ECOLOGICAL ENGINEERING CONSIDERATIONS FOR CORAL REEFS IN THE DESIGN OF MULTIFUNCTIONAL COASTAL STRUCTURES

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A multifunctional structure is being designed for the Kahului Harbor, Maui, Hawai'i, to mitigate operational problems caused by wave energy while also providing coral reef habitat. There is limited information on how the design of a coastal structure can be manipulated to enhance the ecology of targeted coral communities. To inform the ecological engineering of an artificial coral reef, the relationship between substrate characteristics and coral colonization was investigated through coral recruitment experiments and study of field conditions. Three concrete compositions that differed by the use of basalt, limestone, or recycled aggregates were tested in field and laboratory experiments to determine the impact of each substrate on the recruitment of juvenile hermatypic corals. The concrete test plates were deployed in three environments for a period of about one year, after which the coral recruits on each plate were identified and counted. No significant difference was found in the average number of coral recruits on the concrete mixed with basalt, limestone and recycled aggregate (60 ± 9, 83 ± 17 and 77 ± 14, respectively). Significant differences in coral recruitment were found due to the laboratory tanks, deep water, and shallow water field tests environments (86 ± 11, 135 ± 15 and 4 ± 1, respectively). These results highlight the importance of environmental site conditions for the development of coral reef habitat. A field study was conducted in the vicinity of purposed artificial reef site to relate the topographic features of the surrounding environment to the levels of live coral coverage. The benthic zone was surveyed using a drop camera system and by divers who recorded *in-situ* observations. Of the area surveyed, the highest density of coral coverage (>90% cover on 60% of the area) was found on an adjacent natural reef area that was characterized by spur and groove geomorphology with a high degree of macro- and microtopographic complexity. In contrast, sparse coral cover was discovered on the concrete armor units of the existing east breakwater structure, while no live coral cover was observed on the sand and carbonate rubble substrate at the proposed artificial reef location. The high degree of coral coverage on the adjacent natural reef suggests that the artificial coral reef design should emulate the natural spur and groove structure with regards to topographic complexity on multiple scales, orientation with wave direction, and water depth.

Keywords: submerged breakwater; multipurpose reef; coral recruitment; mitigation; benthic survey; topographic complexity; concrete mix design; shoreline protection; armor units

INTRODUCTION

In the process of constructing cities, harbors, highways and other civil infrastructure along shorelines, coastal engineers have had an unavoidable impact on the world's coral reef ecosystems. Healthy coral reefs are important to coastal communities because they provide shoreline protection, critical habitat for marine ecosystems, and recreational benefits (Cesar and van Beukering 2004). These highly valued benthic resources are declining significantly world-wide due to several severe threats including poor land-use practices, overfishing and the impacts of climate change (Hughes et al. 2003; Hoeke et al. 2011; Hoegh-Guldberg 2011). Climate change is highly likely to decrease coral cover because it has increased the frequency of high temperature events that cause coral bleaching and decreased the calcification rates of corals due to ocean acidification (Hoeke 2011). Moreover, the impacts of climate change include accelerating rates of regional sea-level rise (Anderson et al. 2010) and increased intensity of tropical cyclones (Knutson et al. 2010), which will impact coral reefs while also triggering the need for increased investment in coastal infrastructure to protect shoreline communities. Coastal engineers face the challenge of maintaining and developing infrastructure while potentially causing unavoidable impacts to coral reefs. Navigating the permitting process when the project potentially impacts a threatened environmental resource is a challenge that will likely get more difficult as the legal protections for corals get more stringent.

Coral reef resources currently have strong environmental protections in the United States due to several federal statutes including Executive Order 13089 on Coral Reef Protection, the Clean Water Act and the Coastal Zone Management Act. Protecting, preserving and enhancing the health, biodiversity, heritage, and social and economic value of these environmental resources is a pertinent concern of the U.S. Government (Clinton 1998) and as anthropogenic threats continue to endanger the future prosperity of the world's coral reef ecosystems, the environmental regulations protecting these

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resources will likely become more stringent. Already in 2014, the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) decided to list an additional 20 coral species as threatened under the U.S. Endangered Species Act, raising the total number of protected coral species to 22 (U.S. Department of Commerce 2014).

Whether it is the maintenance of an existing pier or the development of a new port, engineering projects that involve dredging or construction in the coastal zone are likely to cause substantial unavoidable losses to coral communities in the surrounding area (Stender et al. 2014a). For these projects to receive approval under Section 404 of the Clean Water Act, compensatory mitigation to replace the function and area of the environmental resource that will be lost is usually required (U.S. Environmental Protection Agency 2004). Among the potential management options available for the mitigation of impending damage to coral reef ecosystems (Jokiel and Naughton 2001) is the development of artificial reefs specifically designed for coral colonization (Naughton and Jokiel 2001; Gilliam 2012).

Artificial reefs have been traditionally deployed for fisheries stock enhancement (Baine 2001), but submerged structures also provide a substrate that can be inhabited by corals either through natural processes or by transplanting living coral colonies (Ferse 2013). The development of a coastal structure such as a breakwater or groin provides an opportunity to create a large-scale artificial reef that will mitigate for lost coral resources. The mitigation will only be successful, however, if healthy coral communities are able to develop on the artificial substrate. Studies of the benthic communities that develop on breakwater substrates have shown that they are distinct from natural reefs and that older structures can have significantly more coral cover than natural reefs in the surrounding area (Burt et al. 2011). There have been relatively few studies, however, that relate the specific design features of man-made structures to their effectiveness at enhancing targeted communities of coral species (Dupont 2008).

When designing an artificial coral reef, the engineer should consider the characteristics of the macro- and microhabitats on neighboring natural reefs in terms of topographic complexity, spatial orientation, materials, and texture along with the biotic and abiotic drivers (Svane and Petersen 2001; Spieler et al. 2001; Chapman and Underwood 2011). The current study was undertaken to gather information on how features of a structure can be manipulated to mimic the characteristics of local coral reef habitats. The response of hermatypic (or reef-building) corals to the material and topographic features of the reef substrate were investigated so that the design of the coastal structure could be optimized for producing robust coral reef resources.

