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The Design, Production and Validation of the Biological and Structural Performance of an Ecologically Engineered Concrete Block Mattress – A Nature Inclusive Design for Shoreline and Offshore construction

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Editor's Note

This article is part of the special series "Incorporating Nature-based Solutions to the Built Environment." The series documents the way in which the United Nations Sustainable Development Goal (SDG) targets can be addressed when nature-based solutions (NBS) are incorporated into the built environment. This series presents cutting-edge environmental research and policy solutions that promote sustainability from the perspective of how the science community contributes to SDG implementation through new technologies, assessment and monitoring methods, management best practices, and scientific research.

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Data Availability Statement

Data, associated metadata, and calculation tools are available from corresponding author Ido Sella (ido@econcretetech.com)

Conflict of Interest

S. Perkol-Finkel and I. Sella are co-founders of ECOncrete Tech ltd., A. Rella is the company's Global Director of Engineering. ECOncrete Tech ltd. is a private company dealing with reducing the ecological footprint of concrete costal and marine structures. This project was performed as a part of the company's research and development, based on previous published work by the authors; and was supported by The Israel-United States Binational Industrial Research and Development Foundation (BIRD). The study site is marked and open to other entities for review.

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In Memoriam

This paper is dedicated in loving memory to Dr. Shimrit Perkol-Finkel, who worked on it for a long time and did not live to see it completed. She was a friend and mentor to us all and will forever be in our hearts. We continue on with her mission to advance science

towards a better world for coming generations, or as she used to call it “bluing the gray”. May she rest in peace.

Key Words

Ecological Engineering, Carbon Sink, Shoreline Erosion, Bio-enhancing Concrete, Articulated Concrete Block Mattress

Abstract

Over the past decade, the scientific community has studied, experimented, and published a notable body of literature on ecological enhancement of coastal and marine infrastructure (CMI). The Nature-Inclusive Design (NID) approach refers to methods and technologies that can be integrated into the design and construction of CMI to create suitable habitat for native species (or communities) whose natural habitat has been degraded or reduced. To examine the compliance of new environmentally sensitive technologies with structural requirements and fiscal restraints, while providing ecosystem and habitat value, this paper presents the findings of a structural-economical-biological analysis of ecologically engineered Articulated Concrete Block Mattresses (ACBM). To evaluate the structural and biological performance of the ECO ACBM's, a pilot project was deployed in April 2017 at Port Everglades, FL, USA and evaluated against controls of adjacent artificial structures and smooth-surface concrete blocks and monitored over a period of 2 years. The elements of ecological enhancement implemented in the fabrication and design of the ecologically enhanced ACBM’s were comprised of bio-enhancing concrete additives and science-based designs. Based on the results of this study, these design alterations have increased the richness and diversity of sessile

assemblages compared to control blocks and adjacent artificial structures, and supported a higher abundance of mobile species. This ecological improvement was achieved within the operational limitations of conventional manufacturing and installation technologies, while complying with strict structural requirements for standard concrete marine construction. The results supported the working hypothesis, and demonstrated that modifications of concrete composition, surface texture, and macro-design, have the potential to elevate the ecological value of concrete-based CMI and promote a more sustainable and adaptive approach to coastal and marine development in an era of climate resilience building.

Introduction

Ecological engineering is a relatively new and evolving discipline (Mitsch 2012) aimed at the integration of ecological principles in planning, design and construction of both land-based and aquatic infrastructure. Rather than mitigation of, or compensation for, ecologically adverse impacts (Korbee et al. 2014), ecological engineering has opened the doors for applied biomimetic technologies, designed to mimic nature's forms and functions to improve structural and ecological performance. When referring to coastal and marine infrastructure (CMI), the harsh environmental conditions dictate compliance with strict building codes and standards. This applies to all levels of construction, from the materials in use (e.g., steel type, concrete mix), to the construction methods and sequencing. Thus, any desired ecological principle or product must fully comply with the industry standards in order to be considered for both coastal and offshore applications. The Nature-Inclusive Design (NID) approach refers to methods and technologies that can be integrated into the design and construction of CMI to create suitable habitat for native species (or communities) whose natural habitat has been degraded or reduced (Hermans et al. 2020).

When examining construction in coastal environments, ecological engineering and NID are mainly conceived as a “soft” approach, used for living shorelines or restoration of tidal wetlands and salt marshes (Currin et al. 2010; Gittman et al. 2014; Popkin 2015). In recent years however, these principles have started to also address “hard” urban / industrial waterfronts and offshore infrastructure, and the scientific community has studied, experimented, and published a notable body of literature on ecological enhancement of CMI and how to increase the habitat suitability of the structure for native species (Coombes 2011; Evans et al. 2016; McManus et al. 2017; Naylor et al. 2011; Naylor et al. 2012; Perkol-Finkel and Sella 2015).

Hard waterfront infrastructure is constructed under strict building codes and standards, and built for intensive use in a prolonged design life. Examples include ports, marinas, breakwaters, oil and gas platforms, wind turbines and alike (Coombes et al. 2015; Davis et al. 2017; Lacroix and Pioch 2011). Any application of ecological enhancements to these facilities is required to comply with (1) local and international construction standards – ASTM international, European Standards (EN), The American Association of State Highway and Transportation Officials (AASHTO), etc.; (2) local construction methods and labor codes; (3) structure design life; and (4) economic justification. These rigorous restrictions often result in a traditional design and construction process, excluding the principles of NID that could result in the infrastructure having limited ability to support marine flora and fauna native to the local ecosystems (Airoldi et al. 2021; Firth et al. 2016).

Although the importance of local biological resources and the ecological footprint of CMI are more widely considered in the project decision-making process today (Dafforn et al. 2015; Evans et al. 2019; Strain et al. 2018), willingness to pay an ecological premium is rare in the cost-driven concrete marketplace. Ecological features are currently perceived by certain industry players as cumbersome, requiring specialist knowledge, or as more expensive than conventional counterparts, and this perception is a barrier to their widespread use (Kleijn et al. 2019). However, when environmental regulations are taken into account, ecological CMI becomes cost competitive (Naumann 2011). CMI are commonly subject to high environmental review penalties, rigorous mitigation requirements, and a prolonged permitting process. Concurrently, many countries have adopted sustainable blue growth strategies (Eikeset et al. 2018), including the integration of NID, which can be an effective tool to not only maintain sustained coastal growth, but also reduce penalties by conserving biological resources and their associated ecosystem values on-site (Lillebø et al. 2017). Integrating NID can create suitable conditions for local marine species, and if well scaled, may be considered by permitting agencies as habitat creation, instead of destruction or displacement that necessitates mitigation (Geist and Hawkins 2016; Hawkins et al. 2010).

