Sustainable Communities and Waste

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Environmental considerations in the use of plastic-reinforced concrete in artificial reef construction.

A review of scientific literature and expert opinion. (IP2.02.03: Plastic-reinforced artificial reef structures; improving understanding).

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Acknowledgments

We acknowledge the Traditional Custodians upon whose ancestral lands we live and work. We pay respect to their Elders, past, present, and emerging, and acknowledge the continuing connection that Aboriginal and Torres Strait Islander peoples have to the land, sea, sky, and waterways. Sovereignty was never ceded.

Thank you to all those experts who graciously participated in interviews, giving their valuable time, and sharing their wisdom and knowledge. Their participation is evidence of the high regard all hold for the National Environmental Science Program and the value of sharing knowledge for the benefit of people and nature. Experts interviewed are listed in Appendix 1.

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Executive Summary

A review of scientific literature and interviews with experts was conducted into the environmental implications of the use of plastic reinforced concrete for artificial reefs. The review is designed to support the development of the permitting system as part of the *Plastics in Artificial Reefs Policy* of the Department of Climate Change, Energy, the Environment and Water (the Department).

Little research has been conducted into the specific issue of the fate and potential impact of plastic reinforcement within concrete reef modules. Additional research is likely to be needed for definitive conclusions to be made. Specifically, we have found no studies that investigate the potential environmental impacts of chemical contamination from the degradation of plastic-reinforced concrete *per se.* In the absence of long-term monitoring for such impacts, impacts can only be inferred from what is currently known about 1) the durability of concrete in the marine environment and hence the likelihood that plastic would enter the marine environment as a result of degradation, and 2) the chemical composition and biotoxicity of the polymers used in plastic-reinforced concrete that might subsequently leach into the marine environment.

Concrete in the marine environment

There is considerable research on the durability of reinforced concrete (RC) in the marine environment due to its very wide application across marine industry and infrastructure. The use of reinforcing supplements such as plastics has been widely adopted and is generally shown to improve the sustainability of marine concrete structures due to their greater durability and lower energy consumption compared to steel reinforced concrete. Plastic-reinforced concrete (PRC) is widely used in the marine environment to increase the durability of coastal and marine infrastructure such as bridges, sea wall, docks and other structures that are designed for use over many decades (typically at least 50 years). The fibres for PRC are derived from a wide range of synthetic polymers including PET (polyethylene terephthalate), PE (polyethylene), PP (polypropylene), nylon, polyester, and many others. Fibres are classified as either macro- or micro-fibres according to their diameter and length, with each having specific advantages in relation to physical properties of the resulting product.

Studies of the environmental impacts of RC, PRC and recycled PRC are focused primarily on the sustainability of production considering factors such as material inputs, energy and water. We could find no published empirical evidence as to the fate of plastic fibres within marine concrete structures such as artificial reefs. It is not clear when PRC artificial reefs were first used, although the use of fibre in concrete dates back to the late 1960s (Zollo, 1997). Lee et al., (2018) undertook a comprehensive review of research on artificial reefs and found only 15 articles dealing with the nature of the reef materials, the first appearing in 1991. Most of these studies concerned the performance of different substrate types in attracting marine organisms. It is also quite possible that whatever data is available on this subject is held by private companies. Based on their reduced environmental impact, as well as being a part of the move to a circular economy, there has been an increasing trend in recent years to substitute virgin fibres with recycled fibres for use

in PRC. The bulk of recent research on the environmental impact of PRC concerns the use of recycled plastic fibres.

The environmental impact of concrete artificial reefs

In general, most studies of the environmental impact of artificial reefs have involved the actual effect of the reef itself on the composition and abundance of marine organisms, and increasingly on social and economic factors. In a few cases where the effect of artificial reefs in the accumulation and concentration of plastic fibres has been studied, the results are an effect of the reef acting as a trap for plastic waste material (e.g., from fishing operations) that would otherwise disperse more evenly in the marine environment. Some research articles were identified concerning the materials used to construct artificial reefs, although very few considered post-manufacture environmental impact (usually such factors as how artificial reefs can alter currents and sediment deposition). Vivier et al. (2021), for example, conducted a meta-analysis of the design, effectiveness and objectives of marine artificial reefs exhibiting a wide diversity in their construction materials, shape, and purpose, of 162 artificial reefs in 127 scientific papers. Most of these reefs were concrete-based although the review does not identify the nature of any reinforcement used. Concrete was found to have the highest effectiveness as habitat for marine organisms and "*a lower environmental impact than plastics such as PVC which are toxic and generate micro-plastic particles.*"

Environmental impacts of plastics in the marine environment

The direct physical impact caused by ingestion of macro plastics in animals such as marine turtles and seabirds is well documented. However, in most plastic products the basic polymer is also incorporated into a formulary (plastic compound) with different additives to improve the performance of the polymer, (e.g., during injection moulding, extrusion, blow moulding, vacuum moulding, etc.), functionality, and ageing properties of the polymer. The most used additives in different types of polymeric packaging materials are: plasticizers, flame retardants, antioxidants, acid scavengers, light and heat stabilisers, lubricants, pigments, antistatic agents, slip compounds and thermal stabilisers. Each of them plays a distinct role in delivering/enhancing the final functional properties of a plastic product.

There is growing concern about plastic marine debris and microplastics as sources or vectors of substances such as toxic additives into the marine environment and organisms (e.g., Hahladakis et al., 2018). There have been several global reviews in recent years of the origin, fate, and impact of persistent bio-accumulative toxic (PBTs) chemicals from plastics, including those that arrive from litter and debris entering the marine environment (e.g., Rochman et al., 2016; Gallo et al., 2018; Hahladakis et al., 2018; Oliveira et al., 2020, Waymana and Niemann, 2021).

Rochman et al., (2016) critically and systematically reviewed the literature regarding the ecological impacts of marine debris. They found "*the majority (82%) of demonstrated impacts were due to plastic, relative to other materials (e.g., metals, glass) and largely (89%) at sub-organismal levels (e.g., molecular, cellular, tissue). The remaining impacts, demonstrated at higher levels of organisation (i.e., death to individual organisms, changes in assemblages), were largely due to plastic marine debris (>1 mm; e.g., rope, straws, and fragments).*"

In general, although studies of the potential environmental impact of plastics and associated additives at different scales is not yet conclusive, sufficient evidence exists for decision makers to begin to mitigate problematic plastic debris now, to avoid risk of irreversible harm.

Concrete structures in the marine environment are designed to last for decades, if not centuries. However, degradation will inevitably occur and any toxic materials will come into direct contact with seawater and potentially enter the marine food-chain as a result. In one of the few published studies, Kim et al., (2008) analysed physical soundness and strength, and chemical measurements of reinforced concrete reefs immersed for 18 – 25 years and found only minor degradation.