Project Background, Objectives and Scope

The current research is part of the engineering design process for a multifunctional artificial reef in Maui, Hawai‘i. The reef has been proposed to provide much-needed wave protection for Kahului Commercial Harbor (Foley and Singh 2011). Kahului Harbor was developed in the early 1900's on a north-facing isthmus formed by two shield volcanoes and is the only deep draft harbor on the island (Sargent et al. 1988). The harbor entrance is exposed to prevailing northeasterly seas and large northerly swells during the fall and winter months. The wave energy has caused serious negative impacts to harbor operations and structures (Sargent et al. 1988; Okihiro et al. 1994; Thompson and Demirbilek 2002). Harbor protection is the primary objective of the submerged breakwater design, but the structure is also being engineered to serve as a multifunctional reef by providing the necessary hard substrate for reef-building corals to enhance their recruitment, growth, and abundance in the area.

Previous research has found that recruitment of corals is influenced by the type of substratum (concrete, gabbro, granite, or sandstone) used in the construction of artificial reefs and coastal defense structures (Burt et al. 2009). The Kahului multifunctional reef is being designed to use precast concrete to compose its volume. Concrete is a suitable material for the reef construction because of its local availability, versatility, and durability in the marine environment (Mohammed et al. 2003; Seleem et al. 2010). Ideally, the concrete can be mixed from materials that are affordable, sustainable, and functional for coral reef ecology. Since aggregates are the major components of a concrete mixture (Kosmatka and Panarese 1988), the choice in aggregate materials will have a large influence on these goals.

In this study, field and laboratory investigations were conducted to obtain pertinent information for engineering the ecological aspects of coastal structures to provide artificial coral reef habitat. The study examined the effect of three concrete mixtures on the development of corals on the reef stratum. The concrete compositions were tested through field and laboratory experiments to determine their impact on the recruitment of juvenile hermatypic corals. Field surveys of the benthic environment in the vicinity of the artificial reef project site were also conducted to gather data on the levels of coral coverage along with macro- and microtopographic features of the substrate. The topographic complexity preferred by stony corals in the surrounding environment will inform the ecological engineering of the multifunctional reef design.

METHODOLOGY

Concrete Experiments

Field and laboratory experiments were conducted to evaluate the suitability of three concrete mixes for the recruitment of corals. Each mix varied only by the aggregates used. The Absolute Volume Method was used to design a concrete mix for the test plates (Kosmatka and Panarese, 1988). Grace Pacific Rocky Mountain Prestress of Kapolei, Hawai'i, manufactured the test plates using the mix proportions shown in Table 1. The mix design was based on the use of basalt rock coarse aggregate material, which is the most common concrete for construction in Hawaiʻi. Two other mixes were prepared using limestone aggregates obtained from the Pacific Aggregate (Sphere, LLC) quarry in Waianae, Hawai'i, and with crushed concrete/asphalt debris salvaged from demolition projects. The use of a recycled aggregate material adds sustainability benefits to the project. Type I-II Hawaiʻian Cement was used for all three mixes. Fine aggregate materials used in the mixes included basalt sand, Maui dune sand and coral sand. Basalt sand mixed with a small proportion of Maui dune sand was used for the basalt and recycled aggregate concrete mixes. The limestone plates were made using only coral sand.

Table 1. Approximate concrete mix proportions used to manufacture test plates (lbs./yd^3).

Cement	658-752
Water	350
Coarse Aggregate	1186
Fine Aggregate	1503

Each concrete mix was poured into formwork to produce multiple test plates (Fig. 1). The top surface of each plate was trapezoidal in shape with side lengths of approximately 30 cm x 33 cm x 23 cm x 33 cm for the long base, side one, short base, and side two, respectively. The calculated area of the top surface was about 870 cm^2. Each plate was about 4 cm thick, so the total surface area was about 2,215 cm^2. The concrete formwork was coated with a retarder to prevent the cement from setting on the surface of the plates. The plates were later power-washed to expose the aggregate material beneath the surface, resulting in a rough surface finish. This texture was desirable because significantly higher coral settlement has been reported on surfaces that contain micro-crevices and small spaces (Nozawa et al. 2011). By exposing the coarse aggregate, the surface area of each plate was increased along with the likelihood of small spaces for coral recruits. The plates were labeled individually using unique identification numbers.

Figure 1. Three concrete test plate types were made with the same mix design and used (1) basalt, (2) limestone, and (3) recycled concrete/asphalt aggregate materials.

The concrete test plates were exposed to the local marine environment in laboratory and field experimental setups conducted at Kāneʻohe Bay on the island of Oʻahu. The laboratory tests took place at the Coral Reef Ecology Laboratory, Hawaiʻi Institute of Marine Biology. The laboratory experimental setup consisted of three outdoor tanks with a flow-through system of ambient seawater (Fig. 2). Each tank had dimension of 116 cm x 116 cm x 45 cm in length, width, and height for a volume of 605.5 L. Four test plates of each aggregate type were randomly selected and positioned upright along the four walls of the tank for a total of 12 plates in each tank. To ensure larval settlement, adult colonies of lace coral, *Pocillopora damicornis*, were placed on the bottom of each tank. Half of the plates from each mix type also had adult corals cemented in the center of the top surface while the other pair had none.

Figure 2. (1) Concrete plates were deployed in seawater test tanks in the laboratory experimental setup. (2) *P. damicornis* were placed in the center of each tank, and (3) were also cemented on half of the test plates.

The field experiments took place at two patch reefs located near the Sampan Channel in Kāne‘ohe Bay (Fig. 3). The wind and wave exposure, water circulation, habitat type, likelihood of coral larval availability and settlement, and accessibility were considered upon the selection of these locations. The environmental conditions at the chosen reefs are similar to those at Kahului Bay because they are exposed to trade wind and constant water motion though the channel. Placing the experiment in a central reef location within Kāne‘ohe Bay also exposes it to greater larval availability and settlement than northern or southern reef locations (Hodgson 1985; Kolinski and Cox 2004). The habitat composition at the selected locations are relatively homogeneous and are mainly characterized by a mixed bottom of live corals (10 to less than 50% cover, Battista et al. 2007), coralline and turf algae, rubble, and unconsolidated substrates. Two experiment sites were established at each location. The ‘deep’ and ‘shallow’ site locations were at average depths of 6.5 m and 1.0 m, respectively. A total of five plots were selected within each of the four sites. Two plates of each aggregate type were randomly assigned to a plot, thus six plates for each plot (Fig. 4).

