Innovations in Precast Concrete Technology for Giant Sea Wall Construction in Indonesia: A Literature Review

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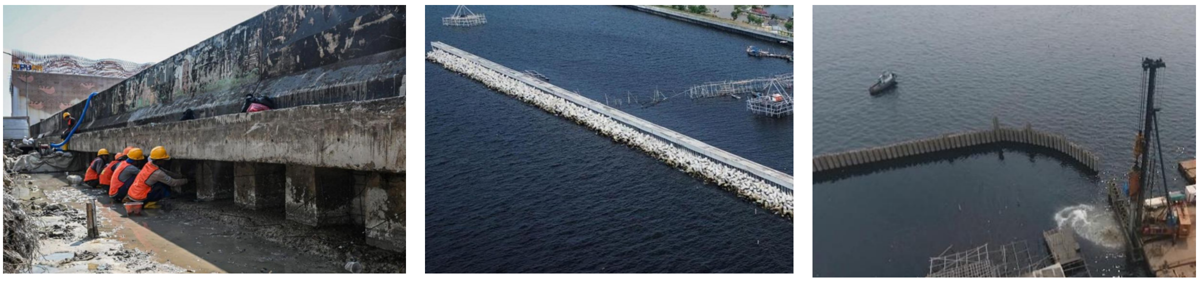
Abstract. Coastal erosion is a major challenge for Indonesia, where extensive shorelines are exposed to high-energy waves and anthropogenic pressures. This study introduces Hexaloc, a novel concrete armor unit with six interlocking arms designed to enhance stability and ease of installation in breakwater structures. The research focuses on the innovation of concrete molds and production systems, enabling scalable fabrication of Hexaloc units with consistent quality. Laboratory-scale trials were conducted to validate compressive strength, density, and durability using Ultrasonic Pulse Velocity (UPV), hammer test, and compressive strength testing. Results confirm that Hexaloc units achieve the targeted strength of 30 MPa and demonstrate effective interlocking performance under simulated wave conditions. The prototype development reached Technology Readiness Level (TRL) 5, with potential for industrial-scale application and community-based coastal protection programs. This innovation contributes to sustainable coastal infrastructure by offering a practical, durable, and environmentally adaptive solution for shoreline defense in tropical regions.

1 Introduction

Indonesia's northern Java coastline is increasingly exposed to compound hazards, including recurrent tidal flooding (rob), accelerated land subsidence, and the projected impacts of global sea-level rise. These phenomena threaten densely populated urban areas such as Jakarta, Semarang, and Surabaya, where critical infrastructure and economic activities are concentrated. In response, the Government of Indonesia has proposed the construction of a Giant Sea Wall (GSW), envisioned as a multi-hundred-kilometer coastal defence system extending from Banten to East Java (shown in Fig. 1). While the project promises large-scale protection, it also raises concerns regarding feasibility, cost, ecological impacts, and social acceptance among coastal communities



(a) (b) (c)

Fig. 1. Jakarta's GSW Construction using: (a) Corrugated Concrete Sheet Piles, (b) Pile Construction Combined with Armour Units, (c) Cylindrical Piles [1]

International precedents demonstrate both the potential and limitations of massive seawall projects. The Afsluitdijk in the Netherlands, completed in 1932, remains an iconic example of coastal engineering that has safeguarded the

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nation for nearly a century [2]. Japan's post-2011 tsunami barriers, extending over 395 km, illustrate the integration of structural defences with ecological measures such as large-scale coastal afforestation [3]. Similarly, innovations in Hong Kong highlight the role of precast concrete technologies in accelerating construction and improving durability [4]. These cases provide valuable lessons for Indonesia in balancing engineering performance with environmental and social sustainability.

Precast concrete systems offer distinct advantages for GSW construction, including factory-controlled quality, rapid installation, and scalability for mass production [5]. However, their application in marine environments requires careful attention to durability against chloride penetration [6] and sulfate attack [7], hydraulic performance under extreme wave loading [8], and long-term ecological compatibility [9]. Recent advances in reinforced precast armour units, eco-engineered block geometries, and protective coatings suggest promising pathways to address these challenges [10].

