Applied Science and Engineering Progress, Vol. 20, No. 2, 2027, 8271

Review Article

Oyster Shell Utilization in Concrete: A Systematic Review of Performance and Sustainability

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Received: 23 May 2026; Revised: 23 June 2026; Accepted: 28 June 2026; Published online: 18 August 2026

Abstract

The growing need for low-carbon construction materials, coupled with the accumulation of oyster shell waste, has increased interest in its use in sustainable concrete. Although previous reviews have examined individual applications of oyster shell waste, comprehensive comparisons integrating mechanical performance, durability, and sustainability remain limited. This study presents a critical review of oyster shell utilization within an integrated performance-sustainability framework. Four application routes are evaluated: cement replacement using calcined oyster shell powder, fine and coarse aggregate replacement using crushed oyster shell, and micro-filler incorporation using finely ground oyster shell powder. The reviewed studies indicate that performance largely depends on the functional role of oyster shell and the underlying mechanisms involved. These mechanisms include particle packing, clinker dilution, and interfacial transition zone behavior. Reported optimum replacement levels are 5-10% for cement replacement, 5-20% for fine aggregates, ≤15% for coarse aggregates, and approximately 5% for micro-fillers. Fine aggregate and micro-filler applications generally exhibit more stable performance, which is commonly attributed to improved packing density and matrix densification. Cement replacement offers greater CO_2 reduction potential but is constrained by energy-intensive calcination and limited reactivity. Coarse aggregate replacement is generally less effective because of higher porosity and lower particle strength. Several studies also report improved performance in hybrid systems incorporating supplementary cementitious materials or fibers. Overall, the reviewed evidence suggests that fine aggregate and micro-filler applications offer a favorable balance between performance and sustainability. Key research gaps remain in standardized processing methods, long-term durability under coupled environmental exposures, and comprehensive life cycle assessment.

Keywords: Cement replacement, Circular economy, Concrete durability, Oyster shell concrete, Sustainability

1 Introduction

The environmental impact of cement production has become a major concern in the construction sector due to its significant contribution to global CO_2 emissions. Cement manufacturing accounts for approximately 7-8% of total anthropogenic CO_2 emissions, primarily driven by clinker production processes involving limestone calcination and high-temperature kiln operations [1-4]. Around 60% of these emissions originate from the calcination of calcium carbonate ($CaCO_3$), while the remainder is associated with fossil fuel combustion required to maintain kiln temperatures above 1400 °C [5-8]. With increasing global infrastructure demand, decarbonizing cement production has become a major priority. Strategies such as clinker substitution, alternative binders, and waste valorisation are key strategies for achieving net-zero emission targets [9-12].

In parallel, marine shell waste, particularly oyster shells, has become an increasing environmental concern in coastal regions with intensive aquaculture activities [13]. Oyster shell (OS) waste represents a major fraction of seafood byproducts and is commonly disposed of in landfills or open dumping sites, causing pollution, odor emissions, and leachate generation from residual organic matter [14-17]. Approximately 300,000 tons of oyster shell waste are generated annually in South Korea alone, with only a limited portion effectively reused [18], [19]. Similar challenges are reported in China, where large quantities of shell waste remain underutilized, reflecting deficiencies in sustainable waste management practices [20]. Other major oyster-producing countries, including Japan, the United States, France, and Australia, also generate substantial quantities of oyster shell waste. Although recycling initiatives have been introduced in some regions, a considerable proportion of this waste is still disposed of in landfills or coastal areas. This situation highlights the global need for sustainable oyster shell valorization within a circular economy framework [13], [21].

Oyster shells therefore present a promising opportunity for sustainable construction applications. Their incorporation as partial cement replacements can reduce CO_2 emissions associated with clinker production, while their use as fine or coarse aggregates can decrease reliance on natural resources such as river sand and crushed stone [22-24]. In addition, their local availability in coastal regions can reduce transportation demands and improve economic feasibility. These advantages align with circular economy principles by transforming waste into value-added construction materials [25-28].

From a materials perspective, oyster shells consist primarily of $CaCO_3$, typically exceeding 90% by weight, making them chemically similar to natural limestone used in cement systems [29], [30]. In their raw state, oyster shells act mainly as inert fillers; however, calcination converts $CaCO_3$ into calcium oxide (CaO), enabling limited reactivity within cement hydration processes [31]. Depending on processing conditions, oyster shells can be utilized as calcined powders for cement replacement or as crushed particles for fine and coarse aggregate applications, where performance is governed by particle size distribution, packing density, and interfacial transition zone characteristics [32-34]. This multifunctional nature distinguishes oyster shell from many other waste-derived materials.

Despite increasing research interest, the existing literature remains fragmented because most studies evaluate oyster shell applications independently, while mechanical performance, durability, and sustainability are often assessed separately. Consequently, a comprehensive framework that systematically compares the different functional roles of oyster shell and integrates performance and environmental considerations is still lacking. In addition, variations in processing conditions, including pre-treatment methods, calcination regimes, particle size distribution, and replacement levels, have resulted in inconsistent findings and limited comparability among studies [35], [36]. Furthermore, long-term durability under aggressive environmental exposures and comprehensive life cycle assessments remain insufficiently investigated [37].

To address this gap, the present study provides a critical and comparative review of oyster shell utilization in concrete across four functional roles: cement replacement, fine aggregate substitution, coarse aggregate replacement, and micro-filler incorporation. Unlike previous reviews, this work adopts an integrated performance-sustainability framework that simultaneously evaluates mechanical behavior, durability performance, environmental implications, and processing-related factors. The review further examines the mechanisms governing performance variability, identifies optimal utilization pathways, and highlights key research priorities to support the development of standardized and scalable oyster shell-based concrete technologies.

2 Bibliometric Analysis and Methodology

A comprehensive bibliometric analysis was conducted to map the scientific evolution, research structure, and emerging trends in the utilization of oyster shells in concrete. Scopus and Web of Science (WoS) databases were selected due to their wide coverage of high-quality peer-reviewed publications and reliable citation indexing. The analysis covers the period from 2010 - 2025, during which research on oyster shell valorization in cementitious materials has expanded significantly.

The temporal distribution of publications in Figure 1 shows a clear and continuous increase in research output over the past fifteen years, rising from 8 publications in 2010 to 57 in 2025. This growth reflects increasing scientific and industrial interest, particularly after 2020, and marks a transition from exploratory investigations toward application-oriented research. The accelerated growth observed in recent years suggests that research has moved beyond proof-of-concept studies toward optimizing material performance, durability, and sustainability for practical implementation.