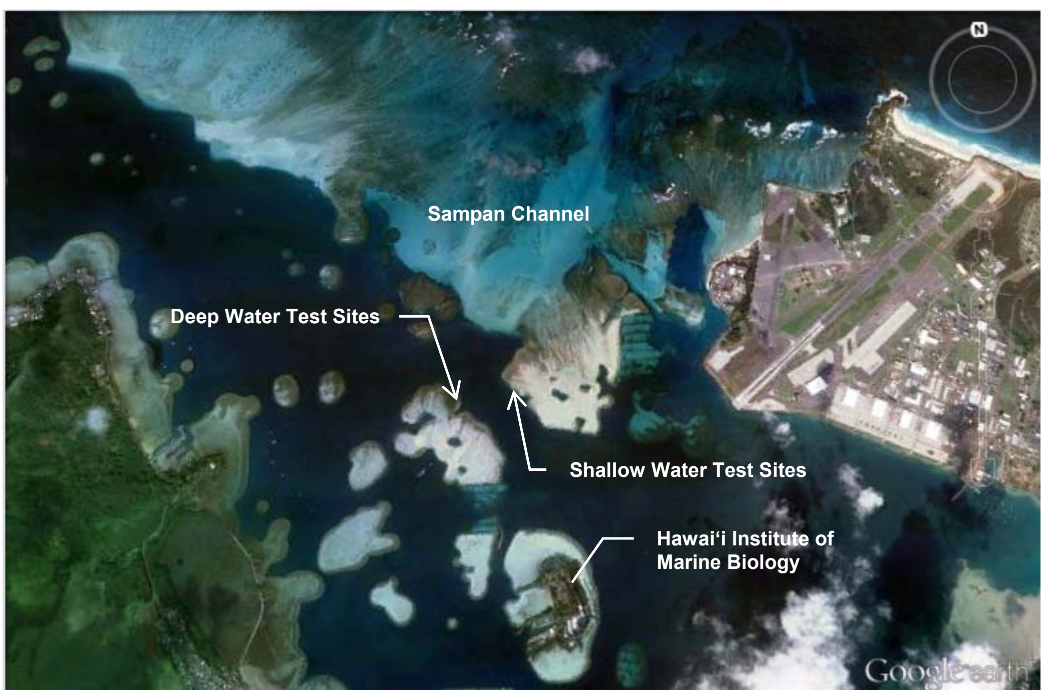

Figure 3. Map of the deep and shallow field experiment test sites located at patch reefs in Kāne‘ohe Bay, O‘ahu (Google Inc. 2014).

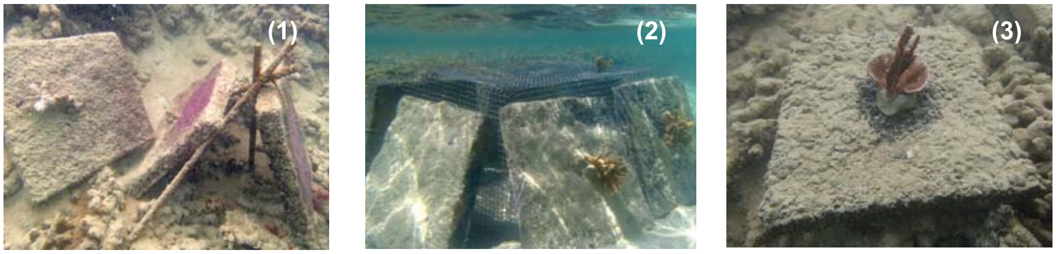

Figure 4. Concrete plates were deployed in plots of six on the sea floor in the field experimental setups at the (1) deep and (2) shallow sites. (3) *M. capitata* were cemented on half the test plates.

The concrete plates were deployed in the laboratory and field experimental setups in December 2012. The peak reproduction of Hawai‘ian corals occurs during summer months (Kolinski and Cox 2004), so the plates remained exposed to the environment throughout the summer. The laboratory and field experiments concluded on September and November 2013, respectively. The plates were removed from the saltwater environment and were rinsed with fresh water to remove soft-bodied organisms and expose the skeletons of coral recruits. Handheld and head worn magnifiers were used to count the number of coral recruits, determine the coral species, and measure the colony size on each surface of each concrete test plate. The average number of coral recruits on each concrete type was calculated for each experimental setup. An independent-sample t-test was used to determine if there was a significant difference between coral recruitment on each of the three concrete types within each experimental setup.

Kahului Bay Field Surveys

Field surveys were carried out on May 29-30, 2013, to characterize the relationship between coral coverage and the topographic features and habitat conditions of the substrate in the vicinity of the proposed artificial reef installation site in Kahului Bay. Survey data was collected through camera transects and *in-situ* observations that focused primarily on the distinct environments in the area. The surveyed areas included the artificial reef site, the harbor breakwater, the navigation channel and a neighboring natural reef (Fig. 5). The location of the artificial reef site was defined according to the recommendations of a numerical modeling study (Sundar and Sannasiraj 2013), which optimized the submerged breakwater location based on the results of wave transformation calculations for structures of various dimensions and alignments.

Seven drop camera transects (T1-T7) (Fig. 5) were conducted using an underwater video (Sea View, Sea View LLC) and photographic camera (GoPro Hero3) system deployed from a 31-foot research support vessel (Alyce C, Moloka‘i). The locations and water depths along each transect were recorded using the vessel’s Global Positioning System and depth transducer, respectively. Non-overlapping images were identified, corrected, and then visually interpreted for types and levels of benthic features. The data recorded by the drop camera system were used to classify geomorphic features and biological cover types as well as to identify presence of marine organisms to the lowest taxonomic level possible. The classification scheme of geomorphic features and biological cover types followed Battista et al. (2007). Benthic cover types included live corals, coralline algae, turf, sand, carbonate rock, and reef rubble. Levels of cover were defined in the following bins: continuous (> 90%), patchy (50 - <90%), sparse (10 - <50%), and none (<10%). These data were analyzed to describe relative occurrence of benthic cover types and the level of coverage among images for each transect as described by Stender et al. (2014b).

