Available online at https://sextante-ensb.com

Revista Sextante

ISSN : 2665-3923

Volume: 34 Issue: 01 (2026)

Structural Behaviour of Eco-Coastal Alkali-Activated Slag-Based Wave-Impact-Resistant Blocks Containing Recycled Seashell Aggregates under Marine Exposure

Noor Muhammad Rafai[a]*, Sadullah Younas Gondal[b], Fammaz Ali[c], Muhammad Munawar[d], Maaz Khan[e], Farhan Khalid[f], Muhammad Mudassar Abbas[g]

[a] *Corresponding Author: NED University of Engineering and Technology (NEDUET), Karachi, Pakistan (nqaz80@gmail.com)*
[b] *ECEC - East Consulting Engineering Company, Jeddah, Kingdom of Saudi Arabia*
[c] *Structural Engineer, Coventry University, United Kingdom (UK)*
[d] *Tehsil Officer (I&S), Local Government Department, Khyber Pakhtunkhwa, Pakistan*
[e] *University of Engineering and Technology (UET), Peshawar, Pakistan*
[f] *Department of Civil, Construction, and Environmental Engineering, School of Engineering, University of Alabama at Birmingham, AL 35294, USA*
[g] *University of Engineering and Technology (UET), Taxila, Pakistan*

Article History
Received August 23th, 2026
Accepted October 29th, 2026
Published November 09th, 2026

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Abstract
Coastal protection units are subjected to combined hydraulic, mechanical, and chemical forces such as multiple wave impacts, abrasion from waves, chloride and sulfate penetration, and wetting–drying. The purpose of this study was to establish an experimental system that could be used to test alkali-activated slag (AAS) blocks using recycled seashell aggregate (RSA) as partial volumetric replacement of natural coarse aggregate (NCA). Five different mixtures were investigated: 0%, 10%, 20%, 30% and 40% seashell aggregate. The subjects included fresh state, density, compressive, splitting tensile, flexural strength, energy absorption under impact load, abrasion, and simulated marine exposure. The article included fresh state, density, compressive strength, splitting tensile strength, flexural strength, energy absorption under impact load, abrasion and simulated marine exposure. A multi-criteria framework and cradle-to-gate life cycle assessment were also identified. Since laboratory measurements are unavailable, the numerical tables of this draft explicitly include illustrative estimates (not experimental data) that underlie the proposed analysis. The illustrative scenario proposed a non-linear response, with a moderate percentage of shell incorporation as a possible compromise for both mechanical properties and waste utilization, and increased absorption for higher replacement percentages, which lead to a decrease in strength retention. These values were not experimental and were not relied upon for statistical significance or as a final optimum. The manuscript will thus be a testable experimental model and a full reporting structure, while the publication of the manuscript as an empirical article would necessitate the replacement of all simulated values with lab and life-cycle values.

Keywords: alkali-activated slag, recycled seashell aggregate, coastal protection, wave impact, marine durability, abrasion resistance, life-cycle assessment and circular construction.

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1. Introduction

1.1. Background and research context

Infrastructure for the coast serves to safeguard settlements, port facilities, transport links and other assets against erosion, inundation, and wave impacts. Seawalls, breakwaters, revetments and armour units are exposed to hydrodynamic, cyclic loading, impact, abrasion and chloride, sulfate and magnesium bearing seawaters. These actions can begin a cracking and surface loss, and can cause the pores to change and begin progressive deterioration. The selection of material for coastal units should not only have compressive strength, but also tensile strength, flexural strength, impact resistance, abrasion resistance, and resistance to representative exposure conditions (Qu et al., 2021; Cai & Liu, 2024). (Cao et al., 2021; Qu et al., 2021; Aliasgary et al., 2025).

The environmental impact of traditional Portland-cement concrete has spurred the search for alternative cements and recycled materials. Alkali-Activated Materials are those that incorporate precursors rich in aluminium and silicon, as ground granulated blast-furnace slag (GGBFS) and are activated by alkaline solutions. Calcium-(alumino)-silicate-hydrate-type reaction products tend to occur in calcium-rich slag systems. However, their performance relies on the precursors' chemistry, the composition of the activators, the ratio of liquid to binder, curing, and exposure regime, and a lower-carbon profile should not be taken for granted without a comprehensive life-cycle assessment (Nikravan et al., 2023). (Nikravan et al., 2023; Hamada et al., 2025).

