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Innovative Concrete Mold and Hexaloc Production System for Sustainable Coastal Protection in Indonesia

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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 coastal regions are increasingly vulnerable to environmental pressures such as shoreline erosion, storm surges, and large-scale reclamation activities [1], [2], [3]. These phenomena not only threaten ecological balance but also pose risks to infrastructure, livelihoods, and long-term coastal resilience. Conventional breakwater systems, typically constructed from natural rocks or standard concrete armor units, have been widely employed to mitigate these hazards. However, such traditional solutions often exhibit limitations in terms of hydraulic stability and structural efficiency, particularly when subjected to high-energy wave environments [4]. The lack of optimized interlocking capacity among conventional units can result in displacement, reduced durability, and higher maintenance costs over time.

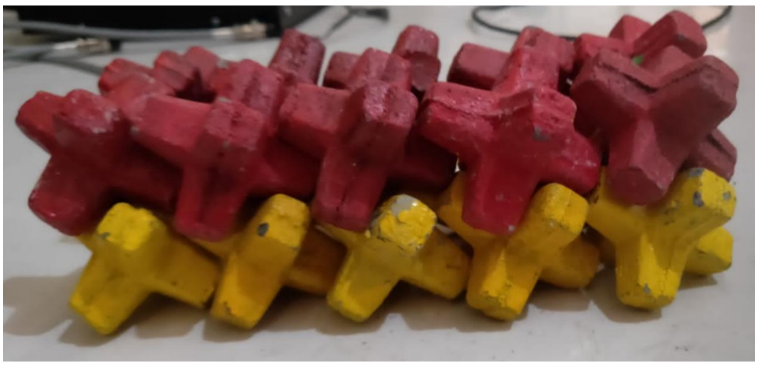

Fig. 1. Interlocking property of the Hexaloc concrete armor units

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In response to these challenges, the Hexaloc unit was conceived as an innovative concrete armor block specifically engineered to enhance coastal protection. Characterized by six symmetrical arms, the Hexaloc design (shown in Fig. 1) aims to maximize interlocking potential and improve overall stability under dynamic wave action [5]. Its geometric configuration facilitates energy dissipation while minimizing movement, thereby offering superior performance compared to conventional armor units. Recent innovations such as BRINpod further demonstrate the potential of novel interlocking designs to strengthen coastal defense systems [6]. The development of Hexaloc represents a significant advancement in coastal engineering, combining structural robustness with practical applicability. By integrating novel design principles into coastal defense systems, this unit contributes to more sustainable and resilient shoreline management strategies in Indonesia and beyond.
Building on prior investigations of artificial roots, armor units, and preliminary numerical analyses of Hexaloc [5], [7], [8], this study seeks to bridge the gap between conceptual design and practical implementation. The primary objective is to establish a reliable production methodology for Hexaloc units, including mold fabrication, concrete mix optimization, and laboratory testing of mechanical properties. By integrating design innovation with scalable manufacturing processes, the research aims to demonstrate the feasibility of Hexaloc as a coastal protection solution that is both structurally robust and environmentally resilient. Ultimately, this paper presents the development, testing, and evaluation of Hexaloc units as a novel contribution to sustainable coastal infrastructure.

2 Methodology

2.1 Mold Innovation

The research successfully produced designs of Hexaloc molds corresponding to unit weights of 0.14 ton (a) and 1.0 ton (b) as shown in Fig. 2. The Hexaloc mold consists of two main parts, the upper and lower sections, which are connected at the center using bolted joints. The lower section is supported by steel columns positioned at the four sides of the mold, ensuring stability and alignment during casting. Openings are provided on all four sides as well as on the top surface of the mold to facilitate the placement of concrete, allowing efficient filling and compaction. On each tip of the arms, openings are provided to aid in the demolding process. In addition, the corners of the mold are deliberately designed at angles greater than 90 degrees to ensure that the concrete surface remains smooth and free of damage when the mold is removed. This design innovation reduces the risk of stress concentration at the edges, prevents chipping during demolding, and eases the release process, thereby improving both the visual quality and durability of the finished Hexaloc units.
By minimizing surface defects and simplifying the demolding process, the >90° corner design directly contributes to lower maintenance costs, reduced rejection rates, and longer service life of the Hexaloc units in coastal applications. The improved surface finish not only enhances durability against abrasion and weathering but also ensures better interlocking performance when units are deployed in breakwater systems. Consequently, the mold design provides both technical reliability and economic efficiency, strengthening the case for industrial-scale production and practical implementation in coastal defense projects.

