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Ecological Contribution to the Replacement of Artificial Coral Reef Settlements Using Concrete Structures made with Hybrid Cements

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ABSTRACT

Studies indicate that artificial reefs for coral reef restoration are often based on concrete structures, and the insertion of these structures is lately produced with hybrid cements that add common Portland cement and other new slag-based cements, as complementary elements in the set of essential raw materials for the study, production and installation of artificial marine reefs, contributing in a stable way to the development of its fauna and flora in a safe and sustainable way, given the use of in situ monitoring processes that combine the obtaining of results from the experiments, regarding their physical and mechanical characteristics in situ.

The application of concrete in reef restoration has several benefits, among which are durability, stability, safety, availability and flexibility of the shape and its chemical composition like the reef substrate.

Constant global variations in coral protection have led to a call for global climate action, for better management of critical places such as overfishing and pollution, as well as an increase in efforts aimed at recovery. The reconstruction of coral reefs has been carried out on smaller scales and experimental actions, leaving ample field for new options.

The underwater environment of coral islands contains concrete structures of different designs and geographical origins, characterized by an open pattern, deposited as cages on mats based on the seabed, creating a zone of biological equilibrium.

The use of these large rigid structures allows the marine environment to be protected from illegal trawling movements, contributing to the recovery of biological diversity in areas of compatible depths, without the force of extreme currents as well as the absence of extreme climatic conditions, to ensure the durability of the structures.

In a different way, in coral maintenance is applied, where corals are first grown in nurseries and then planted on recovered or artificial reefs, given that artificial reefs have different shapes and materials, emphasizing concrete as more specified and applied.

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Introduction

Recent advancements in material science have further refined the use of concrete in artificial reef construction. Researchers are exploring innovative compositions that integrate eco-friendly additives, enhancing the compatibility of the structures with marine ecosystems. These developments aim to accelerate coral growth and promote a self-sustaining cycle of biodiversity, while mitigating environmental impacts. As artificial reefs evolve, attention is increasingly being directed towards optimizing their designs to mimic the complexity and texture of natural reefs, influencing both their ecological functions and appeal to marine organisms.

Models and Purposes of Artificial Reefs

Studies carried out on submerged materials in marine environments, on a continuous basis, address a set of new fields with high potential for attraction and instant settlement of marine organisms, by Knoester et al. [1]. Following the multiplication of organic molecules that dissolved in the water form a coating on its initial covering, ensuring first attractions of bacteria and then of heterotopous protists, by Silva A et al. [2].

With this evolution, the first settlements with larvae of sessile invertebrates appeared, usually polychaetae's, barnacles and mollusks, as verified in classical studies on the subject in temperate regions, by Scheer et al., as well as in subtropical regions, by Silva A et al. [2,3]. From the actions of this pioneer community, the most important producers in these systems were also verified, at times when a new habitat was located in areas of good quality, that is, in more superficial layers of an aquatic ecosystem with sufficient sunlight to carry out photosynthesis, given that the intensity of solar radiation decreases exponentially with the increase in the depth of the water column, by Silva A et al. [2].

Despite the development of this encrusting biofilm, other small species of cryptic fish and schools in small volumes of water are also quickly attracted to these new habitats as protection against predatory elements, by Jardeweski et al. [4]. Taking into account the principles of biological colonization as well as the sustainable application of its various resources, the term "Artificial Reef" is commonly accepted by the scientific community, according to the following added value:

- A group of structures fixed to the seabed creating a basis for biological colonization that, when subjected to natural physical, chemical, and biological currents, gradually develop into an ecosystem like those of the adjacent natural habitats from which their organisms originated. These implantations remodel the scenarios of the seabed with large rigid elements with various origins such as rock blocks, industrial as well as civil construction waste and specially elaborated structures, according to Duclerc J. et al. [5].
- Structures deliberately submerged on the seabed to simulate some features of a natural reef, according to Earrn W [6].
- Objects of natural or human origin purposely settled on the seabed with the aim of influencing physical, biological and socio-economic processes related to marine living resources by Seaman et al. [7].
- Structures oriented with the primary objective of creating, protecting and/or restoring a rich and/or diverse ecosystem, as a set of elements that can induce responses of attraction, concentration and protection to animals, as well as, in some cases, the increase in the biomass of certain species by Ifremer et al., [8].
- Any structure built or installed on the seabed, either in the water column or floating on the surface of the sea, for the purpose of creating new attractions for divers, and or to concentrate or attract plants and animals for fishing activity, according to Great Park [9].