One of the sources of concrete degradation may be colonisation by marine organisms, an outcome that artificial reefs are specifically designed to encourage. In general, it appears that bio-colonisation of concrete marine structures may in fact protect the structure from the degrading effects of light and seawater. Lv et al., (2022) for example, found evidence that colonisation of marine concrete by barnacles improved the durability of marine concrete by enhancing the resistance of the concrete to water absorption, chloride ion penetration and neutralisation, and this positive effect is increased as the coverage area of the barnacles expands.

Environmentally sustainable concrete and plastic alternatives

Natural fibres, such as cellulose, coconut fibre and hemp have been used in concrete for many years. However, concretes made with these materials have generally not been used in the marine environment and mostly show lower durability than those utilising steel or plastic fibre reinforcement. Carral et al. (2020) found that the use of eucalypt fibre and mussel shells was suitable for artificial reefs in an area where both materials were abundant and would otherwise go to waste.

Kalam et al (2018) reported on the use of ceramics as an effective and environmentally preferable alternative to other materials for artificial reefs. The properties of the reefs (chemical constituents, surface texture, water absorbability, mechanical strength, erosion rate, and sustainability) were examined. The ceramic reefs were shown to be nontoxic, pH-neutral, mechanically strong, and sustainable in a hostile shallow sea environment.

In response to the concerns about placing plastics into the environment, some manufacturers have responded by producing plastic-free concrete for use in the marine environment, including for use as artificial reefs. The British company ARC Marine, for example, produces Reef Cubes® which they state are “the only carbon-neutral, plastic-free solution for marine habitat restoration in the world”.

Conclusion

All plastics and their associated additives are potential pollutants. However, whether the toxicity or concentrations of plastics in the environment has significant ecological impacts, and under what circumstances, is still under investigation (e.g., Hahladakis et al., 2018). Accumulation and a possible remobilisation of Ultraviolet (UV) stabilisers in the marine environment may pose risks to wildlife, especially to benthic and sediment-dwelling organisms (e.g., Prak et al., 2022) and may further accumulate in the food chain (e.g., Peng et al., 2017). However, it is not clear whether UV stabilisers are commonly used (or even necessary) in artificial reefs designed to exist in relatively deep water with low light levels. Although there was no consensus on whether the release of plastic into the environment from PRC artificial reefs was likely to be ecologically significant, the precautionary principle would suggest it should be avoided.

All plastics will contain plastic additives. These will likely leach when exposed to seawater. However, the consequence or impact of this leaching will depend on the amount of plastic in the concrete, the release rate of plastics from concrete, and the effects of dispersion and dilution in the seawater or sediment. In terms of plastic volume – while one expert was aware of up to 40% being tested in lab environment, generally the volume of fibre reinforcement is less than 2% of concrete volumes. One expert emphasised the importance of leaching tests in laboratory conditions (e.g., Leaching Environmental Assessment Framework (LEAF) methods) for concrete products, but particularly those containing novel materials.

Depending on the structural stability of the concrete, over long time-frames (likely longer than 30-50 years) there will be a release of contained plastics into the environment. The sediment is the most likely receptor for the plastics unless they are positively buoyant.

Evidence for plastic additive leaching in concrete is scarce as few studies have addressed this question. However, the lack of laboratory-based studies, or long-term monitoring, does not definitively rule out potential harmful impacts such as leaching of additives or release of plastic fibres into the marine environment.

There is no research that specifically investigates the potential for pollution arising from PRC in the marine environment. However, it is possible to infer from research into the use of concrete in the marine environment, the likelihood of artificial reefs using PRC to degrade over a period of 30 – 50 years, and the amount of toxic plastic material and associated additives that may enter the marine food-chain as a result, that the environmental impact risk is likely to be low over this time-period. Regardless, monitoring of desirable and undesirable outcomes should occur throughout the commissioning period.

However, there is good reason to suggest that artificial reefs should be intended to last much longer than 50 years. Artificial reefs are often designed to enhance the marine environment by creating new self-sustaining marine ecological communities. Unless for some reason an artificial reef becomes hazardous, or starts to show negative environmental impacts, the decommissioning and physical removal of an established artificial reef could therefore itself be considered a negative environmental outcome. Artificial reefs that are intended to be in place permanently therefore need to remain environmentally safe throughout their lifetime and eventual degradation. Since it is likely that any plastic materials and toxic chemicals contained within plastic-reinforced marine concrete will eventually enter the marine environment, either directly or through reef dwelling organisms, artificial reefs made of such material constitute an environmental hazard.

1. Introduction

This review is designed to support the development of the permitting system as part of the Plastics in Artificial Reefs Policy of the Department of Climate Change, Energy, the Environment and Water (the Department).

The Department receives requests for sea dumping permits for the placement of artificial reefs that incorporate plastics in concrete modules. However, the department considers the use of plastic fibres in artificial reef modules to be unsuitable due to the potential for subsequent contamination of the marine environment. It is acknowledged however that there is “a lack of long-term studies and therefore scientific uncertainty about the breakdown of artificial reef modules containing plastic fibres over their design life”.

This report is based on a review of recent evidence in the scientific literature together with interviews of experts, information contained in a few official government reports, and some web-site based information. Scientific papers were searched using Google Scholar or were provided by the subject experts interviewed.

We frame this report around four key issues:

1. The impact of plastic fibres as reinforcement for concrete artificial reefs.
2. The potential for chemical contamination of the marine environment from the chemicals in plastic used as reinforcing material
3. The life-cycle of artificial reef modules containing plastics exposed over 30-50 years to oceanic conditions.
4. Natural alternatives to concrete reinforcement.

We caution however that little research has been conducted into the specific issue of the fate and potential impact of plastic reinforcement within concrete reef modules and that additional research is likely to be needed for definitive conclusions to be made. Specifically, we have found no studies that investigate the potential environmental impacts of chemical contamination from the degradation of plastic-reinforced concrete per se. In the absence of long-term monitoring for such impacts, they can only be inferred from what is currently known about 1) the durability of concrete in the marine environment and hence the likelihood that plastic would enter the marine environment as a result of degradation, 2) the chemical composition of the polymers used in plastic-reinforced concrete that might subsequently leach into the marine environment and their biotoxicity. This report is therefore a brief review on these two points together with some information on the potential use of alternative materials in the construction of artificial reefs.

2. Use of reinforced concrete in the marine environment

Cement behaves erratically under varying stresses. It has a high compressive strength but only a very limited resistance to tensile forces. Cement is therefore often combined with an interior steel reinforcement, giving rise to a matrix which performs well under both situations. Despite its effectiveness, steel reinforcement is expensive and of limited duration and requires considerable energy consumption. Furthermore, the permeability of concrete allows water to enter the structure causing corrosion over time and marine concrete structures therefore have a limited life span, usually around 50 years. However, it should be noted that the concept of a "limited" life span for marine concrete is based on the intended use of the structure. There are clear operational safety concerns for many marine concrete structures such as bridges for example, that may be irrelevant for artificial reefs. Should a typical modular cube-type concrete reef suffer major structural failure it would lose much of its ecological value as a reef, but probably represent little safety hazard. New reef modules could possibly be placed over the old reef structure if required.

