# Ecologically Active Concrete for Coastal and Marine Infrastructure: Innovative Matrices and Designs

**Shimrit Perkol-Finkel** ECOncrete Tech LTD, Tel Aviv, Israel.
**Ido Sella** ECOncrete Tech LTD, Tel Aviv, Israel.

## Summary

This paper presents results from a year-long experimental study, evaluating the performance of ecologically active concrete matrices and designs for coastal and marine construction. Results indicate that slight modifications of concrete composition and surface texture can improve the capabilities of concrete based coastal and marine infrastructure (CMI) to support enhanced marine fauna and flora, and provide valuable ecosystem services alongside with economic advantages such as elevated water quality, increased operational life span, structural stability, and absorption of hydrodynamic forces.

## Introduction

With nearly two thirds of the human population living along the coastlines (Creel, 2003), the proliferation of CMI that supply various societal needs such as transportation (ports), energy (pipelines, power stations, rigs) and urbanization (marinas, seawalls, breakwaters etc.) is inevitable. Nowadays >50% of Mediterranean coastlines are dominated by concrete structures (EEA, 1999), and in some regions the growth of cities, ports, and industries has developed over 90% of the coastline (Cencini, 1998). The result is a continuous and increasing trend of coastal hardening, replacing natural coastlines (Bulleri and Chapman, 2010, Dugan et al., 2011).

Despite the increasing dominance of hardened and armored shorelines across the globe, our understanding of species assemblages on CMI, especially in regards to their environmental effects is limited (Connell and Glasby, 1999, Dugan et al., 2011). This knowledge gap severely impairs our ability to manage urbanized coastal environments (Bulleri and Chapman, 2010). The few studies that have examined marine growth on CMI such as pontoons and breakwaters found assemblages that greatly differ from those of adjacent natural habitats (e.g., Connell, 2000, Lam et al., 2009). Communities developing on CMI are typically less diverse than natural assemblages, and are commonly dominated by nuisance and invasive species (Glasby et al., 2007). This mainly results from the unique physical characteristics of CMI, predominantly, composition and design. CMI often include highly inclined, homogeneous surfaces with minimal surface complexity, compressing the intertidal zone to a narrow belt which supports only highly tolerant species (Chapman and Underwood, 2011). Moreover, over 50% of CMI are made of Portland cement, which is known as a poor substrate in terms of biological recruitment, presumably due to high surface alkalinity (pH ~13 compared to ~8 of seawater) and presence of compounds that are toxic to marine life (Lukens and Selberg., 2004, EBM, 2004). Thus, the ability of CMI to provide ecosystem services similar to those offered by natural habitats is severely compromised, and most urban/industrial coastal environments are considered as sacrificed zones in relation to environmental activity.

In the last few years, a different approach has been emerging, utilizing principles of ecological engineering (Bergen et al., 2001) for enhancing the biological and ecological value of CMI (e.g., Li et al., 2005, Naylor, 2011). To date, enhancement measures concentrated on design or textures aspects, aimed at attracting more abundant and diverse natural assemblages (Wiecek, 2009, Goff, 2010, Dyson, 2009) yielding ecological and structural advantages. These advantages are mainly related to biogenic buildup; a natural process in which engineering species like oysters, serpulid worms, barnacles and corals deposit calcium carbonate ($CaCO_3$) skeletons onto hard surfaces thus creating valuable habitat to various organisms (Jones et al., 1994) while also contributing to the structures' strength and stability (Risinger, 2012). Nonetheless, studies attempting to modify the composition of CMI, making it favorable to species of ecological value such as ecosystem engineers, are scarce.

We propose an integrative approach targeting both composition and design. For this, we have developed and tested a series of five innovative concrete matrices aimed at enhancing natural biological assemblages, while still complying with formal requirements of marine construction. The new matrices have reduced alkalinity in comparison to Portland cement, and include various additives that decrease the dominance of Portland cement in the mix, potentially making them more hospitable to marine life. In addition, we have tested the impact of increased surface complexity, which is known to encourage biological development (Perkol-Finkel et al., 2012 and references therein), and its interaction with the concrete matrix.

We present results from a year-long experiment, evaluating the biological performance of the innovative concrete matrices in comparison to standard Portland cement in both tropical (Red Sea) and temperate (Mediterranean Sea) environments. The impact of composition and complexity were experimentally evaluated using a series of long-term field experiments and controlled laboratory tests. We hypothesize that different concrete matrices will recruit different species assemblages (in terms of assemblages, biomass and recruitment capabilities of target species) than standard Portland cement, and that increased surface complexity will yield enhanced growth of natural biological assemblages and calcium carbonate deposition by ecosystem engineers. Results indicate that slight modifications of concrete composition and design can improve the capabilities of concrete based CMI to support enhanced marine fauna and flora and provide valuable ecosystem services. Such enhanced natural biological assemblages do not compromise the concrete's durability; on the contrary, they can provide physical protection with time, through weight addition and bio-protection.

# Materials and Methods

## Field Experiment

We tested the recruitment capabilities (in terms of both flora and fauna) of five different concrete matrices in comparison to standard Portland cement. All matrices tested withstand compressive forces of 30-50 MPa, complying with the different requirements for marine construction (see section "Preparation of Concrete Matrices"). Apart from testing the effect of concrete composition on recruitment we have also tested the effect of surface texture, i.e., smooth vs. textured surface, on recruitment of marine flora and fauna. Recruitment was tested simultaneously in the tropical environment of the Red Sea, at the Inter University Institute in Eilat, and in the temperate waters of the Mediterranean Sea near Ashdod, Israel.