Costs associated with the project's operational lifespan and maintenance can also be reduced by eco-sensitive CMI (Borsje et al. 2011). Ecological enhancement, in practice, means facilitated growth of biota on the CMI surface. The biogenic, often calcitic crust, that develops on ecologically enhanced structures, can serve to protect the structure and reinforce it (Coombes et al. 2013a). Risinger (2012) has demonstrated that oyster growth on concrete significantly increased flexural strength compared to bare concrete. Similar results have been found by the authors (Perkol-Finkel et al. 2017; Perkol-Finkel and Sella 2014a; 2015; Sella and Perkol-Finkel 2015) when exploring the bioprotection capacity of structures whose encrusting layer of marine growth buffers hydrodynamic forces, reduces chloride penetration, and adds mass, therefore increasing stability. Ecologically enhanced CMI bioprotection can promote cost-saving due to increased operational lifespan and reduced maintenance (Borsje et al. 2011).

Where carbon reduction goals and legislation exist, promoting biological activity on CMI can take advantage of potential cost savings in the form of incentives or grants. Apart from adding a strengthening calcitic layer, this "biological crust" of species like oysters, tube worms and corals, provide an active carbon sink. As the calcium carbonate-shelled organisms build structurally complex and heterogenous communities (critical for high-functioning coastal ecosystems), carbon is assimilated into their skeletons in a process called biocalcification (Hily et al. 2013). The potential carbon storage in calcitic skeletons of marine organisms is vast. Every 1000 g of $CaCO_3$ stores ~120 g of carbon. When applied at large-scales, like in port infrastructure or coastal defense schemes, this can serve as a mitigation tool and cost relief when appropriate carbon offset programs are in place.

To assess the compliance of innovative environmentally-sensitive technologies with structural and fiscal requirements, while providing ecosystem and habitat value, we examined a generic concrete product that is widely used in both coastal and marine construction, as well as offshore applications – the Articulated Concrete Block Mattress (ACBM). ACBMs are rectangular matrices made of concrete blocks that are joined together by ropes or cables into a unit with two-dimensional flexibility and a range of thicknesses to suit the required site conditions. They are used for the anchorage and protection of underwater pipelines and cables (Gaeta et al. 2013), and for scour protection of shorelines (Gaeta et al. 2013; Way et al. 1992). With a designated design life of 30-60 years (to match the infrastructure), and a relatively simple installation method (compared to other applications), ACBMs are applied to large scale projects across the globe both in riverine, intertidal and subtidal areas in various climates (Gaeta et al. 2013; Godbold et al. 2014; Gong et al. 2009) and are designed to withstand the intense hydrodynamic forces exerted upon coastal or offshore infrastructure. The individual blocks and full ACBM matrix are both required to endure the forces applied by operational activities, ranging from stockpiling to marine and terrestrial vessel movement (e.g., a beached vessel, a truck loading/offloading a boat). In addition, the weight of a single block and their interlocking capacity play a crucial role in their structural integrity and functionality. As ACBMs are applied in the extreme intertidal conditions (changing salinity and temperature, dry-wet cycles, hydrodynamic forces and freeze-thaw cycles), any addition of ecologically-relevant features should go through extensive structural testing from the level of the sub-unit to the performance of the completely fabricated ACBM. In addition to verifying the design life, no compromise should be made in achieving performance results that meet or exceed that of the standard ACBM. The manufacturing and installation methods of ACBMs are entrenched in the marine construction industry (Scholl et al. 2010; Stovall and Priest 2019), with material and installation costs ranging between $10 to $18 per square foot depending on project specific conditions (mattress thickness, required installation procedures, region, etc.) (Iqbal 2018).

The elements of ecological enhancement being implemented in the fabrication and design of the ecologically enhanced ACBMs in this undertaking included the environmentally sensitive concrete solutions previously developed and validated by ECOncrete® Tech Ltd; including bio-enhancing concrete additives and science-based designs scientifically tested to enhance the biological and ecological value of urban, coastal and marine infrastructure (Perkol-Finkel et al. 2017; Perkol-Finkel and Sella 2014a; Perkol-Finkel and Sella 2014b; Perkol-Finkel and Sella 2015; Sella and Perkol-Finkel 2015). Mitigation, maintenance, and carbon savings offer significant cost reductions throughout the design life of the structure, compared to traditional CMI (Hinkel et al. 2013; Naumann 2011). To examine these differences, this research assesses the practical considerations of minimizing cost differences between the ecologically enhanced units and standard infrastructure by focusing on dry-cast units. Dry-casting is a low-cost, widely used, mass production concrete casting technology, mostly associated with the manufacture of concrete blocks and pavers. To this end, a joint research and development process between two companies, ECOncrete Tech LTD (www.econcretetech.com) specializing in ecological uplift of concrete, and Besser Company (www.besser.com), a manufacturer of production systems and equipment for the concrete industry, was initiated.

In order to evaluate the structural and biological performance of the Ecological Articulated Concrete Block Mattresses (ECO ACBMs), a pilot project was deployed in April 2017 at Port Everglades, FL, USA on a degraded shoreline between the Port Navy station and NOVA university, Halmos College of Natural Sciences and Oceanography (Figure 1). Four 2.4x5.7m ACBMs (weighing ~4,000 Kg each) were deployed and evaluated against controls of adjacent artificial structures and smooth-surface concrete blocks.

This paper presents the findings of a structural-economical-biological analysis of the ECO ACBMs, monitored over a period of 2 years. The findings demonstrate that ECO ACBMs can be adopted for coastal and offshore construction within the operational limitations of conventional manufacturing and installation technologies, while complying with strict structural requirements for standard concrete marine construction.

Materials and Methods

Concrete Blocks Manufacturing and ACBM Preparation

ECO ACBMs (Figure 2) were cast using a marine construction grade concrete mix (specific details of which can be found in the supplemental data). The mix included an ecological admixture, that has shown high structural and biological recruitment capabilities with different concrete mixes, in both laboratory and field trials, in different marine environments around the world (Perkol-Finkel and Sella 2015; Sella and Perkol-Finkel 2015) where the impact of material composition versus rugosity on biological recruitment was also evaluated (Perkol-Finkel and Sella 2014a). Both the ecological and control units were developed in accordance with ASTM D6684, Standard Specification for Materials and Manufacture of Articulating Concrete Block (ACB) Revetment Systems. The ECO ACBMs are comprised of blocks manufactured in a dry-cast block machine. Each ECO ACBM consisted of 203 full block units (30x24x15 cm) and 26 half block units (15x24x15 cm) which were placed at the outer edges of the ECO ACBMs. The forms were designed with high surface complexity to create diverse biological niches, while complying with industry mass production casting rates of 2 units per 3-5 seconds. The aim was to incorporate NID principles into the block design by adding ample edges and creating water retaining features. These enhancements provide intertidal habitats, shelter and refuge for invertebrates and fish that are missing from generic CMI, while compiling with industry standards for structural performance. Mold manufacturing and product casting for the pilot project was conducted in Alpena MI, USA by Besser.