Disintegration of concrete in the marine environment is mostly caused by chemical deterioration due to attack by sulphate, magnesium and leaching (CSIRO 2000). Physical deterioration occurs as a result of the crystallisation of hydrated salts in pores of the concrete, erosion and abrasion. The effects of these attacks is the removal of the cover concrete and exposure of fresh layers to further chemical and physical attack. Longevity of concrete in the marine environment is affected by the type of concrete used (e.g., Portland cement versus fly-ash cement mixtures) and quality of manufacture. Marine concrete is covered by Australian Standard 3600 and provides for a useable life cycle of 40 – 60 years[1].

To overcome the limitations of concrete in the marine environment, and indeed elsewhere, there have been a range of artificial and natural additives investigated to provide for greater structural integrity, lower cost and lower energy consumption in manufacture. The result of this process is known as Fibre Reinforced Concrete (FRC) and can be defined as an amalgamated material constituted of Portland Cement and aggregates, incorporating short isolated and irregular fibres from a variety of natural and artificial sources (see Box 1). The most used fibres are steel, glass, natural cellulose, carbon, nylon and a range of plastics (Wang et al 2000).

There is considerable research on the durability of RC in the marine environment due to its very wide application across marine industry and infrastructure (e.g., Melchers et al. 2017; Melchers 2020; Rubino et al. 2020). The use of reinforcing supplements such as plastics has been widely adopted and is generally shown to improve the sustainability of marine concrete structures due to their greater durability and lower energy consumption (e. g., Dong, Li and Xian et al., 2021). However, it should be noted that such studies are focused primarily on the sustainability of production considering factors such as material inputs and energy, water etc. There is however, almost no direct empirical evidence as to the fate of plastic fibres within marine concrete structures such as artificial reefs. It is not clear when PRC artificial reefs were first used, although the use of fibre in concrete dates back to the late 1960s (Zollo, 1997). Lee et al., (2018) undertook a comprehensive review of

[1] https://www.standards.org.au/standards-catalogue/sa-snz/building/bd-002/as--3600-2009--sup--1-colon-2014

research on artificial reefs and found only 15 articles dealing with the nature of the reef materials, the first appearing in 1991. Most of these studies concerned the performance of different substrate types in attracting marine organisms. It is also quite possible that whatever data is available on this subject is held by private companies.

Plastic-reinforced concrete (PRC) is increasingly used in construction due to its lower costs and environmental impact than steel reinforcement. The fibres for PRC are derived from a wide range of synthetic polymers including PET (polyethylene terephthalate), PE (polyethylene), PP (polypropylene), nylon, polyester, and many others. Fibres are classified as either macro- or micro-fibres according to their diameter and length, with each having specific advantages in relation to physical properties of the PRC (Yin 2015). Based on their reduced environmental impact, as well as being a part of the move to a circular economy, there has been an increasing trend in recent years to substitute virgin fibres for recycled fibres for use in PRC. The bulk of recent research on the environmental impact of PRC concerns the use of recycled plastic fibres.

Box 1. Common Concrete Fibre Types.

Cellulose Fibres: Manufactured from processed wood pulp products, cellulose fibres are used in a similar manner as micro-synthetic fibres for the control and mitigation of plastic shrinkage cracking.

Glass Fibres: Glass fibre reinforced concrete (GFRC) has been predominantly used in architectural applications and modified cement-based panel structures.

Macro-Synthetic Fibres: This newer class of fibres has emerged over the past few decades as a suitable alternative to steel fibres when dosed properly. Typical materials include polypropylene and other polymer blends with the same physical characteristics as steel fibres. They can be dosed from 3 to 20 lbs/yd (1.8 to 12 kg/m3).

Micro-Synthetic Fibres: These fibres are generally used for the protection and mitigation of plastic shrinkage cracking in concrete. Most are manufactured from polypropylene, polyethylene, polyester, nylon and other synthetic materials, such as carbon, aramid and acrylics. Micro-synthetic fibres are generally dosed at low volumes ranging from 0.03 to 0.2% by volume of concrete – 0.5 to 3.0 lbs/yd (0.3 to 0.9 kg/m3).

Natural Fibres: These fibres are used to reinforce cement-based products in non-commercial applications worldwide. They include materials such as coconut, sisal, jute and sugarcane, and come in varying lengths, geometries and material characteristics.

Poly-Vinyl Alcohol (PVA) Fibres: These synthetic-made fibres can alter the flexural and compressive performance of concrete when used at higher volumes.

Specialty Fibres: Covering all other fibre types, this classification generally pertains to newly manufactured or specified materials not common to these categories.

Steel Fibres: These fibres are generally used for providing concrete with enhanced toughness and post-crack load carrying capacity. Typically loose or bundled, they are usually made from carbon or stainless steel, and then shaped into varying geometries such as crimped, hooked-end or with other mechanical deformations for anchorage in the concrete.

Source: https://fiberreinforcedconcrete.org/fiber-reinforced-concrete/fiber-types/

3. Environmental impact of reinforced concrete artificial reefs

Most studies of the environmental impact of artificial reefs have involved the actual effect of the reef itself on the composition and abundance of marine organisms (e.g., Baine 2001; Lima et al., 2019) and increasingly on social and economic factors (e.g., Lee et al., 2018). In a few cases where the effect of artificial reefs in the accumulation and concentration of plastic fibres has been studied, the results are an effect of the reef acting as a trap for plastic waste material (e.g., from fishing operations) that would otherwise disperse more evenly in the marine environment (e.g., Zhang et al., 2020). Lee et al., (2018) reviewed research on artificial reefs spanning over three decades. The most common research topic has been the variations in community structure and compositions in marine ecosystems when artificial reefs are deployed. Some research was concerned with the materials used to construct artificial reefs, although very few considered post-manufacture environmental impact (usually such factors as how artificial reefs can alter currents and sediment deposition).