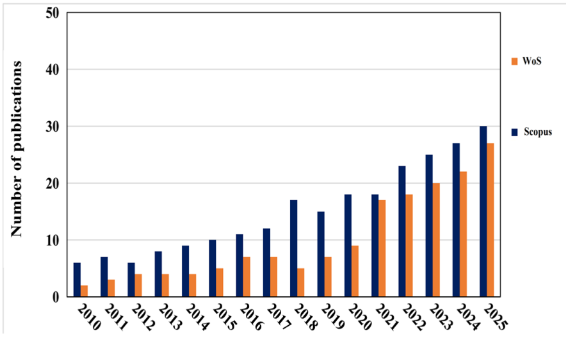

Figure 1: Bar graph for previous publications related to oyster shells based on scopus and web of science.

Bibliometric analysis reveals a clear evolution in research focus. Early studies mainly investigated calcined oyster shells as a cementitious material, where thermal decomposition of calcium carbonate produces reactive calcium oxide that influences cement hydration [38], [39]. While this can enhance early hydration, excessive replacement often reduces compressive strength because of limited calcium silicate hydrate (C-S-H) formation and modified hydration pathways [40-43]. Research later shifted toward using oyster shells as fine and coarse aggregates, with greater emphasis on mechanical properties, workability, and durability [44]. These studies show that acceptable performance can be achieved at optimized replacement levels, although results remain strongly dependent on particle characteristics and dosage [45]. Durability studies, especially under freeze–thaw exposure, indicate that higher replacement levels generally increase porosity and reduce long-term performance [46]. Overall, this trend reflects a transition from chemically driven applications (cement replacement) to physically governed uses (aggregate and filler applications), with increasing emphasis on practical feasibility and material efficiency.

For the present review, a focused bibliometric search was conducted using a predefined search strategy employing keywords including “oyster shell concrete” (168 publications), “waste shell cement” (102 publications), “oyster shell fine aggregate” (142 publications), “oyster shell coarse aggregate” (87 publications), “oyster shell powder” (102 publications), “micro-filler” (92 publications), and “marine biogenic $CaCO_3$ concrete” (56 publications). The search was performed across both Scopus and Web of Science databases and covered publications published between 2010 and 2025.

To ensure the quality and relevance of the reviewed literature, predefined inclusion and exclusion criteria were established prior to the screening process. The inclusion criteria comprised peer-reviewed journal articles and conference papers published in English that specifically investigated the utilization of oyster shells in concrete or cementitious materials, including applications as cement replacement, fine or coarse aggregate substitution, filler materials, durability assessment, and sustainability evaluation. Exclusion criteria included duplicate records, editorials, book chapters, patents, non-English publications, studies unrelated to construction materials, and articles lacking sufficient experimental, analytical, or review content. The screening process involved sequential title screening, abstract evaluation, and full-text assessment to ensure consistency and relevance throughout the selection procedure.

After removing duplicates arising from the overlap of multiple keywords and database indexing, a total of 204 unique records were obtained. Further screening and deduplication between Scopus and Web of Science reduced the dataset to 115 publications. Subsequently, 28 studies were excluded based on the predefined inclusion and exclusion criteria, resulting in a final dataset of 87 publications for detailed analysis. The overall workflow adopted for data collection, screening, and analysis is illustrated in Figure 2.

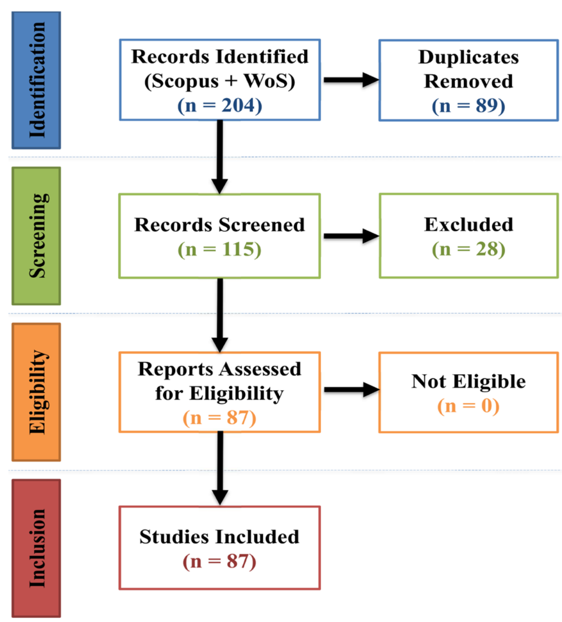

Figure 2: Bibliometric workflow for data collection and analysis.

To identify dominant research themes and conceptual structures within the field, keyword co-occurrence analysis was performed using VOSviewer (version 1.6.20). A minimum occurrence threshold of three keyword occurrences was applied to improve the relevance of the generated network and reduce isolated or weakly connected terms. The resulting network, presented in Figure 3, reveals three major research clusters. The first cluster focuses on cement replacement, with emphasis on hydration mechanisms and durability behavior. The second cluster addresses aggregate applications, highlighting mechanical performance, interfacial transition zone characteristics, and workability. The third cluster is sustainability-oriented, covering CO_2 reduction, waste valorization, and circular economy integration. Strong interconnections among these clusters indicate that sustainability considerations now act as a central driver across all application domains, supporting the transition toward integrated performance-sustainability research. Notably, the identified clusters provide the conceptual foundation for the classification adopted in this review. The cement replacement and aggregate clusters correspond directly to the functional application categories discussed in Section 4, while the sustainability cluster supports the integrated performance-sustainability framework used throughout the subsequent analysis.

Recent studies increasingly focus on application-oriented performance and environmental assessment of oyster shell-based systems [47], while existing reviews highlight both opportunities and limitations, particularly at higher replacement levels [48]. However, a key research gap persists, as most studies evaluate mechanical performance and sustainability separately, with limited integration of durability and life cycle assessment. The lack of comprehensive LCA-based frameworks further limits the development of optimized and scalable solutions [49]. Therefore, there is a need for a holistic evaluation framework integrating mechanical, durability, and environmental performance, which forms the basis of this study.

