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# Materials and Processes of Eco-concrete Mixtures for Artificial Marine Habitats

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## ABSTRACT

Poor quality habitat profiles of artificial coastal structures for biodiversity growth compared to natural shore have led researchers to utilize ecological engineering principles in creating habitat enhancement models mimicking the natural environment to help improve living conditions for marine organisms. Extensive global trials have been conducted with concrete formulations incorporating eco-friendly materials and recycled resources. However, eco-concrete production for marine environment use is still lacking in Malaysia. The technology involved in casting, moulding, and demoulding remains at the experimental stage, with unreported comparisons of different moulding materials used for casting geometrically complex habitat enhancement models. This study evaluated different casting, moulding, and demoulding techniques using locally produced eco-concrete. The main aim of this study is to determine the effect of different materials including plaster of Paris, drilling wood, expanded polystyrene, rubber foam, and vacuum forming on the mould production time, labour requirements and fabrication factors. Vacuum forming mould is highly preferred for its quick production time, less work, design uniformity, and ability to cast larger habitat enhancement models. However, the demoulding methods require improvements and further experimentation to ensure an easier demoulding process and reusability of the mould for long-term production.

## 1.0 INTRODUCTION

Burgeoning world populations and urbanization have resulted in rapid developments and proliferation of coastal zones to compensate for limited land, known as ‘ocean sprawl’ which is the proliferation of coastal zones with artificial coastal structures (Firth et al., 2014). The global construction of artificial islands has become prevalent, notably in Asia and the Middle East, due to the scarcity of available land. These projects encompass developments such as those situated along the coastlines of Penang Island, Malaysia (Chee et al., 2023), as well as iconic developments like The Palm in Dubai and in Qatar (Wiedmann et al., 2012). Natural coastal habitats are being replaced with urbanized structures such as artificial coastal structures (ACS) designed to safeguard against flood, erosion, and degradation from extreme climatic events (e.g., sea-level rise, storm surges, and strong waves) (O'Shaughnessy et al., 2020). Despite these protective measures, there is significant concern regarding the adverse effects of ACS on the marine environment.

Natural coastlines are inherently vulnerable, and the increased encroachment of urbanization along coastal areas poses significant threats to these regions (Kondrat et al., 2021). This threat is exacerbated by rapid development aimed at accommodating growing populations. The introduction of urbanized structures can lead to pronounced alterations in the geomorphology of the natural marine environment, resulting in various knock-on effects (Firth et al., 2014). Furthermore, the implementation of artificial coastal structures (ACS) may lead to sediment deficiency, causing the gradual disappearance of coastal lands. This, in turn, results in habitat loss and the altered distribution of native species, making them more susceptible to the effects of climate change (Firth et al., 2016).

To this day, a significant controversy surrounds the response and behaviour of marine communities on artificial habitats within the marine environment, viewed from an ecological perspective (Becker et al., 2020). The differences between ACS and natural coastal habitats are apparent in many ways. While natural coastal habitats offer refuge from physical stressors (e.g., heat, desiccation, and wave impacts), breeding grounds, and predation (Bradford et al., 2020) through complexities such as pits, grooves, crevices, and rock pools, most artificial structures are devoid of these features (Firth et al., 2014). Furthermore, most marine constructions involve the use of concrete due to its versatility and durability (Becker et al., 2020) to withstand the harsh marine environment (e.g., extreme weather conditions, strong wave actions, and exposure to temperature fluctuations and corrosion due to high salinity of seawater). Concrete is, however, a poor substrate for biological recruitment because of its high surface alkalinity and leaching of metals over time (Dennis et al., 2018; McManus et al., 2018; Sedano et al., 2020). Studies have shown that communities on ACS are less diverse, and are typically colonized by invasive species (Ido & Shimrit, 2015). Therefore, ACS are considered poor surrogates (Firth et al., 2016; Sedano et al., 2020) with no environmental value.

Ecological engineering, often referred to as eco-engineering, is a concept that integrates ecological, economic, and social considerations into the design of man-made ecosystems (Firth et al., 2014). Over the past decade, researchers have increasingly applied eco-engineering principles in the field of marine eco-engineering techniques (see Strain et al., 2018). For instance, studies that incorporate habitat complexities through the use of habitat enhancement models (as shown in **Figure 1**) in the eco-engineering of artificial coastal structures (ACS) have yielded successful results and are recognized as a primary driver in promoting biodiversity (Loke et al., 2019; Strain et al., 2018; Ushiama et al., 2019). Furthermore, this approach can influence the density and abundance of colonizing and associated species (Strain et al., 2020). Habitat enhancement models aim to replicate natural environments and improve living conditions for marine organisms. In addition to this, various eco-engineering initiatives have explored the potential of incorporating recycled materials, such as concrete, to produce eco-friendly alternatives, thereby reducing the carbon footprint. While concrete remains a popular choice in marine construction, research on environmentally-friendly construction materials for eco-engineering has predominantly focused on temperate regions. For instance, the partial replacement of cement with waste aggregates such as shells (Elavarasan et al., 2021), by-products from quarries (Chitkeshwar & Naktode, 2022), and hemp fibres (Dennis et al., 2018). In Malaysia, the production of eco-concrete materials for marine eco-engineering applications, and the associated technology, encompassing casting, moulding, and demoulding techniques, is still at an experimental stage.