The *in-situ* surveys were conducted to validate the information obtained from the drop camera images and to supplement them with detailed field observations recorded by divers using self-contained underwater breathing apparatuses (SCUBA). The divers evaluated the biota and topographic features at six sites (IC, OC, PSB, OHB, IHB, and NRF) (Fig. 5), including the proposed breakwater location and distinct neighboring habitats. OHB, IHB, IC, OC, and PSB are sites within artificial or human-modified habitat while NRF represents natural habitat. Observations were made on presence of benthic organisms, species richness (number of species), and the composition and distribution of the benthos. The similarities in species presence and composition among the six diving sites were also noted. The texture and overall structure of the benthic zone at each site was evaluated to determine how macro- and microscale topographic features relate to the benthos at each site.

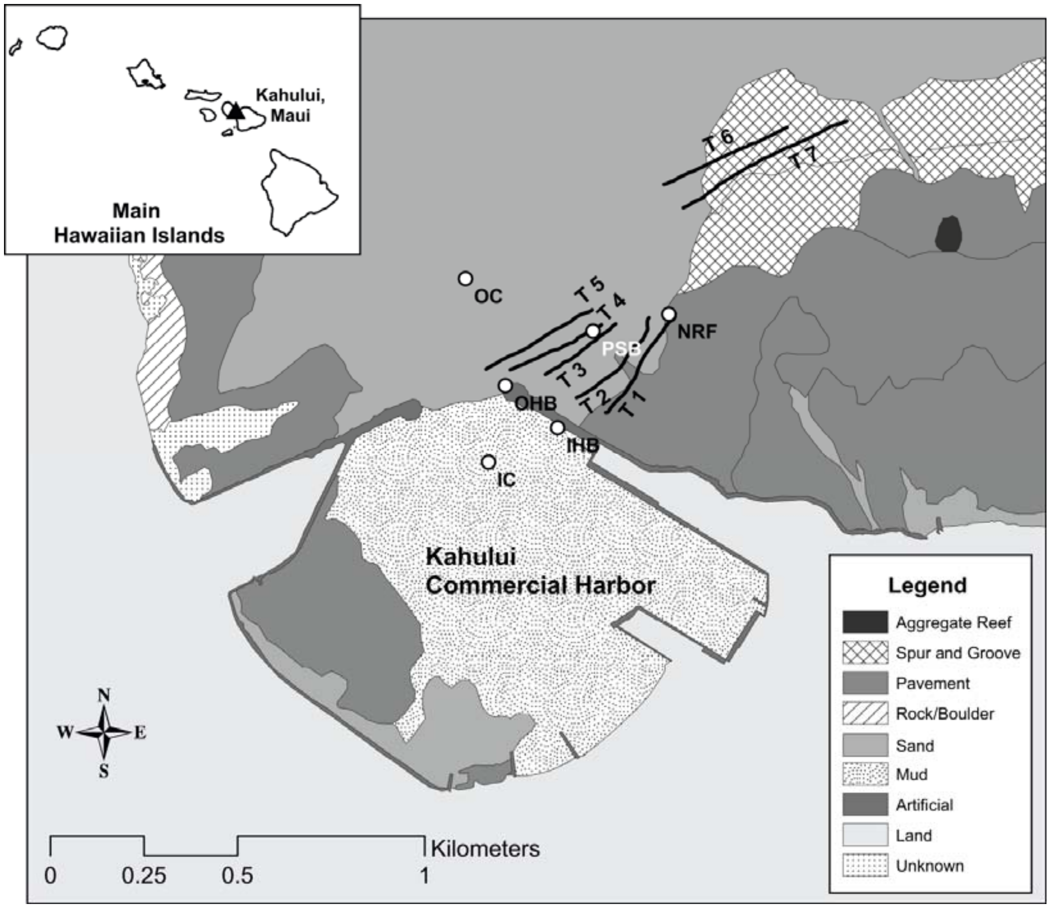

Figure 5. Map of geomorphic features, the camera transect tracks (black lines) T1- T7, and *in-situ* biological evaluation sites (white circles) including the navigation channel outside (OC), the inside channel (IC), the proposed submerged breakwater installation site (PSB), the outer harbor breakwater (OHB), the inner harbor breakwater (IHB), and the natural vertical reef and reef flat (NRF) adjacent to the proposed site in the Kahului Bay area (Stender et al. 2014b). Data source: NOAA NOS Biogeography Branch (Battista et al. 2007).

RESULTS

Concrete Experiments

A total of 3,088 and 8,321 coral recruits were identified at the conclusion of the experiment on the surfaces of the concrete plates deployed in the laboratory and field setups, respectively. Of the total coral juveniles identified on the plates deployed in the field, 8,070 recruits were found on the deep water test plates, while only 251 were found on the shallow water plates. The abundance of coral recruits on each type of concrete and within each test environment is illustrated in Figure 6.

The average number of coral recruits on the plates deployed in the laboratory tanks, deep water, and shallow water field tests were 86 ± 11, 135 ± 15 and 4 ± 1 (mean ± standard error), respectively. The independent-samples t-test showed a significant difference between the mean coral recruitment within each test environment. The laboratory tank environment resulted in significantly less juvenile coral recruitment than the deep water field sites [$t(94) = -2.65$, $P = 0.01$], but significantly more recruits than the shallow water field sites [$t(94) = 7.49$, $P = 7.6E\text{-}09$]. Coral recruitment on the concrete plates deployed at the deep water field sites was also found to be significantly higher than at the shallow water sites [$t(118) = 8.74$, $P = 2.7E\text{-}12$].

The average number of coral recruits found on all the basalt, limestone and recycled aggregate concrete plates deployed in this experiment were 60 ± 9, 83 ± 17 and 77 ± 14, respectively. The independent-samples t-test showed no significant difference between the mean coral recruitment on each of the three concrete types. For each of the three test environments, it was shown with a high degree of certainty ($\alpha = 0.05$) that the three aggregate materials result in the same coral recruitment.