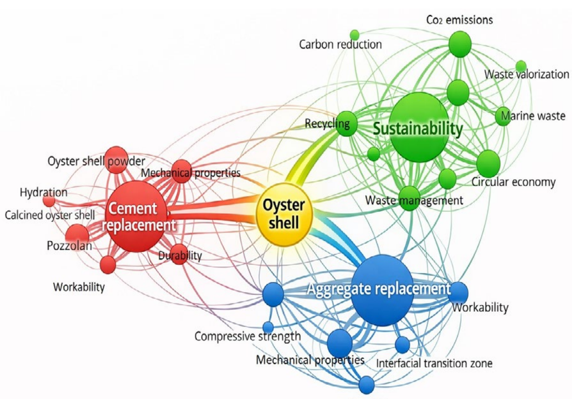

Figure 3: Keyword co-occurrence network showing major research clusters in oyster shell concrete.

3 Preparation and Processing of Oyster Shells for Concrete Applications

The preparation and processing of oyster shells are critical steps that significantly influence their performance in concrete applications. Raw oyster shells contain organic residues, salts, and impurities that may interfere with cement hydration and long-term durability. Therefore, pre-treatment processes such as washing, soaking, and drying are required to remove contaminants [50-53]. Proper cleaning reduces chemical interference, improves interfacial bonding, and enhances mechanical performance while reducing variability across studies [54-57]. However, insufficient control of pre-treatment conditions remains a major source of inconsistency in the literature, highlighting the need for standardized protocols.

After pre-treatment, mechanical processing is applied to obtain usable particle forms through crushing and grinding. Crushed oyster shells exhibit angular morphology that enhances mechanical interlocking. In contrast, finely ground particles improve packing density and contribute to microstructural refinement [58], [59]. Grinding intensity strongly affects specific surface area and water demand, which in turn influence both workability and strength. Wet ball milling has been reported to produce a more uniform particle size distribution and higher reactivity compared to dry grinding. This results in improved early-age strength development [60], [61]. However, excessive grinding increases water demand and may negatively affect workability, indicating a clear trade-off between reactivity and fresh-state performance.

Particle size classification further enables functional optimization of oyster shells in concrete. Fine particles <150 μm are suitable for filler applications or partial cement replacement due to nucleation and densification effects. Intermediate particles <4.75 mm are used as fine aggregates, while larger fractions >4.75 mm serve as coarse aggregates. A well-graded particle distribution improves packing density, reduces void content, and enhances both mechanical and durability performance. In contrast, poorly graded materials increase porosity and weaken the interfacial transition zone, leading to performance deterioration [62]. These findings confirm that particle size distribution is a key design parameter rather than a simple processing step.

To ensure consistency and avoid ambiguity across the manuscript, oyster shell materials are classified according to processing state and functional role. Raw oyster shell (ROS) refers to cleaned and untreated shells without further processing. Crushed oyster shell (COS) denotes mechanically processed material used as a partial fine or coarse aggregate replacement without thermal treatment. Calcined oyster shell powder (COSP) is produced through thermal decomposition of calcium carbonate at 700-900 °C, resulting in reactive calcium oxide primarily used for cement replacement. Finely ground oyster shell powder (OSP) is used as a micro-filler, where performance is governed mainly by physical packing and matrix densification rather than chemical reactivity. This classification is applied consistently throughout the manuscript to improve mechanistic clarity and avoid overlap between material states.

For cement replacement applications, thermal treatment via calcination is required. During calcination at 700-900 °C, calcium carbonate decomposes into calcium oxide, which modifies hydration kinetics and accelerates early-age reactions [63], [64]. However, excessive replacement levels may disrupt C–S–H formation and reduce long-term strength [38]. In addition, the high-energy demand associated with calcination introduces a sustainability trade-off, where environmental benefits from clinker reduction may be reduced by processing-related emissions.

Previous studies consistently demonstrate that processing conditions play a decisive role in determining oyster shell performance. Wet grinding generally produces finer and more uniform particles than dry grinding, resulting in improved reactivity and early-age strength development [60], [61]. Similarly, well-graded particle distributions enhance packing density and reduce porosity, whereas poorly graded materials tend to weaken the interfacial transition zone and increase void content [62]. For calcined oyster shell powder, studies indicate that calcination temperatures between 700 and 900 °C provide effective $CaCO_3$ decomposition and improved hydration behavior, while more intensive processing may increase energy demand without proportional performance gains [63], [64]. These findings highlight that differences in processing routes are a major source of variability among reported results and emphasize the importance of processing optimization.

Overall, the processing route, including pre-treatment, mechanical processing, particle size control, and calcination, plays a decisive role in governing the functional performance of oyster shell in concrete. Variations in these parameters are a major source of discrepancies in reported results, underscoring the need for standardized processing protocols and performance-based optimization strategies. The overall preparation and processing pathway of oyster shells and their corresponding utilization routes in concrete are shown in Figure 4.

Figure 4: Preparation and processing pathways of oyster shells for concrete applications.

4 Classification of Oyster Shell Applications in Concrete

4.1 *Oyster shell as cement replacement*

The use of calcined oyster shell powder as a partial replacement for Portland cement has attracted growing interest as a low-carbon approach to reduce clinker consumption and CO_2 emissions. After calcination, oyster shells mainly produce calcium oxide, which enhances early hydration but has limited intrinsic pozzolanic activity. Consequently, filler effects, nucleation-induced hydration acceleration, and clinker dilution, resulting in a strongly dosage-dependent behavior [38], [65], govern COSP performance. This explains the variability in reported results and indicates that optimization, rather than maximization of replacement level, is the key design strategy.

In the fresh state, COSP effects on workability are inconsistent and mainly controlled by particle characteristics. Improved workability is linked to smoother particle surfaces, reducing interparticle friction [66], [67], while reduced flowability is observed in finer or blended systems due to higher surface area and water demand [68], [69]. Thus, particle size distribution and surface texture are more influential than replacement level alone.

Mechanically, an optimum is generally observed at low replacement levels. About 5-10%, COSP typically maintains or slightly improves compressive strength [66], mainly due to improved packing density and nucleation effects that accelerate early hydration. Beyond this range, strength decreases progressively due to clinker dilution and reduced C-S-H formation [66]. Although CaO promotes early hydration through increased calcium hydroxide ($Ca(OH)_2$) formation [38], the limited pozzolanic reactivity restricts long-term strength development. Similar trends are observed in tensile behavior, where higher COSP contents reduce splitting tensile strength and increase cracking susceptibility [67], reflecting a trade-off between early-age benefits and long-term performance.

Microstructural studies confirm that COSP mainly acts as a calcium-rich inert filler with limited chemical participation. XRD and SEM analyses show that particles remain largely unreacted within the matrix. However, they enhance early hydration kinetics and affect aluminate reactions [38], [65], explaining early strength gains and later performance reduction at higher dosages.