We used 15x15x4 cm concrete tiles for the field experiment. Each tile, weighing ca. 2.5 kg, had one smooth face and one textured. Texture was formed using a plastic form-liner, creating a coral polyp-like texture. Ten replicates were prepared for each of the 5 tested matrices (M1-M5) and of the Portland control. Each tile was tagged with an ID number (1, 2, 3…) that does not reveal the matrix composition. Matrix type for each tile number was listed separately, allowing "blind" sampling (i.e., surveyors sampled tiles without knowing their concrete composition), eliminating byes data collection. The tiles were mounted onto a metal mesh table deployed at sea. At the Red Sea station tiles were placed at 10 m depth, while in the Med Sea station, due to shallower seabed conditions, at 6 m depth. Tiles of the various matrices were laid randomly on the mesh table, with the textured face oriented seaward.

Five tiles of each matrix were sampled 3, 6 and 12 months post deployment. In each monitoring event, tiles were temporarily retrieved from the sea and transferred fully submerged to the laboratory. Both faces of each tile were carefully inspected using a dissecting microscope, photographed, and sampled before re-deployed. Quantification of the cover of recruited taxa on each tile face was performed using a 1x1 cm grid, according to Perkol-Finkel et al. (2008). Data noted included taxa composition, percent cover of colonial organisms (bryozoans, tunicates and sponges), and number of solitary organisms (tunicates, bivalves and barnacles). Taxonomic groups that could not be counted as individuals (i.e., clusters of serpulid worms), or ones differing in density (turf and coralline algae), were ranked as follows: 0 - absent, 1 - sparsely scattered, 2 - densely scattered and 3 - densely uniform. In addition, during the 6 and 12 months post deployment monitoring, chlorophyll concentration and biomass (organic and inorganic dry weight) were measured, by carefully scraping all benthic organisms and algae from one quarter of the smooth face of each tile following Perkol-Finkel et al. (2006). An additional quarter of each smooth face was sampled for chlorophyll content analysis following Greenberg (1995).

Data analysis included univariate 1-way PERMONOVA tests, based on Euclidian Distances similarity index, for organic and inorganic biomass, chlorophyll concentration, and percent live cover, as well as multivariate data analyses of taxa assemblages by a-parametric PERMANOVA tests based on the Bray-Curtis similarity index. In addition, post-hoc pair wise tests were applied when relevant. 2D-MDS plots were used to graphically represent trends in multivariate data. All analyses were performed using the PRIMER/PERMANOVA programs (Anderson et al., 2008, Clarke and Gorley, 2006). Data in figures are presented as average ± SE unless mentioned differently.

## Lab Experiments

In order to quantify the recruitment-enhancing capabilities of the five different concrete matrices in comparison that of standard Portland cement, in-vitro lab experiments were conducted. These included two soft coral species; *Heteroxenia fuscescens* and *Dendronephthya hemprichi*, as well as larvae of the filter feeding Bryozoan *Bugula neritina*. Larvae collection of *H. fuscescens* and *B. neritina* was conducted by incubation of colonies in the laboratory, while for *D. hemprichi* minute fragments were prepared manually from adult colonies using seizers. Settlement of larvae/fragments was monitored 1 week after initiation of the experiment, except for settlement of *H. fuscescens* which was examined a month after initiation of the experiment due to its slower settlement process. During monitoring the number of larvae/fragments settled on each cube was determined.

Test units consisted of 2.5x2.5x2.5 cm concrete cubes corresponding to the five matrices tested in the field (MI-M5) in comparison to Portland cement controls. During each experiment, 5-8 replicates of each matrix (depending on larvae availability) were tested. For this, each concrete cube was placed in an individual 250 ml beaker filled with fresh running seawater and left for 3 days for acclimatization. After acclimatization, a uniform number of larvae were added to each beaker. The number of larvae introduced to each beaker varied according to larvae availability, ranging from a minimum of 5 per beaker to a maximum of 40 larvae per beaker. Water temperature was kept similar to that of natural conditions. Beakers were placed fully submerged in a running water table with good circulation. If mobile larvae were examined, beakers were submerged in the running water system up to 3/4th of their height until initial larval settlement (typically, 24-72 h) after which they were fully submerged. Data analysis included univariate 1-way PERMONOVA tests, based on Euclidian Distances similarity index, and post-hoc pair wise tests, using the PRIMER/PERMANOVA programs (Anderson et al., 2008, Clarke and Gorley, 2006).

## Preparations of Concrete Matrices

The matrices tested in this study varied in the amount of Portland cement in the mix, use of other cements, air content, and add-mixer. Crack prevention 25 mm microfibers were included in all matrices. Matrices were mixed by an 80 litre horizontal mixer and were cast into 10x60x160 cm forms with plastic form liners. After 28 days, the concrete sheets were cut by a water jet marble sow into 15x15 cm experimental tiles. As form liner was applied only to one at the bottom face of the form, each tile had one textured and one smooth face.