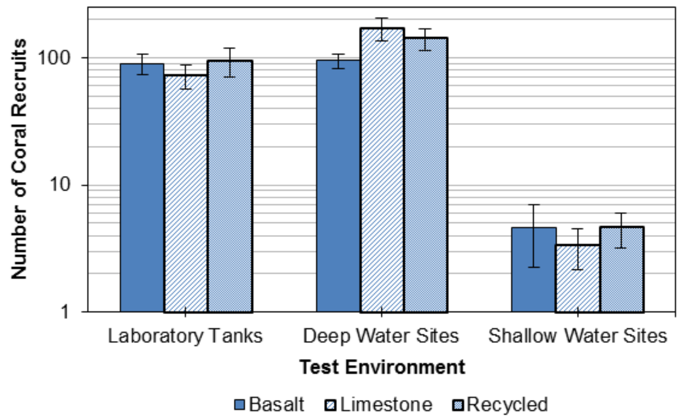

Figure 6. Mean coral recruitment on the three types of concrete plates located within each of the three testing environments. The error bars represent one standard error.

Kahului Bay Field Surveys

In total, approximately 4,682 m^2 of the study area was surveyed by the seven drop camera transects (Fig. 5). Analysis of the video and photographic images (Fig. 7) allowed for quantification of the benthic characteristics including topographic features and live coral cover type and relative abundance. Results showed that the coral coverage was continuous (>90% cover) on at least half of the area within transects T6 and T7, and about 80% and 95% of the area surveyed in these two transects contained some live coral cover (Fig. 8). The majority of the areas in transects T1 and T2 were classified as having none (<10%) or sparse (10-<50%) coral cover, and a small fraction was classified as having a patchy (50-<90%) distribution. No live corals were observed on transects T3, T4 and T5, which included the proposed location for the construction of the artificial reef.

The observations of the seafloor showed that the macrotopography for the majority of T6 and T7 was characterized by high relief spur and groove features (Fig. 8). The natural reef areas of T1 and T2 were characterized by pavement geomorphology, and had less topographic relief on the macroscale than the spur and groove formations. The seafloor topography observed in T3, T4, and the majority of T2 consisted of sparse carbonate rocks and reef rubble mixed with sand. The seafloor in transect T5 consisted entirely of sand. These areas had little macrotopographic relief and, in general, the bathymetry gradually sloped downward to the northeast at a rate of about 2%.

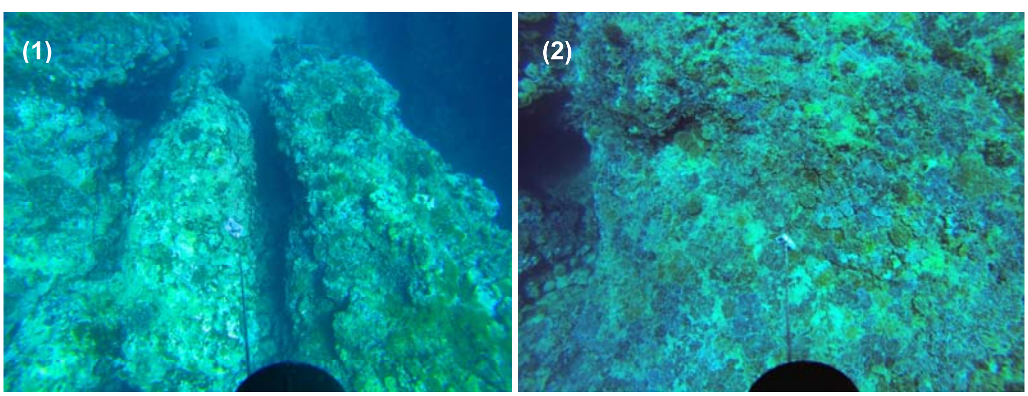

Figure 7. Drop camera photos showed that the natural reef at T6 is characterized by (1) spur and groove reef geomorphic features, and (2) benthic cover of continuous live corals that predominantly consisted of blue rice coral (*Montipora flabellata*).

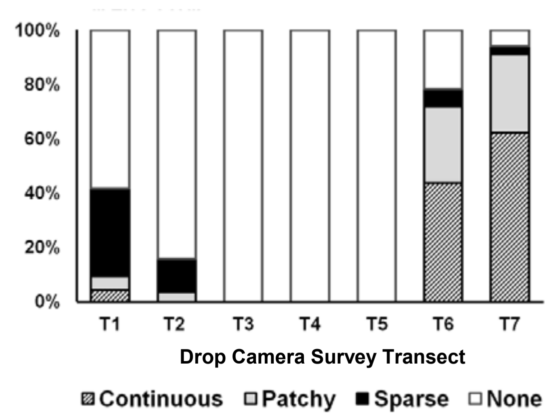

Figure 8. Relative occurrence of live coral coverage in photographic data collected during the camera surveys. The X-axes indicate transect IDs, y-axes show relative occurrence of cover type and abundance (Stender et al. 2014b).

The most abundant live coral cover observed through the drop camera transects (Fig. 7) was genus *Montipora* (rice coral). Transects T6 and T7 contained the greatest relative abundance of *Montipora* species (70% of live corals). These corals also counted for about 50% of the live corals found in T1 and T2. *M. flabellata* (blue rice coral) was found to be particularly abundant in T6 and T7 (Fig. 9). Second to *Montipora*, the genus *Porites* was common, and comprised nearly 25% of the live corals within transects where coral were found. *Pocilloporiids* were less common than the former two genera comprising < 5% of all live corals in T1, T6, and T7 and about 10% of the live corals in T2. Zoanthids, including *Palythoa caesia* and *Protopalythoa heliodiscus*, accounted for about 11-16% of live colonial cnidarians on T1 and T2 and < 5% on T6 and T7 (Fig. 9).