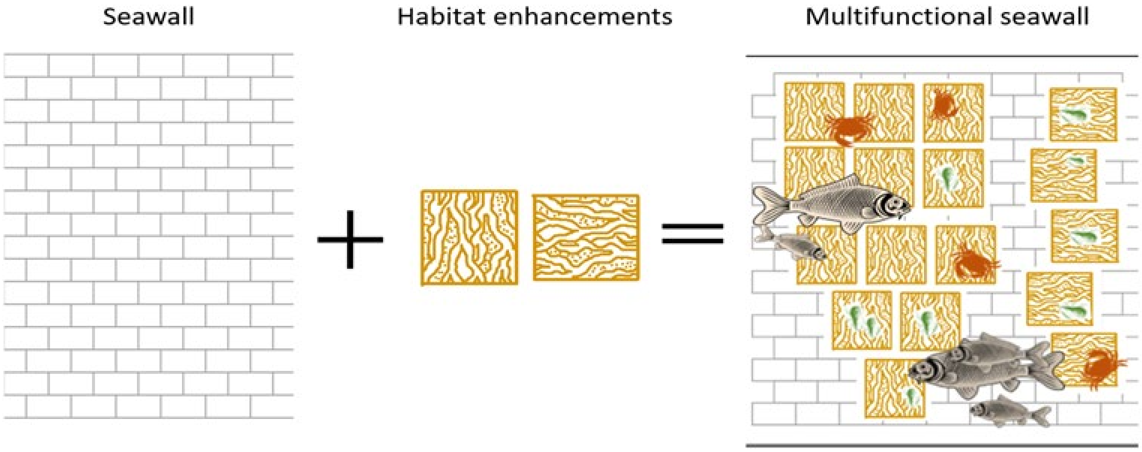

**Figure 1.** Illustration of a habitat enhancement model with textures used in eco-engineering to promote biodiversity (Source: Authors)

In recent years, diverse casting methods have been applied to create habitat enhancement models for marine ecosystems. These methods encompass a wide array of techniques including the use of steel or iron moulds (Coombes et al., 2015), silicone rubber moulds (Evans et al., 2021; Loke et al., 2017), the innovative practice of moulding concrete between boulders to form habitat-enhancing pools (Firth et al., 2016; Hall et al., 2018), and the application of 3D printed moulds (Vozzo et al., 2021). Molds, crafted from diverse materials, play a pivotal role in retaining freshly poured concrete in its intended form until it achieves the required strength for demoulding (Levitt,1982). While a substantial body of literature has explored different mould types and examined the influence of concrete blends (King-Nygren, 2021), a gap pertaining the comparative assessment of the diverse techniques associated with casting, moulding, and demoulding small-scale productions of habitat enhancements with minimal manpower remains. There has been a lack of comprehensive studies comparing different moulding materials and techniques for geometrically complex habitat enhancement models for marine organisms.

The study focuses on investigating a range of casting, moulding, and demoulding techniques, utilizing a locally produced eco-concrete blend partially composed of food and construction waste. The primary objective is to identify the most suitable material among Plaster of Paris (PoP), wood (CNC Drilling), Expanded Polystyrene (EPS), rubber foam, and vacuum forming for casting eco-concrete habitat enhancement prototypes. The selection of materials and processes are based on the prototyping purpose in product design process (Morris, 2016; Lutters et al., 2014). Since the prototype of the artificial marine habitats are built only in small numbers, they do not typically require any tooling and can be produced in a completely different fashion – which contradicted to the mass-manufactured products. As mentioned in Hallgrimsson (2012), it is more cost- and time-efficient to substitute softer material in place of production materials. For example, polyurethane foam is frequently sculpted to study the shapes of injection-moulded plastic parts, while plastic sheet was painted in metallic pigment to look like sheet metal. One primary aim of prototyping design methods is to gather enough data to advance in product development while minimizing time and expenses (Camburn et al., 2017). As a result, each prototype evaluation should address a distinct inquiry. Our research considers factors, including production time, labour requirements, and the subsequent prototype fabrication. We hypothesize that the utilization of vacuum forming moulds will enhance production efficiency and simplify the overall moulding and demoulding processes. The findings from this comparative study will offer valuable insights for the small-scale production of habitat enhancements, contributing to the advancement of marine ecosystem restoration and conservation efforts.

