INCORPORATION OF SURFACE COMPLEXITY IN ECO-CONCRETE PANELS AND ITS EFFECT ON BIODIVERSITY IN COASTAL INFRASTRUCTURE IN PENANG, MALAYSIA

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by

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LIST OF ABBREVIATIONS

ACS	Artificial coastal structures
BC	Blank Portland cement panels
BE	Blank eco-concrete panels
CC	Complex Portland cement panels
CE	Complex eco-concrete cement panels
GGBS	Ground granulated blast-furnace slag
HBP	Housing, Building, and Planning
NNS	Non-native species
PFA	Pulverized fuel ash
SDGs	Sustainable Development Goals
SCM	Supplementary cementitious materials
USM	Universiti Sains Malaysia

LIST OF APPENDICES

PEMERBADANAN PERMUKAAN KOMPLEKSITI PADA PANEL KONKRIT-EKO DAN KESANNYA TERHADAP KEPELBAGAIAN BIOLOGI PADA INFRASTRUKTUR PANTAI DI PULAU PINANG, MALAYSIA

ABSTRAK

Pembangunan di kawasan pesisiran pantai sedang meningkat secara mendadak di seluruh dunia, dengan bandar-bandar yang padat dicirikan oleh struktur tinggi dan teknologi canggih. Untuk melindungi penduduk dan harta benda daripada cuaca melampau, strategi "mengeraskan" pesisiran pantai dengan struktur pantai buatan (ACS) seperti tembok laut dan pemecah ombak, satu perkara yang biasa. Walau bagaimanapun, struktur ini selalunya menyediakan habitat yang kurang sesuai untuk kepelbagaian hidup marin berbanding kawasan semula jadi disebabkan oleh bahan yang digunakan dan kekurangan kompleksitinya. Walaupun prinsip kejuruteraan ekologi telah diterokai untuk menangani isu ini, data khusus untuk kawasan tropika masih terhad. Memandangkan tekanan tinggi yang dihadapi oleh organisma marin semasa air surut di kawasan tropika disebabkan oleh pengeringan dan suhu, kajian ini menyiasat keberkesanan menggabungkan kompleksiti habitat dan jejak pengurangan karbon (eko-konkrit) pada tembok laut untuk menggalakkan kepelbagaian spesies benthik dan meningkatkan fungsi ekologi keseluruhan struktur ini. Sebanyak 20 panel habitat dengan 5 replika bagi setiap jenis rawatan telah ditempatkan di The Light Waterfront di Pulau Pinang, Malaysia, empat kumpulan jenis rawatan tersebut ialah 1) simen Portland kosong (kawalan), 2) eko-konkrit kosong, 3) eko-konkrit kompleks, dan 4) simen Portland kompleks. Panel-panel tersebut dipantau selama 12 bulan (dari Oktober 2022 – Sepetmber 2023) dengan persampelan bulanan. Secara keseluruhan,

37 spesies organisma marin bentik telah direkodkan pada panel sepanjang kajian. Terdapat kelimpahan organisma marin bentik bergerak jauh lebih tinggi pada panel kompleks berbanding panel kosong. Keputusan daripada analisis ANOVA sehala hala bebas menunjukkan kepelbagaian spesies (ANOVA: $F(3, 48) = 79.988$, $p < 0.001$) dan kekayaan spesies ($F(3, 48) = 10.121$), $p = <0.001$) organisma benthik yang jauh lebih tinggi pada panel kompleks berbanding panel kosong. Tambahan pula, kedua-dua panel konkrit kompleks dan eko-konkrit mengandungi kepelbagaian dan kekayaan spesies yang jauh lebih tinggi berbanding panel kosong. Celah dan lubang dalam panel kompleks berfungsi sebagai perlindungan kritikal untuk organisma benthik seperti tiram, kerang, lintah laut dan ketam. Ini mengakibatkan peningkatan ketara dari segi kelimpahan keseluruhan fauna ini berbanding panel kosong. Khususnya, tiada perbezaan ketara yang diperhatikan dalam kekayaan spesies berdasarkan komposisi bahan (eko-konkrit vs simen Portland). Ini menunjukkan bahawa organisma bentik tidak menunjukkan kecenderungan semula jadi terhadap bahan substrat dalam jenis panel kosong. Kajian ini menawarkan maklumat berharga bahawa penggabungan kompleksiti dalam struktur pantai buatan berpotensi untuk memulihkan tahap kepelbagaian biodiversiti. Walaupun campuran eko-konkrit menunjukkan harapan, kajian selanjutnya diperlukan. Penemuan kajian ini memberikan panduan berharga untuk mereka bentuk tembok laut pada masa depan untuk menggalakkan kepelbagaian hidup intertidal di sepanjang pesisiran pantai tropika.

INCORPORATION OF SURFACE COMPLEXITY IN ECO-CONCRETE PANELS AND ITS EFFECT ON BIODIVERSITY IN COASTAL INFRASTRUCTURE IN PENANG, MALAYSIA

ABSTRACT

Urbanization along coastlines is surging globally, with densely populated cities characterized by towering structures and advanced technologies. To safeguard these populations and properties from extreme weather events, a strategy of "hardening" coastlines with artificial coastal structures (ACS) like seawalls and breakwaters has become increasingly common. However, these structures often provide suboptimal habitats for marine biodiversity compared to natural shores due to the materials used and their lack of complexity. While ecological engineering principles have been explored to address this issue, data specific to tropical regions remains limited. Considering the heightened stress marine organisms face during low tides in tropical areas due to desiccation and temperature, this study investigated the effectiveness of incorporating habitat complexity and reduced carbon footprint (eco-concrete) onto the seawall to promote benthic species richness and improve the overall ecological function of these structures. A total of 20 habitat panels of 5 replicates per treatment were deployed at The Light Waterfront in Penang, Malaysia, with four treatment groups: 1) blank Portland cement (control), 2) blank eco-concrete, 3) complex eco-concrete, and 4) complex Portland cement. The panels were monitored for 12 months (from October 2022 – September 2023) with monthly sampling. In total, 37 benthic species were recorded on the panels throughout the study. There was a significantly higher abundance of mobile benthic marine organisms on the complex treatments compared to the blank treatments. The results from the independent one-way