All matrices were tested according to ASTM or EN standards, including: Compression Strength - ASTM C 39 (AASHTO T 22), Water Pressure Penetration Resistance - EN 12390-8, Chloride Ion penetration Resistance - ASTM C1202–12. Concrete pH values were checked by collecting 5 gr of drilled residue from 0.5cm deep drilled holes on the concrete surface and mixing them in 50 ml of distilled water (pH 7). All tested concrete matrices (MI-M5) showed lower pH values than the Portland cement based mix (9-10.5 compared to 12.5-13.5

respectively, Table 1). In terms of compressive strength, M1-M5 had similar or greater strength as that of Portland cement based mix, with values reaching as much as 39.3 MPa (M2). All matrices except for M4 and M5, which had high air content, presented higher chloride ion penetration resistance (<1500 coulombs) than the Portland cement based mix with similar density (2300-2500 kg/$m^3$), and water pressure penetration resistance (<20 mm).

Table 1: Physical parameters of the various innovative concrete matrices in comparison to Portland cement. NR- Not relevant for high air content concrete

| **Matrix** | **Water / Cement Ratio** | **pH** | **Average Compression Strength** (Mpa) | **Weight** (Kg/$m^3$) | **Water Pressure Penetration Resistance** (mm) | **Chloride Penetration Resistance** (Coulombs) |
|---|---|---|---|---|---|---|
| **M1** | 0.3 | 9-10 | 32.5 | 2300-2500 | <20 | <1500 |
| **M2** | 0.3 | 9.5-10.5 | 48.5 | 2300-2500 | <20 | <1000 |
| **M3** | 0.3 | 9.5-10.5 | 39.3 | 2300-2500 | <20 | <1000 |
| **M4** | 0.3 | 9-10 | 31.1 | 1400-1800 | NR | NR |
| **M5** | 0.3 | 9-10 | 31.9 | 1400-1800 | NR | NR |
| **Portland** | 0.30 -0.25 | 12.5-13.5 | 32 | 2300-2500 | <20 | >2000 |

The composition of M1-M5 varied in terms of type of cement and additives. E.g., M1 and M5 are alumina rich cement blends, while M2-M4 are slag based cement with different mixes of pozolans. All matrices include specially designed HWRA (High Water Reducing Admixture) with a fiber blend, where M4-M5 also contain modified high air entrained admixture.

# Results

## Field Experiment

Statistical analyses of community data revealed significant differences in species assemblages between sites (Red vs. Med Sea: *df*=1, *pseudo f*=177.47, P=0.001), months post deployment (3, 6, 12 m: *df*=2, *pseudo f*=83.38, P=0.001), matrix types (M1-M5, Portland: *df*=5, *pseudo f*=2.45, P=0.001) and plate face (smooth vs. textured: *df*=1, *pseudo f*=11.12, P=0.001). Figure 1 illustrates the different community structure of the Red and Med Sea stations, as well as clear temporal patterns indicating that community structure gains similarity with time. This is demonstrated by the relative proximity of 12 months post deployment clusters (dark shades) in comparison to those of 3 and 6 months (lighter shades) which appear farther apart on the MDS.

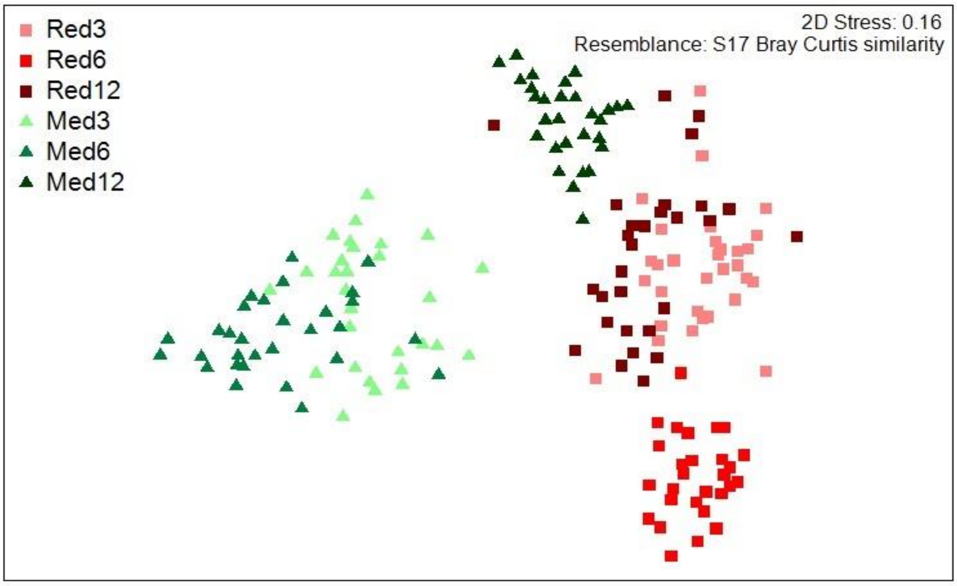

Figure 1: 2D-MDS of community data from the two field stations (Red Sea =

squares of red shades; Med Sea = triangles of green shades) 3, 6 and 12 months post deployment. Each point represents one tile (tile faces pooled).

The taxa composition recruited to the different concrete matrices also varied among sites and with time (significant Site x Matrix interaction term: *df*=5, *pseudo f*=1.50, P=0.049 and Month x Matrix: *df*=10, *pseudo f*=1.37, P=0.037). Yet the general trend indicated that tiles composed of Portland cement clustered separately from the other concrete matrices (MI-5), as seen in Figure 2. The level of similarity amongst the various matrices varied with time and between sites.