This paper consolidates lessons learned from Indonesian and international seawall projects, identifies material and structural challenges specific to precast applications in Indonesia, and proposes a precast-centered construction concept for the GSW. The study emphasizes strategies that combine engineering robustness with ecological integration, aiming to deliver a resilient and sustainable coastal defence system aligned with the United Nations Sustainable Development Goals (SDGs).

2 Lessons learned and structural models

2.1 Indonesian experience and observed issues

Recent coastal reinforcement projects in Indonesia, particularly in Jakarta, have revealed recurring challenges that complicate large-scale implementation. The most pressing issues include the exceptionally high construction costs, significant social impacts on fishing communities, and ongoing debates regarding the balance between engineering effectiveness and ecological or social trade-offs. These concerns underscore the complexity of designing coastal defences that are not only technically robust but also socially equitable and environmentally sustainable. The discourse surrounding these projects reflects the need for integrated approaches that consider hydrodynamic performance, long-term durability, and community acceptance as inseparable dimensions of success.

To address these challenges, several structural concepts have been tested in local contexts. Corrugated Concrete Sheet Piles (CCSP) have been employed for vertical barriers, pile-supported systems combined with armour units have been used to dissipate wave energy, and large-diameter cylindrical piles have provided foundation stability in soft marine soils. Each of these models demonstrates technical feasibility and offers valuable insights into construction practices under Indonesian coastal conditions. However, they also highlight persistent stakeholder concerns, particularly regarding extended construction schedules and the scalability of solutions for national-level projects such as the Giant Sea Wall. These lessons emphasize the importance of adopting innovative precast concrete technologies that can accelerate construction, improve durability, and reduce socio-environmental conflicts in future coastal defence initiatives.

