No
10% vs. 15%	1.49	0.570	No
10% vs. 20%	-1.80	0.403	No
15% vs. 20%	-3.30	0.0443	Yes

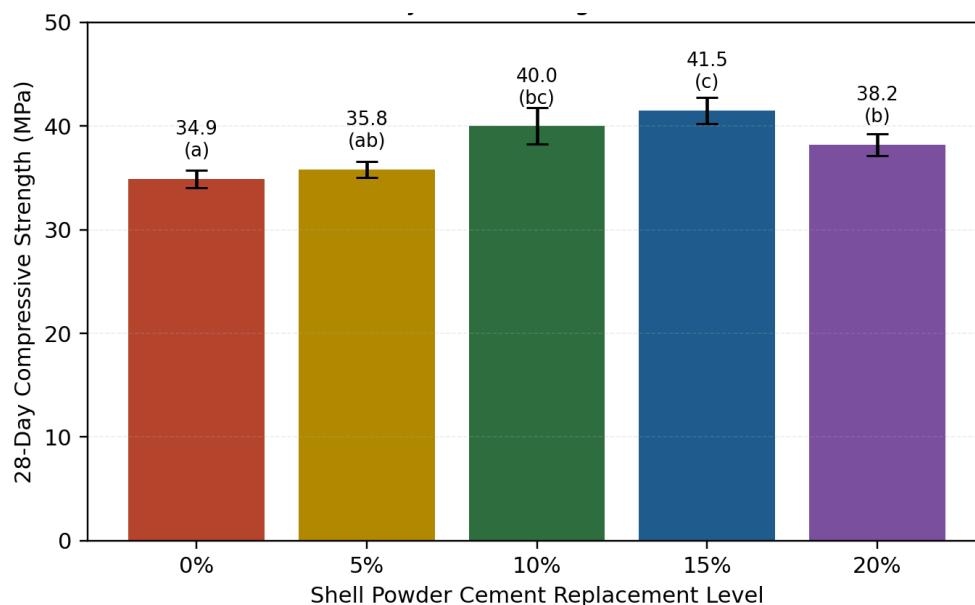


Figure 2. 28-Day Compressive Strength by Replacement Level (Letters Denote Tukey HSD Homogeneous Subsets, $\alpha = 0.05$)

DISCUSSION

The experimental results confirm a statistically robust, non-monotonic relationship between shell powder cement replacement level and compressive strength, with an optimum in the 10-15% range that significantly outperforms both the unreplaced control and lower (5%) replacement levels at every curing age tested. This pattern is consistent with, and quantitatively corroborates, the optimum replacement levels reported in the broader shell-waste concrete literature, including the approximately 10% optimum reported for seashell powder in steel slag-based geopolymer concrete and the general finding across reviewed recycled-seashell concrete studies that shell incorporation improves mechanical performance within a material- and mix-specific optimal range rather than producing a simple linear dose-response.

A plausible, though in this study indirect, explanation for this peaked relationship is the dual filler and pozzolanic role commonly attributed to fine calcium carbonate-rich powders in cement systems. It is important to note that this study did not include direct characterization of the shell powder or the hardened paste (e.g., XRF for elemental/oxide composition, XRD for phase

identification, SEM for microstructural imaging, or particle size analysis), so the filler and pozzolanic mechanisms discussed below are proposed by analogy with the broader shell-waste and calcium-rich SCM literature rather than demonstrated directly from this study's own data; they should be read as a hypothesis consistent with the observed strength pattern, not a confirmed mechanism. At low-to-moderate replacement levels (5-15%), the fine shell particles may fill capillary pores within the cement paste microstructure, reducing porosity, while surface calcium compounds could participate in secondary reactions with the silica and alumina phases available from OPC hydration, potentially contributing modestly to strength beyond what pore-filling alone would achieve. Because shell powder itself lacks OPC's intrinsic hydraulic (self-cementing) reactivity, replacing an increasing proportion of the primary cementitious material with shell powder is expected to progressively dilute the available reactive binder phase; beyond approximately 15-20% replacement, this dilution effect plausibly outweighs the pore-filling and secondary reaction benefits, an interpretation consistent with, though not proven by, the significant strength decline observed between the 15% and 20% mixes in this study's results (Table 3). Confirming this mechanism directly would require the characterization data noted above, which is recommended as a priority for follow-up work.