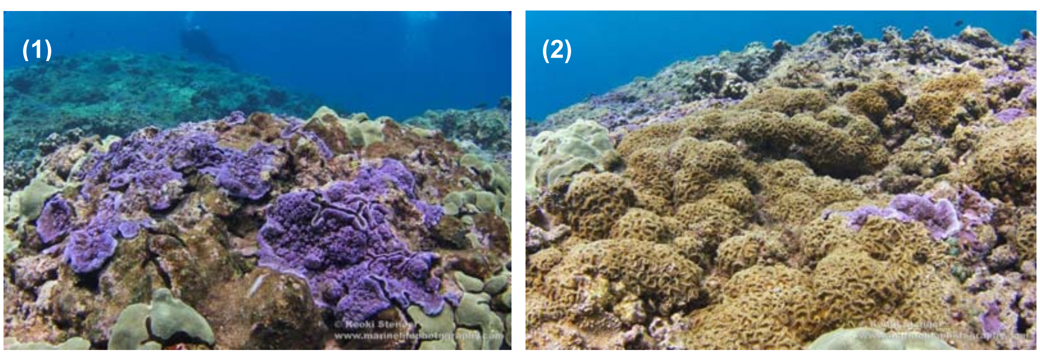

Figure 9. (1) Blue rice coral (*M. flabellata*) was abundant in T6 and T7 and was the most prevalent coral in the study area; (2) Zoanthids (*P. heliodiscus*), often colonized among the stony corals on the hard substrate.

The *in-situ* evaluations confirmed the general findings from the drop camera survey on the topographic characteristics, abundance of coral coverage, and coral species composition within the study area. A total of 13 hermatypic coral species were found among all the *in-situ* survey sites. The highest richness of epilithic species was observed at NRF (20 spp.) followed by OHB (19 spp.), IHB (18 spp.), PSB (12 spp.), and IC (1 sp.). There was no epilithic benthos found at OC.

The *in-situ* survey of the shallow reef flat at NRF identified species generally found on natural reefs in Hawai‘i, including corals, coralline algae, zoanthids, and grazing macroinvertebrates such as sea urchins (Fig. 10). There was a high level of biodiversity in this area, with 8 of the 13 observed coral species being recorded here. The highest proportion of continuous live coral cover was also found at NRF. Abundance of multiple coral species, including blue rice coral (*M. flabellata*), which is usually found in well-circulated high wave energy zones, was found on the shallow surfaces of the reef. Coralline algae and brown rice coral (*M. capitata*) were found to predominantly colonize the deeper surfaces and vertical sides of the spurs that reach down to the sandy seafloor. A high degree of topographic relief and complexity on the macro- and microscales was found during the *in-situ* survey of the NRF. The spur and groove reef morphology created macrotopographic complexity, while the high coverage by living corals created topographical complexity on the microscale (Fig. 10).

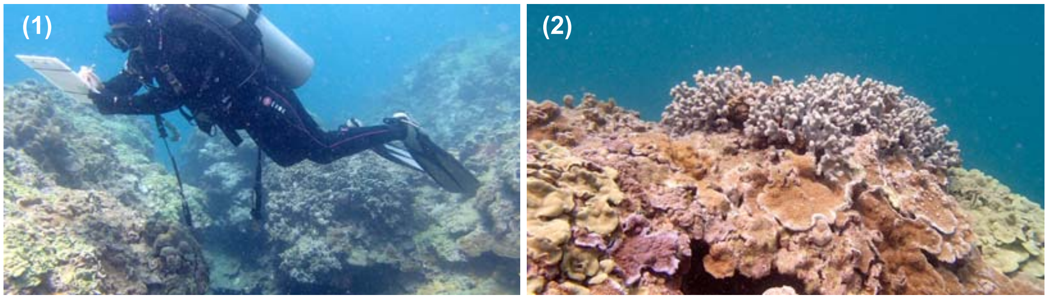

Figure 10. The hard substrate at NRF was characterized by (1) spur and groove geomorphology, and (2) a high density and diversity of hermatypic coral cover. These features added micro- and macrotopographic complexity to the reef structure.

The *in-situ* observations at the proposed artificial reef site (PSB) confirmed that the seafloor consisted of a sandy bottom with scattered rubble rock and little macrotopographic complexity (Fig. 11). The loose carbonate rocks dispersed randomly in the seafloor sediments provided more relief than would a pure sand bed, but microtopographic complexity was low compared to the NRF site due to the lack of coral formations. No species of hermatypic corals were observed during the *in-situ* observations at PSB. The benthos here was dominated by non-indigenous and introduced species. These were mainly filter feeders such as sponges, tunicates, bryozoans, deposit-feeding worms, as well as the invasive spiny seaweed *Acanthophora specifera*.

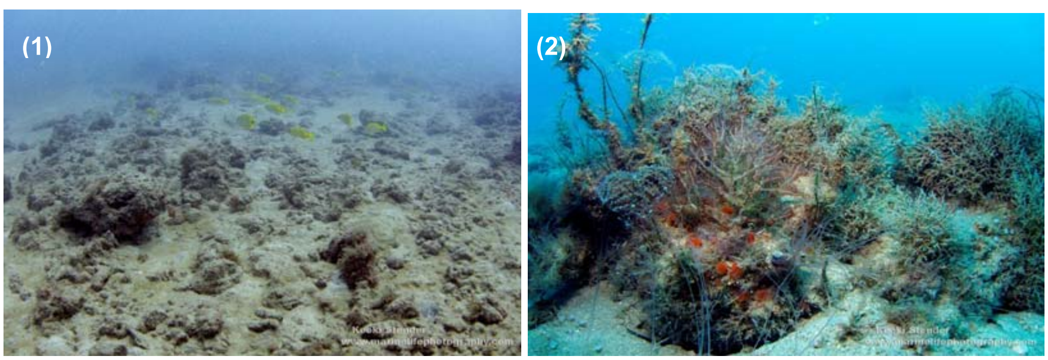

Figure 11. (1) The seafloor at the proposed artificial reef location (PSB) was characterized by a sandy bottom with scattered rubble rock that provided low macrotopographic relief. (2) The carbonate rock was colonized by bryozoans, sponge, hydroids, tube worms, sea anemones, and invasive spiny seaweed (*Acanthophora specifera*). No live hermatypic corals were found at this location.