Experimental Array

The 864 blocks intended for the pilot project were manufactured at the World Center of Concrete Technology (Alpena, MI, USA) in a computer-controlled BESSER V3-12 concrete masonry production plant. Each ACBM was split in two; one half being comprised of textured Ecologically modified blocks, representing an ECO ACBM (treatment), and one half with featureless CEM-I based blocks, representing standard ACBM (control) (Figure 2A). These control blocks were manufactured using the same dry-cast technology, but without the addition of any ecological features and a standard CEM-I based concrete mix. The blocks, both control and ecological, were manufactured with two 1-inch diameter holes running through their width so that they could be laced together by polypropylene rope, with aluminum sleeves securing their placement. Installation was done by a crane (Figure 2B and Figure 2C) placing the ACBMs so that their top edges were level with the Mean Higher High Water (MHHW) line so that 20% of their surface was exposed to intertidal conditions (Figure 2D).

Ecological Monitoring

Community Development

Upon the completion of the deployment, a baseline survey of preexisting adjacent artificial infrastructure was conducted. Three locations, a vertical seawall, a concrete slab, and rip-rap rocks were sampled for intertidal and subtidal sessile communities (Figure 1). The survey was performed using a 30x30cm (~1ft^2) quadrat to mimic the surface area of one ECO block, according to the protocol described below, and photographed using an underwater camera equipped with a fisheye lens to assist in the identification process. The in-situ visual survey of the ACBMs was conducted on pre-selected blocks (both for ECO and control), which were monitored repeatedly at 3, 6, 9, 12 and 24-Months Post Deployment (MPD). In an effort to avoid bias, blocks were pre-selected according to the following criteria – four ECO intertidal, four ECO subtidal, four control intertidal, four control subtidal, no adjacent blocks, no blocks at the interface between the ECO and control, and no blocks at the edges of the ACBM.

Each survey began with a thorough visual inspection of the entire experimental array, noting mobile invertebrates appearing on and in the vicinity of the ACBMs. Such species were added to the overall species list, yet were not included in the statistical analysis. Once the broad visual survey was complete, divers conducted the detailed surveys of the pre-selected blocks. Monitoring protocol followed that described in Perkol-Finkel et al. (2008) and included: overall live cover [%]; cover of encrusting species (sponges, tunicates, bryozoans, etc.) [%]; number of solitary organisms (oysters, tunicates, Polychaete tube worms, etc.) [#]; Taxa that could not be counted as individuals (i.e., Serpullidae worms), or when their exact percentage cover could not be recorded (turf and coralline algae) due to variations in density, were each scored according to their appearance as follows: 0 – absent, 1 – sparsely scattered, 2 – densely scattered and 3 – densely uniform. Species were identified to the lowest possible taxonomic level in the field and samples were taken for laboratory identification when necessary. Each block was surveyed as one sampling unit, including the top and all sides.

Monitoring for fish was conducted 8 times between 3 and 6 MPD and included a visual survey using SCUBA. Two divers inspected each ACBM for 10 minutes, noting all fish species present. Due to the nature of the installation, there was no way to differentiate the fish communities between ECO and control ACBMs. Therefore, at 6 and 24 MPD a GoPro camera was installed to record fish behavior on the ACBMs and identify any treatment related trends of feeding, refuge, etc. The camera was fixed to the ACBM for 1 hour in a way that the captured footage is of half ECO blocks and half control blocks.

Biomass Analysis with Loss on Ignition

Loss on ignition (LOI) is a common and widely used method to measure the organic and inorganic content of a sample (Heiri et al. 2001). At 6, 12 and 24 MPD, blocks were extracted from the ACBMs for biomass analysis. A total of 24 blocks were extracted each sampling event – 12 Control, 12 treatment from both intertidal and subtidal (6 each).

In the lab all blocks were scraped clean from all sides; the scraped material was collected separately from each block. The scraped mass was then dried in an oven (80°C for 24 hours), weighted (Dry Weight), burned in a furnace (650°C for 6 hours) and weighted again (Ash Free Dry Weight). From the resulting weights, the organic and inorganic mass were calculated for each block.

Data Analysis

Statistical analysis of the full community structure was conducted using a three-way PERMANOVA test based on the Bray-Curtis Similarity Index on Log(X+1) transformed data. Factors included Months Post Deployment (Mo: 3, 6, 9, 12, and 24), considered as a random factor, Treatment (Tr: ECO vs. Control), considered as a fixed factor and Zone (Zo: Intertidal vs. Subtidal). Results indicted significant differences ($P<0.05$) when Mo and Tr are main factors, and no significant differences ($P>0.05$) when Zo is a main factor. However, at a 3-way interaction MoXTrXZo, significant differences were found ($P<0.05$); therefore, all further analysis (including biomass analysis) were performed separately on each community. Analysis included: (1) two-way PERMANOVA test based on the Bray-Curtis Similarity Index, conducted on Log (X + 1) transformed data for the factors Mo and Tr; (2) univariate parameters (species richness [S] and biodiversity [H']) were conducted using the same PERMANOVA test design, based on Euclidian Distances similarity index, and conducted on raw untransformed data. Tests were conducted with unrestricted permutation of raw data. Post-hoc pair wise tests were applied when relevant, using Monte Carlo tests in cases where unique permutations were low; (3) MDS plots were used to graphically represent trends for multivariate data sets; (4) SIMPER analyses were conducted on raw untransformed data – two-way (factors Mo X Tr) on the full community structure, and one-way (factor Tr) on each sampling month separately; (5) biomass analysis was conducted using a two-way PERMANOVA test based on Euclidian Distances similarity index, on raw untransformed data. Factors included Months Post Deployment (Mo: 6, 12, and 24), considered as a random factor, and Treatment (Tr: ECO, and Control), considered as a fixed factor. All analyses were performed using the PRIMER V7.0.17 (PRIMER-E, Ltd., Plymouth, UK) and PERMANOVA+ V1.0.3 programs (Anderson et al. 2008; Clarke et al. 2014).

Structural Monitoring

Compressive Strength

During manufacturing, compressive strength tests were conducted according to ASTM C39 (2010) on a full block (no complex indentation) cast with ECOncrete® admix, to validate utilization of concrete mix in dry-cast technology. After 12 months of submersion in tropical waters, 3 blocks from each type (treatment and control) were extracted from the water, scraped clean from organisms, and tested according to ASTM C90 (2014) and ASTM C140 (2011). Testing was conducted on full blocks, and as the ECO block has a complex indentation on the top surface, the actual surface area that experienced the machine's load was much smaller than that of a control block with no indentation. Load results were normalized to the actual surface area in contact with the machine for each type of block. After 24 months of submersion in tropical waters, from the blocks extracted for LOI testing, three blocks from each type were tested for compressive strength. Testing was conducted on concrete coupons cut from each block, according to ASTM C140 (2011) and ASTM D6684 (2004). Additionally, an out of scope compression test, was conducted on five full ECO blocks after 75 freeze-thaw cycles, according to ASTM C90 (2014) and ASTM C140 (2011).

Freeze and Thaw

Testing was conducted by R.S. Scott Associates Inc. at Alpena Community College (ACC) according to ASTM C 1262 (2018). Since the block had a complex indentation on its top surface, slight deviations from ASTM C1262 (2018) were necessary to show the structural integrity of a full block (a list of the deviations, as well as the full testing procedure can be found in the supplemental data). Five ecologically enhanced blocks from production were selected for freeze-thaw testing. Each of the blocks underwent 32 hours of freeze-thaw cycles; from time zero, through complete freeze, to complete melt. A total of 75 of these cycles were conducted to determine the deterioration of the block, as well as to validate how well the complex indentation held its shape.