The wastes from fisheries, aquaculture, and seafood processing have been studied as aggregates and/or binders in cementitious materials. Most shells are calcium-carbonate based biogenic materials but the density, absorption, shape, surface texture and mineralogy varies among species and processing history. Strength has been reported as being maintained or even enhanced at low replacement levels while workability and mechanical performance is reported to decrease at higher contents. The results are influenced by the grading, shell treatment, replacement basis, and matrix compatibility (Bamigboye et al., 2021; Hamada et al., 2023, 2025; Zhu et al., 2024). (Bamigboye et al., 2021; Hamada et al., 2023; Zhu et al., 2024; Hamada et al., 2025).

Slag derived binder along with recycled shell aggregate may help to minimise virgin aggregate usage and provide a value chain for marine wastes. However, the relationship between the two has to be considered as a whole system. A shell particle can change the packing arrangement or the aggregate–binder interfacial transition zone (ITZ), which can affect crack initiation, moisture transport and resistance of cyclic hydraulic and chemical actions. The quality of the interface and the porosity of the concrete are critical to the mechanical and durability characteristics of mussel-shell and recycled-aggregate concrete, as emphasized in recent research (Construction and Building Materials, 2023, 371, 130825). (Chen et al., 2023; Hamada et al., 2023; Zhu et al., 2024).

1.2. Problem statement and research gap

Research has been conducted on all the three mentioned materials, but there is limited evidence that has integrated all three of the above materials used in the construction of AAS blocks in coastal areas. Especially, the tensile and flexural behaviour, impact energy absorption, abrasion, residual strength after multi-ion exposure and hydraulic block stability, after the shell replacement, shall be systematically evaluated. No previous findings on seashell-concrete can be directly applicable to AAS composites, as there are differences in binder chemistry and interfacial reactions. Similarly, material level impact testing does not provide a test for hydraulic stability of an entire armour unit. (Gökçe, 2024; Cai & Liu, 2024; Ma et al., 2025).

A coordinated experimental design was used to fill the research gaps and included: (1) varying the level of the replacement of the shells in the volume; (2) measuring material-scale properties before and after marine exposure; (3) characterizing the microstructures; and (4) testing selected block configurations in a wave flume. The environmental performance was not assumed based on recycled content, but rather considered a comparative life-cycle issue.

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1.3. Aim and objectives

- This study was conducted to investigate the effects of using recycled seashell aggregates in AAS blocks for coastal protection and their environmental impacts.
- The aim is to replace the natural coarse aggregate with processed seashells in the composites by 0%, 10%, 20%, 30% and 40% (by volume).
- To investigate the effect of shell replacement on the density, compressive strength, splitting tensile strength, flexural strength, impact energy absorption and abrasion.
- In order to determine the changes of mass, water absorption and residual strength after exposure to seawater, chlorides, sulfates and wetting–drying cycles, the following laboratory tests were carried out.
- To correlate measurable microstructural properties with mechanical and durability properties and to evaluate some of the mixtures under controlled wave-flume conditions.
- To compare mixtures by using multi-criteria performance assessment and indicators of life-cycle.

1.4. Research hypotheses

Code	Hypothesis
H1	Seashell aggregate replacement level significantly affected the compressive strength of AAS composites.
H2	Seashell aggregate incorporation significantly affected splitting tensile and flexural strength.
H3	Seashell replacement level significantly affected impact energy absorption and abrasion resistance.
H4	Marine exposure significantly affected mechanical properties and residual strength, and the magnitude of the effect varied with shell replacement level.
H5	Quantified microstructural characteristics, particularly porosity and ITZ quality, significantly influenced mechanical performance and marine durability.

2. Literature Review

2.1. Alkali-activated slag binders

To produce AAS binders, finely ground slag is treated with alkaline solutions, usually sodium hydroxide and sodium silicate. Reactive calcium, silicon and aluminium species will be dissolved, followed by the precipitation and reorganization of binding products. The properties of the resulting gel assemblage and pore structure depend on the composition of the slags, the activator modulus, the amount of alkali, the ratio of liquor to binder, the temperature and the curing time. These parameters will affect the setting, strength development, shrinkage, and transport properties. Preliminary trials should therefore be used to determine mix design and the mix should be reported with a degree of sufficiency for repeatability. (Gökçe, 2024; Kucharczyková et al., 2024).