The *in-situ* observations of the seaward surface of the east breakwater (OHB) revealed that the macrotopographic complexity of the structure was high, but was also characteristically different from that of the natural reef at NRF. The substrate here was formed by two layers of 35-ton tribars and by 20 and 6-ton dolosse that were placed on the seaside slope of the breakwater in 1966 and 1977, respectively (Sargent 1988). These interlocking and overlapping concrete armor units formed an artificial reef with a macrotopography characterized by large shaded overhangs and a steep uniform sloping face oriented perpendicular to the wave direction. Although macrotopographic relief was high, the structural features differed from that of the spur and groove and pavement geomorphology observed on the natural reef. On the microscale, the complexity of the structure was low. The smooth surfaces of the concrete armor units did not provide the same amount of microtopographic complexity as the natural coral reef (Fig. 12).

Six species of coral were found in sparsely distributed colonies on the concrete substrate at OHB in water depths of three to five meters. Rice coral (*M. capitata* and *M. patula*) and cauliflower coral (*Pocillopora meandrina*) were relatively common, while elkhorn corals (*P. eydouxi*) were rare on the structure. The shaded areas on the undersides of overlapping units were found to be the preferred location for colonization by introduced and invasive species, which mainly included sponges, soft corals and snowflake coral (*Carijoa riisei*). The zoanthids (*Palythoa caesia*) frequently observed at NRF were also present on the breakwater (Fig. 12)

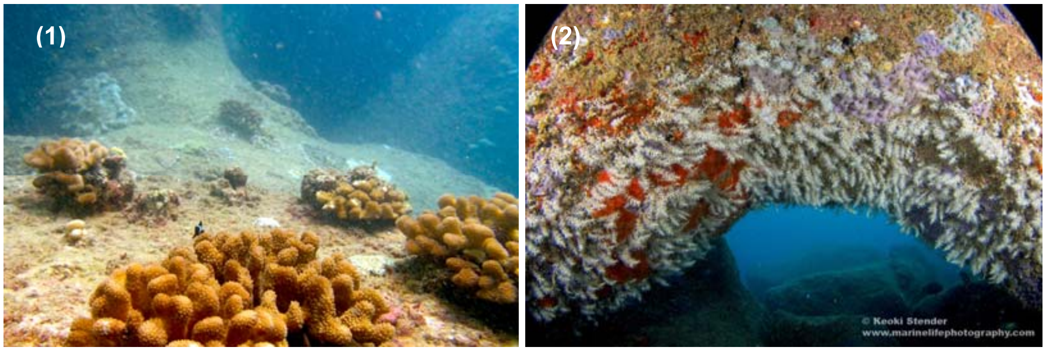

Figure 12. The concrete armor units at OHB formed an artificial reef topography characterized by smooth surfaces and large shaded overhangs. (1) Hermatypic corals sparsely colonized the upper surfaces of the concrete substrate, (2) while snowflake coral (Carijoa riisei) and encrusting sponges (cf. *Haliclona* sp.) colonized on the shaded surfaces.

In-situ survey of the harborside of the east breakwater (IHB) showed that this site was also unique in its macrotopographic characteristics. The surveyed substrate was created in 1984 when 9-ton tribar armor units were placed on the harborside of the breakwater (Sargent 1988). The interlocking units formed a macrotopography characterized by a relatively uniform downward slope (Fig. 13). There were relatively little voids on the macroscale when compared to the seaward slope of the breakwater, which leads to much less vertical relief within the structure. Like the seaward slope, the microtopography on the harborside breakwater was formed of relatively smooth concrete faces, which provided much less complexity compared to the microfeatures of the natural coral reef.

The settlement and growth of hermatypic corals was evident on the concrete substrate at IHB. Seven coral species were recorded at this site in sparsely distributed colonies. Lace coral (*Pocillopora damicornis*) and Brigham's coral (*Porites brighami*) were relatively rare during this study and were only observed at IHB. Rice coral (*M. capitata*) was common on the inner harbor breakwater, but was in poor physical condition compared to the colonies observed at OHB and NRF. Many colonies of this species on the inside harbor wall exhibited a disease called Montipora White Syndrome (MWS), which causes acute or chronic loss of their living tissue often leading to partial or full mortality of a colony. The etiology and association of MWS with particular environmental conditions that may promote prevalence of MWS are current research topics in coral biology (Stender et al. 2014b).

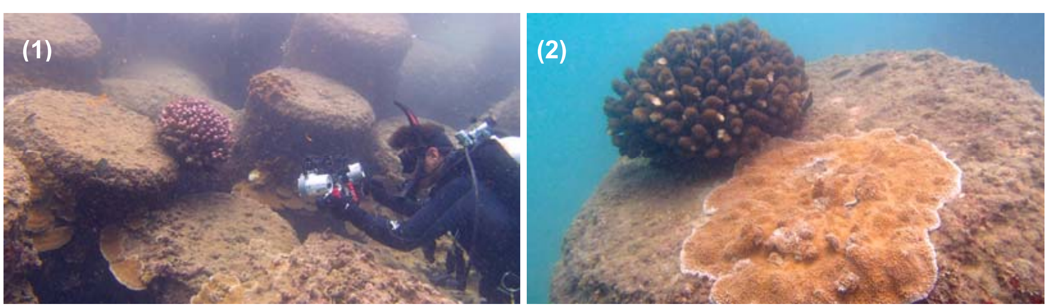

Figure 13. Interlocking concrete tribar armor units at IHB formed (1) an artificial reef topography characterized by smooth horizontal and vertical faces forming a relatively uniform downward sloping surface, and (2) an artificial substrate that was sparsely colonized by hermatypic corals.

DISCUSSION

When designing a submerged breakwater structure, the coastal engineer can reference previous studies on wave transmission over submerged structures (Wamsley et al. 2002) to size the geometry for wave conditions, but little information exists on how the design can be manipulated to enhance the ecology of targeted coral communities (Dupont 2008). The choice in construction material and the shape of the structure are two fundamental design choices. Previous research suggested that the choice of construction materials influenced the coral recruitment and early benthic community development on artificial reefs and breakwaters (Burt et al. 2009) and that breakwaters can develop significantly more coral cover than surrounding natural reefs with time (Burt et al. 2011). The current study aimed to investigate how the choice in concrete aggregate materials and the large- and fine-scale topographic design features would impact the development of local coral reef ecology on an artificial substrate.