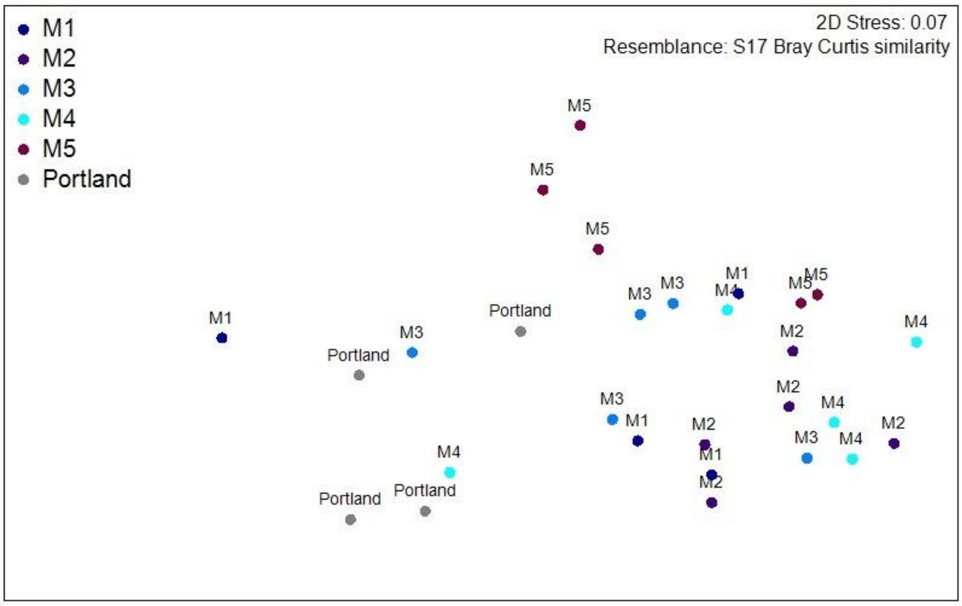

Figure 2: 2D-MDS of typical community data. Each point represents one tile (faces pooled). Example from Red Sea, 6 month post deployment, showing the various innovative concrete matrices (M1-5 colour coded) at the right side of the plot, while Portland cement tiles (grey) clustered at the left.

Analyses of percent live cover (Fig. 3) supported the results of the multivariate community data analyses, revealing that live cover differed between sites (*df*=1, *pseudo f*=6.77, P=0.009), months (*df*=2, *pseudo f*=133.36, P=0.001), Tile Face (*df*=1, *pseudo f*=20.58, P=0.001) and Matrices (*df*=5, *pseudo f*=27.57, P=0.001). The trend in percent cover of the various matrices was consistent among sites, but did change with time and in relation to tile face (significant interaction terms: Month x Matrix, *df*=10, *pseudo f*=4.64, P=0.001 and Month x Face, *df*=2, *pseudo f*=9.00, P=0.001). Pair-wise comparisons show that as early as 3 months post deployment, Portland cement tiles had lower live cover compared to the other matrices, mainly, MI, M4 and M5 who recruited the highest percent live cover.

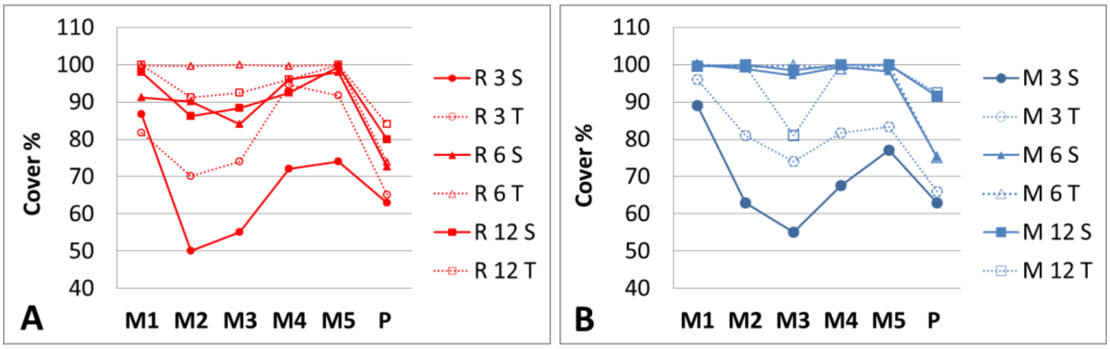

Figure 3: Comparison of percent live cover 3, 6 and 12 months post deployment on various innovative concrete matrices (M1-5) in comparison to

Portland cement. A) Red Sea, B) Med Sea. Solid line represents Smooth tile face while dotted line represents the Textured face.

When examining trends related to surface complexity, it is evident that while in the Red Sea differences between smooth and textured tile face were consistent with time, in the Med Sea, difference between plate faces was significant initially (3 month), yet non-significant 6 and 12 months post deployment. These results are in agreement with the multivariate community data analyses from the red sea, clearly indicating that overall, complex surface texture, as opposed to smooth, recruited more diverse and dense benthic assemblage (Figure 4).

Figure 4: Typical recruitment of benthic organisms onto innovative concrete matrices (example from M4, 6 m post deployment, Red Sea). A) Textured face fully with 100% cover. B) Smooth face of the same tile with limited recruitment. C) 2D-MDS of community data. Each point represents one tile face (Textured face = Red square, Smooth face = Black circle). Example from Red Sea data, 6 m post deployment showing separation between textured (up) and smooth (down) tile face.