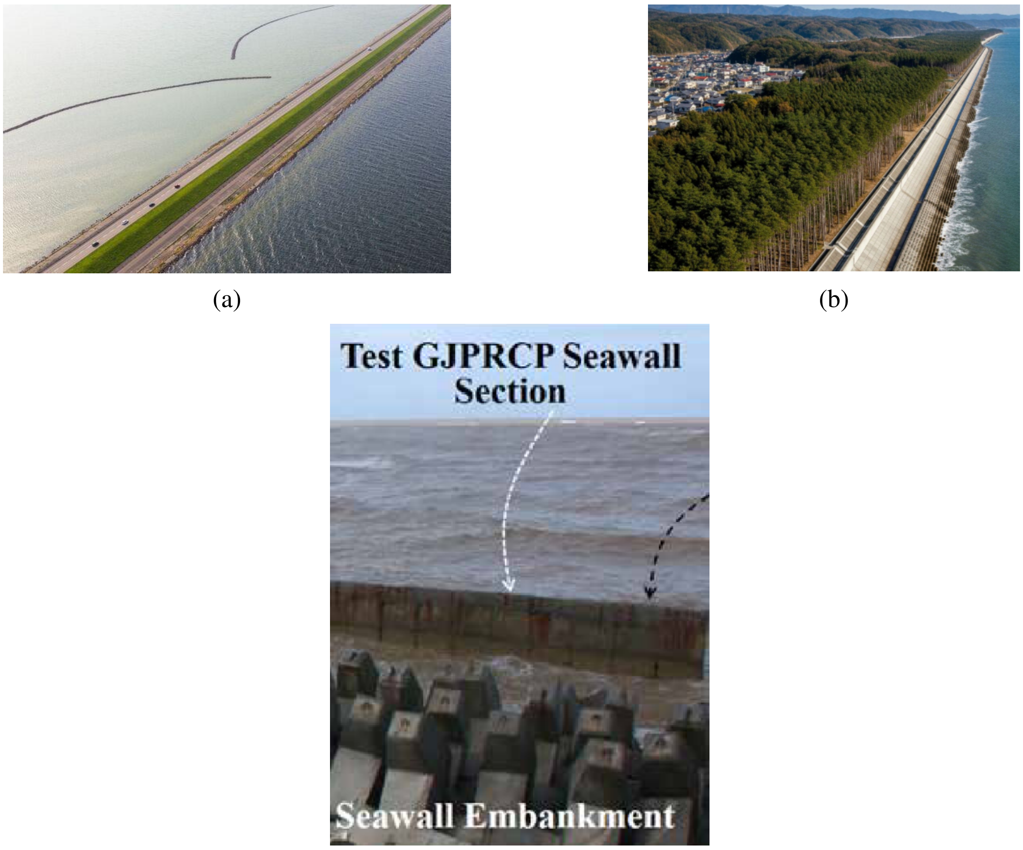
2.2 International precedents

Historical examples such as the Dutch Afsluitdijk and Japan's extensive tsunami barriers show long-term protection benefits but also underline the need for integrated ecosystem measures. Precast armour-unit systems (e.g., Accropode™, Core-loc®, Xbloc) and applications in South Africa, Hong Kong (GJPRCP no-dredge techniques), and Taiwan illustrate diverse technical solutions adapted to site-specific hydraulic loads and environmental constraints.

Historical precedents such as the Dutch Afsluitdijk and Japan's extensive tsunami barriers demonstrate the long-term protective benefits of large-scale coastal infrastructure. The Afsluitdijk, completed in 1932, has safeguarded the Netherlands from the North Sea for over 90 years, while also serving as a multifunctional structure for transport and recreation [2]. Similarly, Japan's tsunami barriers, constructed after repeated catastrophic events, highlight the importance of robust engineering in reducing disaster risks [3]. However, these examples also underline the necessity of integrating ecosystem-based measures, as rigid structures alone can disrupt sediment transport, fisheries, and coastal biodiversity. Modern coastal protection strategies increasingly emphasize hybrid approaches that combine hard infrastructure with ecological restoration to achieve resilience and sustainability.

In terms of technical innovation, precast armour-unit systems such as Accropode™, Core-loc®, and Xbloc have become widely adopted in breakwater and seawall construction. These units are designed to dissipate wave energy efficiently while reducing material use compared to traditional rubble mound structures. The Xbloc system, developed in the Netherlands in 2001, has been extensively tested and applied worldwide, offering resilience against waves up to twice the design height [11]. Such precast solutions provide modularity, rapid installation, and durability in harsh marine environments, making them attractive for large-scale projects like Indonesia's proposed Giant Sea Wall. Their adaptability to different hydraulic conditions ensures that engineers can tailor designs to local site-specific challenges, balancing structural stability with environmental considerations.

Applications across diverse regions further illustrate the versatility of precast systems. In Hong Kong, the GJPRCP no-dredge technique has enabled construction without extensive seabed disturbance, reducing ecological impacts [4]. These international experiences highlight that while the engineering principles are universal, successful implementation requires sensitivity to local hydraulic loads, sediment dynamics, and ecological constraints. These methods are shown on Fig. 2. For Indonesia, learning from these cases can inform a more integrated approach—combining advanced precast technologies with protective coatings, high-performance concrete mixes, and ecological design features to ensure both durability and environmental compatibility.



(a) (b)

(c)

Fig. 2. (a) Afsluitdijk in the Netherlands [2] (b) Japan's Tsunami Barriers [3] (c) GJPRCP Seawall in Hong Kong [4]

2.3 Structural typology for precast seawalls

Vertical and curved solid walls constructed from precast panels represent one of the most straightforward solutions for coastal defense, offering high resistance against direct wave impact and ease of modular installation [2]. In addition, perforated or cellular precast units are widely applied to dissipate wave energy, reducing reflection and turbulence while enhancing structural stability [3]. These systems are particularly effective in environments with high wave energy, as they combine hydraulic efficiency with reduced material requirements. Pile-supported precast caps also provide flexibility in areas with soft seabed conditions, enabling load transfer to deeper strata while minimizing settlement issues [4].

Discrete armour-unit layers, such as Accropode™, Core‑loc®, and Xbloc, are another practical option, designed to interlock and resist displacement under severe hydraulic loads [11]. The choice among these alternatives depends strongly on local wave climate, seabed geotechnical properties, and operational constraints such as dredging allowances and construction access. International applications demonstrate how site-specific conditions dictate the optimal combination of precast technologies. For Indonesia's Giant Sea Wall initiative, integrating these lessons ensures that structural resilience is balanced with constructability and environmental compatibility.