The results of the experimental study on coral recruitment showed no significant difference in the amount of coral recruitment based on the use of locally available basalt, limestone, and recycled aggregates. The study did find a significant difference in the number of coral recruits based on the environment that the artificial substrates were deployed in over the year. These finding coincide with those of a similar study (Burt et al. 2009) and are reasonable given the many environmental factors that are known to influence the development of coral communities on natural and engineered structures (Jokiel 2008). The coral recruitment results emphasize the importance of considering the overall conditions of the environment when designing a structure for coral reef ecology. A successful artificial coral reef project will include an engineered coastal structure that provides a substrate that is suitable for the ecology of hermatypic corals while also imploring means to protect and improve the quality of the marine environment in the area. The establishment and enforcement of marine reserves and the proper control of storm runoff within watersheds (Jokiel and Naughton 2001) are examples of management practices that can be implemented to coincide with the ecological engineering of a multifunctional coral reef structure.

The surveys of the benthic characteristics of Kahului Bay conducted during this study found that the greatest degree of coral coverage occurred on the natural spur and groove reef site. This area was about 500 m away from the purposed artificial reef and was exposed to similar physical oceanographic conditions. Spur and groove reef features are caused by erosion and typically occur in the wave-dominated environment at the fore of coral reefs. The geomorphology is characterized by alternating ridge and channel features that are oriented perpendicular to the shore or bank/shelf escarpment zone of the reef. The spurs have high levels of vertical relief and are colonized by corals. The grooves are thin sand or hard bottom channels (typically one to five meters wide) that separate the spurs from each other (Battista et al. 2007). The high percentage of coral cover that was found in the spur and groove habitat during this study was likely due to the unique environment created by this topography.

The reef spurs create large sloping faces with more exposed surface area for coral colonization than a pavement reef flat or a porous breakwater structure with large voids. The undulating surface of the spur and groove reef creates habitat for a diverse range of corals that are preferential to different water depths. When the spur and groove structures interact with shoaling waves, nearshore circulation cells are induced (Rogers et al. 2013). Water motion is known to be of great importance to the biological and ecological functioning of coral reefs (Jokiel 2008; Nakamura 2010). The wave induced currents will transport coral larvae and will also remove smothering fine sediments from the spurs and deposit them in the grooves where they are carried away from the reef system by draining tides (Storlazzi et al. 2004). In areas with high sediment loads, such as the Kahului Bay (Ziemann 2003), this mechanism could be crucial for the development of a robust coral reef ecosystem.

The Kahului east breakwater was designed to adsorb wave energy. Coastal structures that are designed for wave absorption rather than reflection are known to not induce water circulation cells (Demirbilek 2009). The lack of wave-induced currents, coupled with the large voids and shaded areas within the structure, partially explain why coral coverage on the seaward slope of the Kahului breakwater was sparse. On the smaller scale, it is known that substrates that offer rough and complex microsurfaces are preferable for coral recruitment (Bernal-Sotelo and Acosta 2012). The smooth faces that characterize the microtopography of the armor units offer another explanation for the low coral density observed at the breakwater. These findings from the field survey suggest that to maximize its function for coral reef ecology, the design of a multifunctional breakwater should mimic the spur and groove features found in the natural environment with regards to the macro- and microtopographical characteristics of the structure, orientation with wave direction, and water depth (Perkol-Finkel and Benayahu 2005; Perkol-Finkel et al. 2012).

CONCLUSION

This study was undertaken to gather information for the engineering design of a multifunctional coastal structure intended to provide enhanced coral reef ecology. To serve the design function as an artificial reef, the structure must provide a hard substrate that is suitable for colonization by hermatypic corals found in the surrounding environment. Precast concrete was assumed to be a likely construction material for this type of multifunctional reef. In this study, two important design considerations for the artificial substrate, the concrete mix design and the surface topography, were investigated to determine how they impact the development of coral reef ecology. Three concrete compositions that differed by the use of basalt, limestone, or recycled aggregates were tested in field and laboratory experiments in three test environments. After a period of about one year, the coral recruits on each plate were identified, counted, and compared. The results showed that there was no significant difference between coral recruitment on the three concrete types. The average number of juvenile coral recruits found on all the basalt, limestone and recycled aggregate concrete plates deployed in this experiment were 60 ± 9, 83 ± 17 and 77 ± 14 (mean ± standard error), respectively. The three test environments of the experimental setup, however, were found to cause a significant difference in coral recruitment on the plates. The average number of juvenile coral recruits on the plates deployed in the laboratory tanks, deep water, and shallow water field tests were 86 ± 11, 135 ± 15, and 4 ± 1, respectively.

Many environmental factors will affect the development of corals in the local area. Field surveys were conducted to gather data on the marine environment in the vicinity of the artificial reef project site. The amount of living coral coverage and the macro- and microtopographic features of the benthic environment were investigated through drop camera and *in-situ* surveys. A positive relationship between the abundance of living corals and the amount of multiscale topographic complexly on the reef substrate was found. The adjacent natural reef area that was characterized by spur and groove geomorphology, was found to have the highest density of coral coverage (>90% cover on 60% of the area) within the surveyed area and also the highest degree of topographic complexity on both the macro- and microscales. In contrast, the living coral coverage on the existing harbor breakwater was found to be sparse. Overlapping and interlocking stacks of concrete armor units on the seaside slope of the structure have formed an artificial reef topography that is characterized by a porous macrotopography and a smooth microtopography.

The multiscale differences in the structural features of the substrate will alter the environmental conditions for the development of coral reef ecology. The results of this study suggest that the artificial reef design should emulate the natural spur and groove structure with regards to topographic complexity both macro and microscales, orientation with wave direction, and water depth. If the engineer is successful at designing for coral reef ecology, it is expected that an abundance of multiple coral species, including blue rice coral (*M. flabellata*), will colonize the concrete surfaces of the reef in the well-circulated high-energy wave zones. Coralline algae and brown rice coral (*M. capitata*) can be expected to predominantly colonize the deeper surfaces on the spurs as they reach down towards the sandy sea seafloor.

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