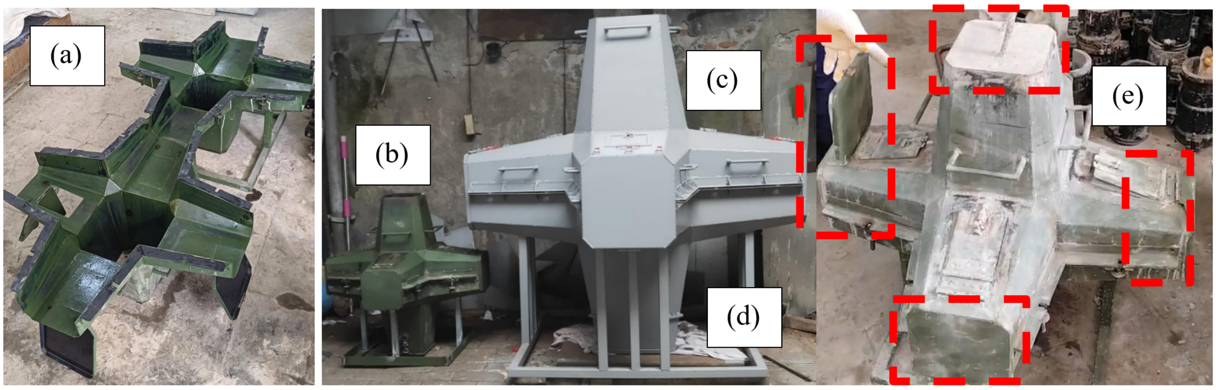

Fig. 2. (a) Two-part Hexaloc molds for unit weights of 0.14 ton (b) and 1.0 ton (c) equipped with (d) steel supports and (e) openings at all six tips of the arms

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2.2 Production Process

The detailed mix proportions are summarized in Table 1, which outlines the material quantities used per cubic meter of concrete. The mix was proportioned to achieve both high strength and durability, with a cement content of 444.44 kg/m³ and using a 0.45 water/cement ratio. The relatively high cement dosage, combined with carefully balanced aggregates (716.22 kg/m³ of sand and 1074.33 kg/m³ of crushed stone) ensured adequate workability while maintaining dense particle packing. The addition of 200 liters of water provided sufficient hydration without compromising strength, as reflected in the low w/c ratio. This mix design was intentionally selected to produce concrete with superior mechanical properties, particularly compressive strength exceeding standard requirements, and to guarantee durability under aggressive coastal exposure conditions. The systematic proportioning not only facilitated consistent production of Hexaloc units but also ensured that the resulting concrete could withstand long-term service in marine environments, where resistance to erosion, abrasion, and chloride penetration is critical.

Table 1. Mix Composition of Hexaloc Concrete f’c 30 MPa

Material	Quantity per m³ of concrete
Cement	444.44 kg
Sand	716.22 kg
Crushed stone	1074.33 kg
Water	200 L
w/c ratio	0.45

2.3 Technology Readiness Level (TRL)

The project successfully achieved Technology Readiness Level (TRL) 5, demonstrating that the Hexaloc prototype could be validated under relevant laboratory conditions. At this stage, the design was tested in controlled environments that closely replicate real coastal scenarios, confirming both its structural performance and stability. Achieving TRL 5 indicates that the concept has moved beyond theoretical modeling and small-scale experimentation, reaching a level where the prototype can reliably function in simulated operational settings. Looking ahead, the next milestone involves scaling the innovation to TRL 6, which requires demonstration in a relevant industrial environment. This progression will be pursued through collaboration with precast concrete manufacturers, enabling the transition from laboratory molds to industrial production systems. Such partnerships are expected to ensure consistent quality, reproducibility, and cost-effectiveness in large-scale fabrication. By advancing to TRL 6, the project aims to bridge the gap between laboratory validation and real-world application, positioning Hexaloc as a viable solution for coastal infrastructure projects that demand durability, scalability, and resilience [9], [10].

3 Results and Discussion

As shown in Fig. 3, the mold was successfully tested for producing Hexaloc units with a weight of 0.14 ton, demonstrating the feasibility of the design at a smaller scale. Visual inspection of the finished product confirmed that the concrete surface exhibited good quality, with smooth texture, uniform finish, and minimal surface defects such as honeycombing or segregation. These observations suggest that the mold design ensures proper compaction and effective concrete flow during casting, which are critical factors for achieving durability and long-term performance in marine environments. Although the assessment was primarily visual, the results provide encouraging evidence that the production system can deliver consistent quality, thereby supporting the reliability of Hexaloc units for coastal protection applications.