Durability is strongly dependent on dosage and exposure conditions. Low COSP levels can improve resistance to sulfate and alkaline attack, with optimum performance around 5% replacement [66]. However, higher contents may reduce durability and increase degradation under aggressive environments such as acid exposure [70]. Performance is therefore condition-specific. Advanced curing methods can mitigate limitations: carbonation curing improves densification through $CaCO_3$ formation [70], while supplementary cementitious materials such as slag or metakaolin enhance hydration synergy and refine pore structure [68], [69].

Overall, COSP is most effective as a partial cement replacement within the 5-10% range, where mechanical and durability performance remains comparable to conventional systems. Beyond this range, dilution and low reactivity lead to performance

Table 1: Summary of mechanical, durability, and fresh-state performance of COSP as partial cement replacement in concrete.

Author (Year)	Replacement (%)	Main Findings	Key Limitation
Seo *et al.*, (2019) [38]	3-12%	Compressive strength increased by about 7% at 3% replacement, but decreased by about 5% at 9% and 22% at 12%.	Limited improvement range.
Ephraim *et al.*, (2019) [71]	7.5-15%	Compressive strength was highest at 7.5% replacement and decreased progressively at 10-15%.	High-strength concrete is sensitive to COSP replacement.
Garad (2019) [72]	5-15%	Compressive and splitting tensile strengths increased up to 10% OSP (6.3% and 24.1%), then declined at 15%.	Dilution effect dominates at high replacement levels.
Tayeh *et al.*, (2020) [66]	5-20%	Compressive strength and durability improved at 5% replacement, while compressive strength decreased at 10-20% replacement.	Optimum performance limited to low replacement levels.
Ubachukwu *et al.*, (2020) [67]	5-25%	Workability increased, whereas tensile strength decreased by about 33% at 25% replacement.	Increased cracking susceptibility.
Liao *et al.*, (2022) [68]	5-10%	Compressive strength increased by up to 22.2% at 8% replacement in blended systems.	Performance depends on SCM synergy.
Han *et al.*, (2022) [69]	30%	Compressive strength decreased by 44.8% at 30% replacement.	Early-age strength reduction.
Xuan *et al.*, (2023) [70]	15-30%	Carbonation curing improved strength and pore refinement.	Requires special carbonation curing conditions.
Yang *et al.*, (2024) [65]	10-20%	Compressive strength decreased by 19.4% at 10% replacement and 39.3% at 20%, while hydration heat and CO_2 emissions were reduced.	Trade-off between strength and sustainability.
Bunyamin (2025) [73]	5%	Compressive strength increased by 35.5% at 5% replacement using COSP at 800 °C, higher calcination temperatures reduced performance.	Strong dependence on calcination temperature.

loss. Thus, COSP is better considered a performance-enhancing additive rather than a full cement substitute. Hybrid systems combining Supplementary cementitious materials (SCMs) and alternative curing methods offer a promising route for performance optimization and sustainability.

Despite extensive research, gaps remain, including limited long-term durability data under combined exposures, insufficient understanding of COSP-hydration product interfaces, and lack of standardized processing and calcination protocols. Variability in experimental methods also limits comparability and guideline development. Addressing these issues is essential for large-scale application. A summary of key findings on COSP as a cement replacement is provided in Table 1, highlighting the roles of replacement level, processing conditions, and mix composition on fresh, mechanical, and durability performance.

4.2 *Oyster shell as a fine aggregate replacement*

The use of crushed oyster shell as a partial replacement for natural fine aggregates is a promising strategy for reducing environmental impacts from shell waste while decreasing reliance on natural sand. In this case, COS mainly acts as a lightweight, porous aggregate and its performance is governed by physical properties such as particle shape, surface roughness, porosity, and water absorption rather than chemical reactivity. This distinguishes it from cement replacement applications, as interfacial and microstructural effects rather than hydration chemistry control its behavior.

From a fresh-state perspective, a consistent reduction in workability is reported with increasing COS content. This is mainly due to the rough, angular texture and high water absorption of crushed shells, which increase internal friction and water demand [74-78]. Consequently, slump decreases with higher replacement levels, and additional water or admixtures are often required to maintain workability [75], [78]. Unlike cement replacement systems, this trend is relatively uniform across studies, indicating that reduced workability is an inherent characteristic of crushed shell aggregates.

Mechanically, COS concrete shows an optimum performance at low to moderate replacement levels 5-20%. Within this range, compressive strength is maintained or slightly improved [79-82], mainly due to better particle packing and pore-filling effects that densify the matrix. Beyond this range, strength decreases due to increased voids, weaker interfacial transition zones (ITZ), and reduced stiffness [74], [76]. This reflects a shift from a packing-dominated response at low contents to a porosity-controlled behavior at higher levels.

These trends are strongly influenced by microstructural factors. The high porosity and irregular geometry of COS particles weaken ITZ bonding, while higher water absorption increases internal void formation. Particle size also plays an important role: coarser particles improve interlocking and performance, whereas finer particles increase water demand and porosity [78]. Similar behavior is observed in tensile and flexural properties, where initial improvements are followed by reductions at higher COS contents [77], [80], [83], indicating a clear trade-off between sustainability and structural performance.

Durability behavior is complex and strongly application-dependent. Increased porosity may negatively affect permeability and long-term durability [77], [78], while higher shrinkage can increase cracking risk [79]. However, some benefits have also been reported, such as improved freeze-thaw resistance in certain mixes and advantageous permeability for pervious concrete applications [84]. This dual behavior shows that COS concrete should be designed according to exposure conditions and functional requirements rather than assuming uniform performance trends.

Hybrid systems significantly improve performance. SCMs such as fly ash, slag, metakaolin, or marble powder help mitigate the limitations of COS aggregates by improving packing density, enhancing secondary hydration, and refining pore structure, leading to better strength and durability [83], [85]. This confirms that COS performs more effectively within composite systems rather than as a standalone replacement material.

Overall, COS can be effectively used as a fine aggregate replacement within an optimal range of approximately 5-20%, where acceptable mechanical performance is maintained alongside environmental benefits. Beyond this range, performance deterioration becomes significant due to increased porosity and weak ITZ formation. Therefore, COS should be considered a partial functional aggregate rather than a full sand substitute, especially for structural applications. Hybrid systems remain the most promising approach for performance optimization in sustainable concrete.

Despite considerable research, key gaps remain, including limited understanding of ITZ behavior, insufficient long-term durability data under coupled exposures, lack of standardized processing methods, and absence of unified mix design guidelines. Addressing these issues is essential for broader practical implementation.

