

Recycled Glass Cullet as an Alternative Beach Fill Material: Results of Biological and Chemical Analyses

Christopher Makowski[†] and Kirt Rusenko[‡]

[†]Coastal Planning & Engineering Inc.
Marine Science and Biological Research
Department
2481 NW Boca Raton Boulevard
Boca Raton, FL 33431, U.S.A.
Cmakowski@coastalplanning.net

[‡]Gumbo Limbo Nature Center
1801 N Ocean Boulevard
Boca Raton, FL 33431, U.S.A.

ABSTRACT



MAKOWSKI, C. and RUSENKO, K., 2007. Recycled glass cullet as an alternative beach fill material: results of biological and chemical analyses. *Journal of Coastal Research*, 23(3), 545–552. West Palm Beach (Florida), ISSN 0749-0208.

Florida's critically eroded beaches pose a myriad of social and environmental concerns, prompting an effort to explore alternatives to more traditional sand sources. One alternative involves the use of recycled glass cullet as coastal beach fill in erosional "hot spots." To determine the biological suitability of glass cullet in marine applications, invertebrate survivability and colonization was assessed through a biological assay program. Experimental bioassays were divided into five, three-container series ($n = 15$), with each series testing 23 kg of proportioned natural sand/glass cullet mixtures. Macro- and microscopic organisms were introduced to each bioassay and analyzed through direct observations. Experimental macrofauna displayed normal active behavior and recorded a mean success rate of $78\% \pm 3\%$. Mortality was attributed to predator-prey interactions rather than sediment contamination. Colonization of interstitial microfauna was successful within the cullet mixtures, and active transport between the cullet grains was documented without adverse effects. Abiotic parameters monitored in conjunction with the biological testing showed that temperature, dissolved oxygen, and pH did not differ significantly among each test series. In addition, ammonia, nitrites, nitrates, and organic phosphates all recorded low risk factor levels. Small amounts of hydrogen sulfide precipitate began to form in the absence of wave action, but when wave simulations were introduced, no microbial zonation was detected. These experiments indicate that recycled glass cullet is a biologically benign material that can be used to mitigate development of erosional hot spots in nourished beaches. By doing so, a proactive recycling program can be initiated to protect one of Earth's most valuable resources, the coastline.

ADDITIONAL INDEX WORDS: *Beach nourishment, bioassays, interstitial colonization, recycled glass, alternative beach fill.*

INTRODUCTION

Since the early 1960s, eroded beaches in southeast Florida have been nourished with the use of a variety of sand sources. Critically eroded shorelines pose numerous environmental problems (*e.g.*, limited nesting habitat for sea turtles and shorebirds, increased risk of inundation of sea turtle nests, destruction of threatened beach flora). Significantly, 34 of the 39 km (~88%) of Broward County beaches (central southeast Florida coast) have been identified as critically eroded (FDEP, 2000).

Potential sources of beach-compatible sand include offshore interreefal sedimentary infills, upland dunes, sand sheet inland deposits, and oolitic sand from the Bahama Banks. In addition, recycled glass (*i.e.*, cullet) has been proposed as a potential alternative source material for beach fill (EDGE, CRUZ-CASTRO, and MAGOON, 2002; FINKL, 1996; KERWIN,

1997; MALCOLM PIRNIE INC. STAFF, 2003; THOMSON, FINKL, and KRUEMPEL, 2004). Recycled glass cullet has physical properties similar to natural silica sands, making it a viable alternative beach fill material along critically eroded shorelines (FINKL, 1996; THOMSON *et al.*, 2004). Recycled glass cullet has many advantages as a potential alternative beach fill material because (1) it is possible to mechanically select grain sizes comparable to those of native beaches; (2) the chemical, mechanical, geologic, and engineering properties of appropriately sized recycled glass cullet are similar to natural sand; (3) it is a readily available recycled product; (4) its use eliminates expensive transportation and disposal fees of recycling material; (5) it creates a pertinent, specific use for recycled glass, thus aiding in the implementation of a proactive recycling program; and (6) it is an inert material that is presumably environmentally safe.

A concern associated with the use of recycled glass on beaches relates to the assimilation of cullet by beach sediments. On the basis of general physical characteristics (*e.g.*, sphericity, roundness, specific gravity, *etc.*), KERWIN (1997) summarized the compatibility of recycled glass cullet with natural beach sand and found that the two materials were

DOI:10.2112/06-0715.1 received 7 June 2006; accepted in revision 3 August 2006.

Financial support for this work was provided by the Broward County Commission, Office of Waste and Recycling Services, and the Florida Department of Environmental Protection.

compatible. In addition, contaminant tests were performed on natural beach sand and recycled glass cullet for lead (Pb); mercury (Hg); total coliform, fecal coliform, and enterococci bacteria; semivolatile organics; total recoverable petroleum hydrocarbons; and total salt content (THOMSON, FINKL, and KRUEMPEL, 2004). The contaminant levels of the beach sand and recycled glass cullet samples were either undetectable or below state reuse target levels for direct residential exposure (THOMSON *et al.*, 2004). Even though these geotechnical and contaminant analyses suggest recycled glass cullet would be a viable source for beach fill material, compatibility tests with biological marine communities had not yet been performed.