ANOVA analysis showed a significantly higher species diversity (ANOVA: $F(3, 48) = 79.988$, $p < 0.001$) and species richness ($F(3, 48) = 10.121$), $p = <0.001$) of benthic organisms on the complex treatments compared to the blank treatments. Furthermore, both complex concrete and eco-concrete panels harboured a significantly higher species diversity and richness compared to their blank counterparts. The crevices and holes within the complex panels functioned as critical refugia for benthic organisms such as oysters, mussels, sea slugs, and crabs. This resulted in a statistically significant increase in the overall abundance of these fauna compared to the blank panels. Notably, no significant difference in species richness was observed based on material composition (eco-concrete vs. Portland cement), suggesting no inherent preference in benthic organisms towards the substrate material within the blank design. This investigation offers valuable insights into how incorporating complexity into artificial coastal structures can potentially restore some level of biodiversity. While the eco-concrete mixture shows promise, further optimization is warranted. The study's findings provide valuable guidance for designing future seawalls that promote intertidal biodiversity along tropical coastlines.

CHAPTER 1

INTRODUCTION

1.1 Overview of study

Coastlines worldwide are increasingly facing threats of flooding, erosion, and degradation due to drastic climatic events and extensive coastal urbanization (O'Shaughnessy et al., 2020). Consequently, the results of 'ocean sprawl' are becoming more evident, with concentrated human activities along the coast, such as shipping and transportation, residential and commercial developments, followed by the construction of artificial coastal structures (ACS) (e.g., seawalls, groynes, breakwaters) to protect valuable assets. In fulfilling the needs of coastal cities to provide space and counteract erosion, land reclamation has become one of the few available options for this purpose, wherein ACS is used as coastal armouring. In comparison to the development of urban structures that alter the biological, chemical, and physical environment of the receiving ecosystem, the introduction of ACS, on the other hand, directly replaces natural habitats, resulting in habitat fragmentation, disruption of ecological connectivity, and habitat loss (Firth et al., 2016). Apart from the negative environmental impacts, these structures are generally associated with poor-quality habitat profiles for biodiversity growth compared to natural shores (Firth et al., 2020; Sedano et al., 2020), lacking the natural complexities (e.g., crevices, pools, bumps, and holes) that offer refugia from physical stressors and predation.

In recent years, global efforts to ecologically engineer ACS have been undertaken to compensate for habitat loss and enhance their ecological value, aligning with conservation goals, stemming from the realization that these structures are permanent fixtures. The field of ecological engineering (or eco-engineering) has emerged to integrate both human needs and environmental sustainability, employing

‘soft’ methods (such as incorporating mangroves, marshes, and sand dunes for natural coastal defense) alongside 'hard' approaches (like physically manipulating ACS). This combined approach is considered a hybrid, involving both hard armament and natural habitats (O’Shaughnessy et al., 2020). Researchers have focused on employing ecological engineering approaches on these hard structures, including altering surface complexities (Coombes et al., 2015; MacArthur et al., 2019), biomimicry (Evans et al., 2021), incorporating habitat features like pools (Chee et al., 2020), grooves (Chee et al., 2021; Vozzo et al., 2021), pits (Hall et al., 2018; Loke et al., 2016), and utilizing eco-friendly concrete mixes (Becker et al., 2020; Dennis et al., 2018) with aims to promote biodiversity and reduce the recruitment of non-native species (NNS). However, the majority of related studies and data have been geographically limited to temperate countries (Strain et al., 2019), with studies in tropical regions still lacking (Chee et al., 2020; 2023).

The trend of urbanizing coastlines has raised significant concerns, particularly in developing tropical regions like Malaysia, which have undergone substantial changes along their coastlines. Presently, major coastal zones in Malaysia have undergone reclamation for urban development, with numerous proposals for further reclamation and coastal development shaping the country’s future plans (Abdul Halim et al., 2019; Tung et al., 2021). An illustrative case is Penang Island, known for its mosaic of natural and artificial habitats. Recent coastal development has expanded beyond just shoreline reclamation to encompass entire islands. This surge is predominantly propelled by the state's high coastal population, establishing it as the region with the most extensive coastal development (Chee et al., 2023).

The northeast of Penang Island is currently experiencing an ongoing coastal land reclamation, with an escalating trend that shows no signs of slowing down. Furthermore, ACS in Penang Island, lacks the necessary features for marine organisms to thrive and recruit. The high temperatures in Malaysia further exacerbate the challenges by inducing desiccation and stress among marine life due to the absence of shelter on these ACS. These observations are supported by the few proofs of concepts hailing from tropical areas (Chee et al., 2020; 2021; Loke et al., 2019a). Additionally, the ACS lining Penang Island's coast are not ecologically engineered to support the requirements of organisms' recruitment, posing potential long-term harm to the marine environment. There is also a need for biodiversity offsetting options in land reclamation projects, as stakeholders and local developers have shown unwillingness to compensate for environmental damage due to the unavailability and high importation costs of habitat panels from foreign countries. Addressing this issue is crucial, particularly in researching eco-engineering strategies for ACS in marine biodiversity, especially within tropical regions as the effects of complexity on local species biodiversity are often specific to the site and species, influenced by diverse abiotic and biotic stressors, and niche requirements within the species pool (Chee et al., 2020).

Introducing eco-engineering through specially designed habitat panels offers a promising solution to address critical concerns in Malaysia's coastal areas, notably the challenges of local weather conditions. These habitat panels, which are designed to increase surface complexity while reducing the carbon footprint on ACS, aim to enhance the recruitment of native species and foster biodiversity. This is one of the few studies that fills a significant knowledge gap by exploring the efficacy of designed habitat panels featuring increased surface complexity, reduced desiccation stress, and

an eco-friendly concrete mixture. Comparatively, these panels will be assessed against standard Portland cement-based seawalls regarding their ability to provide a conducive habitat for benthic organisms.