Most studies relating to the environmental impacts of the material composition of PRC in artificial reefs are concerned with their manufacture, rather than post-manufacture operations (e.g., Merli et al., 2020; Akbar and Liew, 2021; Vivier et al, 2021; Tahir et al., 2022;). Vivier et al., (2021) for example, conducted a meta-analysis of the design, effectiveness and objectives of marine artificial reefs exhibiting a wide diversity in their construction materials, shape, and purpose, of 162 artificial reefs in 127 scientific papers. Most of these reefs were concrete based although the review does not identify the nature of any reinforcement used. Concrete was found to have the highest effectiveness as habitat for marine organisms and "*a lower environmental impact than plastics such as PVC which are toxic and generate micro-plastic particles*." The analysis concluded that: "*Concrete with high roughness is by far the most widely used material and seems to be one of the most efficient. The rugosity of the substrate would increase the surface available for settlement and can consequently increase the biomass, the coverage percentage, and the primary production of the structure. Further studies should investigate the micro-scale topography influence of the AR surface on the first colonization steps after its immersion. In addition, this material ensures high resistance and does not produce pollutants. The construction material seems to be more important than the shape of the structure, but our results nevertheless suggest that cylindrical or cubic designs are best.*"

There has been interest in the past decade in the use of recycled plastic in PRC artificial reefs as opposed to virgin fibres and steel, including in Australia (see Box 2). Due to its lower environmental footprint in manufacture, and the potential to store plastic waste over a long term, there is a widespread view that concrete reinforced with recycled plastics (including PET waste) are "eco-friendly" (e.g., Almeshal et al., 2020). Merli et al., (2020) published a literature review of the use of recycled fibres in reinforced concrete. The paper provides an updated review of all the recycled materials used as fibres in concrete, and an assessment of the focus of recent research into recycled fibres. This review noted that only one paper of the 194 articles reviewed (Yin et al., 2016) was primarily concerned with environmental impacts, rather than technical considerations of concrete properties.

Yin et al., (2016) used Life-Cycle Assessment (LCA) to compare the environment sustainability of producing RC with steel mesh, virgin plastic, and recycled plastic. The LCA results showed that industrial recycled PP fibre offers important environmental benefits over virgin PP fibre. Specifically, the industrial recycled PP fibre can save 50% of CO2 equivalent, 65% of PO4 equivalent, 29% of water and 78% of oil equivalent, compared to the virgin PP fibre. When compared to the Steel-Reinforced Mesh, the industrial recycled PP fibre can save 93% of CO2 equivalent, 97% of PO4 equivalent, 99% of water and 91% of oil equivalent. The domestic recycled PP fibre also generates reduced environmental impacts compared to virgin PP fibre, except for higher consumption of water associated with the washing processes.

Box 2. Case Study: NSW Department of Primary Industry Recreational Fisheries Enhancement Program.

The NSW DPI artificial reef program is building offshore reefs to enhance recreational fishing using a variety of materials including plastic reinforced concretes.

For example: “The Tweed Heads Offshore artificial reef Long Term Management Plan (LTMP) will use a concrete mix design, using Boral Z40-10-POLYFBR, consisting of 100% recycled eMesh (small recycled plastic macro synthetic fibres added to concrete). This will lead to 95.63% reduction in carbon footprint using fibre eMesh in place of steel reinforcing.”

Source: https://www.dpi.nsw.gov.au/fishing/recreational/resources/artificial-reef

4. Potential for contamination of the marine environment from chemicals in plastic used as reinforcing material

Plastics in the marine environment

Among the most common polymers found in the marine environment are low density polyethylene (PE-LD), linear low-density polyethylene (PELLD), high-density polyethylene (PE-HD), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS) and polyvinyl chloride (PVC). It is estimated that, on average, around 80–90% of ocean plastic comes from land-based sources, including via rivers, with a smaller proportion arising from ocean-based sources such as fisheries, aquaculture and commercial cruise or private ships (Gallo et al., 2018).

While the deleterious impacts of plastic ingestion by marine organisms such as turtles and seabirds are well known, there is also growing interest in the roles of plastic marine debris and microplastics as source or vector of toxic substances to marine environment and organisms.

In most plastic products the basic polymer is incorporated into a formulary (plastic compound) with different additives to improve the performance of the polymer, (e.g., during injection moulding, extrusion, blow moulding, vacuum moulding, etc.), functionality and ageing properties of the polymer. The most used additives in different types of polymeric packaging materials are: plasticizers, flame retardants, antioxidants, acid scavengers, light and heat stabilisers, lubricants, pigments, antistatic agents, slip compounds and thermal stabilisers. Each of them plays a distinct role in delivering/enhancing the (final) functional properties of a plastic product.

Hahladakis et al., (2018) provides a short description of the most used additives in plastic materials. There have been several global reviews in recent years of the origin, fate, and impact of persistent bio-accumulative toxic (PBTs) chemicals from plastics, including those that arrive from litter and debris entering the marine environment (e.g., Rochman et al., 2016; Gallo et al., 2018; Hahladakis et al., 2018; Oliveira et al., 2020, Waymana and Niemann, 2021).

Rochman et al., (2016) critically and systematically reviewed the literature regarding the ecological impacts of marine debris. They found "*the majority (82%) of demonstrated impacts were due to plastic, relative to other materials (e.g., metals, glass) and largely (89%) at sub-organismal levels (e.g., molecular, cellular, tissue). The remaining impacts, demonstrated at higher levels of organization (i.e., death to individual organisms, changes in assemblages), were largely due to plastic marine debris (>1 mm; e.g., rope, straws, and fragments)*." Although the evidence of ecological impacts at different scales was therefore not conclusive, they suggested that "*sufficient evidence exists for decision makers to begin to mitigate problematic plastic debris now, to avoid risk of irreversible harm*."

Gallo et al., (2018) found that although plastics will not be the only route by which marine species are exposed to hazardous chemicals, existing evidence supports mounting concern in the scientific community that plastics may nonetheless make a significant contribution to exposures to complex mixtures of chemical contaminants (Rios et al., 2007; Avio et al., 2017). Examples of impacts on marine organisms include fish (Murray and Cowie, 2011; Rochman et al., 2013), baleen whales (Fossi et al., 2012), and bivalve molluscs (Avio et al., 2015).

Hahladakis et al., (2018) reviewed the migration, release, fate, and environmental impact of chemical additives in plastics during their use, disposal, and recycling. The review includes a discussion of the leakage of plastic waste into the marine environment and referenced several studies that have documented its negative consequences (e.g., Wegner et al., 2012; Besseling et al., 2013; Foekema et al., 2013; Koelmans et al, 2014; Hermabessiere et al., 2017). The review states that the various additives present in most plastic-derived material can also contribute to marine pollution.

A range of physical and chemical processes act to degrade plastic over time and at the molecular level further degradation will depend on the type of polymer. Under marine conditions, degradation would be relatively slow as the main mechanisms e.g., solar radiation and slow thermal oxidation are less important (Gregory and Andrady, 2003). The time frame for a complete degradation could be extensively prolonged and up to hundreds of years. Qin et al., (2022) studied the liberation of plastic nanoparticles and organic compounds from three common plastics in water during weathering under UV radiation-free conditions. Over 30 organic compounds derived from additives and impurities were detected.