3 Material and durability considerations for marine precast concrete

3.1 Key degradation mechanisms

In coastal environments, concrete structures are subjected to multiple aggressive deterioration processes that significantly reduce their service life if not properly mitigated. Chloride ingress and sulfate attack are among the most critical chemical mechanisms, as they penetrate the concrete matrix and initiate reinforcement corrosion, ultimately compromising structural integrity. Quantitative thresholds such as chloride concentration at the reinforcement level exceeding 0.4% by weight of cement or sulfate concentrations above 1500 mg/L in seawater are commonly used indicators of durability risk [6]. Mechanical degradation also plays a major role: abrasion and attrition caused by suspended sediments and repeated wave impacts can erode armour units and reduce hydraulic stability [14], [21]. Research suggests that abrasion rates of 0.1–0.5 mm/year under high sediment loads and wave pressures exceeding 50 kN/m² can significantly shorten service life [8]. Together, these factors highlight the necessity of adopting marine‑specific design standards, including low‑permeability concrete mixes (<1000 Coulombs), corrosion‑resistant reinforcement, and protective coatings, to ensure that precast seawall elements achieve the resilience required for long‑term coastal defence [10]

3.2 Effects of marine constituents and curing practices

The use of seawater as mixing water or sea sand as fine aggregate in concrete, when applied without mitigation strategies, has been shown to reduce long‑term compressive strength and significantly increase the risk of chloride‑induced reinforcement corrosion [6]. Elevated chloride concentrations penetrate the concrete matrix, accelerating steel deterioration and compromising structural integrity in marine environments [7]. In addition to chemical attack, curing regimes and initial exposure conditions exert a critical influence on carbonation depth and overall durability. Studies have demonstrated that improper curing, particularly with seawater, can intensify carbonation and weaken the protective capacity of the concrete cover, thereby shortening service life . These findings underscore the necessity of adopting marine‑grade design standards, including low‑permeability mixes, supplementary cementitious materials, and controlled curing practices, to ensure that precast seawall elements maintain resilience under aggressive coastal conditions [8].

Comparative research highlights that curing under moist air conditions has been shown to result in higher carbonation rates than water curing, with carbonation depths nearly double after one year of exposure. The use of supplementary cementitious materials (SCMs) such as fly ash and silica fume, combined with extended curing, has been reported to lower permeability and delay the onset of reinforcement corrosion [6]. These findings underscore the necessity of adopting marine‑grade design standards, including low‑permeability mixes (<1000 Coulombs), SCM incorporation, and controlled curing practices, to ensure that precast seawall elements maintain resilience under aggressive coastal conditions [9].

3.3 Recommended material strategies

To enhance the durability of precast concrete elements in aggressive marine environments, several material and structural strategies must be adopted. Cement selection plays a critical role, with sulfate-resistant cement or Portland-slag cement (PSC) recommended to mitigate chemical attack from chlorides and sulfates [7]. Supplementary cementitious materials such as silica fume and controlled proportions of fly ash are effective in reducing permeability and improving long-term strength [5]. Partial replacement options using locally sourced materials, for example clamshell powder, may also be explored to lower embodied carbon while maintaining performance, provided that rigorous testing validates their suitability. Protective systems which include durable surface coatings, corrosion inhibitors, and densifiers are essential to slow the ingress of aggressive ions and extend service life [10]. Finally, reinforcement strategies should be carefully considered: armour units and slender precast elements benefit from reinforcement or fibre enhancement to limit catastrophic breakage, while unreinforced designs require thorough verification to ensure hydraulic stability and structural integrity [8]. Collectively, these measures provide a comprehensive framework for producing precast seawall components that balance durability, sustainability, and resilience under coastal loading conditions.