The performance of marine products is dependent on their formulation. Several of these processes may occur at the same time, such as chloride binding and transport, sulfate reactions, and alterations of the calcium-bearing reaction products by magnesium. Cai & Liu (2024) summarized the impact of seawater, sea sand and aggressive ions on alkali-activated materials and pointed out that the durability should be determined based on the binder type and exposure environment. In the past few years, experimental studies have also explored the chloride and sulfate resistance of AAS marine concrete incorporating mineral admixtures through various methods, including migration tests, wetting–drying cycles, SEM, XRD, and thermal analysis (Construction and Building Materials, 2024, 411, 134333). (Cai & Liu, 2024; Wang et al., 2023; Ma et al., 2025).

2.2. Recycled seashell aggregate

Seashell waste must be processed in a controlled manner prior to use. Washing and brushing, removes adhering organic matter and salts; drying will help to minimize uncontrolled moisture inputs; crushing and sieving will create a well defined grading. Specific gravity and water absorption should be determined on each different source of shells as it may be necessary to replace the volume if shell and natural aggregate densities are different. The shape of the shell particles can be angular, curved, layered or locally porous. These features may alter the properties of the packing, workability, surface contact and ITZ. (Bamigboye et al., 2021; Hamada et al., 2023; Hamada et al., 2025).

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The mechanical and durability data of shell contained cementitious materials were reviewed and synthesized in the recent years. Bamigboye et al. (2021) found differences in performance among different shell types, replacement percentages and test methods. Similarly, Hamada et al. (2023) found that the effects varied with the replacement of cement, fine aggregate or coarse aggregate with shells. Zhu et al. (2024) discussed about opportunities and limitations of using shells as aggregate or cementitious component. Hamada et al. (2025) also provided a summary of the evidence up to 2025 and found that moderate aggregate substitution may be advantageous in some mixtures while high substitution generally decreased workability and might affect strength. (Bamigboye et al., 2021; Hasan et al., 2023; Zhu et al., 2024; Hamada et al., 2025).

2.3. A.4 Thermal behavior of shapes and components

The compressive strength tests provide an indication of resistance to compression, but do not reflect all failure modes of relevance to armour blocks. If the tensile and flexural testing are performed separately, they will yield data on crack initiation and bending resistance in non-uniform support and/or localized hydraulic action. The impact test provides material level information on first crack and failure energy. The impact energy from a drop-weight test or an instrumented test is not equal to wave-induced force, pressure distribution or armour-unit stability and should be considered separately. (Bamigboye et al., 2021; Chen et al., 2023; Sangeetha et al., 2022).

It is expected that the strength effect of shell aggregate is a non-linear relationship. As the content increases, the matrix continuity can be maintained by the better particle packing or surface roughness at low content, but at high content, defects can be increased due to lower particle stiffness, higher absorption, irregular grading or lower ITZ region strength. To explain why the interface characterization is essential, Chen et al. (2023) found that the bonding between mortar and mussel shell in the RAC was weaker, resulting in the changes of mechanical and durability properties. (Hamada et al., 2023; Chen et al., 2023; Hamada et al., 2025).

2.4. Marine durability

Chemical and physical processes of marine exposure. Pore connectivity, moisture state, and binding are important factors in chloride transport, as is possible modification of the binder phases by sulfate and magnesium, and salt accumulation, crystallization and surface scaling by wetting–drying cycles. Qu et al. (2021) defined marine degradation as a process that takes place across multiple scales, from material degradation to consequences of structures. Especially, Cai and Liu (2024) emphasized the need to assess the alkali-activated systems under the exposure of seawater and aggressive ions. The chloride and sulfate rich solutions, simulated seawater, and cyclic wetting–drying solutions are complementary and do not replace each other. (Qu et al., 2021; Ting et al., 2021; Cai & Liu, 2024; Gökçe, 2024).

2.5. Microstructure and ITZ

The ITZ between the shell particles and the AAS matrix influences stress transfer, crack propagation, pathway of moisture and ion movement. SEM can provide information about local morphology, pores and cracks, and interface continuity; EDS can provide elemental distribution; and XRD can provide information on the crystalline phases. These techniques should be used in conjunction with quantitative porosity or image-analysis parameters and should be correlated with measured properties of strength and transport. H5 can't be tested by just qualitative micrographs. (Chen et al., 2023; Zhu et al., 2024; Chen et al., 2023).