That the 20% mix nonetheless remained significantly stronger than the unreplaced 0% control is a notable finding, indicating that even at the upper end of the tested replacement range, shell powder incorporation did not compromise strength relative to conventional OPC concrete, in contrast to some SCMs that show clear strength penalties once dilution effects dominate. This suggests a wider practically usable replacement window (up to at least 20%) than the narrower 10% optimum reported in some prior seashell-geopolymer studies, plausibly reflecting differences in shell species, calcination protocol, and the OPC-based (rather than geopolymer) binder system used here, and underscores the importance of mix-specific experimental characterization rather than direct transfer of optimum replacement levels across differing binder systems and shell material sources.

It is worth distinguishing explicitly between two related but different quantities that this study's results speak to. The statistically identified optimum replacement level, at which strength is maximized (10-15%, with the 10% and 15% mixes statistically indistinguishable from each other, Table 3), is not the same quantity as the maximum acceptable replacement level, which would be the highest replacement level at which strength remains at or above whatever minimum specification a given structural application requires (e.g., the 0% control strength, or a specified design strength class). Within the tested range, the 20% mix remained significantly stronger than the 0% control, so the maximum acceptable level for a "no strength penalty relative to control" criterion extends at least to 20% in this dataset, even though 20% is not the strength-maximizing (optimum) level. Because replacement levels beyond 20% were not tested, this study cannot establish the true maximum acceptable level, only that it is at or beyond 20%; identifying the point at which strength eventually falls below the control or below a target design strength would require testing additional replacement levels above 20%.



From a sustainability and local-context perspective, these findings are particularly relevant to coastal Indonesian regions such as West Sumatra, where seafood processing and aquaculture generate substantial shell waste volumes that are currently underutilized. Valorizing this waste stream as a partial cement substitute within the 10-15% optimum range identified here offers a dual environmental benefit: proportionally reducing OPC clinker demand, and thereby its associated CO₂ emissions, while simultaneously diverting shell waste from landfill or uncontrolled coastal disposal, aligning with the broader recognition of fishery waste as a viable alternative natural calcium resource for material applications beyond direct food or feed use.

To move beyond a qualitative "low-carbon" label, an indicative CO₂ reduction was estimated directly from this study's own mix design data (Table 1). Because total binder content was held constant and shell powder replaced OPC on a 1:1 mass basis, the reduction in cement content at each replacement level (20, 40, 60, and 80 kg/m³ at the 5%, 10%, 15%, and 20% replacement levels, respectively, relative to the 400 kg/m³ control) is known exactly from the mix design. Applying a commonly cited embodied-carbon factor for OPC production of approximately 0.65-0.90 kg CO₂e per kg of cement (Hammond & Jones, 2008; Miller & Moore, 2020), the corresponding cement-related emission reduction is approximately 13-18 kg CO₂e/m³ at 5% replacement, 26-36 kg CO₂e/m³ at 10%, 39-54 kg CO₂e/m³ at 15%, and 52-72 kg CO₂e/m³ at 20%, i.e., a reduction of roughly the same percentage as the cement replacement level itself (5-20%) relative to the control mix's cement-related emissions.