Results

Ecological Monitoring

Community Structure

The baseline survey performed on the existing infrastructure surrounding the installation site resulted in the identification of 8 taxa in the intertidal area (mainly barnacles and bivalves), and 9 taxa in the subtidal area (mainly sponges and oysters). During the entire monitoring period the ECO blocks supported a total of 18 taxa in the intertidal area compared to the 15 taxa identified on the control blocks. Whereas in the subtidal area, a total of 16 taxa were identified on both the ECO and control blocks (Table 1).

Throughout the two years of monitoring, there was a persistent trend in the increase in univariate parameters (species richness [S] and biodiversity [H']) on the ECO blocks, whereas the control blocks showed fluctuations. Significant differences ($P<0.05$) were found at 12 and 24 MPD at the intertidal for both parameters, at 3 and 24 MPD in the subtidal for average diversity, and at 24 MPD for average richness. The differences found in average richness in the subtidal area at 3 MPD were marginal (Table 2). In most monitoring events, univariate parameters were higher on the ECO blocks compared to the control blocks (Figure 3).

Fish

A total of 36 fish species were recorded on and around the ACBMs with an average of 416.00±11.41 individuals per sampling event between 3 and 6 MPD (Table 3). Further fish observations during additional monitoring events have indicated a presence of both Blennies and Gobies on the ECO blocks, specifically within the top indentation. Footage from the GoPro camera has shown that fish interact with the ECO blocks more often than the control blocks, already at 6 MPD and with higher clarity at 24 MPD (example stills from the video can be found at supplemental data, video footage available upon request).

Biomass

Significantly more ($P<0.05$) biomass had accumulated on the ECO blocks compared to the control blocks in the subtidal area, both for organic and inorganic matter, starting at 12 MPD, and reaching 5 times more accumulation on the ECO blocks (an average of 49 gr/m^2 of organic material and 494 gr/m^2 of inorganic material) at 24 MPD.

In comparison, the control blocks' biomass accumulation averaged 9 gr/m^2 of organic material, and 131 gr/m^2 of inorganic material. No significant differences ($P>0.05$) were found between ECO and control intertidal blocks for both organic and inorganic biomass, which fluctuated between sampling events (Figure 4).

Further analysis of the encrusting taxa on the blocks revealed there was a higher presence of calcifying organisms on the ECO blocks compared to the control blocks. Furthermore, the ECO blocks had a greater total presence of calcifying organisms, and each block accumulated higher numbers of calcifying taxa which grew at a faster rate, both in the intertidal and subtidal areas (Figure 5).

Structural Monitoring

Compressive Strength

Several compression tests were conducted under different ASTM Standard methods and with different baseline conditions (Table 4). After 12 months of submersion, ECO and control blocks endured roughly the same applied loads; however, when taking into account the surface area of blocks experiencing that load, ECO blocks averaged 7,640 psi and control blocks averaged 5,860 psi. After 24 months of submersion, that trend continued; ECO blocks averaged 3,010 psi and control blocks averaged 2,260 psi, this time on concrete coupons with almost the same surface area. Testing was also performed after 75 freeze-thaw cycles (see below) revealing an average compressive strength of 4,730 psi which complies with the minimum 4000 psi requirement specified in ASTM D6684.

Freeze and Thaw

The average weight loss of the ECO blocks after 75 freeze-thaw cycles (Table 5) was 49.1±2.94 gr (0.31%±0.02%) which is lower than the 1% as commonly accepted as a weight loss threshold for ASTM C1262 (2018) (Figure 6).

Discussion

Ecological Monitoring

The ability of ecologically engineered concrete infrastructure to enhance recruitment compared to standard “gray” concrete, has been previously demonstrated under controlled laboratory and field experiments (Loke and Todd 2016; Morris et al. 2019; Perkol-Finkel et al. 2017; Perkol-Finkel and Sella 2014a; 2015). These studies evaluated the discrete effect of concrete composition and surface texture, indicating that each factor influences the resulting communities, and that the cumulative effect of bio-enhanced concrete with textured surfaces provides favorable conditions to enhance biological recruitment. The findings of the current study support the working hypothesis and indicate the ability of ecologically modified hard CMI to generate ecological uplift without compromising on, and even strengthening, the structural performance.

During the monitoring period both intertidal and subtidal communities on treatment (ECO) blocks significantly ($P<0.05$) increased and exceeded control blocks’ values. This trend was shown from deployment to 24 MPD, with ECO blocks presenting 5-7 times the values of species richness and diversity than control at 24 MPD (Figure 3). Additionally, in the subtidal sections, the average biomass accumulation was significantly higher ($P<0.05$) on the ECO blocks than the control blocks (starting at 12 MPD), with a less clear trend in the intertidal segments. These differences were first considered to be related to a higher presence of calcifying taxa in the subtidal, however further analysis found that ECO blocks in both intertidal and subtidal (during all monitoring events) had significantly higher ($P<0.05$) number of calcifying taxa than control (Figure 5). This led the research team to assume that the unclear indications in the intertidal are related to slow succession processes in the tropical area (Perkol-Finkel and Benayahu 2007; Perkol-Finkel et al. 2005), and that the actual calcification potential (by biogenic buildup) of the ECO blocks is higher than the control, both in intertidal and subtidal installations. This assumption can be strengthened by the fact that during the two years of monitoring, the site was hit by numerous Hurricanes – Harvey, Irma, Jose, Maria and Nate at 2017 (NOAA 2018) and Gordon, Leslie and Michael at 2018 (NOAA 2019), which resulted in a dramatic salinity drop for several days (Figure S-6 in supplemental data).

The presence of engineering species like oysters, tube worms and barnacles promote biogenic buildup, elevates the complexity of the habitat and creates additional biological niches (Byers et al. 2006; Hastings et al. 2007; Jones et al. 1994; Jones et al. 1997). Sessile communities developing on hard structures support a diverse motile community in, on, and around the structure (Sella and Perkol-Finkel 2015), and the biogenic buildup on the ECO blocks showed the same effect on higher trophic levels as well. A total of 36 fish species were recorded on and around the ACBMs, with an average of 416.00±11.41 individuals per sampling event. While the experimental setup did not allow researchers to evaluate motile community differences between treatment and control due to the close proximity of the subunits in each mattress, initial under water videos indicated that fish interacted for longer time and more frequently with the treatment than the control.

Implications for Mitigation and Carbon Offsetting

Ecologically enhanced CMI can potentially support much healthier and more productive communities that are better equipped to withstand periodic environmental and physical disturbances as engineering species have substantial ecological implications; by forming a marine community with higher stability/matureness (Airoldi and Bulleri 2011).