2.6. Sustainable Development and Life Cycle Assessment

However, the use of slag and recycled shells can lower the virgin aggregate and binder requirements, which can also be based on clinker, and may improve the environment, depending on the rules of use, the distance of transport, the cleaning and crushing of shells, the production of activators, the energy required for curing and the service life of the cement. Nikravan et al. (2023) demonstrated that the reported life-cycle impacts of AAMs depended on the system boundaries, functional units and inventory assumptions. A fair comparison must therefore be based on identical function and an open list of the components. (Nikravan et al., 2023; Hamada et al., 2025; Zhu et al., 2024).

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2.7. Conceptual framework

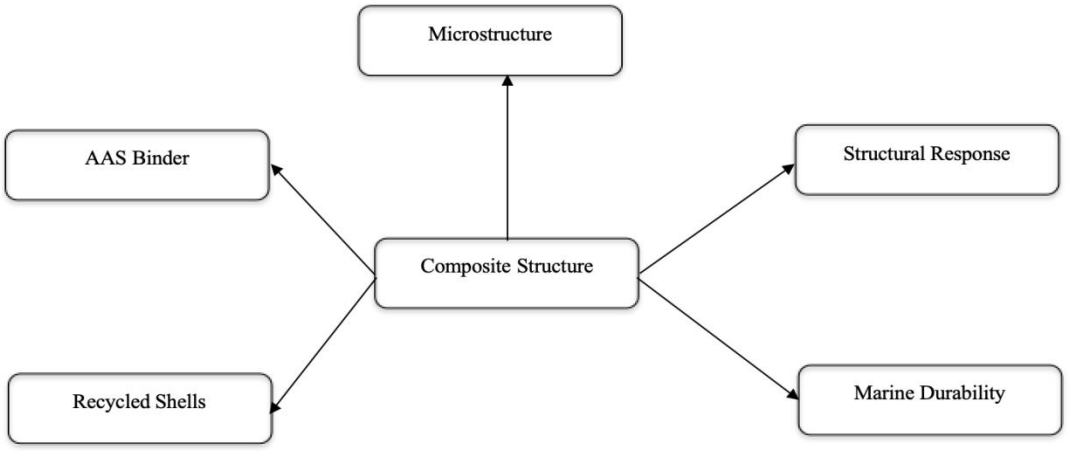

Figure 1. Integrated framework for AAS–shell coastal blocks

The framework considered shell replacement ratio as the main factor in mixture design. It was anticipated that it would have an impact on fresh properties, density, aggregate packing and ITZ properties, as well as compressive, tensile, flexural, impact and abrasion properties. Marine exposure was considered an external stressor which caused an altered mass, absorption, microstructure and residual strength. The quantified porosity and the indicators of ITZ were analyzed as explanatory variables of the mechanical and durability results. As complementary system-level and environmental dimensions, wave-flume response and life-cycle impacts were assessed.

3. Materials and Methods

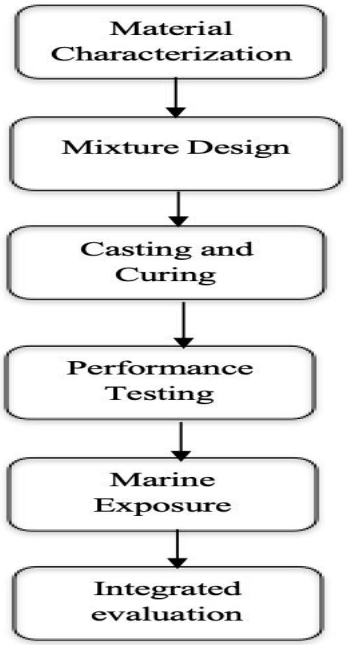

Figure 2. Experimental workflow for mixture development and performance evaluation.

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3.1. Experimental design

Five AAS mixtures were identified for a controlled laboratory programme. Natural coarse aggregate was replaced with shell aggregate at 0%, 10%, 20%, 30% and 40% of its volume. Following preliminary mix optimisation, the following mix parameters were kept constant: Binder composition, Activator dosage, Content of fine aggregate, Total coarse aggregate volume, Curing regime. The five AAS mixture codes did not contain a Portland-cement reference, which was recommended for comparative interpretation and life-cycle assessment.