1.2 Problem statement

The escalating threats to coastal ecosystems, exacerbated by climate change and anthropogenic activities, necessitate innovative solutions. Coastal urbanization and the subsequent construction of artificial coastal structures (ACS) have resulted in significant habitat loss and degradation. While eco-engineering approaches have emerged as promising tools for mitigating these impacts, their efficacy in tropical regions remains understudied. This research aims to investigate the potential of specially designed habitat panels to enhance biodiversity and ecosystem function on ACS in Malaysia. By incorporating surface complexity and employing eco-friendly materials, these panels are expected to provide suitable habitats for marine organisms and contribute to the long-term sustainability of coastal ecosystems.

1.3 Objectives

This study aims to investigate the diversity, species richness, and abundance of benthic organisms on the habitat panels conducted at The Light Waterfront in Penang Island, Malaysia. The research objectives of this study are:

1) To design and construct habitat panels with increased surface complexity and reduced carbon footprint for ACS.
2) To determine the relative abundance, diversity, and species richness of benthic marine organisms that colonize the habitat panels.

1.4 Thesis outline

The thesis began with an introduction outlining the significance of marine habitat enhancement in Malaysia, identifying specific knowledge gaps related to ACS, and formulating research objectives and hypotheses. Chapter 2 delved into a comprehensive literature review, establishing a theoretical framework, and analyzing existing research to identify research opportunities. Chapter 3 detailed the research methodology, including study site selection, experimental design, data collection techniques, and statistical analysis methods. Chapter 4 presented the quantitative and qualitative results, supported by statistical analysis. Chapter 5 interpreted the results, discussing the mechanisms underlying the effects of surface complexity and material composition on marine biodiversity, and acknowledging the study's limitations. Finally, Chapter 6 summarized the key findings, provided recommendations for future research, and highlighted the implications of the study for marine conservation and management.

CHAPTER 2

LITERATURE REVIEW

2.1 Coastlines and burgeoning populations

The world is experiencing the largest wave of urban growth in history, characterized by the domination of high-rise buildings, developments, and cutting-edge technology to accommodate vast growing populations. This widespread landscape modification is especially prevalent in coastal regions worldwide, homing a large proportion of the world's population (Paleologos et al., 2019). There are roughly 2.4 billion people (about 40% of the global population) currently living within 100 km of the coast (Paleologos et al., 2019) and this figure is forecasted to surpass 75% in population by 2025 (Bulleri & Chapman, 2010). Coastal zones serve as important interphases between land and sea, where ongoing interactions continuously alter the demographics of these areas around the world. While specific demographic shifts occur naturally due to factors like wave conditions, winds, and geographical elements, intensified demographic changes are increasingly evident in coastal zones undergoing significant shoreline developments worldwide (Dong et al., 2024). Presently, coastlines are extensively exploited to accommodate burgeoning populations.

Driven by burgeoning coastal populations and exacerbated by climate change, coastlines worldwide have faced increased 'hardening' through the proliferation of ACS (Aguilera, 2018) as they are built to protect humans and assets from extreme climatic events (not only limited to sea level rises and storms) at the expense of natural habitats. Additionally, the scarcity of ocean-front land has led to the construction of artificial islands. Such quintessential example is none other than Penang Island, Malaysia (Chee et al., 2017; 2023) with its highly artificialized east coastline. The global proliferation of ACS edging further towards the sea, is defined as "ocean sprawl" (Firth et al., 2016).

Aside from contributing to the loss and disturbance of natural habitats and species within the vicinity, this phenomenon also triggers indirect consequences involving the altered coastal, oceanographic processes and connectivity (Firth et al., 2016; Heery et al., 2017). Acknowledging the potential adverse impacts of ACS on the marine environment, integrating ecologically sensitive designs into the ever-expanding marine and coastal developments becomes imperative. This approach aims for a sustainable coexistence between humans and marine communities.

2.1.1 Ocean sprawl

"Ocean sprawl" is termed the global proliferation of ACS in the marine environment (Firth et al., 2016), posing a global threat to marine and coastal ecosystems. In the past few decades, coastlines have become progressively "squeezed" with ACS as their common features - leading to the replacements of natural and often sedimentary, hard substrata altered to retain land and protect burgeoning populations. The costs associated with these trends further exacerbate the increasing demand for shoreline development and protection in response to unpredicted climatic events. Therefore, resulting in the loss of a myriad of ecosystem services supported by those habitats (Chee et al., 2017; Evans et al., 2019; O'Shaughnessy et al., 2020) and disrupting natural connectivity between terrestrial and marine systems (Chee et al., 2017; Hindle, 2018; Ryu & Kim, 2021).

Furthermore, the pervasiveness of these structures also alters salinity gradients and pH levels, obliterates sediment and groundwater exchange, replaces vegetated slopes, and planes, and destroys habitat areas. Such change is often cataclysmic, making the urban intertidal and coastal zones "ground zero" for destruction (Hindle, 2018). Incorporating habitat standards into ACS may not undo damages done, but it could aid in narrowing the increasing divide between urbanization and marine ecology.

2.1.2 Threats and impacts to coastlines

2.1.2(a) Natural threats and impacts to coastlines

Coastal and marine environments are inherently unpredictable, shaped by a complex interplay of natural forces and human activities. Beaches and nearshore areas, the most dynamic zones within these systems, are constantly moulded by waves and currents, resulting in diverse and ever-changing landforms (Asensio-Montesinos et al., 2024). These coastal regions experience natural stress on various timescales, from daily fluctuations to annual cycles, and exhibit high environmental variability in factors such as temperature, salinity, and nutrient levels (Alsaffar et al., 2020). This inherent dynamism makes coastal environments particularly vulnerable to both natural changes and the impacts of human development.