In addition to habitat value, the chemical process of biocalcification (biogenic buildup) of calcitic skeletons, utilizes the CO_2 molecules from the seawater to generate $CaCO_3$ skeletons, essentially removing atmospheric CO_2 (Kleypas et al. 2005). At 24 MPD, the ECO blocks accumulated an average of 494 gr/m^2 of inorganic material in the subtidal area (Figure 4). Taking into account that for every 1000 grams of $CaCO_3$ ~120 grams of carbon is stored in these $CaCO_3$ skeletons; these assimilation rates can be translated into significant volumes of carbon sequestration throughout the life span of the infrastructure. When examining annual carbon sequestration rates on the full ECO ACBM (intertidal and subtidal together, Figure 4), values of ~60 grams of Carbon per square meter annually (g C m^{-2} yr^{-1}). Published rates of carbon sequestration from a range of tidal saline wetlands vary from 21 to 1713 g C m^{-2} yr^{-1}, with averages of 22 to 244 g C m^{-2} yr^{-1}, thus the rates determined here fall within the range of published values (Chmura et al. 2003; Davis et al. 2015; Morris et al. 2012; Ouyang and Lee 2014).

By definition, living shorelines are a shoreline management option that involves the utilization of native marsh vegetation for the purpose of erosion control (Currin et al.

2010). However, there are locations and environments where the “soft” approach of living shorelines cannot withstand the hydrodynamic conditions, which calls for “hard” solutions. Thus, implementation of ecological enhancement measures on CMI, can help offset carbon even where living shorelines cannot be implemented. With carbon offset incentives or regulation targeted at reducing the carbon footprints of urban waterfronts, bio-enhancing CMI can help meet those goals.

Structural Monitoring

Designing shore protection measures requires a delicate balance between the mandated level of protection and factors such as cost, aesthetics, and environmental impact (Rella and Miller 2012). In order for the market to assimilate bio-enhanced ACBMs, they need to comply with or exceed industry standards for manufacturing, installation and structural performance (Rella et al. 2017). Both ECO blocks and control blocks were cast from a 4000-psi concrete mix that complies with industry standard; but the un-even, complex surface of the ECO blocks required further evaluation to assess sensitivity to chipping and abrasion.

For this, an extensive freeze-thaw test was performed, as well as compressive strength testing before and after deployment. For transportation infrastructure, many states (US) with freeze-thaw conditions specify a max 1% weight loss threshold after 40 cycles of freeze-thaw. As the ACBMs are applied in the extreme conditions of the intertidal area (saline waters, dry and wet cycles), the ECO blocks underwent 75 freeze-thaw cycles following ASTM C1262 (2018). The minimal average weight loss found (0.31%), and the units’ ability to retain their compressive strength (4730 psi, Table 4) after freeze-thaw testing, is a clear indication on the ability of ecological products to comply with the industry standards.

A major advantage for the structural performance of bio-enhanced ACBMs is the increased development of marine flora and fauna and the structural advantages they provide, on top of the ability to enhance ecosystem services. This biological layer can reduce the effects of deteriorative weathering processes associated with waterfront concrete infrastructure such as thermal fatigue, and chloride ion penetration (Coombes et al. 2013b; Coombes et al. 2016; Kawabata et al. 2012), and can potentially increase expected life span, reduce maintenance needs, and facilitate structural stability and absorption of hydrodynamic forces.

Conclusions

This study set out to evaluate a combined ecological design that included concrete composition, texture, and design, jointly contributing to the enhancement capabilities of the ECO ACBMs. After two years of monitoring, significant ecological enhancement was noted on the ECO ACBMs in comparison to the controls. Communities recruited on the ECO blocks significantly differed from those recruited on the control blocks and the nearby artificial infrastructure, presenting higher values of species richness and diversity. Note that comparison of invasive species on the units, was not in the scope of this paper, and further studies should be conducted. The surface roughness and complex surface features of the ECO blocks were designed to create a variety of habitats and environmental conditions which are absent from standard concrete ACBMs, and the findings reflect their efficacy in doing so. The results supported the working hypothesis, and demonstrated that modifications of concrete composition, surface texture, and macro-design, have the potential to elevate the ecological value of concrete-based CMI. Based on the results of this study, these design alterations have increased the richness, abundance, and diversity of sessile assemblages compared to control blocks, and also supported higher abundance of mobile species. Therefore, NID might promote a more sustainable and adaptive approach to coastal and marine development.

This ecological improvement was achieved within the operational limitations of conventional manufacturing and installation technologies, complying with strict structural requirements for marine construction (such as compression forces, cracking, and resistance to freeze and thaw cycles), while considering biological factors. The study examined the potential for applying ecological engineering principles in active urban/working waterfronts, without compromising the day-to-day functions and services provided by the structure. Mainstream environmental awareness, coupled with a growing number of scientific publications and practical guidelines for the ecological design of coastal infrastructure will help to promote the implementation of environmentally sensitive technologies. Infrastructure capable of addressing both ecological and structural functioning, and which can be implemented in expanding urban, industrial, hardened waterfronts should be considered by policymakers for coastal climate-resilience problems faced today.

Figure 1. Aerial view of the pilot location at Port Everglades, FL, USA. Blue arrow marks the location of ACBMs installation, gray arrows mark the locations of adjacent artificial infrastructure served as baseline. Image source – google earth.

Figure 2. Manufacture and installation procedures of the ACBM. [A] lacing the blocks to form a half-textured ECO blocks (treatment), and half featureless CEM-I based blocks (control); [B] crane lifting; [C] lowering to the water; [D] in place on the riprap aligned with MLLW line.

Figure 3. Difference in univariate parameters between ECO and Control blocks at 3, 6-, 9-, 12-, and 24-months post deployment, for intertidal (left) and subtidal (right) areas. *Represents significant differences ($P<0.05$); +represents marginal differences; Error bars represent standard error.

Figure 4. Differences in organic and inorganic biomass accumulation between ECO and Control blocks at 6-, 12-, and 24-months post deployment, for intertidal (left) and subtidal (right) areas. *Represents significant differences ($P<0.05$); Error bars represent standard error.

Figure 5. MDS bubble plot representing the presence of calcifying taxa on ECO and Control blocks in the intertidal and subtidal areas at 24 months post deployment. Each bubble represents a block and the size of the bubble correlates to the number of calcifying taxa found on that particular block.

Figure 6. A sample of one ECO block. [A] new and untested, [B] after 75 cycles of freeze-thaw, [C] after 6 months submersion.

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Table 1. General cumulative list of taxa identified on and around the ACBMs throughout the monitoring period and at the one-time baseline survey.