3.2. Materials and characterization

The main raw material used was GGBFS. The powder was characterized in terms of its major oxide composition and particle-size distribution with X-ray fluorescence and fineness and specific gravity were measured. Activators used were sodium hydroxide and sodium silicate. The concentration of NaOH used, the proportion of sodium-silicate to NaOH, and the proportion of liquid to binder was determined in the preliminary trials and given in the final laboratory report.

Waste shells were retrieved from a known seafood processing or aquaculture site and then washed, brushed, dried to constant mass, crushed and passed through a sieve to the desired coarse aggregate grading. Specific gravity, water absorption, particle size distribution and morphology were determined. Physical tests were performed on the same tests on natural aggregate. Pre-mixing care was taken to check for shell contamination and residual organic matter.

3.3. Mixture identification

Table 1. Experimental mixture design

Mixture	Natural coarse aggregate (%)	Seashell aggregate (%)	Replacement basis
AAS-S0	100	0	Volume
AAS-S10	90	10	Volume
AAS-S20	80	20	Volume
AAS-S30	70	30	Volume
AAS-S40	60	40	Volume

The absolute quantities of GGBFS, activator, fine aggregate and coarse aggregate were determined with the measured specific gravities and a constant yield. The final mix design of kg/m3 was supposed to be reported after laboratory batching, but was not reconstructed from the source manuscript due to the lack of batch records verified.

3.4. Mixing, casting, and curing

The dry constituents were blended to achieve a uniform distribution. The activator solution was then added slowly and mixing was continued until a uniform composite was formed. The specimens were poured into moulds suitable for each test, and compacted with a uniform procedure. Cubes for compression, cylinders for splitting tensile tests and prisms for flexure were prepared. For impact and abrasion testing, the discs or slabs were cast separately, and larger ones for use in wave-flume trials. The samples were removed from the moulds and allowed to dry at a controlled temperature and humidity. Testing ages were set at 7, 28, 56, and 90 days. A minimum of three replicate mixtures and test conditions were recommended, with more recommended for exposure and wave-flume programmes.

3.5. Mechanical testing

The maximum load was designated as P_{max} and the area on which the load was applied was A, so that the compressive strength, $f_c = P_{max}/A$, was calculated. Tensile strength was determined from the maximum load (P), the length of the cylinder (L), and the diameter of the cylinder (D) and was calculated as $f_{ct} = 2P/(\pi LD)$. Flexural strength was determined by the equation $f_r = 3PL/(2bd^2)$ for the simply supported prism under centre point load condition, where b, d and L represent specimen width, depth and the distance between supports respectively. Test procedures and specimen size were to be in accordance with relevant current ASTM or EN standards, and the relevant standard to be used was to be stated in the final laboratory report.

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The force–displacement records were used to determine impact response. The integration of the absorbed energy was done as $E_i = \int F(\delta)d\delta$ until the failure displacement was reached. First crack energy, total energy, peak force and failure mode were measured. Abrasion resistance was evaluated as mass loss, $M_L = (m_0 - m_1)/m_0 \times 100$, where m_0 and m_1 is the mass of the specimen before and after abrasion.

3.6. Exposure to seawater and remaining performance

Two sets of specimens were exposed to simulated seawater, chloride-rich solution, sulfate-rich solution, and wetting–drying cycles. Simulated seawater preparation to be done per ASTM D1141 if applicable. Immersion based conditions: exposure durations of 28, 56, and 90 days were defined. Immersion and drying times, temperatures, solution changes and cycle counts were measured for cyclic exposure. Mass change was calculated as $M_c = [(m_1 - m_0)/m_0] \times 100$. Strength retention ($R_s$) was determined by comparing the strength of the exposed specimens to that of the unexposed specimens at the same age, and expressed as a percentage.

3.7. Microstructural characterization

The morphology of matrix, pores, cracks and interfaces between the shells and the binder were investigated by SEM. The distribution of the elements Ca, Si, Al, Na, Mg, Cl and S (where present) were determined using EDS mapping. Before and after exposures, the crystalline phases were identified by XRD. The aim of quantifying image analysis was to quantify the proportion of defects in the ITZ and the proportion of pore area within representative fields of view. To minimize operator bias, image acquisition, magnification, thresholding and sampling rules were kept constant.