The wide-ranging impacts of climate change, fueled by historical and ongoing greenhouse gas emissions, intensified storm surges, extreme weather events (Clarke et al., 2022), and drought (Herrera-Estrada & Diffenbaugh, 2020), have triggered catastrophic ecosystem changes (Knights et al., 2017). Coastal erosion and flooding have diminished the size of beaches and dune systems in many parts of the world such as in Bunos Aires, Argentina, and The Holderness Coast in England (Garzo et al., 2023; Nowell, 2023). This degradation not only compromises their natural protective function but also leads to a decline in their aesthetic appeal and tourism value, impacting local economies and ecosystems. These changes have significantly altered coastal habitats to the extent that they no longer serve crucial nursery, feeding, or reproductive functions due to habitat degradation (Brown et al., 2017; Muluneh, 2021), thereby endangering multiple ecosystem services. Ultimately, the cumulative effects of climate change on coastal areas pose a serious threat to biodiversity, economic stability, and the overall health of these vital ecosystems (Asensio-Montesinos et al.,

2024; Muluneh, 2021).

2.1.2(b) Anthropogenic threats and impacts to coastlines

Coastal environments are already subject to natural dynamic forces, but a range of additional pressures are exacerbating the challenges they face. Some of these additional threats from drastic effects of climate change, anthropogenic pressure at spatial and temporal scales from dense human settlements, agriculture, industry, fisheries, transport, recreation, and habitat degradation also pose further impacts to coastal environments (Knights et al., 2017; Kondrat et al., 2021). The term 'coastal squeeze', denoting high levels of coastal urbanization (Doody, 2004), reflects the increasing threats posed by sea-level rise and human activities, precedes as one of the leading indicators of environmental change (Hagenlochera et al., 2018; Lopes et al., 2023).

This situation is likely to worsen with more populations estimated to be living within 100 km off a coast by 2025, calling for the dire need to increase coastal developments and the necessity to defend coasts with different types of ACS. Consequently, pronounced changes to the natural ecosystem matrix from building infrastructure complexes and reclamation results in the highly concentrated population trend. The habitat quality of an ecosystem to provide appropriate conditions for individuals and population will eventually degrade over time due to direct or indirect results of human-driven activities (Raimundo Lopes et al., 2022); eventually negatively affecting the connectivity, and subsequently, integrity and services of both aquatic and terrestrial systems (Waltham & Sheaves, 2018; Wang et al., 2019) by breaking down biogeographical barriers (Dong et al., 2016; Knight et al., 2017) and changing community composition through introduction of invasive species. Although many of these threats are minimally manageable, ecological impacts of anthropogenic activities

and other drivers continue to become the forefront of scientific research today due to their correlative, interactive, and cumulative effects on marine ecosystems.

2.2 Natural coastal habitats and associated ecosystem services

Natural coastal habitats serve as important interphases between land and sea, encompassing both biogenic habitats (vegetated: e.g., seagrass beds, mangroves, and salt marshes or habitats formed by animals: e.g., corals, bivalves, and annelids) and geogenic habitats (e.g., rocky coasts and beaches) (Firth et al., 2016; Seitz et al., 2013). These habitats represent continuous transitional zones where terrestrial and marine domains interact dynamically and remain in constant flux (Burden et al., 2020; Wedding et al., 2022). They play a crucial role in providing ecosystem services and benefits that are immensely valuable to society and coastal communities, serving as primary indicators of environmental change conditions (Raimundo Lopez et al., 2022) and aiding in carbon sequestration. Among the array of ecosystem services they offer, these habitats contribute significantly to flood defense and coastal protection against wave damage, storm surges, rising seas, and coastal erosion, mitigating the effects of coastal flooding caused by natural factors (Narayan et al., 2017; Sherrard et al., 2016; Wedding et al., 2022). For instance, biogenic habitats like warm-water coral reefs in the shallow tropics and subtropics enhance sandy habitats (e.g. sand bars, beaches, and dunes) role as natural coastal defenses by providing the ‘front line’ coastal protection.

Natural processes such as storms, hurricanes and typhoons, tsunamis, winds, and waves inevitably cause continuous erosion to rocks and sediment deposits, resulting in varying erosion rates and accretion. Over time, the weathering processes form physical complexities like pits, grooves, crevices, overhangs, and tidal pools within these habitats. As a result, these formations are found to offer essential elements – such

as habitat, nursing grounds, protection, and foraging areas – that are crucial for the thriving of marine and coastal communities. Additionally, they often act as spawning and nursery habitats, supporting the larvae and juveniles of many fish species (Firth et al., 2016; Macura et al., 2019; Shelamoff et al., 2020), thereby contributing significantly to sustaining biodiversity.

2.2.1 The ecology of natural coastal habitats

Natural coastal habitats provide a wide array of important ecosystem functions for diverse marine organisms in some or all stages of their life cycle (Firth et al., 2016; Macura et al., 2019; Shelamoff et al., 2020). The ecology of these areas differing in hydrodynamics, structural complexity, substrate composition, and changes in movement and deposition of sediments shapes the associated species communities. Consequently, forming a diverse habitat in coastal ecosystems whereby environmental features greatly influence the distribution of organisms whereby water movement, sediment deposition and human activities are the major drivers (Akoumianaki et al., 2013; Yu et al., 2020). For example, the presence of rock pools at rocky shores with complexities from the results of weathering processes helps provide refuge for intertidal organisms from both biotic and abiotic pressures at differing tides (Evans et al., 2021; Hall et al., 2018) as a function of substrate topography.

Natural coastal habitats also encompass different zonation characterized by key organisms (e.g., littorinid snails, barnacles, and algae, respectively) and varying thermal regimes across the distinct horizontal bands (Waltham & Sheaves, 2020). These zones are namely the supratidal zone, intertidal zone, and subtidal zone.