In this study, biological analyses were performed on recycled glass cullet mixtures to evaluate material effects on invertebrate and vertebrate (fish) biotic community assemblages. The habitation and colonization success of lower invertebrates was investigated because they might indicate effects of recycled glass cullet on higher vertebrates. These investigations were conducted in an effort to validate the hypothesis that recycled glass cullet is an environmentally safe alternative to natural sand sources.

The objective of this research was to monitor the colonization and survivability of lower invertebrates and fish through experimental bioassays containing various cullet mixtures. Other studies (PETERS *et al.*, 2002; RINGWOOD and KEPPLER, 2002) have demonstrated that experimental bioassays can accurately detect either adverse or benign effects of sediment on marine organisms. A saltwater flow system simulated natural beach conditions within each test matrix. Direct observations and supplemental biochemical analyses were conducted to determine whether recycled glass cullet has an effect on biological communities.

MATERIALS AND METHODS

Experimental Design

A biological infaunal assay program was developed to monitor invertebrate survivability and colonization within specific proportions of natural sand and glass cullet. Each bioassay was performed within a 24-gallon (91-L) clear plastic container ($84.3 \times 43.3 \times 34.4$ cm), with each container containing approximately 23 kg net dry weight of a specific natural sand/glass cullet mixture (Figure 1). Natural sand (0.39-mm mean grain size) was collected from the mid berm along native beaches in southern Broward County, Florida, and the recycled glass cullet (0.40-mm mean grain size) was obtained through Glass Aggregate Systems (FARIBAULT, Minnesota, USA). Each test mixture of natural sand/glass cullet was manually proportioned, weighed, and mixed by hand to obtain uniform composition.

Experiments were arranged in a single row and consisted of five, three-container series (for a total of 15 containers) that each tested a specific natural sand/glass cullet matrix. The first series served as a control with 100% natural sand, whereas the second series of containers tested a matrix of 75% natural sand and 25% glass cullet. The third series of containers tested a 50% natural sand/50% glass cullet mixture, and the fourth series of containers tested a mixture of

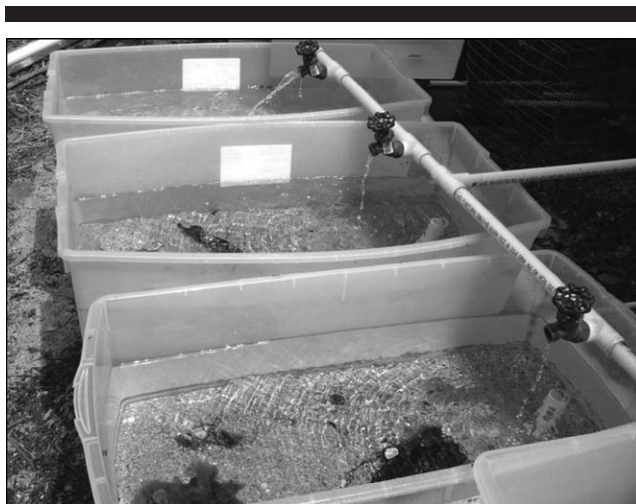


Figure 1. Experimental bioassay design showing the three-container control series. Each container contained 23 kg of proportioned sediment and approximately 38 L of saltwater.

25% natural sand and 75% glass cullet. The fifth series of experiments tested 100% glass cullet. Saltwater, obtained through an oceanic intake system, was delivered through a network of PVC pipes to each test container and provided a constant supply of fresh saltwater (approximately nine water changes over a 24-hour period) to the marine organisms and sediments. With the use of a combination of bulkheads and control valves, a drainage outlet system was constructed on each test container to maintain optimum water volume (~ 38 L).

Biological Monitoring

Marine species were introduced into each test matrix and included local representative microfauna (*i.e.*, copepods, ostracods, nematodes) and macrofaunal organisms (*i.e.*, crustaceans, mollusks, fish). All testing and recorded observations were conducted from May 1, 2005, to July 1, 2005.

Macrofauna were either collected within the Atlantic Intracoastal Waterway and Atlantic Ocean or were taken from established reef organism display tanks. Organisms were immediately introduced to their respective bioassay test container after collection (Figure 2). A 24-hour acclimation period was allowed before monitoring was initiated. Table 1 lists the number of macrofaunal test organisms included in each bioassay series. Live marine shrimp were added weekly as a source of food, and uneaten material was not allowed to accumulate in the containers. Biological monitoring of the macrofauna were conducted through direct visual observations performed at least twice per week for the duration of the study. Macrofaunal success rate was calculated by taking the proportion of survived individuals over the total number of individuals introduced to a specific sediment matrix. Active status of macrofauna was recorded with a digital camera, and a complete census of all individuals was taken on a weekly basis.