3.8. Hydraulic wave-flume assessment

The selected block configurations were set up in a wave flume and subjected to a set of regular and/or irregular wave conditions. Wave height, period, the water depth, the geometry, the arrangement and the scale of the blocks were measured. Use of pressure sensors, displacement transducers, and synchronized video was employed wherever possible. The evaluation separated material damage from instability of the system, such as sliding, uplift and overturning. If scaled models were employed Froude similarity and scale effects were taken into consideration. The conclusions were only limited to the tested geometry and hydraulic regime.

3.9. Statistical analysis

Means, standard deviations, and 95 percent confidence intervals, were used to summarize results. One-way ANOVA was used for mixture comparisons with a common condition. Shell replacement, exposure condition, and their interaction were tested by using a factorial model. Significant omnibus tests were followed by Tukey-adjusted comparisons. Pearson or Spearman correlations and multivariable regression were performed to correlate porosity and ITZ indicators with mechanical and durability properties. Residual diagnostics were used to check assumptions, and robust or non-parametric alternatives used otherwise. $P<0.05$ was used to determine statistical significance, and effect sizes and confidence intervals were provided to prevent over-reliance on P-values.

3.10. Life-cycle and multi-criteria assessment

Show how to conduct multi-criteria assessment and life-cycle assessment of a product. The specific cradle to gate or clearly justified cradle to grave boundary has been set, and the functional unit is a cubic metre of coastal block which needs to meet the same performance. GGBFS, activators, aggregates, shell collection and processing, transport, mixing and curing were all part of the inventory. The global warming potential (GWP) was determined by summing up the individual global warming potentials, defined as $GWP = \Sigma(Q_i \times EF_i)$ with Q_i being each input quantity and EF_i being the emission factors. The assessment included the allocation assumptions for slag and shell waste and sensitivity to distance of transport and dose of the activator. A normalized weighted-sum index, $PI_i = \Sigma(w_j \times S_{ij})$, was used to rank mixtures, where the weights are based on engineering requirements and a sensitivity analysis.

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4. Results and Analysis are presented in the form of illustrative numerical scenario

Important Data Status: The numbers in Tables 2–6 are illustrative and hypothetical, designed to illustrate possible analysis and interpretation. They did not measure, isolate from a data set or statistically test. Replacement should be done with the experimental results at the replicate level prior to submission. No p values, confidence intervals, and decisions of acceptance of hypotheses are made up.

4.1. Fresh and physical properties

Table 2. Illustrative fresh and physical properties (28 days)

Mixture	Fresh density (kg/m³)	Hardened density (kg/m³)	Water absorption (%)	Slump/flow index (relative)
AAS-S0	2,280	2,245	4.2	100
AAS-S10	2,260	2,225	4.3	96
AAS-S20	2,235	2,198	4.7	91
AAS-S30	2,205	2,166	5.3	85
AAS-S40	2,175	2,132	6.1	78

The average results in the illustrative profile displayed an decreasing trend in the fresh and hardened density values with increasing shell fraction. Water absorption and relative flow index decreased as the percentage of replacement decreased. This was consistent with the possibility that the shell morphology and the absorption changed the packing and fresh-state mobility. These were only trends that were to be tested in the experiment, not observed results. (Hamada et al., 2023; Hamada et al., 2025).

4.2. Mechanical performance

Table 3. Illustrative mechanical properties at 28 days

Mixture	Compressive strength (MPa)	Splitting tensile (MPa)	Flexural strength (MPa)	Impact energy (J)
AAS-S0	48.0	3.65	5.80	42
AAS-S10	49.5	3.78	6.05	45
AAS-S20	47.2	3.60	5.72	48
AAS-S30	43.8	3.25	5.20	44
AAS-S40	39.6	2.91	4.61	38

The data shown were the result of a non-linear response; for this reason, the data shown is only for replacement up to 10%, after which the compressive, tensile and flexural values decreased as the shell content increased. The maximum impact energy was set at 20%, which assumed that the amount of controlled shell inclusion before higher porosity and weaker interfaces became dominant increased energy dissipation. The scenario was intentionally presented as a testable pattern to be considered, but not as an optimum. (Bamigboye et al., 2021; Chen et al., 2023; Sangeetha et al., 2022).