Findings from reviewed studies indicate that PSC and blended cements incorporating slag or fly ash consistently reduce chloride penetration depth by 25–40% compared to ordinary Portland cement [7]. Silica fume additions of 8–10% have been shown to lower permeability by up to 50% and increase compressive strength retention under marine exposure [5]. Experimental trials with clamshell powder as partial cement replacement demonstrated comparable strength development to fly ash mixes, while reducing embodied carbon by approximately 15% [12]. Protective coatings and corrosion inhibitors further extend service life, with field studies reporting a 20–30 year delay in reinforcement corrosion initiation when such systems are applied [10].

Material replacement strategies provide both durability and sustainability benefits when carefully validated. The combined use of PSC, silica fume, and fly ash offers proven reductions in permeability and improved resistance to chloride ingress, while innovative local materials such as clamshell powder present promising pathways for lowering carbon footprints without compromising performance. Protective systems and reinforcement enhancements complement these measures, ensuring that precast seawall components achieve resilience under severe coastal loading. Future research should focus on long-term field validation of alternative binders and replacement materials, quantifying durability gains and lifecycle carbon reductions to establish robust design standards for marine infrastructure.

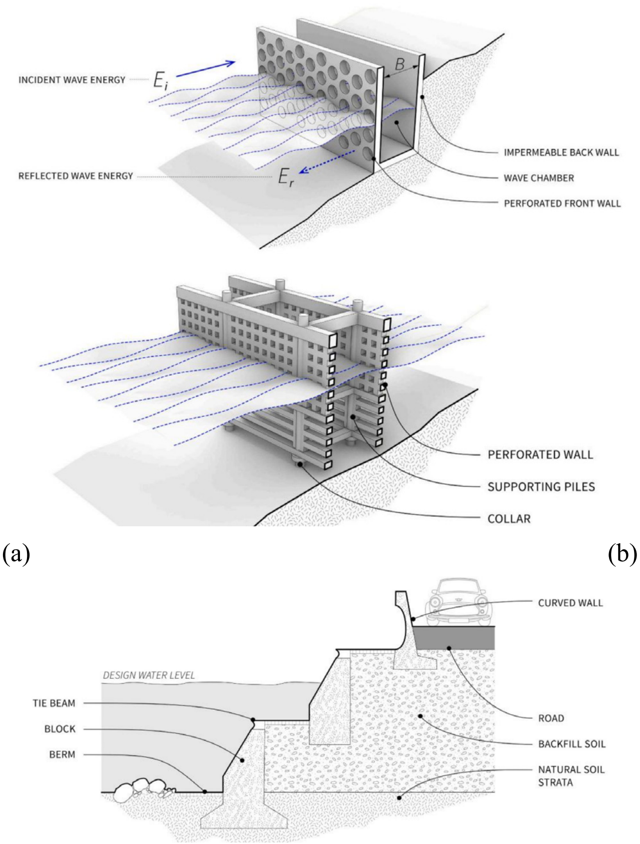
3.4 Quality control and production

Precast concrete production offers significant advantages for coastal defence applications by enabling high-quality casting under controlled factory conditions. Unlike in-situ construction, precast systems allow precise regulation of curing regimes, ensuring optimal hydration and strength development [5]. Factory environments also facilitate the application of protective systems such as surface coatings, corrosion inhibitors, and densifiers, which enhance resistance to chloride ingress and abrasion [10]. These controlled processes reduce variability across units, improve reproducibility, and allow performance certification prior to deployment, thereby ensuring that each element meets marine-specific durability standards [8]. As a result, precast production not only accelerates construction schedules but also provides a reliable pathway to achieving long-term resilience and sustainability in large-scale seawall projects [11].

4 Proposed precast-based Giant Sea Wall concept and implementation strategy

4.1 System concept overview

A modular precast seawall system offers a versatile and constructible solution for large-scale coastal defence, combining structural robustness with ecological sensitivity. The foundation is established through a pile grid composed of large-diameter precast piles or driven precast piles, providing stability in soft marine soils and ensuring long-term load-bearing capacity. Above this, precast capping beams and vertical panels can be assembled to form a continuous barrier where uninterrupted protection is required, while reinforced precast armour units or interlocking concrete elements are deployed along seaward slopes to dissipate wave energy and reduce hydraulic stresses. To further enhance ecological outcomes, perforated or cellular elements [13] may be incorporated in selected stretches, reducing wave reflection and simultaneously promoting habitat formation for marine organisms as shown in Fig. 3. This modular approach not only accelerates construction through standardized components but also enables performance certification, adaptability to site-specific conditions, and integration of ecosystem-based measures, positioning it as a sustainable pathway for Indonesia's future coastal defence initiatives.