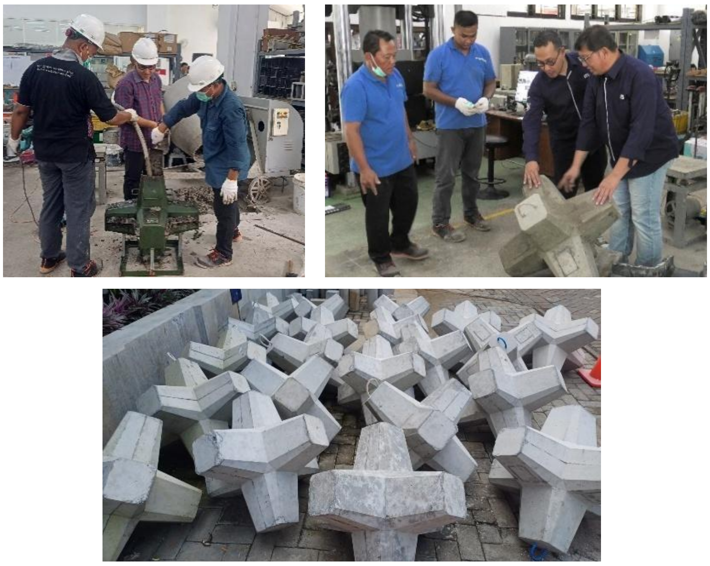

Fig. 3. Laboratory process for producing Hexaloc units

Concrete specimen testing is shown in Fig. 4, where the Hexaloc armor unit's compressive strength was evaluated to determine their ability to withstand structural loads in coastal environments. Test results indicated values ranging between 47–52 MPa, which significantly exceeded the design target of 30 MPa. This performance demonstrates excellent bonding between cement paste and aggregates, as well as effective compaction during casting. The higher strength values confirm that Hexaloc units are capable of resisting both static and dynamic forces generated by wave action and interlocking stresses, ensuring long-term durability in service.

Fig. 4. UPV test, rebound hammer test, and compressive strength test of Hexaloc concrete samples.

The Ultrasonic Pulse Velocity (UPV) test results, as shown in Fig. 5, reveal notable variations in concrete quality across the testing sequence. Two distinct peaks are observed around testing numbers 8–10 and 28–30, where the UPV values approach 4700 m/s, indicating zones of high material density and internal cohesion. According to widely accepted standards such as those referenced in ASTM C597 (as shown in Table 2) and international guidelines, concrete quality can be classified based on UPV values as follows:

Table 2. Grading of Concrete Quality Based on Ultrasonic Pulse Velocity (UPV) [11]

UPV Range (m/s)	Concrete Quality
> 4500	Excellent
3500 – 4500	Good
3000 – 3500	Medium
< 3000	Poor

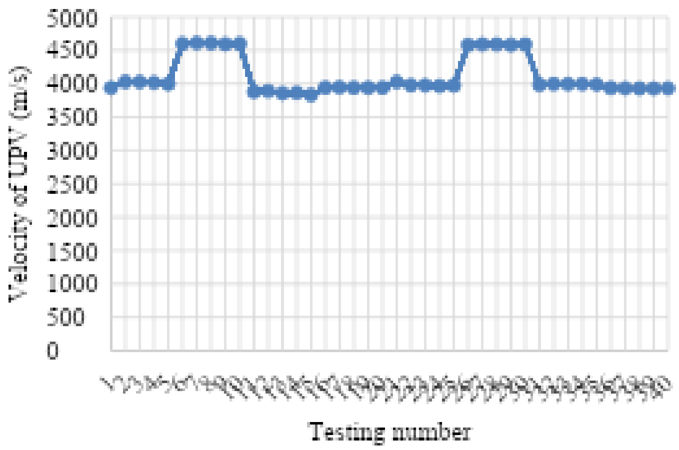

Fig. 5. Variation in UPV Velocity Across Testing Sequence for Hexaloc Concrete Units

Outside the peak intervals, the velocity fluctuates around 4000 m/s, placing most samples within the "Good" quality category, with select batches reaching "Excellent" classification. These fluctuations may reflect differences in curing conditions, compaction quality, or aggregate distribution during the casting process. The presence of high UPV values in specific batches confirms the potential for achieving consistent mechanical integrity in Hexaloc units, while the variability highlights the importance of process control during production. Overall, the UPV data supports the structural viability of the Hexaloc design and provides a non-destructive benchmark for quality assurance in future scaling efforts.