### 1.1 Eco-Concrete Mixture

Concrete production significantly impacts the environment due to its use of aggregate and binder—comprising crushed stones, sand, gravel, and cement (Dennis et al., 2018). To mitigate these environmental concerns, earlier studies have introduced eco-concrete formulations integrating industrial waste materials like seashells, quarry dust, and GGBS (Dennis et al., 2018; Yee et al., 2022). These materials partially replace traditional sand and cement, effectively reducing the concrete's carbon footprint while preserving its structural integrity. The specialized mixture aims to establish a habitat enhancement model suitable for marine environments, fostering the recruitment of marine organisms while ensuring a minimized carbon footprint.

### 1.2 Habitat Enhancement Model

The design concepts of the habitat enhancement model, hereafter referred to as 'the model,' were derived from the findings of baseline studies conducted at a natural coastal habitat in Penang Island, called Miami Beach. These studies provided insights into the habitat preferences of dominant native marine organisms in the region whereby the model's design incorporates features inspired by the natural coastal environment such as grooves, crevices, and tidal pools commonly found on rocky beaches. These textured surfaces offer shaded areas that provide marine organisms with refuge against predation, desiccation, stress, and heat on exposed seawalls in Malaysia's tropical climate. For example, the incorporation of a tidal pool feature in the model creates a water-retaining habitat that addresses the fundamental needs for marine organisms to thrive, as highlighted by Chee et al. (2020).

## 2.0 METHODOLOGY

Different casting materials were used as moulds in this study: 1) Plaster of Paris (PoP); 2) wood (CNC-Drilling); 3) expanded polystyrene (EPS); 4) rubber foam (for basin design only); and 5) vacuum forming. The models were cast using an eco-concrete mix which comprised of 50% Ordinary Portland cement, 50% ground granulated blast furnace slag (GGBS) as binders and 50% quarry dust and 50% seashells as aggregates. All the exposed mould surfaces were covered with impervious paper immediately after casting to ensure moisture retention and prevent concrete from shrinking, which contributes to a weaker structure (Dnyanoba & Madhukar, 2020; King-Nygren, 2021). The casts were left to harden for 24 hours before demoulding to undergo curing (the process of controlling the rate and extent of moisture loss from concrete during cement hydration) for a minimum of 7 days. Two curing processes were used in this study due to size limitations: 1) dry curing (for models) and 2) wet curing (for basin feature only). The dry curing process involved covering the cast models with a sheet of impervious paper and keeping them in a shaded area. On the other hand, the basin features (referred to as the basin hereafter) were fully submerged in a water-filled tank. The strengths and weaknesses of the casting techniques were analysed in this study whereby moulding and demoulding methods were compared based on the:

(a) Demoulding Time Assessment

Demoulding time, a critical aspect of the moulding process, was measured in minutes or hours for each material. This measurement reflects the time required for the successful removal of the mould from the cast as late (Jang & Schunn, 2012) and longer time in prototyping (Yang, 2005) is correlated with unsuccessful efforts. To ensure accuracy, this procedure was replicated across all materials.

(b) Labor Classification

The complexity and labour-intensiveness of each moulding method were categorized into three distinct levels: 'high,' 'medium,' and 'low' as justified by the expertise involved in the process (Lutters et al., 2014). To provide a more precise definition:

(i) High Labor: This classification indicated a complex, labour-intensive process. It typically involved numerous steps, significant physical effort, and often required specialized skills.
(ii) Medium Labor: This level signified a moderate degree of complexity, where the process was less labour-intensive than 'high' but more involved than 'low.'
(iii) Low Labor: A 'low' labour classification identified straightforward, minimally labour-intensive processes, often requiring few steps and minimal physical effort.

(c) Difficulty in Demoulding Assessment

The challenge of demoulding was systematically assessed on a scale ranging from 1 to 5. This scale aimed to provide an objective evaluation of the demoulding process for each material. The criteria for assessment included the force needed to demould, the risk of damage to the cast or mould, and the consistency of results.

(i) Score 1: Represented the easiest demoulding process, requiring minimal force and presenting a low risk of damage to the cast or mould. It consistently produced favourable results.
(ii) Score 5: Indicated the most challenging demoulding process, characterized by a high risk of damage to the cast or mould and necessitating significant force to complete the procedure. This process often yielded inconsistent results.

## 2.1 Experiment 1 (PoP – Manual Sculpturing)

Designs of the model were initially sculptured using modelling clay (**Figure 2(a)**) to achieve the desired size. This sculpting process involved wire-end modelling tools, a sponge, and water to create a smooth finish. To prepare for moulding, the clay model was securely fastened with wooden planks and staples and reinforced using G-clamps along the sides. Plaster of Paris (PoP) was thoroughly mixed with water in a large container using a stirring instrument, with the removal of air bubbles achieved through circular thumping and rotation of the container (as recommended by Szostakowski et al., 2017; refer to **Figure 2(b)**). Once the casing was filled, it was gently rocked to release any trapped air, thereby increasing the density of the plaster. The mould was allowed to set for approximately 45 minutes to one hour. Following this, the modelling clay was entirely removed after the mould had hardened (as depicted in **Figure 2(c)**). The mould was then left to dry completely for 36 hours. Subsequently, a layer of petroleum jelly was applied before casting with the eco-concrete mixture.