Microfauna were introduced to each test container by tak-



Figure 2. Example of macrofauna, blue crab (*Callinectes* sp.), introduced to a 100% cullet substrate.

ing a 2.3-kg sample of “live” sand from established (nitrogen-cycled) native reef display tanks. A 1-week acclimation and colonization period was allowed before monitoring was initiated. Biological monitoring of microfaunal test organisms was conducted through weekly interstitial core analysis. A 50.10-g interstitial core sample was extracted from each test matrix with a 50-cm-long piece of ½-inch (1.3-cm) PVC pipe and a stopcock. Core samples were taken on a weekly basis and analyzed for the presence or absence of macrofauna under a trinocular video microscopy system at a total magnification of 400×. Macrofauna were identified by external characterization, and the active status of individuals was documented with a digital camera. In addition, five random core samples from each matrix were extracted weekly and fixed with HICO microscope fixing agent. At a total magnification of 400×, the field of view (diameter = 0.125 mm) was divided into four equal quadrants to observe whether colonization was interstitially uniform. When a microorganism was observed within

one of the quadrants, a value of 25% of the field of view was reported. The total number of individuals was also counted for each core sample field of view area ($A = 0.012 \text{ mm}^2$). A ratio calculation was then performed to determine the amount of square interstitial area per individual microspecimen. The field of view percentages and microorganism counts were averaged and compared to see whether interstitial colonization rates increased or decreased among the different series over the 2-month testing period.

Organic Matter

Organic matter (%) of each test matrix was analyzed weekly by two methods. The first method (H_2O_2 treatment), as described in MIKUTA *et al.* (2005), included (1) taking an interstitial core sediment sample, (2) air drying the sample and weighing it, (3) adding an excess of 6% hydrogen peroxide (H_2O_2) solution, and (4) allowing the sample to dry overnight. The dry sample was then reweighed. The following equation was used to determine the percentage of organic matter in each sample:

$$\frac{\text{Pretreat Weight} - \text{Posttreat Weight}}{\text{Pretreat Weight}} \times 100$$

The second method (combustion treatment) involved combusting the organic matter at a high temperature. An interstitial core sample was extracted and dried in an oven at 70°C to evaporate all moisture. The sample was then weighed and placed in a HUMBOLDT Mfg. Co. combustion oven set at 475°C. After approximately 4 hours, the oven was turned off, and the sample was allowed to cool down to room temperature. Once the sample had cooled, it was weighed again. The measured weight loss was recorded to be the amount of organic matter present in the original sample.

Abiotic Parameters

A series of chemical analyses of the water column were performed weekly in each test container to determine abiotic factors associated with biological colonization performance. Samples were collected from the water-sediment interface during daylight hours between 1000 and 1500. Dissolved oxygen (O_2), pH, ammonia (NH_3), nitrites (NO_2), nitrates (NO_3),

Table 1. Individual species introduced into each experimental bioassay series. Number of surviving individuals are shown in parentheses.

| Microfauna Species | 100% Natural Sand | 75% Natural/ 25% Cullet | 50% Natural/ 50% Cullet | 25% Natural/ 75% Cullet | 100% Cullet |
|---|-------------------|----------------------------|----------------------------|----------------------------|-------------|
| Sea urchin (<i>Lytechinus variegates</i>) | 8 (8) | 8 (8) | 8 (8) | 8 (8) | 8 (8) |
| File fish (<i>Monacanthus tocheri</i>) | 6 (5) | 6 (6) | 6 (5) | 6 (6) | 6 (4) |
| Sargassum fish (<i>Histro histro</i>) | 1 (1) | 1 (1) | 1 (1) | 1 (1) | 1 (1) |
| Checkered puffer fish (<i>Sphoeroides testudineus</i>) | 1 (1) | 0 | 0 | 1 (1) | 1 (1) |
| Sargassum crab (<i>Portunus sayi</i>) | 8 (5) | 8 (7) | 8 (6) | 8 (5) | 8 (6) |
| Lightening whelk (<i>Busycon sinistrum</i>) | 1 (1) | 1 (1) | 1 (1) | 1 (1) | 2 (2) |
| Blue crab (<i>Callinectes</i> sp.) | 1 (1) | 1 (1) | 1 (1) | 1 (1) | 2 (2) |
| Sargassum nudibranch (<i>Scyllaea pelagica</i>) | 4 (0) | 4 (0) | 4 (0) | 4 (0) | 4 (0) |
| Red-striped hermit crab (<i>Phimochirus holthuisi</i>) | 0 | 0 | 0 | 0 | 1 (1) |
| Total individuals | 30 (22) | 29 (24) | 29 (22) | 30 (23) | 33 (25) |

Table 2. Bioassay mean summary table; (n) number of samples for each parameter.