Differences in the recruitment capabilities of the various innovative concrete matrices in comparison to Portland cement tiles were highly evident from the biomass analyses conducted 6 and 12 months post deployment, specifically, in relation to inorganic material (Fig. 5). While the amount of organic matter recruited onto the tiles differed among sites (*df*=1, *pseudo f*=4.93, P=0.029), no significant trend appeared in relation to months post deployment or between the various Matrices. Nonetheless, concentrations of inorganic matter significantly differed between sites (*df*=1, *pseudo f*=83.53, P=0.001), months (*df*=1, *pseudo f*=11.16, P=0.002) and Matrices (*df*=5, *pseudo f*=7.28, P=0.001). These difference changed with time between sites (significant Site x Month interaction: *df*=1, *pseudo f*=4.23, P=0.039), and pair-wise comparisons indicated that in the Red Sea station M5 and M4 were the ones driving the differences between Matrices, with highest values in comparison to other matrices, while in the Med Sea station M1, M4 and M5 had highest values on inorganic matter compared to the rest of the matrices.

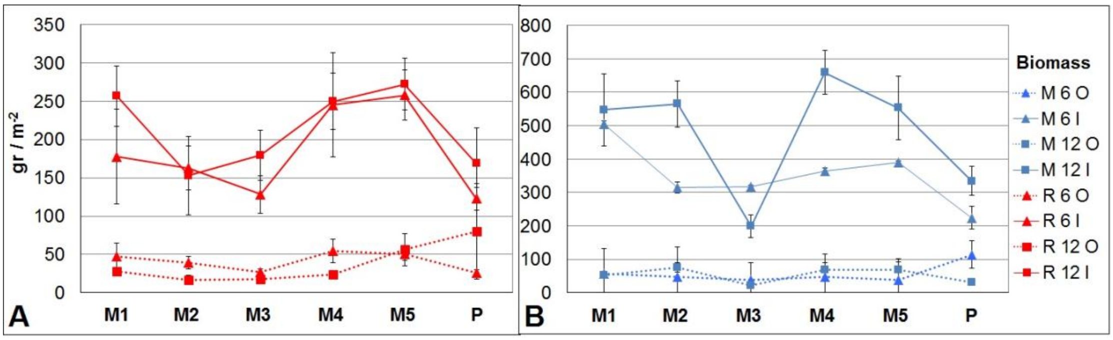

Figure 5: Comparison of organic (dotted line) and inorganic (solid line) biomass accumulated on innovative concrete matrices (M1-5) in comparison to Portland cement. A) Red Sea, B) Med Sea.

The amount of inorganic material recruited onto test tiles in the Med Sea was consistently higher than that recruited in the Red Sea. Nonetheless, values were generally high in both stations with an average of 413.51±25.63 gr/m$^{-2}$ at the Med Sea station and 201.14±10.28 at the Red Sea station. A year after submersion, similar matrices exhibited greatest accumulation of inorganic material in both the Red and Med Sea stations, being M1, M4 and M5 with values at the Med Sea of 547±107.58, 659.51±65.844 and 553.95±94.94 gr/m$^2$ respectively, and 272.31±33.84, 249.79±37.00 and 257.03±39.34 gr/m$^2$ at the Red Sea.

Chlorophyll a content also differed significantly among sites (*df*=1, *pseudo f*=52.62, P=0.001), months post deployment (*df*=1, *pseudo f*=9.09, P=0.001) and matrices (*df*=5, *pseudo f*=4.86, P=0.001). While in most cases chlorophyll a concentrations varied between months and matrices at the two study stations (significant Site x Months x Matrix interaction term: *df*=5, *pseudo f*=2.84, P=0.015), as can be seen in figure 6, one trend was consistent in both stations, where Chlorophyll a concentrations of M1 tiles were significantly higher than those of Portland cement tiles (P < 0.05 at both stations).

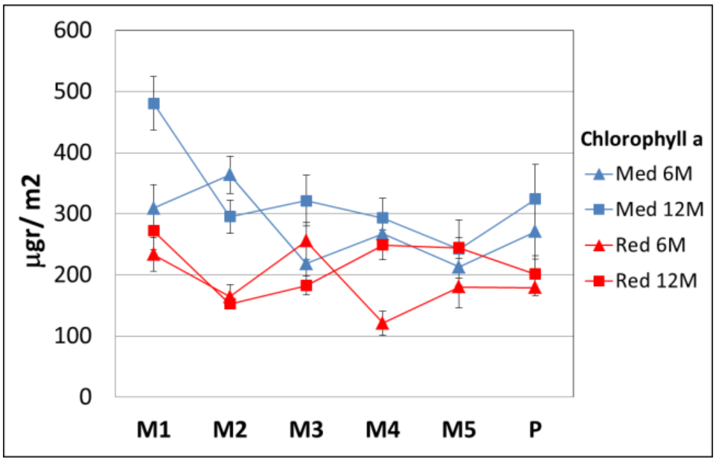

Figure 6: Comparison of Chlorophyll a concentrations on innovative concrete matrices (M1-5) in comparison to Portland cement, 6 and 12 months post deployment at the Med Sea (blue) and Red Sea (red) stations.

Coral recruitment, which was only found in the tropical Red Sea environment, was generally low during the first 6 months post deployment and greatly increasing in the last monitoring (Fig 7). After a year, significant differences in recruitment capabilities were identified between the various matrices, resulting mainly from results of soft coral recruitment (*df*=5, *pseudo f*=3.74 P=0.015). Pair-wise analyses of soft coral data show that M5 and M1 had significantly higher recruitment than Portland cement tiles, regardless of place face.