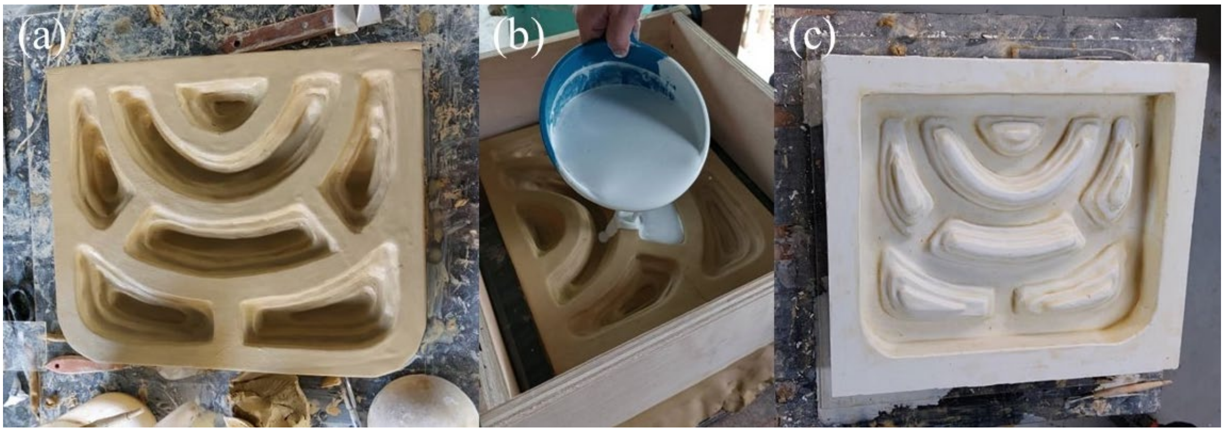

**Figure 2.** (a) Crafting design using modelling clay into its proportions, (b) pouring PoP mixture into the secured 'casing', and (c) demoulding modelling clay to allow PoP mould to harden (Source: Authors)

## 2.2 Experiment 2 (Wood – CNC Drilling)

Rubber wood panels, with dimensions of 18 mm (thickness) x 1,219 mm (width) x 2,438 mm (length), were used for the Computerized Numerical Control (CNC) drilling method as the thickness of the rubber wood panels was in accordance with the design's requirements. Prior to operating the CNC drilling machine, the final model designs were crafted using 3-D modelling software (AutoCAD 2022) for translation into 3-D printing (as shown in Figure 3(a)). The CNC machine's parameters were appropriately adjusted to process the material using a code file, typically with G01 movements from the G-Code or RS-274 standard, before initiating the CNC machine (as depicted in Figure 3(b)). A total of 168 wood pieces were cut out, including an additional set used as the master mould for the vacuum forming experiment. Prior to assembly, an adhesive (Dunlop Contact Adhesive Glue) was applied to the wood pieces. They were then assembled according to their respective designs and affixed to a wooden block board panel. For added stability, they were further secured with screws from behind before assembling the sides to create the mould. All mould surfaces were coated with a layer of grease, applied using a brush, before pouring the eco-concrete mixture.

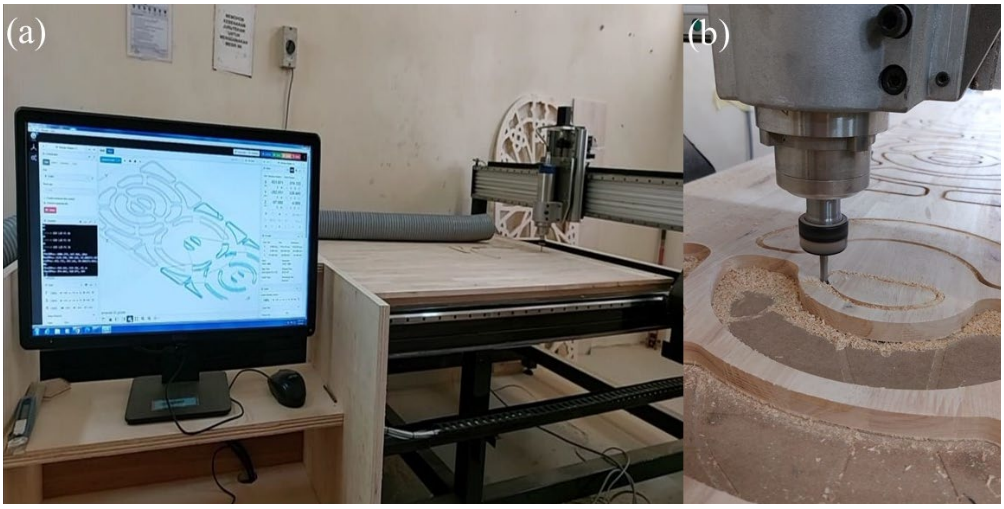

**Figure 3.** (a) G-Code used to run the CNC machine, (b) Drilling habitat enhancement model designs into geometrical shapes via CNC machine (Source: Authors)

## 2.3 Experiment 3 (Expanded Polystyrene (EPS) and Rubber Foam – Manual Forming)

EPS panels (12 mm thick) were utilized for the model designs. They were outlined using extra wood pieces from CNC drilling and cut out using a hot wire. The EPS pieces were affixed to the wooden block board using white glue before securing the sides for casting. One of the EPS designs was coated with a layer of grease, while another was left uncoated to observe the differences during demoulding.