A summary of key findings on COS as a fine aggregate replacement is provided in Table 2, highlighting workability reduction, the optimal replacement range, and the benefits of hybrid systems in improving overall performance.

4.3 *Oyster shell as coarse aggregate replacement*

The use of crushed oyster shell as a coarse aggregate replacement is less developed compared to its use as a cementitious material or fine aggregate. This is mainly due to the inherent physical and mechanical limitations of oyster shells at larger particle sizes. In this application, COS behaves as a porous and relatively weak aggregate, with its performance governed by morphology, porosity, and interfacial characteristics rather than chemical interaction with the cement matrix. This limits its effectiveness compared to fine aggregate applications, where packing effects can partially offset material deficiencies.

From a fresh-state perspective, incorporating COS as coarse aggregate consistently reduces workability due to its irregular shape, rough surface, and high water absorption, which increase internal friction and water demand [88]. At moderate replacement levels 20-30%, significant slump reduction is observed, while higher contents further reduce workability. However, acceptable workability,

Table 2: Summary of mechanical, durability, and fresh-state performance of COS as a fine aggregate replacement in concrete.

Author (Year)	Replacement (%)	Main Findings	Key Limitation
Yang *et al.*, (2005) [76]	5-20%	Compressive strength improved at 5-10% replacement but declined at ≥20%; admixture-modified mixtures showed higher overall performance.	Reduced elastic modulus.
Yang *et al.*, (2010) [79]	5-20%	Compressive strength remained comparable to the control up to 20% replacement; elastic modulus decreased by 10-15% at 20% replacement.	Reduced stiffness and increased permeability.
Kuo *et al.*, (2013) [86]	5-20%	Compressive strength increased by 3% at 5% replacement but decreased by 17-35% at 10-20% replacement.	Shrinkage and sulfate durability concerns.
Alam *et al.*, (2018) [77]	5-20%	Compressive strength increased by 10.5% and 28.4% at 10% and 20% replacement, respectively.	Increased water absorption
Aye *et al.*, (2019) [83]	10-40%	Compressive strength increased by 6.8% (10%), 19.2% (20%), and 4.2% (30%), but decreased by 1.0% at 40% replacement.	Performance depended on filler synergy.
Chen *et al.*, (2019) [85]	30%	30% replacement combined with FA/GGBS achieved near-control strength at later ages and improved chloride resistance.	Early-age strength reduction due to slow SCM hydration.
Ubachukwu *et al.*, (2021) [75]	5-25%	Compressive strength remained comparable to the control up to 20% replacement but decreased by 27.9% at 25% replacement.	Reduced density at higher replacement.
Scuderi (2022) [78]	10-50%	Compressive strength remained comparable to the control at 20% replacement; higher replacement levels required additional mixing water.	Increased water demand and reduced workability.
Kathiria *et al.*, (2022) [82]	5-25%	Compressive strength increased by 7.3% (5%), 13.2% (10%), 21.9% (15%), 26.5% (20%), but declined at (25%) relative to the control.	Optimum performance is achieved at 20% replacement.
Hong *et al.*, (2024) [74]	10-40%	Compressive strength decreased by 22.6% (10%), 31.1% (20%), 26.6% (30%), and 26.7% (40%) relative to the control.	High porosity and water absorption.
Lin *et al.*, (2024) [87]	10-100%	Peak stress and elastic modulus increased up to 20% replacement; water absorption decreased from 4.31% to 3.83% at 20% replacement but increased to 14.68% at 100% replacement.	Performance declined when the replacement exceeded 20% due to air void formation.
Gunathilaka *et al.*, (2025) [80]	10-40%	Compressive strength increased by 3.2% (10%) and 1.9% (20%), but decreased by 12.1% (30%) and 24.9% (40%) relative to the control.	Effective replacement range limited to 10–20%.

including self-compacting concrete, can still be achieved through optimized mix design, superplasticizers, and controlled water content [89], [90], showing that this limitation can be managed through mix adjustment.

Mechanically, a clear threshold behavior is observed. At low replacement levels 10-15%, improvements in compressive, tensile, and flexural strength have been reported, mainly due to improved packing and mechanical interlocking from the angular COS particles. Beyond this range, performance declines progressively with increasing COS content [88]. While moderate replacement levels may still meet minimum structural requirements, stiffness and load-bearing capacity decrease, and full replacement can lead to strength losses exceeding 50% [90].

This behavior is mainly governed by the intrinsic weakness of COS particles and interfacial deficiencies. Oyster shells have lower strength and stiffness than conventional aggregates, and their high porosity increases void content within the matrix. In addition, a weak interfacial transition zone (ITZ) reduces load transfer efficiency [89]. Microstructural observations show that failure often initiates in the ITZ and propagates through the shell particles, indicating a different failure mode from conventional concrete [89]. Thus, performance is controlled more by material weakness than matrix densification effects.

Durability performance generally decreases with COS incorporation due to increased porosity, permeability, and water absorption [90], which may reduce long-term resistance in aggressive environments. However, in applications such as pervious concrete, this higher permeability can be beneficial by improving drainage performance [91]. Therefore, suitability is highly application-dependent and should be based on functional requirements rather than conventional durability expectations.

Hybrid systems offer effective performance improvement. Supplementary cementitious materials such as fly ash refine pore structure and reduce microcracking, enhancing long-term durability [89]. Additionally, steel fibers significantly improve mechanical performance, enabling safer structural use of COS aggregates [89]. These results confirm that performance enhancement relies mainly on system-level optimization rather than the intrinsic properties of the aggregate itself.

Overall, COS can be used as a partial coarse aggregate replacement within a limited range, typically not exceeding 15% for structural applications. Beyond this, significant reductions in strength and durability occur due to increased porosity and weak interfacial bonding. Compared with its use in cement or fine aggregate replacement, COS shows lower efficiency and higher performance variability when used as coarse aggregate, indicating its more restricted applicability.

Despite recent progress, several gaps remain, including limited long-term durability data under severe exposure conditions, insufficient understanding of ITZ behavior and failure mechanisms, lack of standardized processing and grading methods, and limited development of unified design frameworks. Addressing these issues is essential for broader and more reliable application.

A summary of key findings on COS as a coarse aggregate replacement is provided in Table 3, highlighting reduced workability, a narrow optimal replacement range, and the strong influence of hybrid systems and interfacial properties on overall performance.

Table 3: Summary of mechanical, durability, and fresh-state performance of COS as a coarse aggregate replacement in concrete.