Oliveira et al., (2020) covers the period from 1964 to April 2020 and comprehensively gathers investigation on marine plastic and microplastic pollution, negative consequences of plastic use, and bioplastic production. It lists the most useful methods for plastic degradation and recycling valorisation, including degradation mediated by microorganisms (biodegradation) and the methods used to detect and analyse the biodegradation. Common types of plastic waste made with PET and PP, such as plastic bottles and disposable nappies, can persist for 450 years. Other materials such as plastic beverage holders (PET and HDPE), Styrofoam cups (PS), and plastic may last from 20 – 400 years (Chamas et al., 2020). The natural process of degradation of plastics is affected by uncontrollable and unpredictable environmental factors, including abiotic and biotic conditions, and depends on the molecular weight, the polymer structure, and its physical properties. This slow process can be further slowed down when additives are added to the plastic polymers (Min et al., 2020). In the marine environment, abiotic degradation and biodegradation occur simultaneously with a slow rate of polymer weight loss between 0.39 and 1.02% per month (Welden and Cowie, 2017). Some plastics contain Persistent Organic Pollutants (POPs) as additives (e.g., hexabromocyclododecane (HBCDD or HBCD) and/or polybrominated diphenyl ether (PBDE)) at a concentration of 0.7–25% wt. (e.g., UNEP 2015). Ingestion of plastic additives by marine organisms may therefore be more relevant than the accumulated diffusely spread POPs, since the levels are 7–10 orders of magnitude higher (Teuten et al., 2009; Hammer et al., 2012; Koelmans et al., 2013). Even if not ingested the additive containing polymers still constitute exposure sources e.g., increased HBCDD content has been found in oysters in a farm where PS buoys containing HBCDD were used (Hong et al.,2013). On the other hand, the leaching of additives may be more relevant for species with longer gut-retention times, such as fish (Koelmans et al., 2014).

When polymers are exposed to various environmental factors like UV light, degradation occurs, causing problems and reducing their performance and function. In order to enhance the durability and to extend the service life, it is necessary to add UV absorber and light stabilizer to prevent degradation caused by UV light, improving weather resistance and reliability in various applications. Major types of UV absorber include Benzophenone, Benzotriazole and Triazine. Cantwell (2015) found that some Benzotriazoles exhibit behaviours characteristic of persistent organic pollutants, and emerging evidence indicates long-term preservation and persistence in marine sediments. Other Benzotriazoles associated with anticorrosion applications appear to be highly resistant to degradation, relatively water soluble, and toxic to aquatic organisms and should be considered contaminants of emerging concern in the environment with POP-like characteristics.

Ultraviolet stabilisers (UVSs) and antioxidants are the most widely used additives in plastics to enhance the lifetime of polymeric materials. Rani et al., (2016) provides quantitative information about additive chemicals contained in plastic marine debris and their new products. The presence of UVSs and antioxidants was investigated in plastic debris collected from beaches along with their corresponding new plastic products in markets belonging to food, fisheries, and general use. Most additive chemicals were relatively high in new plastics compared to corresponding plastic marine debris, implying their potential leaching or degradation during use or after disposal. Accumulation and a possible remobilisation of UV stabilisers may pose risks to wildlife, especially to benthic and sediment-dwelling organisms (Prak et al., 2022). Because of their bio-accumulative properties, UV stabilisers may further accumulate in the food chain (Peng et al., 2017).

Apel et al., (2018) investigated the presence of Ultraviolet (UV) stabilisers in the marine environment in their study of surface sediment samples from the North and Baltic Seas. The study aimed to 1) investigate the current pollution status, 2) identify distribution pattern and potential contamination sources, and 3) provide a hazard estimation for sediment-associated organisms. Their results suggested that UV stabilisers do not negatively affect benthic organisms in the North and Baltic Seas. However, due to potential bioaccumulation and biomagnification in the marine food web (Peng et al., 2017), the reported environmental concentrations could still pose a hazard to benthic species and species at a higher trophic level. In addition, information on the potential synergistic toxicity of UV stabilisers in mixtures is sparse and effects of a mixture might occur at lower concentrations levels (Baas et al., 2010). More *in vivo* sediment toxicity data for sediment-associated species are needed to fill this gap in knowledge.

Antioxidants and UV stabilisers are also used to improve the durability of polymers (typically polypropylene) used in geotextiles. Geosynthetics are polymeric materials used in the construction of many coastal engineering structures, such as breakwaters, dykes, groynes, seawalls, jetties, artificial reefs, or revetments. Carneiro et al., (2018) investigated the resistance of a nonwoven polypropylene geotextile in the laboratory against some degradation agents present in marine environments and evaluated the existence of interactions between them. The results showed that sodium chloride had a key influence in the thermo- or photooxidative process of the geotextile, probably by acting as a catalyst. The study concluded that recognising interactions between different degradation drivers in the marine environment may enable the development of strategies for enhancing the durability and performance of geotextiles. It is possible that a similar approach might prove useful in understanding the degradation factors affecting PRC artificial reefs.

Release of hazardous chemicals from concrete in the marine environment

Most studies of leaching of hazardous chemicals from concrete are concerned with heavy metals and toxic chemicals (e.g., Marion et al., 2005, Togerö, 2006, van der Sloot 2000).

Vaccaro et al (2021) conducted experiments to test whether the addition of plastic fibres made from food packaging waste to concrete resulted in leaching of heavy metals Tests were conducted for: 1) compliance leaching test of recycled plastic fibres from food packaging waste for their pollutant potential classification, according to the EU Landfill Directive; 2) diffusion leaching test in tank for basic characterisation of pollutant release from concrete made with plastic fibres; and 3) dynamic diffusion leaching test for long term characterisation of pollutant release from PRC. The plastic waste itself did not produce heavy metal contamination and, under the relevant standard, was therefore not classified as hazardous. The use of plastic reinforcement in concrete "*did not release relevant levels of any potential harmful element incorporated in concrete*." They also state that "*most types of common plastic (e.g., PP, PVC) are stable for decades, even for centuries, inside concrete*".

5. Life-cycle of artificial reef modules containing plastics exposed over 30-50 years to oceanic conditions

Durability and deterioration of concrete in the marine environment

The durability and deterioration of cementitious concrete and reinforced concrete (RC) is critical to durability, safety, and sustainability of infrastructures, especially for offshore concrete structures in the marine environment. The mechanisms involved in degradation of RC in the marine environment are therefore well known. Qu (2020) has reviewed the effects of the marine environment on the deterioration mechanism, performance, and durability of concrete materials and structures. The review also assesses some cases studies of RC structures after many years of exposure to marine environment. Melchers (2020) has also reviewed the performance of concrete in the marine environment, and in particular the role of chlorides. While many reinforced-steel concrete structures around the world have withstood many decades (e.g., up to 75 years) without significant degradation, the quality of materials and construction appear to be critically important.

Kim et al., (2008a, b), looked at some physical and chemical issues for reinforced concrete reefs that had been fully immersed for 18 – 25 years. These reefs were commissioned in the 1970s and were expected to have a service life of about 30 years. In addition to tests of physical soundness and strength, chemical measurements of reinforced concrete reefs were made: pH, chloride concentration, diffusion coefficients, long-term prediction of chloride ion penetration and chemical composition. It was also noted that the concrete had been bio-colonised by 103 species of zoobenthos with only minor degradation as a result. From the experimental observations, a minimum cover depth of reinforced concrete reefs is proposed to secure a service life of 30 years or more. The authors concluded that reinforced concrete reefs showed "*sound chemical properties and were sufficiently secure for a further service period*."