As the basins have curves, we incorporated the usage of thick rubber foam to achieve the desired design. Firstly, the rubber foam was cut to size using an electric wood-cutting machine. Part of the piece was halved to allow more flexibility in shaping the basin's curves, while the other remained intact to provide structural support for the weight of the fresh concrete. The pieces of rubber foam were then assembled using screws. Similar to the EPS designs, one prepared mould was coated with a layer of sprayed-on grease, while the other was left uncoated. Gaps were filled with hot glue to prevent the eco-concrete from seeping during casting. A stacked layer of 48 mm thick EPS was glued together and further reinforced with bamboo skewers to hold them in position before crafting with a blade and sandpaper to create the water-retaining feature of the basin (as shown in **Figure 4(a)**). To allow some space at the bottom, the stacked EPS piece was elevated by approximately 3 cm (the thickness of the basin) using bamboo skewers, which were inserted through the rubber foam before casting (as shown in **Figure 4(b)**). One mould was sprayed with grease before casting, while the other was not, in order to assess the effect on the demoulding process.

**Figure 4.** (a) Crafting stacked polystyrene for water retaining feature and (b) basin mould created with thick modelling foam (Source: Authors)

## 2.4 Experiment 4 (Plastic – Vacuum Forming)

Sanded wood design pieces from CNC drilling were employed as the master mould for vacuum forming. They were affixed to a carefully measured wooden block board using superglue and secured at the back of the board with screws (as shown in **Figure 5(a)**). Small vacuum forming holes were drilled at suitable low points around the master mould before it was placed onto the vacuum forming Formech 1250 Vacuum Former platen, with a sheet of 2 mm thick Plastic HIPS (High Impact Polystyrene) on top. As illustrated in **Figure 5(b)** (sourced from the Open University, 2017), the master mould from CNC drilling was used in conjunction with the Plastic HIPS sheet, which was heated until it reached the processing temperature. Subsequently, the heat-softened plastic sheet was draped over the mould surface. The air between the plastic sheet and the mould was evacuated, and shortly thereafter, the plastic sheet conformed to the mould shape upon cooling (as shown in

Figure 5(c)). The formed part was then trimmed with a cutter to remove excess material, sealing the sheet to the block board, allowing it to be used as a cast. The vacuum-formed board was later secured on its sides into a mould for casting.

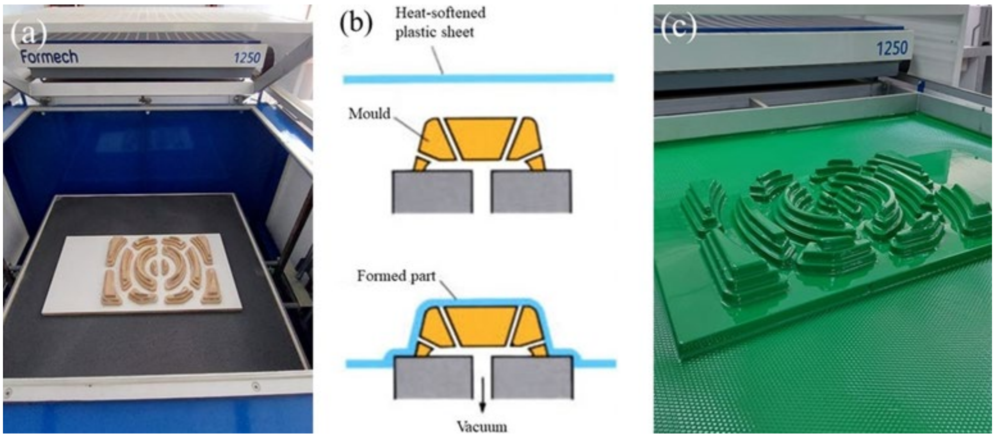

**Figure 5.** (a) Wooden designs from CNC drilling used as the master mould (Source: Author's own work), (b) Image describing vacuum forming process (Source: The Open University, 2017), and (c) vacuum formed mould using Plastic HIPS (Source: Authors)

## 3.0 RESULTS AND DISCUSSION

In this study, different materials for mould making were selected based on moulding and demoulding factors, including time to completion, labour, and scale of production. Results are summarized in Table 1. Evaluation of the ease of demoulding was based on ratings from 1 to 5, with one being the easiest to remove and five being the hardest to remove.