Author (Year)	Replacement (%)	Main Findings	Key Limitation
Razali *et al.*, (2021) [91]	10-40%	Performance improved with increasing oyster shell content, reaching the highest level at 40% replacement.	Suitable mainly for pervious concrete applications.
Reena *et al.*, (2021) [92]	5-15%	Compressive strength increased by 3.69% (5%), 5.26% (10%), and 6.26% (15%); splitting tensile strength increased by 0.3%, 0.94%, and 4.7%, respectively.	Optimum performance was limited to 15% replacement.
Kanaka *et al.*, (2022) [88]	20-30%	Compressive strength remained comparable to the control at 20% replacement but decreased by 20% at 30% replacement.	Weak interfacial bonding at higher replacement levels.
Pinto (2022) [90]	100%	Compressive strength decreased by 55%, while splitting tensile and flexural strengths decreased by 30% and 20%, respectively.	High porosity limited structural applicability.
Luo *et al.*, (2024) [89]	100%	Mechanical strength decreased significantly due to interfacial transition zone (ITZ) failure and crack propagation.	SCMs were required to mitigate cracking.

4.4 *Oyster shell as filler / micro-filler*

The use of oyster shell as a filler or micro-filler in cementitious systems is a relatively recent and less explored application compared to its use as a cement or aggregate replacement. In this case, finely ground oyster shell powder (OSP), mainly composed of $CaCO_3$, and behaves similarly to conventional limestone fillers, contributing primarily through physical mechanisms such as particle packing and matrix densification. Its behavior therefore depends mainly on physical rather than chemical effects, resulting in relatively stable and predictable performance. At this scale, OSP is classified as a micro-filler rather than a coarse or fine particulate material due to its sub-150 µm particle size and high specific surface area.

From a fresh-state perspective, OSP used as micro-filler has minimal to moderate effects on workability. Studies show that mixes containing OSP may exhibit slightly lower initial flowability than those with conventional $CaCO_3$ fillers, although workability can improve within practical dosage limits [93]. In cementitious systems, its influence on fresh properties is generally manageable and does not impose significant limitations on mix design [94]. In hybrid systems, acceptable workability can still be achieved even with fibers, provided proper dosage control is maintained [95].

Mechanically, OSP used as a micro-filler generally maintains or slightly improves strength at low dosages. Polymer concrete systems show compressive and flexural strengths comparable to limestone fillers [93], while cementitious systems with around 5% OSP exhibit slight strength gains due to improved particle packing and matrix densification [94]. These improvements are linked to microstructural refinement, as ultrafine OSP particles fill voids and produce a denser, more homogeneous matrix. In hybrid systems, additional improvements in compressive and bond strength are observed when OSP is combined with well-dispersed fibers, enhancing interfacial bonding and overall matrix integrity [95]. However, its role remains mainly physical, with limited chemical participation in hydration.

Durability results, though limited, indicate that OSP does not negatively affect long-term performance. Polymer concrete incorporating OSP shows stable behavior under aggressive conditions such as sulfuric acid exposure and freeze-thaw cycles, with no significant deterioration [93]. Similarly, cementitious systems exhibit stable structural performance without noticeable cracking or instability [94], [96]. In hybrid systems, durability is influenced more by fiber content than by OSP itself, as higher fiber dosages may increase porosity and water absorption [95].

Overall, OSP at micro-filler scale around a 5% replacement level shows strong potential as a sustainable alternative to conventional limestone fillers. It provides consistent performance, enhances matrix densification, and maintains or slightly improves mechanical properties without significant adverse effects on workability or durability. Compared with its use as a cement or aggregate replacement, this application represents the most stable and reliable utilization pathway due to its purely physical and non-load-bearing role.

Despite these positive outcomes, research remains limited. Key gaps include insufficient long-term durability data, limited application in high-performance and ultra-high-performance concrete, and variability in processing methods affecting particle fineness and consistency. Addressing these issues is essential for standardizing micro-filler-grade OSP as a reliable material in sustainable construction.

A summary of key findings on OSP as a filler material is provided in Table 4, highlighting its minor influence on workability, slight mechanical improvements at low dosages, and overall stable performance.

Table 4: Summary of mechanical, durability, and fresh-state performance of OSP as a filler in cementitious systems.

Author (Year)	OSP Content (%)	Main Findings	Key Limitation
Sung *et al.*, (2010) [93]	5%	Comparable compressive strength with moderate workability improvement	No significant deterioration under acid and freeze-thaw exposure
Zhong *et al.*, (2024) [94]	5%	Slight improvement in compressive and flexural strength with stable overall performance	Limited reporting of fresh-state properties
Mora-Ortiz *et al.*, (2025) [95]	5%	Improved compressive and tensile strength remained stable at optimum fiber content	Increased porosity and water absorption at higher fiber contents

5 Critical Discussion of Oyster Shell Applications in Concrete

The utilization of OS in concrete can be classified into four functional roles: cement binder replacement, fine aggregate replacement, coarse aggregate replacement, and micro-filler incorporation. Each role influences concrete behavior through distinct chemical and physical mechanisms. Performance depends strongly on replacement level, particle characteristics, and system composition [48]. Consequently, OS effectiveness is application-specific rather than universal due to fundamentally different governing mechanisms across these roles [65].

A critical comparison of the four application routes indicates that the balance between beneficial microstructural effects, including particle packing, nucleation, and matrix densification, and adverse effects such as clinker dilution, increased porosity, and weak interfacial bonding governs oyster shell performance. Consequently, the relative effectiveness of oyster shell varies considerably depending on its functional role within the concrete system. This mechanistic distinction explains why similar replacement levels may produce markedly different outcomes across applications.

Among the investigated applications, micro-filler incorporation exhibits the most stable and predictable performance because its contribution is primarily physical, improving packing density and matrix cohesion with minimal influence on hydration chemistry. Fine aggregate replacement also provides a favorable performance window, as moderate replacement levels generally improve matrix densification while maintaining acceptable mechanical properties. In contrast, cement replacement is constrained by the limited reactivity of calcined oyster shell powder, particularly at higher dosages where clinker dilution becomes dominant. Coarse aggregate replacement remains the least effective approach because the intrinsic weakness and high porosity of oyster shell particles adversely affect both strength and durability.

This comparison further reveals a transition from chemically driven applications, where performance depends largely on hydration reactions and calcination conditions, to physically governed applications, where particle packing and pore refinement become the dominant mechanisms. As a result, micro-filler and fine aggregate applications generally exhibit behavior that is more consistent across studies than cement replacement systems.