The application of Hexaloc units for coastal protection at Dalegan Beach, Gresik further illustrates the practical relevance of this innovation (see Fig. 6). The deployment of the interlocking concrete blocks demonstrates how the system can be effectively utilized to mitigate shoreline erosion and reduce the destructive impacts of wave action in real coastal settings. By stabilizing the beach profile and dissipating wave energy, Hexaloc units contribute to maintaining coastal integrity while offering a sustainable alternative to conventional protection methods such as tetrapods or rubble mounds. Field observations confirmed that the modular design facilitated ease of installation and adaptability to varying site conditions, while the high mechanical strength and surface quality of the units ensured durability under continuous marine exposure. This case study not only validates the engineering performance of Hexaloc but also highlights its potential for broader application in Indonesia's coastal management programs, where erosion and habitat loss remain pressing challenges.

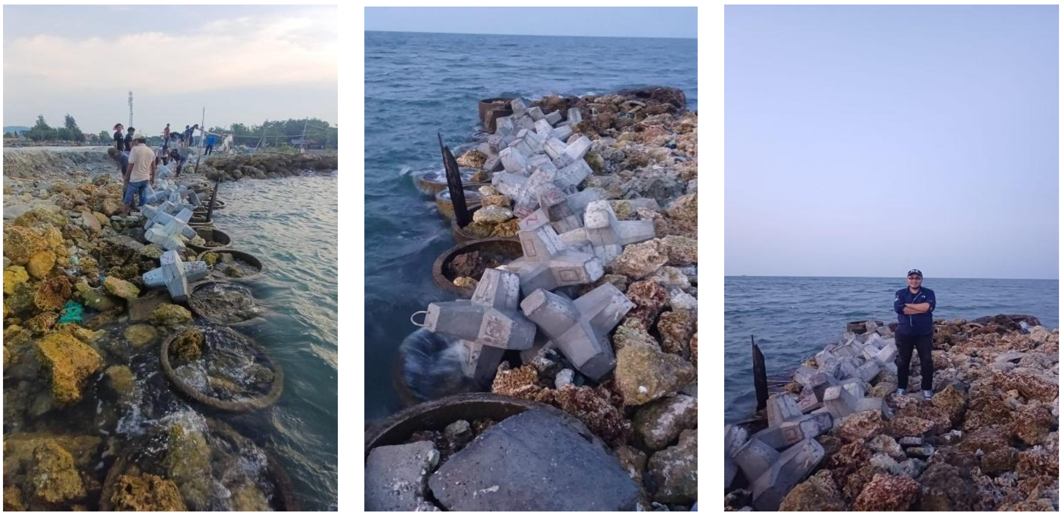

Fig. 6. Application of Hexaloc for coastal protection at Dalegan Beach, Gresik.

4 Conclusion

This study successfully developed and validated innovative molds and production systems for Hexaloc concrete armor units, marking a significant advancement in sustainable coastal engineering. The mold design, characterized by bolted connections, steel column supports, and corner angles greater than 90°, ensured smooth surfaces, reduced stress concentration, and facilitated efficient demolding. Laboratory trials confirmed that the optimized concrete mix achieved compressive strengths of 47–52 MPa, exceeding the design target of 30 MPa, while Ultrasonic Pulse Velocity (UPV) results classified the units within “Good” to “Excellent” quality standards. These findings demonstrate the structural reliability and durability of Hexaloc under relevant laboratory conditions, thereby achieving Technology Readiness Level (TRL) 5.

The pilot application at Dalegan Beach, Gresik further illustrated the practical relevance of Hexaloc, showing its effectiveness in mitigating shoreline erosion and dissipating wave energy. The modular design facilitated ease of installation and adaptability to site conditions, confirming its potential for broader adoption in Indonesia’s coastal management programs. Looking ahead, collaboration with precast concrete manufacturers will enable scaling to TRL 6, ensuring reproducibility, cost-effectiveness, and industrial readiness. Overall, Hexaloc presents a viable, durable, and scalable solution for coastal infrastructure projects, bridging laboratory innovation with real-world application and contributing to long-term shoreline resilience.

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