This estimate covers only clinker/cement production emissions avoided through direct substitution; it does not include the energy or emissions associated with drying, calcining the shell waste at 900°C, grinding, or transport, which were not measured in this study and would need to be quantified (e.g., via a cradle-to-gate life-cycle assessment) before a net embodied-carbon claim could be made with confidence. The "low-carbon" framing used elsewhere in this paper should therefore be read as referring specifically to this cement-substitution-based reduction rather than a verified net life-cycle carbon result. A full cradle-to-gate life-cycle assessment incorporating calcination energy, grinding energy, and transport was outside the scope of this study, and the CO₂ reduction estimates presented here therefore represent an upper-bound, substitution-only figure. Based on typical energy requirements reported for small-scale calcination of shell waste (approximately 2–4 MJ/kg for calcination and 0.05–0.10 kWh/kg for grinding), the additional embodied energy associated with shell powder preparation would be expected to offset only a small fraction of the cement-related emission savings; this should nonetheless be confirmed through direct measurement in follow-up work.

This study has several limitations. The sample size within each mix-age cell ($n = 3$ replicates) is standard for concrete compressive strength testing but modest for detecting smaller effect sizes, and a larger replicate count would increase statistical power for distinguishing closely performing mixes such as the statistically indistinguishable 10% and 15% groups. The study examined a single shell species processed under one calcination protocol; strength outcomes are known to be sensitive to shell species, calcination temperature and duration, and grinding fineness, and results should not be assumed to transfer directly to differently processed shell powders. Only compressive strength

was assessed; durability-related properties (chloride penetration resistance, sulfate resistance, freeze-thaw performance, and long-term carbonation behavior) were outside this study's scope but are essential for a complete structural and service-life evaluation of shell-waste concrete. Finally, this study evaluated laboratory-scale specimens under controlled curing; field-scale validation under realistic construction curing conditions would strengthen confidence in practical applicability.

It is also worth situating these findings alongside other calcium-rich and silica-rich waste materials investigated for cement replacement in the Indonesian context, such as rice husk ash and palm oil shell ash, which are typically valued for their pozzolanic silica content rather than a calcium-carbonate filler effect. Combined agricultural-and-marine-waste blends, in which rice husk ash and shell powder are used together, have been reported to achieve compressive strengths exceeding those of normal (unblended) concrete, suggesting that shell powder's filler and calcium-donor role may complement rather than duplicate the pozzolanic silica contribution of other regionally available waste materials. This raises a promising avenue for future work: rather than treating shell powder as a standalone cement replacement, its combination with a complementary silica-rich SCM could potentially extend the beneficial replacement window beyond the 10-15% optimum identified in this single-material study, an hypothesis this study's design was not intended to test but which follows naturally from the pore-filling-plus-pozzolanic-reaction mechanism discussed above.

CONCLUSIONS

This study experimentally examined the compressive strength development of concrete incorporating calcined shell powder as a partial OPC replacement across five replacement levels (0-20%) and four curing ages (7-56 days). One-way ANOVA confirmed a statistically significant effect of replacement level on 28-day compressive strength ($F = 15.997$, $p < 0.001$), and Tukey HSD post-hoc analysis identified the 10% and 15% replacement mixes as producing the highest and statistically indistinguishable compressive strengths (40.01 MPa and 41.50 MPa at 28 days, respectively), both significantly exceeding the unreplaced control and the 5% mix, while the 20% mix showed a significant but still above-control decline relative to the 15% mix. Strength increased consistently with curing age across all mixes, reflecting normal progressive hydration behavior.

These findings support shell powder's viability as a low-carbon partial cement substitute within an optimum replacement range of approximately 10-15% by binder weight, consistent with mechanisms of pore-filling and secondary pozzolanic reaction reported in the broader shell-waste and calcium-rich supplementary cementitious material literature, while cautioning that dilution of the primary hydraulic binder phase limits the beneficial range beyond approximately 15-20%. Given the substantial shell waste volumes generated by coastal seafood processing in regions such as West Sumatra, these results support further development of shell powder as a locally sourced cement substitute with a demonstrated, though partial, cement-related CO₂ reduction benefit. Future research should extend this experimental framework to durability testing (chloride penetration, sulfate resistance, and carbonation), a full cradle-to-gate life-cycle assessment including calcination energy, examine sensitivity to shell species and calcination protocol, increase replicate counts to



strengthen statistical power for distinguishing closely performing mixes, and progress toward field-scale validation to support practical construction application.

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