(c)

Fig. 3. Illustrations of: (a) Perforated Vertical Breakwater, (b) Vertical Cellular Walls, (c) Thin-Walled Hollow Seawall [13]

4.2 Design principles

The successful implementation of modular precast seawalls requires a holistic design framework that balances robustness, durability, constructability, and environmental integration. Robustness must be achieved by designing for local extreme wave and current loads with redundancy to ensure resilience under rare but severe events. Durability is enhanced by targeting characteristic concrete strengths above 35 MPa [6], employing low-permeability mixes, and applying protective coatings in factory settings to resist chloride ingress and abrasion [10]. Constructability is optimized through extensive off-site production and the use of barge or heavy-lift installation methods, thereby shortening on-site works and reducing disruption; where seabed disturbance is constrained, no-dredge or low-dredge techniques such as grouted jetted precast piling (GJPRCP) should be adopted [4]. Finally, environmental integration is essential, with hybrid nature-engineering measures which include mangrove planting, vegetated berms, and intertidal habitats embedded in cavities that can be introduced to improve biodiversity and foster social acceptance [9]. Collectively, these strategies provide a pathway for seawall systems that are technically resilient, sustainable, and socially inclusive.

4.3 Materials and element specifications (practical guidance)

Precast element design for coastal defence requires careful material and structural specification to ensure long-term resilience under aggressive marine exposure. Portland-slag cement (PSC) or sulfate-resistant cement combined with silica fume is recommended to mitigate chemical attack, with target 28-day cube strengths in the range of 35 – 40 MPa depending on element function [6]. Reinforcement strategies should prioritize corrosion-resistant options, including epoxy-coated or stainless steel bars in critical zones, with internal cathodic protection considered for key elements subject to severe chloride ingress [10]. As presented in Armour units, particularly those with slender geometries, benefit from reinforced or fibre-reinforced designs to limit catastrophic breakage, while interlocking geometries are preferred to minimize displacement and hydraulic instability [8]. Factory-applied offshore-grade coatings, supplemented by sacrificial layers in high-wear zones, provide an additional barrier against abrasion and chloride penetration, extending service life and reducing maintenance requirements [5]. Collectively, these measures establish a robust framework for precast seawall elements that balance durability, constructability, and environmental performance.

(a)

(b)

Fig. 4. Illustrations of Armour Units: (a) Damaged Cube (Left) and Dolos (Right), (b) Accropode (Left), Core-loc (Middle), and Xbloc (Right) [11]

4.4 Construction sequencing and logistics

Phased implementation is essential for the successful deployment of modular precast seawalls, beginning with pilot stretches that validate structural, hydraulic, and social performance under local conditions before scaling to full alignment. Locating factory production facilities close to harbour areas enables efficient logistics, with roll-on/roll-off systems and heavy-lift barges facilitating the transport of precast elements and minimizing on-site construction time [4]. Equally important is the integration of community engagement plans, particularly for fishing communities whose livelihoods are directly affected by coastal infrastructure. Corporate social responsibility (CSR) programs, inclusive access designs, and participatory planning frameworks can foster trust, improve social acceptance, and align engineering interventions with local socio-economic priorities [14]. This combined approach ensures that seawall projects achieve technical resilience while maintaining legitimacy and sustainability in the eyes of affected stakeholders.

5 Discussion and Conclusions

5.1 Benefits and trade-offs

Precast systems provide notable advantages for coastal defence infrastructure, particularly in terms of accelerated construction schedules, improved quality control, and potential long-term cost savings through reduced maintenance requirements [5]. Factory-controlled casting and curing enable reproducibility and performance certification prior to deployment, thereby enhancing durability and reliability compared to conventional in-situ methods [10]. However, these benefits are balanced by trade-offs: initial capital investment for precast facilities and the scaling of supply chains represent significant challenges, especially in regions with limited industrial capacity. In addition, social impacts which include restricted fishing access, altered coastal aesthetics, and community concerns regarding livelihood disruption require proactive mitigation through inclusive design features and structured stakeholder engagement programs [14]. Addressing these trade-offs through integrated planning ensures that precast seawall systems achieve both technical resilience and social legitimacy.