4.3. Illustrative strength development

Table 4. Illustrative compressive-strength development (MPa)

Mixture	7 days	28 days	56 days	90 days
AAS-S0	31.5	48.0	52.0	54.0
AAS-S10	32.8	49.5	53.5	55.2
AAS-S20	30.6	47.2	51.0	52.8
AAS-S30	28.0	43.8	47.2	48.9
AAS-S40	25.4	39.6	42.8	44.5

The age-related increase was estimated to be due to ongoing binder reaction and matrix development. The values were not intended to represent actual reaction kinetics or strength gain as curing temperature, activator chemistry, and composition of the slags might significantly change the profile.

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4.4. Marine durability & residual strength

Table 5. Illustrative residual compressive-strength retention (90-day exposure (%)

Mixture	Simulated seawater	Chloride solution	Sulfate solution	Wetting–drying
AAS-S0	94	96	92	90
AAS-S10	95	96	93	92
AAS-S20	93	94	91	89
AAS-S30	89	90	87	84
AAS-S40	84	86	82	78

To demonstrate, in this illustrative scenario, the strength retention was lowered as shell replacement increased, especially when it was subjected to cyclic wetting–drying. This assumed trend was supposed to indicate the possible effect of the increase in the accessible porosity and the increase in the interfacial defects. It doesn't necessarily mean that AAS-S10 or any other mixture actually performed better in marine environments. (Cai & Liu, 2024; Ma et al., 2025; Qu et al., 2021).

4.5. Abrasion and microstructural indicators

Table 6. Illustrative abrasion and microstructure indicators

indicators Mixture	Abrasion mass loss (%)	Porosity (%)	ITZ defect area (%)
AAS-S0	2.8	8.5	6.0
AAS-S10	2.6	8.2	5.7
AAS-S20	3.0	8.9	6.4
AAS-S30	3.7	10.1	8.2
AAS-S40	4.6	11.8	10.5

The illustrative data showed correlation between increasing porosity and ITZ defect area with increasing shell content and increased abrasion loss. The assumed minimum was consistent with the notional strength trend at 10%. These indicators would have to be calculated from representative image fields and independent porosity tests in the actual study, and uncertainties would have to be reported. (Chen et al., 2023; Chen et al., 2023).

4.6. Wave-flume and integrated ranking

Wave-flume results were not numbered as numerical data were not provided in source manuscript, due to the lack of block geometry, scale, wave heights, periods, water depth, sensor calibration, and measured displacement data. So there would not be any hydraulic stability claim to be made numerically. The study should contain a report of the amount of block movement or damage, the pressure response and any block sliding, uplifting or overturning under specifically documented test conditions.

Illustrative tables were also not used to calculate the multi-criteria ranking. To have a defensible ranking, it needs measured data, required performance levels, legitimate criterion weights and sensitivity analysis. The selection of a mixture should not be made just because the specimen had the highest compressive strength, or because the highest amount of recycled shells was used.

5. Discussion

5.1. Mechanical implications of shell replacement

The suggested mechanism involved shell replacement that impacted the packing, density, water demand, and shell–binder interface quality of aggregates. The illustrative results indicated that there was a moderate-replacement peak followed by a decrease at higher contents. This was consistent with the reviews showing that the performance of seashell depends largely on the type of shell used, replacement ration, processing, and the type of shell used as coarse aggregate, fine aggregate or binder replacement (Bamigboye et al., 2021; Hamada et al., 2023, 2025; Zhu et al., 2024).

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However, the literature does not agree on the optimum percentage; the optimum will have to be determined for the specific shell source and AAS formulation. (Bamigboye et al., 2021; Hamada et al., 2023; Hamada et al., 2025). However, the impact energy and abrasion resistance were two damage mechanisms. The energy absorbed in a rapid material-level event was measured by impact testing and progressive surface wear was measured by abrasion. Moderate shell benefits were proposed and needed to be verified using force–displacement records and repeated abrasion tests. The nature of the fracture of the shell particles, the cohesion of the matrix, the hardness of the aggregate surface, and the exposure of the aggregate should all be taken into account when making an interpretation. Laboratory impact response testing was not sufficient to demonstrate armour-unit stability and hydraulic wave-flume testing continued to be required. (Bamigboye et al., 2021; Sangeetha et al., 2023; Cao et al., 2021). Furthermore, this module examines the impact of the marine environment on materials and the importance of residual strength. The marine durability programme was conceived to isolate the impact of simulated seawater, chloride, sulfate and wetting/drying. This separation was significant as the chemical and physical processes were different. Deterioration under marine conditions was recognized as a coupled process in the literature and the response of alkali-activated binders to aggressive ions was found to be formulation dependent (Qu et al., 2021; Cai & Liu, 2024). All these parameters must be considered in conjunction with each other, including the residual strength. (Qu et al., 2021; Cai & Liu, 2024; Wang et al., 2023; Ma et al., 2025).