For consistency, the criteria presented in Table 5 were derived from the overall trends reported across the reviewed studies. The “optimal range” refers to the replacement level at which mechanical and durability performance is maintained or improved over the control mixture. The “performance trend” summarizes the general response of concrete properties with increasing oyster shell content, while the “key limitation” identifies the dominant factor responsible for performance deterioration beyond the optimum range.

It is important to note that the variability and occasional contradictions reported across the literature are largely attributable to differences in oyster shell source, processing conditions, and mix design parameters. These differences play a major role in governing the observed performance trends. Variations in shell species, geographical origin, impurity content, particle size distribution, calcination temperature, grinding intensity, and water absorption characteristics directly influence shell reactivity, porosity, and interfacial bonding. Furthermore, differences in replacement level, water-to-binder ratio, curing conditions, and the use of supplementary cementitious materials contribute significantly to the observed discrepancies in mechanical and durability performance. These parameters strongly affect hydration behavior and microstructural development. Therefore, many apparently conflicting findings do not necessarily reflect inconsistencies in oyster shell behavior. Instead, they reflect variations in material characteristics and experimental methodologies. This highlights the need for standardized processing and testing protocols.

Hybrid strategies combining OS with SCMs, fibers, or advanced curing methods enhance performance. These approaches improve hydration efficiency and interfacial bonding. This highlights the importance of system-level optimization rather than direct substitution.

6 Sustainability Assessment of Oyster Shell Applications in Concrete

Oyster shell, a by-product of aquaculture and seafood processing, is a calcium carbonate-rich waste material. It is often disposed of in landfills or coastal

Table 5: Comparative performance of oyster shell across different functional roles in concrete.

Functional Role	Optimal Range	Mechanical Trend	Durability Trend	Key Limitation	Ref.
Cement replacement	5-10%	Improves at low replacement, then declines	Limited long-term improvement	Low reactivity and clinker dilution	[38], [66]
Fine aggregate replacement	5-20%	Improves up to the optimum level, then declines	Exposure-dependent	High porosity and weak ITZ	[79], [82]
Coarse aggregate replacement	≤15%	Slight improvement at low replacement, then decline	Generally reduced	Low strength and high water absorption	[88], [92]
Micro-filler	≈5%	Stable or slightly improved	Generally improved	Limited chemical contribution	[93], [94]

areas, which raises environmental concerns. Its use in concrete offers a sustainable pathway for waste valorization and resource efficiency. However, its sustainability performance strongly depends on its functional role in the cementitious system and the associated processing requirements [23], [48], [65].

The environmental benefit of oyster shell is mainly associated with reducing Portland cement consumption and natural aggregate demand. Cement replacement provides direct CO_2 reduction through clinker substitution. In contrast, aggregate and micro-filler applications provide indirect environmental benefits by improving particle packing and reducing material demand [69], [74]. However, the balance between environmental savings and energy consumption governs the overall sustainability outcome.

A complete sustainability assessment should include not only the avoided emissions from clinker or aggregate substitution, but also the emissions generated during shell collection, washing, drying, crushing, grinding, transportation, and thermal treatment. Therefore, the net environmental benefit of oyster shell utilization is application-dependent and cannot be evaluated only based on replacement levels.

Energy demand is a key factor controlling sustainability performance and has been widely recognized in various material conversion and pretreatment systems as a key indicator of process efficiency [97], [98]. Cement replacement requires high-temperature calcination at 900-1000 °C. This leads to high-embodied energy and associated emissions, which may partially reduce its environmental benefit. In contrast, aggregate and micro-filler applications rely mainly on mechanical processing. These processes require significantly lower energy input and therefore show better environmental performance under typical production conditions [99].

From a life-cycle perspective, cement replacement presents a clear trade-off. Although clinker substitution reduces CO_2 emissions, part of this benefit may be offset by energy consumption during calcination and fine grinding. In addition, transportation distance becomes important, especially when oyster shell sources are far from production sites. As a result, the environmental advantage of calcined oyster shell powder depends on the balance between avoided emissions and processing-related emissions.

In comparison, fine aggregate, coarse aggregate and micro-filler applications involve only washing, crushing, grading, and limited grinding. Since these routes avoid thermal treatment, their energy demand is lower. Consequently, they generally achieve more stable and favorable environmental performance.

Among all applications, micro-filler and fine aggregate replacement provide the most balanced sustainability performance due to low energy requirements and stable mechanical behavior. Cement replacement offers the highest potential for CO_2 reduction but is limited by energy-intensive processing. Coarse aggregate replacement shows the lowest sustainability efficiency due to mechanical limitations and limited environmental gains.

Table 6 compares the sustainability performance of oyster shell applications, including waste valorization, CO_2 mitigation potential, energy demand, and overall sustainability effectiveness. The qualitative rankings (high, moderate, low, very low) are based on clinker reduction potential, processing energy demand, waste utilization efficiency, and reported environmental outcomes. This framework provides a consistent basis for comparing sustainability trade-offs across different applications.

Table 6: Integrated sustainability assessment of oyster shell applications in concrete.

Application Type	Optimal Range	Waste Valorization	CO_2 Mitigation Potential	Energy Demand	Performance Trend	Key Insight	Ref.
Cement replacement	5-10%	Moderate	High (direct reduction)	High	Optimal then declines	Highest CO_2 reduction but energy-intensive	[65], [69]
Fine aggregate replacement	5-20%	High	Moderate (indirect reduction)	Low	Stable then declines	Best performance-sustainability balance	[74], [82]
Coarse aggregate replacement	≤15%	Moderate	Low (indirect reduction)	Low	Slight improve, then declines	Limited structural applicability	[88], [90]
Micro-filler	≈5%	High	Moderate (indirect reduction)	Very low	Stable or slightly improved	Most energy-efficient application	[93], [94]

From an economic perspective, the cost-effectiveness of oyster shell applications depends on both functional role and processing requirements. Fine and coarse aggregate applications generally show better economic viability because they require only mechanical processing, such as washing, crushing, and grading. This reduces production costs compared with cement replacement systems. In contrast, calcined oyster shell used as a cement replacement requires high-temperature processing. This significantly increases energy consumption and overall production costs, despite its higher CO_2 mitigation potential. In coastal regions where oyster shell waste is readily available, reduced demand for natural aggregates and lower disposal costs can partially offset processing expenses. As a result, aggregate-based applications can become economically competitive with conventional materials. Therefore, economic feasibility should be evaluated based on local availability, transportation distance, processing requirements, and regional material prices using comprehensive life cycle cost assessment (LCCA) [45], [48].