2.2.2 Natural hard bottom communities

Natural hard bottom communities comprise of benthic organisms living on the ocean floor, either associated with substrata (epifauna or epifloral), buried, or burrowing

within sediment (infauna), or dwelling just above it (hyperfauna) (Joydas & Borja, 2019). These communities are ubiquitously distributed and highly diverse, particularly in shallow and exposed marine systems (Joydas & Borja, 2019). They encompass a wide array of species, primarily dominated by invertebrates such as Polychaetes, Palecypods, Anthozoans, Mollusks, Crustaceans, and Echinoderms. Their distinct ecology, life cycles, and body sizes categorize them into various habitat groups (e.g., infauna, epifauna, and hyperfauna), habitats (e.g., soft- bottom habitats and hard-bottom habitats), and body size (e.g., macrofauna, meiofauna, and microfauna) (Stratmann et al., 2020).

Hard bottom communities are amongst the integral biological components of ecosystem functioning due to their diverse feeding habits and adaptive capabilities in varying environmental conditions (Pandey & Thiruchitrambalam, 2019). They play a fundamental role in the energy flow across different tropic levels and greatly influence the abundance and species composition of tertiary consumers (Mandal & Harkantra, 2012; Pandey & Thiruchitrambalam, 2019). These assemblages serve as valuable study systems for ecologists, particularly as bioindicators in assessing environmental conditions (Hamdy et al., 2023; Mohd Kasihmuddin & Che Cob, 2021) like coastal pollutions such as water quality (Miskon, et al., 2015), owing to their limited mobility, and different stress tolerances. Furthermore, hard bottom communities actively contribute to the sea's energy cycle by mineralization, sediment mixing, oxygen flux into sediment substratum, and the recycling of organic matter and nutrients between substratum and water column (Pandey & Thiruchitrambalam, 2019). These processes indirectly enrich the planktonic community by supplying meroplankton, thereby establishing a critical linkage in the marine food web's energy flow.

Although hard bottom communities are globally distributed, they predominantly inhabit tropical regions compared to higher latitudes areas, where marine biodiversity has notably decreased (Canning-Clode, 2009). A study by Pesiu et al. (2022) highlighted he high local species richness within Malaysia's marine environment, particularly within Marine Protected Areas. The features of shallower continental shelves with reduced water depth in Peninsular Malaysia, offer numerous benefits for these communities, providing improved foraging grounds and better guild establishment (Mohd Kasihmuddin & Che Cob, 2021). Notably, several regions in Penang, Malaysia have shown great abundance of hard bottom communities such as gastropods in seagrass meadows (Vian et al., 2022) and mangrove crabs in mangrove forests (Salleh-Mukri & Shuhaida, 2021). However, based on a study conducted in Penang Island, Malaysia, it was revealed that increasing coastal reclamation poses a significant threat to the distribution and diversity of benthic assemblages due to habitat disruption (Chee & Sim, 2016).

2.2.3 Ecosystem engineers

Ecosystem engineers are prominent organisms that directly or indirectly modulate the resources available to other organisms by influencing biotic or abiotic materials (Jones et al., 1994). They are classified into two categories: (i) autogenic engineers, organisms that changes to the environment occurred through their own physical structure (e.g., own living and dead tissues, coral reefs, animal burrow linings) and (ii) allogenic engineers, organisms that transform living or non-living materials from one physical state to another (e.g., changed sediment particle size and binding by extracellular polymeric material) via mechanical means (Jones et al., 1994; Meadows et al., 2012). In marine coastal communities, many autogenetic engineering species play crucial roles in ecosystem and community functioning.

Benthic macroinvertebrates, found extensively across seafloors worldwide, serve as ecosystem engineers purposed with creating a habitable sediment environment for diverse marine organisms to thrive (Mohd Kasihmuddin & Che Cob, 2021). For instance, filter feeders like oyster and mussel colonies, when attached on hard surfaces, act as epifaunal ecosystem engineers. They filter water columns, create complex sub-habitats, and influence nutrient dynamics and hydrodynamics in coastal oceans (Meadows et al., 2012; Vaughn & Hoellein, 2018; Vozzo et al., 2021). Previous research has highlighted the role of biogenic buildup by ecosystem engineers, such as oysters, serpulid worms, barnacles, and corals, attributing in the reduction of wave energy in coastal zones and enhancing the structural stability of ACS (Ochi Agostini et al., 2017; Becker et al., 2020; Chowdhury et al., 2021). This buildup alleviates stressors, creating hospitable habitats for other organisms. In rocky shores of Penang Island, ecosystem engineers like oysters (*Saccostrea cucullata*) and barnacles (*Amphibalanus amphitrite* and *Chthamalus malayensis*) were the commonly observed species (Chee & Sim, 2016; Chee et al., 2020).

Barnacles have been widely studied for their role as ecosystem engineers and are among the most widely distributed animals in the marine habitat. They are known to be pivotal space occupiers and habitat-forming species occupying the intertidal rocky shores (Ochi Agostini et al., 2017; Coombes et al., 2015; Hall et al., 2018). The colonization of these habitat-forming species has positive impacts on species richness, abundance, and community productivity of algae, sessile and motile invertebrates, and fishes through facilitated community succession with their empty shells (called ‘tests’) (Coombes et al., 2015; Moisez et al., 2020; Ramos-Sánchez et al., 2021). Moreover, the settlement of organisms with calcium carbonate skeleton like barnacles, also provides

bio-protection to structures against weathering and erosion (Ido & Shimrit, 2015; Morris et al., 2018).

