Use of Pulverized Recycled Glass for Beach Nourishment: A Review

Coastal erosion caused by increased extreme weather events and sea level rise is escalating the rate and extent to which beaches are washing away. Traditionally, inland and offshore sand and dredged material from rivers, canals, and the ocean have been used to nourish beaches, but these resources are becoming increasingly expensive and difficult to obtain due to increased demand and the necessity of environmental safeguards. Because of this, alternative materials for beach nourishment are becoming more attractive. One of these alternatives is pulverized recycled glass. However, before recycled glass can be placed on a beach it must undergo a series of tests to ensure the material will match native beach sand for color and grain size and will not negatively impact the coastal habitat. In addition, local governments must make responsible fiscal choices when considering the use of recycled glass as there are many factors that determine its availability and cost. This paper will review the geotechnical, biological, and abiotic analyses conducted on the experimental placement of recycled glass on beaches in Florida. It will also describe the experiences local governments have had when considering the use of recycled glass as an alternative material for beach nourishment.

Introduction

Glass recycling produces crushed fragments, referred to as cullet, which are obtained by processing any type of glass product (*e.g.*, bottles, containers, tanks, etc.). Recycled glass cullet has many advantages for use in beach nourishment. Glass cullet has physical, chemical, mechanical and engineering properties similar to natural sands, and, since glass can be separated by color, the cullet can be specifically selected to match the color of sand from a particular beach (Edge et al. 2002). Glass cullet can be either tumbled or heat-treated to remove points and sharp edges, and grain sizes can be matched to specific beach characteristics (Fig 1). In addition, glass cullet is an inert material the use of which can be made part of a comprehensive recycling program (Finkl and Kerwin 1997).

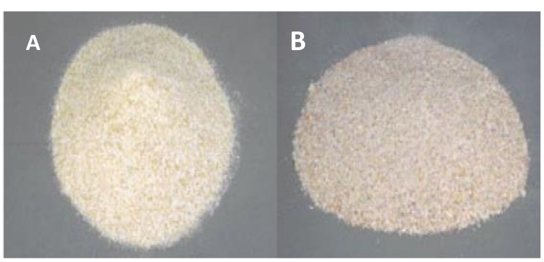

Figure 1. Natural sand (A) is similar in consistency to recycled glass cullet (B). http://www.broward.org/BeachRenourishment/Documents/beaches.pdf

Although recycled glass has yet to be used for beach nourishment in the U.S., glass cullet has been employed on beaches by commercial entities in New Zealand and the Caribbean island of Curacao. In 2003, a subdivision of the Town of Lake Hood, New Zealand created a beach made up entirely of glass cullet on an artificial recreational lake in order to encourage recycling and increase environmental awareness (Makowski et al. 2007). Glass cullet was also placed on Curaçao beaches at the Hilton Hotel on Piscadera Bay and at Zanzibar Park. The volume of glass cullet placed at the Hilton Hotel is unknown, but at Zanzibar Park approximately 110 yd^3 of glass cullet was mixed with varying amounts of native beach sand in a 1,000 ft^2 area. In a study of the effects of the cullet, beachgoers favored the native sand/glass cullet mixtures over a plot filled only with glass cullet but they did not express a preference between the various sand/glass ratios. Although turtle nesting occurred on beaches at both sites, there is no official data available from the local government agency regarding nesting or hatching success (Makowski et al. 2007).

Research

Research has been conducted on the suitability of recycled glass cullet for use as alternate fill material beginning in the 1990s. These studies focused on the geophysical properties of glass cullet and its effect on coastal flora and fauna.

Geotechnical Analysis

In order for glass cullet to be viable aggregate material for beach nourishment it must be similar in size and appearance to native sand as well as react comparably to the physical forces of waves, currents, and wind. The results of a 1993 study of various physical and engineering properties of glass cullet compared to natural aggregates of comparable grain size (e.g., offshore sand) showed that all the materials tested performed very similarly to each other (Finkl et al 1997) (Table 1). A study by Edge and others (2002) expanded on these findings by comparing the geotechnical properties of glass cullet to those of native sand in physical model experiments using a 3-D wave tank. The tank was divided into two channels containing either glass cullet or native sand and subjected to regular waves for varying amounts of time (15-120 minutes). Beach profiles (i.e., distance the material traveled) and reflection coefficients for both materials were subsequently determined. The findings showed that glass cullet performed similarly to native sand showing little variation in beach profiles. The wave reflection coefficient for the glass cullet was slightly smaller than that for native sand, which the authors suggested indicated that glass cullet absorbs wave energy better than sand (Edge et al. 2002).