## 3.1 PoP (Manual Sculpturing)

Although an excellent casting medium at low cost and noticeably advantageous, PoP as a mould for casting eco-concrete has been proven unfeasible. Demoulding the casted eco-concrete was difficult despite the petroleum jelly coatings. Holes needed to be drilled on all four corners of the plaster mould to allow compressed air to push through the eco-concrete cast for demoulding (Figure 6(a)). Corners of the plaster mould needed to be broken using a rubber mallet (Figure 6(b)) when compressed air did not work. After removal, attempts to reuse the mould were ineffective unless reattached using clay and then hot glued to prevent leakage when casting. The process was time-consuming, and the mould was discarded. Mould production using PoP was also ineffective as sculpting the clay was also time-consuming. Inconsistency mould designs occurred when creating more plaster moulds, and if the habitat enhancement model were to be made bigger, using PoP moulds would not suffice. Thus, this is not a feasible method for mass production of the model.

To enable easier PoP demoulding, different mould release agents (RAs), such as water-based RAs, powder-based RAs, or other oil-based RAs (Liang et al., 2022), can be further investigated. However, finding the best RA for easier demoulding is the least of its concerns, as creating designs using modelling clay took longer. The CNC drilling approach can be used to carve designs onto the hardened PoP to overcome design inconsistency, length casting, and demoulding processes. This method would save time but will only work on small-scale model production due to size limitations. Literature on using PoP as moulds to cast concrete, let alone eco-concrete, is limited; however, it has been documented that conventional PoP used for ceramic slip casting can produce as few as 40 casts before it becomes saturated (Al-Dawery et al., 2009; Ab Wahab et al., 2017). PoP moulds are known to degrade over time especially when used for slip casting due to external heat radiation (Ab Wahab et al., 2017), followed by cracked and powdery surfaces after several mouldings (Nor et al., 2015; Ab Wahab et al., 2017). Additionally, reusability of PoP moulds for casting concrete can vary based on several factors (i.e., mould quality, complexity of mould designs, maintenance, and the type of concrete mixes).

**Figure 6.** (a) Drilling holes onto corners of the plaster mould for compressed air to push through casted concrete and (b) broken sides of plaster mould which was held together by clay, hot glue, and clamps for next casting (Source: Authors)

### 3.2 Wood (CNC Drilling)

The choice of using wood as a mould for the model was made in this study due to wood's easier handling, assembly, flexibility, and light weight compared to steel moulds (Shah et al., 2019). Demoulding the model from the wooden block board (mould casing) and disassembly was successful due to its smooth surface. However, despite thick applications of grease coating around the grooved designs, the CNC rubber wood remained stuck to the hardened eco-concrete, causing it to dislodge from the block board upon removal (**Figure 7(a)**). The only solution for removal resulted in destroying the rubber wood pieces in the process (**Figure 7(b)**). Although there were time constraints and difficulties in demoulding, the use of wood pieces was the most standardized approach and resulted in smooth finishes for the designs.

Wooden moulds have traditionally been employed to create large moulds for building developments, particularly for curbs and house footings, where uncoated wood is typically used. In housing developments and various types of wooden formwork, single-use and cost-effective materials like melamine board are often preferred for mould-making. However, in this experiment, rubber wood was used due to challenges in material sourcing. While wood types such as melamine board, timber, and plywood have shown success in concrete demoulding, the depth of the recesses in our model designs influenced our choice to use rubber wood in this study, with the mould casing made of wooden block boards. In our pursuit to replicate the construction industry's wood mould reuse frequency (typically 30-50 times before reconstruction) for complex forms (Armstrong et al., 2023), we aspired to achieve this with our wooden moulds, yet found it unattainable.

A study by Shah et al. (2019) suggested that wooden formwork used in construction could be made more water-resistant by covering it with cellophane tape. This approach is practical primarily when working with small-sized concrete models. Concrete is known to adhere to wood, so when wood materials are employed as moulds for concrete casting, a release agent is required to facilitate removal. Although grease was used as a lubricant in this study, it may be necessary to treat the wood, both internally and externally, with oil-based blends to make it more resistant to adhesion. The type of wood could be another factor contributing to adhesion with concrete. In summary, the uniform process of CNC drilling wooden pieces for the model designs resulted in consistent design patterns but was only suitable for single-use.