| Experimental Parameter | Control, 100% Natural Sand | Test Matrices | | | |
|---------------------------------|----------------------------------|----------------------------|----------------------------|----------------------------|-----------------|
| | | 75% Natural/ 25% Cullet | 50% Natural/ 50% Cullet | 25% Natural/ 75% Cullet | 100% Cullet |
| Temperature (°C) | 25.9 ± 0.4 (75) | 25.9 ± 0.4 (75) | 25.9 ± 0.4 (75) | 25.8 ± 0.4 (75) | 25.9 ± 0.4 (75) |
| pH | 8.2 ± 0.1 (75) | 8.2 ± 0.1 (75) | 8.1 ± 0.1 (75) | 8.2 ± 0.1 (75) | 8.2 ± 0.1 (75) |
| Dissolves O ₂ (mg/L) | 6.9 ± 0.1 (75) | 6.9 ± 0.1 (75) | 6.8 ± 0.1 (75) | 6.9 ± 0.1 (75) | 6.8 ± 0.1 (75) |
| Ammonia (mg/L) | 0.01 ± 0 (75) | 0.01 ± 0 (75) | 0.01 ± 0 (75) | 0.01 ± 0 (75) | 0.01 ± 0 (75) |
| Nitrites (mg/L) | 0.02 ± 0 (75) | 0.02 ± 0 (75) | 0.02 ± 0 (75) | 0.02 ± 0 (75) | 0.02 ± 0 (75) |
| Nitrates (mg/L) | 0.2 ± 0 (75) | 0.2 ± 0 (75) | 0.2 ± 0 (75) | 0.2 ± 0 (75) | 0.2 ± 0 (75) |
| Organic phosphates (mg/L) | 0.02 ± 0 (75) | 0.02 ± 0 (75) | 0.02 ± 0 (75) | 0.02 ± 0 (75) | 0.02 ± 0 (75) |
| Hydrogen sulfide (mg/L) | 0.2 ± 0 (42) | 0.2 ± 0 (42) | 0.2 ± 0 (42) | 0.3 ± 0.1 (42) | 0.3 ± 0.1 (42) |
| Organic matter (%) | 3.9 ± 0.2 (150) | 3.7 ± 0.3 (150) | 3.8 ± 0.4 (150) | 3.7 ± 0.3 (150) | 3.7 ± 0.3 (150) |
| Macrofauna success rate (%) | 73 | 83 | 76 | 77 | 76 |

and organic phosphates (PO₄) were all tested weekly with Salifert marine test kits. In addition, hydrogen sulfide (H₂S) levels were measured with a Lamotte hydrogen sulfide test kit in the second month of experimentation. Water temperature was measured and recorded at least twice a week.

Statistical Analysis

A paired two-sample t test was performed on the H₂O₂-treated organic matter data vs. the combustion oven organic matter data from each test series to determine whether the data sets differed significantly from each other. A paired two-sample t test was used to determine whether the control series microfauna observation averages differed significantly from each of the experimental treatments. A two-way analysis of variance (ANOVA) was conducted to determine whether temperature, dissolved oxygen concentrations, pH, and organic matter percentages differed significantly in the experimental bioassays when compared with the natural sand control series.

Analyses were conducted with SPSS software, with $p \leq 0.01$ significant. Mean values are followed by standard deviations (\pm SD) unless otherwise noted.

RESULTS

Biological Analysis

Within the natural sand control series, an average 3.9% ± 0.2% of the interstitial sediments was organic matter. Both methods (H₂O₂ treatment and combustion treatment) measured data with insignificant differences ($t = 1.49$, $p = 0.14$). Among the test treatments that included a percentage of recycled glass cullet, the 50% cullet series showed the highest average organic matter content, at 3.8% ± 0.4% of the interstitial sediments. Both methods (H₂O₂ treatment and combustion treatment) measured data that were not significantly different ($t = 0.92$, $p = 0.36$). The remaining three test treatments averaged an organic matter content of 3.7% ± 0.3% within the interstitial sediments. In all experimental treatments, data obtained through both the H₂O₂ and combustion treatments did not differ significantly (Table 2).

Successful colonization of the interstitial sediments was verified through microscopic analysis. For the control series and all the experimental treatments, the following microfauna

were identified and documented throughout the duration of the 2-month testing period: amphipods, copepods, nematodes, and ostracods. The interstitial copepod *Harpacticus*, which belongs to the Order Harpacticoida, was the most abundant species of microfauna found. In addition, the cyclopoid copepod *Macrocyclus albidus* was detected swimming among the sediment/cullet grains. Other species frequently observed in all the bioassays included the myodocopid ostracod *Agrenocythere spinosa*, the intertidal amphipod *Globosolenbos smithi*, and the marine interstitial nematode *Epsilonema*. Within the control series core samples, microfauna were found in an average 92% of the microscope's field of view, with an average of 18 ± 2.1 individual specimens (1 specimen per 6.67 × 10⁻⁴ mm² of sediment) counted each week during the testing period. These results differed significantly from the 100% cullet series, which showed microfauna in an average 61% of the microscope's field of view ($t = 4.4$, $p < 0.01$), with an average of 8 ± 1.4 individual specimens (1 specimen per 15.00 × 10⁻⁴ mm² of sediment) counted ($t = 10.6$, $p < 0.01$). Even though all the experimental treatments had significantly lower total averages than the control series, they all contained at least 14 microfaunal individuals (1 individual per 8.57 × 10⁻⁴ mm² of sediment) in 100% of the microscopic field of view by the end of the 9-week testing period (Figures 3a and 3b).