Biological degradation of marine concrete

Cement-based structures, such as concrete, are bioreceptive, that is they can be colonised by marine organisms. The level of bioreceptivity depends on intrinsic properties of the cement matrix such as porosity and roughness (Manso et al., 2015). Over time, concrete in the marine environment will undergo chemical, physical and biological degradation (Georges et al., 2021).

Biological degradation of marine-based FRC includes microbial action, such as the penetration of the concrete structure by algae (Jayakumar and Saravanane, 2009; Georges et al., 2021) and microbes (Hughes et al., 2014, Chlayon et al., 2020). Hayek et al., (2020) investigated microbial colonisation of marine concrete and an overview of the impacts of biological colonisation in relation to "*eco-friendly marine infrastructure and develop green-engineering projects*." Djelal et al., (2020) conducted experimental investigations of concrete beam, unreinforced and reinforced with carbon plates and carbon rods, performance in a marine environment. Results obtained showed that beams stored in the marine environment have a better behaviour than those stored in the laboratory. It is suggested that the development of living organisms (in a marine environment) which acted as additional adhesive and sealing, providing some protection of the concrete structures against damage.

Lv et al., (2022) found evidence that colonisation of marine concrete by barnacles improved the durability of marine concrete by enhancing the resistance of the concrete to water absorption, chloride ion penetration and neutralization, and this positive effect is increased as the coverage area of the barnacles expands.

Monitoring and decommissioning of plastic fibre reinforced concrete artificial reefs

Although there has been very little long-term monitoring of artificial reefs, some new reefs in Australia have a long-term management plan. The Tweed Heads Offshore artificial reef LTMP (2020) for example, includes a long-term monitoring program that includes consideration of structural integrity and potential release of plastic fibres (Box 3). A decision-tree relating to the fibre reinforcement exposure or release issue has been prepared as part of the monitoring program (see Figure 1).

Box 3. Extract from monitoring plan for Tweed Heads Offshore Artificial Reef

Composition: Plastic reinforced concrete mix design, using Boral Z40-10-POLYFBR, consisting of 100% recycled eMesh.

Monitoring Focus: Reef structural integrity and stability

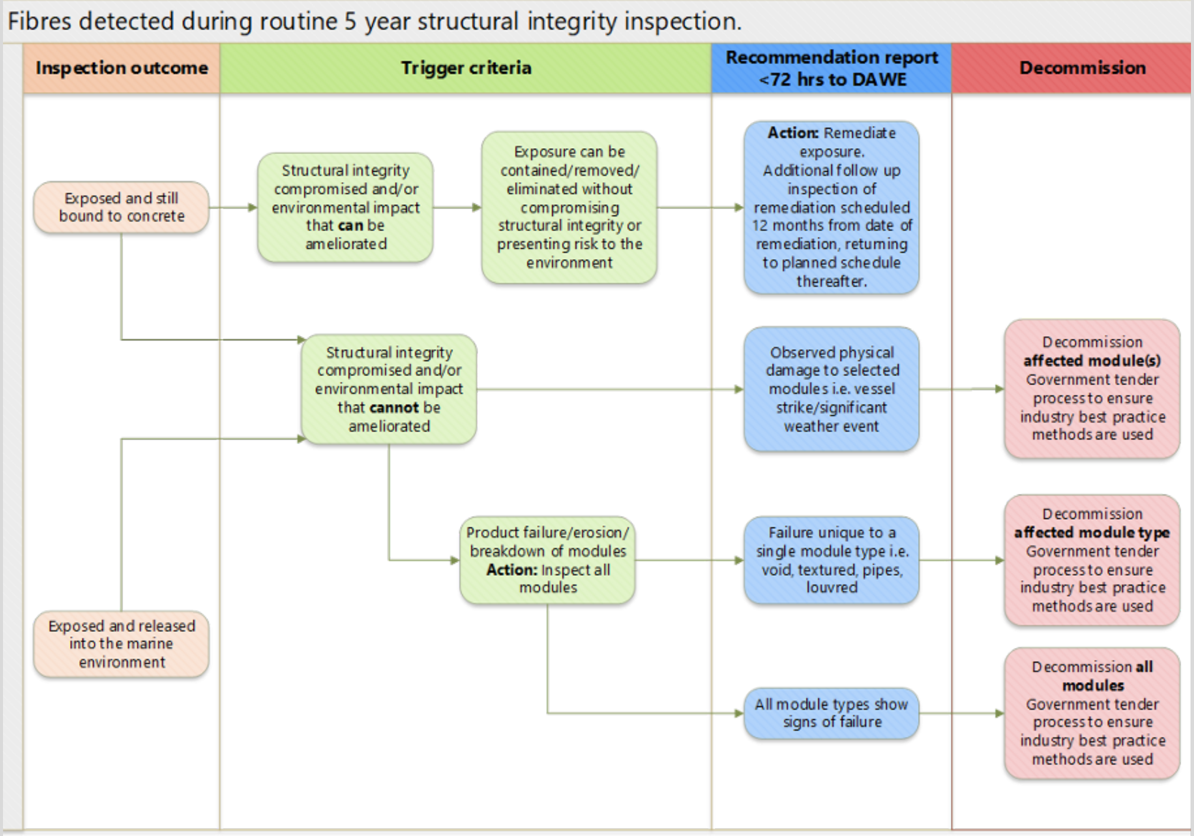
- Frequency: Quarterly every 12 months for 3 consecutive years post installation, annually thereafter. Following large storm events which produce a significant wave height ≥ 4.1 m)
- Method: ROV camera surveys would be conducted by staff a minimum of 4 times a year; these surveys will allow a visual inspection of the reef to document reef stability and structural integrity, corrosion, investigate seabed/sediment characteristics

Monitoring Focus: Assess Fibre reinforcement exposure or release

- Frequency: 5 Yearly
- Method: Professional subsea inspection of a randomised representative sample of concrete modules to detect any exposure or release of fibres to the marine environment. Refer to figure 32 for a decision-making process guideline for inspections that have detected fibres exposed to the marine environment. A report will be generated from each 5 yearly inspection and be submitted to the Department of Climate Change, Energy, the Environment and Water (formerly DAWE).

Source: NSW Department of Primary Industries (2020) Long Term Management Plan – Tweed Heads offshore artificial reef

Figure 1. Decision making process for exposed fibres (Tweed Heads Offshore Artificial Reef, NSWDPI).