**Figure 7.** (a) CNC wood pieces stuck to casted model and (b) removal of CNC wood pieces via destruction (Source: Authors)

## 3.3 Expanded Polystyrene (EPS Foam) and Rubber Foam (Manual Forming)

### 3.3.1 Expanded Polystyrene (EPS Foam) mould

The use of EPS as moulds to cast concrete has been in the construction industry for a long time whereby, they are used as prefabricated and in-situ concrete (Martins et al., 2015). Additionally, the usage of EPS mould in this study was its cost-effectiveness in moulding complex concrete forms (Seo & Hong, 2017; Yun et al., 2021). In this experiment, both greased and ungreased EPS designs produced similar results after demoulding. Larger EPS design pieces were reusable, while smaller ones remained stuck and had to be discarded (**Figure 8(a)**). The demoulding process for coated EPS was the easiest among the various mould types, but it was less pleasant to work with due to the fragmented plastic deposits. For improved demoulding results, it is recommended to apply releasing agents to prevent sticking and reduce water absorbency of the moulds before pouring the concrete (Mohammadi et al., 2014).

Stacked EPS to create the water retaining feature also faced similar challenges whereby demoulding results were the same with or without coating. EPS moulds were selected because they are frequently employed to create geometrically shaped or complex designs. However, they are often utilized for a single test as they must be torn apart when demoulding the specimen (Mohammadi et al., 2014; Yun et al., 2021). While comparatively weak, they offer insulation and protection from vibration for freshly foamed concrete cubes (Coombes & Naylor, 2011; Coombes et al., 2017). As the models are set to be deployed in the marine environment, fragmented plastic from residual EPS on the model is problematic. These remnants (**Figure 8(b)**) make a substantial contribution to marine pollution and can harm marine life when exposed to ultraviolet (UV) rays, as EPS can transform into a highly toxic substance that can move up the food chain (Turner, 2020). Thus, EPS is not suitable for casting.

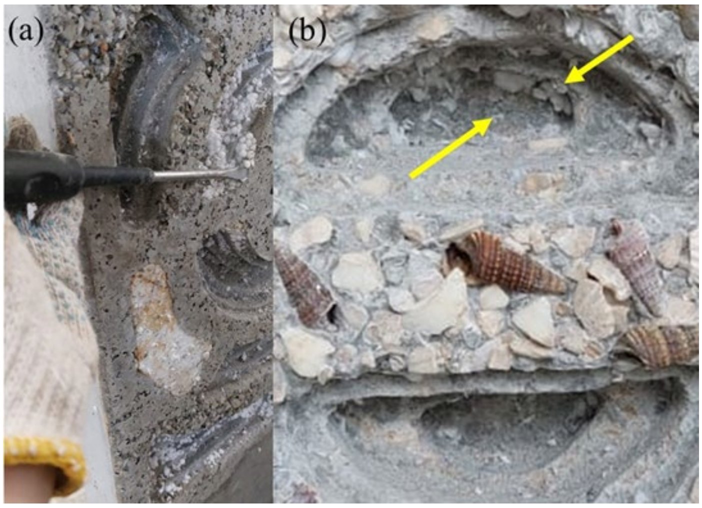

**Figure 8.** (a) Polystyrene pieces (coated and uncoated) stuck onto habitat enhancement model and (b) large number of residues still left after demoulding (Source: Authors)

### 3.3.2 Rubber foam mould

Demoulding the rubber foam pieces was the easiest among all the mould types tested, whether they were coated with sprayed-on grease or uncoated, as they did not adhere to the cast. Rubber foam moulds created for the basin can be reused up to five times each if demoulded without forceful exertion. Therefore, using this material for basin-making has proven to be a time-efficient process. However, one limitation was the slight variation in sizes among the casted basins. Although skewers were pierced on the sides of the rubber foam mould and through the stacked EPS, it was not sufficient to prevent the stacked design from elevating, resulting in variations in volumes. To address this issue, additional skewers were added to reinforce and hold the stacked polystyrene design in place. This approach worked as intended but introduced more holes, approximately 5 mm in size, on the hardened basin design. Since these holes could cause leakage, they were covered with the same eco-concrete mix and left to harden before placing the basin in a water-curing tank. The choice to use this material for creating a mould for the basin design was based on its versatility and durability, given its composition of various blends of polymers and elastomers.

Improvements in casting the basin can be achieved by using the same material without EPS. The adoption of CNC drilling or a wire-cutting machine to carve the rubber mould can ensure consistency in basin volumes and enhance time efficiency in the casting processes for small-scale production. Rubber moulds are well-regarded for their tensile strength, flexibility, and resistance to water and other fluids, making them a top choice for casting complex geometric concrete moulds, such as garden sculptures (King-Nygren, 2021). Therefore, future experiments in casting the models and basins can benefit from employing moulding methods commonly used for garden sculptures.

## 3.4 Vacuum Forming

Vacuum moulding captured nearly all surface details, resulting in a highly detailed mould. Wood was chosen for the master mould due to its heat resistance and its ability to withstand the pressure of draping, heated plastic sheet. The demoulding process exhibited similarities to wood (CNC Drilling), with the entire formed sheet adhering to the casted habitat enhancement model (**Figure 9(a)**). Attempts to demould using compressed air proved unsuccessful, and efforts to separate the formed sheet also resulted in damage, ultimately destroying the wooden master moulds. Despite using screws to secure the wooden master moulds to the base, this proved insufficient to release the vacuum-formed mould. The removal of the formed sheet proved to be the most challenging among all the methods, necessitating the destruction of the mould piece to achieve complete demoulding (**Figure 9(b)**). The substantial mould size and wooden master mould were identified as key factors contributing to demoulding difficulties.