Experimental macrofauna showed no signs of mass mortality when in direct contact with the sediment matrices. Of the 30 macroorganisms introduced to the control series, 22 individuals survived the duration of the testing period and recorded the lowest mean success rate with 73%. Three sargassum crabs, *Portunus sayi*, four sargassum nudibranchs, *Scyllaea pelagica*, and one file fish, *Monacanthus tockeri*, either died or fell prey to other individuals. The 25% cullet series recorded the highest mean success rate of all the bioassays at 83%; only one sargassum crab and four sargassum nudibranchs were found deceased. The 50% cullet series and 75% cullet series recorded mean success rates of 76% and 77%, respectively. Among the 45 macrofaunal test specimens introduced between the two series, five sargassum crabs, eight sargassum nudibranchs, and one file fish perished during the testing interval. The 100% cullet series recorded a mean success rate of 77% for the 33 individuals introduced. Two sargassum crabs, four sargassum nudibranchs, and two file fish either died or fell prey to other individuals.

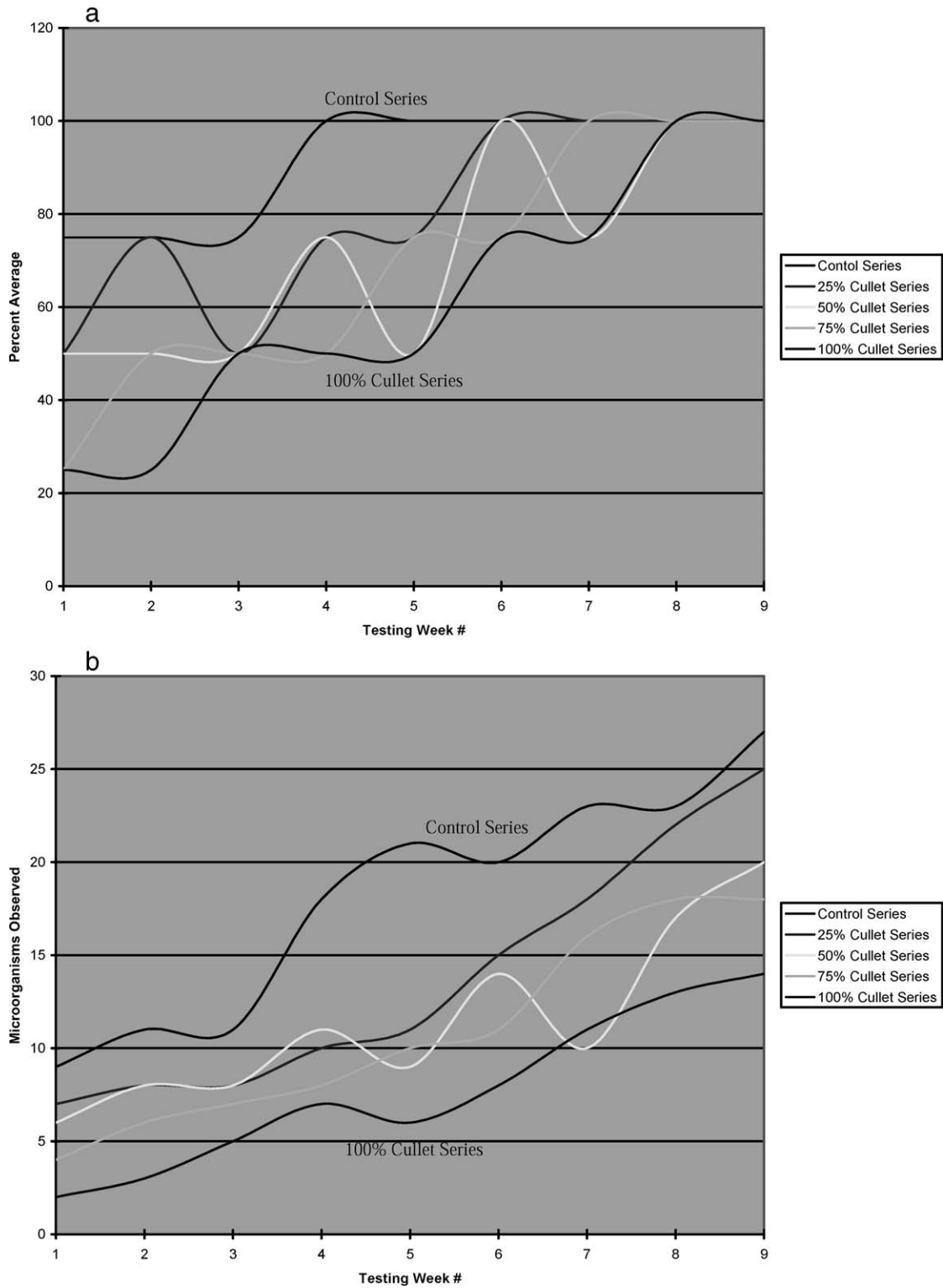


Figure 3. (a) Average field of view percentage containing microfauna *vs.* the testing week interval. By the end of testing week 9, all the series recorded microfauna in 100% of the microscope's field of view. (b) Average amount of individual microfauna observed from interstitial core samples *vs.* the testing week interval. Even though significantly more individual microfauna were observed in the control series, all the treatments showed an increase in average microfauna counts.