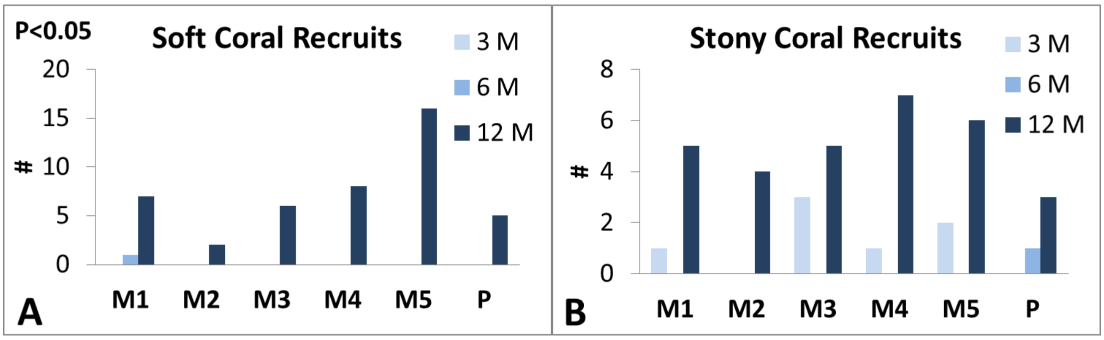

Figure 7: Comparison of coral recruits onto innovative concrete matrices (M1-5) in comparison to Portland cement. Values represent total number of recruits per concrete matrix (tiles and tile faces pooled). A) Soft corals, B) Stony corals.

## Lab Experiments

Natural attachment of *D. hemprichi* fragments was significantly different between the various matrices (Fig. 8A, *df*=5, *pseudo f*=2.75 P=0.042), where Portland cement had lowest attachment rates (16±9.42% attachment), while M1 and M5 had the highest attachment rates (44±11.86% and 36±6.69% respectively). A similar yet non-significant trend was also evident from the experiment with *H. fuscescens* larvae (Fig. 8C). Although Portland showed lowest average than the ecologically active matrices, due to high variability in the results this was not supported by the statistical test. Nonetheless, pair-wide comparisons did find a marginally significant difference between M5 and Portland cement (P=0.067). The experiment with *B. neritina* larvae however did yield significant results (Fig. 8C, *df*=4, *pseudo f*=4.05 P=0.009), where Portland cement had lowest settlement rates (2.35±1.25% attachment), while M1 and the highest recruitment rates (14.14±7.20%). Note that M5 results were not included here as due to a technical error M5 was not included in the experiment.

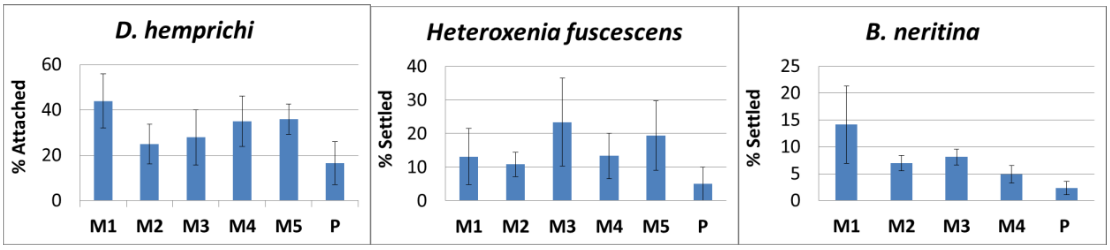

Figure 8: Comparison of A) natural attachment of *D. hemprichi* fragments, B) settlement of *H. fuscescens* larvae, and C) settlement of *B. neritina* larvae onto innovative concrete matrices in comparison to Portland cement.

## Discussion

With global predictions of increased growth in coastal populations, the trends of coastal hardening and expansion of coastal cities is expected to further increase. Moreover, in light of processes related to global climate change, coastlines are facing growing threats related to sea-level rise and increased storminess (Dugan et al., 2011 and references therein), calling for immediate revision of current coastal defense measures. This work examines an innovative approach of applying slight modifications to the composition and surface texture of concrete, aimed at facilitating marine grow and encouraging enhanced biogenic buildup. Three of the five matrices tested (MI, M4 and M5) were found to be ecologically active, exhibiting enhanced recruitment capabilities in comparison to standard Portland cement. This was evident from most of the biological parameters examined in the lab and at the field, at both sampling stations. Overall, these ecologically active matrices recruited greater live cover (Fig. 1), more inorganic matter (Fig. 5), and had higher settlement rates of corals and target organisms (Figs. 7-8) than the standard Portland cement based mix. Enhanced recruitment capabilities of natural assemblages of marine flora and fauna onto concrete based CMI yields valuable structural, environmental and socio-economic advantages.

In terms of structural advantages, as CMI are often used for coastal defense (e.g., breakwaters and seawalls), weight and stability plays a major role in structural performance. In this study, ecologically active concrete matrices accumulated significantly more inorganic matter than Portland cement. Biogenic buildup of ecosystem engineers like oysters, serpulid worms, barnacles and corals, increases the structures' weight, contributing to its stability and strength (Risinger, 2012). According our results, an average of 413 (Med Sea) – 201 (Red Sea) gr/m$^2$ can be added to ecologically active concrete surfaces within a 12 m period, reaching maximal values of 1 kg/m$^2$ in the Med Sea and nearly 0.5 kg/m$^2$ in the Red Sea.