5.2 Sustainability and SDG alignment

The proposed modular precast seawall approach is designed to align with the United Nations Sustainable Development Goals (SDGs), ensuring that coastal defence strategies contribute to broader global sustainability objectives. By protecting vulnerable coastal communities from flooding and erosion, the system directly supports SDG 11 on sustainable cities and communities. Through the adoption of resilient infrastructure solutions—including precast elements with enhanced durability, factory-controlled quality assurance, and redundancy against extreme hydraulic loads—the approach advances SDG 9 on industry, innovation, and infrastructure. Furthermore, the integration of hybrid nature-engineering features (illustrated on) such as mangrove planting, vegetated berms, and perforated habitat modules preserves marine ecosystem services and biodiversity, thereby contributing to SDG 14 on life below water. Collectively, these measures demonstrate how engineering innovation can be harmonized with social and ecological priorities to deliver coastal infrastructure that is both technically robust and globally sustainable [15].

(a) (b)

Fig. 5. Coastal Protection Structures using (a) Temporary Geobags and (b) Mangrove Plants [15]

5.3 Limitations and research needs

Site-specific geotechnical and hydrodynamic investigations are indispensable for the design of modular precast seawalls, as they provide the foundation for load assessments, pile installation feasibility, and hydraulic stability under local extreme events. Long-term performance data are required for locally adapted precast concrete mixes, including innovative partial replacements such as clamshell powder, to validate strength, permeability, and durability under Indonesian marine exposure. Full-scale trials of reinforced armour units in regional seas are equally critical to assess interlocking behavior, breakage resistance, and hydraulic performance under site-specific wave climates [8]. Beyond engineering validation, socioeconomic studies must accompany technical plans to evaluate the displacement of fishing activities, ensure equitable compensation, and foster community acceptance through participatory frameworks [14]. Integrating these technical and social dimensions ensures that seawall projects achieve resilience, sustainability, and legitimacy in the Indonesian context.

5.4 Conclusions

Precast concrete technologies have the potential to serve as the backbone of Indonesia's Giant Sea Wall initiative, offering a constructible, durable, and more sustainable alternative to conventional in-situ methods. By leveraging factory-controlled production and modular installation, precast systems can accelerate construction schedules while ensuring consistent quality across large-scale coastal defence structures. Their adaptability to marine-specific standards makes them particularly suited to withstand the harsh conditions of Indonesia's coastal environment.

The success of such an approach depends on several technical imperatives. Durable, low-permeability concrete mixes are essential to resist chloride and sulfate attack, while reinforced or fibre-enhanced armour units can provide greater resilience against hydraulic loads and mechanical abrasion. Protective factory-applied coatings further extend service life by limiting chemical ingress, and construction methods that minimize seabed disturbance reduce ecological impacts during installation. Together, these strategies position precast concrete as a viable pathway to deliver a Giant Sea Wall that balances engineering robustness, environmental sustainability, and long-term socio-economic benefits for coastal communities.

5.5 Recommendations

To ensure the successful implementation of the Giant Sea Wall, it is recommended to initiate pilot projects spanning 1–3 km that employ the proposed precast system, thereby validating both design parameters and logistical feasibility under real site conditions. Parallel to this, the development of local precast supply chains with strict quality control and marine-grade concrete standards will be essential to guarantee durability and scalability. Engineering design should be complemented by ecosystem-based measures such as mangrove planting and the incorporation of habitat cavities to enhance ecological resilience. Early engagement with affected coastal communities is critical, including the provision of compensatory programs and access arrangements to secure social acceptance. Finally, targeted research on the use of local materials, long-term durability performance, and comprehensive lifecycle environmental impact assessments will provide the evidence base needed to refine strategies and ensure that the Giant Sea Wall achieves both technical robustness and sustainable outcomes.

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