Abiotic Parameters

Water temperatures remained relatively consistent; the control series and the 25%, 50%, and the 100% cullet series all recorded an average of $25.9^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ ($78.6^{\circ}\text{F} \pm 0.7^{\circ}\text{F}$) over the 2-month testing period. The only variation was reported for the 75% cullet series, which recorded an average water temperature of $25.8^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ ($78.5^{\circ}\text{F} \pm 0.7^{\circ}\text{F}$). Average pH was uniform for all the bioassays at 8.2 ± 0.1 . Dissolved oxygen (O_2) levels remained constant among the bioassays; the control series and the 25% and 75% cullet series all recorded averages of 6.9 ± 0.1 mg/L. The 50% and 100% cullet series recorded average dissolved O_2 levels of 6.8 ± 0.1 mg/L. The NH_3 , NO_2 , NO_3 , and PO_4 were all recorded at the lowest detectable levels according to applied methods; average concentrations of 0.01 mg/L NH_3 , 0.02 mg/L NO_2 , 0.2 mg/L NO_3 , and 0.02 mg/L PO_4 were documented for each bioassay over the study period. Average concentrations of hydrogen sulfide (H_2S) were not recorded above 0.3 mg/L for any bioassay series. A complete list of abiotic parameters recorded for each bioassay series is provided in Table 2.

DISCUSSION

This study is among the first to document the effects of recycled glass cullet on marine biological communities. Over a 2-month testing period, five series of bioassays, each containing a different sediment matrix, were analyzed to record how newly introduced organisms (macrofauna and microfauna) were affected by the cullet grain substrates. In addition, chemical parameters (toxic and nontoxic) were monitored in conjunction with observations of the living organisms. This research will help ascertain the environmental suitability of an alternative sand source to offset critical beach erosion.

Experimental Bioassays

The effect of marine sediment contamination on biological processes goes beyond digestive uptake and chemical solubility; rather, it is a complex result of compound-particle interaction (AHLF *et al.*, 2002). Bioavailability of particle-associated contaminants has been shown to be influenced by sediment-specific properties, such as organic matter and surface area (CHUNG and ALEXANDER, 1998) and can affect different organisms through varying exposure routes (HARKEY, LANDRUM, and KLAINE, 1994; LISS and AHLF, 1997). Because of this complexity, attention has been increasingly given to bioassays that examine the potential toxicological effect of sediments directly exposed to the test organisms (AHLF *et al.*, 2002; HEISE and AHLF, 2005). The experimental bioassays performed in this study were designed to allow for the compound-particle interaction between representative local fauna and varying glass cullet concentrations to identify whether recycled glass cullet exposes organisms to particle-adhered contaminants or whether it would be an environmentally benign substrate.

Biological Analysis

After a 2-month exposure to recycled glass cullet sediments, it has been determined that an artificial cullet sub-



Figure 4. Sargassum crab (*Portunus sayi*) using recycled glass cullet as camouflage. This defensive measure caused no adverse effect to the crustaceans.

strate does not adversely affect macrofaunal habitation or microfaunal colonization. This was evident with the uniform lack of mortality observed in the introduced individuals and the active presence of interstitial microfauna. Previous studies (*e.g.*, CARR and CHAPMAN, 1992; LONG *et al.*, 1995) have shown that marine sediment bioassays reveal different patterns of toxicity, expressed ultimately through mass mortality, on mollusks, crustaceans, echinoderms, and fish. However, in the recycled glass cullet bioassays, the experimental macrofauna showed a mean success rate of $78\% \pm 3\%$. Species that were most hearty and exhibited no mortality included the variable sea urchin *Lytechinus variegates*, the sargassum angler fish *Histrio histrio*, the lightening whelk *Bu-sycon sinistrum*, and the blue crab *Callinectes* sp. All specimens of sargassum nudibranch showed mortality, most likely from the spatial limitations of the experimental containers and the lack of hydroids needed for ingestion (TODD, 1981). When the nudibranchs were eliminated from the mortality totals, the mean success rate for the cullet bioassays increased to $91\% \pm 3\%$. Minimal mortality (*i.e.*, never more than four individuals per series) was seen in the sargassum crab and the slender file fish; however, it is believed that this was not a function of sediment contamination but, rather, the result of an encounter with a larger individual or from pre-existing compromised physiology.

Individuals displayed normal active behavior within the cullet matrices and showed no adverse signs of physical stress. Of particular note was the use of the cullet as defensive camouflage by the test crustaceans and mollusks. To shield themselves from predators or direct ultraviolet light, the sargassum and blue crabs would thrust their carapaces backward into the cullet until they were completely covered (Figure 4). This behavior was shown repeatedly over the testing period, with no harm to the crabs. Similarly, the whelks would burrow deep into the cullet as a protective measure

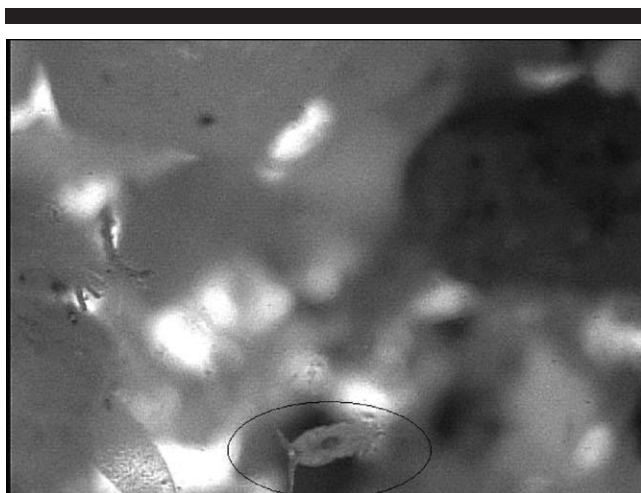


Figure 5. Interstitial copepod moving within 100% glass cullet (400 \times). Colonization of microfauna was observed in all the experimental treatment series.

and would do so with no observed injury to their foot or mantle.