Nevertheless, it was observed that the master mould could withstand the weight of fresh concrete and exhibited no deformations after casting. The plastic surface also resulted in a smooth, high-quality finish on the model following demoulding (**Figure 9(c)**). This underscores the significance of employing smooth master moulds for vacuum forming. A similar experiment could be conducted using an alternative material for the master mould, such as polyurethane (PU) foam. PU foam is commonly employed in the industrial sector for crafting customized moulds and differs from EPS, functioning as a thermosetting plastic with excellent heat resistance (King-Nygren, 2021). Another advantage of vacuum forming in this study is the Formech 1250 Vacuum Former platen's ability to accommodate exceptionally large components for mould creation and its widespread commercial availability.

Vacuum forming is one of the most common and extensively used methods for creating product design prototypes, intended for further development through other processes. It is also widely employed in the production of moulds for casting various products, ranging from simple packaging trays to high-impact aircraft cockpit covers (Lusing, 2015). Furthermore, vacuum forming remains a viable choice for crafting complex moulds through 3D milling (King-Nygren, 2021). Consequently, vacuum forming represents a preferred option for casting the model, particularly for large-scale production.

**Figure 9.** (a) Vacuum formed mould stuck to model, (b) removal of vacuum formed mould via destruction, and (c) smooth surfaced appearance of the model's designs (Source: Authors)

**Table 1.** Summary of the advantages and disadvantages of moulding and demoulding different mould types

| Type of Mould | Demoulding time | Labour* | Fabrication | Difficulty in demoulding** |
|---|---|---|---|---|
| Plaster of Paris (PoP) mould (Manual sculpturing) | • Time-consuming when demoulding, which took almost an hour. | High | • The cost of mould materials was approximately RM 150.00 (USD 35).<br>• Mould materials were commercially available.<br>• Inconsistency in model designs.<br>• Reusability was limited (1-2 times) and prone to leakage if not reattached properly. | 3 |
| Wood mould (CNC Drilling) | • Time-consuming when demoulding, which took 1 hour. | Medium | • Mould materials were easily obtained.<br>• CNC drilled pieces were not reusable.<br>• Cost for rubber wood panels was approximately RM 300 (USD 69).<br>• The usage of wood through CNC drilling was suitable for casting larger products. | 5 |
| Vacuum forming mould (Using plastic HIPS) | • Time-saving in mould assembly (less than 45 minutes) but time-consuming when demoulding (approximately 30 minutes).<br>• Consistent designs of the habitat enhancement after demoulding.<br>• Vacuum formed mould was strongly stuck onto the cast despite coating. | Low | • Material to construct the mould was easily sourced.<br>• The usage of vacuum forming was suitable for casting larger products.<br>• Moulds were not reusable. | 5 |
| Polystyrene foam mould | • Demoulding required approximately 30 minutes.<br>• Not environmentally friendly. | Medium | • The cost of mould materials was approximately RM 200.00 (USD 48).<br>• Materials were easily sourced.<br>• Moulds were not reusable.<br>• Designs of the casted habitat enhancement were slightly inconsistent due to manual hot-wiring. | 3 |
| Rubber foam mould | • Time saving when demoulding (less than 15 minutes), but time-consuming.<br>• Easy removal when demoulding. | High | • Cost of mould materials was approximately RM 100.00 (USD 23).<br>• Materials were easily sourced.<br>• Designs of the casted habitat enhancement were slightly inconsistent due to manual size indifference. | 1 |

*Labour - High, medium, low

** Difficulty in the level of 1 - 5, 1- easiest to demould, 5- hardest to demould.

## 4.0 CONCLUSION

Habitat enhancement models serve as mimics of natural environments, where textures, manipulated via eco-engineering by researchers, foster optimal conditions for marine organisms. While numerous methods exist for habitat enhancement across scales, scant attention has been paid to identifying ideal mould materials for casting sizable eco-concrete-based models. This study endeavours to pinpoint the most suitable mould type for crafting and releasing habitat enhancement models made from eco-concrete, prioritizing production efficiency, labour, and fabrication processes pivotal for large-scale production. Following an exhaustive evaluation of various mould-making materials, vacuum forming using Plastic HIPS emerged as the optimal choice for casting the eco-concrete mixture. This technique streamlined the production of large, uniform designs, significantly reducing labour demands. However, challenges arose during demoulding, rendering the mould non-reusable. To facilitate seamless demoulding and ensure prolonged mould usability for large-scale production, further research is imperative. Focusing on enhancing demoulding methods while utilizing the vacuum forming mould will be pivotal for achieving ease of release and reusability in the long term.

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