Taxa	Intertidal			Subtidal		
	Baseline	Control	ECOncrete	Baseline	Control	ECOncrete
Sponges	+	+	+	+	+	+
Oysters	+	+	+	+	+	+
Spirorbis	+	+	+	+	+	+
Serpulidae	+	+	+	+	+	+
Bryozoans			+		+	+
Coralline Algae		+	+		+	+
Tunicates			+		+	+
Sabellidae		+	+	+	+	+
Barnacles	+	+	+	+	+	+
Bivalves	+	+	+	+	+	+
Limpet	+	+	+			
Dasychone		+	+	+	+	+
Gastropods	+	+	+	+		
Hydrozoa		+	+		+	+
Anemone			+			
Red Algae		+	+		+	+
Green Algae						+
Macro Algae		+				
Corals					+	
Unidentified			+		+	+
Mobile		+	+		+	+
Total	**8**	**15**	**18**	**9**	**16**	**16**

*Table 2. Univariate parameters PERMANOVA (Monte Carlo) results for differences between ECOncrete and control blocks, throughout the 24 Months monitoring for intertidal and subtidal areas. Where P is PERMANOVA, perm is permutations, and MC is Monte Carlo. *Represents significant differences; +represents marginal differences (p values slightly higher than 0.05).*

Parameter	Depth	Months	P(perm)	Unique perms	P(MC)
Species richness [S]	Intertidal	3	0.871	11	0.746
	Subtidal		0.089	8	0.053+
	Intertidal	6	0.11	10	0.073
	Subtidal		0.165	12	0.138
	Intertidal	9	0.132	13	0.119
	Subtidal		0.896	12	0.77
	Intertidal	12	0.003*	23	0.001*
	Subtidal		0.292	18	0.265
	Intertidal	24	0.001*	24	0.001*
	Subtidal		0.001*	25	0.001*
Biodiversity [H’]	Intertidal	3	0.858	16	0.8
	Subtidal		0.007*	78	0.007*
	Intertidal	6	0.1	487	0.122
	Subtidal		0.357	978	0.338
	Intertidal	9	0.247	997	0.256
	Subtidal		0.748	996	0.755
	Intertidal	12	0.006*	997	0.007*
	Subtidal		0.551	999	0.576
	Intertidal	24	0.001*	995	0.001*
	Subtidal		0.001*	992	0.001*

Table 3. Average abundance and standard errors of fish species identified on and around the ACBMs, between 3MPD to 6MPD.

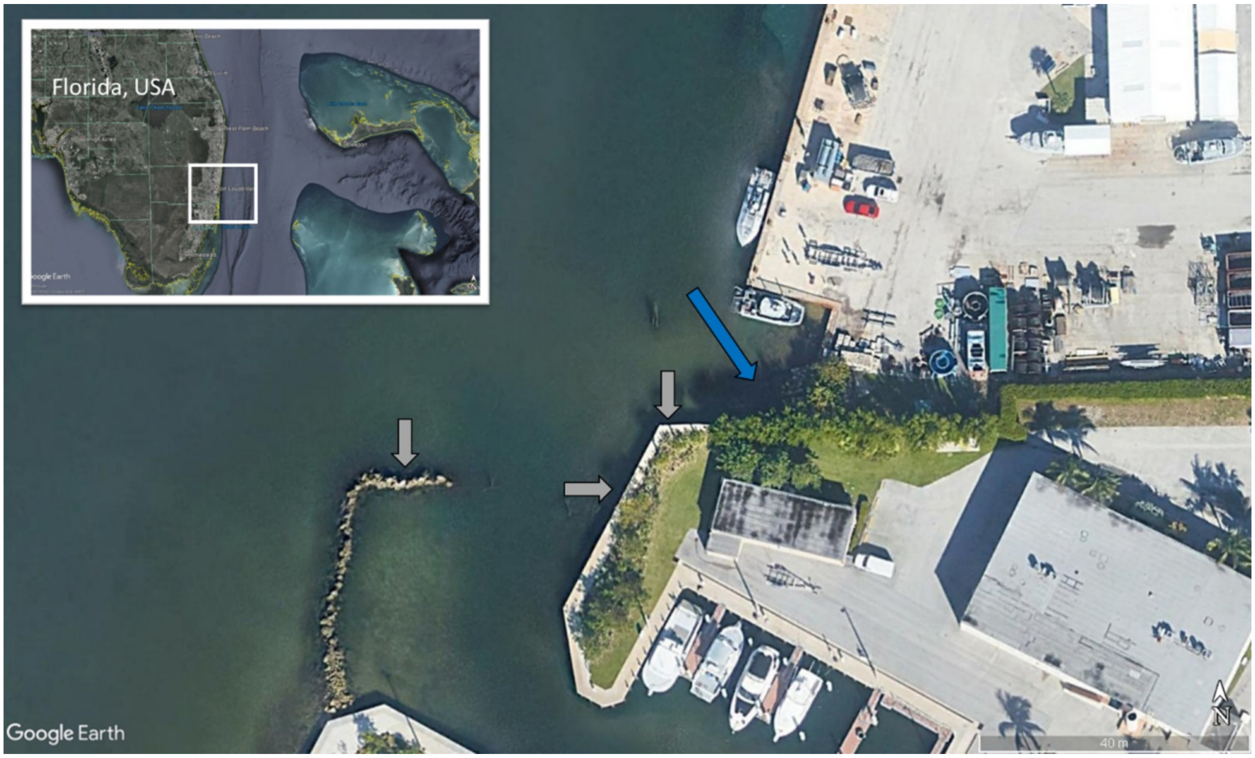
Family	Genus	Species	Common name	Average	St Err
Pomacentridae	*Abudefduf*	*saxatilis*	Sargent major	79.25	4.78
Acanthuridae	*Acanthurus*	*chirurgus*	Doctorfish	12.13	1.82
Haemulidae	*Anisotremus*	*surinamensis*	Black morgate	6.50	1.47
Haemulidae	*Anisotremus*	*virginicus*	Porkfish	13.25	1.45
Tetraodontidae	*Canthigaster*	*rostrata*	Sharpnose puffer	0.75	0.27
Carangidae	*Caranx*	*hippos*	Crevalle jack	3.88	0.72
Carangidae	*Caranx*	*bartholomaei*	Yellow jack	1.00	0.24
Centropomidae	*Centropomus*	*undecimalis*	Common snook	1.88	0.44
Ephippidae	*Chaetodipterus*	*faber*	Atlantic spadefish	0.50	0.18
Haemulidae	*Haemulon*	*flavolineatum*	French grunt	68.75	6.54
Haemulidae	*Haemulon*	*aurolineatum*	Tomtate	82.88	8.06
Haemulidae	*Haemulon*	*plumierii*	White grunt	9.13	2.14
Kyphosidae	*Kyphosus*	*sectatrix*	Bermuda chub	9.50	1.14
Sparidae	*Lagodon*	*rhomboides*	Pinfish	3.63	0.55
Lutjanidae	*Lutjanus*	*cyanopterus*	Cubera snapper	0.13	0.04
Lutjanidae	*Lutjanus*	*synagris*	Lane snapper	0.75	0.11
Lutjanidae	*Lutjanus*	*griseus*	Mangrove snapper	7.50	2.45
Lutjanidae	*Lutjanus*	*apodus*	Schoolmaster snapper	31.63	1.45
Atherinopsidae	*Menidia*	*menidia*	Atlantic silverside	13.63	4.82
Pomacanthidae	*Pomacanthus*	*paru*	French angelfish	0.13	0.04
Blennidae	*Scartella*	*cristata*	Molly miller	1.38	0.49
Scaridae	*Scarus*	*vetula*	Queen parrotfish (IP)	0.63	0.22
Scorpaenidae	*Scorpaena*	*plumieri*	Spotted scorpionfish	0.63	0.15
Scaridae	*Sparisoma*	*viride*	Stoplight parrotfish (IP)	0.88	0.23
Scaridae	*Sparisoma*	*viride*	Stoplight parrotfish (TP)	0.50	0.13
Scaridae	*Sparisoma*	*viride*	Stoplight parrotfish IP	8.88	1.75
Pomacentridae	*Stegastes*	*adustus*	Dusky damselfish	14.25	0.90
Labridae	*Thalassoma*	*bifasciatum*	Bluehead wrasse	2.25	0.47
Labridae	*Halichoeres*	*bivittatus*	Slippery dick	5.75	0.71
Serranidae	*Cephalopholis*	*cruentata*	Graysby	0.13	0.04
Gerreidae	NA	NA	Mojarra	27.00	2.78
Clupeidae	NA	NA	UNID clupeidae	0.38	0.13
NA	NA	NA	"Mullet"	0.13	0.04
NA	NA	NA	"Occhiata"	0.50	0.13
NA	NA	NA	"Silversides"	5.25	1.86
NA	NA	NA	“Sheepshead”	0.75	0.19