Microscopic analyses showed that colonization by interstitial microfauna was successful within the cullet mixtures. All the same groupings of microfauna (Order Amphipoda, Class Copepoda, Phylum Nematoda, and Class Ostracoda) were observed in the control series, as well as the experimental replicates. The bottom-dwelling copepod *Harpacticus* was observed in the highest abundance throughout the bioassays. These interstitial copepods were observed crawling over and burrowing between sediment/cullet grains with the aid of thoracic limbs. Interstitial movements of all microfauna were documented by digital video and showed that microfauna were able to actively transport within the varying cullet mixtures without adverse effects (Figure 5). Uniform colonization of the sediment mixtures was also reaffirmed by the consistent organic matter readings in all the test series. Even though initial rates of organic matter concentration within the cullet took significantly longer than the natural sand (ANOVA DF = 4, 32; $p < 0.01$; $\alpha = 0.05$), all the test series contained similar sediment organic content at the end of the testing interval, with a mean of $38\% \pm 1\%$ (Table 2). This correlated directly with the interstitial core sample analysis results, in which all the experimental treatments had initially significantly lower total averages of microfauna observed than the control series—possibly a function of established microfauna within the natural sand at time zero. However, by the end of the testing interval, all the bioassays were recording uniform distribution of established microfauna (Figure 3a).

Abiotic Parameters

Abiotic parameter testing revealed that marine water chemistry was not negatively altered when in contact with recycled glass cullet. Water temperature steadily increased over the testing interval and was not significantly different

among the five series (mean = $25.9^{\circ}\text{C} \pm 4^{\circ}\text{C}$; ANOVA DF = 4, 74; $p > 0.01$; $\alpha = 0.05$). Dissolved oxygen was readily available for all the test series organisms and did not significantly deplete in the presence of the cullet (mean = 6.9 ± 1 mg/L; ANOVA DF = 4, 74; $p > 0.01$; $\alpha = 0.05$). Similarly, pH readings were consistent and did not significantly differ among series (mean = 8.2 ± 0 ; ANOVA DF = 4, 74; $p > 0.01$; $\alpha = 0.05$). Of the initial toxic chemicals monitored, NH_3 , NO_2 , NO_3 , and PO_4 were all measured at the lowest risk factor levels.

An important and unexpected observation during the study was the formation of a blackish film that began to develop on the different cullet sediment mixtures after 3 weeks of testing, first starting on the 100% cullet and then appearing on all the other experimental series, including the controls near the end of the testing period. Further analysis determined that the black film was a precipitation of hydrogen sulfide. This anaerobic sulfide-reducing process has been documented in stagnant coastal waterway systems that lack influential wave action (CARLSON, YARBORO, and BARBER, 1994). However, when sediments containing the cullet were mixed and allowed to aerate by directing water movement into the substrate (wave simulation), the visible hydrogen sulfide accumulations disappeared and no microbial zonation was detected. Hydrogen sulfide test readings also showed that levels decreased after wave simulation and aeration was initiated.

It is postulated that the hydrogen sulfide was more apt to accumulate on the glass cullet because of the nature of its grain shape. Natural sand grains are primarily spherical in shape, whereas the cullet has a slightly more flattened, angular shape. It is suspected that this flattened cullet shape limits the aeration of inundated sediment in the absence of wave action. Therefore, it is recommended that the application of recycled glass cullet for alternative beach erosion control would best be served if placed directly in the active surf zone, where wave action will facilitate aeration and mixing of the material into the native beach sands.

Conservation Implications

Erosion is a natural process that threatens coastlines worldwide. With a historic rise in average sea levels, now estimated to be increasing at about 25 to 30 cm per century (TITUS and NARAYANAN, 1995), not only are residences and businesses threatened, but also a host of critically endangered animals that include sea turtles and shorebirds. By finding environmentally friendly alternative methods to combat erosional hot spots, scientists and engineers can take another step to protect beaches. This study demonstrated that recycled glass cullet is a biologically safe alternative method for marine sediment applications; however, this material carries another conservation implication. The use of glass cullet as alternative beach fill would designate a specific targeted use for this processed material and would help create a public awareness toward local proactive recycling programs.

ACKNOWLEDGMENTS

Technical support was provided by the Broward County Commission, Office of Waste and Recycling Services; the Bro-

ward County Environmental Protection Department; Gumbo Limbo Nature Center of Boca Raton; Malcolm Pirnie; and Coastal Planning & Engineering Inc. We extend special recognition to the project management team of P. Bresee, H. Burton, T. Campbell, P. Foye, S. Gutner, S. Higgins, C. Kruempel, R. Spadoni, and G.G. Thomson. We thank the following individuals for their generous contributions to this research: P. Bardes, R. Baron, A. Delaney, C.W. Finkl, A. Marsh, J. Newman, and M. Simini.