5.2. Microstructure–performance relationship

For H5, quantitative evidence was needed. The real analysis needs to be conducted to establish whether the porosity and ITZ defect area is predictive of the compressive strength, tensile/flexural resistance, abrasion loss, or residual strength following exposure. The images from SEM should be collected according to a predetermined sampling procedure, EDS and XRD should be used to complement and not replace quantitative performance measurements. The relationship should be investigated by regression analysis including relevant mixture/exposure variables. (Chen et al., 2023; Chen et al., 2023; Zhu et al., 2024).

5.3. Environmental implications

The use of GGBFS and waste shells could help to ensure resource efficiency but does not ensure an environmental benefit. Some impacts can be significant on the part of the alkali activators and some benefits can be mitigated by the collection, washing, drying, crushing and transport process. Nikravan et al. (2023) highlighted the sensitivity of AAM life-cycle results to the system boundaries and to the inventory assumptions. The comparative LCA should thus present the allocation methods, transport distances, the electricity mix, data on the production of activators, and functional equivalence. (Nikravan et al., 2023; Gökçe, 2024; Hamada et al., 2025).

5.4. Hypothesis evaluation

Hypothesis	Required empirical test	Status in this draft
H1	ANOVA/factorial model for compressive strength across shell levels	Not tested; illustrative values only
H2	Separate mixture comparisons for splitting tensile and flexural strength	Not tested; illustrative values only
H3	Impact energy and abrasion mass-loss comparisons	Not tested; illustrative values only
H4	Factorial analysis of shell level × exposure condition	Not tested; illustrative retention values only
H5	Regression of quantified porosity/ITZ measures against performance	Not tested; illustrative microstructure values only

6. Engineering Implications

The study design presented a pathway to determining if the industrial slag and processed seashell waste can be introduced into coastal units while maintaining important mechanical, and durability, criteria. For practical use, a characterization of the sources would be needed, consistent grading, quality control of activator solutions, reproducible curing and trials in production scale would be necessary. In addition to the properties of the material, the Armour-unit geometry, density, interlocking, placement, and hydraulic stability should be taken into account. Findings should only be applicable to the materials tested and the conditions of exposure. (Cao et al., 2021; Aliasgary et al., 2025; Hamada et al., 2025).

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This paper outlines the limitations of the current research and suggests future research directions.

The only drawback to this manuscript draft was the lack of actual laboratory data, batch records, micrographs, wave-flume observations, and life-cycle inventory data. All the numerical tables were therefore described as illustrative and no optimum or inferential statistics were given. Future studies should include more shell sources, more grading distributions, a Portland-cement control, quantify pore connectivity and ITZ, test for longer exposure periods and combinations of ions, and replicate hydraulic testing at a specified scale. To further enhance engineering relevance, long-term field exposure and cost analysis would be helpful.

7. Conclusions

An integrated experimental procedure was designed to investigate the coastal protection blocks that contain sequences of recycled aggregate from seashells with varying proportions of recycled aggregate (0–40%) by volume. A combination of mechanical testing, impact and abrasion assessment, simulated marine exposure, microstructural characterization, hydraulic wave-flume evaluation, multi-criteria optimization, and life-cycle assessment were combined in the framework. The illustrative numerical scenario was used to illustrate the non-linear response and potential moderate-replacement trade-off, but was not used to define actual material performance. Until the laboratory measurements could be made, the five hypotheses were not tested. The results for this experiment, therefore, showed no mixture that was determined to be an experimentally proven optimum. The coordinated research design and the clear reporting of results from the study were its contribution during this stage, empirical conclusions had to be drawn by replacing the simulated values with verified data. (Bamigboye et al., 2021; Cai & Liu, 2024; Nikravan et al., 2023; Hamada et al., 2025).

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