Source: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/1271809/Tweed-offshore-artificial-reef-long-term-management-plan-LTMP.pdf

The decommissioning of artificial reefs has not received a great deal of attention in the scientific literature. Na et al., (2016) produced an overview of decommissioning procedures together with some historical examples, especially of the now largely discontinued practice of using used tyres as reef substrate. They noted that there is the potential for artificial reefs which have reached the end of their operational lifespan to "*become rubbish on the seabed*" and that the decommissioning of artificial reefs "*will need to be considered as part of any proposal*". In terms of concrete artificial reefs, they reference the decommissioning of the steel reinforced cube-type concrete modules used in Korea and studied by Kim et al., (2008a, b).

Given that the few known studies show that concrete artificial reefs have remained intact over many decades, it is worth considering whether the default position is that they should be considered permanent structures. While some artificial reefs act simply as fish-attracting devices (i.e., they mostly just attract fish from elsewhere) others are designed to create self-sustaining marine ecosystems. Artificial reefs are often designed to enhance the marine environment by creating new self-sustaining marine ecological communities. Unless for some reason an artificial reef becomes hazardous, or starts to show negative environmental impacts, the decommissioning and physical removal of an established artificial reef could itself be considered a negative environmental outcome. For this reason, monitoring of desirable and undesirable outcomes should occur throughout the commissioning period.

6. Natural alternatives to concrete reinforcement

Natural fibres like jute, coir, bamboo, and sisal have been used as reinforcement materials in concrete mixtures for many years, especially in developing countries (e.g., Sajjalak, 2017). The main benefits of reinforcing concrete with natural fibres are related to low cost and high availability. The relevance of these studies (and many other studies on natural fibres), to marine structures is debatable as they are generally concerned with the making of low-cost housing.

The performance of natural fibre-reinforced concrete varies enormously depending on the material used. El-Nadoury (2020) tested the performance of concrete reinforced with banana, palm trunk and sugarcane fibres and found positive improvement compared to non-reinforced concrete. Awwad et al., (2012) compared the performance of hemp fibres as concrete reinforcement with steel and polypropylene fibres, as well as control samples without fibres. Although the compressive strength was partially reduced, the presence of hemp fibres allowed ductile flexural performance, instead of the brittle failure found in plain concrete. The hemp fibre mixes show similar performance with respect to polypropylene mixes. Zhou et al., (2017) looked at how the properties of hemp-reinforced concrete can be enhanced for use in low-cost housing construction. The use of hemp in the construction industry, including for bricks, is also reviewed by Nováková (2018).

In a paper regarding the use of natural fibres for use in artificial reefs, Carral et al. (2020) stated that the performance of natural fibre reinforced concretes is variable and often lower than synthetic or metal fibres. Environmental analysis was undertaken in this study using a combination of mussel shells and eucalyptus fibres in different combinations and rates of substitution for cement, sand, gravel, and steel frames. The study concluded that the use of natural fibres did result in increased environmental outcomes in terms of energy and materials used in production, and the use of discarded mussel shell waste. The "Green Artificial Reefs" were deemed to be suitable for the region which has an abundance of mussel shell waste and eucalyptus trees.

Dennis et al., (2018) carried out a pilot study to trial alternative cast-able Reefcrete™ concrete mixes, with reduced environmental footprints, for use in the marine environment. They used partial replacement of Portland cement with recycled ground granulated blast-furnace slag (GGBS), and partial replacement of coarse aggregate with hemp fibres and recycled shell material. The estimated carbon footprint of each concrete blend deployed in replicate tiles in the intertidal environment for 12 months. The hemp and shell concrete blends had reduced carbon footprints compared to both ordinary Portland cement-based concrete and the GGBS based control concrete. At the end of the experiment, the hemp and shell blends supported significantly more live cover than the standard GGBS control blend.

Vivier et al., (2021) concluded from their extensive review that: "*the development of biogenic materials such as ECOncrete® , with addition of marine products including oyster shells to replace part of the sand, represent a sustainable solution which strengthen the coherence of AR projects by limiting the environmental footprint (Lima et al., 2019a; Perkol-Finkel et al., 2018; Walles et al., 2016)*."

Kalam et al., (2018) reported on the use of ceramics as an effective and environmentally preferable alternative to other materials for artificial reefs. The properties of the reefs (chemical constituents, surface texture, water absorbability, mechanical strength, erosion rate, and sustainability) were examined. The ceramic reefs were shown to be nontoxic, pH-neutral, mechanically strong, and sustainable in a hostile shallow sea environment.

In response to the concerns about placing plastics into the environment, some manufacturers have responded by producing plastic-free concrete for use in the marine environment, including for use as artificial reefs. The British company ARC Marine, for example, produces Reef Cubes® which they state are the "only carbon-neutral, plastic-free solution for marine habitat restoration in the world"[2].

[2] https://www.arcmarine.co.uk/homepage/technology/#reefcubes

7. Subject-matter interviews

Interviews were conducted with academic subject-matter experts, relevant government agency representatives, and a manufacturer of concrete reef modules, to supplement the literature review on the scientific and practical application of plastic reinforced concrete in artificial reefs. The list of interviewees can be found in Appendix 1. The list of guiding questions used for the interviews can be found in Appendix 2, noting that the discussions were semi-structured and focused on each person's area of expertise or experience.

There was agreement amongst the subject-matter experts on the lack of data and research into this specific area (plastic used in concrete for artificial reefs) and that existing knowledge falls into two major topics: 1) reinforced concrete/marine concrete research and 2) marine plastic/plastic toxicity research. None of the interviewees were able to recommend a subject-matter expert that bridges the gap between these areas and at least one recommendation was made to promote research on this topic in Australia. There was confirmation from the experts that some relevant data may be held by private companies.

There was agreement amongst the subject matter experts on the uncertainty of the release of plastic reinforcement material from concrete. Although there was no consensus on whether the release of plastic into the environment from artificial reefs was likely to be ecologically significant, the precautionary principle would suggest it should be avoided. Predicting the stability and corrosion of marine infrastructure and resulting release rate of contaminants was described as "a very uncertain exercise." While the research of additives and chemicals from plastics into marine environments is developing, there is no research on the leaching of additives from plastic inside concrete. In terms of plastic volume – while one expert was aware of up to 40% being tested in lab environment, generally the volume of fibre reinforcement is less than 2% of concrete volumes. One expert emphasised the importance of leaching tests in laboratory conditions (e.g., Leaching Environmental Assessment Framework (LEAF)) methods for concrete products, but particularly those containing novel materials.

The main conclusions from interviews with subject matter experts are as follows:

- Predicting the stability and corrosion of any marine infrastructure, and resulting release rate of any contaminants, is a very uncertain exercise.
- There is a common understating of the durability of concrete (and reinforced concrete) in the marine environment, and in fact a key factor for durability is the quality of concrete and its manufacture process.
- Depending on the structural stability of the concrete, over long time-frames (likely longer than 30-50 years) there will be a release of contained plastics into the environment. The sediment is the most likely receptor for the plastics unless they are positively buoyant.
- All plastics will contain plastic additives. These will likely leach when exposed to seawater. However, the consequence or impact of this leaching will depend on the amount of plastic in the concrete, the release rate of plastics from concrete, and the effects of dispersion and dilution in the seawater or sediment. Leaching

testing (e.g., LEAF) was identified as important prior to the use of concretes containing novel materials or additives.