LITERATURE CITED

- AHLF, W.; BRAUNBECK, T.; HEISE, S., and HOLLERT, H., 2002. Sediment and soil quality criteria. In: BURDEN, F.R.; MCKELVIE, I.; FORSTNER, U., and GUNTHER, A. (eds.), *Environmental Monitoring Handbook*. New York: McGraw-Hill, pp. 17.1–17.8.
- CARLSON, P.R., Jr.; YARBORO, L.A., and BARBER, T.R., 1994. Relationship of sediment sulfide to mortality of *Thalassia testudinum* in Florida Bay. *Bulletin of Marine Science*, 54, 733–746.
- CARR, R.S. and CHAPMAN, D.C., 1992. Comparison of whole sediment and pore-water toxicity tests for assessing the quality of estuarine sediments. *Journal of Chemical Ecology*, 7, 19–30.
- CHUNG, N. and ALEXANDER, M., 1998. Differences in sequestration and bioavailability of organic compounds aged in dissimilar soils. *Environmental Science & Technology*, 32, 855–860.
- EDGE, B.L.; CRUZ-CASTRO, O., and MAGOON, O.T., 2002. Recycled glass for beach nourishment. In: *Proceedings of the 28th International Conference on Coastal Engineering* (Cardif, Wales, ASCE), pp. 3630–3641.
- FDEP (FLORIDA DEPARTMENT OF ENVIRONMENTAL PROTECTION) STAFF, 2000. State of Florida Strategic Beach Management Plan. Tallahassee, Florida: Department of Environmental Protection, 35p.
- FINKL, C.W., 1996. Beach fill from recycled glass: a new technology for mitigation of localized erosional 'hot spots' in Florida. In: *Proceedings of the 9th National Conference on Beach Preservation Technology* (Tallahassee, Florida, Florida Shore and Beach Preservation Association), pp. 174–175.
- HARKEY, G.A.; LANDRUM, P.F., and KLAIN, S.J., 1994. Comparison of whole-sediment, elutriate, and porewater exposures for use in assessing sediment-associated organic contaminants in bioassays. *Environmental Toxicology and Chemistry*, 13, 1315–1330.
- HEISE, S. and AHLF, W., 2005. A new microbial contact assay for marine sediments. *Journal of Soils and Sediments*, 5(1), 9–15.
- KERWIN, L., 1997. Potential Applications for Recycled Glass in Beach Management: Emergency Stabilization of "Hot Spots" in Broward County, Florida. Boca Raton, Florida: Florida Atlantic University, Master's thesis.
- LISS, W. and AHLF, W., 1997. Evidence from whole-sediment, pore-water, and elutriate testing in toxicity assessment of contaminated sediments. *Ecotoxicology and Environmental Safety*, 36, 140–147.
- LONG, E.R.; MACDONALD, D.D.; SMITH, S.L., and CALDER, F.D., 1995. Incidence of adverse biological effects within range of chemical concentrations in marine and estuarine sediments. *Journal of Environmental Management*, 19, 81–97.
- MALCOLM PIRNIE INC. STAFF, 2003. *Beach Renourishment Pre-Feasibility Study*. Fort Lauderdale, Florida: Malcolm Pirnie, Inc.
- MIKUTTA, R.; KLEBER, M.; KAISER, K., and JAHN, R., 2005. Organic matter removal from soils using hydrogen peroxide, sodium hypochlorite, and disodium peroxodisulfate. *Soil Science Society of America Journal*, 69, 120–135.
- PETERS, C.; BECKER, S.; NOACK, U.; PFITZNER, S.; BULOW, W.; BARZ, K.; AHLF, W., and BERGHAHN, R., 2002. A marine bioassay test set to assess marine water and sediment quality—its need, the approach, and first results. *Ecotoxicology*, 11, 379–383.
- RINGWOOD, A.H. and KEPPLER, C.J., 2002. Comparative in situ and laboratory sediment bioassays using juvenile clams, *Mercenaria mercenaria*. *Environmental Toxicology and Chemistry*, 21, 1651–1657.
- THOMSON, G.G.; FINKL, C.W., and KRUEMPEL, C.J., 2004. Broward County Beach Demonstration Project Geotechnical Investigation Report: Technical Memorandum. Boca Raton, Florida: Coastal Planning & Engineering, Inc. (prepared for Malcolm Pirnie, Inc., Fort Lauderdale, Florida), 12p.
- THOMSON, G.G.; FINKL, C.W.; KRUEMPEL, C.J., and KRAUSE, K., 2004. *Broward County Beach Demonstration Project: Literature Review*. Boca Raton, Florida: Coastal Planning & Engineering, Inc. (prepared for Malcolm Pirnie, Inc., Fort Lauderdale, Florida), 14p.
- TITUS, J.G. and NARAYANAN, V., 1995. The Probability of Sea Level Rise. Washington, DC: U.S. Environmental Protection Agency, 230-R95-008, 186p.
- TODD, C.D., 1981. The ecology of nudibranch mollusks. *Oceanography and Marine Biology Annual Review*, 19, 141–234.