2.2.4 Benthic macroinvertebrates

Benthic organisms are bottom-living plants or animals, generally dominated by invertebrates further subdivided based on their habitats (Bendary et al., 2023). Within the classification of macroinvertebrates, these organisms typically measure 0.5 mm or more and include a variety of species such as sea sponges, mollusks, cnidarians (e.g., sea anemone, sea pen, corals) echinoderms (e.g., starfish, sea urchin, and sea cucumber), ascidians (e.g., sea squirts), and arthropods (e.g., crustaceans) among others (Fadli et al., 2019). Benthic macroinvertebrates play various ecological roles; they serve as algal feeders, detritivores, and deposit feeders, colonizing diverse habitats. These organisms provide ecosystem services by sustaining commercial fisheries (Hamli et al., 2012), positively influencing water quality, and being reliable environmental indicators (Baharuddin et al., 2018; Halim et al., 2019; Mohd Kasihmuddin & Che Cob, 2021). Additionally, they constitute a crucial component of marine food chains across different trophic levels. Many suspension feeding organisms, such as oysters and mussels, form complex habitats that support diverse communities through enhancement of area availability on hard substrates for attachment and grazing, whilst providing microhabitats (Vozzo et al., 2021).

Benthic macroinvertebrates, dependent on suitable water quality for survival, typically seek sheltered spaces to minimize risks of predation, desiccation, and dislodgement during low tides. Their geographical distribution is influenced by environmental factors, particularly in different bands of zonation along rocky shores, where sun exposure and desiccation levels vary (Carvalho et al., 2021). In tropical high-tide zones, morphologically adapted species like *Chthlamalus sp.*, *Littorina sp.*,

Cellana sp., and *Nodilittorina sp*. commonly thrive in hostile conditions (Ahmad et al., 2011). Conversely, rock oysters (*S. cucullata*) dominate the middle to lower zones of rocky shores (Ahmad et al., 2011). Other inhabitants, such as limpets with dome-shaped shells, orientate their bodies according to prevailing currents or wave directions to avoid dislodgement, resulting in varied orientation patterns (Fraser et al., 2014).

The alarming trend of reclaimed areas for urban development in Malaysia is characterized with the lack of niche habitats for organisms to seek refuge from predation and desiccation (Strain et al., 2017; Chee et al., 2020; 2023). Subsequently, this impacts ecosystem functioning and a myriad of anthropogenic-induced effects on the marine environment. Despite awareness of diminishing natural habitats, ongoing urban development in Malaysia persists, underscoring the importance of studies on benthic macroinvertebrates to assess natural and human-induced disturbances (e.g., land reclamation) through examining their distribution and diversity (Baharuddin et al., 2018; Chee et al., 2023).

2.3 Artificially engineered structures and its characteristics

As coastal cities anticipate the challenges of climate change, there is a global trend of increasing artificially engineered structures in the marine environment (Elrick-Barr et al., 2022; Griggs & Requero, 2021). Scarce land leads to vertical (high-rise buildings) and horizontal (land reclamation) expansions to accommodate growing populations (Chee et al., 2023). Such development rampantly replaces natural sloping habitats with artificial materials and monolithic concrete build forms along the intertidal zones. These modifications armoring coastlines (e.g., breakwaters, seawalls, rock revetments, pilings, bulkheads) primarily prioritize engineering and financial criteria (Bishop et al., 2017; Morris et al., 2018), are obligatory for public safety. Despite their

intended functions, ACS inadvertently serve as habitats for certain marine organisms although majority lack hospitable conditions for thriving ecosystems (Komyakova et al., 2022; Loke et al., 2019a).

ACS are typically made of rigid, human-mediated materials that vastly differ vastly from natural habitats in their physical (Grasselli & Airoldi, 2021), chemical (Becker et al., 2020; Hsiung et al., 2020), and biological (Lawrence et al., 2021) compositions. These plain, predominantly vertical concrete forms are devoid of surface complexities (e.g., holes, pits, crevices, pools) which serves as refuges from physical stressors and predation for intertidal organisms (Aguilera et al., 2018; Evans et al., 2021). The absence of such features exposes these organisms to harsh conditions, leading to homogenization and amplified temperature regimes that impacts their settlement patterns (Strain et al., 2017). This puts mobile species (e.g., gastropods) at risk of dislodgement and potential mortality, while it is highly likely for sessile organisms (Fraser et al., 2014) as they are built in high-energy environments. Although some ACS such as breakwaters and tetrapods incorporate structural complexities by creating spaces between boulders, these areas often constitute as hotspots for litter accumulation (Aguilera et al., 2016).

Besides that, ACS are typically composed of concrete man-made materials, known to have adverse effects on the marine environment (Becker et al., 2020; Dennis et al., 2018; Vozzo et al., 2021). Studies have shown that leaching rates of heavy metals into the marine environment from these structures have different impacts to the surrounding environment (Becket et al., 2020), influencing certain species' settlement (Dennis et al., 2018) and providing opportunities for NNS through the introduction of new hard substrata. Additionally, the reduced settlement and abundance of native organisms on ACS, coupled with low biodiversity, adversely promotes greater number

of NNS as compared to natural habitats (Tan et al., 2018) resulting in competition and contribution to distinct assemblages between the following. ACS often exhibits steeper intertidal gradient and less topographic complexity, resulting in competition for space due to a compressed intertidal zone, unlike expansive horizontal rocky shores (Strain et al., 2017). Moreover, maintaining the structural integrity of ACS in high-energy environments often involves ecological disturbances whenever removing large areas of habitats which significantly impacts the ecosystem.

2.3.1 Concrete in artificial structures

Concrete stands as one of the most extensively used materials globally, especially in coastal constructions due to its availability, formability, and cost-effectiveness (Becker et al., 2020; Gagg, 2014). Its composition- primarily cement, aggregates, water, and minor chemical additives – grants it exceptional durability, often maintaining strength for 50 to 100 years based on component quality and construction practices (Gagg, 2014). This enduring quality proves vital in civil engineering, particularly in harbor and offshore projects (Becker et al., 2020). Research even suggests that utilizing granulated ground blast-furnace slag (GGBS), a by-product of pig iron production, in concrete for ACS offers technological advantages (Dennis et al., 2018; Natanzi et al., 2021). This material's adaptability for moulding into diverse three-dimensional shapes has further popularized its use. However, despite meeting engineering and financial criteria, unresolved ecological controversies persist, focusing on the response and behavior of marine species towards these introduced artificial habitats.