Artificial Reef Settlement Methodology and its Objectives

The historical past on the inhabitation of artificial reefs indicates a set of standards, shapes and materials used in projects focused on durability, excluding toxic elements or those likely to cause damage to the environment, with records of artisanal settlements in the USA, in the decades of 1835, in the bays of South Carolina. Waste wood logs from the construction of huts was installed there, by McGurrin et al. [10]. Further large-scale settlements began in 1935, following the sinking of four vessels off the coast of New Jersey, according to McGurrin et al. [10].

A set of materials such as industrial remains, scrap metal, pyrex and civil construction remains, train cars and subways, buses and planes also including war tanks, by Seaman W et al. [11]. This practice of waste submersion began in Florida in 1966, through a combined program between local associations, the New University, as well as the Municipality of Porte Envergardes. However, the uses of these materials were later regulated with the emergence of new material manuals, unit forms, as well as more appropriate arrangement groups accepted by the regulatory bodies of the settlements on the American coast, by Seaman et al. [12]. Subsequently, North American projects aimed mainly at water tourism as well as sport fishing, in which concrete structures are the most common on a local scale, being practiced by fishing associations and municipalities, and can be adjusted according to the requested complexity, thus also moving to an industrial scale, according to Rinkevich B [13]. The construction of artificial reefs using concrete, among other applications, is worth mentioning in the example of the contract in the municipalities of Oura, Anca, as well as Tavira in the Algarve region, all in Portugal, by Mota-Engil [14]. These three ambitious systems were composed of a total of 10190 open concrete block structures, as well as 126 modules installed in a mesh, in a predefined way to attract and increase the variety of marine fauna as well as balance the ecosystem of the region, as shown in Figures 1, 2 and 3. Having been composed in a contract, prefabricated in a shipyard and installed, off the ocean at bathymetry levels between (-15) and (-30) meters, by Mota-Engil [14].

Figure 1: Reef Transport to the Installation Zone, by Mota-Engil 2025

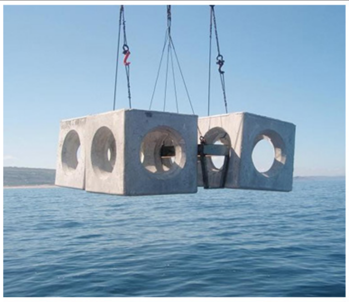

Figure 2: Reef Facility and **Figure 3:** In-situ behavioral monitoring, by Mota-Engil 2025

Although the oceans occupy about 70% of the globe, the truly productive areas represent a tiny part of this immense area. Deep areas, far from continents and islands, are essentially biological deserts. There is significant productivity only in places where the euphotic zone is at the same time rich in nutrients that can establish plant-herbivore-carnivore food chains, by Ross DA. et al. [15].

Thus, about half of commercial fisheries are carried out in coastal regions and upwelling zones (rising currents that bring nutrient-rich deep waters to the surface and occur between coasts and major ocean currents), which represent only a small fraction (about 0.1%) of the total ocean area, according to Michael et al. [16].

Marine animal populations are subject to high pressure from season to season and from year to year. The predators are many:

Other animals, man and more recently pollution and climate change, by Cushing et al. [17]. It is in this context that artificial reef technology has a great future and can contribute decisively to a turnaround in the current state of fisheries, as well as to the presser- vation of resources and their exploitation in a profitable and sustained way with time-bound rehabilitee-rations, by Clark S. et al. [18]. Artificial reefs can be built from purpose-built modules, usually geometric figures of concrete, steel, wood or combinations of these materials. However, opportunity materials are also used, such as obsolete ship hulls, construction waste materials, old tires and various types of rocks, according to MacGurrin et al. [10]. The objectives of artificial reefs are, above all, the protection of fishery resources, creating reserve space and serving as a fisheries management tool, increasing fishing income and tourism (sport fishing and recreational diving). Illegal trawling, altering the characteristics of the substrate and suspending sediments, has the consequence of over-exploitation of resources and a decrease in water quality, which has proven to be a serious problem in certain more sensitive habitats, by Moreno et al. [19]. Artificial reefs have been increasingly used as another way to solve this problem, by Moreno et al. [19]. The general objectives of these structures are fundamentally twofold:

- Promote the aggregation of specimens and pelagic aquatic animals by facilitating their capture and reducing fishing effort, and:
- To increase the area of hard substrate available for colonization by sessile and Gemi-sessile organisms, to serve as a breeding ground, feeding ground and shelter for juveniles (nursery). To these two main objectives, they are currently added that of constituting an environmental man- agement instrument. Their presence is a discouraging measure for the use of bottom trawling, and other heavy and destructive fishing techniques, in certain areas, according to Bell M. et al. [20]. Artificial reefs can also be used as biofiltering structures, especially when associated with the production of bivalves. The purification effect of coastal waters achieved through the installation of artificial reefs colonized by filter bivalves, can be important as long as the biomass is removed from the system periodically. Finland, Sweden and Poland are at the forefront of the use of artificial reefs for this biomass purpose, by Antsulevich AE et al. [21].

In the West, more solid structures were used from the beginning, namely old tires with various structural arrangements, and other materials of opportunity (oil rigs, ship hulls, construction waste materials, car carcasses, etc.). These materials obtained at low cost and placed without major mod- ifications other than the removal of potentially harmful substances to the environment, by Woodhead et al., today constitute 80% of the artificial reef structures in the United States, by MacGurrin [10,22].

Until the 1980s in the United States, most artificial reefs had been made of metal or fiberglass, and in more recent years, of concrete and plastic, by Shieh CS et al. [23]. They developed comparative studies between artificial reefs made with tires and artificial reefs built in concrete and concluded that concrete modules were more efficient than tires in terms of fish abundance by volume and that such structures could increase biological resources in relatively unproductive areas, according to Chojnacki JC et al., experimentally, in work carried out in the southern Baltic, demonstrated that the rough surface of concrete constructions presented a better hard substrate that was used, offering results for the fixation of sessile organisms that corresponded to those obtainedby other researchers, specifically, Fitzhardinge RC et al., Relini G. et al., as well as Collins KJ et al. [24-27].

Influential Materials Used in Reef Establishment Artificial

Comparative studies between artificial reefs and natural reefs, prepared by Brock RE.et al. showed that fish densities and total biomass were higher in artificial reefs, which is justified by the higher structural complexity projected for this purpose, by Ogawa Y, et al. [28,29]. Also authors such as Chang KH et al. They said that the greater the degree of complexity, the greater the effectiveness of the reefs [30]. There is a huge amount and diversity of materials susceptible to be used in the construction of artificial reefs, namely simple concrete, iron, steel, reinforced concrete, plastic, plasticized concrete, ceramic materials and others that have the same physical characteristics, mechanics and durability, by Buckley RM et al. [31]. Also, Helen Pickering et al. [32]. He considered that currently the most used material for the assembly of artificial reefs is concrete, because in addition to its durability and resistance to seawater, it allows it to be molded into the desired shape and has led to good results, regarding its colonization by marine organisms. On the other hand, materials such as fiberglass, polyvinyl chloride (PVC) and plastic have shown some flaws in terms of stability, according to Bombace G. et al. [33]. Studies carried out in Italy on artificial concrete reefs have shown that, in this real case of concrete as an applied material, the concentration of fish and mussels "Mytilus sp" has increased substantially, by Bohnsack JA et al. [34]. Also, other comparative studies between artificial reefs and natural reefs, developed by Bohnsack JA et al. showed that the densities of fish and biomass in total were higher in artificial reefs, a fact justify- cable by the greater structural complexity performed there, by Ogawa Y et al. [29,35].

Eggleston et al., found that when the height of the lobsters "Palinurus argus" was reduced from 6.0 to 3.8 and/or 1.9 cm, there was a lower mortality of small and medium-sized individuals [36]. For M.C. Manuel C. Molles et al. The variation in the size of the opening of the structures did not correlate with species richness or with the composition of the group of species that inhabit the reef [37]. Also, William W. et al. stated that the configuration of the openings seems to have no effect on the composition of the species that seek a certain reef during the time, although it is more important during the night [38].