Table 1. Summary of physical properties tests on glass cullet and compatibility with native offshore sand fill.

Test	Compatibly	Comments
Specific Gravity (Relative Density)	Yes	Cullet = 2.5 to 2.65 Native sand aggregate = 2.68
Gradation	Yes	Shows little or no gradation
Particle Shape	Yes	Suitable for mechanical handling; low potential for punctures and cuts
Durability	Yes	Less than crushed rock but close to normal for roadway aggregate
Compaction	Yes	Little or no gradation changes, compaction curves are relatively flat, material insensitive to moisture content
Permeability	Yes	Medium to high permeability corresponding to medium sand and gravel aggregate
Thermal Conductance	Yes	Slightly lower than natural aggregates, glass cullet conducts heat somewhat more slowly
Shear Strength[1]	Yes	Glass cullet exhibits good to excellent CBB values; cullet has resilience moduli > 29 ksi at a bulk stress of 25 psi

(1) Measures the ultimate stress level that a material can sustain and includes consideration of factors that influence the loading capacity of a material, thermal “interparticle friction” based on particle surface texture, shape, void ratio (compaction), size, and gradation.

Adapted from Finkl et al. 1997

Edge and others (2002) also determined the rate of abrasion and mass losses due to abrasion of glass cullet using a tumbler machine to simulate wave action, current, and wind. This experiment measured mass loss for two samples: one consisting only of glass cullet and one made up of a mixture of glass plus native sand. After 7, 14, and 36 days of tumbling, the samples were sieved, dried, and measured. Results showed that although the glass-only sample had a very high initial rate of abrasion, the rate eventually stabilized and was comparable to the glass/sand mixture by the end of the experimental period (Edge et al. 2002).

Abiotic Analysis

In order to avoid negative impacts on the habitats of coastal macro and microfauna, the effects of glass cullet on abiotic factors such as moisture, temperature, and gas exchange must be similar to those of native sand. This was tested in a study evaluating the effects of recycled glass cullet on invertebrate and vertebrate communities which analyzed several abiotic factors associated with biological performance. Test containers were filled with 100% native sand (control), 100% glass cullet, and sand/glass mixtures of 75%/25%, 50%/50%, and 25%/75%. Over a two-month period, water temperature, dissolved oxygen, pH, ammonia, nitrites, nitrates, hydrogen sulfide and organic phosphates levels were measured. At the end of the experimental period, monitoring results showed that temperature, dissolved oxygen, and pH did not differ significantly among the five series tested. Although small amounts of hydrogen sulfide precipitate began to form in the absence of wave action, this disappeared once wave simulations were introduced. The authors concluded that marine water chemistry was not negatively altered by contact with recycled glass cullet (Makowski and Rusenko 2007).

Another study of the abiotic parameters of glass cullet focused on the material's effect on sea turtle nesting. Temperature, moisture content (i.e., dew point temperature and relative humidity), and respiratory gas exchange were measured as all are important abiotic variables affecting sex ratios and survivability of sea turtle embryos. For the experiment, simulated nesting boxes were constructed and filled with either 100% native sand (control), or sand/glass mixtures of 75%/25%, 50%/50%, and 25%/75%. Moisture content, temperature, and gas exchange were measured for two nesting seasons: March through May and June through August. Data analysis showed that the simulated nests containing glass cullet recorded average temperatures (27.0–31.4^{0}C) that fell within the acceptable incubation range for sea turtles and moisture content readings showed no significant differences from the beach sand controls. Similarly, high concentrations of oxygen ($\geq$ 20.0%) were recorded from all the experimental nests containing glass cullet with no significant variations from the beach sand controls (Makowski et al. 2008).

Biological Analysis

Biological considerations such as survivability and mobility are also important in determining the suitability of glass cullet for beach nourishment. To test these factors, Makowski and Rusenko (2007) assessed vertebrate and invertebrate survivability and colonization using test containers filled with 100% native sand (control), 100% glass cullet, or sand/glass mixtures of 75%/25%, 50%/50%, and 25%/75%. Species introduced into each test matrix included local microfauna (i.e., copepods, ostracods, nematodes) and macrofauna (i.e., crustaceans, mollusks, fish). At the end of the two-month experimental period, the macrofauna displayed normally active behavior and had a mean survival rate of 78%. Any mortality that did occur was attributed to predator-prey interactions rather than adulteration from the glass cullet. Microfauna colonization was also successful within the cullet mixtures, and microfauna movement between glass cullet grains was observed without adverse effects (Makowski and Rusenko 2007).