Concrete vastly deviates from natural substrates in their chemical composition, colour, and physical properties such as porosity and micro-textures (Becker et al., 2020). Despite being utilized in over 50% of ACS construction, Portland cement, a common substrate in concrete, inadequately supports biological recruitment and often displays

lower native diversity. This limitation stems from its high surface alkalinity (with a pH of around 13, as opposed to seawater's pH of approximately 8) and the presence of compounds that are harmful to marine organisms (Ido & Shimrit, 2015; Waltham & Dafforn, 2018). Additionally, metals leaching from ACS into the surrounding water column over time (Dodds et al., 2022; Heery et al., 2017; McManus et al., 2018) potentially hinder the settlement of native marine organisms (McManus et al, 2018).

Moreover, concrete is also known to contribute a substantial carbon footprint (Dennis et al., 2018), compounded by environmental footprint from its aggregate components such as crushed stones, or sand and gravel. Rocks and materials in the intertidal zone, whether occurring naturally or introduced through coastal engineering, undergo a repetitive process of submersion, exposure to saltwater, and radiative heating and drying (Coombes & Naylor, 2011). These cycles can elevate surface temperatures, potentially creating lethal conditions for epibiota during low tides (Coombes & Naylor, 2011). This further concludes that the warming and drying of different composition and designs of concrete ACS under varying intertidal conditions, may also affect colonizing organisms that are adapted to specific temperature ranges, but such area requires more study.

2.3.2 The ecology of artificial coastal structures

The pervasive nature of ACS significantly reshapes the composition and structure of most benthic communities, ultimately promoting the dominance of stress-tolerant species (Taormina et al., 2020; Bishop et al., 2017). In certain scenarios, these structures, influenced by varying light exposure, hydrodynamics, or sediment rates (Heery et al., 2017; Macura et al., 2019; Sedano et al., 2020) provide manipulated conditions conducive to certain marine species such as barnacles and oysters. Nevertheless, ACS fundamentally differ from and cannot substitute as surrogates of

natural habitats (Firth et al., 2016) for its poor diversity. Typically, the ecology of ACS is only limited to a handful of resilient communities adapted to the harsh intertidal conditions, starkly contrasting the richness of natural habitats (Bishop et al., 2017).

Diatoms and bacteria constitute the major components of biofilm in the marine environment and will instantly colonize any clean surface submerged in the sea as they favor the surface-associated living mode (Caruso, 2020; Salta et al., 2013) – including surfaces like ACS. These biofilm-forming microorganisms subsequently forms a highly complex three-dimensional (3D) surface structure which induces early colonization processes of diverse benthic communities, although considered as micro- and macro-foulers in the engineering aspect (Salta et al., 2013). For one, ACS fosters the colonization of dominant alko-tolerant taxa such as barnacles due to its high surface alkalinity (Guilbeau et al., 2003; Bone et al., 2022). These encrusting species are key space occupiers that readily colonize ACS as they settle on any hard substrates after their free-swimming larval phase; similarly, to mussels, oysters, bryozoans, and hydroids (Hall et al., 2018).

2.3.2(a) Non-native species

Non-native species (NNS) are alien or invasive species, with highly adaptive and pervasive traits, that easily threaten the ecological stability of native species and habitats. Colonization of NNS mainly occurs in intertidal and subtidal habitats through human-mediated activities such as transportation, from shipping ballast water to unintentional escapes (Ido & Shimrit, 2015) and speculated invasion through floating debris (García-Gómez et al., 2021) across major geographic barriers. Consequently, developments of new, hard, artificial substrata have welcomed NNS and opportunistic species (e.g. macroalgae, biofilm, barnacles, and oysters) to be more prevalent on ACS than any other natural habitats (Becker et al., 2020; Firth et al., 2014) where the main

cause of this lies in topographic complexity loss. Moreover, closely built ACS on predominantly soft sediments sometimes facilitate the establishment of NNS; utilizing ACS as corridors to move along a coast (Firth et al., 2014).

Oysters and mussels have been well documented in literature bodies to colonize ACS; acting as ecosystem engineers (Vozzo et al., 2021). However, in cases of invasion by NNS such as Pacific Oysters with similar habitats preference to native oyster and green mussel respectively (*Crassostrea iredalei* and *Perna virdis*) will directly or indirectly modify or destruct existing habitats, causing displacement of native organisms (National Committee on Invasive Alien Species in Malaysia, 2018). While marine invasions are a global concern, its impact in the South China Sea is particularly strong being one of the most important marine aquaculture and fishery harvest areas worldwide with six countries (China, Indonesia, Vietnam, Philippines, Malaysia, and Thailand) among the top 15 countries having substantive marine aquaculture and open water harvest fisheries (FAO, 2018) whereby intense ACS developments only aids in the problem.

2.4 Ecological engineering

Ecological engineering (or eco-engineering) is a relatively new and evolving concept aimed at incorporating sustainable ecosystem designs with engineering principles, integrating ecological, economic, and social needs with the natural environment, for the benefit of both (Chapman & Underwood, 2011). It is often used as a nature-based solution to tackle social issues of flooding, climate change, and poverty through sustainable management, protection, or restoration of the natural ecosystem in combating environmental change (Naylor et al., 2017). Concepts of eco-engineering and green infrastructure have shown strong growth over the last decade (Naylor et al.,

2017) through the incorporation of environmental enhancements and natural capital into engineered developments, being well established in terrestrial and freshwater systems (Evans et al., 2019).

In freshwater systems, research on optimal design of culverts and dams for fish migration has been embedded in freshwater development projects and restoration initiatives (Newbold et al., 2014). In comparison to the adapted engineering principles in freshwater systems, eco-engineering in marine systems is still an emerging concept, though exploration of interests on ACS has been carried out among researchers since the early 2000s trialling marine eco-engineering techniques (Strain et al., 2017).