Collectively, these findings indicate that the sustainability of oyster shell incorporation is governed by application-specific trade-offs rather than a single optimal solution. In this context, hybrid approaches combining low-level cement replacement with micro-filler or fine aggregate incorporation represent the most balanced strategy, as they achieve meaningful CO_2 reduction while maintaining mechanical integrity, minimizing energy demand, and enhancing overall resource efficiency.

From both environmental and economic perspectives, selecting the optimal application should consider mechanical performance alongside processing requirements and life cycle costs.

7 Challenges and Research Gaps in Oyster Shell-Based Concrete

Despite increasing research on oyster shell-based concrete, several challenges still limit large-scale application. These issues are mainly related to material variability, processing inconsistency, mechanical and durability limitations, and incomplete sustainability assessment. All of these factors affect the reliability and scalability of OS-based systems.

A major challenge is the inherent variability of oyster shell characteristics. This variability is influenced by oyster species, geographical origin, environmental conditions, and post-consumption handling practices [35], [48]. Oyster shells consist predominantly of calcium carbonate $CaCO_3$. However, variations in shell thickness, mineral composition, crystallinity, density, and impurity content may still occur depending on biological species and habitat conditions.

Environmental factors such as seawater salinity, temperature, pollution level, and nutrient availability also affect shell formation and microstructure. These factors lead to differences in physical and mechanical properties. Furthermore, post-consumption handling, including storage duration, contamination with organic residues, washing efficiency, and drying conditions, may introduce chlorides and organic matter. These impurities can adversely affect cement hydration, interfacial bonding, and long-term durability if not properly removed [35], [48].

These variations contribute to the inconsistent performance reported in the literature. They also complicate the development of standardized mix design procedures. This challenge is further intensified by the lack of standardized processing methods. Variations in calcination temperature, grinding techniques, particle size distribution, and pre-treatment procedures significantly influence shell reactivity, filler efficiency, and hydration behavior. As a result, reproducibility is reduced and reliable design standards are difficult to establish [35], [48].

From a mechanical perspective, the low intrinsic strength and high porosity of OS remain major limitations, particularly in coarse aggregate applications. At low replacement levels, performance may improve due to packing effects. However, higher contents generally reduce compressive, tensile, and flexural strength. This is mainly due to weak interfacial transition zones (ITZ) and reduced stiffness. In addition, the mechanisms governing interfacial bonding, crack propagation, and failure behavior remain unclear. Durability performance also remains uncertain. Most studies focus on isolated exposure conditions. Long-term behavior under combined actions such as chloride ingress, sulfate attack, carbonation, and acid exposure is still limited.

Another important gap concerns hybrid systems incorporating OS with supplementary cementitious materials, fibers, or alternative curing methods. These combinations can improve performance. However, the synergistic mechanisms affecting hydration, pore refinement, and long-term durability remain insufficiently investigated.

From a sustainability perspective, current assessments are often incomplete. Most studies focus on CO_2 reduction from cement substitution. However, they do not fully account for energy demand from calcination, grinding, transportation, and processing. In addition, economic aspects such as processing cost and regional availability are rarely considered. Therefore, the net environmental and economic benefit of OS utilization remains uncertain, especially for thermally treated shells. This highlights the need for integrated LCA and LCCA. These should evaluate environmental, energy, and economic indicators simultaneously.

A further limitation is the lack of field-scale validation. Most studies are conducted under laboratory conditions. Limited attention has been given to real construction environments. Practical issues such as material supply, processing scalability, quality control, and long-term in-service performance remain insufficiently addressed.

Overall, the use of oyster shell in concrete is constrained by interconnected challenges related to material variability, processing, performance, sustainability, and scalability. Future research should focus on standardized processing protocols, comprehensive characterization of shells from different species and geographical origins, deeper investigations of interfacial transition zone behavior, long-term durability under coupled environmental exposures, optimization of hybrid systems, and integrated LCA-LCCA studies supported by large-scale field validation. Addressing these gaps is essential for transforming oyster shell from a laboratory-scale waste material into a reliable and sustainable construction resource.

8 Conclusions and Future Perspectives

This review investigated oyster shell utilization in concrete as cement replacement (calcined oyster shell powder), fine and coarse aggregate replacement (crushed oyster shell), and micro-filler incorporation. The reviewed studies indicate that its performance is highly dependent on processing conditions, particle characteristics, and replacement level, leading to distinct and non-linear behavior across applications.

Overall, the available evidence suggests that the balance between beneficial mechanisms such as particle packing, nucleation, and matrix densification, and adverse effects including clinker dilution, increased porosity, and weak interfacial transition zones largely governs performance. Consequently, each application exhibits a different performance-sustainability trade-off.

Based on the reviewed evidence, micro-filler incorporation and fine aggregate replacement generally provide the most favorable balance between performance and sustainability. Micro-filler incorporation typically maintains stable performance through improved packing density and microstructural refinement, while fine aggregate replacement often improves or maintains mechanical properties at replacement levels of 5-20%. In contrast, cement replacement offers the highest CO_2 reduction potential but is limited by low intrinsic reactivity and the energy demand of calcination. Coarse aggregate replacement is generally less effective because of the high porosity and relatively low mechanical strength of oyster shell particles.

From a sustainability perspective, oyster shell represents a promising circular economy material that can reduce both waste disposal and natural resource consumption. However, its environmental benefit is strongly influenced by processing intensity. Mechanical processing routes (filler and aggregate applications) generally provide better energy-carbon efficiency than thermally treated cement replacement systems.

Despite these advantages, several limitations remain, including variability in raw material properties, lack of standardized processing protocols, insufficient understanding of interfacial transition zone behavior, and limited long-term durability data under real exposure conditions. These issues restrict reliable large-scale application.

Future research should prioritize three key directions: standardization of processing and characterization methods, investigation of long-term durability under coupled environmental exposures, and comprehensive life cycle assessment incorporating processing energy, transportation, and emissions. Addressing these aspects is essential for improving the reliability and scalability of oyster shell-based concrete.

Based on the current evidence, oyster shell appears more suitable as a functional supplementary material than as a full replacement for primary cementitious or aggregate constituents, where it can enhance concrete performance through microstructural improvement when incorporated into optimized composite systems.

Acknowledgments

This work was supported by the authors' own resources.

Author Contributions

K.T.: Conceptualization, Methodology, Visualization, Writing-original draft. M.M: Methodology, Validation, Writing-review & editing. T.A.: Supervision, Validation, Writing-review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

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