In 1990, the Food and Agriculture Organization (FAO.org) recommended a preferential prin- ciple for the use of artificial reefs in coastal countries, which may be interested in the Eco-Systemic application of their marine resources, recommendations on the need for fisheries cooperation, with the objective of avoiding the destruction of coral reefs in various places, having unanimously recognized the high value of coral reefs by the tourist industry in the Island States, [39]. The management of artificial reef settlements has been the determinant of their potential for socio-economic development in coastal areas, including artisanal subsistence fisheries, small-scale commercial fisheries, as well as recreational fisheries and underwater tourism, by Arena Rt. [40]. In recent decades there has been a consensus on the biodiversity and biomass of exemplary fish species as being higher in artificial reefs, compared to those existing in natural habitats, given the optimization of ecological processes combined with the factors of control and development of natural ecosystems, by Arena Rt. [40]. Due to the greater structural complexity obtained in the construction of concrete modules, marine biodiversity can be even greater in artificial habitats, compared to adjacent natural habitats, due to the optimization of ecological processes, by Spieler RE [41].

Depending on the place and season, the sinking of ships at the end of their useful life has a large volume and biomass of reef animals, relatively in adjacent natural habitats, namely species of great tourist and/or recreational interest, by Arena Rt [40].

In recent decades, different programs have been developed in 19 countries, with different applications but all focused on increasing fish stocks on the Atlantic coast of the Iberian Peninsula, as well as on the environmental preservation associated with underwater tourism on the Mediterranean shores, by Charbonnel E [42]. The Reef Company, Smart Reef solution 2025, by Reef Company presented a new project on artificial reefs at the World Ocean Summit & Expo 2024 by in a session attended by its founders [43,44].

The start-up The Reef Company is initially evolving in the Portuguese maritime area with the eco-reef project, called Basic Wave. The aim of the project is to regenerate marine ecosystems, collect data and absorb carbon. Martim Clara, co-founder of The Reef Company, said that the company's mission is to "fight climate change". The reefs designed in this new generation, called Basic Wave Reef Structure, as shown in Figure 4, developed in ReeF Company, by Jeroen et Martin, will have a data collection system by new technology equipment with the ability to record and transmit data "BluBoxx™" for a variety of applications, serving entities in the fields of coastal defense, tourism, biotechnology and academic scientific research, by Jeroen et Martin [43].Through 4K sensors and cameras, it is estimated that it is possible to measure salinity, temperature, pH, dissolved oxygen, pressure, carbon dioxide, as well as other options, by Jeroen et Martin [43]. Its public presentation was held during the International Coral Reef Initiative-ICRI. World Ocean Summit & Expo, agreed (ICRI, 2024), and in it the model with a design was released "Basic Wave™" [44].

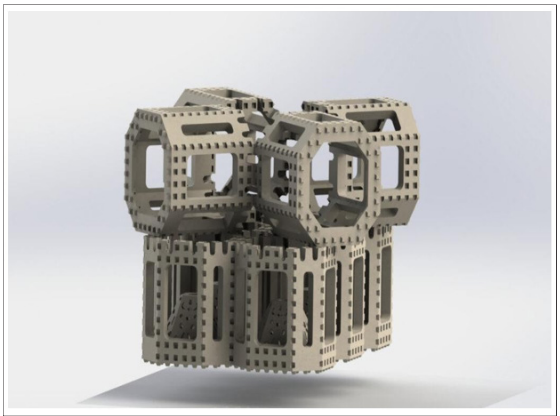

Figure 4: Basic Wave Reef Structure, by Reef Company 2004

At the 2024 United Nations summit, greater emphasis was placed on actions with a series of "How To" workshops that presented a set of practical and conclusive solutions for individuals and organizations committed to restoring ocean health, agreed [44].

Still on the 2024 agenda, the health of the oceans was addressed, in terms of industry strategies for a sustainable ocean economy and its ocean-climate solutions, by more than 180 specialized speakers, in various cross-sections of the ocean community, including companies, governments, national and international policy makers, as well as civil society and academia, agreed ICRI [44]. The 2024 event on sustainable development established a perfect platform for inspiring new partnerships, solutions and objective strategies to meet the 2030 targets, with evidence in the United Nations Sustainable Development Goals No. 14 which addressed the changes in the way ocean management and business have been carried out, agreed ICRI [44]. As a new and future artificial reef, the SS United will be sunk and installed in Okaloosa County on Florida's Gulf Coast, joining the other 500 302-meter-long tourist diving attraction reefs. It can be remembered that in Europe there is the Ocean Revival, as the largest artificial reef, consisting of four sunken warships and located in Portimão, Algarve, by Euronew [45].

Conclusions

Although this variation of new materials and technologies can apparently be seen in the establishment of new artificial reefs, they present identical results to those of the past, both in the physical and mechanical characteristics of the materials, as well as in the behavior of the animal species.

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