While there are cases where growth of marine organisms, mainly burrowing sponges or certain species of green algae, can deteriorate concrete surfaces (Jayakumar and Saravanane, 2010, Scott et al., 1988), our results indicated of beneficial bio-protective effects. In addition to contributing to the overall weight of CMI, biogenic growth of coralline algae, oysters, corals and serpulid worms can strengthen concrete surface. For example, Risinger (2012) who examined the influence of oyster growth on concrete strength found that concrete covered with marine growth showed a significant ten-fold increase in flexural strength over a two years period. Apart from weight addition, biogenic buildup also increases the bond between adjacent infrastructure elements (armoring units, seawall precast elements, etc.), as marine growth acts as biogenic glue that can help absorb wave energy and reduce surge impact of the structure. Such biogenic buildup, which with time can cover the surface with a calcitic layer (Fig. 9), also adds to the durability of the structure by absorbing hydrodynamic forces and protecting the concrete from chloride attacks and chipping.

Figure 9: Scrapped material composed of calcitic biogenic growth accumulated onto an M4 tile 3 month post deployment.

Although such intense growth might disrupt visual surveys of the infrastructures' state, inspection can be achieved by scraping off sections of the growth at random (typically, no more than 10% of the surface), which will re-grow with time. In light of the above, application of ecologically active concrete matrices in CMI can help make them more sustainable, and in the long term might reduce the need and cost of maintenance work.

Apart from structural advantages, ecologically active concrete matrices are also associated with substantial environmental benefits. As evident from the results, matrices that have proved ecologically active had significantly higher live cover than standard Portland cement (average cover of MI, M4 and M5 tiles was nearly 100% in both stations 12 months post deployment, while Portland tiles averaged 82% - 92%). Much of the live cover consisted of ecosystem engineers that contribute to biogenic buildup (oysters, corals, barnacles and serpulid worms) on one hand, and filter feeding organisms that can elevate water quality and clarity on the other (e.g., tunicates, sponges, oysters and mussels). Moreover, as evident from both the in-situ and in vitro settlement experiments, corals and other typical intertidal organisms such as *B. neritina* showed clear preference to ecologically active matrices, predominantly M1 and M5. Creating CMI with enhanced ability to recruit corals and species that provide valuable ecosystem services such as filter feeders and biogenic builders is of great ecological importance. By enhancing the biological productivity and ecological value of CMI we can reduce their ecological footprint and utilize them as urban nature zones, instead of viewing them as scarified "urbanized-industrial deserts".

Another environmental advantage of some of the innovative concrete matrices tested is reduced carbon footprint. As matrices include various additives that can significantly reduce the amount of Portland cement in the mix, which is known for its high carbon footprint (Matthews et al., 2008), such matrices can be considered more ecological. For example, M2 and M3 did not perform much differently from standard Portland cement under the given time frame, yet as they have a reduced carbon footprint, they can still be considered more ecological than standard concrete mixes. Nonetheless, evaluating the carbon footprint of the various concrete matrices was not the scope of the current research and requires further investigation.

Finally, as CMI are an integral part of waterfronts throughout the globe, we cannot ignore their socio-economic implications. Nowadays, when environmental awareness is in constant rise, environmental agencies are calling for ecological compensation (Puig and Villarroya, 2013) and mitigation policies. Sustainable "green-blue" marine construction technologies can provide an efficient tool for managers and policy makers, reducing the environmental footprint of CMI. On top of this, integrating complex textures and designs to CMI, which promotes natural marine assemblages, also promote enhanced esthetic qualities that create urban marine nature zones, capable of elevating the environmental awareness among coastal communities.

### Conclusions

Slight modifications to concrete based CMI, taking into account concrete composition, surface texture and macro-design, have the potential to elevate their ability to support engineering species forming biogenic buildup, as well as associated filter feeding assemblages. The result is a unique benthic assemblage providing enhanced ecosystem services alongside with economic advantages such as elevated water quality, increased operational life span, structural stability, and absorption of hydrodynamic forces. These advantages are of great importance in CMI that must cope with aggressive salt-water environments.

## Acknowledgments

We thank Dr. Nadav Shashar from Ben Gurion University (BGU) for his support in the Red Sea Sampling Station, and Mr. Oded Golden for his support in the Med Sea Sampling Station. We would like to note the work of two BGU biotechnology students, Uria Tal and Malkiel Abehsera. We also thank the Interuniversity Institute of Eilat for strategic support, the Israel Nature and Parks Authority for permits, and the Biotechnology students from The Ruppin Academic Centre (Michmoret Campus).

## References

Anderson, M., Gorley, R. & Clarke, K. (2008) *PERMANOVA+ for PRIMER. Guid to Software and Statistical Methods. PRIMER-E, Plymouth UK, 214pp*

Bergen, S. D., Bolton, S. M. & Fridley, J. L. (2001) Design principles for ecological engineering. *Ecological Engineering,* 18**,** 201-210.

Bulleri, F. & Chapman, M. G. (2010) The introduction of coastal infrastructure as a driver of change in marine environments. *Journal of Applied Ecology,* 47**,** 26-35.