2.4.1 Ecological engineering of artificial coastal structures

In recent years, eco-engineering solutions in the coastal zone have already been globally applied to ACS projects in several cities (Morris et al., 2018; Sella et al., 2018) such as Sydney, San Diego, Singapore, and Hong Kong for ecological gains with designs mimicking nature's forms and functions. The field of eco-engineering of ACS widely encompasses three fundamental approaches (see Figure 2.1) involving (i) hard (manipulations of non-removeable ACS and in environments in which soft approach cannot be applied) (Chapman & Underwood, 2011; Firth et al., 2014); (ii) soft (inclusion of natural elements such as marshes, mangroves, and sand dunes as natural coastal defenses) (Morris et al., 2018); and (iii) hybrid (the combination of soft approaches such as vegetation and or / habitat-forming organisms onto ACS) (O'Shaughnessy et al., 2020). In Malaysia, strict building codes and standards in ACS construction is exemplified by the General Administrative Circular No. 5 of 1987. This stringent regulatory framework ensures compliance across all construction phases, including materials, methods, and sequencing. Consequently, ecological principles and products intended for coastal and offshore applications must not only be

ecologically sound but also adhere to these industry standards (Komyakova et al., 2022). This ensures that ACS projects are both environmentally and structurally robust enough to withstand the harsh marine environment.

Adaptations to ACS takes on many forms. This includes eco-engineering trials manipulating designs by increasing habitat complexity (Chee et al., 2020; Loke et al., 2019b; Ushiama et al., 2019) o improve habitat heterogeneity, incorporating alternative construction materials to reduce their environmental footprint (Dennis et al., 2018; McManus et al., 2018), and directly transplanting target species onto ACS in support of threatened populations (Farias et al., 2017; O'Shaughnessy et al., 2020). Though there have been many produced examples of multifunctional structures armed with various biodiversity benefits and with a good aim, the possibility of being misused for greenwashing purposes remains (Firth et al., 2020). There are also setbacks in implementing eco-engineering at multiple sites requiring social license (Strain et al., 2020). Furthermore, eco-engineering support differs between geographic locations depending on the varying responses of stakeholders to new policies or conservation projects (Kienker et al., 2018) making it hard for eco-engineering projects to proceed.

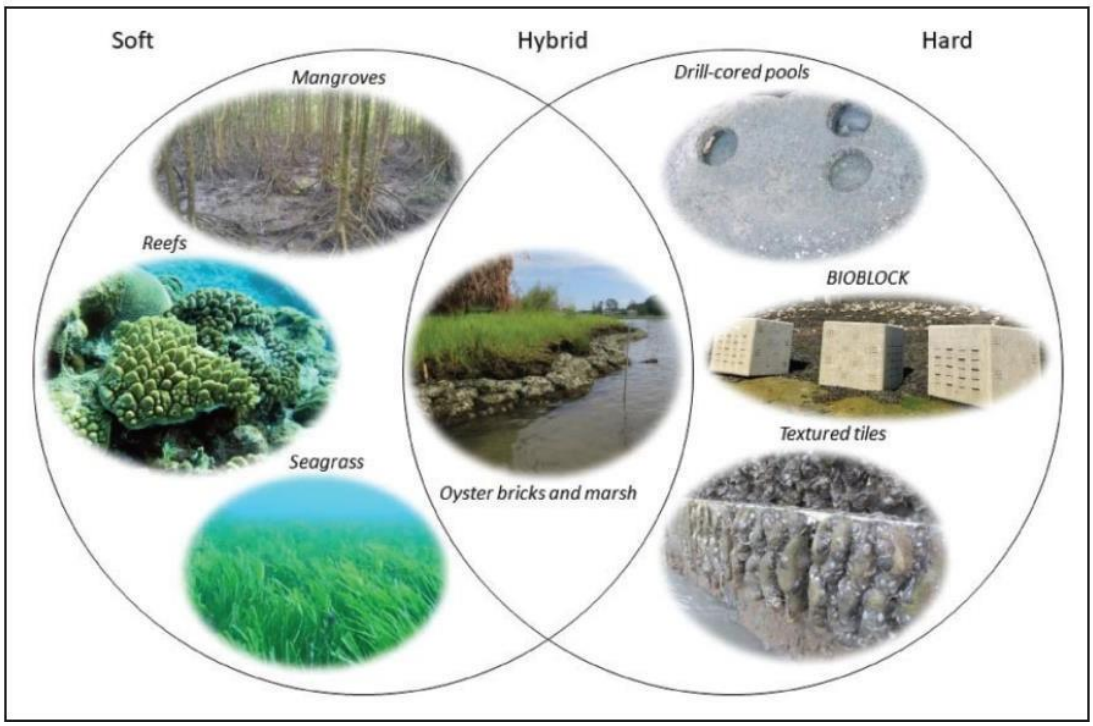

Figure 2.1 The various ecological engineering approaches (Chee et al., 2020).

2.4.2 Ecological enhancement designs

Little to no effort to improve designs of ACS in marine settings to achieve secondary management endpoints have led researchers to advocate for topographic complexity in order to yield multiple biodiversity benefits. Different designs inspired by nature have been implemented to manipulate these structures, such as experimenting at micro (μm- mm) scale (by creating textured surfaces), at small-to-medium (mm-cm) scale (by adding artificial pits, crevices, and pools), and at macro (cm-m) scale by incorporating pre-cast habitat units into ACS designs (Evans et al., 2019) (see Figure 2.2). These added complexities have been easily and inexpensively achieved simply by manipulating wet mortar surfaces. For example, scratching with a trowel or wire brush (to create grooves), pushing in a stick (to create pits) (Firth et al, 2014), or even using aggregates (to achieve surface roughness) (Coombes et al., 2015). Other eco-engineering trials such as increasing surface roughness of concrete (Coombes et al., 2015), adding water-retaining features (e.g., drilling holes (Chee et al., 2020; Firth et