Table 4. Summary of compressive strength test conditions and results conducted on the ECO and control blocks throughout the monitoring period.

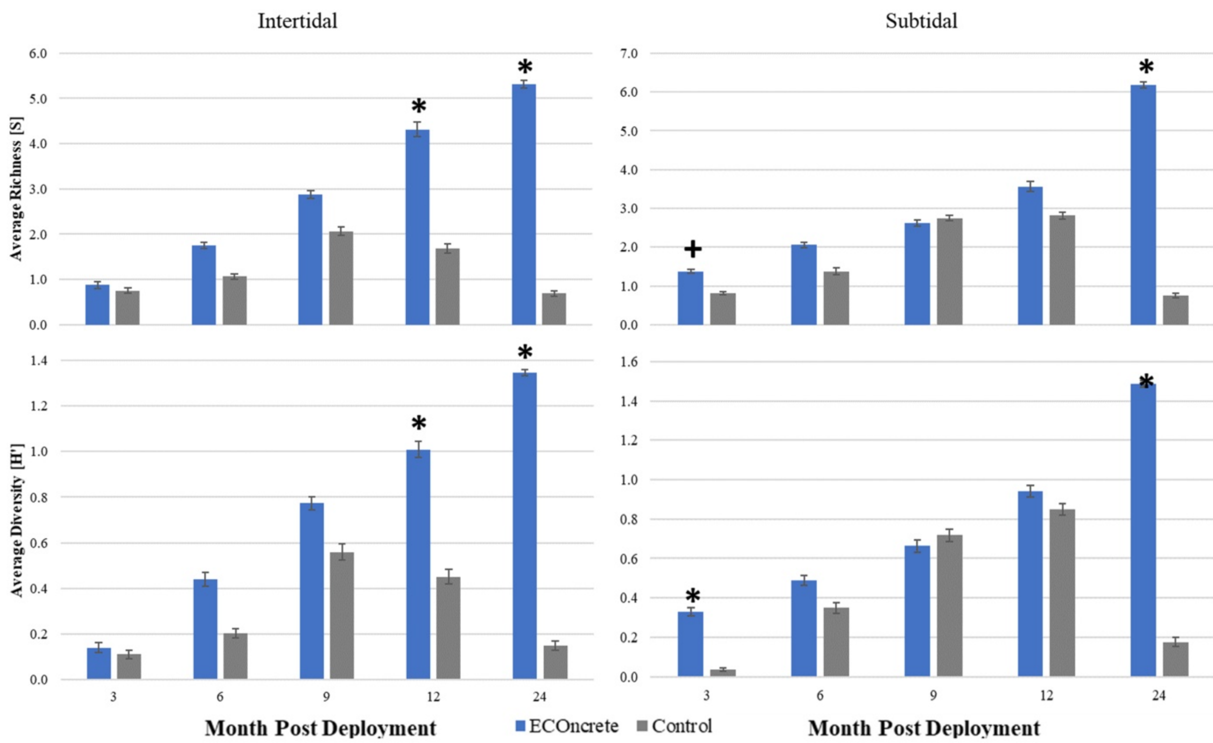
Specimen Tested	3 Full Blocks After 12 Months Submersion		3 Concrete Coupons After 24 Months Submersion		5 Full Blocks after 75 freeze-thaw cycles
	ECOncrete	Control	ECOncrete	Control	ECOncrete
Calculated Surface Area [sq. in.]	53.9	72.75	9.05	9.64	53.9
Average Applied Load [lbs.]	411,985	426,523	27,177	25,435	254,865
Average Compressive Strength [psi]	7,640	5,860	3,010	2,260	4,730

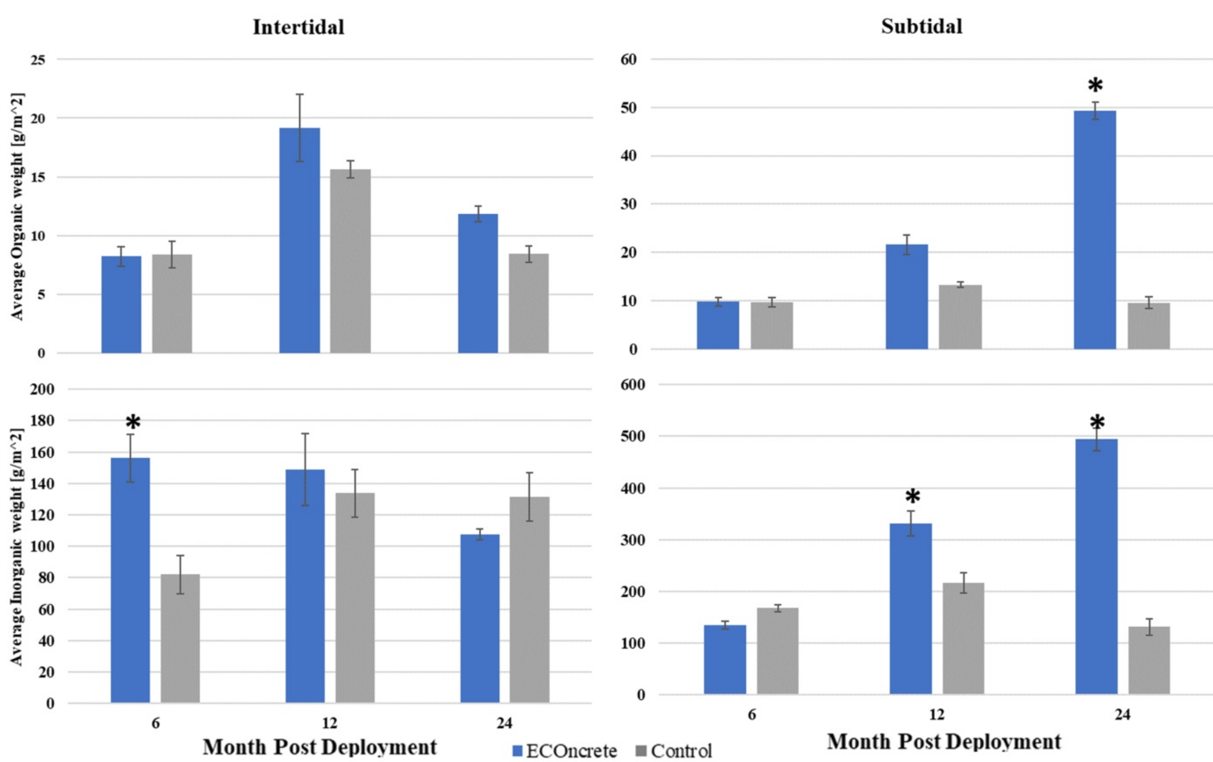
Table 5. Summary of ECO block weights before and after 75 freeze-thaw cycles, and their calculated weight loss.