In addition to animal life, beach vegetation plays an important role in forming coastal habitats and is also subject to negative impacts from glass cullet. In order to determine the fitness of recycled glass cullet as a growth medium for native sea plants, Makowski and others (2013) tested how native vegetation reacted when transplanted into medium containing glass cullet. Following construction of an artificial dune, glass cullet and native sand were used as growth mediums for dune-stabilizing vegetation. Immature transplants of sea oats (*Uniolapaniculata*) and panic grass (*Panicum amarum*) were planted in the artificial dune and evaluated over a 1-year growing period. During this time the overall performance of the salt-tolerant plants was determined by measuring fresh and dry weight, new shoot development, and root and stalk length. Results showed that both species of vegetation planted in a recycled glass medium outperformed those specimens growing in the native sand controls. The authors speculated that this may have been due to a slight increase in the angularity of the glass cullet compared to the native sand grains. The small difference in the surface area of the grains may have contributed to higher moisture content within a glass cullet dune, thus optimizing growing conditions for dune vegetation (Makowski et al. 2013).

Feasibility Studies on the Use of Recycled Glass Cullet

The idea of using recycled glass as beach fill originated from a 50-year-old oceanside dump site near Fort Bragg, California. Over time the organic materials in the dump decomposed or were washed away and the solid materials were broken down by wind and wave action ultimately resulting in a beach primarily consisting of polished glass particles. This glass beach inspired the City of Encinitas, California to investigate the possibility of nourishing their eroding beach with glass cullet and, in 1992, the City commissioned a feasibility study (Finkl and Kerwin 1997).The study determined that recycled glass cullet is generally suitable as beach material in as much as glass cullet; “1) generally resembles natural materials making up local beaches; 2) can be obtained in reasonably sufficient quantities to create localized beaches or supplement larger beach areas; and 3) can be made in a size range generally comparable to local sand size with minimal treatment” (Woodward-Clyde 1993). Based on these results, in 1995, the City proposed to substitute recycled glass cullet for the 15,000 m^3 of sand it annually used for beach nourishment. However, for unknown reasons, this action was never implemented (Edge et al. 2002).

In 2003, Broward County, Florida launched the Broward County Beach Demonstration Project to investigate the feasibility of using the 15,000 tons of glass recycled annually by the County to augment its beach nourishment needs especially in high erosion areas (Makowski et al. 2007). Phase I of this project consisted of a feasibility study, a public perception study, and biotic and abiotic analyses of glass cullet. Geotechnical and contaminant analyses of grain size, distribution, munsell color, carbonate content, and grain angularity were also conducted during this phase. Results from these studies indicated that the glass cullet was closely comparable to the native sand of Broward County's beaches and that the material was biologically and chemically safe for marine sediment use (Makowski and Rusenko 2007).

Following the favorable results of these preliminary studies, in 2008, the County secured permits for a pilot project in which approximately 2,000 yds^3 of glass cullet would be placed at the shoreline below the mean high water mark and monitored for its performance and similarities to the native sand when subjected to wind and wave action. As part of this phase, the County also would also investigate the feasibility of long-term methods of producing sufficient quantities of glass cullet (Foye 2008). The cost of this pilot project was to be shared with the state of Florida, however, following the recession in 2008, cost considerations prevented further progress on the project and in 2010 the state withdrew all financial support. In 2013, Broward County commissioners decided against paying for the pilot project, opting instead to commission a cost comparison of more traditional beach nourishment materials, such as mining inland sand (Candea 2013).

Drawing from the results of Broward County's initial Beach Demonstration Project studies, the City of San Padre Island, Texas proposed a project to investigate the environmental, economic, and regulatory feasibility of using local recycled glass as an alternative material for dune building in 2012. Phase I of the project included a feasibility assessment as well as geotechnical lab testing and analysis for grain size, color, compositions and variability compared to native beach sand. Phase II would be comprised of the demonstration project site selection, design, permitting, and installation (Bagley and Trevino 2012). It is unclear whether this project was ever carried out as no further information regarding it could be found.