- Evidence for plastic additive leaching in concrete is scarce as few studies have addressed this question.
- The lack of laboratory-based studies, or long-term monitoring, does not definitively rule out potential harmful impacts such as leaching of additives or release of plastic fibres into the marine environment.

8. Summary of key findings

In our literature review and discussions with experts we have reached the following general conclusions that may be relevant to the questions raised about the environmental significance of using PRC in artificial reefs.

1. Most studies relating to the environmental impact of reinforced concrete are concerned with the ecological footprint of the manufacturing process (e.g., material and energy consumption) rather than post-manufacture operations (e.g., Merli et al., 2020; Akbar and Liew, 2021 Tahir et al., 2022;). Plastic-reinforced concrete has significant environmental benefits over steel-mesh reinforced reefs in terms of production such as the consumption of material inputs and energy (e.g., Dong et al., 2021). The use of recycled plastic waste in concrete has greater environmental benefits compared to both steel-mesh and virgin polymers and diverts material from the waste stream (e.g., Yin et al., 2016).

2. Most studies of the environmental impact of artificial reefs have involved the actual effect of the reef itself on the composition and abundance of marine organisms (e.g., Baine 2001; Lima et al., 2019) and increasingly on social and economic factors (e.g., Lee et al., 2018).

3. No long-term in situ studies concerning the fate of plastics in reinforced marine concrete could be found. In a few cases where the effect of artificial reefs in the accumulation and concentration of plastic fibres has been studied, the results are an effect of the reef acting as a trap for plastic waste material (e.g., from fishing operations) that would otherwise disperse more evenly in the environment (e.g., Zhang et al 2020).

4. All plastics and their associated additives are potential pollutants. However, whether the toxicity or concentrations of plastics in the environment has significant ecological impacts, and under what circumstances, is still under investigation (e.g., Hahladakis et al., 2018).

5. Accumulation and a possible remobilisation of Ultraviolet (UV) stabilisers in the marine environment may pose risks to wildlife, especially to benthic and sediment-dwelling organisms (e.g., Prak et al., 2022) and may further accumulate in the food chain (e.g., Peng et al., 2017). However, it is not clear whether UV stabilisers are commonly used (or even necessary) in artificial reefs designed to exist in relatively deep water with low light levels.

6. Over time, concrete in the marine environment will undergo chemical, physical and biological degradation (e.g., Georges et al., 2021). However, the biocolonisation of concrete in the marine environment may also improve the durability of artificial concrete reefs by protecting them from damage (e.g., Djelal et al., 2019).

7. The limited evidence available would suggest that natural fibres are much less effective as a concrete reinforcement material than plastic polymers or steel and are primarily designed to be used in low-cost housing in developing countries.

8. Under particular circumstances, the use of natural fibres such as cellulose, shell and hemp as a reinforcing additive may improve the environmental sustainability of concrete reefs (e.g., Dennis et al., 2018; Carral et al., 2020).

9. Ceramics may be the most effective and environmentally sustainable material for artificial reefs relative to other materials in use (e.g., Kalam et al., 2018).

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Disclaimer

Appendix 1. Interviewee Details

The subject matter experts were chosen based on initial recommendations made by the UNSW SCaW team and referrals from the interviewees themselves.

Details of subject-matter experts interviewed:

Name	Title/Position	Organisation	Date
Dr Darren Koppel	Research Scientist	AIMS – Environmental Risk Assessment	29.08.2022
Prof. Robert Melchers	Professor, School of Engineering	University of Newcastle	01.09.2022
Dr Xihong Zhang	Senior Research Fellow	Curtin University, Faculty of Science and Engineering	05.09.2022
Ass. Prof. Wahidul Biswas	Associate Professor	Curtin University, Sustainable Engineering Group	09.09.2022

In addition:

- Dr Neill Mattocks (GBRMPA) was contacted but stated his work was not of relevance to the issue of concrete artificial reefs.
- Mr Benjamin Doolan and Mr Chris Weire (NSW Department of Primary Industries) were interviewed about the management and monitoring of artificial reefs.
- Mr Max Morgan Kay / Mr Steve Wright ARC Marine (UK) were interviewed about their plastic free concrete reef modules.

Appendix 2. Interview Guiding Questions

National Environmental Science Program (NESP) - Sustainable Communities and Waste (SCaW) Hub "IP2.02.03: Plastic-reinforced artificial reef structures; improving understanding"

The problem: plastic as concrete reinforcement in artificial reefs

Many artificial reefs have been deployed in Australian waters, often for fisheries enhancement or for tourism enhancement.

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) has issued a draft interim policy on the use of plastics in Artificial Reefs. The policy is under the *Environment Protection (Sea Dumping) Act 1981* which regulates the placement and construction of artificial reefs.

Reason for this interview

Several issues were highlighted as warranting further investigation through a literature review before the policy and procedures can be finalised. Under the NESP SCaW hub, TierraMar is conducting a literature review and interviews with subject matter experts to inform the finalisation of the policy and guidelines.

Artificial Reef Research Questions

Topic 1: Impact of plastic fibres as reinforcement for concrete to inform the permit application process for purpose-built artificial reef structures – Information is needed concerning best-case scenarios at the end of the permit period (30-50 years) on leaving these modules in place versus removal.

a.	Is there any evidence to suggest that after 30-50 years the reefs would degrade and leak plastic into the environment? How much do we know?

(Additional question: what about polymer made from glass filaments coated in epoxy and sprinkled with river sand?)

Topic 2: Chemicals in plastics – Information is needed to guide the inclusion of plastic with additives such as ultraviolet (UV) stabilisers, which may leach into the environment via microplastics when they are bound in concrete over time.

b.	Is there any evidence regarding leaching of plastic additives from concrete reinforced with plastic?

Topic 3: Environmental impacts of the breakdown of concrete modules containing plastics – Investigation is required into the life-cycle of artificial reef modules containing plastics exposed over 30-50 years to oceanic conditions. In addition, information is needed to understand the effect of reef colonisation on module stability and the potential release of plastic microfibers.

c.	Has there been any life-cycle analysis of concrete containing plastics?

d.	Is there any research on the effect of reef colonisation on module stability and the potential release of plastic microfibers

Topic 4: Natural alternatives to concrete reinforcement – Guidance on possible alternatives to plastics in artificial reef structures, such as hemp and other products/technologies.

e.	Is there any research on natural materials in concrete reinforcement?

Other Questions

f.	Are there any issues that have not been considered?

g.	Is there anyone you would recommend to us for interview?