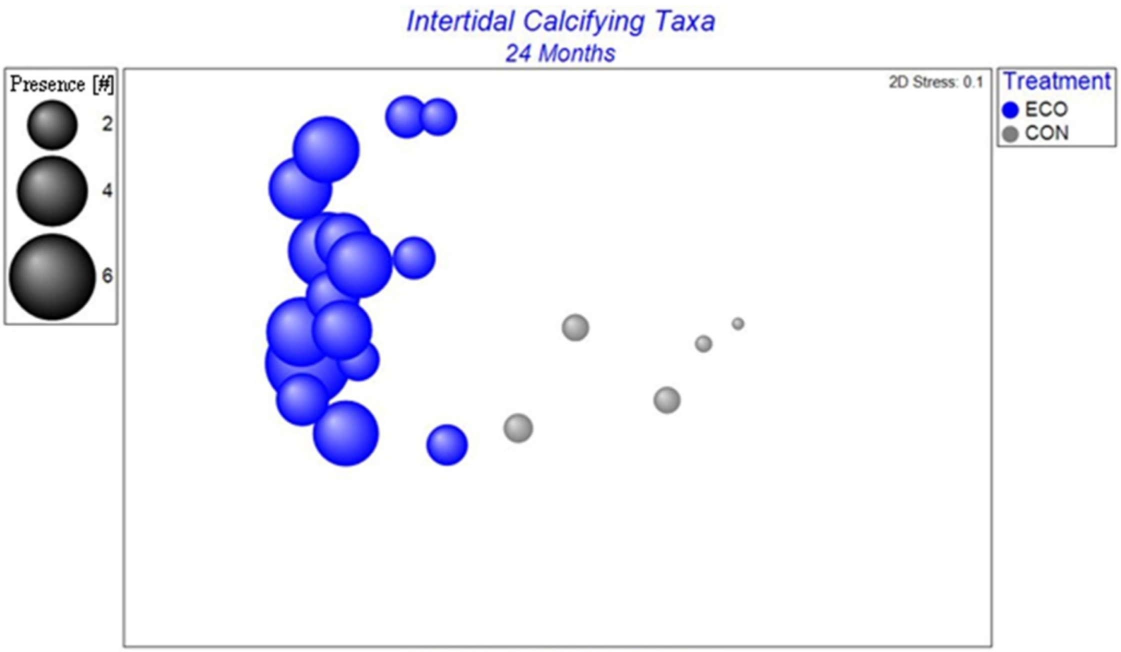
ECOncrete Block #	Initial Weight [gr]	Final Weight [gr]	Total Loss [gr]	Percent Loss [%]
1	15878.4	15840	38.4	0.24
2	16154.6	16110	44.6	0.28
3	15929.4	15870	59.4	0.37
4	15944.0	15910	34.0	0.21
5	15909.0	15840	69.0	0.44

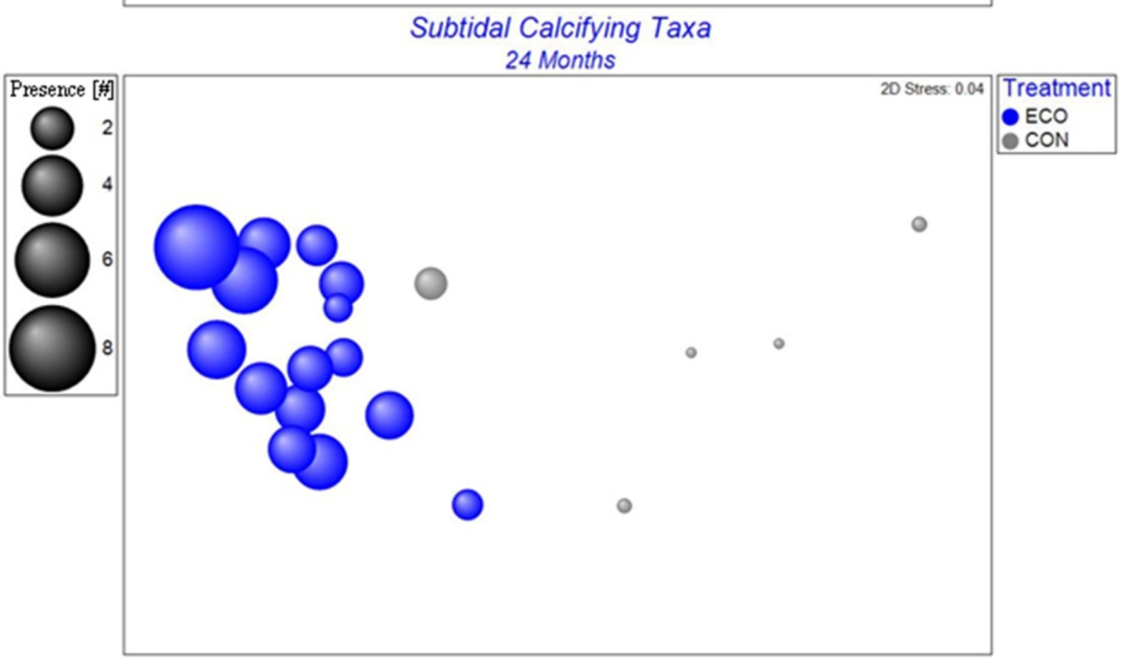

Florida, USA
Google Earth
40 m
N


A
B
C
D


Intertidal
Subtidal
Average Richness [S]
Average Diversity [H']
3
6
9
12
24
Month Post Deployment
ECOncrete
Control
Month Post Deployment


Intertidal
Subtidal
Average Organic weight [g/m^2]
Average Inorganic weight [g/m^2]
6
12
24
Month Post Deployment
ECOncrete
Control
Month Post Deployment


Intertidal Calcifying Taxa
24 Months
Presence [#]
2
4
6
2D Stress: 0.1
Treatment
ECO
CON


Subtidal Calcifying Taxa
24 Months
Presence [#]
2
4
6
8
2D Stress: 0.04
Treatment
ECO
CON


A
B
C