Figure 2. Glass Packaging Institute (http://www.gpi.org/recycling/glass-recycling-facts)

Economic cost

The economic cost of using glass cullet as an alternative material on beaches is an important consideration for local governments. The price of recycled glass includes costs for processing, transportation, and fees paid to recyclers. Typically, glass and other recyclable materials are collected and taken to material recovery facilities (MRFs) where they are separated by type (e.g., paper, plastic, glass) (Fig 2). Glass is then sent to a processing company where it is separated by color, pulverized according to the specifications of the end user (e.g., glass container manufacturers), and transported.

Local governments that want to use glass cullet for beach nourishment can either purchase intact bottles from an MSF or buy glass cullet directly from a processing company. If they chose the former, the local government must set up its own processing facility where the recycled bottles would be broken down, pulverized into cullet, and stored if necessary. This option reduces the transportation costs of hauling the glass from the local government to the MSF and then back again but leaves the government responsible for the entire processing cost (Woodward-Clyde 1993).

Alternately, the local government can purchase crushed glass directly from a regional glass processor and pay the transportation fees to have the cullet hauled to the project site (Woodward-Clyde 1993). Drawbacks of this option include the possibility that processing plants may not be located near enough to the buyer to make the transportation costs affordable (Robinson 2016). For example, in Georgia there are only two processing facilities (located in Atlanta and College Park) that process and sell glass cullet to end use markets (GPI 2016).

A review of Broward County, Florida's cost assessment for pursuing recycled glass as a source of material for beach nourishment demonstrates how the financial aspects of glass cullet application work out in real life (Table 2). Following completion of a feasibility study (Phase I) and permitting (Phase II) for a pilot beach project (Phase III), the County commissioners met to examine the cost of renewing the project after a five-year lag due to state and federal funding cuts. Consultants prepared an estimate of future costs for the project and the three years of monitoring required by the project permits (which had by then expired). The estimate indicated that Phase I and Phase II cost the County $945,751. Phase III project costs were estimated to be an additional $1.4 million, nearly $1 million of which consisted of the cost of buying, transporting, testing, and storing glass cullet (Broward County Agenda 2013).

Table 2. Broward County Cost Spreadsheet for Beach Renourishment Project

Task	Phase I(1)	Phase II(2)	Phase III(3)	Total Cost
Design & Permitting	$240,783	$482,048	$141,986	$864,817
Regulatory permits			$20,000	
Glass sourcing			$25,000	
Grants applications			$25,000	
Project Management			$71,986	
Construction	$108,367		$936,246	$1,044,613
Material Procurement			$620,000	
Construction Contract			$156,615	
Storage			$78,308	
Geotechnical and Contaminant Testing			$31,323	
Construction/Processing Management			$50,000	
Monitoring	$114,553		$368,830	$483,383
Infauna Monitoring			$211,432	
Beach & Hydrographic Surveys			$76,743	
Compaction testing			$12,789	
Annual Report			$67,867	
Total Costs	$463,703	$482,048	$1,447,062	$2,392,813

(1) Feasibility study; public perception study; physical/chemical analysis
(2) Regulatory permit process – state and federal permits; sourcing studies; material production reviews
(3) Sourcing; construction; monitoring

Adapted from Beach Renourishment Project – recycled glass spreadsheet exhibit 1 of the Broward County Commission Meeting Agenda (08/13/2013)

One factor adding to the project's cost was the absence of a company in Florida with the capacity to produce the amount of recycled glass cullet required (Wallman 2010).The commissioners declined to pay for Phase III of the demonstration project, preferring to wait for possible future state funding (Candea 2013).

Conclusion

Research conducted to date indicates that recycled glass cullet is a viable and compatible fill material that can be safely used for beach nourishment. Geotechnical analyses of glass cullet show that grain size, color, and angularity are similar to native beach sand and biological and abiotic testing both demonstrate that recycled glass cullet is a biologically benign material that will not negatively impact microfauna or macrofauna, or interfere with sea turtle embryo development.

However, despite this evidence, economic concerns seem to play a role as to why no beach nourishment projects in the U.S. have been implemented to date. The cost of recycled glass may be prohibitive compared to the cost of inland or offshore sand mining, especially when the latter may be eligible for federal and state funds to offset the costs to local governments (Candea 2013). However, as the demand for beach nourishment material increases, the economic situation may change and local governments may reconsider recycled glass cullet.

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