Cencini, C. (1998) Physical processes and human activities in the evolution of the Po delta, Italy. *Journal of Coastal Research,* 14**,** 774-793.

Chapman, M. G. & Underwood, A. J. (2011) Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. *Journal of Experimental Marine Biology and Ecology,* 400**,** 302-313.

Clarke, K. & Gorley, R. (2006) *PRIMER v6: User Manual/Tutprial. PRIMER-E, Plymouth UK, 192pp*

Connell, S. D. (2000) Floating pontoons create novel habitats for subtidal epibiota. *Journal of Experimental Marine Biology and Ecology,* 247**,** 183-194.

Connell, S. D. & Glasby, T. M. (1999) Do urban structures influence local abundance and diversity of subtidal epibiota? A case study from Sydney Harbour, Australia. *Marine Environmental Research,* 47**,** 373-387.

Creel, L. (2003) Ripple Effects: Population and Coastal Regions *Population Reference Bureau, MEASURE Communication.*

Dugan, J. E., Airoldi, A., Chapman, M. G., Walker, S. & Schlacher, T. (2011) Estuarine and coastal structures: environmental effects. A focus on shore and nearshore structures. IN WOLANSKI, E., ELLIOTT, M. & DUGAN, J. E. (Eds.) *Treatise on Estuarine and Coastal Science: 8. Human-induced problems (uses and abuses).* New York, Elsevier

Dyson, K. L. (2009) Habitat Enhancing Marine Structures: Creating habitat in urban waters. Master of Marine Affairs Thesis. School of Marine Affairs, College of Ocean and Fishery Sciences, University of Washington.

Ebm (2004) Environmental Best Manangement Practice Guideline for Concreting Contractors. Department of Environment and Conservation (NSW)
Sydney.

Eea (1999) Annual report. Copenhagen, European Environment Agency.

Glasby, T. M., Connell, S. D., Holloway, M. G. & Hewitt, C. L. (2007) Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? *Marine Biology,* 151**,** 887-895.

Goff, M. (2010) Evaluating Habitat Enhancements of an Urban Intertidal Seawall: Ecological Responses and Management Implications. MSc Thesis University of Washington

Greenberg, A. E. (1995) Standard methods for the examination of water and wastewater, 19th Ed. APHA, Washington, DC

Jayakumar, S. & Saravanane, R. (2010) Biodeterioration of Coastal Concrete Structures by Marine Green Algae. *International Journal of Civil Engineerng,* 8**,** 352-361.

Jones, C. G., Lawton, J. H. & Shachak, M. (1994) Organisms as ecosystem engineers. *Oikos,* 69**,** 373-386.

Lam, N. W. Y., Huang, R. & Chan, B. K. K. (2009) Variations in Intertidal assemblages and zonation patterns between vertical artificial seawalls and natural rocky shores: A case study from Victoria Harbour, Hong Kong. *Zoological Studies,* 48**,** 184-195.

Li, B., Reeve, D. E. & Fleming, C. A. (2005) Design for enhanced marine habitats in coastal structures. *Proceedings of the Institution of Civil Engineers-Maritime Engineering,* 158**,** 115-122.

Lukens, R. R. & Selberg., C. (2004) Guidelines for Marine Artificial Reef Materials. *A Joint Publication of the Gulf and Atlantic States Marine Fisheries Commissions.*

Matthews, H. S., Hendrickson, C. T. & Weber, C. L. (2008) The importance of carbon footprint estimation boundaries. *Environmental Science & Technology,* 42**,** 5839-5842.

Naylor, L. A., Venn, O., Coombes, M.A., Jackson, J. Thompson, R.C. (2011) Including Ecological Enhancements in the Planning, Design and Construction of Hard Coastal Structures: A process guide. Report to the Environment Agency (PID 110461). University of Exeter

Perkol-Finkel, S., Ferrario, F., Nicotera, V. & Airoldi, L. (2012) Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. *Journal of Applied Ecology,* 49**,** 1457-1466.

Perkol-Finkel, S., Zilman, G., Sella, I., Miloh, T. & Benayahu, Y. (2006) Floating and fixed artificial habitats: effects of substratum motion on benthic communities in a coral reef environment. *Marine Ecology Progress Series,* 317**,** 9-20.

Perkol-Finkel, S., Zilman, G., Sella, I., Miloh, T. & Benayahu, Y. (2008) Floating and fixed artificial habitats: Spatial and temporal patterns of benthic communities in a coral reef environment. *Estuarine Coastal and Shelf Science,* 77**,** 491-500.

Puig, J. & Villarroya, A. (2013) Ecological quality loss and damage compensation in estuaries: Clues from a lawsuit in the Basque Country, Spain. *Ocean & Coastal Management,* 71**,** 46-51.

Risinger, J. D. (2012) Biologically Dominated Engineered Coastal Breakwaters. PhD Thesis, . *Department of Biological and Agricultural Engineering.* Louisiana State University and Agricultural and Mechanical College.

Scott, P. J. B., Moser, K. A. & Risk, M. J. (1988) Bioerosion of Concrete and Limestone by Marine Organisms: A 13 year Experiment from Jamaica. *Marine Polhttion Bulletin,* 19**,** 219-222.

Wiecek, D. (2009) Environmentally Friendly Seawalls A Guide to Improving the Environmental Value of Seawalls and Seawall-lined Foreshores in Estuaries, Department of Environment and Climate Change NSW on behalf of Sydney Metropolitan Catchment Management Authority. Sydney.